Table of Contents

Page

Structural/Loads Monitoring

RNLAF/F-16 Loads and Usage Monitoring/ Management System
F. C. te Winkel / National Aerospace Laboratory NLR / NL

Acoustic Wave Propagation Phenomena Modelling and Damage Mechanisms in Ageing Aircraft
W. J. Staszewski / University Sheffield / UK
C. Boller / EADS / D

Measurement Development Technologies for Health Monitoring Applications
A. Reutlinger, R. Graue / Kayser Threde / D

New Concepts

The Topology of AIMS Data Transfer Structures
D. Jesse / Flight Data Services Ltd. / UK

An Approach to the Analysis of Data from Aircraft Integrated Monitoring Systems and Flight Simulators Intended to Support the Development of Agents Assisting the Assessment Diagnosis of Man/Machine Interactions
F. Köster, K. Mehl / Universität Oldenburg / D

The I-22 Iryda Power Plant Expert Aided Condition Monitoring System
R. Szczepanik / Air Force Institute of Technology / PL

CONDITION MONITORING MADE MORE EFFICIENT, RELIABLE AND COST-EFFECTIVE USING TESPAR®

Darren Stratton, Domain Dynamics Ltd., Thames Tower, Station Road, Reading, Berkshire, UK RG1 1LX
Tel: +44 118 9023790 Fax: +44 118 9023789 email: darren.stratton@ddl.co.uk

INTRODUCTION

The twenty first century has brought us massive data overload coupled with demands for product shrinkage and reduced costs. To tell us what is important in sufficient time for the appropriate action to be taken, we have become ever more reliant on signal processing that is accurate and trustworthy. Smart sensors on all sorts of equipment, using remote and accurate waveform diagnostics solutions, are required to warn of impending fault conditions before they occur so that maintenance intervals may be optimised and expensive unplanned industrial downtime is avoided.

The various criteria for success, including lower costs, quicker response times, increased functionality and improved performance pose mutually exclusive challenges on all equipment designers. They do, however, open up a challenge to industry to come up with better ways of doing the things that we have all been doing for years. No longer is it acceptable to do it this way "because that's how it has always been done". We have to question the established needs and methods to find ways of increasing our efficiency and effectiveness.

This paper introduces TESPAR® for Condition Monitoring from Domain Dynamics Ltd. as one way of meeting many of the objectives.

WHAT IS TESPAR®?

TESPAR® is a simple, new, efficient and patented signal processing technology for describing all time varying waveforms. It does not matter whether the waveforms are generated from acoustic, vibration or electrical signals. TESPAR® is not based on conventional frequency domain techniques like Fourier Analysis; it is simply based on a mathematically proven approach that analyses the shape of the waveform. The waveform is coded into a simple symbol stream using a proprietary TESPAR® coder. A multitude of different ways of analysing and comparing signals is made available depending on how this symbol stream is presented. The technique was invented by Professor Reg King at the University of Bath in the 1970s and Domain Dynamics Limited, which now owns all the intellectual property rights, was set up to exploit TESPAR® commercially.

ABOUT DOMAIN DYNAMICS

Domain Dynamics is a private company formed in 1990, specialising in novel signal processing and pattern recognition techniques. It has developed the TESPAR® technology and a strong international patent portfolio. Initially, primarily a Research & Development company, two significant injections of private capital have helped DDL move into the world of significant commercial exploitation.

DDL licenses TESPAR® to third parties for integration and development into end user products across various markets. To date some 30 licences have been signed for a variety of applications in condition monitoring as well as word recognition and voice authentication.

In the Condition Monitoring field, successful applications have included locating oil slugs in pipelines for BP Exploration, portable automotive diagnostic equipment for GenRad, perimeter intruder detection devices for Geoquip, automated testing of speech quality on telephone networks for Rotadata and the passive detection and identification of radar signals for digital Radar Warning Receivers for QinetiQ (formerly DERA at Farnborough). Other licences have addressed a number of process control activities as well as the detection of faults in rotating machinery. In addition to this, a comprehensive range of successful feasibility studies has been carried out for international customers on a range of continuous and impulsive waveforms in areas as diverse as crumbling bridge structures, turbine blade cracking and the breakdown of insulation in high voltage cables.

ADVANTAGES OF TESPAR®

TESPAR® offers many unique advantages.

- It lowers production costs as it requires little processing power
- It enables battery powered portable equipment as current drain is small
- It fits easily onto existing processors – even down to 8-bits
- It has low memory requirements – any signal may be represented in 58 bytes
- It is reliable and resilient in noisy environments, and
- It can distinguish between waveforms of similar spectral content

The real advantage of TESPAR® in Condition Monitoring is in its economic template and processing. This means that many existing monitoring systems can be made far more efficient by changing the analysis method to one using a TESPAR®-based solution. This will either enable the creation of “spare” memory and processing power so that additional functionality may be added for no extra cost or enable lower cost components or miniaturisation to be more economically achieved.

TESPAR® also enables a new approach to testing using battery-powered portable monitoring equipment to give a simple decision on whether equipment is working properly. This means that, for example, that subsystems of major assemblies, like for instance aircraft engines, can often be tested in situ and only removed from service when shown to be in need of service, tuning or repair.

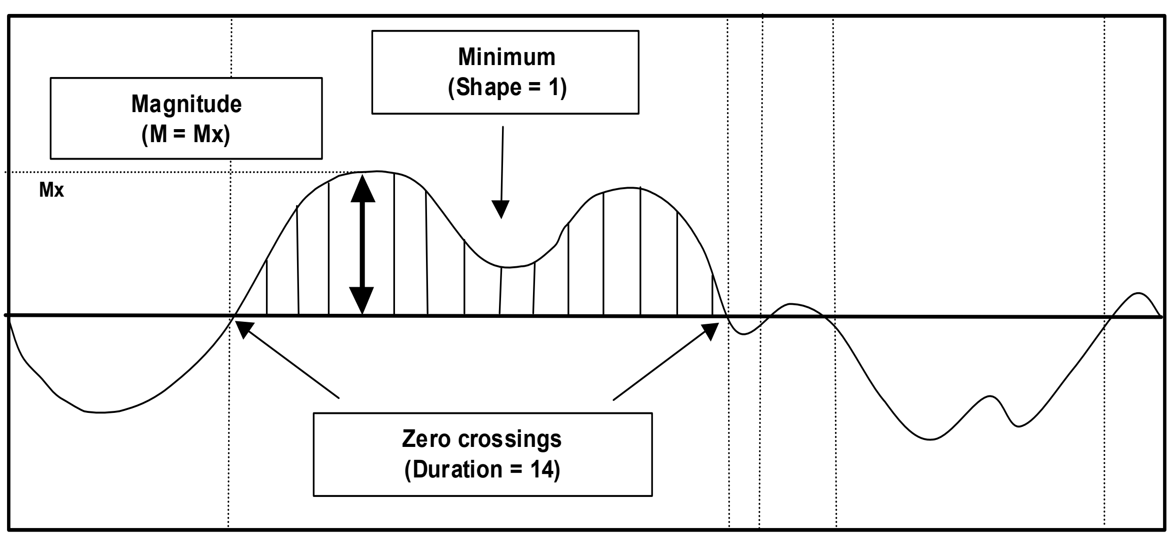
There are also instances, particularly relating to rotating machinery, where conventional technology has problems recognising and classifying changes of condition. In many of these situations, the use of a TESPAR® solution not only enables the false alarm rate to be radically reduced but also improves the recognition ability so that it becomes possible to offer a classification capability in addition to the straight GO or NO GO decision.

HOW DOES TESPAR® WORK?

The raw signal is collected from the equipment being monitored by means of an appropriately placed sensor. The sensitivity and bandwidth of the sensor must of course be sufficient to contain the area of interest of the signal. This may not necessarily be the same area as reviewed by FFT techniques and Domain Dynamics have developed and offer consultancy advice and assistance in determining the specification for any application.

The signal is then pre-amplified, if necessary, and filtered before being input to an analogue to digital converter sampling at a significantly higher rate than Nyquist. As a default, a filter range of between 10:1 and 20:1 is preferred and a 12-bit ADC is typical; neither of these are however prescriptive. Then, depending on the type of signal a wide range of pre-processing algorithms, including integration and differentiation, are available to put the digitised signal into the most effective form for processing. This pre-processing is designed to ensure that there is sufficient data for effective classification and that all parts of the signals are treated with similar status by the TESPAR® process. Finally, before input to the coder, any DC offset is removed to ensure that, when comparisons are made, like is being compared to like.

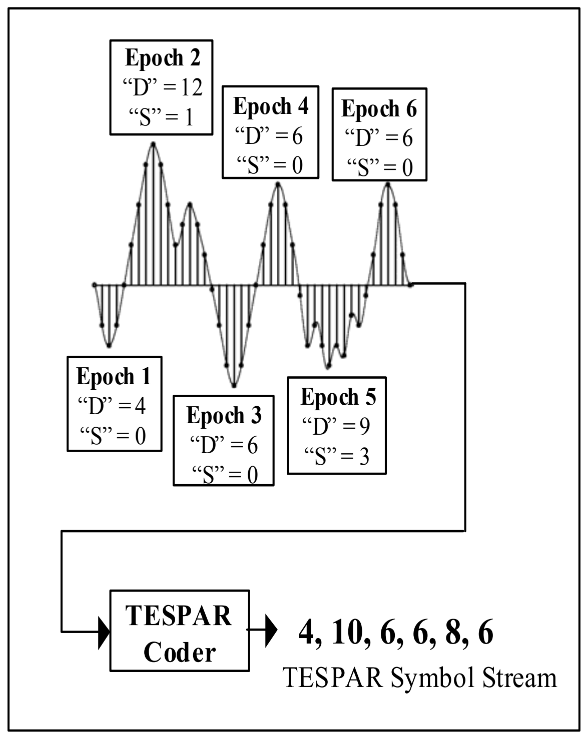
The proprietary TESPAR® coding process is then undertaken as shown in the diagrams that follow.



The pre-processed waveform is sampled appropriately. The proprietary coder identifies the zero crossings of the waveform and, for each consecutive pair of crossings (called an epoch) it calculates three features namely the duration or number of time samples, the shape or number of positive minima or negative maxima, and the peak amplitude. From that information, by means of a look-up table, part of which is shown below, it converts each epoch into a symbol, and thus the whole waveform into a simple symbol stream.

The table was developed initially empirically before its mathematical foundations were researched. It groups various epoch shapes together in a manner that has been scientifically proven to represent an excellent approximation to the waveform, it also excludes combinations of shape and duration which can not occur given the bandwidth of the signal. By this means it reduces the number of symbols required to describe any waveform to an alphabet of 29. It should be noted, however, that because it is an approximation, it is not possible to reconstruct the original signal accurately from the coded one.

	S=0	S=1	S=2	S=3	S=4	S=5
D=1	*1*					
D=2	*2*					
D=3	*3*					
D=4	*4*	*4*				
D=5	*5*	*5*				
D=6	*6*	*6*	*6*			
D=7	*6*	*6*	*6*			
D=8	*7*	*8*	*8*	*8*		
D=9	*7*	*8*	*8*	*8*		
D=10	*7*	*8*	*8*	*8*	*8*	
D=11	*9*	*10*	*10*	*10*	*10*	
D=12	*9*	*10*	*10*	*10*	*10*	*10*
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
D=37	*23*	*24*	*25*	*26*	*27*	*28*



The resulting symbol stream can then be represented in a number of ways, the simplest of which is a histogram, or S matrix, which records the number of times each symbol appears in the stream. Since there are only 29 symbols available to describe the waveform, it follows that, to 16-bit accuracy, every signal can be represented in 58 bytes. Although this is the simplest case, more typical representations either segment the waveform to give better discrimination or use a two-dimensional matrix representation constructed from the number of occurrences of pairs or symbols. Even in the worst case, the template to describe a signal can never exceed 2 Kbytes, whatever the duration of the signal.

Having created a matrix of whatever kind, to represent the signal, the next stage is very straightforward. It can be compared with a pre-stored library of matrices representing known conditions; it can be compared with a matrix taken earlier from the same equipment to see if anything has changed; or it can be added to previous matrices to form an "archetype" from which generalisations or trends may be deduced. The facility also exists to create artificial archetypes, by averaging two different archetypes, to represent an operator created alarm level part way between known good, or normal operating condition and a known fault so that the operator can be alerted to take action before the fault condition actually manifests itself.

The methods of comparison are standard. Typically for condition monitoring applications, statistical correlation techniques, which are simple to apply, work well but, in more complex cases, smarter classifiers such as neural networks may be used. The TESPAR® representation is ideal in this case as the size of the matrix being used as input to the network remains constant whether or not the signals being compared are of the same duration. This is a significant advantage and enables the relevant networks to be trained in seconds. The combination of TESPAR® and Fast Artificial Neural Networks is part of the DDL patent portfolio.

TESPAR® IMPLEMENTATION

Implementation of TESPAR® solutions in Condition Monitoring is no more difficult than introducing a conventional system and, given some of the unique advantages, it may well end up much simpler.

The key to the effectiveness of any monitoring system is the selection and placement of the appropriate sensor. DDL has a wealth of experience in this field. Customers are actively encouraged to seek advice to ensure that the sensor is placed appropriately and that any connections from it to the monitoring system are made in an effective fashion so that the raw signal is collected and transmitted as cleanly as practical to the analysis engine.

Once this is done and the signal is available, efforts are then directed at determining which part of the signal contains the key information to enable decisions to be made and then an initial TESPAR®specification is created for that. This is typically done by means of a funded feasibility study where, if necessary, DDL will assist in the data collection and then undertake the analysis to prove that the signals of interest can be identified and separated.

The next stage is to optimise the specification and then to incorporate the selected front-end processing into the TESPAR® engine.

The solution can be as simple as 200 lines of C code to provide a six condition recogniser, with each condition being represented by an archetype as described above.

Such solutions can then be implemented on a stand-alone basis on an 8-bit processor such as the industry standard 8051 or can be ported onto whatever existing processor or DSP is already available to control the process.

TESPAR® EFFECTIVENESS

TESPAR® enables high performance solutions that are typically up to two orders of magnitude simpler and cheaper than conventional options. The economy of these solutions is primarily based on the small signal template and the resultant solutions can be implemented on existing hardware.

In addition, TESPAR® can be used in conjunction with conventional technology. Because the fundamental technological approaches are different, each solutions strengths and weaknesses are different thus combining the two will enable increased discrimination otherwise not available.

Finally, TESPAR® enables different waveforms of similar spectral content to be distinguished providing additional reliability.

SUMMARY

The advantages of TESPAR® listed below provide a new set of tools for the Condition Monitoring industry that enable more efficient and cost effective solutions to be implemented.

These advantages include

- Fixed and compact data representation
- Low computing power, memory and current drain
- Resistant to impulsive and background noise
- Overcomes time variability problems
- Ideally suited for input to smart classifiers
- Enables effective data fusion
- Excellent performance
- Low cost of implementation.

Combination of these advantages leads to product enhancement, problem solving and innovation and as has been demonstrated TESPAR® is cost effective, easy to use, quick to get results, protected by patents and available now.

ARCHITECTURE OF THE AIRBUS A380 ACMS

Mark Wiegmann

Airbus Deutschland GmbH
Kreetslag 10
21129 Hamburg

1. INTRODUCTION

A couple years ago, the Airbus Data Recording Systems Group started with the experience from the A340 / A320 and a collection of new ideas and suggestions to design the ACMS for the novel Airbus A3XX to come [1]. Meanwhile, not only the name of the aircraft has evolved but also the architecture of the A380 ACMS has become more specific. Since the A380 will introduce a number of new technologies to Airbus aircraft, or even more general, to commercial aircraft, the ACMS design tracks these technologies to use them efficiently for condition monitoring purposes. Especially the different architecture of the A380 avionics, including the Avionics Full-Duplex Switched Ethernet (AFDX), influenced the design of the A380 ACMS on a wide scale. This paper is intended to give some insight into the architecture of the A380 ACMS, which will differ in some details significantly from the ACMS, as we know it from today's aircraft, like the A340.

2. COTS AND CLASSICAL AVIONICS TECHNOLOGY FOR A NEW GENERATION OF ACMS

The usage of Commercial Off-The-Shelf (COTS) hardware and software is a current issue when talking about aircraft system (re-)design. This is also true for non-critical avionics applications onboard the A380. As an example, large parts of the processing of maintenance data will be no longer done by a dedicated avionics computer but by the aircraft Network Server Unit (NSU), which relies on COTS components. This server and its peripheral hardware form the environment which A380 developers call the "open world" to have a clear distinction from the classical avionics.

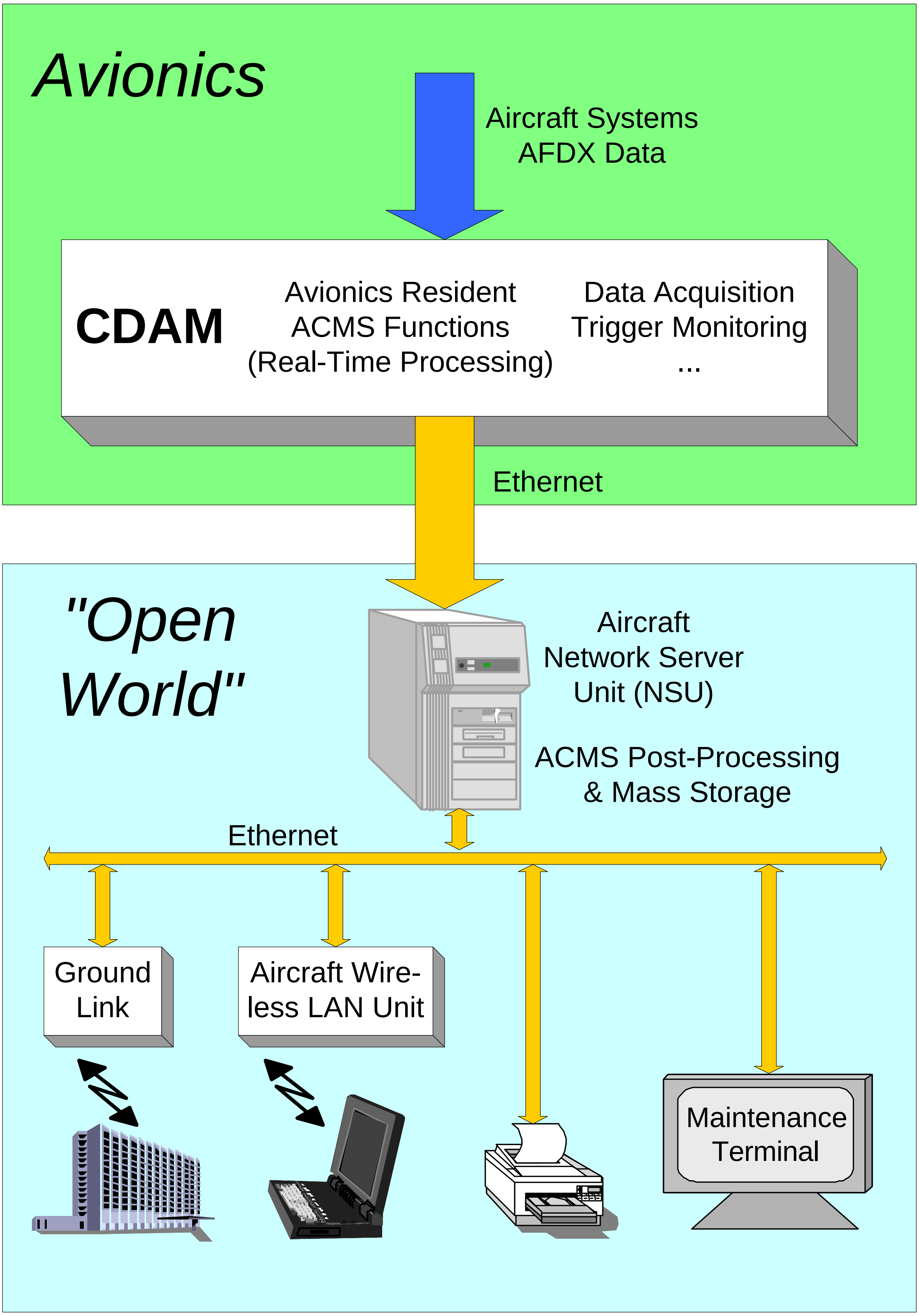


Fig 1: ACMS partitioning and integration onboard the A380

This “open world” NSU will also host parts of the A380 ACMS, along with other applications, since ACMS is a non-critical application. The advantages of this approach are evident. The processing power, the amount of memory and the non-volatile storage capacity provided by COTS components in the NSU are easily scalable and upgradeable at competitive costs. But, as said before, this concept is only viable for non-critical avionics functions. For most avionics applications safety and integrity issues inhibit the use of COTS components. So, the classical avionics with its special to type design, following approved design procedures, will still play a major role onboard the A380.

While regarding the advantages of an “open world” implementation of the ACMS, it has to be seen that the ACMS requires some real-time capabilities in order to deliver meaningful data. Besides that, the ACMS collects nearly all of its condition monitoring data from aircraft systems located in the classical avionics. Consequently, it is not sufficient to implement ACMS just as a function on the NSU, which is not able to provide real-time services. A dedicated hardware to interface the ACMS with the avionics is necessary. Moreover, this hardware must deliver a noticeable amount of processing power to cope with the large number of aircraft systems parameters to be acquired. So, the ACMS is split up between the avionics on the one hand and the “open world” on the other hand. Besides the ACMS server application on the NSU there is the Centralized Data Acquisition Module (CDAM) in the avionics. The purpose of the CDAM is to collect the data from all systems monitored, and it ensures that the parameters collected from the aircraft systems are processed in real-time. Although the definition of real-time in the context of the ACMS may not adhere to the strict definitions of control and automation theory, it still guarantees that a maximum latency due to the processing is not exceeded, so that simultaneous events can be detected as such and the order of occurring events in time is preserved.

As soon as the events are correctly registered through CDAM real-time monitoring, the related data can be sent to the ACMS server application on the NSU for further processing and storage. Moreover, the graphical display capabilities and broadband communication means (Satcom, Wireless Gate-Link, Portable data loading media) of the “open world” can be used.

3. AFDX APPLICATION ONBOARD THE A380

3.1 General concept of AFDX networking

One feature that distinguishes the A380 from all previously built Airbus aircraft is the use of an AFDX network as the main communication means for avionics applications. AFDX means Avionics Full-Duplex [X] Switched Ethernet. The word Ethernet hints again at the use of COTS technology. It is not necessary to re-invent messaging protocols, addressing schemes or the principle of packet switching, to mention only a few arguments. So it was convenient to reuse huge parts of Ethernet as defined by IEEE 802 [2]. But due to the special requirements for intra avionics communications, Ethernet had to be enhanced to form AFDX.

The reason that inhibits standard Ethernet from being used for control purposes is its lack of determinism. AFDX overcomes this shortcoming with a twofold strategy.
Firstly, AFDX is a full-duplex switched Ethernet. This means, the aircraft systems connect with their AFDX interfaces, the AFDX End Systems (E/S), to special AFDX switches. As a consequence, the connections from the E/S to the switch are always collision free domains. So, packets travelling on the links between AFDX switch and E/S have an extremely high probability to reach their destination within a determined period of time.
Secondly, AFDX uses the concept of Virtual Links (VLs) to ensure a bounded latency for connections crossing the AFDX network through a number of switches. A VL is basically a fixed route through the network for which a specific portion of the network bandwidth is allocated and which has exactly one starting point and at least one destination point. This allows packets to travel on these VLs without the danger of being stuck in a network congestion.

The network management has to ensure in every network section that the sum of the bandwidth allocated to the VLs in a particular section does not exceed the available network bandwidth. In order to facilitate this task, the routing in the A380 AFDX network will be static. Additionally, the AFDX E/Ss have to ensure by traffic scheduling not to send more data into the VL than the allocated bandwidth allows.

Besides this physical purpose, the VLs also serve as a logical grouping. Where ARINC 429 buses have been used in the past, VLs will be used in the A380. While ARINC 429 buses form a physical and logical entity, the VL relies on the shared physical medium AFDX. But from the logical viewpoint VLs and ARINC 429 busses are interchangeable, both have exactly one source and at least one destination plus a guaranteed bandwidth.

3.2 AFDX network as a source for ACMS data acquisition

The introduction of the AFDX network in the A380 meant a big change in the design of the ACMS hardware for the acquisition of aircraft data compared to the hardware used in previous Airbus aircraft. Instead of a number of ARINC 429 receivers, the A380 ACMS needs AFDX interfaces to "listen" to the data sent over the network. The CDAM located in the A380 avionics will be the hardware to host these interfaces, as depicted earlier.

From a logical point of view, it would be sufficient to equip the CDAM with a single AFDX interface and to use the potential of internetworking to relay all relevant data from the aircraft systems over the AFDX network. In contrast to that, the actual CDAM designed for the A380 will have a number of AFDX interfaces so that it connects directly to each AFDX switch onboard the aircraft. The reason for this dimensioning is the potentially huge amount of AFDX traffic that has to be routed to the CDAM. The analogy of VL and ARINC 429 bus shows that the CDAM has to be a subscriber of a particular VL as soon as any information has to be acquired which is transported on this VL. So, all VLs in the whole A380 AFDX network could be routed to the CDAM, in principle. If there were only a single AFDX interface on the CDAM, this would incorporate a huge amount of additional AFDX traffic to be transported through the network to this interface just for condition monitoring purposes. Thus, the ACMS would be a sizing factor for the whole AFDX network. To make things worse, the amount of additional network traffic may vary substantially depending on the programming of the ACMS, which is widely reconfigurable by airline users. To avoid the impact of the ACMS data on the AFDX network the CDAM is connected directly with a dedicated AFDX interface to each switch onboard the A380. This way, the data traffic generated by any E/S for ACMS is taken directly off the network in the particular switch to which the generating E/S is connected and the network remains unaffected, no matter how much data is sent to the CDAM. This architecture thus supports the task of network load balancing.
To clarify the situation explained above: The data on the VLs, which the ACMS receives for condition monitoring, is usually sent from one aircraft system to another but is not explicitly pointed at the ACMS. The latter only takes a copy of the AFDX messages that are already available for

its own purposes. Generally, the ACMS does not influence the amount and kind of traffic on the network through its condition monitoring tasks.

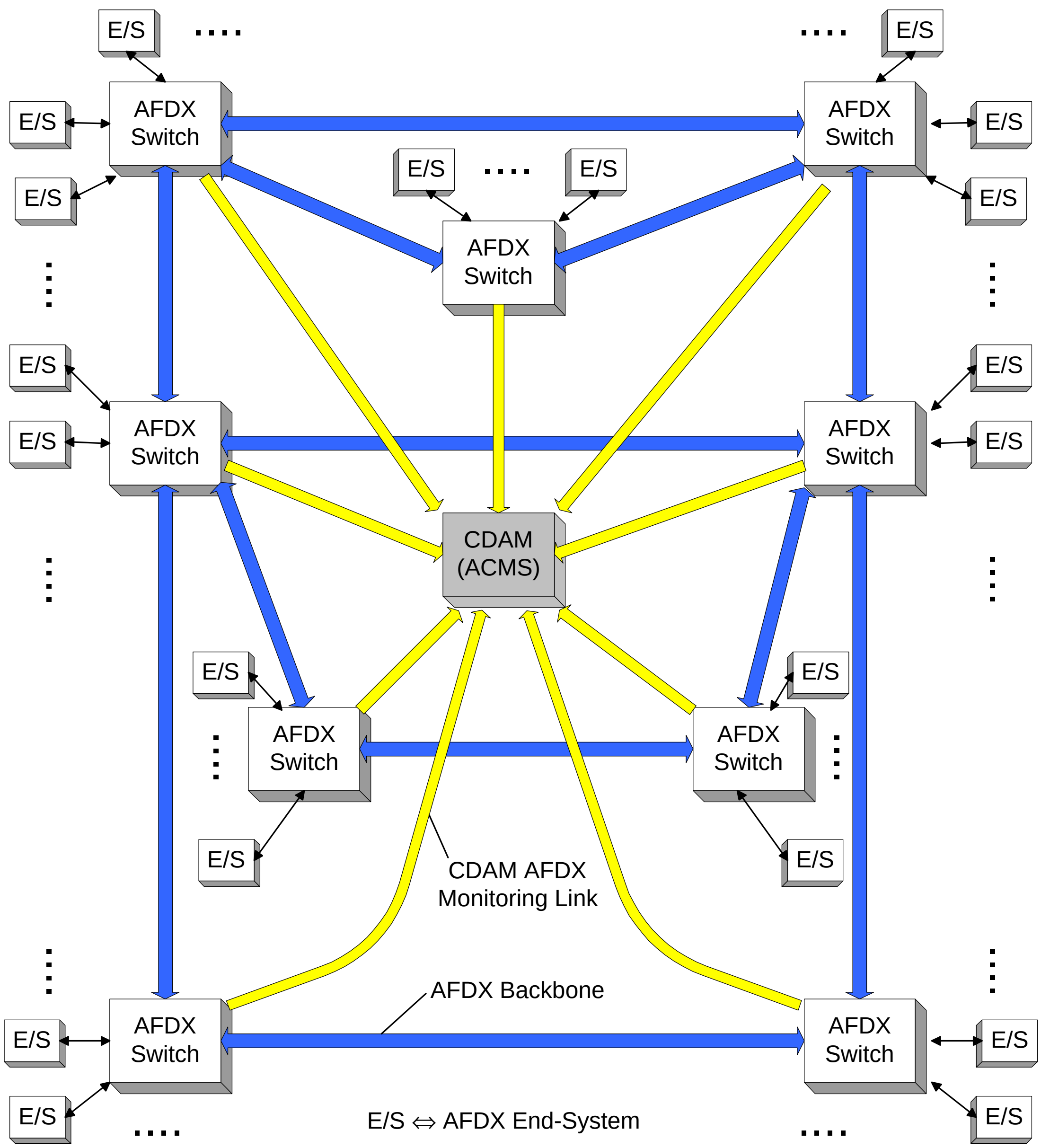


Fig.2 : CDAM collects data from the AFDX network

The great advantage, which the use of AFDX for data acquisition brings to ACMS, is that the decision, which aircraft parameters to acquire, is no longer determined by hardwiring but by software programming. So with the right provisions, this ACMS architecture allows the arbitrary acquisition of every parameter in the aircraft, as long as it is broadcast on the AFDX network. This constraint should not be a restriction, since AFDX is the main communication means for the A380 avionics, so that every system has access to it and can publish its parameters on it. Consequently, the selection of parameters to be acquired can be modified very quickly by pressing a few buttons onboard the aircraft or remotely on the ACMS Ground Support Equipment.

4. WIDE SCALE PROGRAMMABILITY OF ACMS

As pointed out in the previous sections, the new architecture for the ACMS onboard the A380 leads to the situation that its configuration is mainly controlled by software. All VLs carrying AFDX packets of potential interest for ACMS are routed into the CDAM, which hosts the smart AFDX data acquisition interface of the ACMS. If the VL carries only packets that are not requested for acquisition in the current ACMS set-up, all these packets will be discarded in a very early stage of the CDAM processing chain. But as soon as there is data to be acquired on a VL, all packets on it will be examined to sort out the ones carrying the desired information. Since this process is completely software controlled, it is quite easy to change the definition of the data compilation that has to be acquired by the CDAM.

The ACMS will comprise software that runs on a computer on the ground, the so-called Ground Support Equipment (GSE). This GSE offers the full configuration possibilities for the ACMS. The ACMS set-up defined with the GSE is transferred to the ACMS aboard the aircraft by data-loading operations. This data transfer can be supported by the application of the broadband communication means of the “open world” (e.g. Satcom, Wireless Gate-Link, Portable Data Loader) in combination with the AFDX and Ethernet networks onboard the A380.

The ACMS in the A380 will generally offer three functions, which are ACMS Reporting, Smart ACMS Recording (SAR) and Real-Time Parameter Display. All three functions are fully configurable through the GSE and thus are at the disposal of the airline engineering. For the reporting it can be individually defined which aircraft parameters shall be in a report, in which representation and under which conditions the report shall be generated. The latter definition is also known as “trigger logics”. The same options are modifiable for the SAR, since it is the time-continuous extension of the reporting function. Of course, some extra properties, like sampling rates etc., can be individually defined with the GSE for this function. For the Real-Time Parameter Display function it is intended to pre-define a number of application or system specific display screens containing a compilation of parameters of frequent interest in the scope of the application or system.

The software onboard the A380 offers a subset of the GSE functionality, since it is not convenient to do extensive configuration work onboard the aircraft. The onboard software supports the modification of margins and thresholds for existing reports and SAR definitions, as well as the selection of additional parameters for the Real-Time Parameter Display function.

5. ADDITIONAL SERVICES OF ACMS FOR OTHER SYSTEMS

Due to its architecture and hardware capabilities the ACMS in the A380 is able to offer some extra services for other aircraft systems, besides the three original functions discussed in the section above (Reporting, SAR and Real-Time Parameter Display). One of the distinctive extra services are the Remote Server Acquisition (RSA) function and the Avionics Broadcast-Data Collector (ABDC) function.

As explained earlier, the A380 avionics will be divided into two parts. On the one hand, there is the classical avionics. On the other hand, there is the “open world” relying on COTS components. The applications residing on various computers in the “open world”, not necessarily installed and certified by Airbus, often request to have access to avionics parameters, like airspeed or heading, e.g.. For reasons of practicality and security, the direct access from the “open world” to the avionics is technically disabled. So, there is the need for a special interface for the “open world” applications to gain access to avionics parameters. To extend the ACMS for providing this interface is an obvious choice for two reasons. Firstly, it is located as well in the avionics as in the “open world”. Secondly, nearly all parameters that could be requested from “open world” applications are collected by the ACMS, anyway. And finally, the ACMS can provide virtually every requested parameter due to its programmable acquisition capabilities.

Consequently, the ACMS provides the depicted interface with the combination of the CDAM RSA function and the NSU hosted ABDC function. If an “open world” application needs an avionics parameter, it publishes its request towards the ABDC function. The ABDC function provides an Application Programming Interface (API) for this kind of requests. As soon as the ABDC software receives such a parameter request, it checks if the parameter in demand is already available within its database. In case of a positive answer, the parameter is sent back to the requesting application via the API. If the parameter is not already available, the ABDC can reconfigure the tables of parameters to acquire for the RSA function. After collection of the requested parameter from the avionics by the RSA function in the CDAM, the parameter is sent to the ABDC function and finally provided to the requesting “open world” application through the API.

6. CONCLUSIONS AND OUTLOOK

The design of the A380 ACMS moves the limits of ACMS towards new boundaries and challenges. With the use of AFDX the ACMS is no longer limited to the processing of the parameters selected for acquisition by hard wiring. Virtually every avionics parameter onboard the aircraft is now available for condition monitoring purposes. The arising challenge is to cope with the huge amount of data to handle. Firstly, it is a challenge for the hardware to cope with the concurrent processing of thousands of parameters at possibly high sampling rates. Secondly, it is a challenge in terms of efficient information management. With the new kind of ACMS onboard the A380 it is possible to acquire Gigabytes of data during a long-range flight. At the same time, transferring this amount of data on wireless links will induce considerable costs, even when using the most modern broadband communication means.

But for both challenges perspectives are quite good. Computer processors are becoming more and more powerful. Memory capacity for mass storage and on silicon is rapidly growing. So the hardware for the ACMS will be powerful enough, although the airborne use puts constraints on the sizing factors weight and power consumption.

Concerning the issue of information management, the need evolves for computer based ACMS data analysis tools. But this seems to be more than natural: computer generated data should be processed by computers, not by humans. A sophisticated pre-processing of ACMS data onboard the aircraft will allow to transfer only the very essential data from the aircraft to the ground in order to enable the engineering staff to derive the appropriate decisions. In this perspective, this new generation of ACMS, as it is designed for the A380, forms a basis for advanced system diagnostic and analysis tools to be developed in the future.

7. REFERENCES

[1] “Concept for A3XX Aircraft Condition Monitoring”, Michael Verhufen, Proceedings of the 19th Symposium Aircraft Integrated Monitoring Systems, Garmisch-Partenkirchen, Germany, 1998

[2] IEEE 802 LAN/MAN Standards Committee http://www.ieee802.org

DEVELOPMENT OF A DATA ACQUISITION AND PROCESSING SYSTEM FOR A MICRO-AERIAL-VEHICLE (MAV)

Marco Buschmann, Thomas Kordes, Peter Vörsmann

Institute of Aerospace Systems, Technical University of Braunschweig,
Hermann-Blenk-Straße 23, 38106 Braunschweig, Germany

ABSTRACT

Micro-Aerial-Vehicles (MAV) are small fixed-wing or rotary-wing aeroplanes with the size of birds and the capability of (semi-)autonomous flight. Hence the applications for such a system for both civil and military missions are mainfold. The Institute of Aerospace Systems (University of Braunchweig, Germany) is now developing a fixed-wing MAV with a wing-span of 40 cm that shall be capable of fully autonomous navigation. For this purpose, a miniaturized INS is under development, based on low-cost micromechanical gyroscopes and linear acceleration sensors. It is planned to integrate GPS into the navigation system in order to to utilize such low-precision sensors for the purpose of flight control and autonomous flight. For development and evaluation of the sensor hardware and future flight control systems, an on-board flight computer is now under development as well. This system basically consists of a data acquisition system and a data processing computer, which is connected to a ground base via a telemetry link to allow data recording and real-time visualization.

INTRODUCTION

Micro Air Vehicles

The term Micro Air Vehicle (MAV) describes a class of aircraft that have the size of small birds. Future plans even include the development of MAVs as small as insects. Additionally of being the smallest man-made aircraft, MAVs also represent miniaturized, intelligent, and autonomous flying robots. Due to their special characteristics, there is a wide range of applications for these small vehicles. Equipped with special sensors, they can fulfil reconnaissance and surveillance missions like air quality determination or traffic monitoring. As further examples, they are able to monitor hostage situations or locate sources of contamination after chemical or radioactive accidents.

The Project "Carolo"

Several approaches were made worldwide towards a microplane with sub-meter wingspan. For example, Grasmeyer et al. [1] and Morris [2] describe remote-controlled microplanes with wingspans less than 15 cm. However, the integration of completely autonomous navigation capability is still a big challenge. At the Institute of Aerospace Systems, the project "Carolo" does not try to minimize size and weight to its extent, but puts emphasis on the capability of fully autonomous navigation. The name "Carolo" is derived from the name of the "Technical University Carolo Wilhelmina of Braunschweig". The design of the first prototype "Carolo I" is shown in Figure 1.

Figure 1: Prototype “Carolo I”

To achieve the goal of completely autonomous navigation, several special subsystems are essentially important, like a microminiature Inertial Measurement Unit (IMU) and a small GPS-receiver. The development and first experiences with two different kinds of micro-machined angular rate sensors and a first approach to integrate these sensors into an Inertial Measurement Unit is described in the first part of this paper.
The second part of this paper describes the on-board computer concept for the first micro-plane prototype “Carolo I”. The on-board computer consists of an already developed and tested Main System Controller (MSC) that acts as an interface to sensors, actuators and telemetry. Integration of a Flight Data Processing Unit (FDPU) to host the rather complex flight control and navigation algorithms is in progress.

SIMULATION OF A MICROPLANE

It is an important part of the design process, especially for controller design, to get a realistic image of the dynamic behavior of a microplane. For this reason the development of an advanced simulation tool is in progress as described below.
Due to their small mass and moments of inertia, MAVs have very dynamic characteristics, especially in a real environment with turbulent atmosphere and gusty winds. The usual assumption of small angles, particularly the EULER angles, is not valid. Hence the state space formulation with the linearized equations of motion is not sufficient to describe the coupled dynamics of these vehicles. Because of the fact that the vehicle and the wind velocity have the same order of magnitude, the simplification of linear aerodynamics cannot be applied. There are also some special MAV related effects like the angular momentum of the propulsion system which have to be considered.
The atmosphere’s movement is the major cause of the disturbance of the trajectory and flight attitude. Especially these small vehicles are very sensitive to atmospheric influences. For this reason static and turbulent wind models are implemented in the simulation environment [3]. In order to take these effects into account, a model with the complete non-linear differential equations of motion [4,5] in consideration of actuator dynamics and non-linear aerodynamics is derived.
This package provides a base for controller design and allows to derive requirements for actuator characteristics and sensor accuracy. The simulation tool is based on the MATLAB/SIMULINK® software package. Figure 2 shows the complete model.

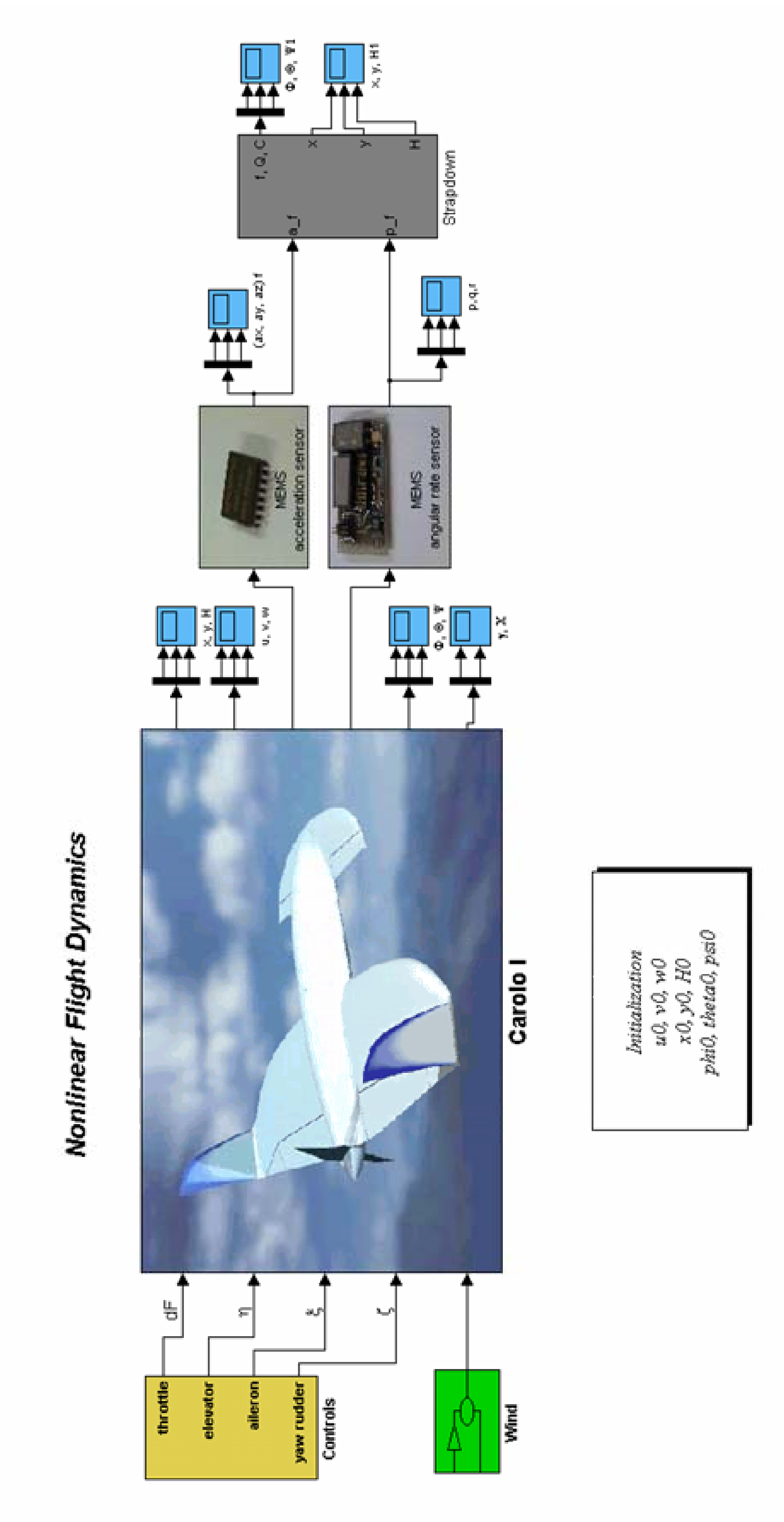


Figure 2: Simulation Environment

THE INERTIAL NAVIGATION SYSTEM

For attitude control as well as trajectory control, the EULER angles of the MAV have to be determined. This is done with a strap-down algorithm that uses the linear acceleration and angular rate. Linear acceleration and angular rate are measured by the Inertial Measurement Unit (IMU). Usually, all 6 degrees of freedom are taken into account by measuring the three angular rates and the three linear accelerations. To meet the severe constraints of size, weight and power consumption for a microplane, conventional IMUs or complete INS as used in conventional planes are not applicable.

Inertial Measurement Sensors

For the use in microplanes, only micro-electromechanical systems (MEMS) seem to be applicable. As an example, a 2-axis acceleration sensor made by Analog Devices [6] as shown in Figure 3 has a footprint of 10 mm x 10 mm, a height of 5 mm and a weight of less than 5 g.

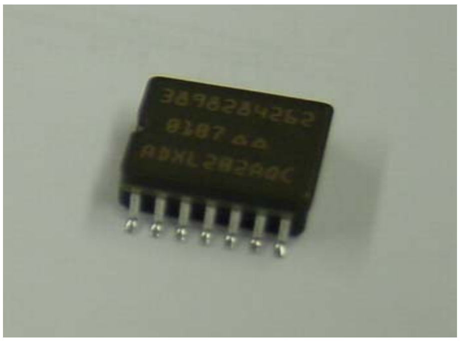


Figure 3: Two-Axis MEMS-Sensor (Analog Devices Inc.)

Based on low-cost MEMS angular rate sensors made by Murata [7], a simple 2-axis sensor module for angular rate was developed. The unit measures 40 mm x 25 mm and can be equipped with a third low-cost angular rate sensor to determine all three angular rates. The assembled sensor module is shown in Figure 4.

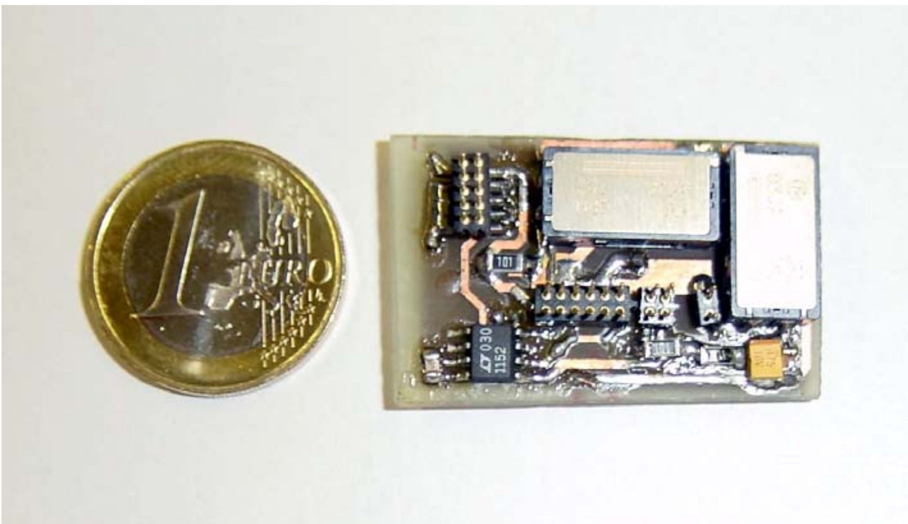


Figure 4: Two-Axis Sensor Module for Angular Rate

Since this module was developed for test purpose only, acceleration sensors have not been integrated. The weight of the unit is less than 15 g and the power consumption is approximately 50 mW, using a power supply of 3.3 Volt.
Simulations as described in the previous sub-section have shown that sub-meter-range microplanes are highly dynamic systems and thus very high angular rates can be expected. The chosen rate sensors allow the measurement of angular rates up to ±300 deg/s with a sampling rate of up to 50 Hz.
The inherent problem with MEMS angular rate and linear acceleration sensors is the rather poor accuracy compared to conventional sensors for IMUs. The main problem is the rather high drift and temperature dependency of the output signals. The developed 2-axis angular sensor module allows the determination of very fast angular movements, but the long-term accuracy of the system is very poor. First tests showed fluctuations of the output bias of up to 1 deg/s at constant room temperature (changes of less than 0.5 °C). Since the EULER angles are calculated from the measured angular rate data by integration, the sensor drift results in unacceptable angular errors.

Integration of GPS

To compensate the drift errors of the IMU, the fusion of IMU data with reference data of higher accuracy is possible. One common way is the use of GPS position data. Commercially available GPS receivers deliver the absolute position with accuracies of ±10 m and better even without the use of differential GPS. However, GPS provides only information about position and velocity, not about the EULER angles.
Several filter techniques exist to combine GPS position data with IMU data, the most common are complementary filtering and Kalman filtering. Different implementations of these filtering techniques are now tested with the described simulation environment. A promising approach for data fusion is described by Wagner et al. in [8].

ON-BOARD COMPUTER

The main tasks of the on-board computer are to manage the data flow between the different subsystems and to host the algorithms for flight control and navigation. The first task mainly requires the capability to read and generate different kinds of electrical signals. This depends primarily on the hardware components, it is hardware-based. The second task, hosting the control algorithms for flight control and navigation, is mainly software-based. Due to this principal separation of tasks, a modular structure for the on-board computer was chosen:
The Main System Controller (MSC) ensures communication with the MAV-subsystems and the Flight Data Processing Unit (FDPU) hosts the software for flight control and navigation. Both modules communicate with each other via a robust synchronous serial connection. Additional modules can be added to integrate special payloads into the microplane. Figure 4 shows the actual configuration.

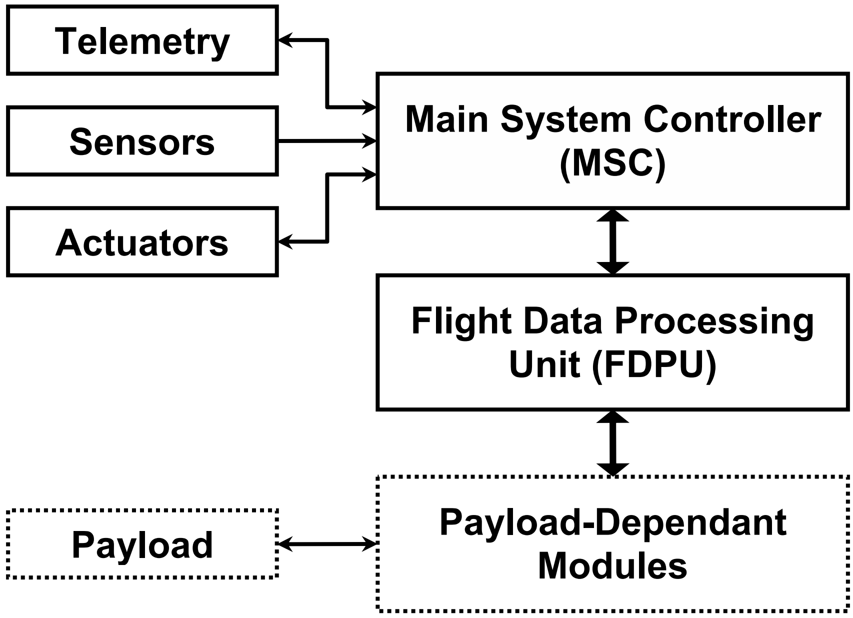


Figure 4: On-Board Computer Structure

This separation into software-based and hardware-based tasks has several advantages:

1. Major changes of the overall subsystem configuration can be easier accomplished, since only the MSC module has to be adapted. The FDPU-module can probably remain unchanged.
2. Significant changes of the control algorithms can be implemented without changing the hardware interface to the other subsystems, thus avoiding the risk of unintentionally reprogramming or reconfiguring the interfaces to the subsystems.
3. The telemetry system is connected to the MSC and not directly to the FDPU. When testing new control algorithms, there is a significant chance for a critical program error to occur. Even though modern operating systems for embedded computers prevent the complete system from crashing in most cases, the danger remains. Due to the rather simple structure of the MSC's program, the MSC has a much higher reliability. Thus rendering the MAV still of being capable to be remote-controlled even in the case of critical failure of the FDPU.

Main System Controller (MSC)

The Main System Controller consists of a 16-bit RISC-like microcontroller running at 4 MHz which integrates most of the demanded hardware interfaces. In its present state, the MSC offers the following interfaces:

- 8 analog input channels (12 bit resolution)
- 6 digital pulsewidth-modulated outputs, suitable for controlling model servos
- 1 asynchronous serial interface for telemetry
- 1 synchronous serial interface to the FDPU
- 14 digital general-purpose I/O lines, for additional periphery or digital control functions

The on-board analog channels are used to measure the angular rates of the described sensor module and will later be used in combination with acceleration sensors to form a complete IMU with the Main Systems Controller. The resolution of only 12 bits seems to be too low for adequate inertia measurement, but considering the rather bad quality of the sensor signals themselves, this resolution should be sufficient. This fact once more stresses the importance of integrating GPS data into the IMU to achieve long-time reliability.
The first implementation of the MSC was developed at the Institute of Aerospace Systems as a Final Project in 2001 [9]. The developed printed circuit board of the Main System Controller is shown in Figure 5.

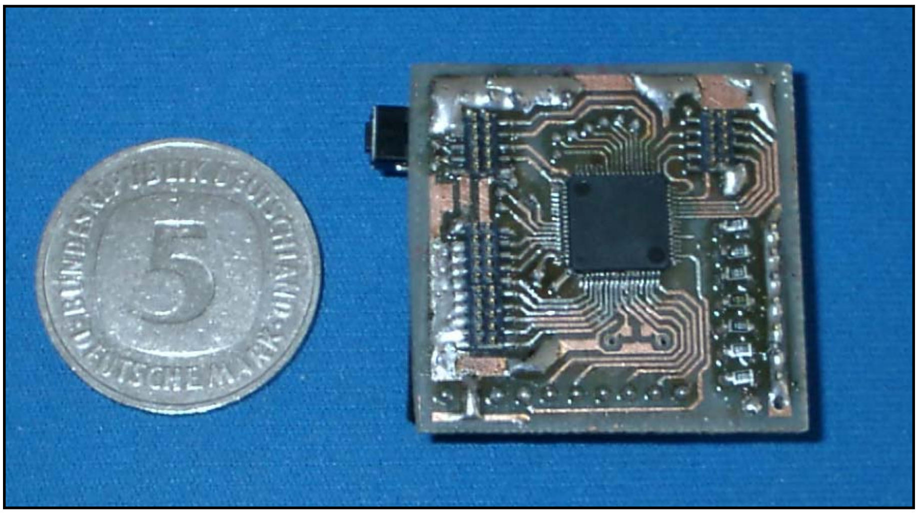


Figure 5: Main System Controller Board

The module's dimensions are 40 mm x 40 mm x 5 mm (without servo connector pinheads) with a mass less than 8 g. The power consumption of the module is approximately 35 mW, using an internally regulated voltage of 3.3 V. The first software was written in assembler, ensuring high code efficiency for the data interfacing tasks.

Flight Data Processing Unit (FDPU)

For in-flight data processing, a separate module is used. Due to the complexity of the control algorithms, a 32 bit RISC processor was chosen. The FDPU was manufactured by the company μ-Blox and is shown in Figure 6.

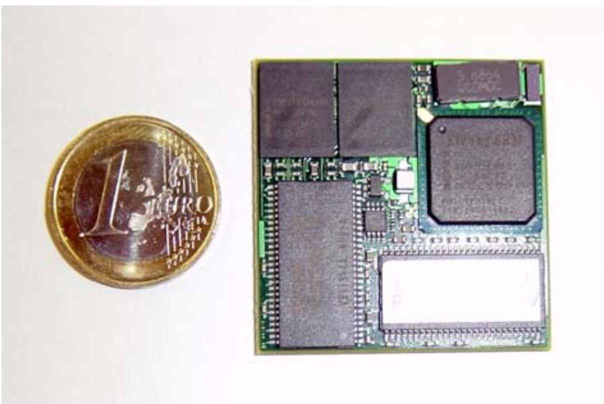


Figure 6: Flight Data Processing Unit

In addition to the CPU with 200 MIPS, it contains 32 MB Flash-ROM and 64 MB SD-RAM. All components are integrated into a multi-layer board. Its dimensions are 40 mm x 40 mm x 8 mm. The weight of the unit is less than 10 g and the average power consumption at full operation is less than 500 mW.
On the one hand considering the calculating power, the memory resources and the power consumption, the FDPU seems to be oversized for the given task of attitude control and navigation. On the other hand, the module offers enough spare capacity to host even very complex algorithms that are not runtime-optimized. This allows easy implementation and debugging of new algorithms. The size of the on-board memory also allows the implementation of extensive databases for high-resolution digital maps. Considering the fact that the first prototype "Carolo I" will implement a propulsion system of approximately 15 to 20 W, the power consumption for the FDPU of 0.5 W is fully acceptable.
Future implementations of the FDPU could utilize a customized board which is optimized for a specific task, e.g. highly optimized control algorithms. This could lead to the use of other CPUs from the same processor family with less calculating power, less memory and thus less component count. These implementations would result in a reduction of size, weight and power consumption.

TELEMETRY

A common PC is used for ground control which is connected to the microplane via telemetry modules. For first tests, a transceiver-module manufactured by Radiometrix [10] was implemented, which uses the 433 MHz IMS band and allows a quasi-bidirectional data rate of 1200 bps at a range of approximately 30 m. Figure 7 shows the configuration of the Main System Controller with a transceiver module.

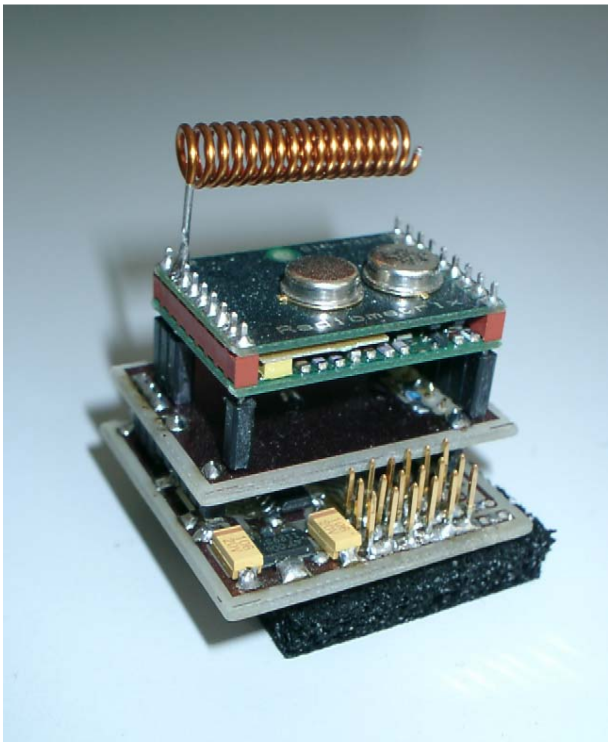


Figure 7: Main System Controller with Telemetry Module

The range and data rate were sufficient for basic tests of on-board computer concept and hardware design, but are not suitable for a flying microplane. For the first prototype, a DECT transceiver module made by Höft & Wessel [11] will be implemented. This module uses the 2.4 GHz IMS band and has a range of 300 m in the open field with a data rate of approximately 100 kbps. On one side, the use of the license-free IMS band has the advantage of commercially available transceiver modules of small size, weight and power consumption. On the other side, the heavy use of this band for all kind of voice and data transmission for private use makes the use of this band virtually impossible for future applications like traffic control or disaster control, where wide-ranged reliable data connections are an essential demand. The use of GSM or UMTS in the future promises a convenient solution of this problem.

GROUND CONTROL

The goal of the project "Carolo" is the development of a fully autonomous microplane. This would principally render a telemetry system and a ground control obsolete, but of course, for testing, commanding and data delivery (e.g. images taken by an on-board camera), a ground control is necessary.

Hardware

In the first implementation of a ground control, a second Main System Controller with telemetry module as shown earlier in Figure 6 was used. The MSC is plugged onto an interface board that allows the connection of an analog joystick for generic data input (e.g. remote control of the plane) and a common PC via a standard RS-232-compatible serial port. The configuration is shown in Figure 8.

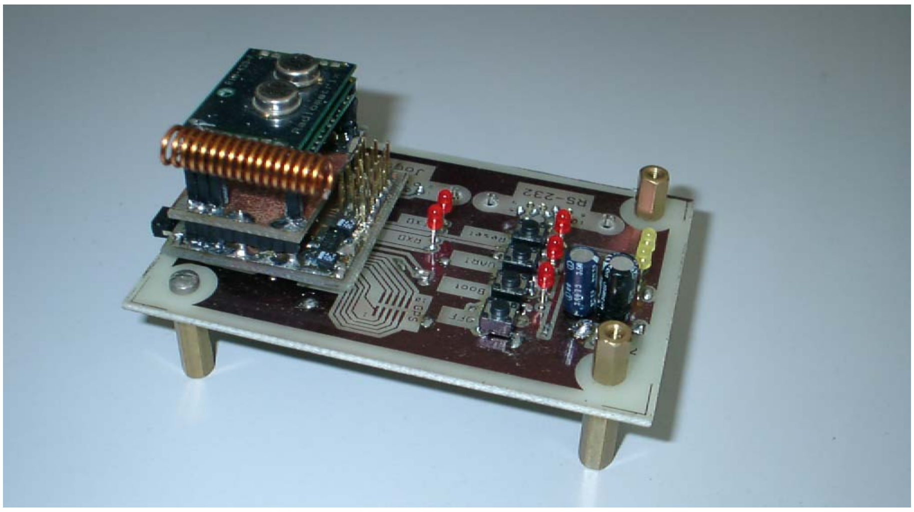


Figure 8: Ground Control Hardware

Software

Special software was developed that allows to directly remote-control the microplane and to transfer data to and from the microplane's payload via a graphical user interface. Flight patterns can be generated and altered interactively by selecting waypoints on a digital map. The ground control software is a modular server-client application written in Delphi, allowing the use of multiple PCs connected by a network to host the different tasks [12]. This capability is especially interesting for imaging applications. For example, pictures made by a camera-equipped microplane can be transferred via internet to clients worldwide. Figure 9 shows a screenshot of the developed software. The upper half shows the software module for flight simulation and sensor data visualization, the lower half of the screen shows the digital topographic map for waypoint navigation.

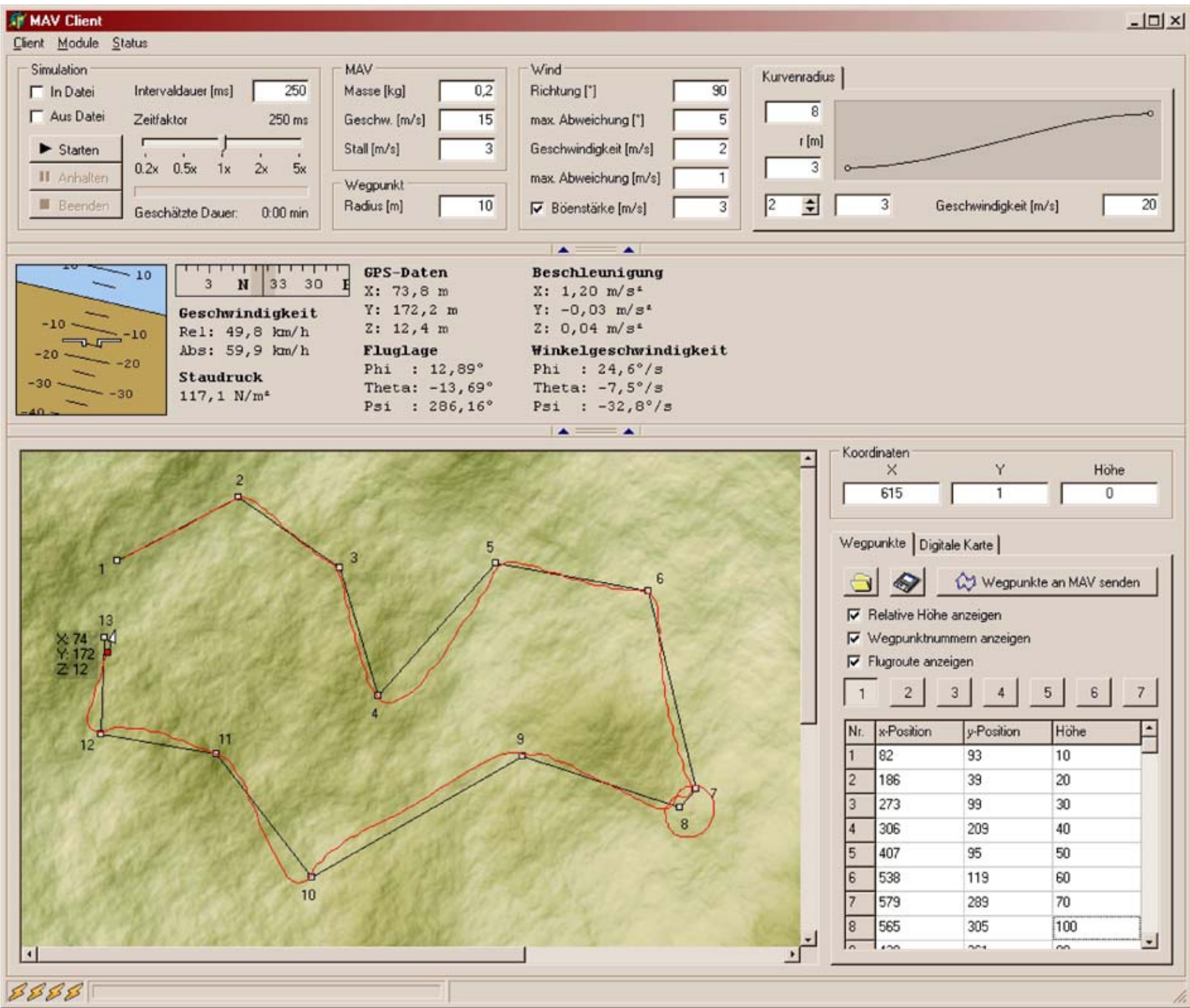


Figure 9: Flight Data Processing Unit

SUMMARY AND OUTLOOK

In this paper, the project “Carolo” of the Institute of Aerospace Systems of the TU Braunschweig is described. The goal of this project is the development and manufacturing of a fully autonomous microplane with a wingspan of 40 cm and a weight of approximately 400 grams. To accomplish this, a special simulation environment was developed, allowing the realistic simulation of microplanes. Based on the simulation, a wind tunnel model was manufactured and is now being tested at the wind tunnel of the Institute of Fluid Dynamics at the TU Braunschweig. The results of these tests will be integrated into the simulation environment and will be used for control algorithm design.

For attitude control of conventional planes, usually an IMU is implemented. Several low-cost MEMS sensors for angular rate and linear acceleration were tested to evaluate their suitability for the use in microplanes. Besides the evaluation of sensor concepts, miniaturized actuators are now being tested to determine the actuator’s transfer function.

The modular on-board computer consists of two main modules: The first module is the Main System Controller, which already prove its capability of interfacing sensors, actuators and telemetry. Integration of the second module for flight control and navigation is under progress. Ground control consists of a common PC with especially developed software allowing in-time sensor data visualization and waypoint navigation on a digital map.

Telemetry link between the microplane and ground control is made for test purpose via DECT radio modules. It is planned to replace these modules by UMTS radio modems to drastically increase radio range and thus allow an even wider range of applications for the microplane. The first remote-controlled flight of "Carolo 1", with all main sub-systems integrated, is scheduled for summer 2002. The first fully autonomous flight is also planned to take place this year.

REFERENCES

[1] Grasmeyer. J.M. and Keennon, M.T., "Development of the Black Widow Micro Air Vehicle", 39th AIAA Aerospace Sciences, Meeting&Exhibit, Jan. 2001, Reno, NV, AIAA 2001-0127

[2] Morris, S. J., "Design and flight test results for micro sized fixed wing and VTOL aircraft", Proceedings of 1st International Conference on Emerging Technologies for Micro Air Vehicles, Georgia Institute of Technology, Atlanta, Georgia, 19-20 Feb. 1997

[3] Bange, J., "Flugexperimente in der planetaren Grenzschicht: Numerische Simulation und erste Messungen mit der Hubschrauberschleppsonde HELIPOD in der nächtlichen Grenzschicht", Bd. 55., Berichte Inst. Meterol. Klimatol., Hannover, 85 S., Dissertation., Hannover 1997

[4] Brockhaus, R., "Flugregelung", Springer Verlag, Berlin, 1994

[5] Brüning, G., Hafer, X., Sachs, G., "Flugleistungen", Springer Verlag, Berlin, 1993

[6] Analog Devices, Inc., "Data sheet for 2-axis acceleration sensor ADXL 202", published by Analog Devices, Inc.

[7] MURATA Manufacturing Co., Ltd., "Data sheet for Gyrostar ENC-03J", published by MURATA Manufacturing Co., Ltd., Japan 2001

[8] Wagner, J., Wieneke, T., "Integrated Satellite and Inertial Navigation - Conventional And New Fusion Approaches", Proceedings of the 15th IFAC Symposium on Automatic Control in Aerospace, Bologna, 2001

[9] Buschmann, M., "Entwurf eines Bordrechner-Konzeptes für ein Mikroflugzeug", diploma thesis at the Institute of Aerospace Systems, Technical University of Braunschweig 2001

[10] Radiometrix Co. "Datasheet for BiM-433-F Transceiver Module", published by Radiometrix Co., United Kingdom 1998

[11] Höft & Wessel AG, "DECT transceiver module HW86010", Datasheet No. DB1232, Hannover 2001

[12] Schulz, I. „Aufbau eines Netzwerks für die Bodenstation eines Mikroflugzeuges und Entwicklung der Software zur Kommunikation im Verbund", diploma thesis at the Institute of Aerospace Systems, Technical University of Braunschweig 2002

AMOS Aims High As It Checks On Czech's L-159

Larbi Ouchelouche, Ph.D.,
Ing. Jiri Svoboda,
Ing. Josef Šlechta,
Dr. Jiri Vidiecan,

Speel Praha, Ltd.,
Beranovych 130, 199 05 Praha 9 – Letnany,Czech Republic

Abstract

This paper provides technical details on Speel's AMOS-B system that has been designed for a two-seat version of the new Czech's L-159 light-attack jet trainer, and gives an insight into how a modern aircraft monitoring system really works both in the air and on the ground.
Along the way, the reader will discover how Speel's AMOS system has evolved from the A version to AMOS-B, a more capable system, which allows for remote data acquisition, including new features such as fuel data control and management for in-flight refueling, and cockpit voice recording onboard the L-159B.
The paper describes how MIL-STD-1553B databus techniques are used to design the distributed architecture of AMOS-B, and explains its interactions with other avionics systems on-board the L-159B.
A close look at a complete Mission De-briefing and Analysis Workstation (MDAW), built as a big plus for AMOS-B ground support using COTS technology, highlights the way all recorded information, covering the whole of each flight, is downloaded and replayed on MDAW station through its various graphical views, and shows how it helps flight and maintenance crews manage information for safer aircraft and get their job done easier than ever before.

Contents

List of Abbreviations

AMOS	Aircraft MOnitoring System
ADPCM	Adaptive PCM
BC	MIL-STD-1553 Bus Controller
BITE	Built-In-Test Equipment
CAF	Czech Air Force
CAM	Cockpit Area Microphone
CMP	Central Maintenance Panel
CMU	Crash Memory Unit
CVFDR	combined Cockpit Voice/Flight Data Recorder
DSP	Digital Signal Processor
DTS	Data Transfer System
ECU	Engine Control Unit
FDAU	Flight Data Acquisition Unit
FQ	Fuel Quantity measuring unit
FSP	Function Signaling Panel
GSE	Ground Support Equipment
GSU	Ground Support Unit (rugged portable computer)
HUD	Head Up Display
LDAU	Local Data Acquisition Unit
LRU	Line Replaceable Unit
LVDS	Low Voltage Differential Signaling
MDAW	Mission Debriefing and Analysis Workstation
MFD	Multi Function Display
MOPS	EUROCAE's Minimum Operational Performance Specification
PANDA	Program for ANalyzing DAta
PCM	Pulse Code Modulation
PMU	Portable Memory Unit
RCU	Refueling Control Unit
RT	MIL-STD-1553 Remote Terminal
SMS	Store Management System
TSO	FAA's Technical Standard Order

1 Introduction

Among the requirements for the Czech's L159 avionics system design, there is a quest for data loading and recording for maintenance purposes, crash investigation, mission planning, debriefing and data transfer aids.

Beyond the simple function of data gathering and recording, there is a need for a more comprehensive system that, in addition to fully accomplish the above requirements, provides a complete aircraft monitoring and diagnostic in real time.

This is driven by the fact that such a system proves to be an important tool for managing safe operation and proper maintenance throughout the service life of the L159.

Like the telecom industry, which demands high availability (so-called 5 nines), the aerospace industry is even more demanding in terms of requirements. The most common way to keep the systems up and available throughout the entire mission is through redundancy. To achieve an even higher availability, one needs to monitor aircraft systems and watch their trend to identify potential failures before they happen and actively prevent them.

For the single seat version of the L159, Speel has designed AMOS-A, whose FDAU operated as a MIL-STD-1553B based Remote Terminal within L159's avionics suite, interactively communicating with the pilot through the MFDs and processes acquired data from various transducers in real-time. AMOS-A Crash-survivable unit consisted of a crash survivable flight data recorder, whose main purpose is to record mandatory flight parameters for incident evaluation.

Today, Speel is designing AMOS-B for the two-seat version of the aircraft. AMOS-B handles the function of a Remote Terminal on the main databus and, in addition, operates as a Bus Controller for in-flight refueling management. The system now includes a combined Flight Data and Cockpit Voice Recorder (CVFDR), which integrates in the same foot-print voice and more data than that of AMOS-A, yet allowing for faster access to flight data.

The objective of this paper is to describe this system that Speel has come up with as a solution to respond to L159B requirements.

The first part of this paper explains the motives behind Speel's Aircraft Monitoring System (AMOS) design by describing the requirements that led to AMOS-B.

This part also describes the design approach that yielded a solution to these requirements, and addresses the individual components that form AMOS-B system by concentrating on issues that are felt of interest to the reader.

The second part examines the way flight data are dealt with on the ground by pilots for mission debriefing and by maintenance crews for data evaluation and analysis.

2 Target Platform- L159B - Background Information

Aero Vodochody's single seat (L159A) and two-seat (L159B) Advanced Light Combat Aircraft are subsonic jet trainers (Figure-1), originally designed to respond to the Czech Air Force's (CAF) operational requirements. As a matter of fact, the CAF wanted a multi-role combat aircraft capable of close air support, tactical reconnaissance, air defense, border patrol, anti-ship mission, and weapons training. The system is to be designed such that the pilot will benefit from accurate navigation and weapons delivery, wide range of stores, avionics integration via MIL-STD-1553 databus, thereby allowing for future growth.

Based on these requirements, a single seat named L159A was developed by Aero Vodochody in co-operation with Boeing as the avionics integrator.

Soon after L159A series production has begun, AeroVodochody started the development of L159B as a strategic move to face jet trainer competition in the world and to respond to potential customers worldwide who expressed their interest in a two-seat version[1].

In fact, the L159B brings numerous benefits over the single seat version such as improved avionics suite, longer range thanks to its in-flight refueling capability. In addition, training on the L159B will surely cost less than flying a supersonic fighter. L159B is aimed at training pilots whose next step is to fly high-performance supersonic fighters. Consequently, the avionics suite's look & feel on the aircraft is pretty much similar to that of F-16C/D Block 50, commonly known as "full glass cockpit" philosophy.

L159 Performance [2]:

- 936 km/hr max. speed, +8g/-4g load factor, 62.1m/s climb rate, 13200 m ceiling.
- Honeywell/ITEC F124-GA-100 turbofan engine (28 kN max. thrust)
- Man-machine interface compatible with latest generation high-performance fighter aircraft (HUD, MFD, HOTAS, RWR, IFF, NVG cockpit)
- 7 pylons - 6 under wing and 1 under the fuselage centerline.

Figure-1: L159 advanced light combat aircraft

The L159B is currently in development at Aero Vodochody, and the maiden flight is expected this summer. Most of the operational characteristics and system design features are identical for both versions. In addition, L159B will feature an in-flight refueling system for controlling the activities of refueling during the flight.

3 AMOS-B System Design Approach

3.1 Requirements and Solution

Since its inception, AMOS has been thought of as a system with growth potential; that is, the goal was to design a system based on a modular architecture using state-of-the-art technology. This led to AMOS-A, which was described in breadth and depth in a paper presented at AIMS' 98 [3]. At that time, it was already obvious that the best solution would be to design a system so that it can be seamlessly integrated to the MIL-STD-1553B based avionics suite of the L-159.

The data loading and recording portion of L159's avionics suite block diagram, not shown here for a limited space reason, comprises HUD camera, two onboard video recorders (HUD and MFD), a DTS unit, and Speel's Aircraft Monitoring System(AMOS).

From the operational standpoint, the solution that Speel has come up with implements the following individual system functions and capabilities:

- data acquisition,
- real-time data processing and management,
- data recording,
- voice recording,
- airframe fatigue monitoring,
- engine data monitoring,
- fuel data monitoring,
- in-flight Refueling sequence management,
- airborne video record synchronization with AMOS data,
- preflight checklist,
- onboard post-flight diagnostic,
- in-system programmability,
- growth potential.

Individual components addressing each of these functions are combined to form an optimal monitoring system tailored to customer's requirements for L159B and meeting design trade-offs and affordability. The solution proposed to respond to the above requirements is described in the following sections.

3.2 Centralized vs. Distributed Acquisition

A centralized data acquisition approach would certainly bring some advantages to the design of the system, and the FDAU architecture would be fairly identical to that of L159A, thus reducing time to market.

However, the drawbacks are numerous. Long signal paths would be required to bring signals from various transducers. FDAU size would also be greater as more pcboards would be required to perform all the tasks to account for the 67 % increase in the number of measured parameters in comparison with the A version of the box, consequently resulting in complex cabling mainly in the mid-section of the fuselage.

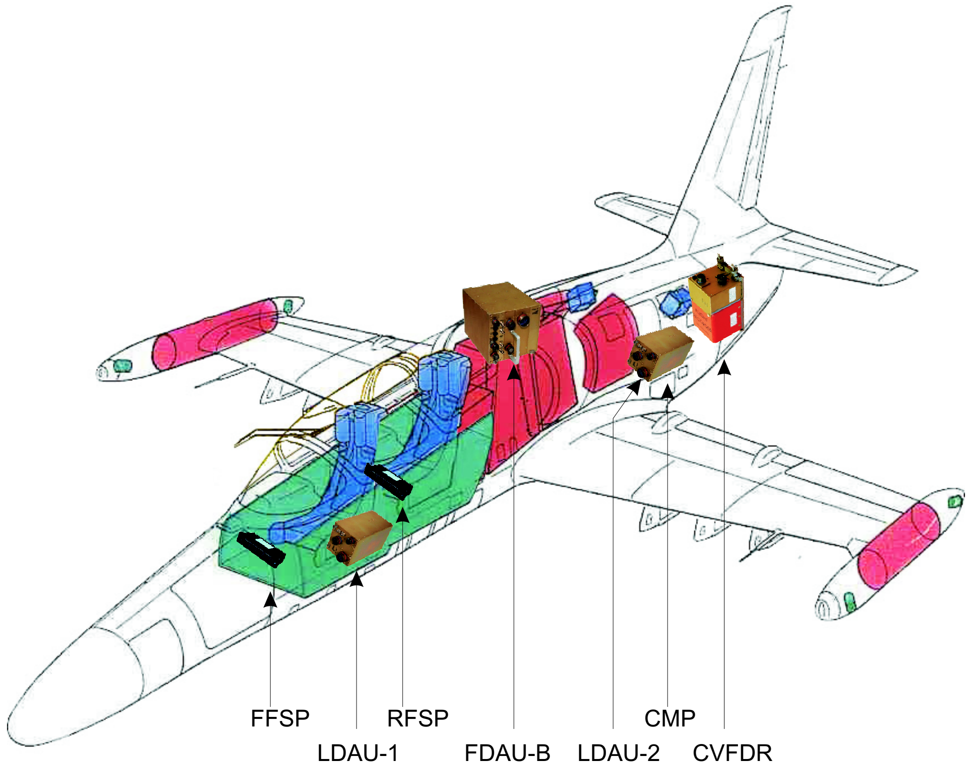


Figure-2: AMOS-B LRUs and their location on the L159B.

Therefore, unlike on the L159A, where data acquisition is handled using one centralized FDAU unit, on the L159B a distributed data acquisition approach is adopted, especially as this is driven by the increase in the number of parameters to monitor. This is accomplished using one main FDAU as a central unit and several remote LDAU units located at adequately selected areas on the aircraft with high concentration of transducers.

On L159B, such sensor-populated areas could be found around the cockpit, around the engine, and in the area beneath the cockpit floor. That is where AMOS LRUs are located (Figure-2).

Although there are significant software changes and increase in overall system cost, the advantages of this approach are obvious: shorter signal paths, simplified cabling, open architecture, hence growth potential.

4 Technical Description of AMOS LRUs

In the distributed approach, AMOS remote units, designated LDAU-1 and LDAU-2, provide a direct connection to remote sensors, and forward collected data to FDAU-B central unit. The design uses a combination of RS-422 links and MIL-STD-1553 databus to convey various types of information among the acquisition units.

As shown in Figure-3, the MIL-STD-1553 databus is the mainstay in the design of the B version of AMOS because of its proven reliability and inherent versatility that make it very suitable for a distributed architecture.

In a system, in which real-time local processing and data transfer is computer controlled, distributed units combined with the utilization of MIL-STD-1553 technique bring the benefit of reduced wiring on the aircraft, easy upgrade and potential growth, and better signal distribution, acquisition, and processing by the monitoring system.

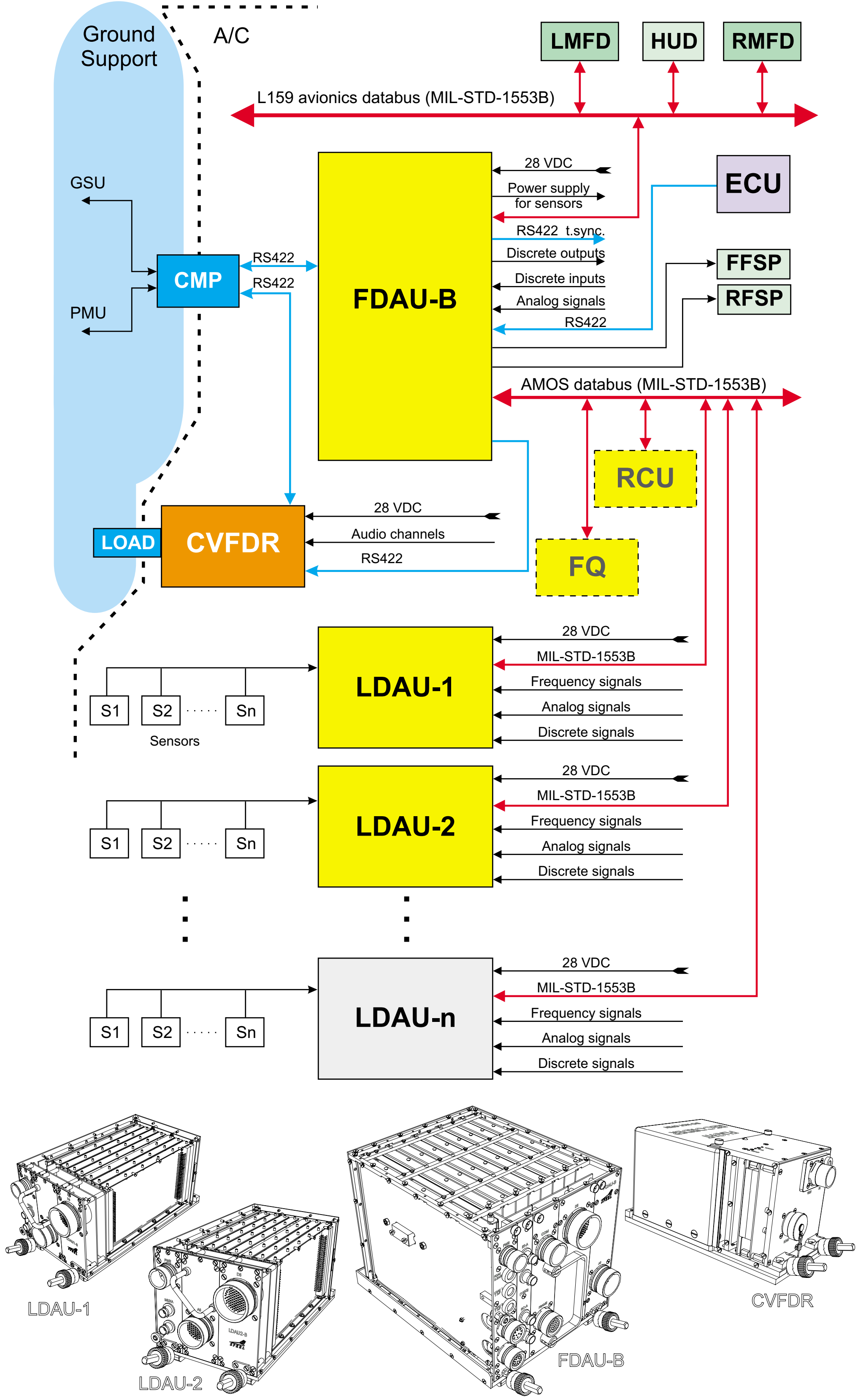


Figure-3: Functional block diagram of AMOS-B system. Outline drawings of system LRUs clearly show the modularity of the design

Data is distributed for storage and retrieval in internal mass memory; that is, in FDAU's internal non-volatile memory for routine maintenance, and in the crash-protected memory module of the CVFDR to support post-accident/ incident analysis. Data collected from L159B's various systems include:

- 223 discrete signals, 47 spare inputs
- 20 inputs for measuring DC voltages, 10 spare inputs
- Signals from 10 RTDs
- Signals from 14 position sensors
- 11 variable frequency signals

To the above list are appended MIL-STD-1553 based parameters from the main bus controller (navigation, air data, mission data, SMS data), fuel data from RCU and FQ units, and RS-422 data from the ECU unit, thus making it over 500 parameters monitored overall.

4.1 FDAU

The flight data acquisition unit exhibits a modular architecture (Figure-4). The arrangement of the pcboards inside the unit is familiar as it is inherited from the A-version of the system.

The system is designed in such a manner as to allow unit's LRUs to be interchangeable to a degree never seen before. Input signals are grouped by categories and each card handles signals of the same type as follows:

ABF_UDC, and ABF_APR cards: DC voltages, strain gauge voltages and RTD sensors.

ABF_FRA card: This card is intended for airframe fatigue monitoring. Strain gauges and acceleration sensor output signals are conditioned prior to their multiplexing and conversion into digital format by A/D converters. FRAME module samples input signals at 400Hz, which are used as inputs by a computation algorithm to locate local maximums. When a local maximum is detected, FRAME module stores in its built-in non-volatile memory a set of appropriate parameters along with the time of occurrence for further airframe strain analysis on the ground.

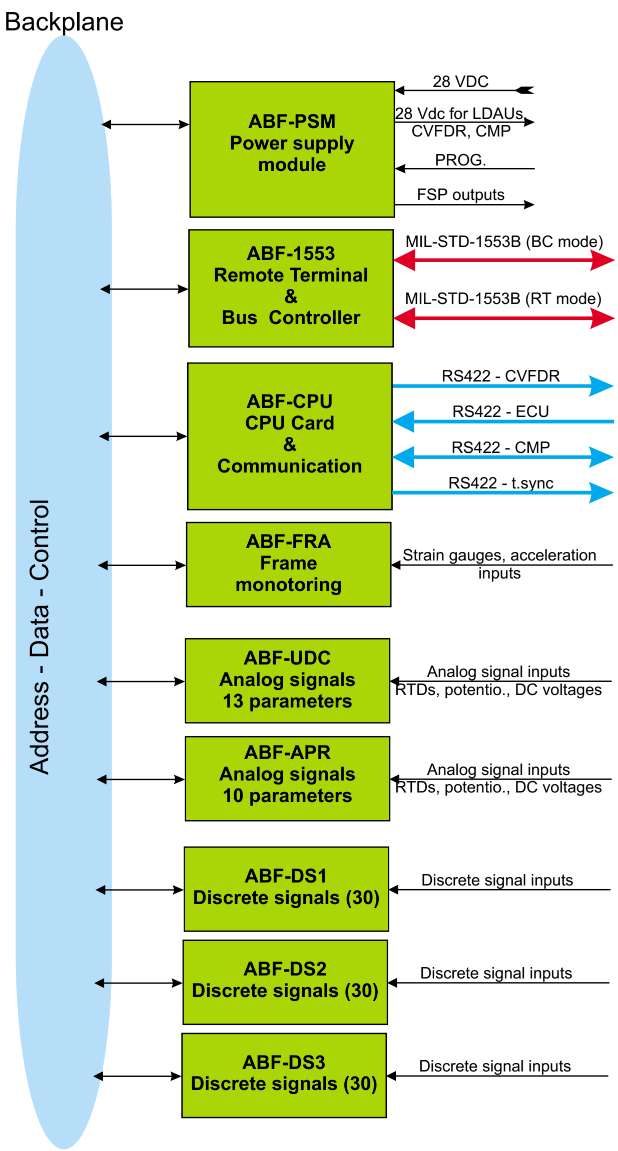


Figure-4: FDAU-B top level block diagram

This module also handles RS422 communications with the PMU for frame data downloading.
ABF_DS1/DS2/DS3 cards: process discrete signals from various aircraft systems. Each module is capable of converting 30 input signals to data readily available on FDAU's 1553 databus.
ABF_CPU card: accomplishes main tasks such as data gathering and management as well as most communications with AMOS local units including CVFDR, RCU, FQ, ECU, BEC, and LDAU units. This card also handles most of RS422 communications on the ground. This includes PMU, GSU, and engine data downloading.
ABF_1553 card: handles two levels of communication over MIL-STD-1553 databus; one with the main avionics databus in Remote Terminal mode; and the other with LDAUs, RCU, and FQ in Bus Controller mode for remote data gathering and fuel data management respectively.

4.2 LDAU-1/2

Similar to the FDAU, local acquisition units of AMOSB, LDAU-1 and LDAU-2, are designed on a modular basis using the same state-of-the-art technology, thereby allowing interchangeability between system's LRUs. The units have basically the same type of acquisition modules as FDAU-B's, except for FRAME module and the 1553 mode as these units operate as Remote Terminals on the secondary MIL-STD-1553 databus under the control of FDAU unit.
Two other units are connected to AMOS on the secondary Mil-Std-1553 databus, as described in the following section.

4.3 FQ and RCU

Fuel system is intended for fuel storage and its distribution on board the L159.
Unlike the single seat version, the L159B is equipped with an in-flight refueling probe, along with a refueling system that measures fuel quantities in the various tanks and controls the refueling activity.
During engine operation, the fuel flows successively from outer tip tanks, drop tanks, and eventually from internal tanks located in the frame.
L159B has 5 independent fuel tanks with a total capacity of 1177 liters.
Fuel Quantity (FQ) unit and Refueling Control Unit (RCU) are connected to AMOS's MIL-STD-1553 databus and operate in Remote Terminal mode.
Upon request, AMOS-B displays an appropriate page on the MFD, which provides refueling instructions for the pilot to follow during in-flight refueling sessions.
The communication protocol between AMOS and these units is defined such that all data related to refueling activity is exchanged between these units via AMOS. In this way, AMOS fully monitors the refueling process and relays to the pilot relevant fuel data that is displayed on the appropriate MFD page.
Data shown includes instantaneous values of fuel quantities in the various tanks as well as fuel level control/signaling and drop tank configuration of the aircraft. Part of this data is used to compute fuel flow rate and to provide other avionics computers with fuel quantities.

4.4 CVFDR

One of the intents of a flight recorder is to tell the tale of accidents, and whenever possible, prevent an accident from happening. Paradoxically, flight recorder design has been improving over the years in terms of capabilities and ability to survive a crash thanks to the lessons learned from previous accidents.

4.4.1 Design considerations

The trend of the requirements on flight recorders, summarized below, is not only driven by technological advancements but also by the experience gained from these accidents:

- Increasing the number of recorded parameters,
- Improving the ruggedness by issuing more stringent TSOs and MOPS,
- Recommendation for increasing the recording duration with a Recorder Independent Power Supply (RIPS) unit after a power cut-off,
- EUROCAE Working Group 50 drafted a video recorder requirements as a basis for future considerations,
- Solid-state FDRs/CVRs will become mandatory on all transport aircraft by 2005,
- Increasing the probability of post crash recovery of flight information with dual-redundant installation; that is, two separate crash survivable recorders storing both cockpit voice and flight data information (ref. NTSB, ARINC 767 draft document),
- And so forth...

As concluded by the WG50 in their last report on airborne video recording considerations, the trend is obvious: having combined recorders using solid-state memory to record audio, video, flight parameters, data-link messages (CPDL) in a single crash protected box.

Speel's CVFDR is an integrated cockpit voice and flight data recorder that has been designed as a modern replacement for Speel's existing flight data recorders and cockpit voice recorders with improved functionality and capabilities. This is achieved by designing into a single box all functions required for recording pilot voice and cockpit sounds, as well as flight data stream transmitted from the FDAU. The CVFDR can be configured to record audio only, flight data only, or both functions at the same time. As a result, the system's memory can be configured and allotted depending upon actual needs.

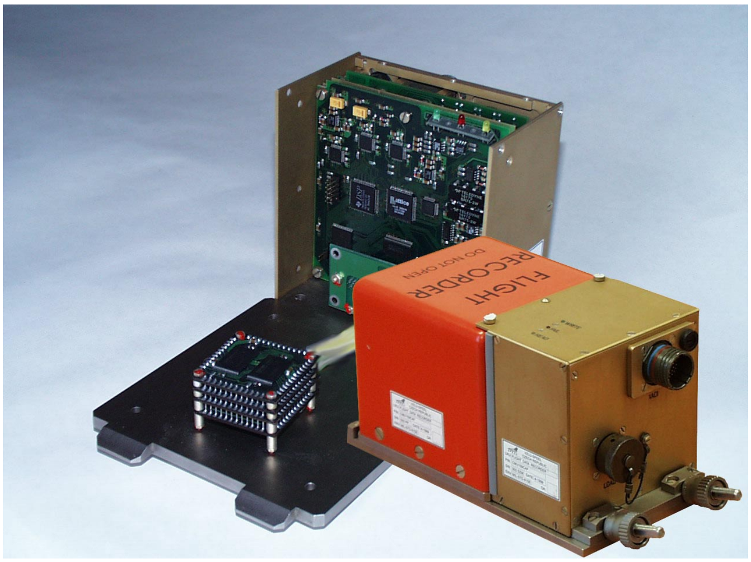


Figure-5: Speel's combined Cockpit Voice/ Flight Data Recorder – CVFDR (foreground). The open unit (background) shows the audio acquisition pcboard and the memory stack connected to it via a flexible cable.

The system design is based on a study of current worldwide requirements for the recorders as listed above, which shows that there is a need for integrated voice, data, and even video capability in one unit, and a redundant use of such units throughout the aircraft. The study has yielded a recorder (Figure-5) exploiting most of these worldwide requirements and fitting them to L159B needs.

The CVFDR fulfills the following basic functions:

- Storage of flight data transmitted from AMOS FDAU unit via an RS422 link.
- Recording of two audio channels conveying pilot voice, pilot communication with the ground station and other aircraft.
- Recording of one audio channel conveying the sounds captured by the cockpit area microphone (CAM).
- Transfer of recorded audio and flight data in binary format from the CVFDR's internal memory to ground evaluation equipment.
- Direct playback of recorded audio channels from within the CVFDR.

4.4.2 CVFDR Technical Description

The system has been designed to comply with EUROCAE's ED55 MOPS for data recording and with ED56A for voice recording requirements.

The CVFDR consists of 3 blocks (Figure-6): interface card, voice/data acquisition card, and a crash survivable memory unit (CMU).

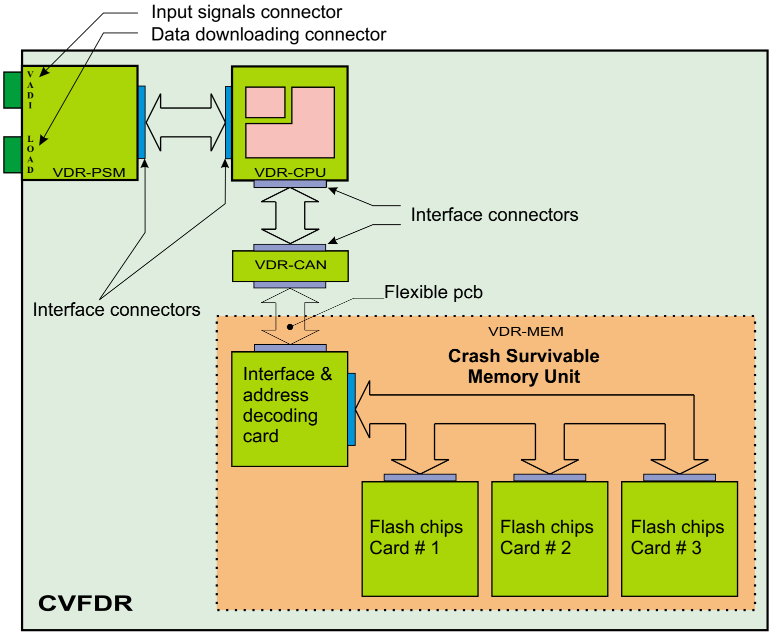


Figure-6: Top level block diagram of Speel's CVFDR

The interface card (VDR-PSM) features two mil-specs circular connectors - one input filter connector (VADI) for data and voice channels, and one output connector (LOAD) for accessing the recorder's contents using a communication link when the system is connected to an appropriate device (PMU, GSU, or a PC) on the ground.

The card provides all power supply voltages needed, including a BIT signal from all modules of the CVFDR that is sent to the FDAU unit.

The power supply circuit is designed to fulfill RTCA's DO-160D requirements in terms of electrical, EMI/EMC, and environmental characteristics.

This card also contains interface circuitry for communication links - one RS232 for communication with a portable PC, two RS422 links for PMU/GSU communication, and a high-speed LVDS link.

The voice/data CPU card (VDR-CPU) processes 3 channels of audio and receives data streams transmitted from the FDAU via an RS422 serial link at 38400bps.
It is built around a DSP processor, which handles all communications; that is, CVFDR⇔FDAU, CVFDR⇔AUDIO channels, CVFDR⇔GSU,CVFDR⇔PMU,CVFDR⇔PC.
Audio channels consist of two crew headsets, and one cockpit area microphone.
Each audio signal feeds the input of a codec whose PCM output is converted by a DSP processor into an ADPCM sample that is transferred into the crash memory unit. Prior to ADPCM conversion, sampled data is looped back to the AOUT output, which can be used by an operator to check in real time what the CVFDR is actually recording.
The DSP also receives concurrently data streams transmitted by the FDAU and stores them in a temporary buffer. This buffer is used to group data/audio bytes into packets prior to their transfer to the crash survivable module. The time lag in this case is less than 30 milliseconds, which turns out to be better than ED56A's MOPS specification, which allows for the loss of up to 50 msec of processed information in the worst case.

Crew audio channels are sampled at 8 kHz within 150-3500 Hz bandwidth, and the CAM channel at 16 kHz within 150-7000Hz bandwidth.
The CAM is an omnidirectional microphone, located in the cockpit between the two seats, and is utilized to pick up all the sounds surrounding the pilots.
On the L159B, the CAM is powered by LDAU-1 as this unit is located nearby.
The CAM module is actually comprised of the microphone itself, a pre-amplifier with an automatic gain control (AGC) device, and a power supply circuitry. The normalized output signal feeds the codec on the CVFDR's VDR-CPU card.

The crash survivable memory unit (VDR_MEM) utilizes flash memory chips as a recording medium. The memory is subdivided into several areas, each of which is comprised of a set of flash memory chips. Storage of data, audio channels 1 and 2, and audio channel 3 (CAM) are in separate physical memory locations as dictated by EUROCAE requirements.
VDR_MEM capacity provides for 36 hours of flight data recording at 512 bytes/sec, while audio capacity is 120 minutes of audio records for each channel with a quality that exceeds ED56A requirements.
In addition, the entire memory content is duplicated in a backup memory ensuring 100% data and voice record redundancy, including Hamming coded information of SEC-DED type (i.e. a single error is detected and corrected, while a dual error is only detected).
An audio monitoring output is made available (Headphone Jack on the control panel) for the operator to playback recorded audio channels without having to download the recorder's memory content.
Although not implemented on the L159B, there is also a provision for a backup power supply. The backup power module uses ultracapacitors and allows the CVFDR to operate during 10 minutes after a power cut-off.

5 AMOS-B System Operation

On the L159, a lot of components are controlled by software like on most modern systems, and information is exchanged among various subsystems via the use the MIL-STD-1553 databus.

The strength of such a MIL-STD-1553 based system is that, in most cases new functions can be added by updating the firmware without any additional hardware. The following sections describe how AMOS system utilizes MIL-STD-1553 to exchange information with other avionics systems.

5.1 AMOS-B's MIL-STD-1553 Protocol

The FDAU is a multi-processor, real-time, mission critical unit, which operates as a Remote Terminal (RT) within L159's avionics suite. Data transmitted from the Bus Controller (BC) over the MIL-STD-1553 databus is processed and stored into FDAU's built-in maintenance recorder.

FDAU firmware, which runs in a cyclic executive manner, handles several concurrent tasks in the course of a flight. One of them is a pre-flight checklist described in the next section as an example to demonstrates the flexibility of AMOS and the power of the software controlling the system thanks to the use of MIL-STD-1553 standard.

During a preflight check out, the pilot and the maintenance crew follow a checklist displayed by AMOS on the MFD. AMOS provides the checklist sequence on MFDs via the MIL-STD-1553 databus in form of pages. Mission data upload is also managed by AMOS during the preflight sequence by displaying on the MFD an appropriate page, referred to as *Data Entry Form* (DEP). When this page is displayed, pilot identification code and other data related to the mission are uploaded using the Data Transfer System (DTS). If they are not entered properly or are not uploaded at all, the FDAU provides an interactive capability to the pilot to enter them on the DEP page via the avionics keypad. When performing a checkout sequence, MFD push buttons enable the operator to confirm a task, return to the previous item of the checklist, enter the result of a test, or interrupt the pre-flight check out procedure at any time.

5.2 Real-time Data Analysis

On power up, the FDAU starts to acquire and process in real-time collected data by running a set of algorithms describing airborne systems states and failure conditions. Unlike the traditional way in which the pilot is informed about occurring events through a failure warning panel comprised of a matrix of annunciators, these events (i.e. failures and states) are converted by the FDAU into meaningful information (messages) and sent via the MIL-STD-1553 databus to the MFD.

On the L159, failure events are divided into three categories based on priority and criticality levels: Warnings, Very Important Messages, and Fault Messages. This provides a consistent way of presenting the information on the MFDs, thereby improving pilot's reaction. Warnings are displayed on the current MFD page as a short text defining a failure or a state in a flashing box. The pilot can tell the FDAU to delete this message via MASTER CAUTION button activation, WARN RESET switch on the

HUD up-front control panel or through the FLT push-button on the MFD. FLT button is always enabled when AMOS system evaluates an active event. Its depression causes the test page with the list of active events to be displayed. If AMOS evaluates more than one event, the first message is displayed in the box on the current MFD page and, after depressing the MASTER CAUTION button or the WARN RESET switch, the next message on the queue is displayed. When the Fault event page is selected, all messages are deactivated at once.

For maintenance purposes, the FDAU stores all events evaluated during the flight into its built-in non-volatile memory module. Access to this database is performed by TEST push-button depression on the MFD menu page. The database provides information on airborne system identifier in which a failure has been detected, event code, number of fault occurrences, and time of the first occurrence. Because this table can be accessed without connecting external ground equipment, it provides the technician with invaluable information for troubleshooting on site.

6 Ground Support Equipment - Tools and System Operation

Essential information captured by AMOS is recorded into its various memory modules. Part of this information is processed during the flight in real-time as described in the previous sections, while the other part is exploited on the ground for post-flight evaluation and analysis. But, in order to benefit from and get the most of AMOS capabilities, it is necessary to process this voluminous amount of information in such a manner as to present it to ground crews in a meaningful way rather than running before the operator's eyes long lists of parameters and numbers that don't say anything. For this purpose, Speel provides a set of tools, which form L159 Ground Support Equipment (GSE).

GSE consists of MDAW workstation, PANDA software package, a portable memory unit (PMU) for data downloading, and a GSU rugged portable computer.

This equipment enables AMOS system to achieve a high degree of flexibility by allowing the operator to program and configure AMOS airborne LRUs, read out and display flight parameters in various formats, analyze the mission, and get results from user-defined flight analysis.

6.1 MDAW Station And The Software Behind It

For L159 post-flight evaluation and analysis, Speel has developed a Mission De-briefing and Analysis Worksation (MDAW159) as part of a through-life logistic support of the L159.

Built on a commercial-off-the-shelf (COTS) hardware using state-of-the-art computing and graphics rendering technology, SPEEL's MDAW159 is a high performance yet affordable integrated hardware/software tool that is intended for use by instructors, pilot students, and maintenance crew for comprehensive mission review and analysis. The system development is based on field experience and the inputs from the very people who use it in their everyday routine work. In return, it provides all the functions required by ground crews to efficiently analyze a mission.

The system consists of a set of PC computers (Figure-7), which show L159 silhouettes, scene, and flight data in various views, as well as real forward outside views and MFD views from airborne videos. The ability of the station to replay AMOS data, including video records of several aircraft at a time is particularly useful for combat training situations.

MDAW159's core software called PANDA (Program for ANalyzing DAta) is a Windows 98/2000 based GUI application designed to allow *immediate* mission debriefing and flight data analysis thanks to the access-as-is to flight data recorded by airborne LRUs of AMOS system.

Figure-7: Speel's MDAW station (in the inset). From the upper left corner clockwise are screen shots of some of PANDA's program modules: Video159, 2D-Map, VIEW, ANIM.

The kernel of PANDA software is designed to allow for multiple display synchronization; that is, software generated graphical views and the views from the video records run concurrently under the same time-base. PANDA has been developed using state-of-the-art software development environment and high-end computers to analyze flight data interactively by replicating the instruments and aircraft movements in 3-D, thereby presenting to the operator flight parameters in as an intuitive manner as never before.

The software has been developed on a modular basis. It consists of individual program modules, each of which accomplishes a defined function (Table-1). Most of PANDA modules can be used independently, thus increasing PANDA versatility.

Module Name	Description
MANAGER	Main module, which ensures system configuration, access authorization, and data file directory management.
CALB	Used for initialization and calibration of analog parameters in the recorders; that is, conversion of analog parameters from their binary form into their physical values using curve fit equations.
LOAD	Used for flight data downloading from the flight recorders and internal memory modules of aircraft monitoring systems. This module automatically formats and generates appropriate data files for processing by a ground station.
VIEW	Used for comprehensive graphical visualization and analysis of data files. Display of graphs corresponding to selected parameters on a time-based chart. Analog and discrete parameters are shown concurrently. User defined analysis execution on selected parameters to locate anomalies and specific events that may have occurred during the flight.
REAL	When a notebook running this module is hooked up to a flight recorder or a data acquisition unit used on the aircraft, data stream flowing into the recorder can be monitored. Useful tool for troubleshooting.
FRAME	Used for airframe fatigue monitoring using data downloaded from FRAME module of AMOS's FDAU.
2-D MAP	Shows L159 silhouette moving above a map. Relevant information about the flight is also displayed (flight time, aircraft speed, altitude, etc). A control panel allows the user to perform browse functions such as feed-forward/backward, reset, start/stop, and real-time run (actual flight time).
VIDEO159	For immediate and easy control of video playback units (2 videos per aircraft). Selection of video to play, synchronization of videos with AMOS data, control buttons for start/stop, feed-forward/backward, frame search, etc.
TRACE	Used to display aircraft silhouette and trajectory in 3D. More than one aircraft (3D models) can be shown at a time evolving over a 3D area. Capability for domain rotation, zoom in/out on a selected aircraft to watch the battlefield from within that aircraft as seen by the pilot through the HUD.
ANIM	GUI Instrument View application. It shows a realistic view of L-159 cockpit. The instruments accurately re-play collected flight data as previously seen by the pilot during an actual flight. When running in multi-mode, TRACE, 2-D map, and Video159 modules handle several L-159s at a time. In this mode, ANIM module instantaneously shows instrument state corresponding to the selected aircraft. Selecting another L159 is done by simply clicking on its object in one of these modules, at which time ANIM automatically updates displayed instruments.

Table-1: Main PANDA software components and their tasks

As a summary, the following list depicts the main functions implemented in PANDA:

- Data downloading from the flight recorders, monitoring systems, and PMU unit into the ground evaluation equipment (portable computer, desktop computer, ground workstation).
- Computation of calibration data, storage and editing of calibration files.
- Visualization of all parameters in graphical and tabular formats.
- Data processing based on user-defined event (exceedances) analyses.
- Aircraft silhouette visualization in 3D.
- Flight trajectory visualization over a map.
- Instrument board view.
- Database administration.
- Data backup and export to standard formats.

At the flight line, AMOS data can be accessed by ground crews through the Central Maintenance Panel (CMP) located on the aircraft (Figure-8) using either Speel's PMU or a GSU. The sections below explain how this can be done.

6.2 Using a Portable Memory Unit (PMU)

When a PMU is used, the downloading task is performed automatically thanks to the protocol implemented in this *intelligent* portable memory unit. The unit detects the FDR type and automatically searches recorded data and stores in a directory within its internal non-volatile memory individual flights, which are later uploaded onto a ground station (GSE) for flight data evaluation.

PMU connects to LOAD connector of the CVFDR if crash data is to be retrieved, or to AMOS's connector on the CMP panel if maintenance data is needed. The latter is the most frequent downloading activity as this type of data is required for a complete system diagnostic and to watch the trend of systems behavior.

The unit can be used to download all data recorded by AMOS LRUs; that is, event history data, crash and maintenance data, and frame data.

One key feature of the PMU is its programmability. This feature is particularly valuable as the operator doesn't have to learn the downloading process, which is often the case when a portable computer is used, because the downloading software must be learnt, and dealing with it at the aircraft site is time consuming. A better way consists of programming the PMU using a desktop station. Once programmed, the unit can be taken by any ground crew member to the aircraft site, and all is needed to do is connect it to the CMP panel, and the unit automatically identifies the system and starts downloading appropriate data.

The downloading speed is 450 kbps when the PMU communicates with AMOS, and 900kbps when connected to the CVFDR. The transfer of downloaded data to a workstation (PC computer) is insured via an RS422 link at 900 kbps.

6.3 Using a Ground Support Unit (GSU)

When a GSU unit is used, the connection with AMOS system is done via L159's CMP connector. In this case, the user can use PANDA's LOAD program module on the GSU for downloading fault event history data, frame data, CVFDR's data, or REAL program module to monitor the data flow between the FDAU and the CMU unit. The latter is particularly useful when a troubleshooting task is conducted at the aircraft because the operator can monitor flight parameters being measured by AMOS in real-time.

The user can also run CALB program module on the GSU for FDAU programming. This includes performing sensor calibration, and defining what parameters to measure and at what sampling rate. Configuration information generated by CALB module during this process is uploaded onto the FDAU unit, and the system is ready to acquire data accordingly. This means that, the way AMOS performs the measurements can be changed at anytime by ground crews without having to alter the hardware, hence the programmability feature of the FDAU.

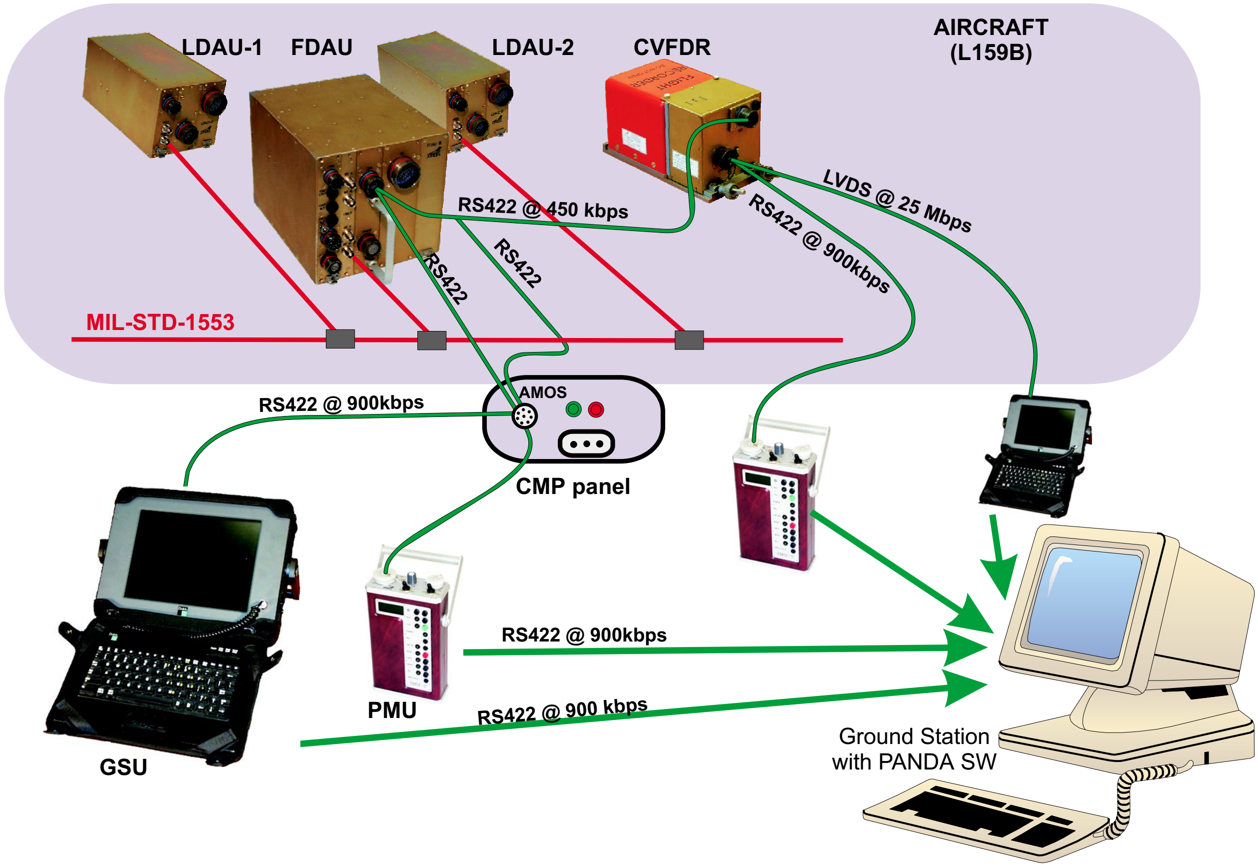


Figure-8: Ground Equipment. Access to AMOS data through L159's CMP panel using Speel's GSU and PMU

As a result, part of downloaded data comprises configuration information, which is required by PANDA modules for flight data analysis. The advantage of this is that AMOS system carries all needed information with it in order to perform complete post-flight evaluation anytime and anywhere.

The access to audio data depends on how this information is to be dealt with. The operator can connect a headphone directly to the CVFDR for real-time audio playback.

If the audio is to be downloaded, the user can connect the GSU to LOAD connector on the CVFDR. In this case, voice can be retrieved through an LVDS link at 25 Mbps, thereby requiring typically 2 minutes for the downloading operation to complete.
Data transfer from the GSU to the GSE is ensured via a legacy RS-232C link at 115200 bps maximum, or via an RS422 link at 900 kbps using an appropriate interface PC card.
At these various serial link speeds, downloading the entire data memory of the CVFDR (64 Mbytes) takes less than one minute through the LVDS link at 25Mbps, and typically 15 minutes via the RS422 link at 900kbps (30 minutes if backup memory content is to be downloaded too).

As can be seen in Figure-8, a single connector on the CMP panel (labeled AMOS) is used for a quick access to all of AMOS memory contents including maintenance data, crash-related data, audio, and engine data.
In addition, the CMP features two lamps, which provide an indication on aircraft system status. During the flight the FDAU processes data in real-time and continuously monitors all systems onboard. The result of this diagnostic is translated into a green light (all systems checked OK) or red light (system failure) for ground crew information. This provides a quick checkout of systems prior to subsequent flight without having to download data, thereby significantly reducing time to next sortie.

Conclusion

AMOS-B has been designed to be more than just a tool for L159B systems monitoring and maintenance purposes. It forms an integral part of the avionics suite on which the L159B fully depends.
The greatest benefit of Speel's AMOS-B system, when used in conjunction with MDAW workstation, is that it allows pilots and instructors perform *immediate* mission de-briefing and helps ground maintenance crews conduct L159B systems troubleshooting *on-site*.
As of this writing, AMOS-B system is undergoing tests, and the firmware is still under development. But there is no doubt, AMOS-B will certainly prove to be, just like the A version of the system did, a high-performance yet cost-effective solution for L159B through life logistics support.

References

[1] Martin Mamula, Chief of L159B project, "Aero L-159B", Aviation & Cosmonautics Magazine, issue 17/2001.

[2] Michal Stolár,"AERO L159 ALCA", Copyright © Perun Press Publishing, Bratislava, Slovakia 2000, ISBN 80-968388-2-2.

[3] Jiri Vidiecan, Jiri Svoboda, Larbi Ouchelouche, Vzlu-Speel, Ltd. “Aircraft Monitoring System for L-159”. AIMS '98, Proceedings of the 19th Symposium, Aircraft Integrated Monitoring Systems. May 4-7,1998-Garmisch-Partenkirchen, Germany, pg. 155-169.

SUGGESTIONS FOR A NEW DATA MANAGEMENT SYSTEM ON MILITARY AIRCRAFT

Martin Geisreiter
European Aeronautic Defense and Space Company – EADS
81663 Munich
P.O. Box 80 11 60
Tel: +49 89 607 240 62
martin.geisreiter@m.eads.net

Abstract-- Development of new airplanes or upgrade programs of in service systems increasingly face small customer budgets. Most in service systems are split up into various data systems with dedicated, but incoherent subsystem solutions, resulting in uncorrelated data recording. Nevertheless, the requirements are to upgrade present systems to a level which is state of the art, thus to satisfy the tactical demands for e.g. low turnaround times and the desire for low operating costs.

Currently, in most cases, high costs result from the need for a multiplicity of special ground equipment, dealing with different data formats and the personnel using it. Yet the information flow is far from being optimal. The predominant method to limit expenses and expenditures demands the use of COTS and the extension of existing subsystems (pickaback solutions) and the use of commercial devices.

In this talk, basic suggestions are presented to solve this dilemma by harmonization of data formats and devices by a linkage of subsystems still separated at present.

TABLE OF CONTENTS

FLEET USER NEEDS

Operational Concepts for new airplanes includes of course autonomic logistic concepts which demands little human intervention and e.g. ordering spare parts etc. /1/.
In reality the concepts of currently existing logistic systems have been driven by the simple need of recorded data. In-service aircraft do this, but in a shape that is formed by isolated manufacturer ideas, airforce's routines and journey though life. Within the last years, the change of the armed forces environment and new tasks constrains the airforces to adapt their maintenance routines to the new requirements. But the major challenges for monitoring and diagnostic systems are not in line with the decreasing defense budgets. The airforces are not able or willing to buy new expensive diagnostics/prognostics systems. In a more general view all airforces want to minimize the LLC to keep the airforces operable.
Prognostics and Health management Systems have the potential to be a

beneficial system of the air vehicle and therefore to support the need for lower costs and higher operability. Those are in terms of reduced operational costs, support costs and life cycle costs and improved safety.
The evolution of aircraft processing capability and recording systems allows realizing new concepts for diagnostics/prognostics systems that support the fleet users with cost effective solutions.
The main needs for fleet users are:

- Quick Turn Around Time
- High Availability
- Low Number of Spares
- System Performance Feedback
- Configuration Tracking
- No false Alarms
- Minimum of Inspections
- Small logistic and maintenance organizations
- Usable out of homebase

PAST HEALTH MONITORING

For the most aircraft, maintenance actions are only undertaken because there was made a report that a particular plane is not operating properly. Another reason is to perform periodic inspections to ensure that the status of health of a particular part is good enough to continue to operate the aircraft. Sometimes unexpected stops are the results.
Many of the needs and wants of the maintainers are self-evident. Mostly, the activities are driven by reports which give only fragmented information about malfunctions.
In currently running systems the ground stations have been developed separately from onbord monitoring/diagnostics systems. This has a fatal flaw when trying to manage effectively and to utilize the data being provided by the air vehicle. The different ground stations do not have full visibility of all data or control of the transportation of data off-bord. The processing methods to obtain necessary and useful information about the aircraft performance are separated in time and space from decision about the aircraft usage. This leads to data dropout, lost data, incomplete data, inefficiently used and stored data, and a general lack of confidence in that information that is obtained. The full system capability could not be realized due to the on-bord diagnostic algorithms and analysis techniques were developed separately, on different timelines and by different responsible organizations.
To realize current operational requirements, the customer ask for new ideas to harmonize small budgets and new claims driven by new situations.
On a commercial view, the huge special test and support equipments itself are responsible for the high LCC. The usage of special equipment increases the costs and decreases the effectivity of maintainers.

VISION

Basic solutions One way to follow the needs of the customer is to install new high-priced systems similar to the complex new airplanes. But only a small number of potential customer have the financial power to act this way.
The other way is the retentive adaptation of existing onbord systems in conjunction with pertinent reconfiguration of ground facilities. A distributed Information Management System between onbord data collecting components and offbord-stored data is the basis for this suggestion.

Onbord modification The modifications at the onbord systems are expensive and time consuming. They shall be reduced to a minimum, which makes the data mergeable. Normally the simplest way to make the data comparable is time stamping. Another simple way is storage in a central memory with internal marking features.

Offbord Modification The proposed offbord information system consists in stored information and processing capabilities, which combines the actual on- and offbord information with historical information. The interconnection between diagnostic capabilities, operational requirements and commercial aspects of maintenance/operational activities produces the basis for maintenance and operational actions. Activities can be planned and executed in a correlated manner and supports operational requirements.

Data Merger An important precondition is the merger of onbord data and offbord information. That is the basis for this new Data Management System (DMS).
Well-trained and experienced maintainer knows what happens when an aircrew describes a failure. He knows that items that are not connected directly to the malfunctioning item cause sometimes failures. He knows the fastest way to find the failure-generating item. This human data and knowledge fusion technology, normally in the heads of good maintainers, shall be organized in a smart DMS (Fig.1).
The bases for the proposed DMS are:

- Comprehensive knowledge of the actual aircraft status before beginning work
- All the necessary material on hand before beginning maintenance
- Interactive guidance available in real time to provide supplementary information as required

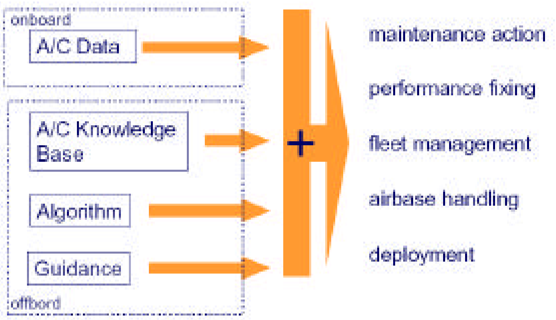


Fig.1 Data combination and consequential Actions

Long Distance Requirement Operations far away from homebase are difficult for maintenance affairs. A lot of supporting tools are only available with delay and sometimes the best-trained maintainers are not right away. A knowledge-based DMS can fill up the knowledge gap if it is immediately available and easy to move. A useful system should therefore run on standard equipment that is obtainable at the operational base or easy purchasable at the homebase.

Usage of common industry standards One of the major features for a new DMS is the usage of commercial industry standards for HW, SW and interfaces. Only this principle enables the user to built up fast a maintenance infrastructure in a non-familiar environment and with little own material. They had to transport information and know-how and not heavy items which are available around the world in a standard quality and with standard interfaces (HW and SW).

CUSTOMER EFFORTS

The basis for an effective diagnostic or prognostic system is the understanding that not only the fault and failure modes of specific components and subsystems are essential. An additional is the understanding of the science behind the failure, which are reflected by effective models and the maintenance infrastructure.
It would be formidably beneficial to utilize the failure modes and data from failures of other existing aircraft. The stored database shall include test results of "generated faults" and older failure information. In this way the customer can use their own knowledge about the aircraft to adapt the system to their own environment and procedures.
The described DMS will have a modular structure, which enables a fleet carrier to establish the system step by step. The usage of offbord components does not require expensive airborne items.
The proposed type of system would yield a large diagnostic solution at a minimal cost to the customer and therefore reduce the LCC of a fleet and support the flexibility usage of a fleet.
A way to calculate system benefits are described in the Health Management Strategies for the 21st century /2/.

ADDITIONAL WORK NEEDED

Life Cycle Costs can be reduced through implementation of health monitoring technologies, optimal maintenance practices and continuous design improvements /3/.
A lot of the needed data are present on the different buses, in flight and mission computers and in different avionics and control items. But not all information is deliverable for an acceptable diagnosis from a/c systems due to increased costs for additional sensors and provisions. These missing information can be adapted by experience and simulation results /4/.
The present data and the processed results from such a model can then be used to feed e.g. neural network or probabilistic-based autonomous system or other helpful tools for a "real-time" failure prognostic prediction.
A prerequisite is the use of interface standards, which allow a 3rd party to connect the system modules with their own systems. The following problem to handle and correlate the available information in a sensitive way has to be solved in the described way.

SUMMARY

Customer ask more and more for low-cost solutions of Prognostics and Health Management Systems (PHM). Mostly the solutions shall be used for in-service aircraft.
In practice, when developing a PHM, both, the on-bord and off-bord components need to be developed as one cohesive unit to realize maximum benefits. That way is not practicable for designers of upgrades for monitoring systems. They have to expand existing systems.
About in-service aircraft a lot of information are available but distributed in different "human memories", documents and information systems The proposed way described a procedure which allows the customer to optimize his results with a minimum of new airborne components and an effective usage of his own knowledge on basis of low-cost commercial ground equipment. As a top he gets more flexibility for his operational tasks for lower costs.

REFERENCES

1) Andrew Hess and Leo Fila *"The Joint Strike Fighter (JSF) PHM Concept: Potential Impact on Aging Aircraft Problems"* IEEE Aeroconference, Big Sky, MT, March 2002

2) G.J. Kacprzynski and M.J. Roemer "*Health Management Strategies for 21st Century Condition-Based Maintenance Systems"*, COMADEM Congress, Housten, TX, Dec 2000

3) EADS internal docs

4) Correspondence with GAF

AUTHORS BIOGRAPHY

Martin Geisreiter is a system engineer in the design and engineering department of EADS-D. He studied electrical engineering at the Technical University of Munich from 1979 -1984. He received the Master of Science in Electrical Engineering (Diplom-Ingenieur) in 1984. In 1985 he started at MBB (Messerschmitt Bölkow Blohm GmbH). One of his first tasks was the design of a radar ground mapping system and the analysis of collected huge radar data sets in the radar department. After a period in the quality management department and as an EMC responsible for the HAF AUP he is now responsible for diagnosis and recording systems at the military aircraft division of EADS-D. His main working area is design of life usage monitoring systems and aircraft diagnostics systems. His current projects are the EADS LCA program (MAKO) and new programs at EADS for the German Airforce (GAF) and other airforces.
He is a member of VDE and INCOSE.

UTILIZATION OF CELLULAR COMMUNICATION AND INTERNET INFRASTRUCTURE FOR AUTOMATIC DELIVERY OF FLIGHT DATA

Tamás M. Iglói

Teledyne Controls
Los Angeles, California

1 SYNOPSIS

The paper describes Teledyne experience integrating mobile telephone and Internet services into an aircraft wireless data delivery system.

Teledyne recently completed the development of the Wireless GroundLink™ system implementation. This system automates the secure delivery of flight data from the aircraft to the airline/operators data center, utilizing existing public communication infrastructure. The aircraft installed component of the system operates as a Quick Access Recorder during the flight - from engine start to shut down. Upon landing the data recorded during the flight is compressed, encrypted, and transmitted to the ground station via multiple built-in cellular (mobile) radios and the Internet. The data is rapidly delivered (in about 5 minutes for a five-hour flight segment) to the ground station and is available to maintenance and operational personnel.

The paper discusses Teledyne's experience from concept development through trials on revenue flights to obtaining FAA Supplemental Type Certificate for aircraft installation of the Wireless GroundLink Quick Access Recorder (WGL-QAR).

2 BACKGROUND

Transport aircraft commonly acquire and record data relating to flight operations, engine performance, weather data, etc. The data collected may be used for flight operations monitoring, engine performance and trend analysis, detection of faulty components, and to initiate maintenance action.

The data is typically collected on the aircraft by a flight data acquisition unit, commonly know as DFDAU. The DFDAU formats and sends the data to the mandatory flight data recorder as well as to a quick access recorder (QAR). The data that is sent to the QAR may also include report data, including aircraft condition monitoring (ACMS) exceedence reports and crew initiated reports, along with the mandatory data set.

Since the purpose of the QAR is to enable the operator to quickly gain access to the data, the recorder is equipped with a removable storage media, such as optical disk, PCM/CIA memory device, or cartridge tape that can be found on older aircraft.

Periodically, which could be daily, weekly or longer period defined by the operator, the recording media is manually removed from the QAR and transported to the flight operations or maintenance center. At the center the data is transferred to a computer system for processing and the media is “preped” and rotated back to the aircraft. Some operators store the media with the data intact for some extended period of time before the data is erased and the media is rotated back to the aircraft.

This manual process carries with it some consequences including labor cost, latency of the data, and some degree of data loss. The cost associated with the manual handling may vary from $2,000 to $3,500 per year per aircraft. The data latency can be anywhere from a day to a week or more, depending how frequently the media is removed from the aircraft. The data loss is attributed to media damage or deterioration, and to the loss of the media. Some operators indicated that they experienced up to 20% data loss. The loss of media is especially high with the PCMCIA storage element.

3 THE OBJECTIVE

Teledyne embarked on a program in 1998 to develop a system implementation with the following goals:

- eliminate the data loss
- reduce data latency
- provide a solution at a cost comparable to the cost of present day data recording and manual delivery

It was determined in the early phase of the system definition, that to achieve the low cost solution the implementation will need to rely on existing services and infrastructure.
The characteristics that we felt to be imperative to make the solution cost effective included:

a) A wireless implementation to move the data from the aircraft
b) Services and infrastructure to support the wireless operation to be available at airports world wide.
c) Services and infrastructure to move the data is to be deployed, maintained and up dated to new technology by the service providers, i.e, financing of the deployment, maintenance, and improvement of the infrastructure must be drawn from wide area of users, as not to be carried solely by airlines and aircraft operators.
d) The bandwidth of the technology utilized must be sufficient to meet the data transport needs of today.
e) A clear path must exist to meet the needs of future growth in aircraft recorded data volume.
f) The implementation is to provide a secure method for data delivery.
g) Minimize aircraft installation costs, (if possible, avoid the use of fuselage mounted antenna).

4 DEVELOPMENT OF SOLUTION

4.1 Data Delivery Considerations

The items b), c), d), and e) above steered the design toward the used of existing services that are available word wide and whose operation is aimed at, and supported by a large public user base. This pointed us to consider the combination of the commercially available wireless communication services and the Internet as the data delivery media.

Once it was determined that the data can be delivered reliably over the public wireless and Internet services, the focus was directed at the selection of the wireless services to be used. The services that were considered included satellite service (SatCom, Globalstar and Iridium) and terrestrial cellular services.

A comparison was drawn to determine how the performance, service availability, coverage, service cost, installation cost, and the expected future growth of the services stack up against the expectation of the end user (airlines/operators). A simplified form of the comparison is illustrated in the table below. The costs for transmission of 1 Megabyte of data is shown based on list prices and are provided for comparison purposes only. The charges shown include air time, only. The activation, initial SIM charges, and monthly fees are omitted. The actual charges may vary depending on the specific contract that is negotiated by the airline with the service provider.

	SatCom	Globalstar	Iridium	Cellular - CDMA	Cellular - GSM
Data Rate (kbps)	64 or 128	9.6	2.4	14.4	9.6
Near Term Future Capability (kbps)	64 or 128	9.6	2.4	144 (1XRTT) 384 (3XRTT), (WCDMA)	~50 (GPRS) 384 (EDGE)
Real Time Transmission Capability	Yes*	No	Yes*	No	No
Relative Aircraft Installation Cost	Very High	Medium	High	Low	Low
Per Megabyte Airtime Cost	$33.75	$13.86	$78.40	$1.67	$2.50

*Includes coverage over water.

As can be see from the table above, the lowest cost of data delivery can be provided via the terrestrial GSM (Global System for Mobile Communication) and CDMA (Code-Division Multiple Access) cellular method. The advantage of the terrestrial cellular method still exists for this application, even when compared with the high speed capability of the SatCom. Multiple cellular channels (radios) may be used simultaneously in parallel to increase the through put capability at a significantly lower cost. For example, the present day technology eight CDMA radio configuration provides a gross through put of 115.2 Kbps, which is comparable to a dual ISDN (Integrated Services Digial Network) SatCom capability at the fraction of the cost.

The planned deployment of the 1XRTT, GPRS (General Packet Radio Services), UMTS (Universal Mobile Telecommunications System) 3XRTT, WCDMA (Wideband Code-Division Multiple Access), and EDGE (Enhanced Data rates for GSM Evolution) technologies by the cellular service providers assures that the proposed method has a significant future growth path. These new technologies will be able to support the higher data acquisition rates of new aircraft systems along with the expected reduction in data delivery costs. Currently GPRS infrastructure has already been deployed in some countries in Europe, notably in the UK, Germany, and France. The 1XTRR and GPRS is expected to be deployed in the United States by the end of 2002. The EDGE and 3XRTT technologies with per channel the data rate capability of 384 Kbps are expected to be deployed within the next two to three years.

The data delivery performance can be further enhanced and the cost reduced by the use of data compression that reduces the recorded file size prior to transmission.

While the cellular network does not support real time data delivery from an aircraft in flight, the delivery of the data following the landing complements the real time delivery of the exceedence reports by the ACARS/CMU/TELELINK. It offers a far superior delivery method of the complete data set to todays manual handling of data media. The data, which is delivered to the data processing center after the aircraft is parked or pulled up to the gate, can also assist aircraft maintenance. With the full flight data set at hand, the reported (by ground processing or ACARS/CMU/TELELINK) in flight exceedances can be fully analyzed and dispositioned by the maintenance crew.

4.2 Data Reliability and Security Considerations

There were two other data delivery related considerations that had to be addressed before the system could be deployed for trial operations on commercial flights with air carriers. These were the solutions to the needs of airlines for the reliable and secure data delivery over the wireless networks and the Internet.

Encryption was selected as the preferred method to assure data security. Teledyne elected to use our proprietary symmetrical encryption algorithms. This algorithm was derived from our prior experience developing Interrogate Friend or Foe (IFF) systems for the US government. Encryption Key management software was also made available, allowing the user to remotely manage the symmetrical encryption keys. The use of encryption algorithms coupled with key management software to periodically update the encryption key provides data security that meets air carrier expectations for data security.

It was determined that the reliability of the data delivery consideration can be answered by the use of commercially available software in conjunction with a Teledyne developed protocol. The implementation selected employs a Teledyne proprietary transfer protocol that utilizes the User Datagram Protocol (UDP) and the TCP/IP network protocols. The protocol supports multiple concurrent phone connections, where each phone (cellular radio) establishes a separate PPP connection with the base station. The protocol supports operation over both the packet and the circuit switched connections.

In operation, after the aircraft has landed, the transfer is initiated. First the session information is exchanged with the base station. This is followed by the transfer of the compressed and encrypted versions of the data file that was recorded during the flight. The file is transferred as a series of fixed length blocks, usually set to 1Kbytes, which are sent over any of the available connections, i.e. phones. Each block is acknowledged by the base station upon successful receipt of the block. After all blocks are transferred, any unacknowledged blocks are retransmitted. This continues until the receipt of all blocks have been successfully acknowledged by the base station. Integrity checks at the packet, block, and file level are included guaranteeing data integrity. The protocol is designed to be tolerant of packet loss and out of order arrival conditions that may be experienced on the Internet. It is also tolerant of circuit busy and dropped call conditions that may be experienced on the wireless networks. If the transfer is interrupted due to a change in the hardware interlock, it will be resumed when possible. The interrupted transfer will be completed at the available transmission time.

The base station software is designed to support reliable, secure connection of the flight operation center's secure, trusted local area network with the unsecured, untrusted public Internet. It consists of three separate software components. The first is a Windows NT/2000 service that communicates simultaneously with multiple WGL-QARs and stores on its local disks only the compressed, encrypted archive file. There are also two applications that communicate with the service via TCP/IP sockets; one that decrypts, decompresses, and extracts the individual files from the received file, and a user interface that allows the activity of the service to be remotely monitored. These components may reside on the base station computer, or on separate computers.

4.3 Aircraft Installation Considerations

When it comes to installing equipment on the aircraft, there is a concern regarding the impact of the installation. This impact has several factors, including equipment weight, size, power consumption, and installation requirement. Which all relate to installation costs and operating expenses. In this case, since the equipment is intended to utilize wireless communication, there is also a concern (cost impact) with regards to antenna mounting. Avoiding the fuselage mounted antenna configuration is highly desirable.

It was determined that the impact can be minimized by configuring the new system as a functional replacement of an existing on-board equipment with identical physical configuration and equal or smaller weight and power consumption. This lead to decision to configure this new wireless equipment plug compatible with QAR. The intent is to have the unit operate as a QAR during the flight and transmit the data after landing. With this approach, at least with aircraft already equipped with QAR, one can replace the existing recorder with this new device with no impact on weight and balances and power consumption and very little impact on aircraft wiring. The installation on aircraft not provisioned for QAR can still be achieved with minimal design, since STCs for QAR are available practically for most transport aircraft. The wiring that needs to be added over and above of a QAR wiring is minimal and consists of two to four wires to provide interlock to prevent radio transmission during aircraft operation and enable data transmission once the aircraft has landed and it is parked.

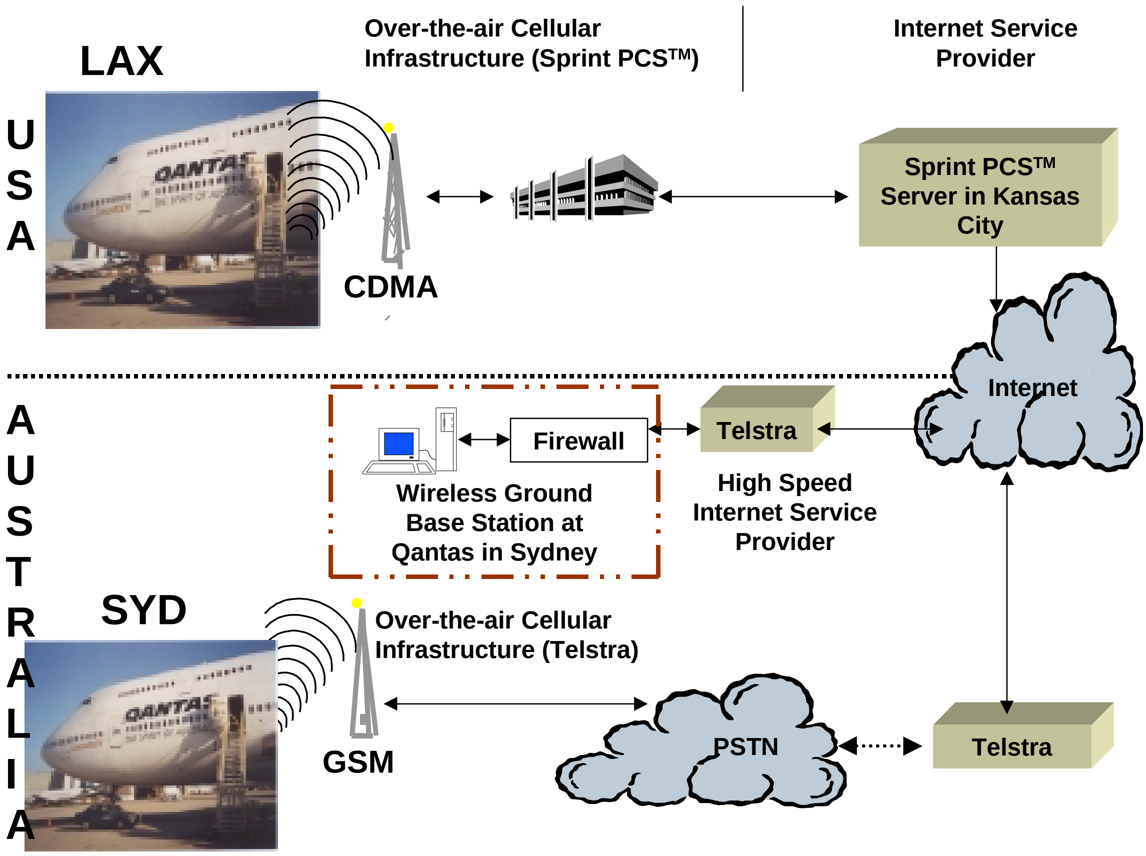
While the physical configuration of this new device is relatively straight forward, the determination of antenna placement needed considerable analysis and measurements. From the very start, the goal was to arrive at a configuration that will minimize the installation cost, that is, at the minimum, it will not require fuselage mounting of the antenna. The preference being an antenna integral to the face plate of the unit.

To establish the feasibility of operation with antenna internally mounted to the fuselage, Teledyne, with the cooperation of various airlines conducted surveys and cellular radio RF measurements in the electronics bay of different aircraft types at various airports in the US and in Europe. The results of the measurements indicated that sufficient RF signal strength can be maintained with the antenna placement on the face plate of the unit and the unit being mounted in the electronic bay of the aircraft. The antenna placement is illustrated in the accompanying photo of the WGL-QAR. The antenna shown is the 1900MHz unit.

5 APPLICATION OF THE TECHNOLOGY

With all the results of the analysis, experiments and measurement in our pocket, Teledyne embarked on trial operation of the system on revenue flights with air carriers. One system with eight CDMA radios with Sprint PCS™ wireless services was installed on a Qantas Airways B747-400 in August 2001. The photo below illustrates the B747 e-bay installation.

This trial showed that the system reliably transmits data from US airports to the Qantas facility in Sydney. The experience repeatedly demonstrated that data can be transmitted reliably around the world over the cellular and Internet network. The recorded data of 14 hours flight legs were routinely delivered from Los Angeles International Airport (LAX) to the processing center at Sydney, Australia in about 12 minutes without any loss of data and human involvement. The trial with Qantas was expanded with the use of a unit equipped with four CDMA radios using Sprint PCS™ services and four GSM radios using Telstra wireless and Internet services. This configuration, illustrated below, provided experience to transmit data over various networks and service providers.



A similar trail is being conducted with a US carrier on a B737-800 aircraft. The equipment was installed under FAA STC that was issued to Teledyne for installation on B737 aircraft. The unit used on this trial was configured with eight CDMA radios and uses Sprint PCS™ wireless services. This trial, operating since November 2001, also shows that the cellular wireless network and the Internet delivers the data without loss in a timely manner.

6 CONCLUSION

The results of the trials demonstrate:

- The mobile cellular services and the Internet, when coupled with the appropriate communication protocols, error recovery and security measures will provide a reliable means of transporting aircraft data world wide in a timely manner.

- The installation of the system on-board can be achieved at a minimal impact to aircraft configuration.

- The data is delivered economically.

The experience also shows that this technology may provide the way to extend data delivery to other areas. It can, as an example automatically route and the deliver ACMS generated engine performance and monitoring reports with extended data sets directly to the engine manufacturer for analysis.

In conclusion, it is believed that the wireless technology is a valuable, cost effective tool for the delivery of data to/from the aircraft.

MILITARY FLIGHT OPERATIONS QUALITY ASSURANCE

Everett W. Smith
U.S. Air Force Safety Center
9700 G Avenue SE
Kirtland AFB, NM 87117-5670
United States
Everett.smith@kafb.saia.af.mil

Peter Clapp
Spirent Systems
The Lodge, Aviation House
Harmondsworth Lane
West Drayton, Middlesex
UB7 0LQ, England
Peter.clapp@spirent.com

ABSTRACT

Civil Air Carriers have integrated Flight Operations Quality Assurance (FOQA) programs into their corporate operations. These programs have subsequently achieved significant cost savings and safety benefits. In 2000, the U.S. military safety chiefs endorsed the adoption of FOQA within the Department of Defense (DoD) to reap the benefits currently being realized in commercial aviation. The U.S. Air Force Chief of Safety funded a one-year Military FOQA (MFOQA) demonstration project to explore the feasibility and potential benefit to military aviation. The C-17 was chosen as the test fleet due to its transport yet tactical mission. This choice of aircraft allowed the project to leverage civil aviation groundwork while exploring military mission nuances. This paper will discuss project structure, resources and processes and how they were influenced by civil aviation groundwork and lessons learned in FOQA. Operational dissimilarity will be discussed highlighting specific considerations for a military FOQA program. Examples of military operational issues will be highlighted with discussion of benefits achieved.

INTRODUCTION

The U.S. military services each have staff organizations to oversee safety. The Safety Chiefs of these services meet semi-annually to address safety issues of mutual interest. In October of 1999 at Quantico Virginia the Safety Chiefs agreed in principle and in August of the following year signed a Memorandum of Agreement[1] to promote the introduction of FOQA to military aviation.

Each service also accepted during the Quantico conference that each should pursue application of MFOQA to different missions. This "divide and conquer" approach was advocated to leverage military funding to the maximum benefit. Each service could then share lessons learned for application to common mission platforms. This approach was reaffirmed at subsequent MFOQA conferences with the USAF targeting transport aircraft, the Army targeting helicopters, and the Navy targeting fighter aircraft.

This paper discusses the U.S. Air Force C-17 MFOQA demonstration project.

PROGRAM OBJECTIVES

The primary objectives were to demonstrate the technical feasibility and potential benefits of applying FOQA to military operations.

From a technical feasibility standpoint our initial concern was whether a FOQA program could be implemented using the most prevalent USAF recorders. While many USAF transport aircraft utilize recorders common to civil air carrier operations, Smiths Industries recorders have

[1] Endorsement of Flight Operations Quality Assurance – Military (FOQA-M), August 2000

become the most prevalent USAF recorder pedigree. USAF history with Smiths, formerly Lear Sieglar, started in the early eighties when the military services were searching for a flight data recorder that would be both survivable and small enough for installation in fighter aircraft. To record significant amounts of data in a miniscule volume using the solid state memory technology of the 1980's required some innovative data compression and optimization techniques. Consequently, these techniques introduced some technological challenges. The straightforward, standard formats and recording rates of main stream recorders were all FOQA vendors had experienced to this point.

To reduce technical risk each potential FOQA contractor was provided a test flight and an additional 1000 flights of data. Each contractor was instructed to use this data to demonstrate their ability to accurately interpret the test flight and to demonstrate FOQA products. These demonstrations, along with other criteria, were critical in selecting the FOQA contractor. Through this process we had ensured data formatting and recording processes were surmountable prior to contract award.

The next obstacle in validating technical feasibility was event set creation. Event sets have historically been constructed with commercial air carrier operations in mind. Excessive bank angles or descent rates were measured in increments of a few degrees or hundreds of feet per minute. MFOQA had the challenge of crafting an event set that would apply the same flight standards when equivalent transport operations were underway yet are able to differentiate when the mission transitioned to a tactical or "military" role where 60 degree bank angles and thousands of feet per minute descent rates were the norm. To construct a military event set it is essential to include a subject matter expert in the operation of that aircraft. In other words, a pilot that understands how the aircraft is flown and how it operates within the defined mission. While engineers and safety professionals can define an initial set of events that may reveal mishap precursors it will be the pilots that inject context into the process.

Finally, after demonstrating technical feasibility we must address the financial viability of the project. Unfortunately FOQA bears the same burden of all other safety programs. That is, how do you detect and quantify the accident you prevented? The accident never occurred and therefore was never quantified or reported. One can only postulate statistically that FOQA initiatives were responsible for safety improvements that many other parochial interests will also claim responsibility. This is why it has been obvious from the very beginning that maintenance and training benefits from MFOQA will probably justify funding before safety. However, with that said, one MFOQA finding will be discussed where safety benefits alone would justify many years of MFOQA funding.

PROJECT STRUCTURE

Civil air carriers normally have a single office that advocates and manages their FOQA efforts. This office is generally integrated into the overall corporate management structure under safety.

The USAF has numerous safety offices at various levels within the organization. More than 6800 aircraft ranging from gliders to stealth bombers are managed by several different Major Command (MAJCOM) headquarters. This diversity and shear size poses significant management challenges to introducing FOQA to the "corporation". Convincing a single management structure of FOQA's benefit is insufficient to assure corporate buy-in. A multi-tiered approach is necessary to obtain authorization for a demonstration project.

These same management structure issues would be common to other military organizations pursuing FOQA introduction.

To address this required multi-tiered buy-in the MFOQA project was structured to include representation of all shareholders in C-17 operations. The project is funded and managed by the USAF Safety Center as the highest safety management authority. As a Forward Operating Agency (FOA) of the USAF headquarters staff the Safety Center could promote and promulgate FOQA across the service at large. Air Mobility Command (AMC), as the lead MAJCOM for the C-17 and all transport aircraft, joined as a key partner of the team and is targeted as the initial MFOQA customer. AMC is instrumental to the success or failure of MFOQA because it can promote and promulgate application across all USAF transport fleets if convinced of its benefit. The 62nd Airlift Wing at McChord AFB was included as a key member to bring C-17 operational expertise, assess the benefit of analysis capability at the lowest organizational level and facilitate line pilot buy-in.

PROJECT RESOURCES

Project resources are very dependent upon which FOQA vendor joins the team. Computational hardware requirements can range from off the shelf desktop computers to sophisticated servers with massive storage capabilities.

Air Carrier operations normally consist of one physical location that receives flight data from operating locations on various storage media. This data is then loaded onto the host system and processed for analysis at that location.

The MFOQA philosophy is to provide information to decision makers at all levels of the organization. Therefore, it was imperative to demonstrate a project that minimized maintenance workload while maximizing data availability across the organization on a real-time basis. This necessitated placing resources at all levels to prototype the concept.

Desktop computers were place at the three demonstration locations, Kirtland AFB, Scott AFB and McChord AFB. These computers were off the shelf, dual 1.4 GHz Dell processors. Graphical and storage capabilities of the machines were dictated by FOQA software visualization requirements and the expected fleet database size. Upgrading the machines beyond their delivered capabilities to meet project requirements only added a few hundred dollars.

The computer at the Safety Center (Kirtland AFB) was the project central processor where configuration management, data archival, database management and processing was accomplished.

PROJECT PROCESSES

To get the data from operating locations to the Safety Center without imposing a new logistical burden we took advantage of an existing data transfer process. The C-17 has an integrated structural usage and flight data recorder system. There is an existing maintenance process to periodically download the structural usage system when its memory is 80% full. When the structural data is downloaded and subsequently electronically uploaded to Tinker AFB the flight data is also transferred. Software was developed in 2000 to segregate this mishap investigation flight data and make it available for transfer to Kirtland. Software on the Safety Center MFOQA machine was also developed in 2000 to periodically poll the Tinker AFB computer and download data as it became available. The data is archived and then automatically processed and appended to the MFOQA database for analyses. Within 40 minutes from the time an airman uploads the data to Tinker it is available for analysis.

Our objective to provide current data to all locations necessitated an innovative data transfer scheme. It was resource prohibitive to routinely transfer scores of gigabytes of data to the remote locations through either telecommunications or physical media.

Each remote site is updated nightly with event statistics to enable trending and identification of specific flights to investigate. Once a flight is identified for further analysis by the remote location the flight of interest is downloaded from the Safety Center to the remote site. This scheme avoids the burden of sending all data to the remote sites by only providing the flights of interest when desired.

OPERATIONAL DISSIMILARITY

Early perceptions were that FOQA was not applicable to military operations because the military “flies different” than the civil world. This later point is, of course, very true. Aggressive flight profiles that are necessary for tactical military missions would be totally unacceptable for revenue generating commercial flights.

Descent rates in thousands of feet per minute, bank angles in excess of 60 degrees and aggressive approach angles are perfectly acceptable in some mission profiles. The challenge in Military FOQA is knowing how to determine what mission is being flown. The C-17 has a mode select that inhibits nuisance ground proximity warnings to the crew when in a tactical mode. Fortunately this discrete is provided to the data recorder and used to differentiate when events should be conditioned for tactical flight to suppress non-contextual events.

Low level operations are another area where we differ significantly from civilian aviation. Pilots are aware of low level military training routes in which airspeeds greater than 250 knots are allowed. Events that trigger on the civil aviation speed restrictions below 10,000 feet are only valid when not in a military training route or Military Operating Area (MOA).

And lastly, Go-Arounds are routine for our crews because unlike civil aviation we are either conducting military operations or training to conduct military operations. So a go-around is either dictated by the situation or pre-planned with no concern for financial impacts.

MILITARY OPERATIONAL ISSUES

Air carriers fly to large national airports with well established approach and departure procedures. Navigation aids and approach systems are also common along with an Air Traffic Control (ATC) system.

Military transport aircraft may be required to fly into austere temporary airfields that did not exist weeks before. Similarly, existing runways at formerly hostile destinations may have been damaged in earlier combat flights reducing usable runway length significantly until repaired.

Another concern is that civil aviation is characterized by seasoned pilots flying relatively benign flight profiles from departure to destination. Military transport flights range from mundane long haul cargo flights to aggressive tactical transport to training.

For these reasons military analyses are more complex than civil FOQA analyses.

BENEFITS

One early analysis looked at event statistics from almost 15,000 flights. Specifically we focused on “high g at landing” events. What was found from analysis of these flights was 680 landings with vertical accelerations of 1.6g or greater. Furthermore, 40 of these landings were 2g or more.

Unlike conventional aircraft the C-17 is flared by application of power rather than increased back pressure on the stick/yolk.

Most of the analyzed hard landings occurred at night over unlighted terrain where the crew was subject to the black hole illusion. This visual illusion leads the pilot to perceive his aircraft higher than actual on approach resulting in landing far short of the runway. The immediate reaction of the pilot when terrain impact becomes apparent is to instinctively react according to their training. In these cases rather than adding power and not applying stick force, which exacerbates the sink rate, the pilots pulled back on the stick.

This trend detection and analysis had been performed and briefed to higher management but was yet to be acted upon when a $3.3M mishap occurred where this improper technique was found to be causal. If we had been able to rectify this trend, perhaps through increased proficiency, we could have funded MFOQA projects for many years upon the savings.

Another unintended benefit of providing a MFOQA infrastructure was the enabling of an investigation capability at McChord and Scott. This reduces Kirtland investigative manpower requirements by enabling AMC to perform their own analyses and animations of less than major accidents. Now when a C-17 accident or incident occurs we request the field to upload the flight data to the MFOQA system and within 40 minutes the flight data can be reviewed by AMC and the Safety Center.

CONCLUSION

While initially discounted as not applicable to the military, FOQA has proven beneficial to all aviation operations. It is fundamentally the characterization of flight operations and trending to detect areas for optimization whether they are safety, design, maintenance, operations or training.

The military is arguable the area of most potential for mishap prevention and financial benefit. The relatively lower experience levels coupled with aggressive flight profiles provides a target rich environment for MFOQA analyses.

So in summary, the C-17 demonstration project has shown FOQA is feasible and desirable in military operations. Our current plans are to continue the C-17 MFOQA operations and initiate demonstrations in our KC-135 and commercial aircraft fleets. We are also investigating how best to prototype the technology in trainer, bomber and fighter aircraft.

Departure Warning System for TORNADO Aircraft

Dr. Achim Schönhoff
Dr. Matthias Heller
Karl Bollfrass
EADS Military Aircraft
81663 Munich

Wolfgang Nosse
EADS Dornier
88039 Friedrichshafen

Abstract. This paper describes the development process of the 'Departure Warning System' (DWS) for the TORNADO multi role combat aircraft having being developed by EADS Military Aircraft and EADS Dornier. A successful First Flight of basic DWS functionality was performed on October 29th 1999 with the final flight test performed on 6th December 2000.

Special attention is drawn on the system and software development process, which is embedded into an evolutionary tool concept at EADS Military Aircraft.

Furthermore, a description of the technical concept and its realisation is given.

SYSTEM DESCRIPTION

Scope. The introduction of the Departure Warning System into German Air Force TORNADO aircraft is aiming at an improvement of the overall TORNADO flight safety. This is achieved by improving the aircrews situational awareness due to an acoustic aircraft and flight status monitoring.

This improvement is achieved by providing an acoustic warning to the aircrew while approaching aircraft configuration and state dependent flight limitations with respect to aircraft stall and spin. External loads of the aircraft are of special importance for the definition the limitations to be applied, which are given as flight clearance limitations in the flight manual.

Basic System Principle. The Departure Warning System's basic idea is to provide specific tone output to the aircrew reflecting the distance between the actual Angle of Attack (AoA) and the applying valid AoA limit which depends on manoeuvre type and external stores.

Also taken into account is the dynamic behaviour of the aircraft and the resulting AoA in order to avoid overshoot during highly dynamic manouvering.

Intensity of the tone output is increased by rising tone frequency, volume and pulse rate as the applying AoA limit is approached. Figure 1 shows the basic layout of the tone scheme.

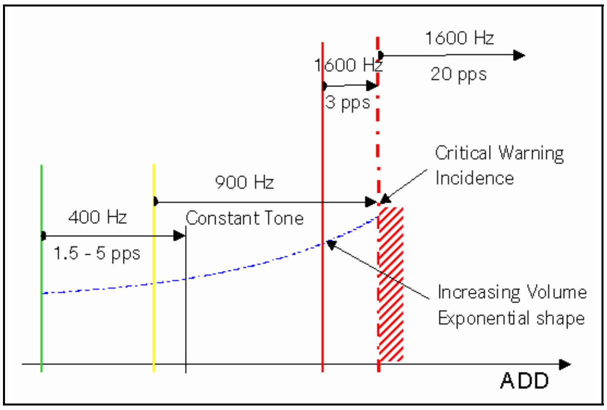


Figure 1. DWS Tone Scheme

The tone scheme starts with a 400Hz pulsed tone with a pulse rate increasing from 1.5 to 5pps (pulses per second) as the AoA passes a range considerably far away from the clearance limit.. The 400Hz tone is followed by a 900Hz constant tone. As the AoA increases further towards the clearance limit a 1600Hz pulsed tone is provided. Below the clearance limit the 1600Hz pulsed tone has a pulse rate of 3pps and in addition the 900Hz tone is still provided. A significant increase of the tone volume in this area provides maximum situational awareness for the aircrew.

As the clearance limit (‘critical warning incidence’) is exceeded, the pulse rate is raised to 20pps and the volume is doubled. For the 400Hz pulsed and 900Hz constant tone an exponential increase of the volume is implemented.

Areas of mixed 400Hz pulsed / 900Hz constant tone and 900Hz constant / 1600Hz pulsed tone are foreseen to further improve the aircrew’s situational awareness. Furthermore these areas of mixed tones are aiming at providing a more or less continuous tone scheme despite of the discrete AoA areas with their specific tone frequencies.

It is possible for the aircrew to adjust the DWS volume according to personal preferences. Nevertheless the volume is partially fixed in order to prevent the aircrew from switching the DWS off. The non-adjustable level of the volume is increased as the clearance limit is approached to raise the aircrew’s attention in case of critical situations.

Additionally, the Departure Warning System is designed to give the aircrew information about its system status by generating voice messages. In case of minor errors which allow degraded system functionality providing conservative warning the aircrew is given a ‘Departure Warning degraded’ message. Major errors results in a ‘Departure Warning failed’ message. Return to normal operation is announced with ‘Departure Warning restored’. Return to normal operation is not foreseen for store configuration failures.

In all three messages the keyword is repeated to provide maximum consciousness about the system status for the aircrew. An active status check cannot be performed by the aircrew. In order to overcome this point a DWS failure is indicated by an amber caption on the aircraft’s Central Warning Panel (CWP) in addition to the failure voice message.

SYSTEM DESIGN

Phased Approach. In order to meet the target date November 2nd 1999 of an in-flight demonstration of the Departure Warning System, a phased approach has been chosen.

Phase 1 functionality to be developed from May 1999 on until October 1999 comprised only Clean Aircraft functionality, i.e. external store information was not taken into account.

Phase 2 started in parallel in May 1999 and lasted until October 2000. During phase 2 the full DWS functionality was established.

System Concept. Major requirement for the DWS was, that introduction of an additional Line Replaceable Unit (LRU) into the TORNADO had to be avoided under any circumstances. Furthermore, cockpit modifications had to be kept at a minimum.

Additionally, in order to minimise extra aircraft wiring, the Departure Warning System had to be implemented in an LRU where already most of the data necessary for the DWS is available. The necessary data consists of the following signals:

- Angle of Attack (AoA)
- Store Configuration
- Pilot inputs at stick and pedals
- Aircraft configuration (Wing sweep, Flap/Slat position, System status, Failure status)

The Data Acquisition Unit (DAU) of the TORNADO aircraft turned out to be the perfect LRU for the implementation of the Departure Warning System. The DAU is part of the Flight Data Recorder (FDR) functionality, which implies that most aircraft data is already available. The growth potential of the DAU1D (Digital FDR version) allowed to introduce the DWS for an upgrade towards the DAU1E.

Figure 2 shows the system concept of the DWS. Only additional wiring for the signal of the Starboard ADD-Probe and for the connection from the DAU to the Crew Communication System (CCS) Junction Box and to the Central Warning Panel (CWP) has to be introduced into the aircraft. This extra wiring minimises the effort for the aircraft modification, since only minimal working space is required below the front cockpit region.

Due to the use of already existing, no longer used Cockpit Voice Recorder (CVR) inputs at the CCS, cockpit modification could be minimised to label changes at the CVR control panel and the Central Warning Panel caption.

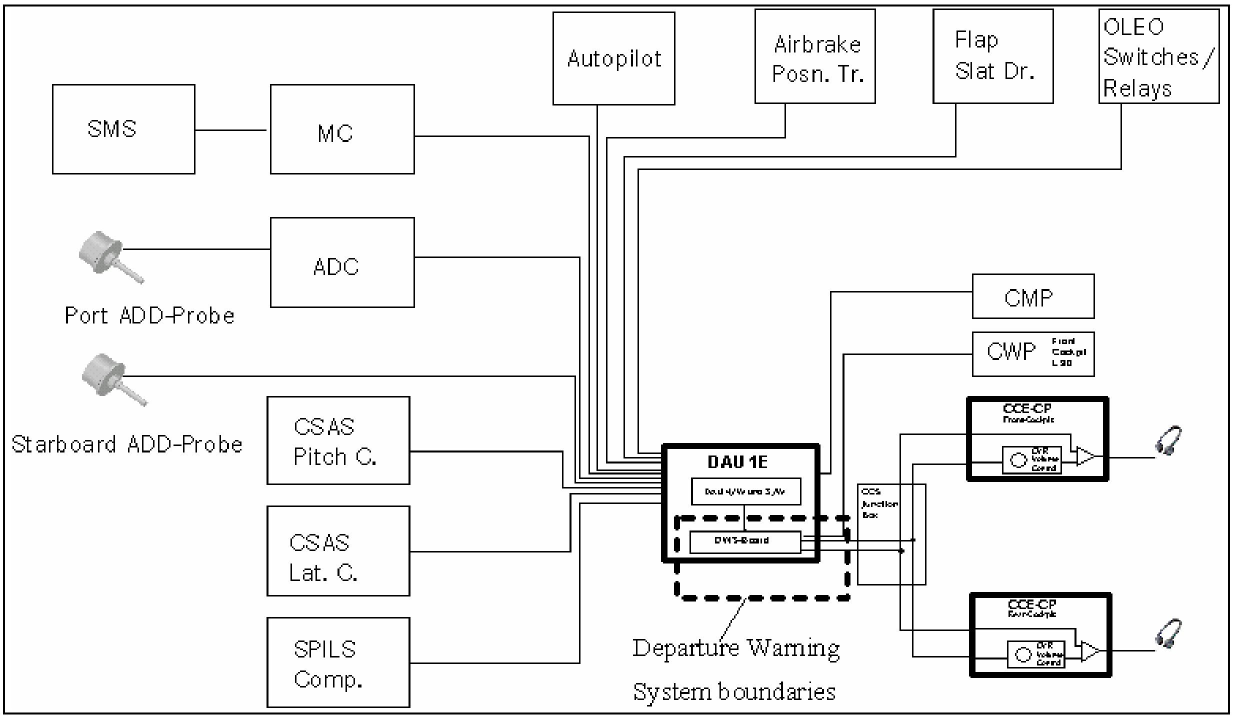


Figure 2. System Concept

FUNCTIONAL LAYOUT

Functional Design. The Departure Warning System algorithm has to provide the following features in order to calculate the correct tone output:

- Normalisation and Filtering of stick and pedal inputs
- Sideslip compensation of starboard and port ADD probe signals (independently in order to allow ADD probe monitoring)
- Selection of Most-Nose-Up Compensated ADD-Signal; Filtering of this ADD-Signal
- Calculation of AoA time derivative
- Determination of store configuration
- Selection of flight condition (Airbrake, Airspeed, Flap/Slat position)
- Selection of manoeuvre type (symmetrical / coarse lateral / cross control / pedal only manoeuvring)
- Assignment of clearance limit curves
- Calculation of ADD limits
- Calculation of damping increment
- Calculation of sound limits
- Management of history values

Simulation Example. Figure 3 shows a simulation example (pitch up manoeuvre) of the Departure Warning System functionality.

The top graph in Figure 3 shows the Angle of Attack and the calculated thresholds for each of the three warning tones. The middle graph depicts again the AoA and its time derivative. The bottom graph shows the pitch stick input for the shown manoeuvre.

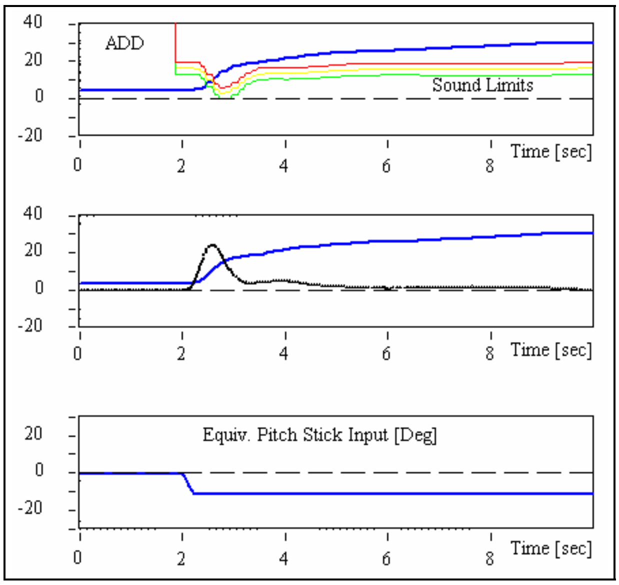


Figure 3. Simulation Example

Due to the high pitch stick demand, the AoA rises very quickly, thus resulting in lowering the warning tone thresholds significantly. The highest warning level (1600Hz pulsed tone) threshold is lowered from 20Units ADD ($\partial\alpha/\partial t$ = 0) to approximately 7Units ADD.

This gives the pilot the pilot the chance to relax stick input in order to prevent the aircraft from overshooting the clearance limitations (20Units ADD in the given example). Flight testing showed clearly the successful design of this part of the functionality. As stick input is not relaxed in this simulation example, significant overshoot has to be notified.

EQUIPMENT ENGINEERING

Equipment Design / Functionality. TORNADO's Data Acquisition Unit offered enough growth potential to introduce a new processor board to implement Departure Warning System functionality. Figure 4 shows the structure of the DAU.

The DAU is the central element of the Flight Data Recorder for data collection and conditioning. Therefore it is the ideal platform for monitoring tasks, since many signals from different sensors and equipment, airframe and engines are already available.

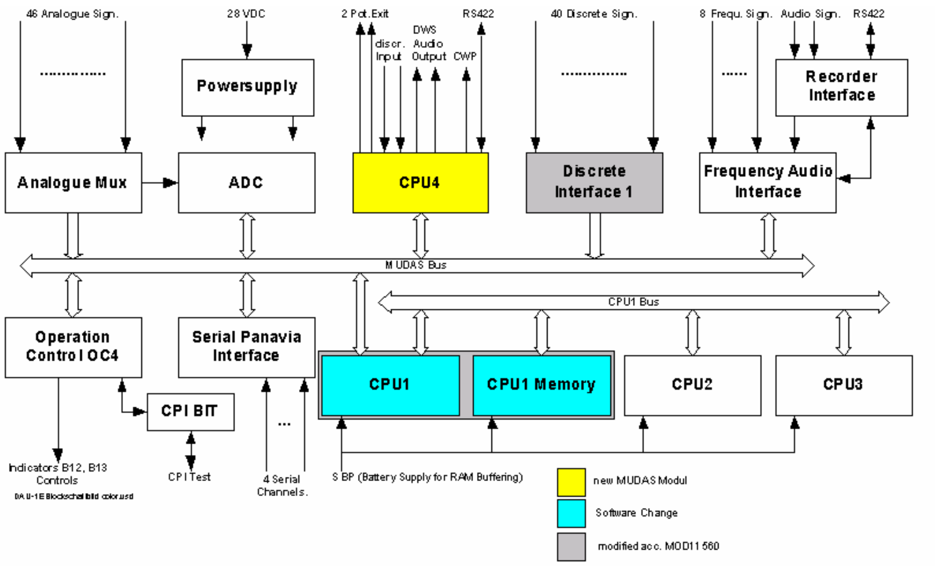


Figure 4. Structure of the Data Acquisition Unit (DAU)

Figure 5 shows the structure new processor board introduced into the Data Acquisition Unit to incorporate DWS functionality. This structure consists of the following main elements:

- Motorola CPU MC68360, ca. 4,5 MIPS@25 MHz
- 32 Bit Databus
- Glue- and BIT-Logic in CPLD and FPGA
- PCB-Test via Boundary Scan Interface

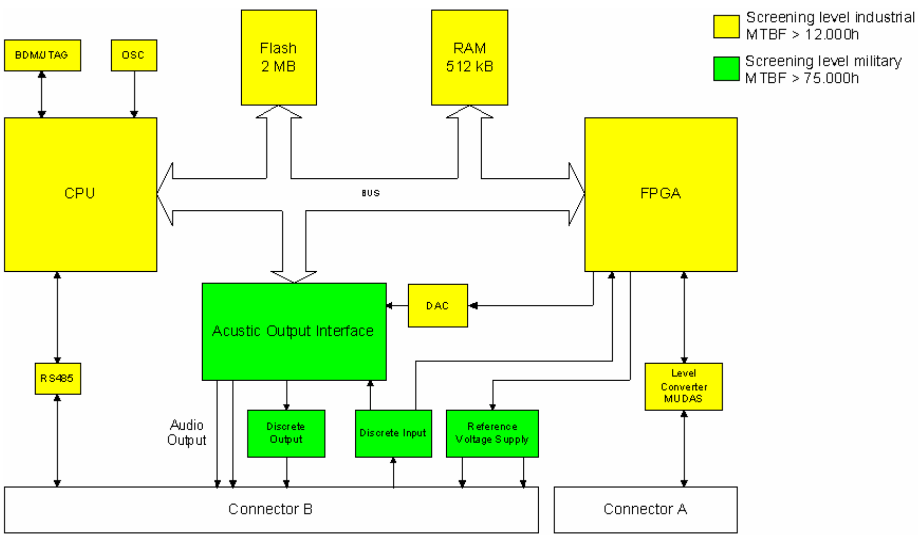


Figure 5. Structure of the DWS processor board

Figures 6 and 7 show the front side and the rear side of the DWS module.

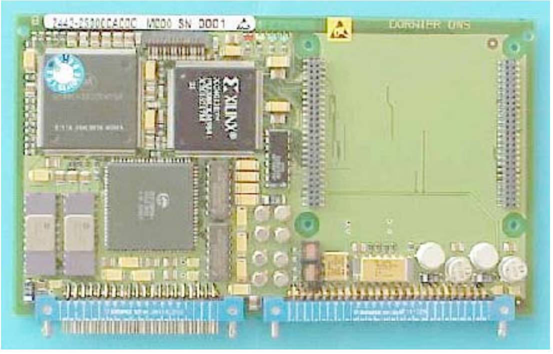


Figure 6. DWS module (front side)

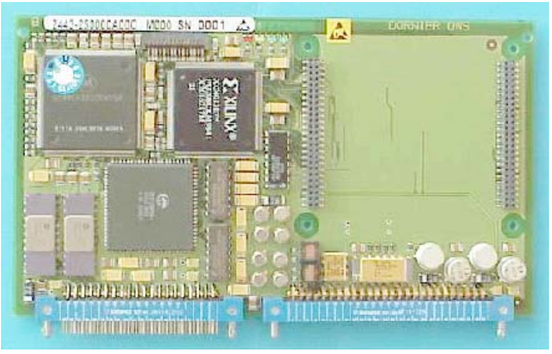


Figure 7. DWS module (rear side)

REQUIREMENT ENGINEERING

Document Structure. Prior to the start of any development activities customer requirements were compiled in a User Requirement Document (URD) and agreed with the customer.

This URD is the basis for the System Specification which fixes the contractually relevant requirements top level requirements for the system to be developed.

From the System Specification the System Design Specification is derived, defining the detailed technical design of the system. This document defines the basis for the application software requirements to be defined in the Software Requirement Document (SRD) and for the equipment requirements defined in the Equipment Specification Appendix (due to the fact that the Data Acquisition Unit is an already existing LRU, no separate equipment specification is established).

Figure 8 shows the top level document tree. Corresponding to the specification/development branch is the test/clearance branch. This branch contains the test plan/procedure/result, verification and clearance documents leading to the Final Declaration of Design and Performance (F-DDP).

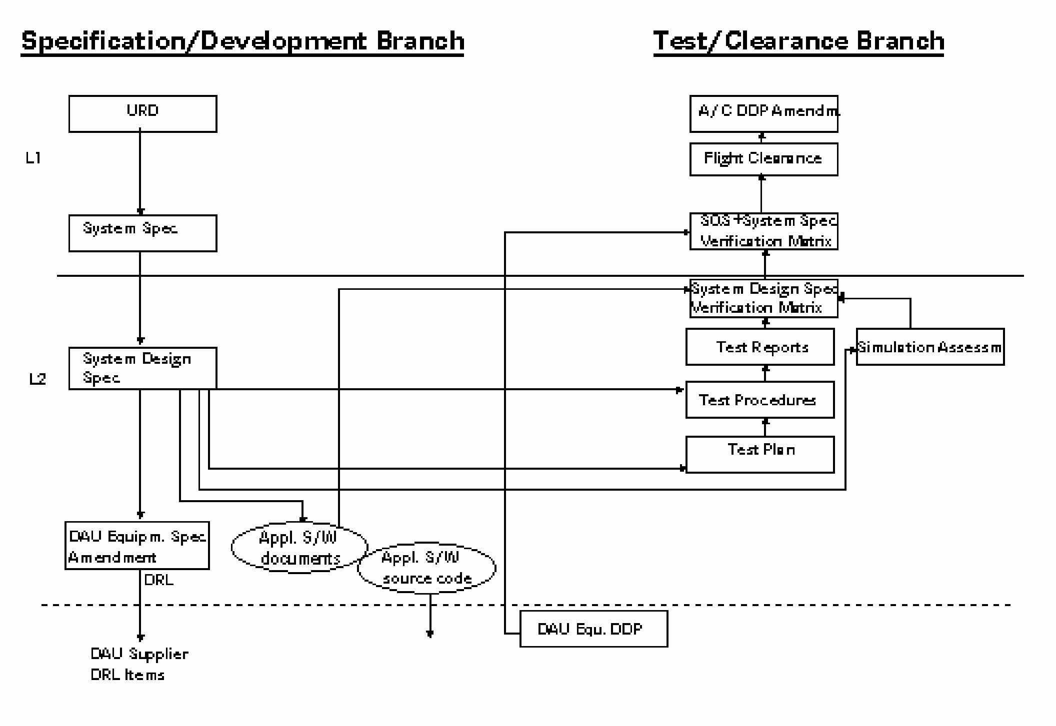


Figure 8. Top Level Document Tree

Requirements Management Tool Support. In order to support the requirement engineering process and to give full traceability of all requirements and their verification, DOORS is applied as a requirement- and document management tool.

Due to the fact, that the technical solution will be refined over time, project data varies by phase. Therefore also the necessary information and reports varies as well.

It must be understood, that Requirements Engineering concentrates on the process of engineering but Requirements Management (RM) provides the following features in addition:

- RM deals with the structure and management of information
- RM supports the elaboration, analysis and agreements of requirements
- RM supports the progress and traceability of requirements all over the product lifecycle

The introduction of DOORS into the DWS development process and the following implementation from the DOORS side of view is shown in figure 9.

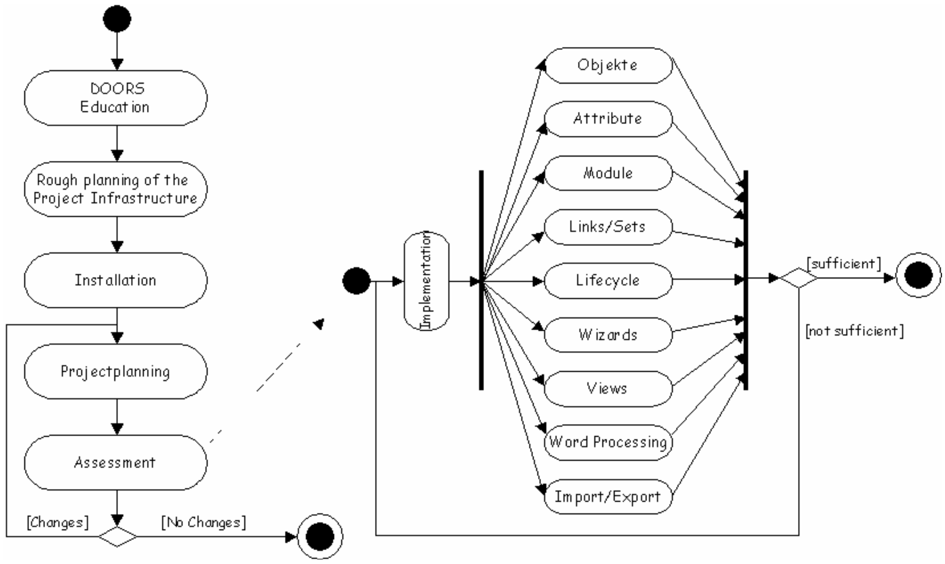


Figure 9. Introduction and Implementations of DOORS

Since DOORS provides Descriptive- Formal- and Linkmodules, the connection (for traceability) of the required modules for the development of the Departure Warning System are as shown in Figure 10:

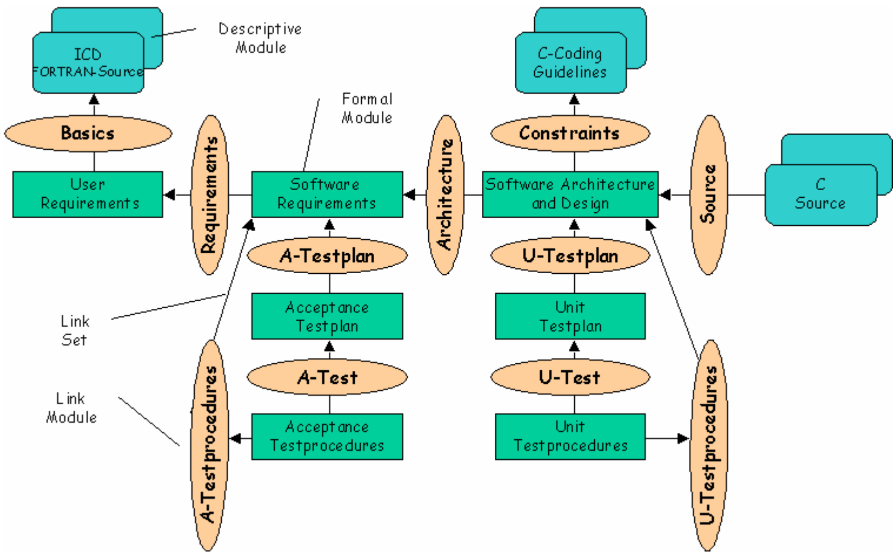


Figure 10. Traceability using DOORS

SOFTWARE ENGINEERING

Software Workshare Structure. In order to save time and to optimise usage of available resources, software development was split into the development of the equipment software which was performed at EADS Dornier and the application software which was developed by EADS Military Aircraft.

The equipment software performs the following tasks:

- Scheduling of tasks
- Input / Output handling of DWS data
- Control of tone generation and message output
- Equipment software and hardware monitoring
- Build In Test (BIT: pre-flight and continuous)

The application software performs the following main tasks:

- Store algorithm
- Calculation of required tone and message output
- Functional monitoring

In between the two software layers an appropriate interface (SW/SW and HW/SW) was agreed between Dasa-M and Dornier.

The following static architecture of the Application software has been derived in the design phase:

Segments:

- Init (elaboration of values,.filter build up)
- Main (activated by the equipment software every 8 Hz)

Units of the Main Segment:

- Input data preprocessing
- Range checks and functional monitoring
- Table (Store/Clearance) processing
- Calculation of the actual store configuration
- Computation of the AoA boundary algorithm
- Control of the Tone signal Generator
- Mode Handling
- Error Handling

Tables:

- Store Table
- Clearance Table
- Wave Table

In order to allow upgrades of the aircraft configuration, the tables can be modified and loaded separately to the software.

Since the DWS considers nominal behaviour and failure conditions, the software must be able to handle different modes as demonstrated in Figure 11:

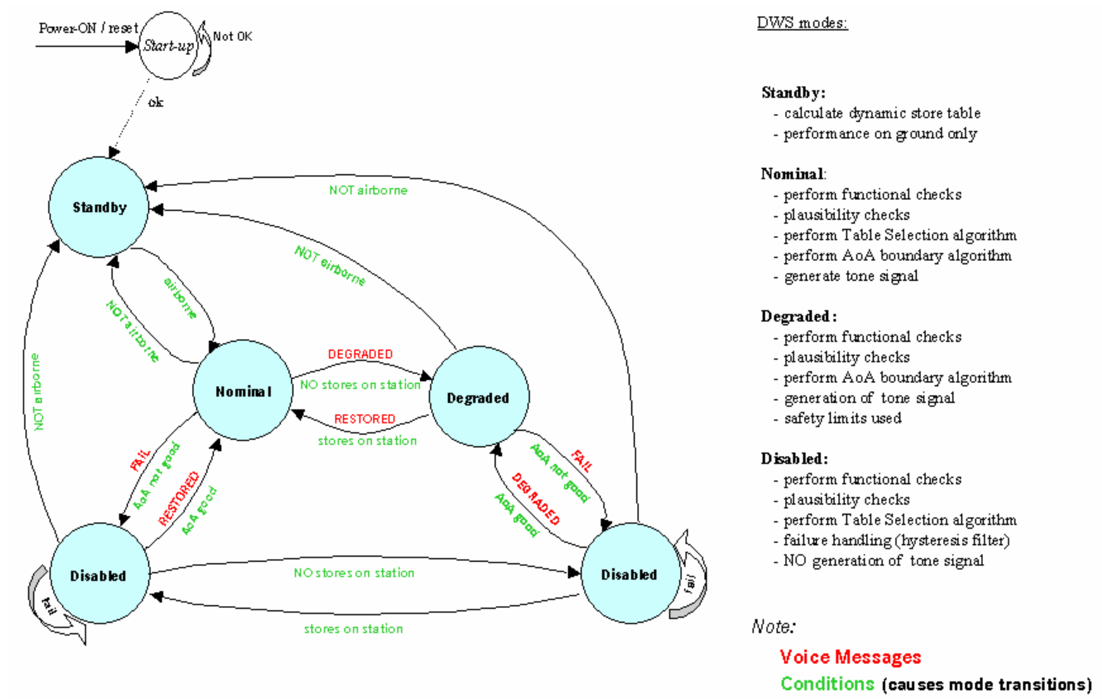


Figure 11. DWS Modes

Software Lifecycle Model. Due to the fact that the DWS algorithm is developed in an iterative, phased approach, the chosen software lifecycle supports this approach by using an evolutionary prototyping process followed by a V-model lifecycle for the final software. It was required by the customer, to apply the 'V-Modell '97. The four submodels of the model were tailored according to the risk class and needs of the DWS software.

The advantage is that the iterative approach does not attempt to start with a full set of software requirements. Further, no SW-QA will be necessary at this stage of the DWS program. After the DWS functionality is considered mature enough, the V-model lifecycle with all its consequences is valid for all further software activities.

Since the specification is executable (Fortran code from simulation), parts of the software process are being treated as an software reengineering process. The difference between rapid and evolutionary prototyping is, that the evolutionary prototyping uses the last increments, which will be further treated according to its requirements.

Figure 12 shows a graphical representation of the applied reengineering- and software development process.

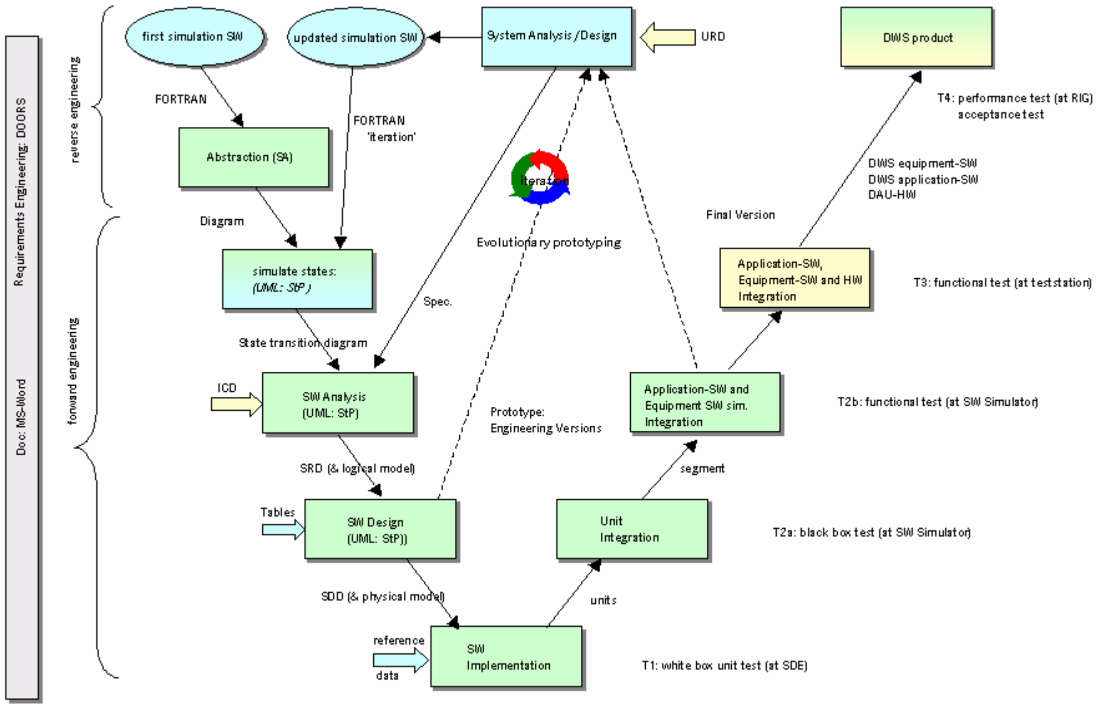


Figure 12. Software Lifecycle Model

The Unified Modeling Language (UML) was applied for the software development process. Since the DWS is a typical real-time application, appropriate graphical models of UML were chosen to create the logical and the physical model. The re-engineering process was splitted into reverse-engineering (to analyse Fortran) and into forward-engineering.

Since UML allows parallel activities concerning analysis and design the re-engineering approach fits very well into the applied software lifecycle. E.g., the diagrams shown in Figure 13 on the following page are created by the use of the tool 'Software through Pictures' (StP):

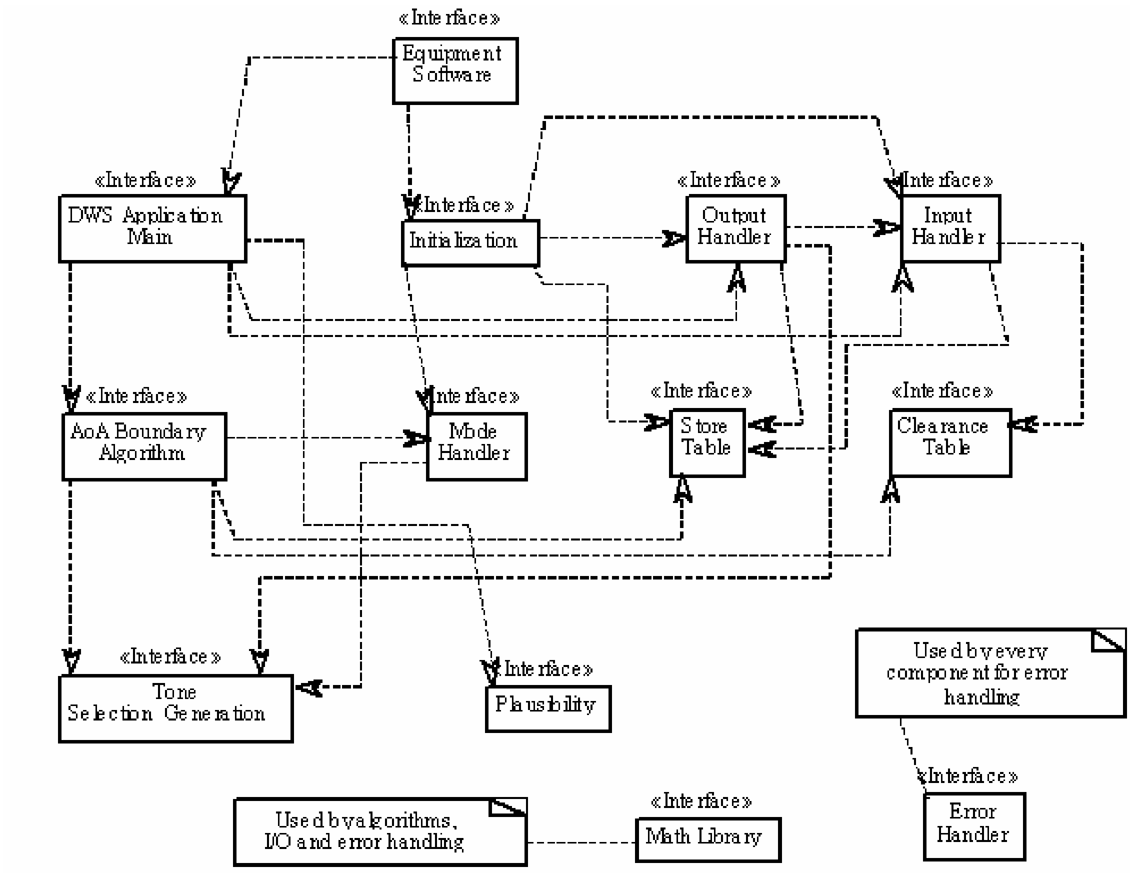


Figure 13. UML Interface Diagram

Software Tool Concept. The software development process is supported by a set of tools, which are derived from an evolutionary process of software development toolset selection for various production and technology programs at EADS Military Aircraft shown in Figure 14.

Phase	TRN	FADS	DWS	FCP
Requirement engineering / Documents / etc.	DOORS, WORD, ...	DOORS, WORD, ...	DOORS, WORD, ...	DOORS, WORD, ...
System analysis	n/a (re-engineering)	Rapid prototyping MATlab --> MatrixX	Evolutionary prototyping (V-Modell '97)	Evolutionary prototyping MatrixX, *Statemate, CTE*
SW Analysis (algo. part) / SW Analysis (other part)	UML (Visio 5.0)	UML (Visio 5.0)	UML (SW_through_ Pictures)	UML (SW_through_Pictures)
SW Design	UML (Visio 5.0)	UML (Visio 5.0)	UML (SW_through_ Pictures)	UML (SW_through_Pictures)
Implementation	Object Ada 95	SCADE Object Ada 95	ANSI-C	ICC Ada Compiler (i960)
Verification	Metrics, stubs	Metrics, stubs AdaTest / CTE	stubs Pure Coverage	Metrics, stubs AdaTest / CTE
Validation	RAPIN (simulation)	Demonstrator (PowerPC)	SW-Simulator / Rig	FCP Bench (Marconi Astronics)

Figure 14. Coverage of the process by methods and tools

For the software development of the Departure Warning System the following set of tools listed in Table 1 has been chosen.

Tool Task	Method	Tool Name	Platform
Requirements Management	Editor	DOORS	NT and Solaris
Documentation	Editor	MS Word	NT
Config Control		CVS	NT
Analysis	UML	StP	SUN
Design	UML	StP	SUN
Implementation	Coding	ANSI-C	NT
Test	Unit test	Pure Coverage/Purify	NT
Test	Simulation	SW Simulator	NT

Table 1: Software development toolset

The core of the listed toolset is the application of Unified Modelling Language (UML) by using Software through Pictures (StP) as explained earlier in this paper.

Since the textual requirements are managed by DOORS and the logical and physical models are created by StP a link to ensure traceability between the requirements and the corresponding diagrams has been established.

TEST, VERIFICATION, VALIDATION

Software Test. Since the Data Acquisition Unit is part of the Digital Flight Data Recorder functionality, this device can be used for software testing.

The FDR allows to record DWS output data plus internal equipment software data for test purposes during rig testing.

In order to provide automatic test capabilities as far as possible, a Software Simulator has been set up. This Software Simulator consists mainly of processing Script files (Test Procedures) which contain a DWS specific test language. The features of the Automated Test Procedures are described below:

- Controls the test execution by commands
- Failure injection possible
- Processes different formats of input data
- Compares automatically expected results against actual derived results for each time step) using certain limits
- Provides GO/NOGO information (Testreport)
- Allows regression tests

The SW Simulator is able to perform functional tests by using simulated flight profiles.

Note, that the SW-Simulation separates strictly between the Unit Under Test (UUT) and the Test modules.

The structure of the Software Simulator is shown in Figure 15:

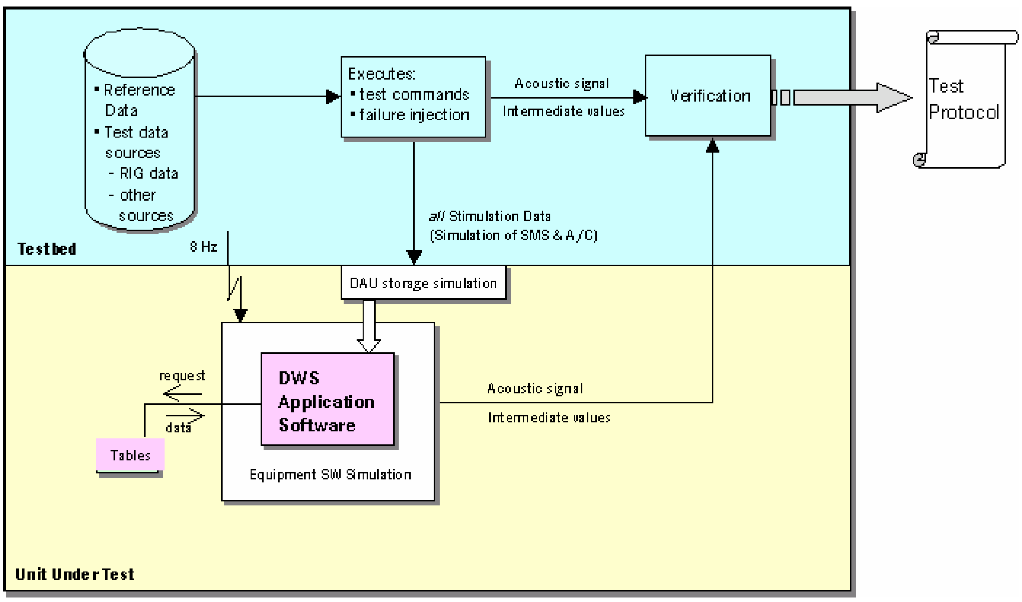


Figure 15. Software Simulator

Rig Test. Prior to Flight Test an end to end test comparing DWS tone output from the DAU and from the simulation has to be performed. For this end to end test an automated test process has been set up as well.

This has been achieved by synchronous recording of simulated and equipment generated tone output.

In case of discrepancies between the simulated DWS output and the actual DAU output, fast manual comparison is possible in order to decide whether small deviation can be assessed (e.g. due to data transport lag to and from rig and simulation) or whether an actual implementation fault has to be corrected.

Figure 16 shows the comparison of Departure Warning System audio output applying a commercial wave editor / analyser.

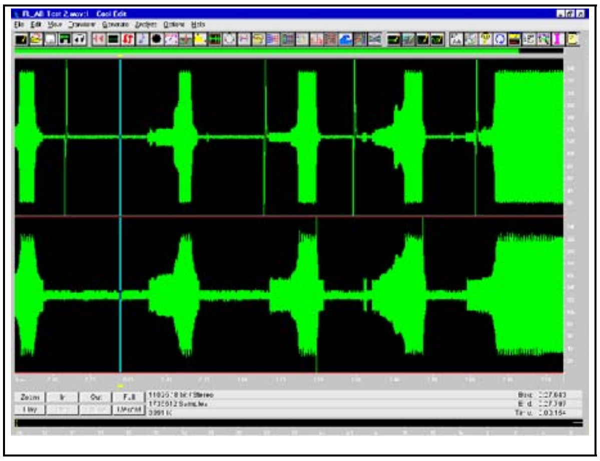


Figure 16. Comparison of Audio Output

Flight Test. Phase 1 flight test was conducted between October 29th and December 3rd 1999. Flight Testing for the full functionality developed during phase 2 was resumed in June 2000.

During phase 1 flight test, three successful test flights were performed. The system layout and design were confirmed. Only minor modifications regarding volume setup were required by the aircrew.

During phase 2 flight test, again three successful test flights were performed. The following configurations were taken into account.

- Clean Aircraft
- 2 Tanks under fuselage
- 3 Kormoran stand off missiles, 2 under fuselage, 1 under inboard wing (one of the most asymmetric configurations)

The system layout and design, this time especially of the store algorithm were again confirmed. Only minor modifications regarding functional monitoring and store data were required after evaluation of the flight test results.

Immediately after each EADS-M flight test phase an operational evaluation of the DWS was performed by the customer. This evaluation in operational scenarios confirmed the operational capabilities of the DWS.

The DWS is ready for introduction into the German Air Force's TORNADO fleet.

REFERENCES

Douglass, Bruce Powell and Harel, David, *Real Time UML: Developing Efficient Objects for embedded Systems*. Addison Wesley Publishing Company, 1997.

N.N., *V-Model: – Development Standard for IT-Systems of the Federal Republic of Germany – Lifecycle Process Model*. IABG, München, 1997, (http://www.v-modell.iabg.de).

Oestereich, Bernd, *Objektorientierte Softwareentwicklung – Analyse und Design mit der Unified Modeling Language*. Oldenbourg, München, Wien, 1998.

FLIGHT PROFILE SENSING FOR PILOTS TRAINING

Helmut Rauch

Jens Wagener

Bodenseewerk

P.O Box 10 11 55

D-88662 Überlingen

GERMANY

AIMS International Symposium, May 2002

Garmisch Patenkirchen, Germany

ABSTRACT

The need for a NATO common military flight training is supported with a GPS based application for improved military pilot training and military flight safety control, the flight profile recorder (FPR). It is based on a 10 Channel GPS Rockwell Collins receiver and an FOG IMU package, coupled with a 23-stage Kalman filter. Mounted in a Sidewinder tube it can be operated on almost every western aircraft, where it is already certified.

Its core elements are very accurate attitude and position data, which are used for collision warnings, area warnings, monitoring of flight limits, any type of flight hazards With an integrated NATO standardized S-band data link, all aircraft can train simulated missile launches and get in-time hit/miss results. The data link can be extended via other relay a/c and enables i.E. ground based flight test and training crews to track complex scenarios and safety rules.

The position accuracy of 2-3m (1σ) is also required for no drop bomb release training. The navigation is completely autonomous inside the pod, although some specialized downgraded versions can get GPS data via MIL Bus from a/c and only operate with pod internal IMU. The navigation data are also used as reference for evaluation of ground based sensors (Radar, IR etc.) and also currently for flight test set-ups with EF2000 a/c, where it is essential to have a common identical data source for navigation data.

As results of a real application we show some flight tests data results of russian aircraft (MIG29) recorded form the estern equivalent of the MIL Std Bus 1553.

Flight Profile Recorder System

The Flight Profile Recorder system is an application which primary improves military jet pilot training. The system is composed of Airborne Pods and Ground Stations. The Pod functions include acquiring aircraft data, measuring and acquiring Time, Space and Position information, capturing weapon events, and recording the preceding information for post mission replay. Addiotionally the system has MIL Bus 1553 and/or 1760 interface to be connected to aircraft controller systems. The Ground Station performs pre-mission configuration set-up, and post-mission debriefing including integrated display of all aircraft data and weapons systems involved in the mission as well as their interactions and results mainly for pilot training purposes.

The Data Link option and its implemented features, such as real-time weapon simulation, notifying air crew of weapon event result, providing air collision warning to the air crew, improves training with aircraft formations.

The GPS based navigation system inside the pod is one of the core element of its functionality.

The system has key features in different areas like

Training

Can be operated without fixed installations on ground, also mobile station

Weapon simulation for different systems

What-if simulation

Safety

Restrictions watch dog controls safety limits, like g-limit or angle of attack restrictions. Flight areas are controlled and reported to the pilot via voice message

Mid air collision avoidance system controls critical situations and distributes warnings via datalink to other aircraft.

Ground collision and flight level hazards are controlled

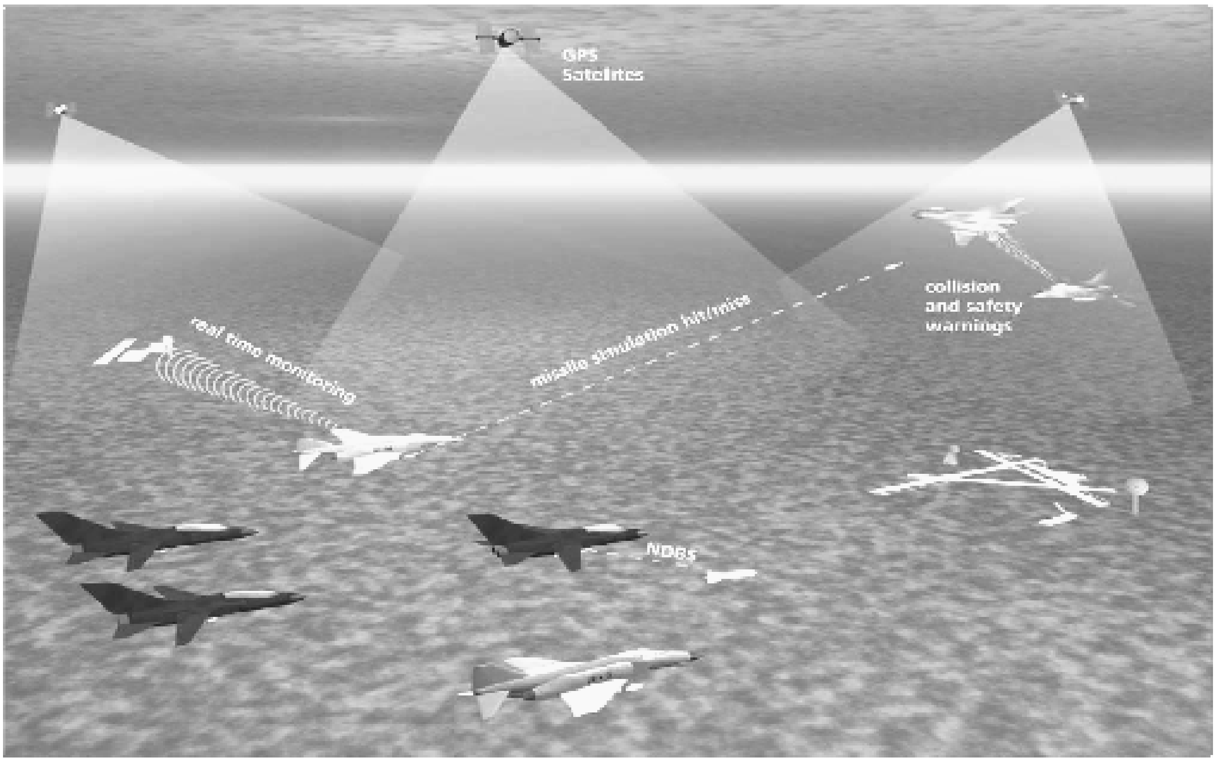
Control

Flight can be displayed in real time on ground

Digital aircraft bus inface

Can operate as MIL Bus remote terminal or monitor, depending on software setup

The concept of the system



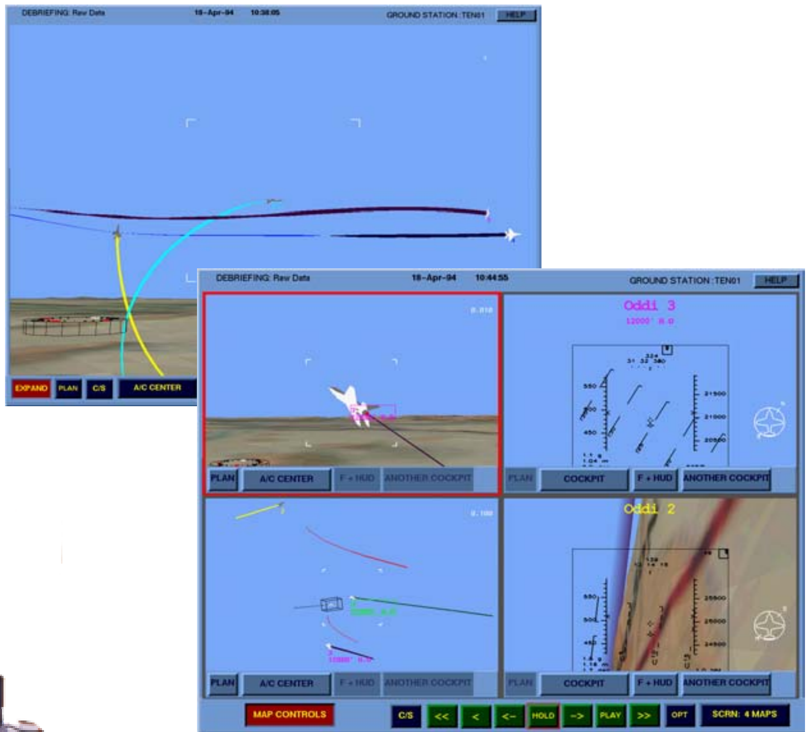
The data display is done on a PC or UNIX type ground station. Independent of aircraft type, the pod uses the same sensor package, the flight data of all participants are recorded and finally merged on the ground station. This enables the pilots to display complex scenarios in 3D graphic display and to focus on critical items, like safety violations, collision risks etc.

The aircraft equipment

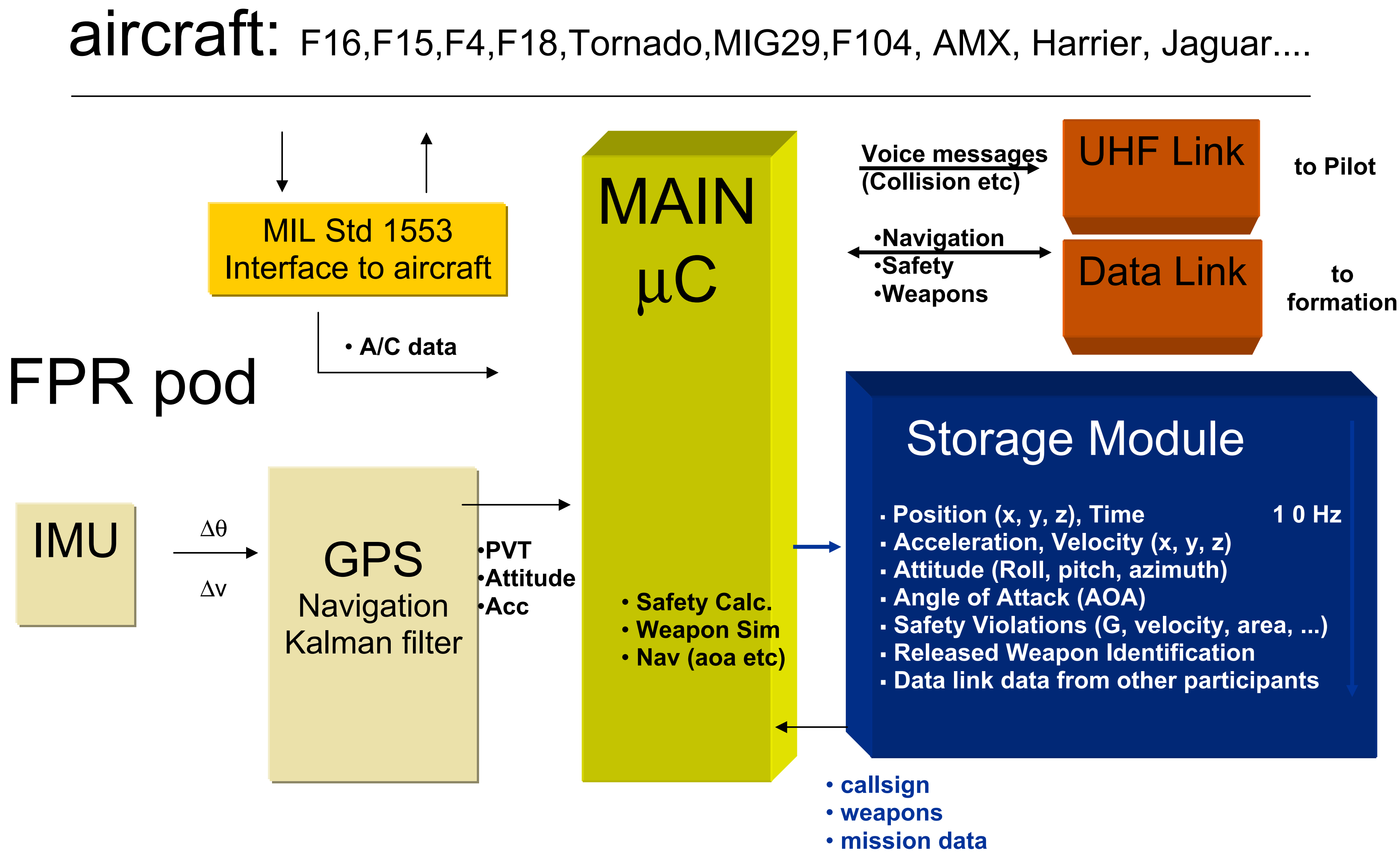
The Pod is mounted on standard launcher stations on aircraft wing positions. The GPS antenna at the pods nose can be aligned to the launcher attitude, depending on the aircraft. The system can be used on several different types of launcher stations.

The data display Station

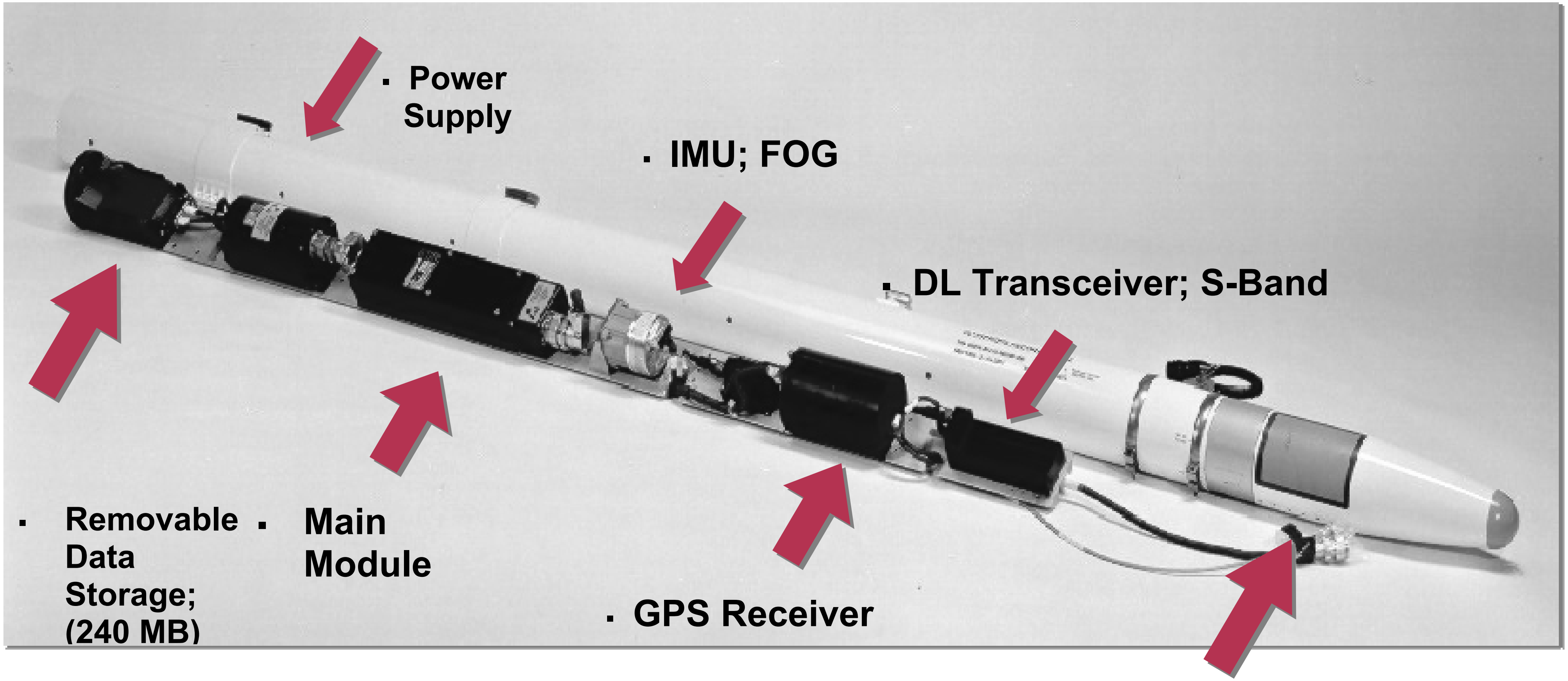
The display station is the 3D display system for the recorded flight data. It can be used with projectors and large displays for auditoriums. It is operated like a video recorder. The user can change the aspect view, time, map displays etc and rerun the complete mission or parts of it.



FPR System Design



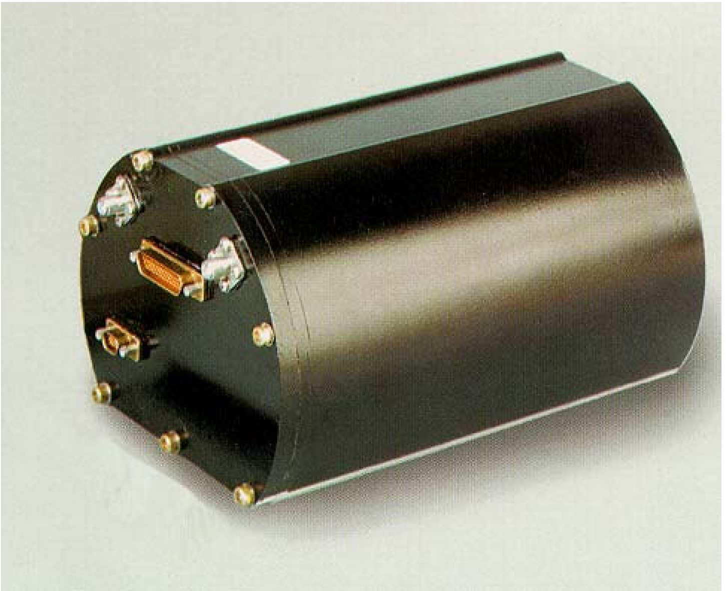
Pod Configuration



- GPS/DL Antennas
- Aircraft Interface

Navigation Sensors

GNP 10 Rockwell Collins



- Off-the-shelf design
- 10-channel all-in-view track and navigation
- Tight coupling capability
- Fast TTFF/High anti-jam capability
- DGPS (C/A and P/Y code)
- WAGE
- 24 state Kalman filter
- Strapdown navigation
- Integrated with Litton LN-200
- Inflight Alignment after power down

LN200 Litton

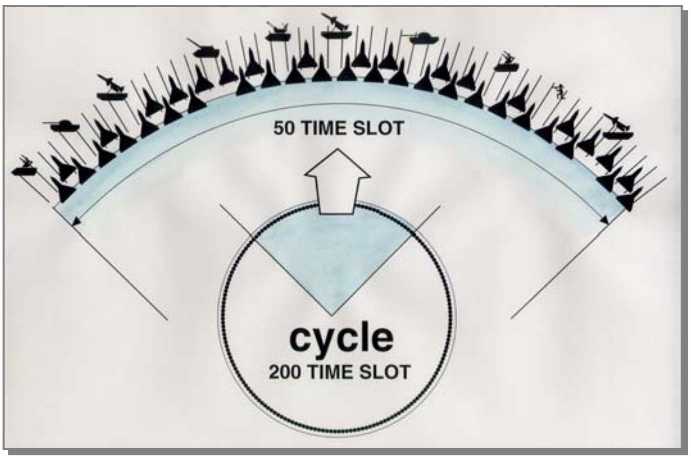
Weight	1.54 pounds (700 g)
Size	3.5“ (8.9 cm) diameter x 3.35“ (8,5 cm) high
Power	10 Watts steady state
Cooling	Conduction to mounting plate
Mounting	4 mounting bolts - M4

Performance - Gyro

Bias Repeatability	1.0 / 1 hr σ
Random Walk	0.07° / $\sqrt{}$hr Power Spectral Density (PSD) Level
Scale Factor Stability	100 ppm 1σ
Bias Variation	0.35° / hr 1σ with 100-second correlation time
Nonorthogonality	20 arcsec 1σ

The GPS system does not use alignment data from the host aircraft. The only data required are the attitude of the pod relative to the aircraft body axis and the distance of the pod relative to the center of gravity of the aircraft. The alignment of the system is performed with GPS velocity data, gyrocompassing procedures are not used. This enables the system also for in flight alignments after power down conditions while airborne. The GPS system can be operated in C/A or P(Y) Code operations.

The Data Link



The data link transfers data from the pod-system sensors and other pod systems (i.E. collision warnings) or training related events to system controllers on ground. The number of participants is unlimited as the transmission rate drops linearly down from 10 Hz with increasing number of aircraft. The protocol uses a dynamic time slot allocation with 200 time slots per second, distributed to all participants. This protocol requires no master for communication. The data link operates is the S-Band frequency range, currently on 2.320 GHz and 2.335 GHz. The aircraft can also serve as relays, which extends the range up to 120 Nm.

The data are also transferred to ground to enable real time tracking and survey of the flight mission. The S-band communication band requires line-of-sight conditions. The platform of the directional antenna is controlled by the ground station. Additionally is an omni directional antenna used.

Flight Test results

FPR as system data recorder

Russian missiles on German MIG 29 aircraft

Missile system data from MIG 29 aircraft were recorded on the FPR system. The MIG29 aircraft has an Russian type digital bus system equivalent to MIL Bus Std 1553, additionally are many analogue and digital lines with missile status information. A weapon interface module (WIM) was designed and manufactured as a prototype, which translates all Russian interface data into appropriate MIL Std 1553 Messages. This WIM module was installed inside the launcher of MIG29 and the FPR system used a special software to record all relevant messages from the converter box. This tests could not be performed on ground because of operational (i.e. no targets for missiles) and safety restrictions (i.e. no radar operations/slaving on ground). The tests were performed with different Russian types of missiles like

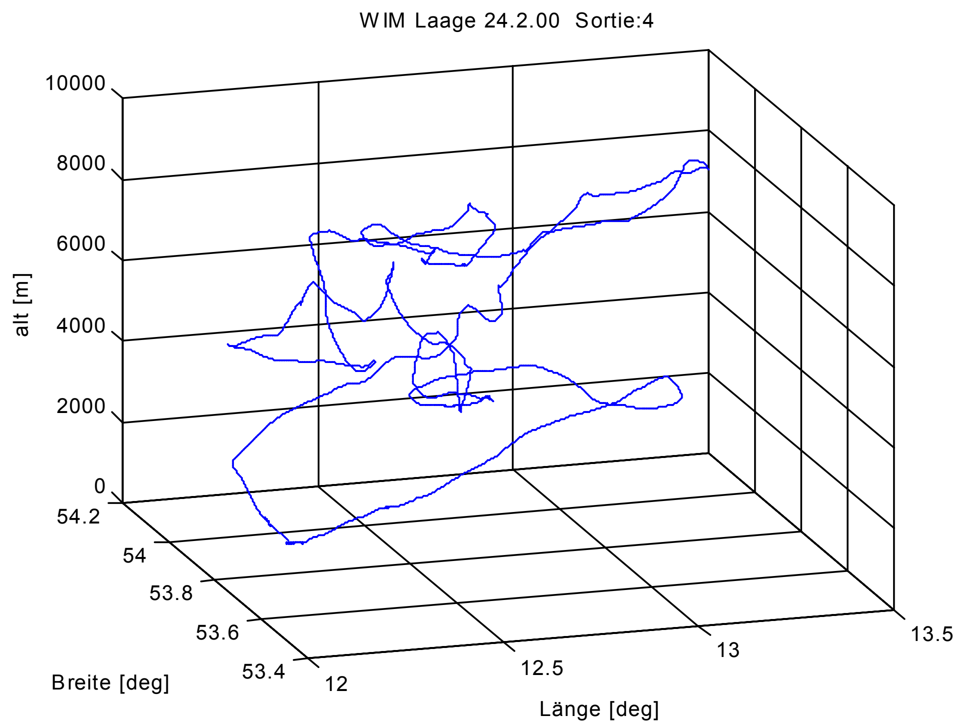
- AA10 R27 Alamo semiactive radarhoming
- AA8 R60 Aphid IR homing
- AA11 R73 Archer IR homing

The FPR system was mounted on launcher station 2 and the missile under test was on station 1. All relevant data were available via the weapon interface module

Some elements of recorded data from Russian missiles

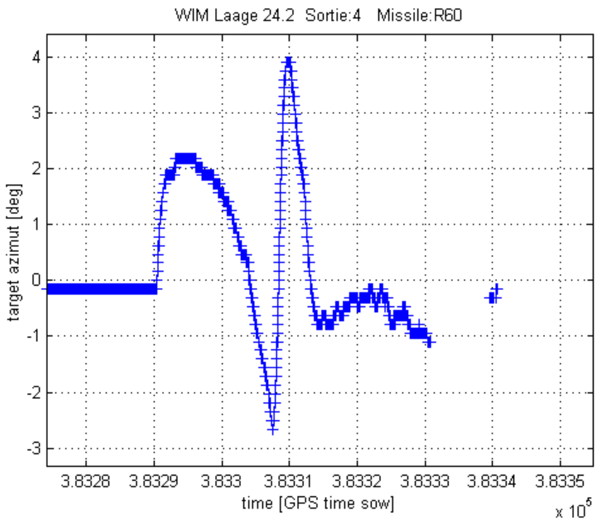
	AA10	AA8	AA11
Missile ready	J5-21	N/A	J5-21
Motor fire (Simulator)	N/A	N/A	J5-17
Bore sight signal	J5-26	N/A	N/A
Launch command	J5-18	J5-18	J5-18
Weapon ID	J5-6/14	J5-6/14	J5-6/14
Gun fire	J5-4	J5-4	J5-4
Missile preparation	N/A	N/A	J5-16
Target size	N/A	N/A	J5-19/20
Los rate of change	N/A	J5-11	J5-11
Target angle 1	N/A	J5-24	J5-24
Target angle 2	N/A	J5-25	J5-25

Test results

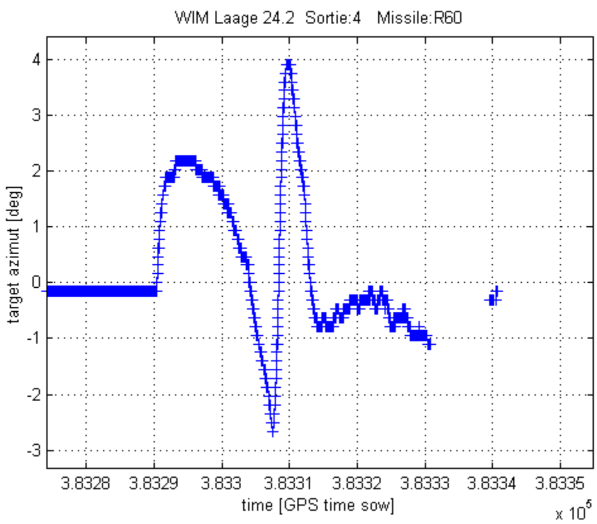


Graph 1

3D Trajectory of a test flight , recorded with FPR on board navigation system

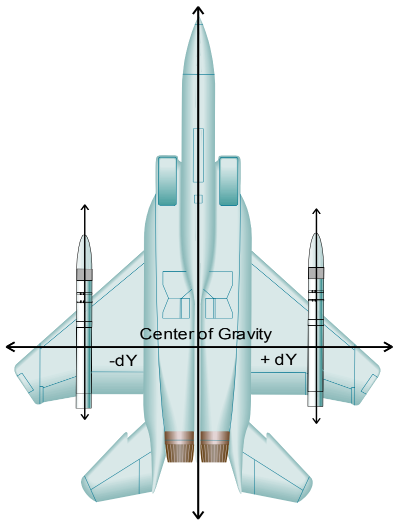


Graph 2 This Plot shows the seeker azimuth angle of a russian AA8 IR homing missile while locked on a flying target.



Graph 3 This Plot shows the seeker elevation angle of a Russian AA8 IR homing missile while locked on a flying target .

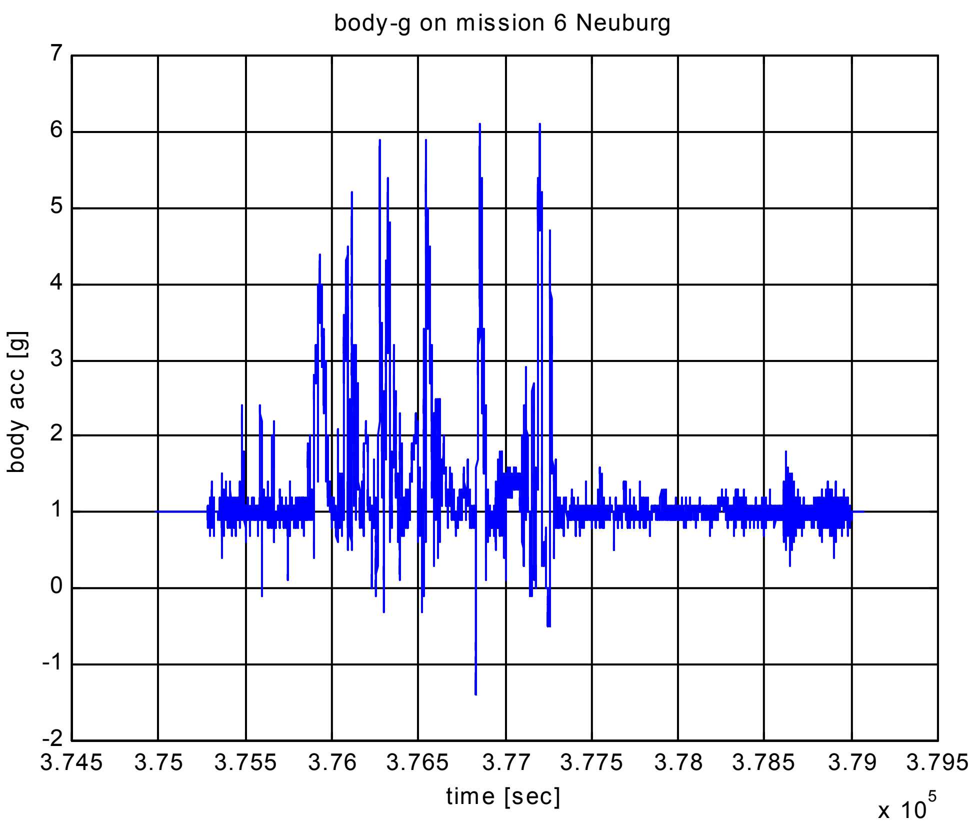
FPR as flight navigation data reference



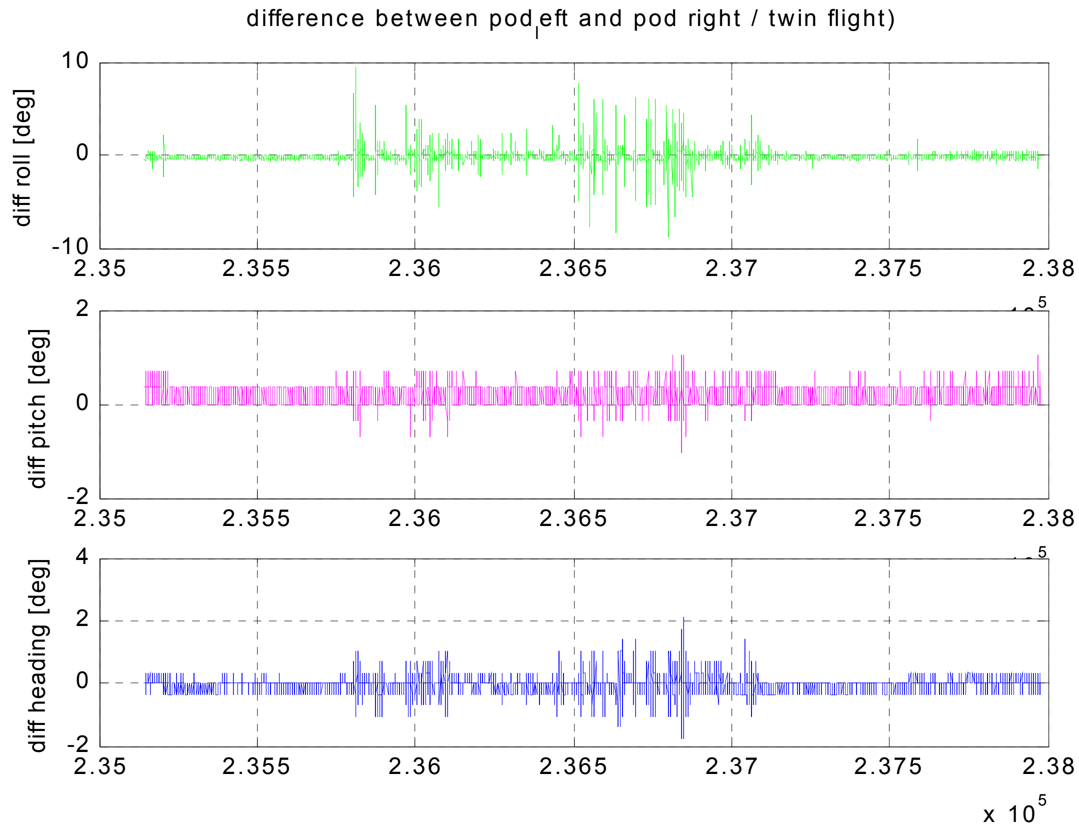
The pod has also been widely used for flight test data recording on different aircraft. One of the first tests was the system verification. To verify the navigation performance we used two pod , flown at the same aircraft. Both FPR systems see different satellites because they are isolated by the shape of the aircraft. All displayed data were recorded in P(Y) Code, in 1998, while GPS selective availability (SA) was still active.

The measured system accuracy:

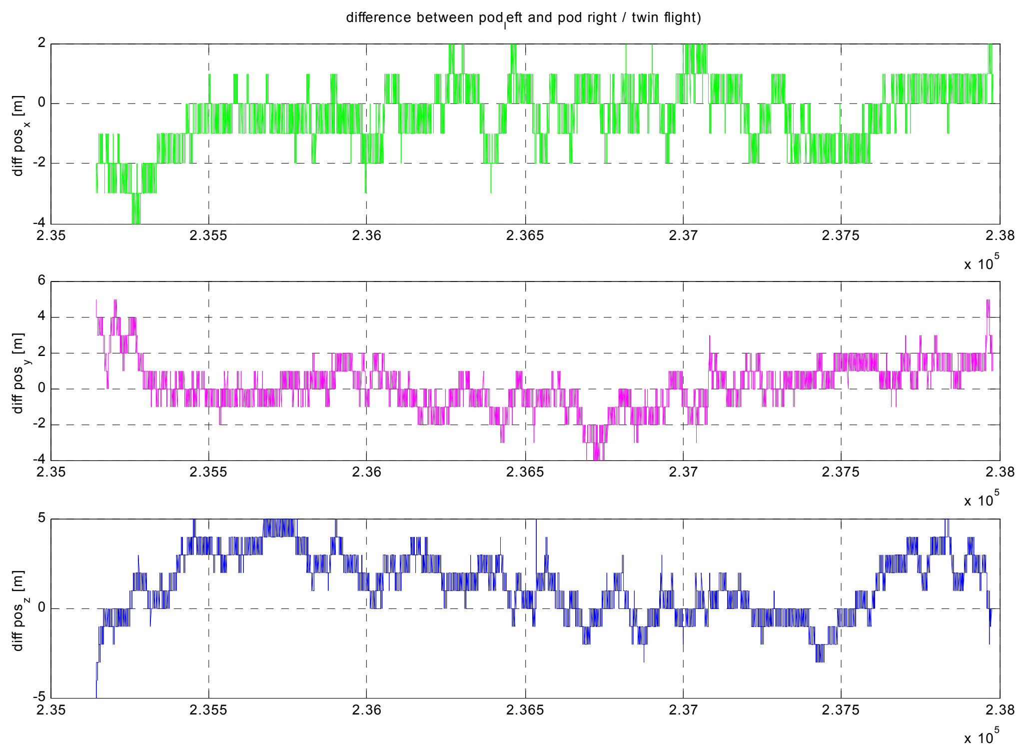
position	1-3m (1σ)
Velocity	0.3 m/s (1σ)
attitude	0.3 ° (1σ)



Graph 4 acceleration aircraft z- axis [g]



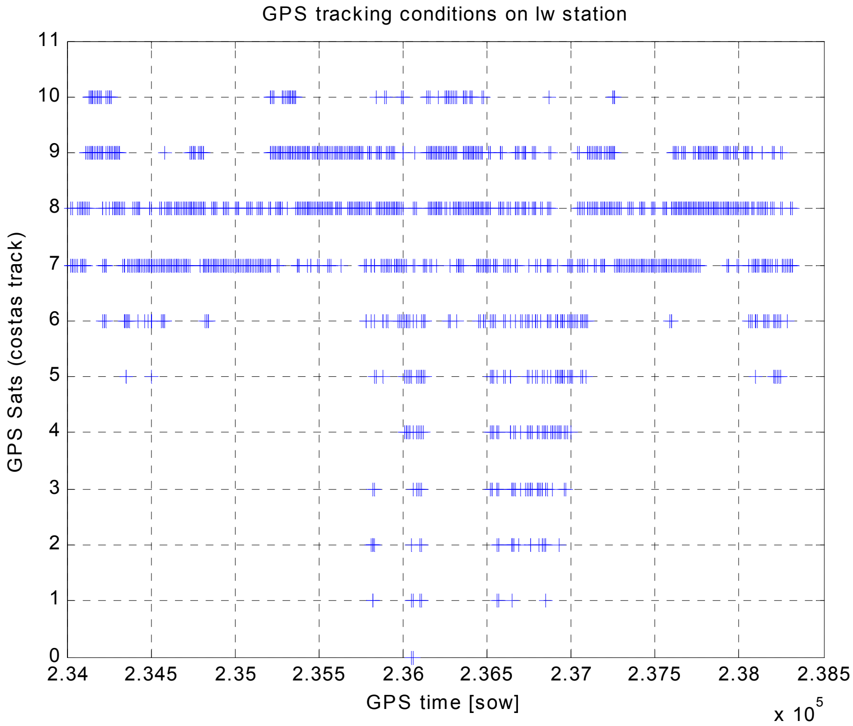
Graph 5 attitude difference (error) pod left vs. pod right



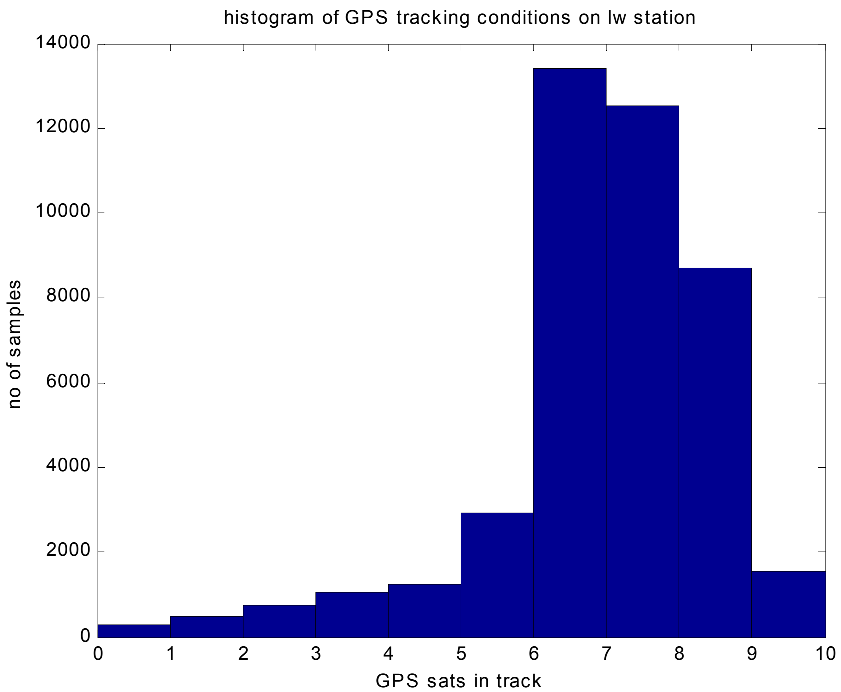
Graph 6 position difference (error) pod left vs. pod right

GPS Tracking condition on flying jet aircraft

The plots show the number of tracked GPS satellites during a standard mission of about 90 min. The GNP 10 provides the tracking mode of each channel (of 10) in output telegrams. Only the satellites in mode 5 (code track) are displayed.



Graph 7 GPS tracking conditions on aircraft wing station



Graph 8 histogram of GPS tracking conditions (number of satellites)

Using AIMS During AIRBUS Aircraft Acceptance Phase in Hamburg

by
Dipl.-Ing. J.Schedautzky
Dipl.-Ing. S.Knoop

AIRBUS Deutschland GmbH
Kreetslag 10
D-21129 Hamburg
Germany

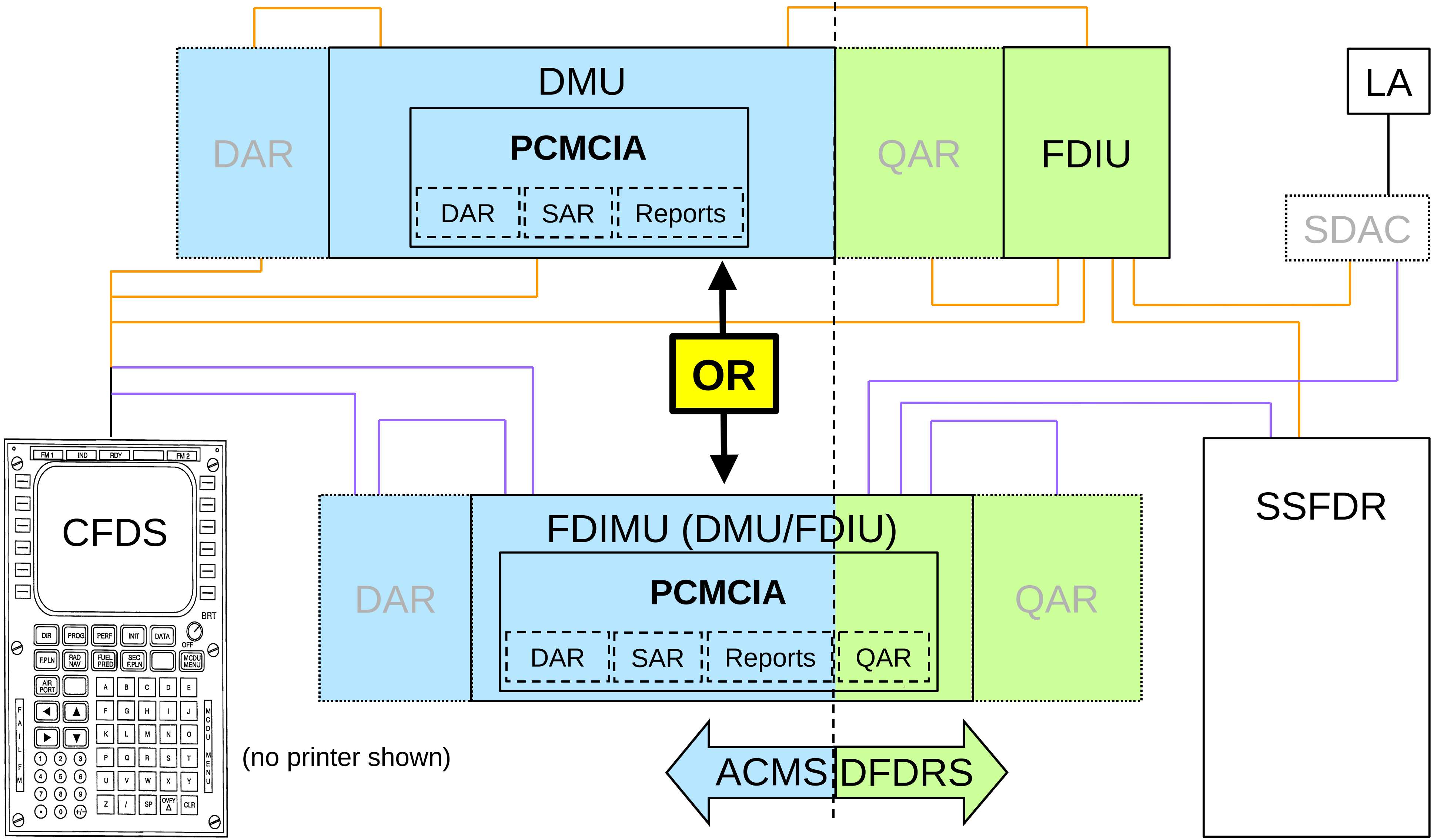
Content

0. Glossary

ACMS	Aircraft Condition Monitoring System
ACT	Additional Centre Tank
ADC	Air Data Computer
ADR	Air Data Reference System
AFS	Auto Flight System
AOA	Angel Of Attack
AP	Auto Pilot
APU	Auxiliary Power Unit
DAR	Digital AIDS (ACMS) Recorder
DFDR	Digital Flight Data Recorder
DH	Decision Height
DMU	Data Management Unit
ECB	Engine Control Box
ECS	Environmental Condition System
FAA	Federal Aviation Authority
F/CTL	Flight Control
FCU	Fuel Control Unit
FD	Flight Director
FDIU	Flight Data Interface Unit
FDIMU	Flight Data Interface and Management Unit
FFT	Fast Fourier Transformation
FL	Flight Level
FMS	Flight Management System
FPA	Flight Path Angel
FTR	Flight Test Request
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
IAS	Indicated Airspeed
IGV	Inlet Guide Vane
IR	Inertial Reference system
LA	Linear Accelerometer
LDG	Landing Gear
MCDU	Multifunctional Control Display Unit
MMO	Maximum Operating Mach number
MMR	Multi Mode Receiver
PFR	Post Flight Report
PTCH	Pitch Angel
RTO	Rejected Take Off
RVSM	Reduced Vertical Separation Minimum
SAR	Smart AIDS (ACMS) Recorder
SDAC	System Data Acquisition Concentrator
SCV	Surge Control Valve
TOGA	Take Off Go Around
VMO	Maximum Operating Airspeed

1. AIRBUS Single Aisle a/c AIMS System Architecture

general



(no printer shown)

DMU and FDIU (or FDIMU) are connected to almost all a/c systems via ARINC 429 bus

2. DFDR Validation

- **57 mandatory parameter (FAA §121.344 (a)(1) through (a)(57)**
  (88 mandatory parameter (a)(1) – (a)(88) after 19/08/2002)
  checked after first R(ejected) T(ake) O(ff).

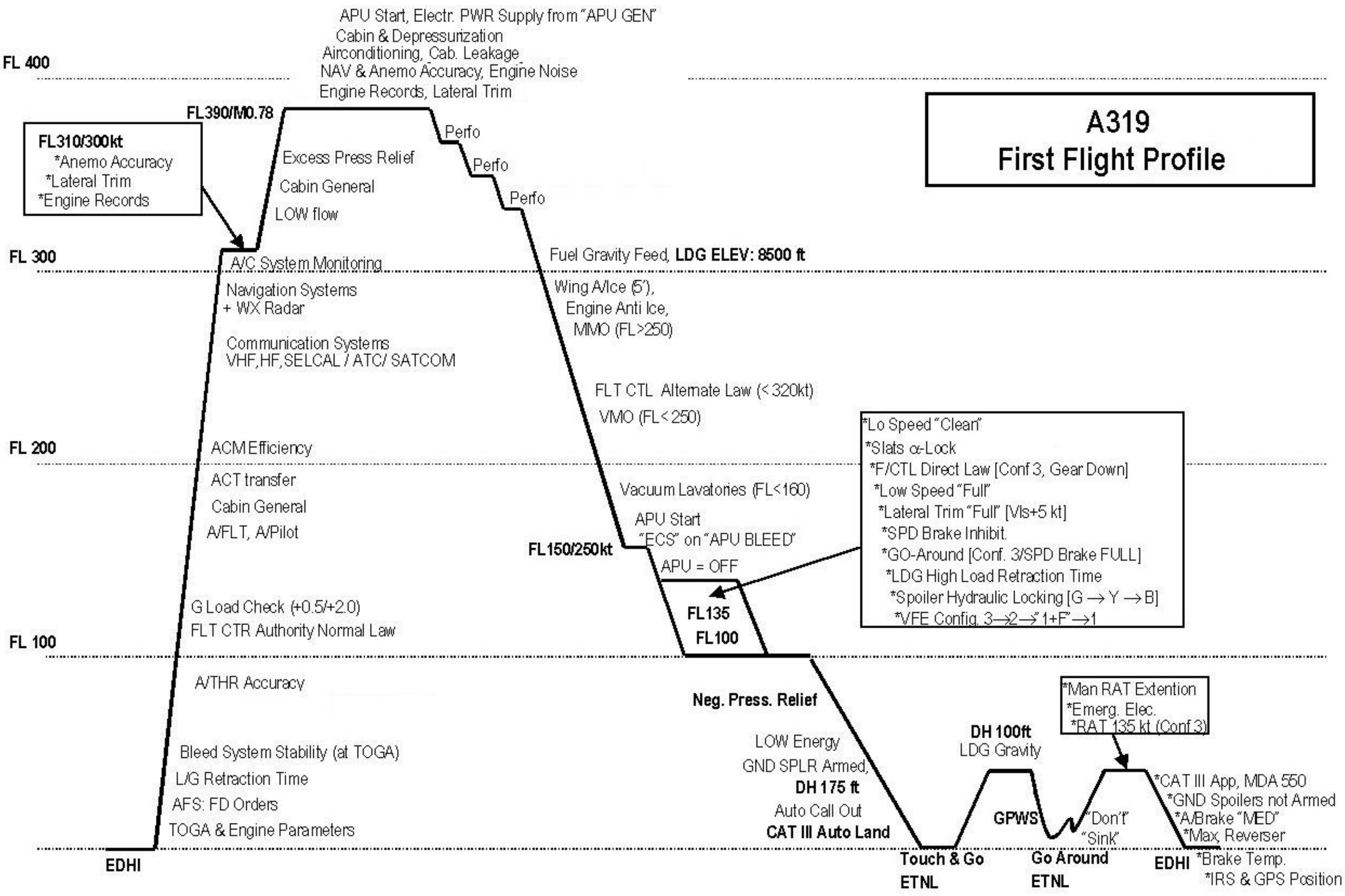
- **all parameter recorded (and) evaluated from matrices checked after first flight following a standard flight profile**
  (~ 450 parameter (57 mandatory) with recording speed rate of 128 W/sec
  ~ 890 parameter (88 mandatory) with recording speed rate of 256 W/sec)

- **PFR Messages used for evaluation of failure warnings/messages on DFDR**

- **software to convert 12bit frame format into engineering values using Oracle database**

- **Plausibility Check of Parameters included in software**
  (e.g. Auto speed-Modes and Mach/Speed Indications, etc.)
- **Decoding of matrices is done by using software**
  (e.g. TCAS advisories / AP modes, etc.)

2. DFDR Validation



2. DFDR Validation

- All (intentionally evoked) system anomalies will be compared to DFDR parameter read-out (if recorded)

- All anomalies are well known from standard first flight profile.

MAINTENANCE
POST FLIGHT REPORT

DB/N

A/C ID	DATE	GMT	FLTN	CITY PAIR
		0814/1122	F1	EDHI EDHI

WARNING/MAINT.STATUS MESSAGES

GMT	PH	ATA	
0821	02	34-48	NAV GPWS TERR DET FAULT
0834	06	22-00	AUTO FLT RUD TRIM1 FAULT
0834	06	22-00	AUTO FLT RUD TRV LIM 1
0835	06	22-00	AUTO FLT YAW DAMPER 1
0835	06	22-00	AUTO FLT YAW DAMPER SYS
0835	06	22-00	AUTO FLT RUD TRIM SYS
0835	06	22-00	AUTO FLT RUD TRV LIM SYS
0835	06	27-00	F/CTL ALTN LAW
0835	06	22-00	AUTO FLT RUD TRIM1 FAULT
0835	06	22-00	AUTO FLT RUD TRV LIM 1
0846	06	21-31	CAB PR SAFETY VALVE OPEN
0901	06	21-61	AIR PACK 1+2 FAULT
0903	06	21-31	CAB PR EXCESS CAB ALT
0903	06	21-26	VENT BLOWER FAULT
0924	06	34-00	NAV TCAS FAULT (3)
1010	06	28-00	FUEL R TK PUMP 1+2 LO PR (2)
1011	06	28-00	FUEL L TK PUMP 1+2 LO PR (2)
1022	06	22-00	AUTO FLT RUD TRIM1 FAULT
1022	06	22-00	AUTO FLT RUD TRV LIM 1
1023	06	22-00	AUTO FLT YAW DAMPER 1
1023	06	22-00	AUTO FLT YAW DAMPER SYS
1023	06	22-00	AUTO FLT RUD TRIM SYS
1023	06	22-00	AUTO FLT RUD TRV LIM SYS
1023	06	27-00	F/CTL DIRECT LAW
1023	06	22-00	AUTO FLT RUD TRIM2 FAULT
1023	06	22-00	AUTO FLT RUD TRV LIM 2
1029	06	27-00	F/CTL SPD BRK DISAGREE (2)
1032	06	29-00	HYD G ENG 1 PUMP LO PR
1032	06	29-00	HYD G SYS LO PR
1033	06	29-00	HYD Y ENG 2 PUMP LO PR
1033	06	29-00	HYD Y SYS LO PR
1034	06	29-00	HYD B SYS LO PR
1038	06	21-61	AIR PACK 1+2 FAULT
1039	06	21-31	CAB PR LO DIFF PR
1041	06	21-31	CAB PR SAFETY VALVE OPEN
1047	06	22-00	AUTO FLT AP OFF
1111	06	29-00	HYD B SYS LO PR
1114	06	24-00	DC BUS TIE

FAILURE MESSAGES

GMT	PH	ATA		SOURCE	IDENT.
0818	02	32-42-34	AFS:BSCU2	AFS	
0821	02	34-41-33	WXR2 (1SQ2) BUS HAZARD / GPWC (1WZ)	GPWC	
0835	06	22-66-34	AFS:FAC1/P-B SW 12CC1	AFS	
0835	06	22-66-34	AFS:FAC2/P-B SW 12CC2	AFS	
0835	06	27-93-34	ELAC1 OR WIRING FROM FAC1/2	EFCS 1	EFCS 2
0911	06	24-22-55	AFS:28V PWR 11XU1	AFS	
0924	06	34-43-34	TCAS (1SG)	TCAS	ATC 1 ATC 2 EIS 1 EIS 2 EIS 3
0930	06	34-43-33	FWC1 :NO DATA FROM TCAS	ECAM 2	ECAM 1 CFDS
0935	06	24-00-00	POWER SUPPLY INTERRUPT	TCAS	
0951	06	34-52-33	NO ATC 1 DATA (INTM)	CFDS	TCAS
0952	06	34-52-33	NO ATC 2 DATA (INTM)	CFDS	
1032	06	27-93-34	AFS:ELAC2	AFS	
1032	06	29-32-12	AFS:HYD G 1151GN	AFS	
1119	09	27-51-34	SFCC1	EFCS 2	EFCS 1

3. Aircraft Performance

to prove aircraft fuel consumption and consistent quality of both aircraft (aerodynamic) performance and engine performance

- Standard performance analysis

- **parameter set containing ~30 parameters recorded via DFDRS for performance analysis following every first flight**
- **at least 5 predefined 'performance points' (depending on customer)**

  (Performance Points – particular flight conditions as IAS, Altitude, etc.)

- Extended performance evaluation

- **parameter set containing ~55 parameters recorded via DAR using extra fuel metering units connected via ARINC 429 bus with the Flight Data Interface and Management Unit (FDIMU) or DMU**
- **to evaluate both, aircraft performance while flying about 12 predefined 'performance points', and quality of aircraft installed series fuel metering units**

4. SAR Recording via Data Management Unit (or FDIMU)

SAR – Smart ACMS Recorder

- Standard 'First Flight Software' (Database)

- **6 channel (+2 spare channels) recording 128 W/sec each (Sagem Unit)**
- **each channel dedicated to a specific ATA chapter recording parameters most likely continuously needed (e.g. Engine; F/CTLs)**

(• ~25+ reports available with this database, continuously and/or for specific investigations) (for details see chapter Reports)

- Enhanced 'First Flight Software' incl. DAR set-up

- **database complemented by specific DAR set-up to record performance parameters for extended performance evaluation and / or Flight Test Request (FTR)** (for details see chapter FTR)

All parameters included in 'First Flight Software' (+ Alpha Call-Up's, Call-Up Menus, and Reports) are available at any time, to support and speed-up troubleshooting activities!

5. AIMS - Noise Recording Interconnection

- typically emerged frequency peaks at certain system conditions (e.g. engine speeds, hydraulic pumps, aerodynamically generated noise, etc.) can be evidenced using DFDRS and SAR/DAR recordings

- therefore, noise recording with following analysis using Fast Fourier Transformation and 1/3 Octave filtering including recalculation of aircraft conditions using DFDRS/SAR /DAR is done.

- online FFT (currently under test) to compare directly with aircraft state (in flight)

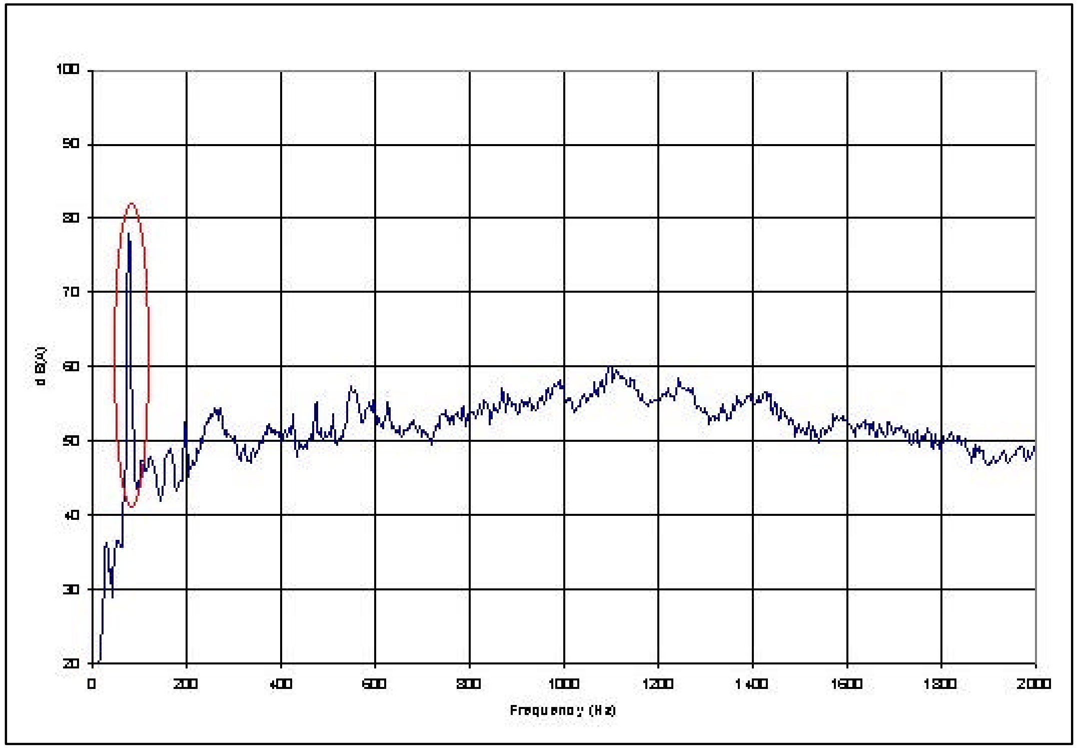


Figure 3 Engine N1 speed recognizable after FFT analysis

6. Specific Reports

- Asymmetric Flight Report <31>

- **Recording of Flight Control Data to verify correct a/c attitude and Aileron behaviour under certain flight condition**.
- **Conditions are:**
  - Flaps Config. Full at FL 135
  - Flaps Config. Clean at FL 310/300Kt
  - Flaps Config. Clean at FL 390/M0.78
- **Report is manually triggered by Flight Crew**
- **Parameter are recorded at**:
  - Pre Event in 4 sec interval
  - Post Event in 20 sec. average interval
- **Quality Targets are defined for**:
  - ROLL < ABS 0.5°
  - RUDD < ABS 1°
  - RUDT < ABS 2°
  - Config. Full Aileron delta < 1.0°
  - Config. Clean Aileron delta < 0.2°

```
   ASYMMETRIC FLIGHT REPORT <31>

   A/C ID DATE  UTC    FROM TO   FLT
C1 D-     NOV03 105348 EDHI EDHI

   PH CNT   CODE ..BLEED STATUS... APU
C2 06 00000 1000 53 0010 0 0100 53 X

   TAT  ALT   CAS MN  GW   CG  DMU/SW
C3 N020 13999 123 242 5176 238 I73031

   ESN    EHRS  ECYC  AP
C4 011094 00002 00003 71
4C 011096 00002 00003 71

   PRE EVENT, 4 SEC INTERVALS

   ROLL AILL AILR RUDD RUDT SLP  UTC
C5 N000 0050 0044 N008 N007 N003 105332
C6 0001 0045 0049 N008 N007 N002 105336
C7 0000 0047 0048 N008 N007 N002 105340
C8 N004 0049 0044 N008 N007 N003 105344

   AT EVENT, FUEL QUANTITY AND THRUST
   LEPR  LWFQ    CTFQ    RWFQ   REPR
C9 1180  05123   00000   05214  1179

   AT AND POST EVENT, 20SEC. AVER. VAL.
   ROLL AILL AILR RUDD RUDT UTC
C0 N001 0049 0047 N008 N007 105348
E1 N002 0052 0044 N009 N008 105408
E2 N001 0049 0046 N010 N008 105428
E3 N001 0043 0053 N009 N008 105448
```

6. Specific Reports

- Anemometry Report <32>

- **Recording of Air Data Parameter to verify RVSM behaviour: Static Ports and AOA Sensors.**
- **ADC 1, 2 and 3 data is set in relation to validate Static Ports and AOA Sensors.**
- **Report is triggered:**
  - automatically at MMO (FL>250)
  - automatically at VMO (FL<250)
  - manually via remote print in cruise at perfo/stable condition
- **Quality Targets are defined for:**
  - RVSM delta ADR1/2 < 130ft
  - RVSM delta ADR1/2/3 < 195 ft

  - AOAref = PTCH – FPA
  - AOA#1,2,3 – AOAref <= +/- 0.5°

```
    A/C ANEMO REPORT <32>

    A/C ID DATE  UTC    FROM TO   FLT
C1  D-      JAN12 092113 EDHI EDHI

    PH CNT   CODE ..BLEED STATUS... APU
C2  06 00000 1000 50 0010 0 0100 50 X

    TAT  ALT   CAS MN  GW   CG  DMU/SW
C3  N442 39010 241 780 5760 174 I63002

    AT AND POST EVENT, 4 SEC INTERVALS

    ALT1  AOA1 CAS1 MN1 TAT1 PTCH1 FPA1
    2/3   2/3  2/3  2/3 2/3  2/3   2/3
C4  39010 0020 241  780 N442 0018  N0000
C5  39036 0020 241  781 N450 0018  N0000
C6  38897 0015 239  774 N442 0019  N0000

C7  39009 0019 241  781 N442 0018  N0000
C8  39032 0020 241  782 N450 0018  N0000
C9  38892 0014 240  775 N442 0019  N0000

C0  39005 0019 241  782 N442 0017  N0000
E1  39030 0020 242  783 N450 0018  N0000
E2  38889 0014 240  775 N445 0018  N0000

E3  39006 0019 242  782 N442 0018  N0000
E4  39032 0020 242  783 N447 0018  N0000
E5  38883 0014 240  776 N445 0019  N0000

E6  39005 0019 242  782 N442 0018  N0000
E7  39032 0020 242  784 N447 0019  00000
E8  38886 0014 240  776 N445 0019  N0000
```

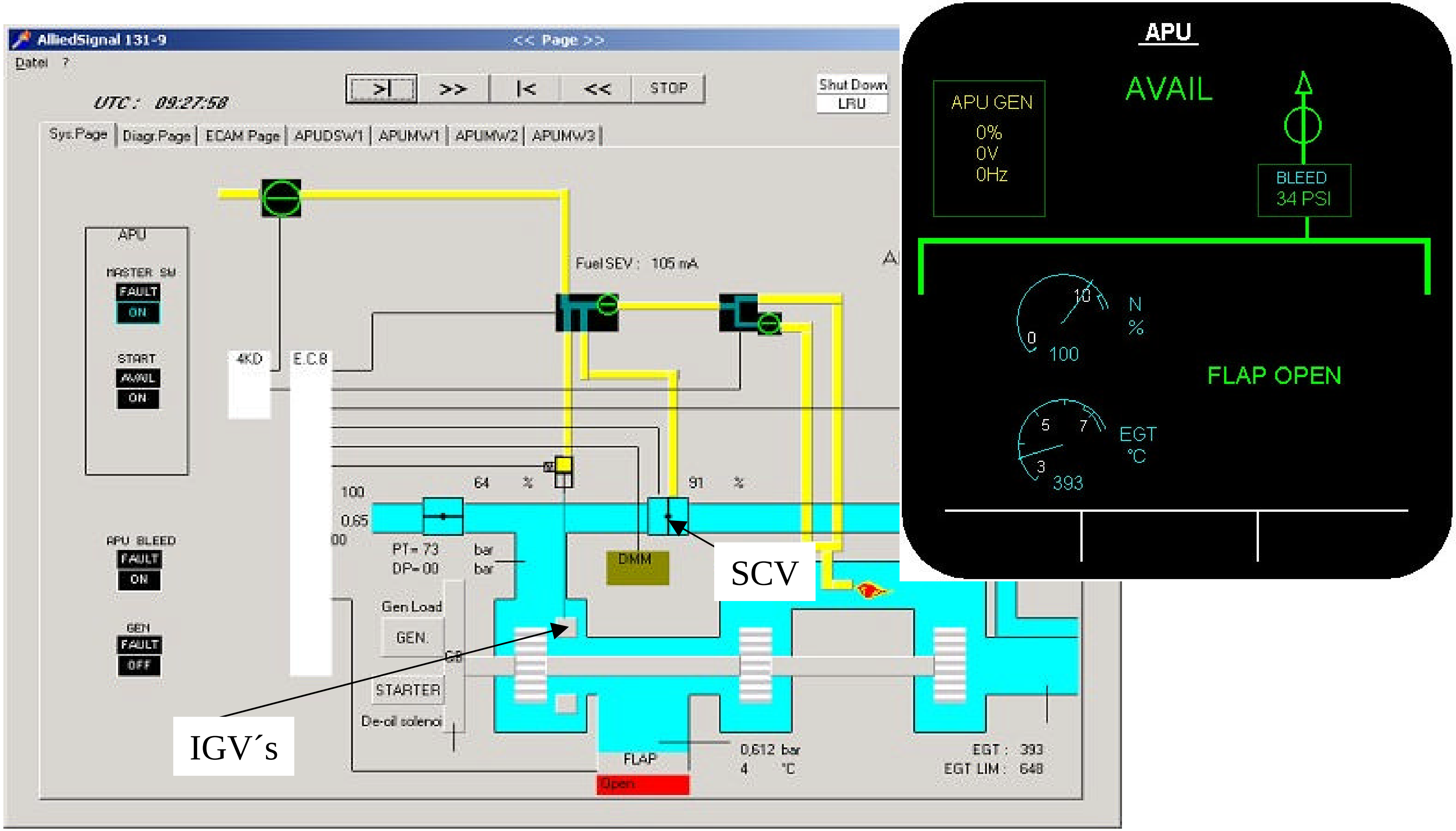
7. A/C System Simulation Tools

- **Why an a/c System Simulation**
  - Reproduce system behaviour with real a/c data.
  - Identify causes of system malfunction.
  - Understand system reaction under certain condition
  - Verify system reactivity by simulation of specific condition.
- **What kind of a/c System Simulation are available:**
  - Fuel System
  - Bleed System
  - Flight Control
  - APU
- **Attributes of the Simulation Tools**
  - Own programmed Delphi application
  - Simulation well adapted for T/S uses
  - Simple import of DMU SAR Data
  - Data embodied in First Flight database. Hence, available after each flight.

- **EXAMPLE of T/S by using APU System Simulation**
  - **Complain**: APU bleed supply in FL 150, bleed valves first connected but then pressure dropped to 6psi (34 psi before) with effect APU bleed disconnection. Than bleed tried to connect again and disc. again. Nothing on PFR.
  - **Results (ref. APU Simulation Charts):**
    - Reason of problem is the slope pf APU rpm at bleed load.
    - APU rpm slope induces the ECB to close the IGV's which also closes the bleed valves.
    - Hence, the APU rpm and bleed pressure increases again. Then the loop starts again.
  - **Corrective Action:**
    - ***Fuel Control Unit (FCU) replaced***. Problem already identified on other a/c.

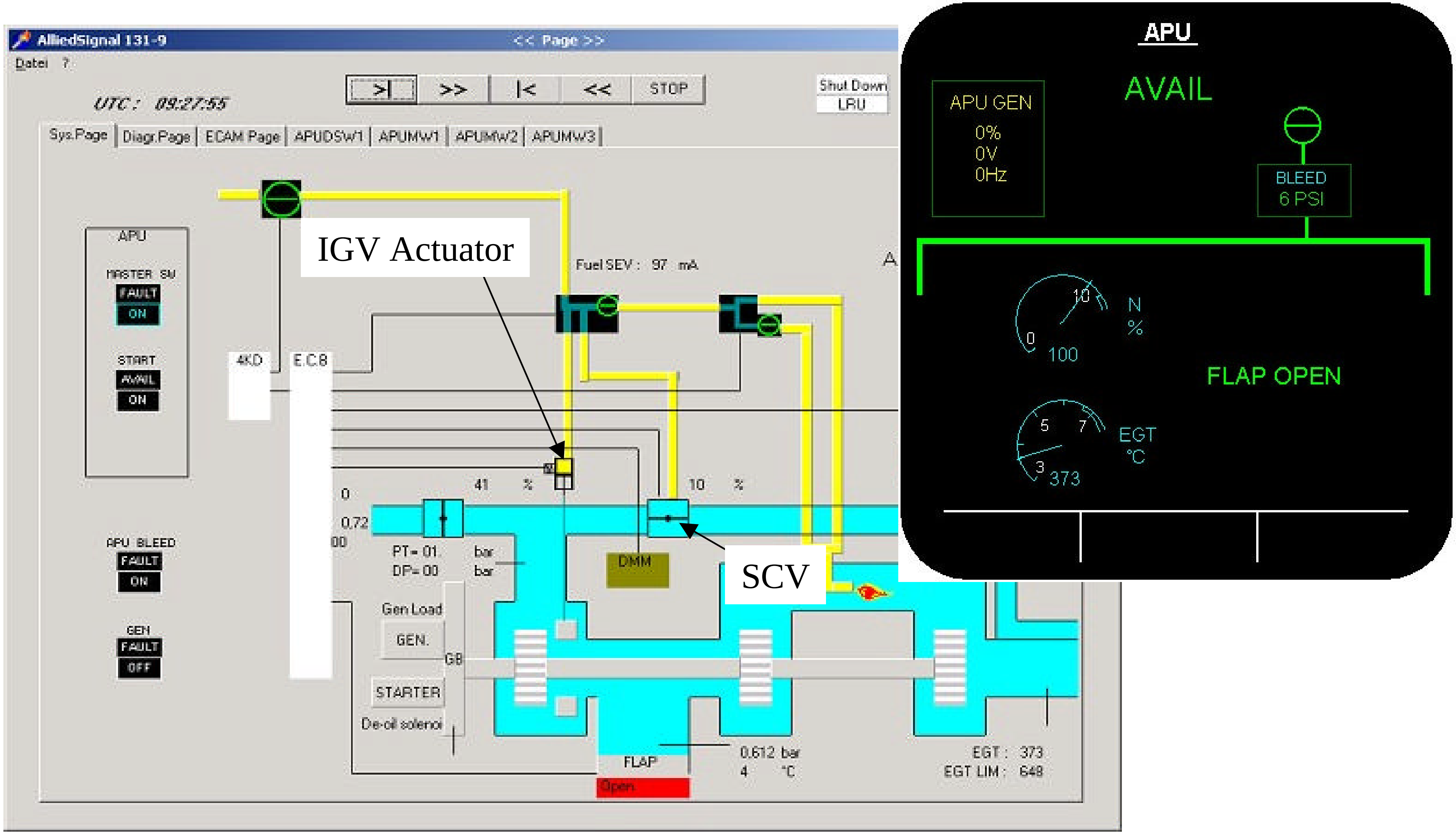
7. A/C System Simulation Tools

- **APU SIMULATION SYSTEM PAGE showing showing normal behaviour**



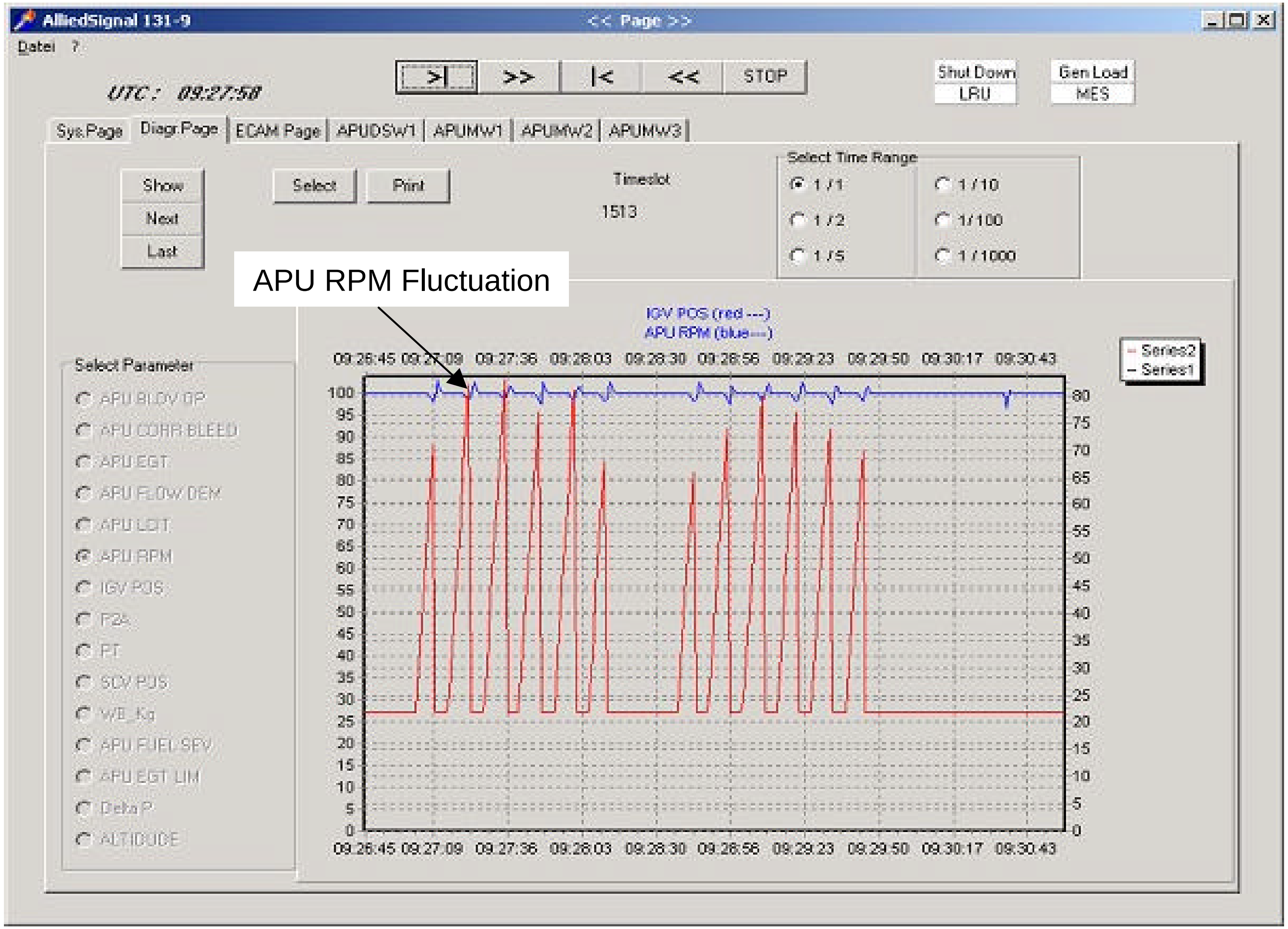
7. A/C System Simulation Tools

- **APU SIMULATION SYSTEM PAGE showing described anomaly**



7. A/C System Simulation Tools

- **APU SIMULATION DIAGRAM PAGE showing described anomaly**



8. DMU Database Application for Flight Test Requests (FTR)

- **Specific Parameter Recording for Flight Test investigation**
  - To validate system requirements for certification purposes.
  - To examine unexpected system behaviour to launch corrective action.
- **FTR Example:**
  - GPIRS/GPS Primary Function behaviour – recording of GPS and GPIRS parameter by a DMU
    - GPS Data dashed on -MCDU GPS MONITOR- page.
    - GPS PRIMARY LOST message on one/both NDs
    - ECAM warning –NAV FM/GPS POSITION DISAGREE-.
- **Modification of a/c wiring:**
  - Temp. Installation interconnection of DMU and MMR1/2 using DMU ARINC 429 spare inputs

EXAMPLE of FTR (see next figure)

- **Definition of recorded parameter:**
  - Both FMGCs:
    - Label 270: FMS Mode and GPS Primary Information (bits 11 to 13 and 26)
    - Label 310: FMS Latitude (bits 9 to 29)
    - Label 311: FMS Longitude (bits 9 to 29)
  - Three ADIRUS:
    - Label 310: IR Latitude (bits 9 to 29)
    - Label 311: IR Longitude (bits 9 to 29).......
  - Both MMRs:
    - Label 110: GPS Latitude (bits 9 to 29)
    - Label 111: GPS Longitude (bits 9 to 29)........

8. DMU Database Application for Flight Test Requests (FTR)

- **Excerpt from DMU/SAR Readout of recorded FTR Data in Excel Format**

UTC	GPIRS1_ STATU	GPIRS2 _STATU	GPIRS3 _STATU	GPS_ FM1	GPS_ FM2	HFOM_IR 1	HFOM_IR 2	HFOM_I R3	HIL_IR 1	HIL_IR 2	HIL_IR3	LATP_ 1	LATP_ 2	LATP_ 3	LATP_FM	LONP_1	LONP_2	LONP_3
						NM	NM	NM	NM	NM	NM	DEG	DEG	DEG	DEG	DEG	DEG	DEG
:03:50	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:51	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:52	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:53	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:54	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:55	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:56	10600	10000	10600	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:57	10630	100C0	10630	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:58	10630	100C0	10630	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:03:59	10630	100C0	10630	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:04:00	10630	100C0	10630	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:04:01	10630	180C0	10630	140	140	399.988	399.988	399.988	*01*	*01*	*01*	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:04:02	10630	180C0	18630	142	140	399.988	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	*01*	E9.8	E9.8	E9.8
:04:03	18630	180C0	18630	142	142	399.988	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:04	18630	180C0	18630	172	142	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:05	18630	180C0	18630	172	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:06	18630	180C0	18630	172	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:07	18630	180C0	18630	1972	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:08	18630	180C0	18630	1972	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:09	18630	180C0	18630	1972	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:10	18630	180C0	18630	1972	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:11	18630	180C0	18630	1972	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8
:04:12	18630	180C0	18630	1972	1972	0.21906	399.988	0.05621	*01*	*01*	0.14856	S36.5	S36.5	S36.5	S36.5	E9.8	E9.8	E9.8

Pilot Assistance Gate to Gate

Jan Merkel
email: Jan.Merkel@dlr.de
Institute of Flight Guidance
German Aerospace Center, DLR
Lilienthalplatz 7, D-38108 Braunschweig

12th April 2002

Abstract

The Institute of Flight Guidance of DLR pursues research and development of advanced on-board and ground-based concepts, solutions and procedures to ensure the safe, efficient and economic conduct of the rapidly growing air traffic. In order to maintain the high level of safety in air traffic and to facilitate the required increase of capacity in the forthcoming years, new solutions for optimal co-operation and integration of highly developed on-board flight guidance technology and air traffic management have to be developed. Situational awareness, support from intelligent systems or components, adequate share of work and responsibility, and smooth interaction between semi-automated systems and pilots / air traffic controllers are of key importance to success.

The Intelligent Pilot Assistant is developed at the Institute of Flight Guidance to provide a framework in which new assistance functions can easily be added and combined with the existing functions. The Pilot Assistance system is going to support and assist a cockpit crew of modern transport aircraft with it's hard and software components to handle the growing task of air traffic management, taxi and ramp management and future objectives like autonomous separation assurance in Free Flight scenarios. Therefore the assistance system will provide situation assessment methods which are needed for example by planning and control functions of the Flight Management System. Furthermore all supported methods are using a consistent display layout and operating philosophy.

Introduction

The knowledge and recognition of different states like on-board aircraft systems, workload of pilots, surrounding traffic and weather associated with appropriate preparation and representation of mentioned situation will increase the situation awareness of cockpit crew members and safety during flight and ground operation.

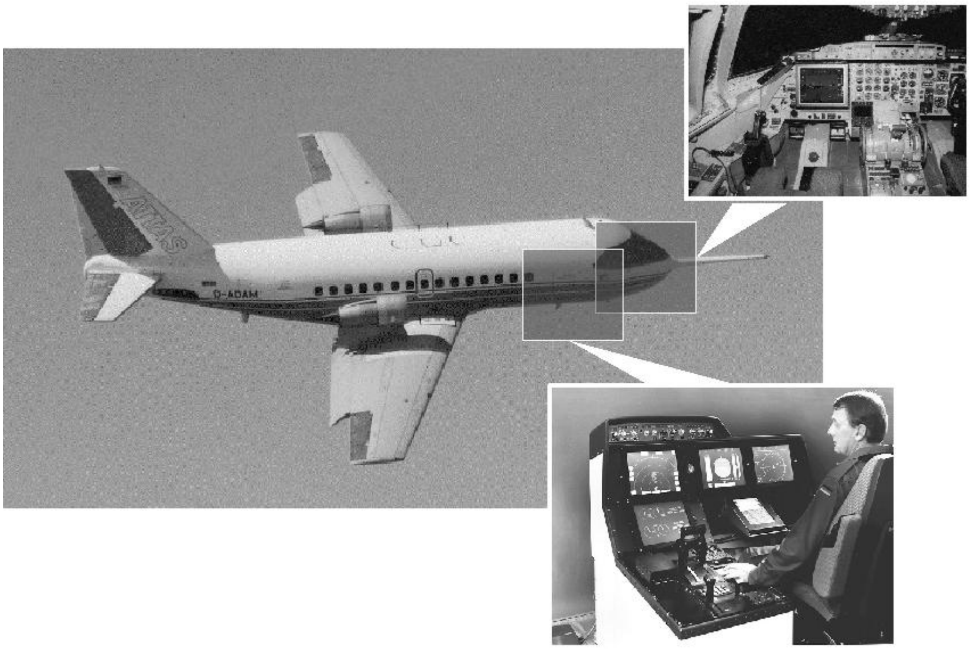


Figure 1: Research aircraft ATTAS (VFW614) with the experimental cockpit in cabin compartement.

Traditionally new ATM concepts which increase situation awareness and safety have been designed in separate systems where the cockpit crew has to collect the required information from a number of devices with non-uniform display and input formats. One approach to solve the problem is a Pilot Assistance System, where all required methods and functions are integrated into an overall intelligent system with a single man machine interface.

The main tasks for Pilot Assistance System are:

- Display of situation related data and information to cockpit crew.
- Monitoring and valuation during flight process and ground operation.
- Planning tools and decision advice.

This paper describes a generic concept of an intelligent Pilot Assistance system that currently is being developed at the Institute of Flight Guidance. This assistance system could handle mentioned aims and should be ready for complex future ATM objectives like planning economic trajectories in Free Flight Airspaces for cruise phase of the flight process or using functions from TARMAC (Taxi and Ramp Management Control) and EVS (Enhanced Vision Systems) for approach and ground operation with a uniform display and control layout to cockpit crew. For the Intelligent Pilot Assistant the generic architecture based on object oriented methods and providing templates for function modules has been developed that significantly reduces development and integration costs for new assistant functions.

Within the development one focal point is the support of Free Flight. A key requirement for Free Flight is the capability of the aircraft to ensure safe separation without support of ATC controllers. While the safety requirements for autonomous separation could be complied by an enhanced TCAS, economic operation in Free Flight needs advanced trajectory planning methods, which should provide near optimal trajectories to destination. These methods perform

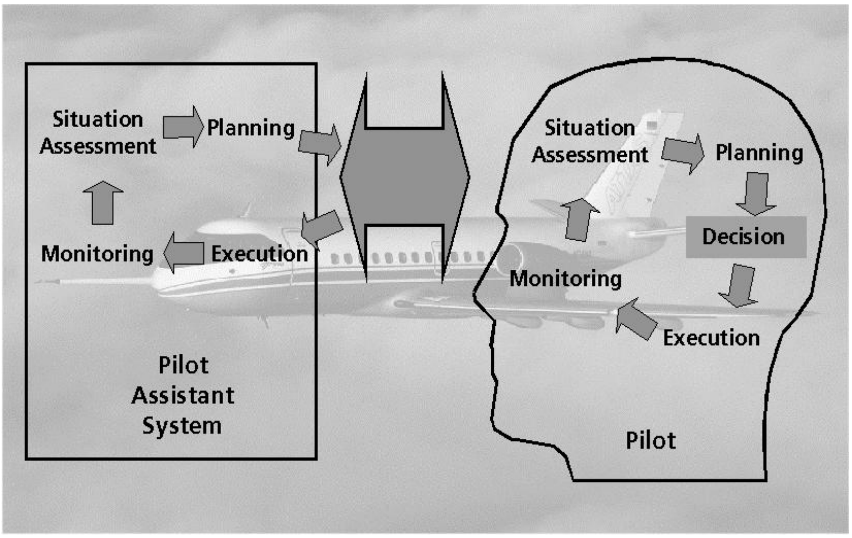


Figure 2: Recognize-Act-Cycle.

a planning covering long term conflicts with practical solutions, where the planning range is determined by data-link capabilities.

For the main approach of an Gate to Gate System the Free Flight Assistance System will be extended by mentioned methods of TARMAC

and EVS [2].

Generic concept of the Pilot Assistance System

As mentioned in introduction there are three main tasks for an assistance system:

- Display of situation related data and information to cockpit crew.
- Monitoring and valuation during flight process and ground operation.
- Planning tools and decision advice.

These objectives specify main function modules of situation assessment, planning, display and communication. In the generic architecture for the integrated Pilot Assistance System the functions of assessment, planning and display are implemented in function modules grouped around an application independent core system consisting of a central Data Pool, which handles the communication (figure 3).

The origin of messages can be either the data pool itself or in most cases the connected modules. E.g. when a monitoring module detects a long term conflict with other aircraft it sends a message to Data Pool with information about the conflict. The data pool itself forwards the message to the HMI displays and the planning module which have registered as readers of conflict messages.

When using the generic concept of the assistance system in modern transport aircraft the main modules can be subdivided into more certain submodules (figure 4). The important block of

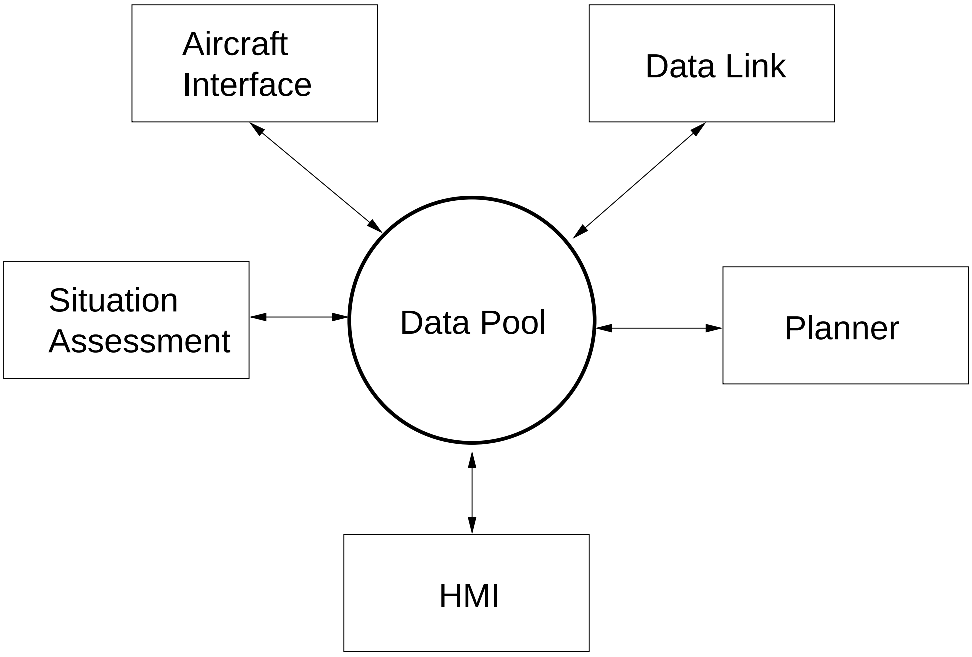


Figure 3: Generic concept of the Pilot Assistance System.

situation assessment on left side can be subdivided into different modules responsible for collecting information to display current situation like information about flight progress or information about surrounding traffic. The planning block on the right side could subdivide into an Advanced Flight Management System for generating economic trajectories, an ASAS/Free Flight planner to avoid long term conflict and for short term conflicts a TCAS.

Sophisticated data handling methods are implemented in this architecture to allow modules to be notified whenever relevant data have changed. This architecture allows sequences of actions performed by the system to be modeled entirely by specifying which input data are required for certain functions. Changes in these data will trigger the corresponding messages to all registered modules which are interested in specified data.

Free Flight Assistance System

Conflict detection and resolution has a long history of investigation, but further investigation is necessary as a result of new Free Flight policies with regard to new technologies (new data link, GPS and new avionic technologies) and with an increased emphasis on economic and market factors.[1]

As the first target application for the generic concept of an assistance system the Free Flight has been chosen to cover a complex ATM concept as a base of the Gate to Gate Pilot Assistance System. In case of the Free Flight assistant system the application modules shown in figure 4 will be included. Some of the the modules have been mentioned in previous section. In the following sections information about Traffic Monitor, Free Flight Planner, Airborne Human Machine Interface (AHMI) and Advanced Flight Management System (AFMS) is given. The other modules are either standard systems providing interfaces to the Data Pool like Aircraft Interface, Data Link, Displays and CDU or modules providing additional information not relevant for this paper.

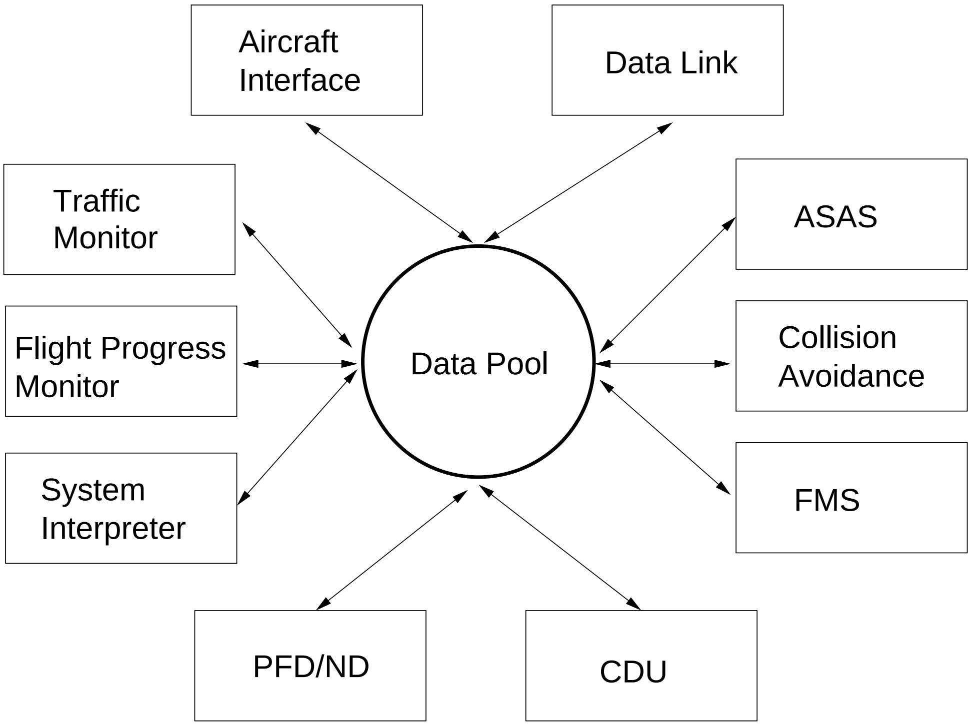


Figure 4: Pilot Assistance in a Free Flight Scenario.

Traffic Monitor

The Traffic Monitor module performs two tasks. The first is to generate the necessary data for a traffic situation display from data received via data-link. The second task is conflict detection, the task of predicting whether a conflict will occur in case that the involving aircraft continue on their planned trajectories. A fundamental requirement for conflict detection is that aircraft exchange information about their position and intended trajectory. It is assumed that this exchange will take place via ADS-B and that in addition to current position (4D) and speed also several intended 4D-waypoints will be broadcasted by all equipped aircraft.

Free Flight Planner

In several published concepts [1, 3] the responsibility for separation assurance will be shifted away from air traffic control to the individual aircraft with a policy of intervention by exception. While en route, an aircraft will be allowed to fly autonomously as long as no other traffic crosses an Alert Zone around the aircraft. If the Alert Zone is violated, air traffic controllers will intervene to assist in conflict avoidance. Therefor, a Free Flight planning algorithm has to cover the far-term strategic conflicts of Alert Zone violation, which can be smoothly resolved so that they never become near-term threats, which cannot be avoided without immediate action by e.g. TCAS.

In the first stage the Free Flight Planner computes a trajectory defined by a set of 4D-waypoints that is free of conflicts with other aircrafts and static objects e.g. restricted airspaces and provides an economic flight to destination. This set of waypoints is passed to the FMS via Data Pool in form of a constraint list message. Then the FMS will generate a flyable trajectory,

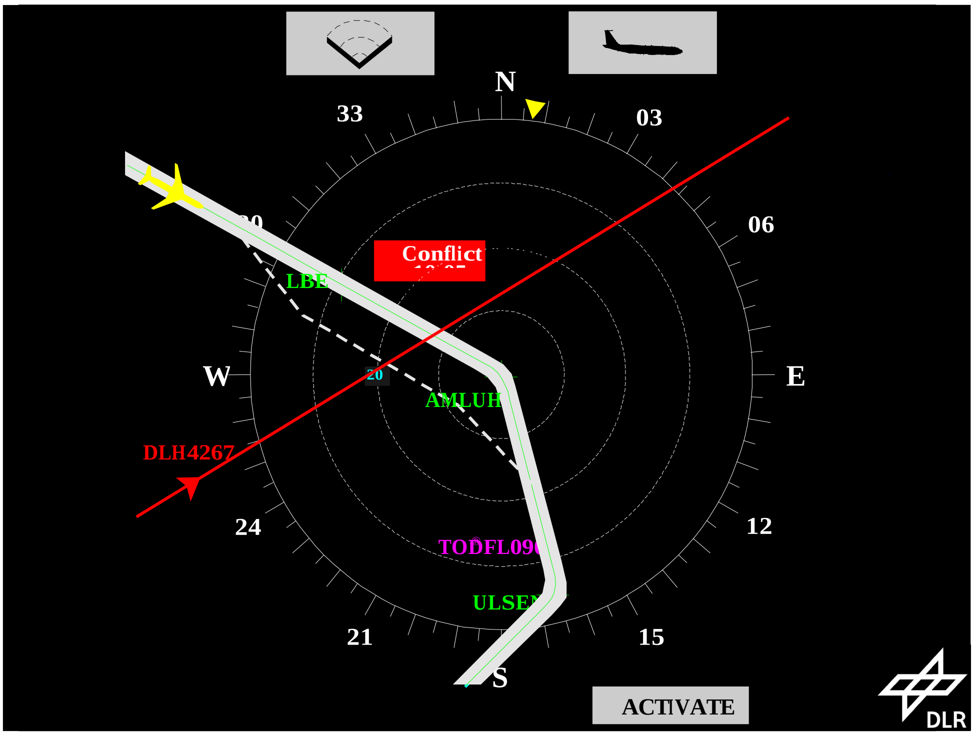


Figure 5: Conflict situation with another aircraft and display of a proposed solution.

which can be followed automatically with the guidance module available within the FMS and the autopilot (figure 5).

Finding the most economic trajectory in a dynamic environment is a complex planning problem. Asking for true optimality requires examining nearly all possible trajectories. The use of most common planning algorithm is prohibited by the number of dimensions, since the computation time is increasing exponentially with the number of dimensions and hence will be quickly beyond the available time. Frequently decoupling is used to reduce the complexity of the planning problem and to speed up the computation. As an example this could be done by examining only separate lateral or vertical maneuvers to resolve the conflict. However, the optimal trajectory may require a combination of both maneuvers and hence, the true optimum cannot be found in the decoupled search space.

It appears obvious that the best trajectory should be found at a point where only minimal maneuvers are required and a point time left to find a near optimal trajectory. Hence, a compromise between early and late activation time must be found. The latest activation time possible is given by the time required for actual avoidance maneuver (such as the Alert Zones do not touch) plus an additional amount of time for the pilot to evaluate the plan and to activate the new trajectory.

A frequently used algorithm to determine the optimal solution for a planning problem in standard airspace is the A* algorithm. Instead of quickly finding a complete trajectory from start to destination, all possible candidates for the first waypoint are examined. Then, the algorithm appends all possible waypoints to the so far most promising candidate (evaluated by a cost function) and again selects the most promising candidate. This procedure repeats until a candidate represents a complete and feasible trajectory. On average this algorithm will find the best trajectory faster than other planning algorithm. In large search spaces it will require a lot of time. This could result in not having any trajectory available in time. Therefor a planning algorithm is needed that will also make intermediate results available by finding less economic solutions.

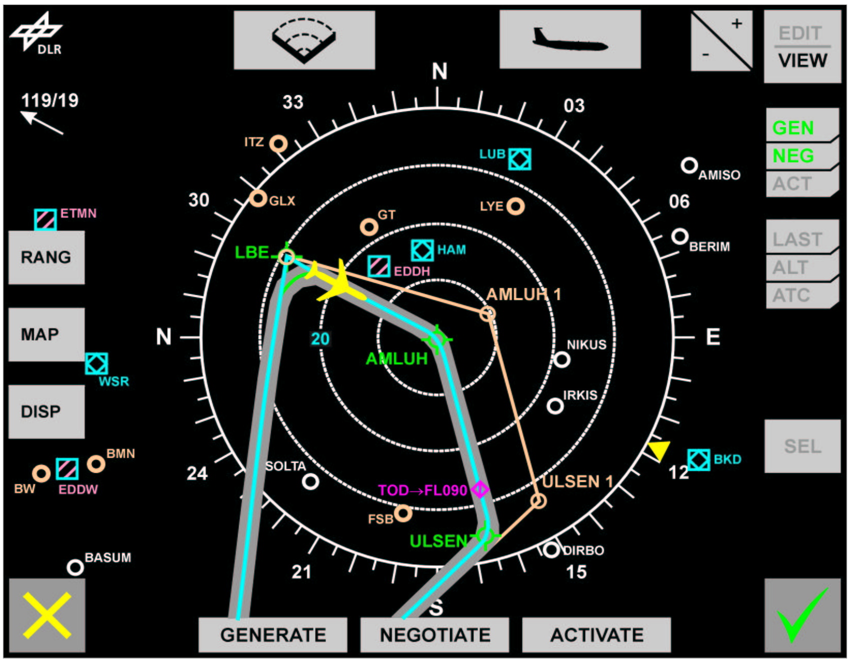


Figure 6: Planning mode of AHMI.

To achieve this the planner has to do a deep-first search at the beginning of its computations. While completing the initial guess of the solution by appending waypoint by waypoint, the algorithm abandons this trajectory only if it is unfeasible, not if there might be a better solution with the same amount of waypoints. This allows quickly generate non-optimal solutions so that is assured that the conflict can be resolved. Unfortunately the quality of these initial solutions may be very poor. Hence a hybrid algorithm was developed to combine depth-first search and the A* algorithm.

Additional improvements can be gained by using heuristics during the search process[3]. Heuristics can control the search process using knowledge (as a rule of thumb) to find a good solution, e.g. looking for vertical maneuvers first if experience shows that these are generally the better ones. Unfortunately, since the concept of Free Flight is quite new, such heuristics are not available at the moment and must be obtained from extensive simulations.

Airborne Human Machine Interface (AHMI) and Advanced Flight Management System (AFMS)

One of the most important parts of any complex cockpit system is the human machine interface. This is especially true for systems meant to assist an operator in performing a variety of tasks. The HMI for the pilot assistance system described here is based on the AHMI, which has been developed by PHARE partners for the EFMS system. It features a high resolution display with graphical input capability via touchpad or trackball and allows a quick and straightforward editing of trajectories and the controlling of the data-link to negotiate trajectories and other functions (figure 6). The conventional CDU is needed only for pre-flight inputs like initialization of the FMS. For Free Flight the AHMI is expanded to display traffic and planning information.

The Free Flight planner described above generates waypoints that can be used by the FMS to compute and follow the active trajectory automatically. In the system the Experimental Flight

Management System (EFMS) is used for this purpose. The EFMS takes a list of 2D-waypoints and constraints (altitude and time) to generate a 4D-trajectory. This trajectory can be negotiated with ATC (this function is not used in the Free Flight scenario). Once the trajectory is activated, the EFMS guidance function computes the necessary autopilot commands to follow the trajectory accurately.

Conclusion

DLR's Institute of Flight Guidance sets up a couple of projects to contribute to the effort of aviation community in improving flight safety by developing and implementing new ATM concepts. A very promising way in this sense is the development of systems for pilot assistance. In this paper a Pilot Assistance System is presented to improve situation awareness as well as trajectory planning and decision advice. This system concept is very flexible and easily extensible to cover complex ATM concepts like Free Flight, TARMAC and EVS. This characteristics can be achieved through a core Data Pool where all modules are grouped around.

In a first development state a system for Free Flight Scenario based on the Integrated Pilot Assistance System has been build up. In this system general assistance methods like an improved man machine interface and situation assessment are extended by functions to display and solve far-term strategic conflicts so that they never become near-term threats.

At the end of year 2002 the DLR's Institute of Flight Guidance is planning to demonstrate the Integrated Pilot Assistance System for a Free Flight scenario on it's research aircraft ATTAS in a pre-released version to show its efficiency. At the end of year 2003 extended assistance functions from TARMAC and EVS will be merged in for an all-in-one Integrated Pilot Assistance System from Gate to Gate.

References

[1] NN. Special issue free flight. *Air Traffic Control Quarterly*, 5(3), 1997.

[2] B. Korn T. Ludwig P. Hecker, H.-U. Döhler. In J.G. Verly, editor, *Enhanced and Synthetic Vision 2001*, volume 4363, pages 58–66, Orlando, Florida, USA, 16.-17.04 2001.

[3] Frank Höppner Reiner Suikat. On-board trajectory planning for automatic separation assurance in free flight. Technical report, DLR, Institut of Flight Guidance, 1997.

Enhanced Vision Systems: Automatic Situation Assessment for Safe Aircraft Operation*

Bernd Korn, Hans-Ullrich Doehler, and Peter Hecker

Institute of Flight Guidance
German Aerospace Center, DLR
Lilienthalplatz 7, D-38108 Braunschweig
email: Bernd.Korn@dlr.de

ABSTRACT

Adverse weather conditions affect flight safety as well as efficiency of airport operations. The problem becomes evident in critical flight phases such as approach, landing, take-off, and taxiing, in which the reduced visual range decreases pilot's situational awareness. In such situations Enhanced and Synthetic Vision Systems can overcome this problem. Data acquired by weather penetrating sensors are combined with digital terrain data and status information by application of data fusion techniques. The resulting description of the situation is given to the pilot via head-up or head-down displays. One promising sensor for Enhanced Vision application is the 35 GHz MMW radar "HiVision" of EADS.
This paper is about the automatic analysis of HiVision radar images with regard to the requirements for approach, landing and taxiing. This includes the integrity monitoring of navigation data by conformity checks of data base information with radar data, the detection of obstacles on the runway (or/and on taxiways) and the acquisition of navigation information by extracting runway structures from radar images. The performance of our system is demonstrated with real data acquired during numerous flight tests with approaches to and landings at different airports in Germany.

Keywords: enhanced vision, millimeter wave radar, navigation monitoring, obstacle detection, autonomous landing

1. INTRODUCTION

Approaches and landing maneuvers are some of the most critical tasks in civil aviation. Especially under adverse weather conditions (when the runway can't be seen) pilots need additional information to improve their situational awareness. Therefore, a new prospering field of aircraft guidance research called *Enhanced and Synthetic Vision Systems (ESVS)* has been established.
The principle concept of our ESVS approach is depicted in figure 1. The ESV system consists of two main parts, enhanced or sensor vision and synthetic vision. Synthetic vision usually generates a virtual out-the-window view and its accuracy and reliability depends on precise databases as well as on accurate navigation data, e. g. provided by differential GPS (DGPS). The additional use of forward looking imaging sensors offer the possibility to detect unexpected obstacles, the monitoring of the integrity of databases and navigation data and the extraction of navigation information, e. g. the relative position of the runway to the aircraft, directly from the sensor data. The latter is very important if ILS or DGPS is disturbed or not available.
Due to the lowest weather dependency, radar systems seem to be the most adequate EV sensors.

* This work is sponsored by EADS, Military Aircraft, Munich, Germany

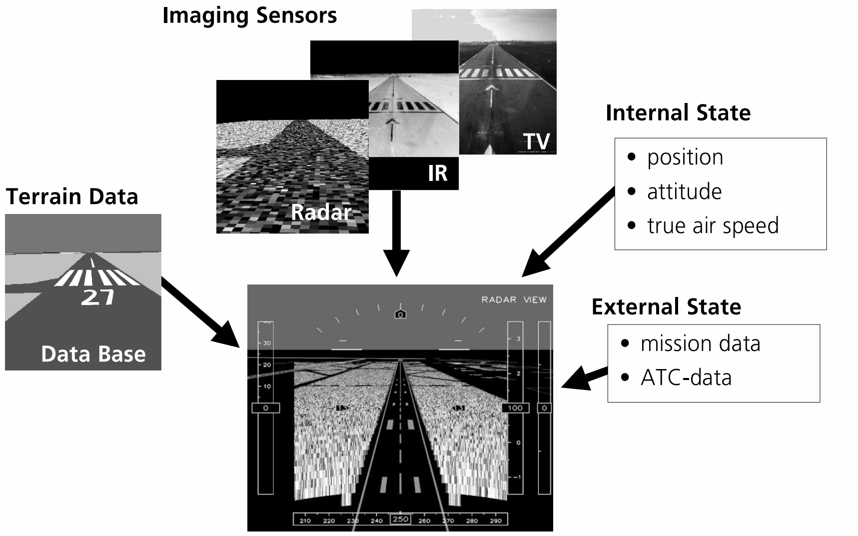


Figure 1. The concept of an Enhanced Vision System.

In the ALG project [1,2] radar images of a 95 GHz radar were presented on a Head-Up-Display (HUD) with a frame rate of 10 Hz, giving the sensor data analysis tasks up to the pilot. The APALS^{TM} [3] project used a modified X-band weather radar. The navigation information was extracted by correlating sensor data with a-priori acquired radar images of the airport and its vicinity, which are attached with high precision navigation information (DGPS). Thus, the applicability of this system is reduced to those airports for which such reference images are available. In our system, the HiVision radar[4–6] from EADS, Ulm, a 35 GHz MMW radar with a frame rate of about 16 Hz (see figure 2) is used as the primary EV sensor. Section 2 describes, how the integrity of database and navigation information can be monitored and how obstacles can be detected by the analysis of HiVision radar images. In section 3 an overview about the radar image based navigation for approach and landing is presented. The only a-priori knowledge we use to determine the position of the runway relative to the aircraft is the approx. runway heading, the width and the length of the runway and the input from the aircraft's INS. These runway information can be obtained from approach charts.

2. INTEGRITY MONITORING AND OBSTACLE DETECTION

In figure 3 our concept for integrity monitoring of the database and navigation by radar image analysis is depicted. In a first step a so called object image is generated from the database using navigation data (position and attitude of the aircraft from INS and GPS) and the imaging parameters of the radar sensor (resolution in range and azimuth). Consequently, this object image is pixel synchronous to the radar image. If a pixel represents a correct azimuth direction and range from the sensor to an object, it contains a unique label which identifies the object and the object class (e. g. like buildings, fences, ..) and an intensity information regarding the object's reflexivity properties with respect to the wave length of the radar. Of course, theses properties have to be modelled in the database. The way the object image is generated is the same as our MMW radar image simulator [7] works.

Figure 2. The HiVision sensor from DASA, Ulm on DLR's DO 228. It is an imaging FMCW radar with center frequency of 35 GHz, field of view of 41°/3.5 km, RF output 0.5 W, azimuth resolution 0.25° per pixel, range resolution 6.67m per pixel, vertical beam width about 10.0° and a frame update rate of about 15 Hz.

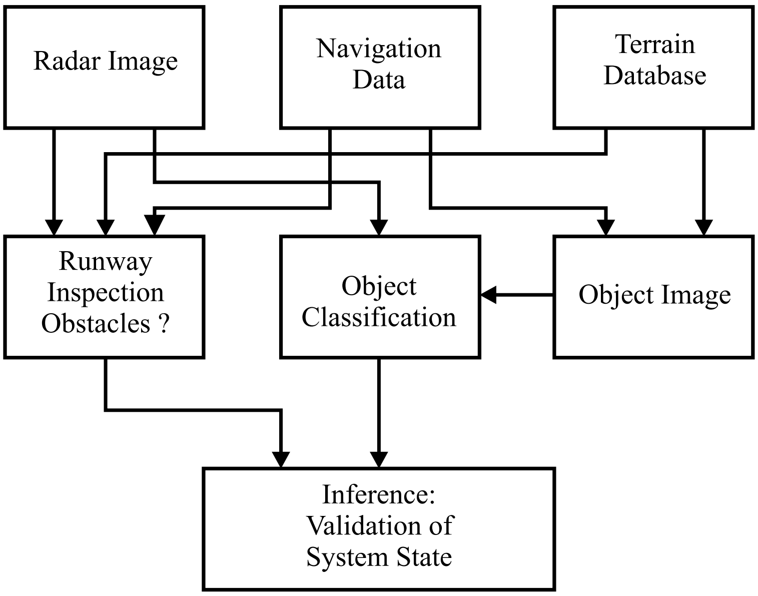


Figure 3. The concept for integrity monitoring of database and navigation

From the radar image objects are extracted because of their intensity distribution [8] which is different from those of grass, forrest areas or clutter. In the classification step radar image objects and database objects are classified into three different sets as follows:

- Radar image objects which can be explained by database objects

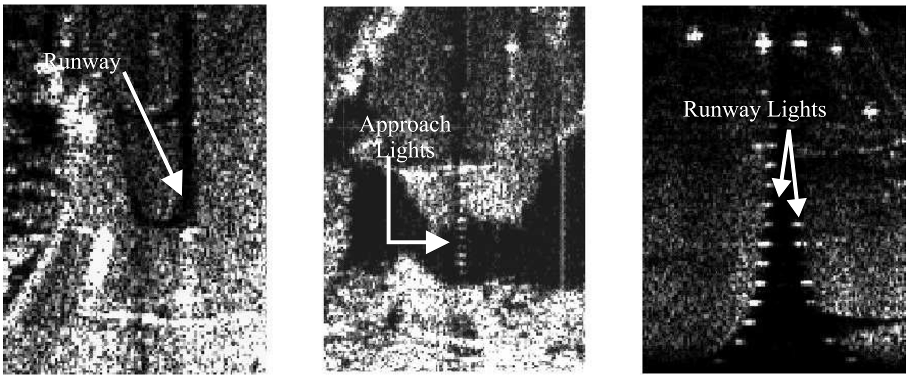


Figure 4. Runway structures in radar image: Left contrast between asphalt and grass areas. Middle: Blobs representing approach lights. Right: Blobs representing runway lights

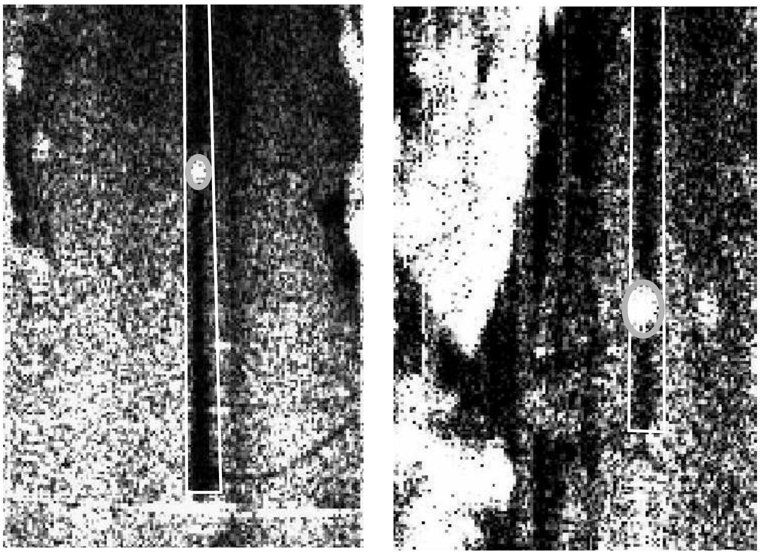


Figure 5. Runway and obstacle detection. Left approach to Braunschweig 26 (test van as obstacle), right approach to Cologne-Bonn (aircraft as obstacle)

- Radar image objects which cannot be explained by database objects
- Database objects which cannot be assigned to any radar image objects

Due to the two image being pixel synchronous this classification is straight forward and can be done very efficiently.
In the inference process the integrity state is determined by a rule based fuzzy controller using these three sets with rules like:

> IF *size of set one* IS *small* AND *size of set two* IS *small* AND *size of set three* IS *big* THEN *integrity* IS *low*

Concurrent to this classification the radar image is searched for runway structures at those parts of the images where they should appear. Typical runway structures which can be identified in radar images are shown in figure 4. If such structures can be identified at the expected locations

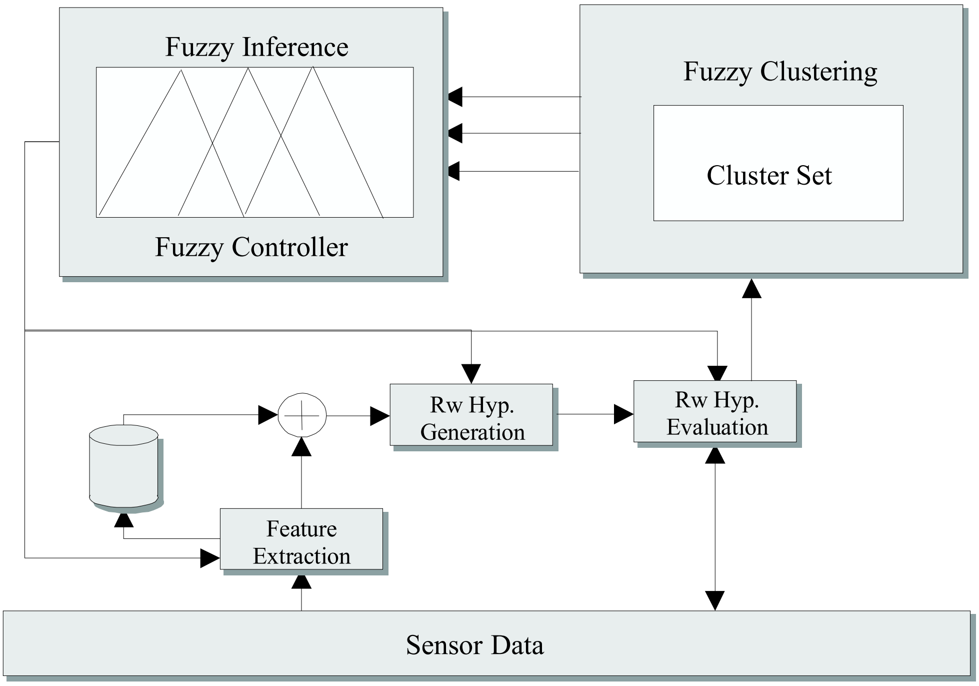


Figure 6. Concept of a sensor based navigation system for approach and landing

the value of the integrity is increased, otherwise decreased.
Furthermore, the image analysis shows whether the runway is clear or if there are obstacles on the runway. In figure 5 two examples of the obstacle detection are given, one during an approach to runway 26 in Braunschweig, with a test van as obstacle, the other during an approach to runway 32L in Cologne-Bonn with an aircraft on the runway.

3. RADAR IMAGE BASED NAVIGATION

If there is no sufficient information about the exact position of the runway relative to the aircraft due to non-precise databases and/or non-precise onboard navigation this navigation information has to be derived from the radar images for a board autonomous approach and landing operation under adverse weather. The concept of our sensor based navigation system [9,10] is depicted in figure 6. It consists of two layers, the inference and fusion layer and the extraction layer. Within the extraction layer the radar image is searched for radar structures as they are depicted in figure 4. The main feature hereby is the contrast between the image of runway asphalt and its surrounding grass area. Normally, the sensor data analysis process of the extraction layer generates more than one runway hypothesis from a single radar image. These hypotheses are evaluated with regard to the quality of their features in the image and then sent to the inference layer. Because of this hierarchies additional sensors or sensor data analysis processes can be integrated in the system quite simple[10]. In the inference layer, incoming runway hypotheses are clustered using adapted fuzzy [11–13] or possibilistic [14] clustering algorithms. This clustering consolidates the set of runway hypotheses $X = \{x_1, \cdots, x_n\}$ to a set of cluster prototypes $V = \{v_1, \cdots, v_c\}$, with $c << n$. In figure 7 the effect of information consolidation is depicted for an approach to Hannover 27R. Within a single frame several runway hypotheses are extracted. The fusion of all these hypotheses from several frames using the clustering algorithm ends up in the correct determination of the runway.

Figure 7. Result of the fusion process of several runway hypotheses of different frames during an approach to runway Hannover 27R

The output of each cluster is used as input for a common rule based fuzzy controller [15] to judge the state of the system and to determine whether runway structures should be searched for within the entire sensor data in the extraction process or in certain regions-of-interests (ROI) or even tracked, when there is a high reliability for only a few runway hypotheses.
Furthermore, the position of the aircraft relative to the runway threshold is calculated[16] if the output of the clustering allows a reliable and unique determination of the runway. From this calculated position, information such as the deviation from an optimal 3° glide path can be derived and be displayed head up or head down by ILS-like localizer and glide slope indicators.
During our flight tests we acquired about 90000 radar images within more than 50 radar image sequences from approaches to several runways from different airports in Germany (e.g. Hannover, Colgne-Bonn, Braunschweig). In every sequence the runway was extracted correctly. The average distance between runway threshold and aircraft at time of extraction was about 1800 m, which is larger than the minimum RVR (Runway Visual Range) for a non-precision approach.

4. CONCLUSION

Enhanced and Synthetic Vision Systems increase the situation awareness of pilots under adverse weather particulary during approach and landing. These systems show an artificial view of the terrain ahead. Thereby, the integrity of the necessary terrain database and navigation is monitored by onboard forward looking imaging sensors. Due to the weather independency in data acquisition radar sensors play an important role among feasible EV sensors.
In this paper the analysis of HiVision radar images for enhanced vision purposes is presented. The integrity monitoring of navigation and database is realized by a comparison between database objects and objects extracted from the radar images. An additional analysis of special runway structures in the images supports the evaluation of the system state. Furthermore, navigation data like the aircraft position relative to the runway is derived directly from the radar images.

REFERENCES

1. J. A. Brown, "The autonomous landing guidance program," in *Enhanced and Synthetic Vision 1996*, J. G. Verly, ed., vol. 2736, pp. 21–26, SPIE, 1996.
2. L. Bui, M. Franklin, C. Taylor, and G. Neilson, "Autonomous landing guidance system validation," in *Enhanced and Synthetic Vision 1997*, J. G. Verly, ed., vol. 3088, pp. 19–25, SPIE, Apr. 1997.
3. J. J. Hvizd and O. W. Dieffenbach, "APALS^{TM} program status, pre-production flight test results and production implementation," in *Enhanced and Synthetic Vision 1996*, J. G. Verly, ed., vol. 2736, pp. 27–34, SPIE, Apr. 1996.
4. F. J. Tospann, M. Pirkl, and W. Gruener, "Multifunction 35GHz FCMW radar with frequency scanning antenna for synthetic vision applications," in *Synthetic Vision for Vehicle Guidance and Control 1995*, vol. 2463, pp. 1–9, SPIE, Apr. 1995.
5. M. Pirkl and F. J. Tospann, "The HiVision MM-wave radar for enhanced vision systems in civil and military transport aircraft," in *Enhanced and Synthetic Vision 1997*, J. G. Verly, ed., vol. 3088, SPIE, Apr. 1997.
6. K. Helleman and R. Zachai, "Recent progress in mm-wave-sensor capabilities for enhanced vision," in *Enhanced and Synthetic Vision 1999*, J. G. Verly, ed., vol. 3691, pp. 21–28, SPIE, Apr. 1999.
7. H.-U. Doehler and D. Bollmeyer, "Simulation of imaging radar for obstacle avoidance and enhanced vision," in *Enhanced and Synthetic Vision 1997*, J. G. Verly, ed., vol. 3088, pp. 64–73, SPIE, Apr. 1997.
8. B. Korn, H.-U. Doehler, and P. Hecker, "MMW radar data processing for enhanced vision," in *Enhanced and Synthetic Vision 1999*, J. G. Verly, ed., vol. 3691, pp. 29–38, SPIE, Apr. 1999.
9. B. Korn, H.-U. Doehler, and P. Hecker, "Weather independent flight guidance: Analysis of MMW radar images for approach and landing," in *15th International Conference of Pattern Recognition 2000, Barcelona*, vol. 1, pp. 350–353, IAPR, Sep. 2000.
10. B. Korn, H.-U. Doehler, and P. Hecker, "Robust sensor data fusion for boar autonomous navigation during approach and landing," in *International Symposium on Precision Approach and Automatic Landing, ISPA 2000, Muenchen*, pp. 451–457, DEGON, Jul. 2000.
11. J. C. Dunn, "A fuzzy relative of the ISODATA process and its use in detecting compact well-separated cluster," *Cybernetics* (3), pp. 32–57, 1973.
12. J. C. Bedzdek, *Pattern Recognition with Fuzzy Objective Function Algorithms*, Plenum Press, New York, 1987.
13. J. C. Bedzdek and S. K. Pal, eds., *Fuzzy Models for Pattern Recognition*, IEEE Press, New York, 1992.
14. R. Krishnapuram and J. Keller, "A possibilistic approach to clustering," *IEEE Trans. on Fuzzy Systems* (1), pp. 98–110, 1993.
15. R. Kruse, J. Gebhardt, and F. Klawonn, *Fuzzy-Systeme*, B.G. Teubner, 1993.
16. B. Korn, H.-U. Doehler, and P. Hecker, "MMW radar based navigation: Solutions of the vertical position problem," in *Enhanced and Synthetic Vision 2000*, J. G. Verly, ed., Apr. 2000.

COST BENEFIT BY ENGINE VIBRATION MONITORING
– A CASE STUDY OF ACMS USAGE IN BOEING 737NG.

Staffan Elmén, M.Sc.
Scandinavian Airlines System
Engineering – Development, Airworthiness & Documentation
Stockholm, Sweden

1 ABSTRACT

After a number of blade losses in the engine's low pressure turbine an extensive program started combining different measures to minimize the impact on normal traffic, e.g. changed flight procedures, changed EEC SW & readout of AVM after each flight. The latter was a major drawback and cost driver. The AVM readout has to be done by a certified mechanic and on many flights that used to be "PFI" (pilot performing the pre-flight check), a mechanic has to be onboard.

The measures also included introducing a tailor-made ACMS report. The engine manufacturer conducted a thorough analysis of all the incidents. This resulted in an algorithm combining vibration amplitude and phase angle. The ACMS manufacturer Honeywell, then provided SAS with revised software, that included these calculations. After several tests a final version was installed fleet-wide in the SAS Boeing 737NG fleet. After that, the readout of AVM was no longer necessary and we were able to go back to normal routines.

Despite a number of "nuisance warnings", that caused delays and/or cancellations, the introduction of the new ACMS report saved more than $100,000 by reintroducing PFI and no need for mechanic assistance after each flight.

2 TABLE OF CONTENTS

3 BACKGROUND

Deliveries of the BOEING 737NG's to SAS started in September 1998. They were intended to replace the older Fokker F-28 and DC-9-41. The total order was for more than 50 aircraft. Flawless introduction in SAS traffic started in October 1998.

4 PROBLEMS ARISE

In April 1999 a pilot remarked that an engine was not behaving normally. A slight increase in EGT (Exhaust Gas Temperature) and vibration levels was noticed. In the course of a borescope inspection, a broken blade was found in the first stage of the Low Pressure Turbine (LPT). The engine, CFM56-7B, was removed and sent to the manufacturer for investigation. In October the same year a similar incident occurred and the engine manufacturer CFMI intensified their search for the root cause.

Before the investigations of the two cases were finished, there were more occurences and within less than six weeks we had three more of the same type. It was soon revealed that the problem had to do with our DAC's, Double Annular Combustor. The problem had not been seen on operators with the conventional SAC – Single Annular Combustor. In certain flight phases, in particular the descent, the fuel nozzles had a particular "burning pattern" ('DAC Mode') that initiated a vibration in the first stage LPT blades, that was leading to a fatigue rupture.

5 CAMPAIGN

To try to minimize impact on our traffic, a broad campaign started in anticipation of a final fix. The campaign involved the following steps:

- Close monitoring of engine vibration parameters by flight crew incl. filling in a special form
- Readout of the AVM (Airborne Vibration Monitoring Unit) after <u>each</u> flight
- Changed flight procedures during descent
- Changed software in the EEC (Electronic Engine Control)

The new routines entailed dramatically increased cost, mainly because the AVM readout had to be done by a certified mechanic. This was done if a SAS mechanic was onboard the flight or with extra maintenance assistance at the destination. This meant that "Pilot PFI" (Pilot Pre-Flight Inspection) could not be carried out at many stations.

6 ACMS USAGE

At an early stage the possibility of using ACMS was discussed as one additional tool for vibration monitoring. The problem was that in almost all cases only very small changes in various parameters had been found. One might think, that loss of a blade would suddenly lead to very high vibration levels. However, this was not the case. The blade separated in a portion of the flight (descent), when engine power is relatively low and vibration not significant. Thus, the existing ACMS Engine Exceedance Report would not trigger. In most cases the engine made a complete flight, and it was only when beginning next flight that the problem presented itself.

Since SAS was already using ACARS/Datalink for downlink of ACMS Reports, the infrastructure was in place for quick actions if a downlink was received. However, would it be possible to achieve a solution within a reasonable time frame?

The schedule comprised the following steps:

- The engine manufacturer CFMI proposes an algorithm
- The ACMS mfg Honeywell reviews it and discusses with CFMI för adjustments
- Programming a new version with a tailor-made ACMS report
- Shipping SW to SAS, test installation and evaluation in one aircraft for a shorter period
- If evaluation is OK – fleet-wide installation. If not OK – update ACMS software
- Fleet-wide installation and revised maintenance procedures

7 CFMI EVALUATION

The engine manufacturer was provided with huge amounts of flight data from all incidents for evaluation. Vibration behaviour is measured by two sensors, one inside the engine (No.1 Bearing) and the other on the fan frame compressor case (FFCC). It became clear that it was not as easy as one might think to detect a problem. There was a great deal of scatter that interfered with the vibration signals when the blades ruptured.

However, an algorithm was proposed that contained amplitude and phase angle calculations and vectorial deviation comparison. When the deviation was higher than a pre-deterimed threshold, the report triggered.

8 SCOPE – PROPOSED ALGORITHM

- data acquisition of time, vibration amplitude & phase angle, engine rotor speeds (rpm)
- calculate vibration vectors for FAN and LPT

- put the calculated vibration vectors in engine "rpm slices"
- in each "rpm slice", calculate average vibration vector
- store average vibration vector in each "rpm slice" (V1 AVG, V2 AVG)
- for each N1 slice calculate difference between current and previous flight (D AVG)
- calculate amplitude of each D AVG and store
- compare with limits

It also contained:

- for each data point calculate max. difference with average during the current flight

9 REVIEW AND PROGRAMMING BY HONEYWELL

The calculations necessary consisted of

- conversion of "System Units" to "Mils"
- conversion of phase angles from degrees to radians
- use of trigonometric functions for vectors
- collecting in "rpm bands"
- calculation of averages
- comparing with limits

This vibration monitoring logic was very complex and required much more of the CPU resources than a typical ACMS Report would consume. This made it necessary to adjust the initial proposal. There were different ways to solve the problems:

- Reduce the number of <u>other</u> ACMS reports currently used

- Reduce the number of N1 rpm-bands

- Eliminate and/or simplify calculations

Since SAS is an extensive user of ACMS, we were concerned with the first item. ACMS reports for structural exceedances (overspeed, hard landing) and routine reports for the ground-based engine monitoring program are very important, and we did not want to eliminate them. However, we had some other reports that could be disabled, to create more room for the new vibration report. One of them was the "Weather Observation Report". This provided weather observations routinely and was forwarded outside SAS to the Swedish Meteorological and Hydrological Institute directly. We decided to disable that together with some others of minor interest. The number of "rpm bands" and their interval was adjusted, and some calculations were also simplified, and this resulted in the new "Vibration Deviation Detection Report".

10 INSTALLATION IN SAS FLEET

One aircraft was equipped with the new software, and though simulation tests were done at Honeywell, there are always surprises in the "real world". ………..

After approx. two weeks evaluation with one aircraft, the fleet-wide update continued. Every flight generated ACMS Report No. 65, regardless of limit exceedance or not. This was also a part of the evaluation, and the engine manufacturer received the data directly as it was downlinked via SITA. This meant several hundreds of messages per day.

However, delays in the schedule could not be avoided. The original time plan was already overdue, and was there any point in continuing? Other parts of the campaign would eliminate the need for this type of monitoring, i.e. engine replacements with new blade sets were catching up. By the end of June, CFMI considered the evaluation closed and a go-ahead was decided. All direct transmission of data to them was then stopped.

A new ”cleaned-up" SW version was ready in July and installation completed fleet-wide the same month. It was partly de-activated since automatic print in cockpit was put on hold.

To continue the process, two weeks was needed for preparations within the maintenance organization and for information to pilots. That meant distribution of e.g. Maintenance Bulletins, Flight Operations Information and introducing new troubleshooting procedures within Line Maintenance

On August 17th, 2000 it all started, and the ACMS report No. 65 was fully activated fleet-wide through individual uplinks. This made it possible to go back to the Pilot-Preflight Inspection (PFI), and the Maintenance organizations went back to normal routines.

We did not have to do many flights before the first report was triggered. The pilots got an automatic short printout in cockpit telling them that a "Vibration Step Change" has been detected by ACMS. Simultaneously, the full ACMS report was downlinked, advising maintenance personnel what had happened (Fig 1 & 2)

```
ACMS VIBRATION DEVIATION DETECTION REPORT <65>


REP AC REG AC TYPE     DATE    FLT  NUM     DEP   DEST  FLCT  DBID    AC EFF
065 OY-KKK B737-600    000713  SK1009       ESNS. ESSA. 0159 SK3706   YE106:

UTC       FM    ISFC  PALT  CAS    MACH     SAT   TAT    LATP     LONP     AGW
09.12.34 TA    8967  00512 045     .15     010.2 010.4  N5939.4  E1755.3 52037::

TRIGGER CODE-REASON                  AVM FAULT CODES
4010 VIBRATION-STEP-CHANGE-ENG-1     NO-FAULT::
```

Fig. 1 Cockpit Printout (short form)

```
ACMS VIBRATION DEVIATION DETECTION REPORT <65>

REP AC REG AC TYPE  DATE    FLT NUM DEP   DEST  FLCT  DBID   EFF
065 OY-KKK B737-600 000713  SK1009  ESNS. ESSA. 0159 SK3706 YE106:

UTC       FM ISFC PALT  CAS MACH SAT   TAT    LATP     LONP   AGW
09.12.34  TA 8967 00512 045  .15 010.2 010.4 N5939.4 E1755.3 52037::

TRIGGER CODE-REASON           AVM FAULT CODES
5010   VIB-DEV-ENG1           NO-FAULT::

N1 RANGE       D1 AVG  D2 AVG  D2 MAX
070.2-072.5    00.00   00.00   00.00::
072.5-075.0    00.00   00.00   00.00::
075.0-077.5    00.00   00.00   00.00::
077.5-080.0    00.00   00.00   00.00::
080.0-082.5    00.00   00.00   00.00::
082.5-085.0    00.25   00.94   02.38::
085.0-087.5    05.29   09.97   12.29::
087.5-090.0    08.76   19.34   25.75::
090.0-092.5    07.13   13.38   19.14::
092.5-095.0    00.10   00.41   00.74::
095.0-097.5    00.15   00.56   01.17::
097.5-100.0    00.09   00.72   00.84::

LIMIT-1-2-3    06.25   16.00   20.25::
LIMIT-4-5-6    06.25   16.00   20.25::
```

Fig. 2 Downlink & Cockpit Printout (long form)

The maintenance procedures consisted briefly of the following:

- Verify limit exceedances on the ACMS Report
- Examine engine exhaust and rotate LP-rotor
- Do a BITE check on the AVM
- Do a FOD/Birdstrike inspection
- Do a borescope inspection of the LPT (if previous steps require)
- Download AVM for flight history
- Reset the ACMS

We found nothing wrong with the engine. Obviously the diagnosis was not working very well. Unfortunately this continued and we soon had two or three events per week – all of them false alarms - resulting in several delays and/or cancellations with many problems in the daily traffic. So the question was: did we activate the ACMS Report too quickly? Would it have been better to fine tune the algorithm and wait longer? The occurrences were less than 0.5% of our flights, but gave the whole organization a major headache. We could not see any advantage in raising the limits – this might result in missing a real event. The decision was to continue, since it was better than going back to what we previously had.

11 DE-ACTIVATION OF VIBRATION REPORT

After almost two months, it was decided to de-activate the functions. The engine replacement program had reached a state that minimized further events. Once again we used individual uplinks to do this.

During the period under study, there were both pros and cons:

Pro: we were able to go back to normal routines for all personnel
Con: many false alarms resulting in delayed and/or cancelled flights

12 ESTIMATES OF COST AND SAVINGS

From 17AUG00 to 12OCT00, more than 15,000 revenue flights were performed. Less than 0.5% resulted in an unscheduled maintenance action due to triggering of the Vibration Deviation Detection Report .

Additional costs for the revised maintenance routines that started in April, were estimated at USD ~43,800 per each 10 days. Thus, the 57-day period in question saved USD ~250,000. On the other hand, the costs for delays and cancellations are estimated at USD ~115,000. Manhours in engineering and maintenance organizations are considered marginal.

Savings:	+250,000
Unscheduled costs:	-115,000
Total savings:	+135,000

13 CONCLUSION

The case described is a good example how ACMS can be used in an airline. Our cooperation with specialists from manufacturers in France and USA was excellent, even if the final result was not completely satisfactory.

The savings were not as great as we had hoped, but it certainly was a good experience for all involved.

14 ACKNOWLEDGEMENTS

Thanks to Lars Andersson and Joakim Söderblom, 737 Powerplant Engineering in Stockholm, Sweden, and to Steve Wilmot, Honeywell, Redmond, WA, USA for their comments and support.

Thanks also to Donald MacQueen, my neighbour and friend, for his valuable comments to the manuscript.

15 ABBREVIATIONS

ACARS	Aircraft Communication, Addressing & Reporting System
ACMS	Aircraft Condition Monitoring System
AVM	Airborne Engine Vibration Monitoring Unit
BITE	Built In Test Equipment
CFMI	CFM International, aircraft engine manufacturer (GE & Snecma)
CPU	Central Processing Unit
DAC	Double Annular Combustor
EEC	Electronic Engine Control
EGT	Exhaust Gas Temperature
FFCC	Fan Frame Compressor Case Vertical (Vibration Sensor)
FOD	Foreign Object Damage
LPT	Low Pressure Turbine
MFG	Manufacturer
N1	Low Rotor Speed
PFI	Pre-Flight Inspection
RPM	Revolutions per minute
SAC	Single Annular Combustor
SW	Software

ADVANCE SYSTEM FOR VIBRATION MONITORING AND DIAGNOSIS ON HIGH POWER AERO ENGINEERING

Dr. Jorge Moreno Barragán

MTU Aero Engines GmbH
Engine Dynamics
Dachauer Strasse 665
D-80995 Munich
phone: ++49 89 1489 4191
fax: ++49 89 1489 99902
email: J.Moreno-Barragan@muc.mtu.de

ABSTRACT

An advanced vibration monitoring and diagnosis system (VMS) consisting of on-board and on-ground tasks is presented in this paper. The on-board part of the VMS includes the detection of vibration incidents by monitoring of defined vibration amplitude values and comparison with prescribed absolute and relative vibration limits, where the relative vibration limits are specific for each particular engine. Exceeding of defined vibration alarm limits trigger a cockpit warning. The processing and acquisition of different vibration data sets using several algorithms are additional tasks of the on-board vibration monitoring function. The on-ground part of the VMS comprises the trend analysis of vibration signals as well as the diagnosis of vibration events which includes data generated on wing, test-bed and the results of numerical simulations performed using extensive structural Finite Element whole engine models.

On this paper the strategy for vibration incident detection and the data sets which are necessary to carry out the vibration monitoring function are described in detail. Finally selected cases of the extensive experience gained during the application of the presented VMS to EJ200, the engine of the Eurofighter EF2000, are reported and discussed.

Key words:
engine vibration, signal processing, incident detection, vibration diagnosis

1 LIST OF ABBREVIATIONS

BSD	Bulk Storage Device
CSMU	Crash Survivable Memory Unit
DECU	Digital Engine Control Unit
ECMS	Engine Condition Monitoring System
EF	Eurofighter
EF2000	European Fighter Aircraft
EHM	Engine Health Monitoring
EMS	Engine Monitoring System
EMU	Engine Monitoring Unit
EO	Engine Order (spool speed harmonic frequency)
GSS	Ground Support System
HP	High pressure (rotor/system)
IPU	Interface Processor Unit
LP	Low pressure (rotor/system)
MAS	Vibration Maximal Amplitudes Store
MDP	Maintenance Data Panel
MPR	Vibration Max Per Run
OOB	Out of balance
PMDS	Portable Maintenance Data Store
RMS	Root Mean Square
RPM	Revolutions Per Minute
RVE	Residual Vibration Energy
THS	Vibration Time History Store
VMS	Vibration Monitoring System

2 INTRODUCTION

One of the most sensitive parameters for continuos monitoring of the condition of aero-engines are engine vibrations. These vibrations signals are captured by one or more accelerometers mounted at carefully selected casing positions. With these in-service gained signals and additional operational parameters, used for aircraft and engine control, it is possible to reliably monitor engine health and, if necessary, to diagnose the reason for the engine malfunction.

The main objectives of the engine vibration monitoring can be summarised as:

- increased safety through identification of dangerous vibration conditions at all engine speeds and thrusts, including steady state and transient operation, and through generation of the corresponding cockpit warning,
- avoidance of major secondary damage by way of early failure identification,
- reduction of maintenance expenditure through isolation, localisation and diagnosis of the vibration causes and
- optimisation of maintenance by means of consideration of the current engine condition.

In the current paper an advanced vibration monitoring system will be presented which aims to satisfy the above requirements.

3 DATA ACQUISITION AND PROCESSING

Vibration monitoring is one of the most substantial parts of the Engine Monitoring System (EMS) of EJ200, the engine of the EF2000. The tasks of the vibration monitoring function are distributed over airborne and ground equipment, where the airborne equipment comprises vibration transducers and the Engine Monitoring Unit (EMU) and the ground equipment comprises the Engine Health Monitoring system (EHM) as an element of the Ground Support System (GSS).

As shown in Figure 1, this data is transferred to GSS using several devices - Interface Processor Unit (IPU) , the Bulk Storage Device (BSD) and the Portable Maintenance Data Store (PMDS) - and stored in the corresponding data base within the GSS.

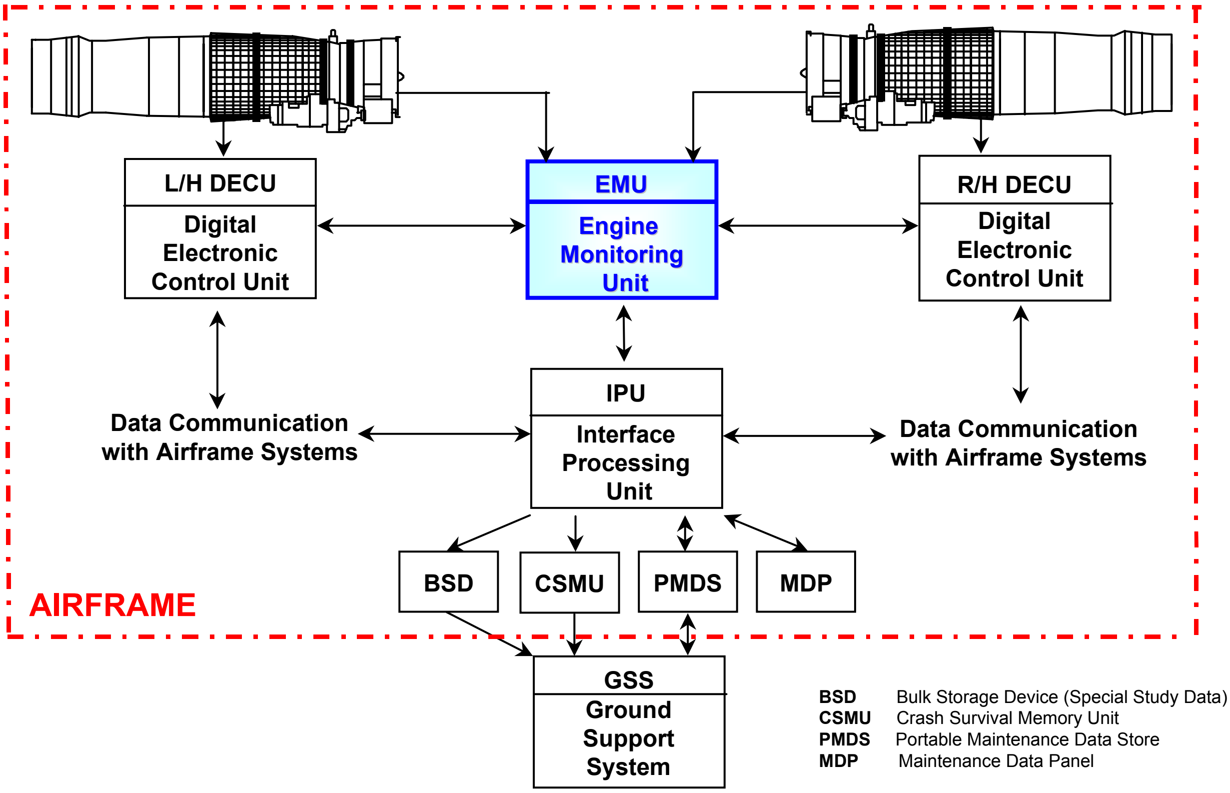


Figure 1: Data flow of the engine monitoring system

The location of the two engine vibration transducers is shown in Figure 2. The transducers are attached to the engine casings at carefully selected positions which allow monitoring of the dynamics of the rotors in the frequency range below 1 kHz. The vibration transducers are hardwired to the EMU and also positioned to ensure simple maintenance.

The transducer signals are conditioned by the EMU to produce band pass filtered velocity analogue signals. The health of the vibration transducers and of the EMU signal conditioning interfaces is continuously monitored and status information is stored together with the sampled and derived data. The resulting velocity signals are continuously sampled by EMU for analysis and storage.

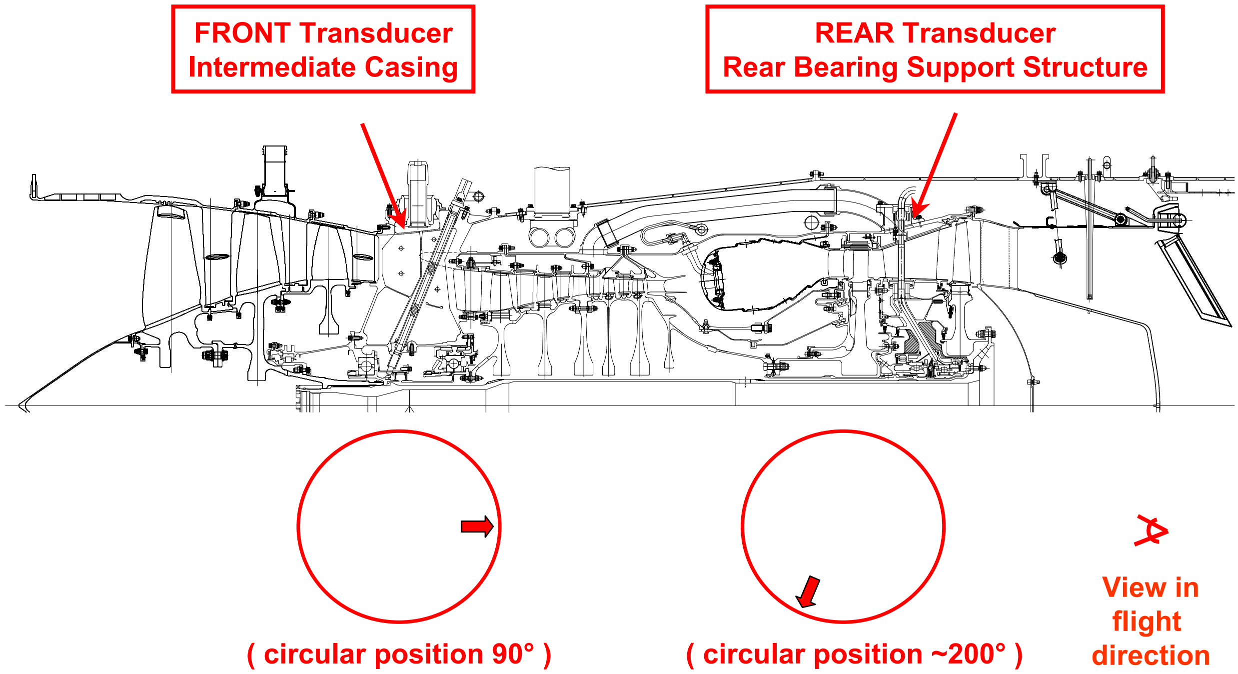


Figure 2: Vibration transducers attached to the EJ200 engine

Additionally, hardwired engine speed signals are provided from the Digital Engine Control Unit (DECU) to the EMU, see Figure 1. They are also conditioned by the EMU hardware. A number of values, like the current time for one revolution of the different spools, are generated, describing the rotor dynamics characteristics of the low pressure spool (NL) and the high pressure spool (NH). These values are then used for the generation of the vibration monitoring parameters.

The analysis of vibration related data is performed by the EMU during engine operation based upon a periodic timing cycle of 500 *ms* to collect and analyse the data. During each of these cycles two vibration sample sets in time domain are captured simultaneously, one for each vibration transducer.

These vibration sample sets correspond to individual speed bands (SB), characterised by defined NL speeds and NL speed changes with respect to the time (i.e. rpm/sec), and are the basis of the vibration monitoring function as illustrated in Figure 3.

There are 100 SB which are derived from the NL spool speed. SB 0 covers NL spool speeds up to 30% of the nominal NL speed, SB 99 covers NL spool speeds higher then 103% of the nominal NL speed, SB 1 to 98 are evenly distributed between the values corresponding to 30% and 103% of the nominal NL speed.

The SB corresponding to acceleration and deceleration conditions are processed and stored separately.

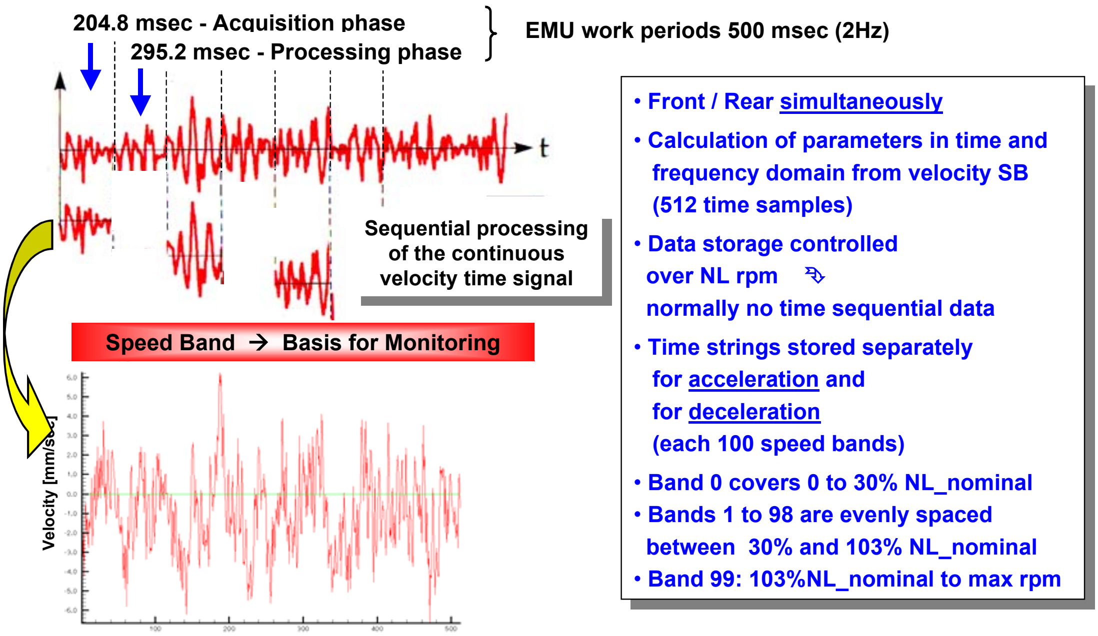


Figure 3: EMU work periods and data capture

The following vibration monitoring parameters (**derived amplitude values**) are generated from these vibration sample sets $g_{(n)}$ for the FRONT and REAR transducers:

- Amplitude values corresponding to the first order of the NL fundamental spool frequency, identified as **1EO NL**. The amplitude values are derived via Discrete Fourier transform (DFT) using a subset of N_{nl} samples of the entire sample set that corresponds to 10 complete revolutions of the NL spool according to the equations below

$$\text{1EO NL} = \sqrt{real\_part\_H_{(f)}{}^2 + imag\_part\_H_{(f)}{}^2} \tag{1}$$

$$real\_part\_H_{(f)} = \frac{2}{N} * \sum_{n=0}^{N-1} (g_{(n)} * \cos(2 * \pi * f * n / N)) \tag{2}$$

$$imag\_part\_H_{(f)} = \frac{2}{N} * \sum_{n=0}^{N-1} (g_{(n)} * \sin(2 * \pi * f * n / N)) \tag{3}$$

where
f is the number of NL complete cycles included in the time interval *N_nl * t*
t is the sampling period
N corresponds here to N_{nl}
$H_{(f)}$ is the vibration component associated to the low pressure spool rotational speed

- Amplitude values corresponding to the first order of the NH fundamental spool frequency, identified as **1EO NH**. The amplitude values are derived via DFT using a subset of N_{nh} samples of the entire sample set that corresponds to the number of completed revolutions of the NH spool for 10 NL spool revolutions during the recording of the sample subset.

In this case the equations (1) to (3) are applied considering for f the number of NH complete cycles included in the time interval $N\_nl * t$ and for N the corresponding number of samples N_{nh}

- Amplitude values corresponding to a programmable frequency, that is calculated from a programmable order of the NL spool frequency plus a programmable order of the NH spool frequency plus a fixed frequency, identified as **PROG.** The amplitudes are derived via DFT using the same subset as used for the calculation of the amplitude value for 1 EO NL.
- Overall broadband energy amplitudes for the front and rear transducers are calculated via a Root Mean Square (**RMS**) extraction algorithm using the complete sample set according to following equation

$$\mathrm{RMS} = \sqrt{\frac{1}{N} * \sum_{n=0}^{N-1} (g_{(n)}{}^{2})} \qquad (4)$$

- Residual Vibration Energy (**RVE**) amplitudes are calculated according to equation (5) by subtracting the DFT amplitudes for 1 EO NH, 1 EO NL and PROG from the corresponding RMS amplitude, that is the RMS value calculated under consideration of the same subset of samples which was used for generation of the DFT amplitudes, separately for FRONT and REAR. These amplitudes describe the energy content of the vibration signals in the observed time interval $N\_nl * t$ excluding the contribution of the 1 EO NL, 1 EO NH and PROG vibration components.

$$\mathrm{RVE} = \sqrt{\mathrm{RMS}_N^2 - 1/2 * (1\mathrm{EO\ NL}^2 + 1\mathrm{EO\ NH}^2 + \mathrm{PROG}^2)} \qquad (5)$$

The measured and derived vibration data are continuously monitored and stored to different data set stores controlled by specific overwrite criteria to download to the Ground Support System.

Using these monitoring parameters and associated data, the following tasks can be performed within the vibration monitoring system:

- vibration incident detection with subsequent indications and warnings
- vibration trend analysis and
- vibration diagnosis.

The following data sets are available within the EMU for the vibration monitoring functions:

- Vibration **Datum** store (Datum)
  This data set contains the reference vibration signature of the engine, describing the reference vibration characteristics of the engine captured, for instance, during the corresponding pass-off test. It consists of all derived amplitude values (1 EO NL, 1 EO NH, PROG, RVE and RMS) for both FRONT/REAR transducers and for each speed band under ACCEL/DECEL conditions. This data set is used for the generation of relative, engine specific limits for vibration incident detection.

- Vibration **Maximum Amplitude Per Run** store (MPR)
  The MPR store contains the derived amplitude values for FRONT and REAR transducers during acceleration and deceleration for all speed bands that have been operated during a single engine run. This data set includes the following additional parameters -ambient static pressure, aircraft acceleration along the normal axis (g_z), aircraft angular velocity about the normal axis (r), Mach number (Ma) and intake temperature (T2)- which describe the associated operational conditions. The structure of this data set is illustrated in Figure 4. The store is reset at the start of each engine run. During engine operation, the data for the different speed bands are overwritten and the MPR store records the highest achieved vibration levels for each speed band.

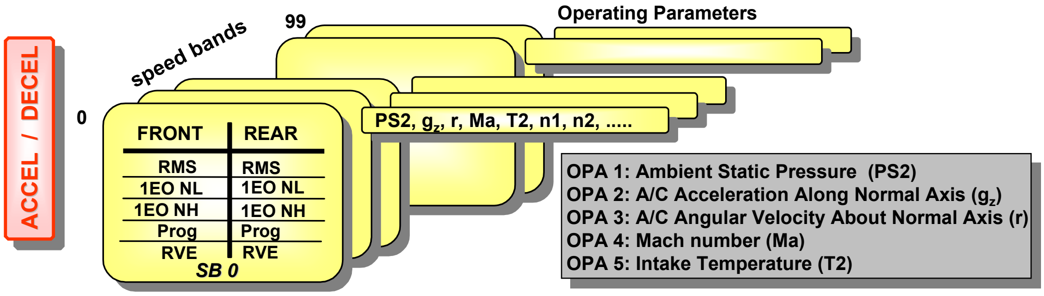


Figure 4: Max Per Run (MPR) → Incident detection and trend analysis

- Vibration **Maximum Amplitude Store** (MAS) in conjunction with Vibration **Time History Store** (THS).

  The MAS data set contains the maximal amplitudes of the different derived vibration parameters for the time interval since last EMU reset (data cumulated over several engine runs). The data for the different speed bands are overwritten, if no data have already been recorded for the corresponding speed band or if a weighting algorithm for the different amplitudes stored in the MAS indicates a higher vibration level for the new data than the previously stored data. Additional conditions for data overwrite are, that no surge is detected simultaneously and that the changing rate of the spool speeds related to the time (%NL/s) is within a defined range. This data set will be stored separately for accelerating and decelerating conditions.

  The THS contain measured velocity data sample sets for FRONT and REAR transducers in time domain for the different speed bands. The overwrite of these data sets is controlled by the overwrite criterion of the MAS data sets as described above. Figure 5 shows the structure of these data sets including the corresponding operational parameters.

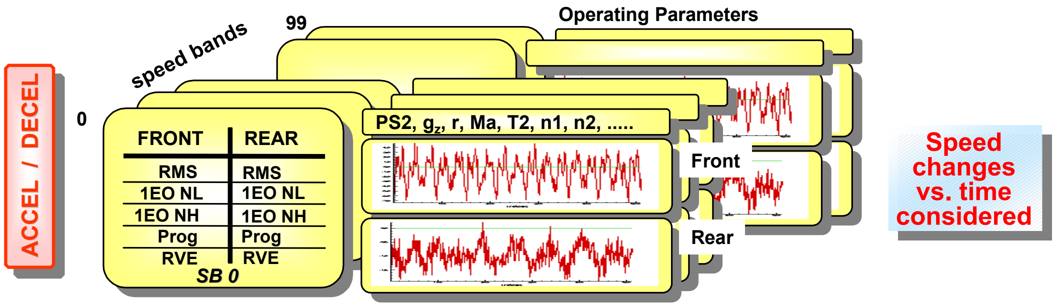


Figure 5: Max Amplitude Store (MAS) + Time Histories Store (THS) → Diagnosis

- **Vibration Incident Time History Store (VITHS)**
  VITHS contains continuously sampled, time based vibration velocity data for an specified period of time before and after a vibration incident has been detected. There are two VITHS in the data set. VITHS 1 is overwritten after the first vibration incident has been detected during engine operation. VITHS 2 is overwritten if a subsequent vibration incident has been detected, that is more severe than the first vibration incident and either the VITHS 2 is empty or the detected vibration incident is more severe than the incident already stored in VITHS 2.
- Vibration **Special Study Data (SSD)**
  SSD contains all the derived vibration parameters for the FRONT and REAR transducers stored continuously with respect to time with a frequency of 2 Hz. The corresponding operational parameters, stored partially with frequencies higher as 2 Hz, are also included in this data set.

With exception of VITHS and SSD, each of these data sets contains areas to store data for 100 speed bands separately for front and rear transducer data measured during acceleration and deceleration of the engine. A complete store therefore consists of data for 400 speed bands.

All of the data sets are tagged with status information (store status, transducer status, status of signal conditioning interfaces) and with operational parameters.

Vibration incident detection
In order to detect vibration incidents, each of the derived amplitude values is compared with a set of predetermined limits as shown in Figure 6.

Incident indications of different types are generated, depending on the limit exceeded:

- Cockpit warning:
  Warning to the pilot due to exceeding of an absolute vibration limit
- Maintenance warning:
  Warning to the ground crew due to exceeding of an absolute vibration limit, which is lower than the cockpit limit
- Relative maintenance warning:
  warning to the ground crew because the ratio between current vibration amplitudes and the Datum store engine vibration signature, which is specific for the current engine, exceeds a defined limit

Each of these warnings can be generated according to its duration in two different categories:

- steady state warning:
  limit exceeding longer than a defined time interval
- transient warning:
  limit exceeding within a defined time interval

Different limit values are used for both, transient and steady state warnings.

Additionally, each vibration warning (incident) is classified according to the actual flight manoeuvres (normal flight conditions or high g and/or gyro-loads). The cockpit warning signals are relayed via the DECU to the aircraft systems.

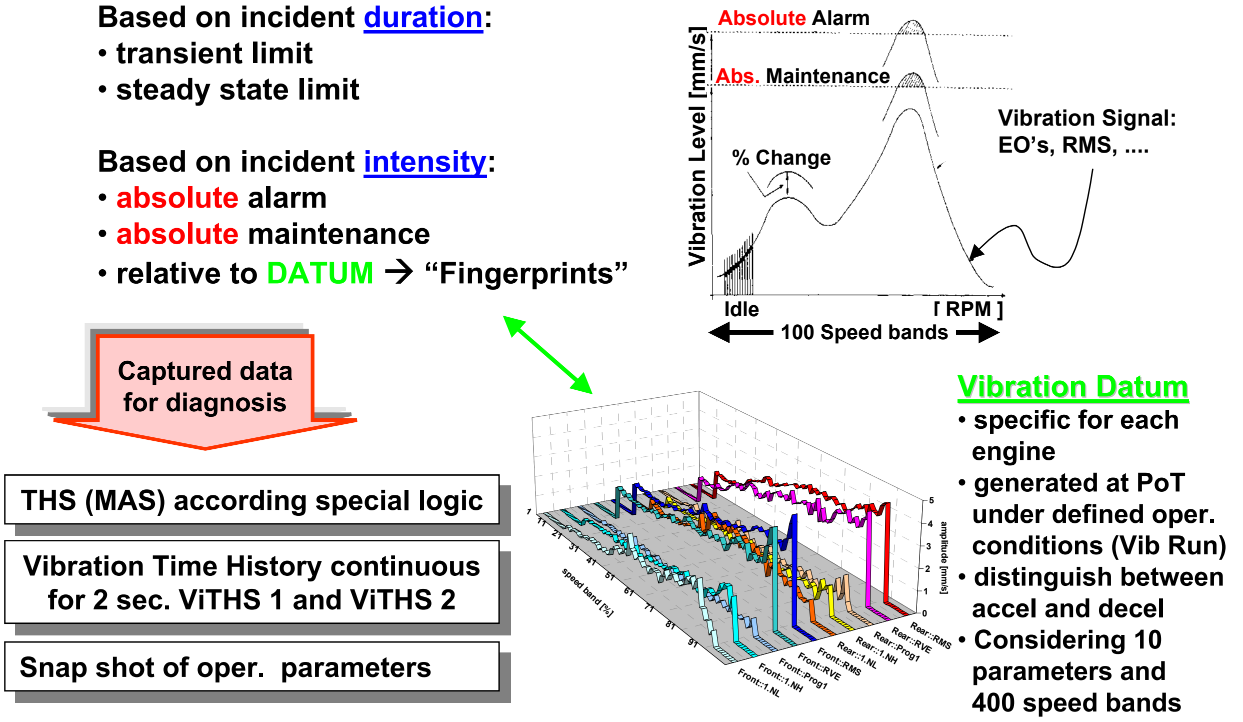


Figure 6: Concept for incident detection → Exceeding of vibration limits

Vibration trend analysis

Trend evaluations are performed to predict problems, preventing engine failure. The purpose of this analysis is to derive prognoses from downloaded data sets from a number of engine runs. The trending is carried out based on the observation of an overall increase or decrease of engine vibration levels. The data sets on which vibration trending is based are the Max Per Run (MPR), Maximum Amplitude Store (MAS) and Time History Store (THS). The current data is compared with the reference data and deviations are evaluated. A trending curve can be generated with regression techniques to predict when the engine will exceed allowable limits. The consideration of the associate operational parameters which describe the flight conditions is mandatory for vibration trend analysis, as the corresponding vibration amplitudes depend on these parameters.

Vibration diagnosis

The vibration data are transfer into the frequency domain using Discrete Fourier Transform, for tracked orders of engine spool speeds, and Fast Fourier Transform to obtain amplitude spectra in the frequency domain. For diagnosis purposes the use of waterfall plots is very useful. These diagrams are generated by arrangement of the different spectra with respect to the spool speed as shown in Figure 7.

Selected indicators, as for example changing of the engine orders, sub-harmonics, side-bands, fixed frequencies, resonances, jump ups / kick downs and noise floor, will be generated based on waterfall diagrams in order to create vibration patterns.

These vibration patterns are compared to a library of known vibration induced patterns obtained from typical engine fault situations. Therefore, identification of the cause of certain engine vibrations (i.e. a defect source) is supported.

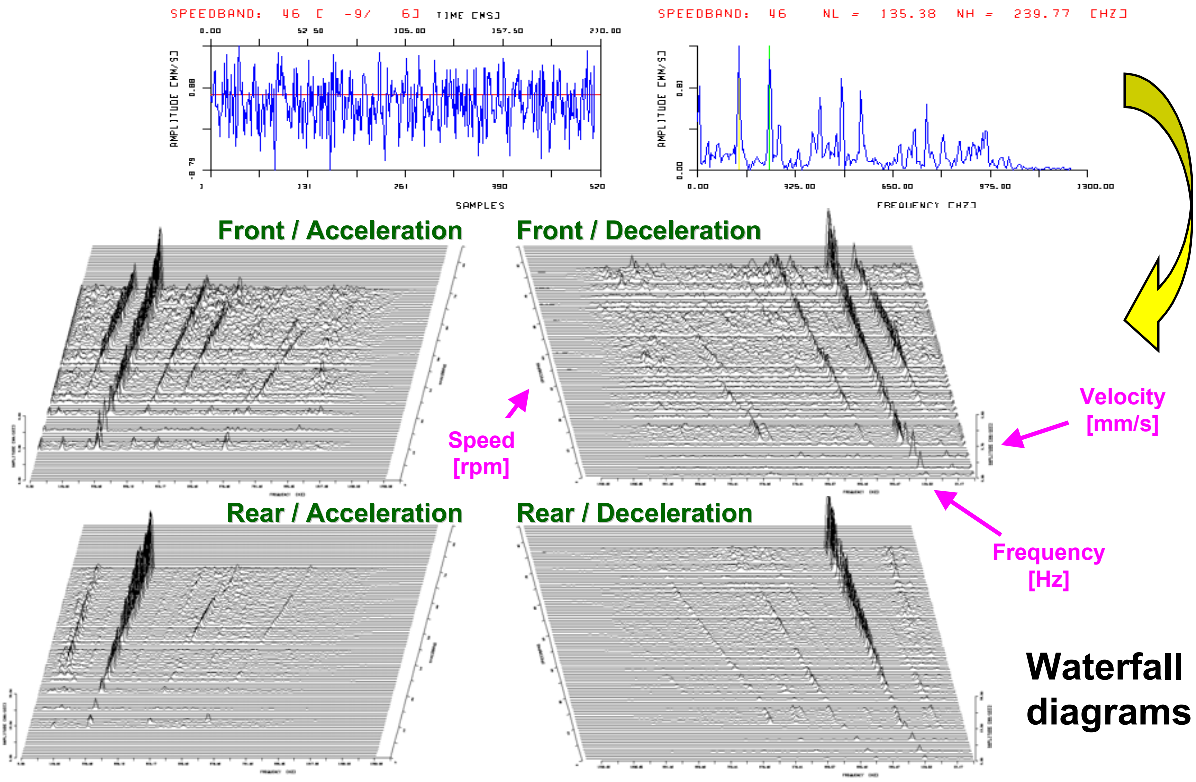


Figure 7: Transformation of the THS in the Frequency Domain Using FFT

Semi-automatic analysis is provided for pattern recognition by the vibration monitoring function presented here. This means, that the current vibration characteristics (pattern) are derived automatically from download data. A correlation analysis between the current pattern and the patterns in the library is performed, leading to a proposal of the most probable matching pattern.

The vibration data necessary for generation of patterns library are collected mainly on wing, at the different operating flight test centres, but also on the test-beds of the diverse companies involved in the production of the considered engine. Simulations of the transient mechanical engine response due to different excitations using very extensive 3D Models are also a substantial source of data for generation of vibration patterns, in particular by extreme or catastrophic situations.

Some mechanical faults which can be detected and diagnosed by this vibration monitoring system are:

- increased out of balance due to "normal" deterioration
- ice build up LP compressor blades under icing conditions
- aircraft buffeting
- excessive out of balance due to FOD, bird strike, blade loss
- instabilities due to malfunction of squeeze-films, rub, loose joints
- low bearing thrust
- misalignment due to internal distortions broken bearing support / mounting links

In particular the vibration monitoring system combined with an extensive 3D structural Finite Element Model of the whole engine is a very powerful tool for the evaluation and interpretation of the impact of vibration events on the mechanical integrity of the engine and its parts.

4 APPLICATIONS

In this section experience gained during the application of the presented vibration monitoring system on the EF2000 engine EJ200 will be presented and discussed. Only a sample of selected cases will be reported giving an impression of the flexibility and reliability of the system.

The initial set of three examples concentrates investigations related to the high pressure turbine (HPT). That means, it can be expected that high vibration parameters amplitudes mainly associated with the HPT (1.EO NH / REAR and RMS / REAR) will be detected, the remaining vibration parameters amplitudes will continue within the usual boundaries.

For the first two investigations the evolution of the vibration amplitudes signals with respect to time were analysed. Using this representation it was possible to identify and diagnose the vibration causes considering continuous changes of the amplitudes after reaching defined operational conditions.

Figure 8 shows an out of balance (OOB) occurrence on the HP turbine which can be identified by an increase of the amplitudes of the vibration parameters 1 EO NH and RMS captured with the rear transducer. It was noted that the vibration level started to increase at about 80% NH during acceleration from idle to max dry. At max dry the amplitude of the 1 EO NH is approx. 10 mm/s and increases continuously to a maximum value of 18 mm/s during an engine stabilisation period of 1-2 min. This cycle was repeated two times.

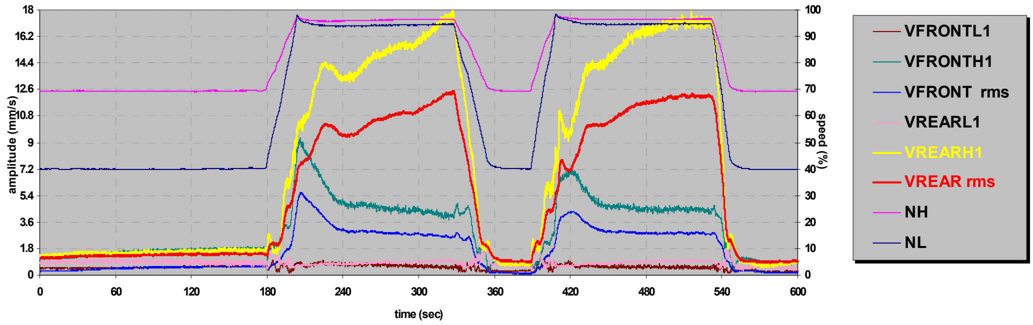


Figure 8: HPT out of balance – Case (a)

Analysis of the manufactured tolerances of the involved parts, shown in Figure 9, identified the cause of the vibrations to be as follows:

A heavy interference (top limit) on pos. 1 combined with a loose interference on pos. 2 (bottom limit) leads to loss of interference on pos. 2 during engine operation causing high unbalance, which increases with time at constant speed.

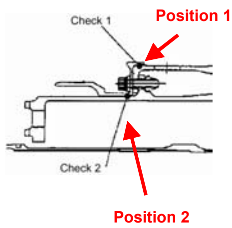


Figure 9: Vibration cause HPT case (a)

A similar investigation, case (b), was performed using a modified design of the involved parts shown in Figure 9 in order to compensate out of balance effects. The signals of the relevant vibration parameters in Figure 10 show also an increasing of the amplitudes. Reaching the rotor speed of about 80%NH the amplitudes of the 1 EO NH are about 7 mm/s in the first run and about 9 mm/s in the second run. The vibration level increases continuously up to max dry, 1 EO NH amplitudes of about 29 mm/s and 34 mm/s for the first respectively second run were achieved. A vibration step change is visible, the maximal amplitudes difference is approx. 17%. After reaching max dry the vibration level decreases continuously contrasting with the case above, and reaches values of about 18 mm/s respectively 21 mm/s after about 2 minutes of engine stabilisation.

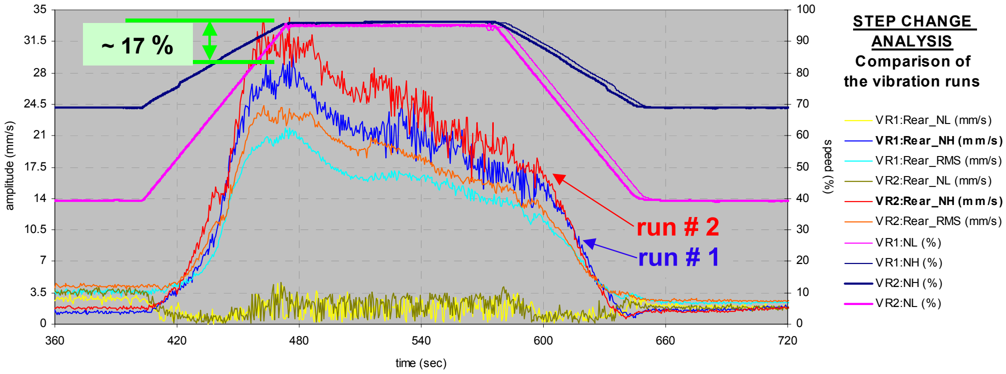


Figure 10: HPT out of balance – Case (b)

In this situation the cause of high vibration was identified as follows:

Similar to case (a), high unbalance resulting of loss of interference on pos. 2 is detected, but here other thermal effects related to additional masses (resulting of a balancing procedure) according to Figure 11 are identified. These effects compensate the high unbalance resulting of the loss of interference after some seconds of engine operation and the vibration level decreases continuously at constant speed.

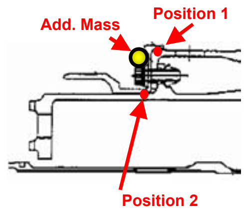


Figure 11: Vibration cause HPT case (b)

HP turbine blade deterioration also has a significant effect on vibration levels. Figure 12 shows max per run (MPR) data stored during vibration runs (slow acceleration – stabilisation – slow deceleration) over several engine runs. During early runs the amplitudes of the 1 EO NH / REAR reach maximum values of approx. 26 mm/s. During later runs the maximum amplitudes achieve approx. 37 mm/s, showing a vibration level increase of some 40%.

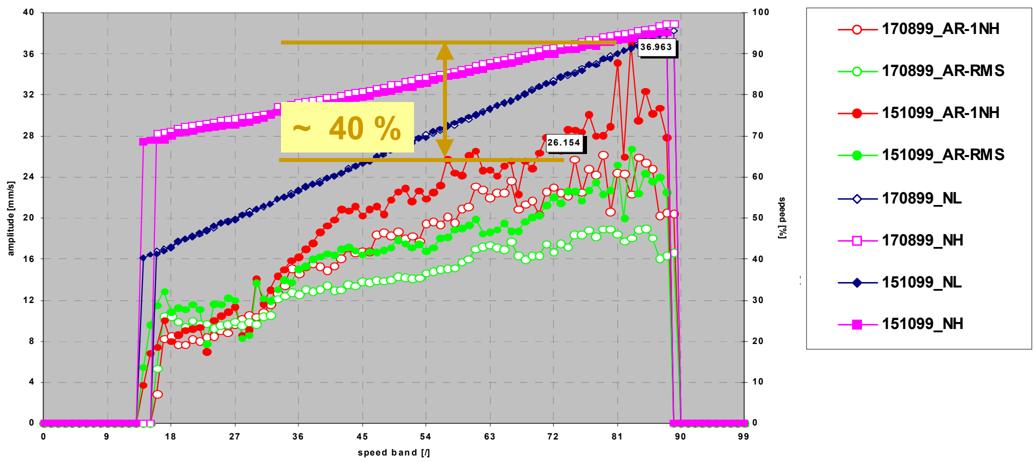


Figure 12: HPT out of balance – Case (c)

In this case the cause of high vibration levels was identified as follows:

Incremental deterioration of the tip of HPT blades due to a malfunction of the blade cooling system progressively increasing out of balance (and consequently vibration amplitudes) with time. Figure 13 illustrates a damaged HPT blade after test conclusion.

Figure 13: Vibration cause HPT case (c)

Vibration monitoring and investigation during icing tests showed high out of balance effects on the LP compressor rotor.

Figure 14 shows waterfall diagrams generated from the acceleration and deceleration vibration signals recorded during special icing tests. The corresponding four first engine orders (EO) associated with the LP rotor are exposed on the right hand part of the figure.

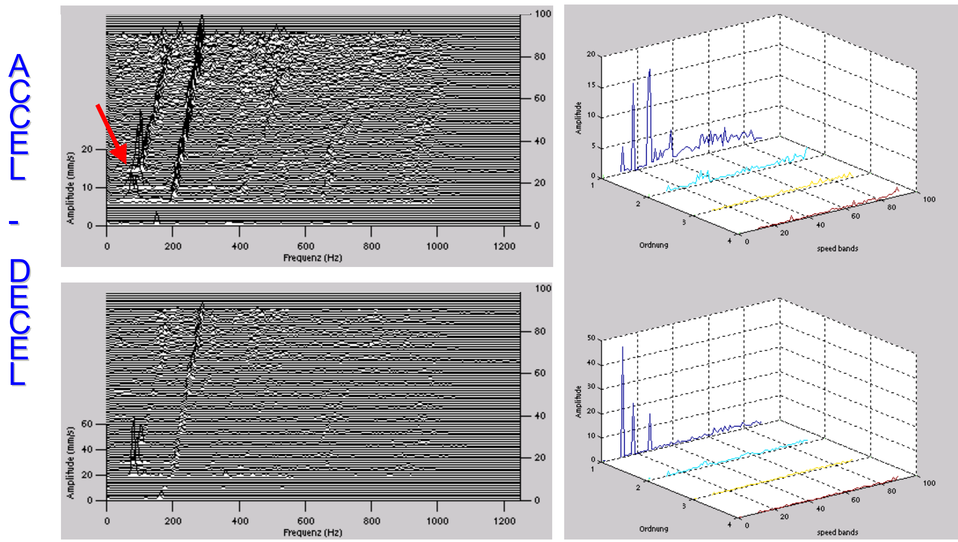


Figure 14: LPC out of balance due to ice build up

The amplitudes of the 1 EO NL near idle reach abnormally high values for both acceleration and deceleration conditions. These dominating amplitudes can be easily identified in the waterfall diagrams.

The THS corresponding to a selected acceleration speed band captured simultaneously for the FRONT and REAR transducers are plotted in Figure 15. The left hand side of the figure in the time domain and the right hand side in frequency domain.

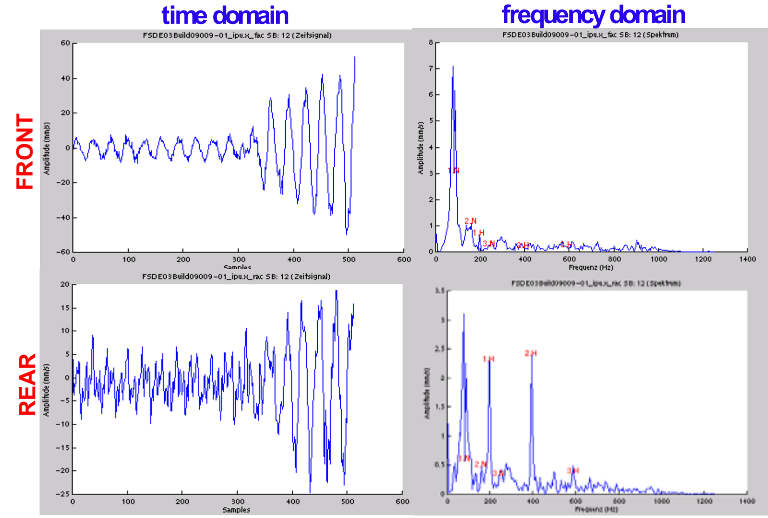


Figure 15: THS acceleration speed band 11 / FRONT and REAR transducers

The increase of the vibration level at a certain time results from the build up of a non-symmetric ice layer in the front stages of the LP rotor and consequently generates a high level of unbalance. After shedding of the ice layer the engine resumes an stable condition and the vibration levels of engine return to normal values.

To illustrate the use of the vibration time histories (VITHS) an example of surge investigation is exposed. Figure 16 shows different parameters versus time. At a selected operational condition (constant spool speeds), the nozzle throat area is continuously reduced in order to generate an engine surge with the corresponding increase of the vibration level and subsequent vibration incident detection.

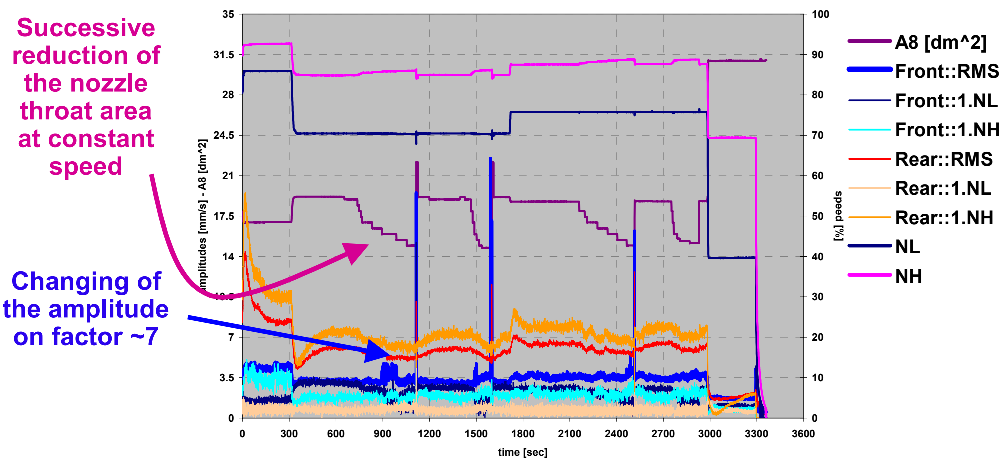


Figure 16: Engine surge due to continuous reduction of the nozzle throat area

The evaluation of the VITHS in Figure 17 shows maximal vibration velocities of approx. 95 mm/s p-p at the FRONT transducer. Moreover in a time period shorter then 1 second three impacts can be clearly identified.

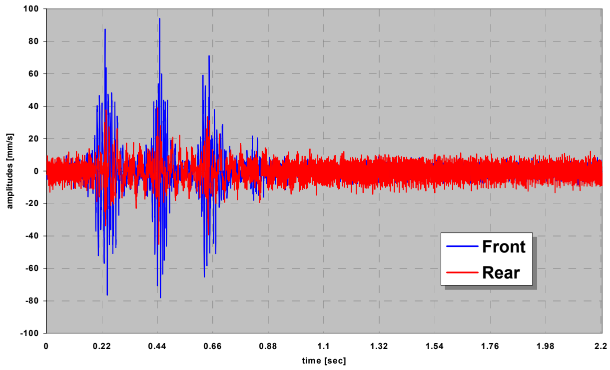
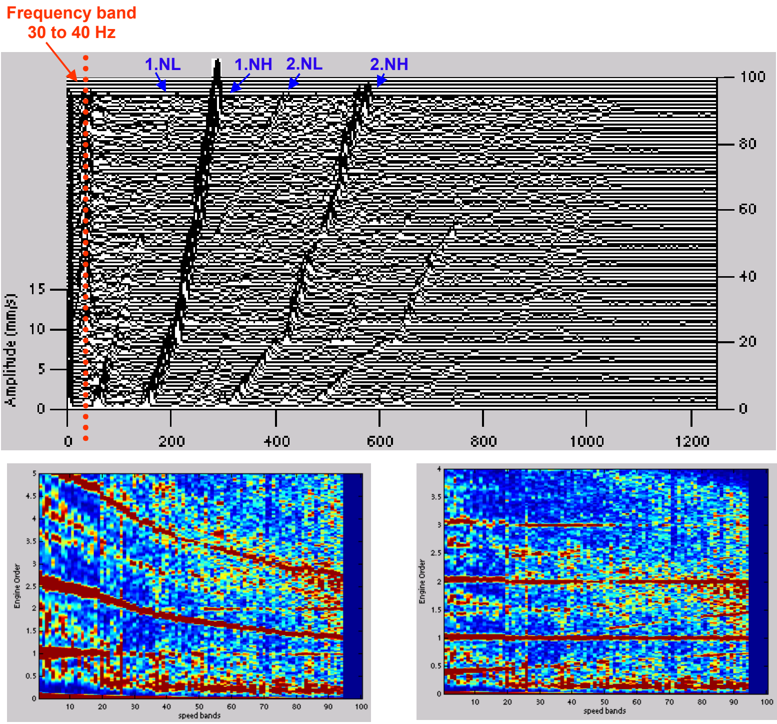


Figure 17: Surge analysis / Vibration Time History

The vibration monitoring system presented in this report also enables engine external excitations to be detected and analysed. The aircraft buffeting resulting of the application of the air brake is one such case. The engines are excited with a vibration component with a constant frequency of about 35 Hz independent on the speed of the rotors. The upper part of Figure 18 shows a waterfall diagram generated using the vibration time histories captured at the REAR transducer during decelerating conditions. In particular the first two EO of the HP rotor can be identified as well as high vibration amplitudes at a constant frequency band between 30 and 40 Hz. The same conclusions can be extracted using an order analysis as shown on the left hand lower part of Figure 18 for the LP orders and on the right hand lower part of the figure for the HP orders. Also here the constant vibration components are readily identifiable.

Due to air brake buffeting in the rear section of the core engine, high vibrations with amplitudes up to 3 mm p-p can be induced which, depending on the duration of the excitation, can be detrimental to the engine or to its parts.



Engine Order Analysis - NL -

Engine Order Analysis - NH -

Figure 18: Waterfall diagrams – Excitation due to air brake buffeting

The use of the vibration monitoring system presented in this report in combination with an extensive 3D structural Finite Element Model of the whole engine represents a powerful tool for a detailed analysis and evaluation of the mechanical impact of vibrations to the condition of the engine and its components in terms of displacements and stresses as well as for diagnosis of the causes of vibration.

5 CONCLUSIONS AND OUTLOOK

The capabilities of the vibration monitoring and diagnosis system presented in this report to satisfy the requirements:

- increased safety by identification of dangerous vibration conditions at all engine speeds and thrusts, including steady state and transient operation and through the generation of the corresponding cockpit warning,
- avoidance of major secondary damage by way of early failure identification,
- reduction of maintenance expenditure through isolation, localisation and diagnosis of the vibration causes and
- optimisation of maintenance by means of consideration of the current engine condition.

are being demonstrated during the first phase of application.

The initial findings are favourable with respect to the quality of the signals, the philosophy for vibration incidents detection and the logic for storage of the different vibration data sets. The diagnostics and prognostics facilities currently developed will be extended, improved and automated by the use of artificial intelligence for pattern recognition. Additional data will be collected during further applications of the VMS to continue these efforts and to determine the cost and performance benefits.

RNLAF/F-16 LOADS AND USAGE MONITORING/MANAGEMENT PROGRAM

Authors F.C. te Winkel, D.J. Spiekhout
Structures and Materials Division
National Aerospace Laboratory NLR
P.O. Box 153, 8300 AD Emmeloord
The Netherlands

0. SUMMARY

Structural load monitoring of the RNLAF/F-16 fleet is carried out by NLR as a routine program since the early nineties.

A more sophisticated electronic device capable of in flight data reduction of a strain gage signal replaced the ex factory mechanical strain recorder. A representative sample of each squadron was instrumented and final results were extrapolated to each individual aircraft to gain insight in the severity of operational usage. Later hardware upgrades made it possible to record some flight and engine parameters as well.

In recent years a completely new monitoring system has been developed. Main features are an increase to five strain gage locations, a flexible selection of flight, engine, and avionics parameters available via the MUX-BUS and fleetwide implementation. A relational database was developed for storing, managing and processing the raw measured data combined with flight operational data obtained from the RNLAF computerized maintenance/debriefing system.

Most recently the resulting fleet management information for the end users by means of an interactive interface becomes feasible.

1. INTRODUCTION

Load monitoring on the F-16 fleet of the Royal Netherlands Air Force (RNLAF) has been performed since the introduction of the aircraft in 1979. Through the years several monitoring systems were used. However, the main load parameter monitored was the strain measured at one of the major carry through bulkheads in the centre fuselage (figure 1). The strain at this location is an accurate measure for the wing root bending moment, which is a representative figure for the operational loads and can therefore be used as an indicator for the usage severity.

The original on-board load monitoring device evolved from a relative "simple" mechanical strain recorder to the advanced FACE system nowadays. Main features are the increase to five strain gage locations, a flexible selection of flight, engine, and avionics parameters available via the MUX-BUS and in-flight data reduction. Along with the development of the load monitoring equipment itself it was decided that for the second half of the operational life of the RNLAF F-16 fleet fleetwide implementation of the FACE system would be favourable. In chapter 2 a brief overview of this development and a description of the FACE instrumentation package will be given.

Switching over from a sample load monitoring program to fleetwide individual load monitoring combined with the flexible way of measuring a wide range of additional flight parameters required a different approach of handling the data. This resulted in a tailor made information system built by NLR for storing managing, analyzing the collected measured flight data (MFD) with the on-board FACE system together with the administrative flight data (AFD) from each aircraft obtained from the RNLAF computerized maintenance/debriefing system CAMS. By making use of such a centralized information system efficient data handling is achieved. As well as for ad hoc analysis as for generating routine status reports for fleet management purposes. Recently the resulting fleet management information by means of an interactive interface with the use of the OLAP-tool (On-Line Analytical Processing) PowerPlay is becoming feasible. In chapter 3, the load monitoring program and information system will be described in more detail.

2. LOADS AND USAGE MONITORING INSTRUMENTATION

2.1 Overview development instrumentation

The first F-16 was introduced into the RNLAF in 1979. From the very beginning loads and usage monitoring has been taken care of. For this purpose a sample of the fleet was ex factory instrumented with a Flight Loads Recorder (FLR) for Loads Environment Spectrum Survey (L/ESS) recordings and a Mechanical Strain Recorder (MSR) was installed on each aircraft for individual aircraft tracking (IAT). The results however were not very satisfactory in terms of reliability and quality. Together with long turn around times, cassettes of both the systems had to be read out by the USAF, it was inevitable to abandon this way of loads and usage monitoring.

After the first update of the Fleet Structural Maintenance Plan (FSMP) for which L/ESS data was recorded with the FLR in 1985, the FLR was completely removed from the fleet. Note that by doing so the RNLAF had no L/ESS capability anymore. For replacing the MSR, the RNLAF and NLR decided that it should be replaced by a full strain gage bridge at the same location as the MSR (FS325) and to do this only on a (representative) sample of the fleet. Also a choice had to be made for the on-board electronic device. Selected was an instrument capable of recording the strain gage signal according to the peak-and-trough data reduction algorithm. The Spectrapot system produced by Spectralab in Switzerland was chosen for this purpose. In 1994 the one channel version of the Spectrapot was replaced by a four-channel version through which a limited L/ESS capability was obtained. This meant that besides the strain at FS325 also speed, altitude and vertical acceleration or engine RPM was recorded.
Within each squadron three to four aircraft were continually equipped and in total ten aircraft had “provisions for” to fly with a Spectrapot. This was necessary to keep the number of measured flights on an acceptable level in case of long time maintenance.

When in 1994 the updated 4-channel version of the Spectrapot was introduced it was already clear that this would and should only be a temporary solution. Since 1990 serious exchanges of views between the RNLAF and NLR took place about what would be the most favourable load monitoring program for the second half of the operational life of the F-16 fleet.

Two major modification projects were foreseen, Falcon Up and the Mid Life Update (MLU). The Falcon Up project is mainly a structural modification of the four main carry through bulkheads whereas MLU is basically an avionics upgrade of the aircraft. As a result of the structural upgrade it was expected that the mid fuselage section would give less fatigue problems in the future. Consequently, other parts of the structure would become fatigue critical. The main indicator for the loading experience of the aircraft, the strain gage bridge at main bulkhead FS 325, would therefore not be sufficient enough for monitoring the fatigue experience in other parts of the aircraft like outer wing, fuselage and stabilizers. Moreover some fatigue cracks were already found in these other parts. It was concluded that an increase of the number of strain gage bridges would be needed.
The number of strain gages is increased to five in the current program. Besides the strain gage on carry through bulkhead at FS 325, strain gage bridges are located at the lower skin of the outer wing at BL 120, at the keelson in the centre fuselage at FS 374, at one of the aft fuselage bulkheads at FS 479 and at one of the attach fittings of the vertical tail at FS 462, see figure 3.
A special measuring program was carried out with two instrumented aircraft. During 330 operational flights the signals of ten strain gage bridges were recorded and analyzed. The locations of these ten bridges were chosen in close co-operation with LM Aero.

One of the basic assumptions for the sample program was that aircraft in the same squadron flew more or less the same mission mix. This was certainly true for the first years of operation of the RNLAF F-16. In later years aircraft started to switch more often from squadron to squadron and the number of "out of area operations" increased with a significant difference in usage and loading experience. It was obvious that a sample program would not be sufficient enough and the decision was taken to go for a fleetwide implementation of a load monitoring system.

In that same period the RNLAF was also looking for an independent pilot debriefing system. RADA Electronic Industries in Israel could offer their Autonomous Air Combat Evaluation System (ACE) to do this task. The ACE system compiles a relevant selection of flight data from the aircraft's MUX-BUS and inserts these onto the airborne video system. A ground station capable of handling a maximum of a large number of tapes synchronizes the data offering a graphic and a video replay of the flight manoeuvres for debriefing and evaluation.
During test flights carried out with the ACE system in 1993 the idea came up to investigate the possibility of combining the autonomous debriefing system with the need for a new extended load monitoring system. NLR was contracted to specify the requirements for the "Fatigue Analyzing" part of the combined system and to codevelop with RADA the so to be called Fatigue Analyzer & Air Combat Evaluation system (FACE). A testflight carried out in 1994 showed that it was indeed possible to combine the pilot debriefing and load monitoring function. In 1995 the RNLAF signed the contract to implement the FACE system fleetwide and shortly after the first test flights took place. During this development and test phase close contact was kept with Lockheed Martin to ensure a proper installation of the FACE system. Special

attention was given to the connection with the MUX-BUS, hard- and software and the wiring for the MLU configuration. The first operational flight with the FACE system took place in 1997. At this moment about 80% of the fleet is instrumented with FACE.

2.2 FACE instrumentation

As mentioned before the FACE system combines the pilot debriefing and the load/usage monitoring function. The combined airborne part consists of four components:

- Flight Monitoring Unit (FMU)
- Data Recording Unit (DRU)
- Data Recording Cartridge (DRC)
- Strain Gage Amplifiers

On the ground both functions are completely separated. At each squadron two ground stations are located. The Operational Debriefing Station (ODS) offering the pilots a synchronized graphic and video replay and a PC-based Logistic Debriefing Station (LDS). The LDS offers readout of the flight recorded data from the DRC (after every 10 flight hours nowadays), storage of flight data and Setup Configurations Files for the airborne FMU (figure 4).

The FMU collects data from a number of data sources (figure 5) depending on the loaded Setup Configuration File (SCF). The SCF dictates which processes/signals are to be measured, which data reduction algorithms have to be used and onto which storage devices the results finally are to be recorded:

- *input:*
  The FMU can interface with MUX-BUS channels as a monitor, analogues, discretes and serial channels. Via the MUX-BUS channels data like flight parameters, attitude, accelerations and store configuration are available to record. For engine monitoring data is required from the Digital Electronic Engine Controller/Engine Diagnostic Unit (DEEC/EDU) which are made available via the MUX-BUS. In this way all digital engine data can be recorded, such as RPM, pressures and temperatures. Both, MUX-BUS channels and DEEC/EDU handle in total a few hundred of signals. The strain gage signals for load monitoring are an example of analogue input. In total 15 analogue input signals can be monitored if required. Further some discrete values are monitored. The last group of input signals into the FMU are the video signals for debriefing purposes

- *output:*
  Three types of output devices can be distinguished. The Data Recording Cartridge (DRC) which is used for collecting the data for loads and usage monitoring of the airframe and the engine. Nowadays every 10 flight hours a cartridge is changed. A Video tape is used for debriefing and mission evaluation. Additional data from the MUX-BUS channels is written onto the tape for the ODS to produce a graphic display of the actual flight. Video tapes are normally removed after each flight. As a third storage device the Voice

And Data Recorder (VADR) will be installed. The VADR will only be used for mishap investigation. It remains on-board and recorded data is cyclic overwritten.

In the FMU a choice has to be made which signals are to be monitored and which data reduction algorithm is to be used for those selected signals. For this purpose an input file, the so called Setup Configuration File (SCF), is uploaded into the FMU. An SCF can easily be generated on the LDS via a user friendly interface. Next step is to upload the SCF into the FMU with a Software Load Data Recording Cartridge (SLDRC). If no new SCF is uploaded the FMU uses the resident SCF.
Up to a total of 15 processes can be specified which are monitored simultaneously. A master and a number of slaved signals define a process. Per master signal a maximum of 50 slaved signals can be selected. In total 200 master/slave combinations are possible.

For each process a suitable, depending on the specific usage of the recorded data, data reduction algorithm has to be selected. Three main types of data reduction algorithms are possible:

- *Peak And Trough (PAT):*
  The PAT algorithm searches the master signal for peaks and troughs. A specified range filter is used to filter out small cycles. In this way only cycles which are of importance for fatigue are stored in their actual sequence (figure 6). This algorithm is used for all the strain gage signals.

- *Time At Level (TAL):*
  In the TAL algorithm crossings of specified levels are recorded in their actual sequence (figure 7). Up to 100 levels can be specified. As a result the time spent between two levels can be calculated. For example, the use of the after burner during a flight. Note that no slaved signals are possible with this algorithm.

- *SAMPLE:*
  The SAMPLE algorithm gives the possibility of a constant sample rate by skipping a number of samples in the master signal before the next recording takes place. At the moment of recording a sample of the master signal the slaved signals are recorded as well (figure 8).

One has to bear in mind that the available sample rates for the different signals in the aircraft is not the same. On the MUX-BUS channels the highest sample rate of a signal available is 50 Hz. This for example is the case for accelerations and roll-, pitch- and yaw-rates. DEEC signals however are at the most sampled with 4 Hz.
For the analogue signals the highest sample rate possible is 1000 Hz which is used for the strain gage signals.

Data reduction is further possible by selecting the flight mode: ALL, AIR or GROUND during which the recording should take place. Also a time slot during a flight can be specified or a combination of two signals with a specified range for both signals. For example: only record if the Mach number is between 0.8 and 0.9 and if the altitude is between 500 an 1000 ft.

Taking the above mentioned into consideration it should be clear that every RNLAF F-16 instrumented with the FACE system can more or less be used as a fully instrumented test aircraft. And that besides for the airframe and the engine a lot of data can be made available for health monitoring of the avionics systems.

3. F-16 MONITORING PROGRAM AND INFORMATION SYSTEM

Load monitoring of the F-16 fleet of the RNLAF is carried out as a routine program by the National Aerospace Laboratory (NLR) since 1990 when the Spectrapot capable of processing in flight the signal of a strain gage bridge replaced the previous Mechanical Strain Recorder. In both cases the direct strain measured at main carry through bulkhead FS 325 is representative for the wing root bending moment.

At the time, the F-16 fleet was monitored on a sample basis. The information gathered with three to four aircraft per squadron was thought to be representative for the loads and usage experience of that squadron assuming that all aircraft belonging to a specific squadron flew more or less the same mission mix. Additional operational flight administrative data such as flight duration, mission type and external store configuration were taken from a special debriefing form and since 1995 directly extracted from the Core Automated Maintenance System (CAMS) of the RNLAF. Combining the load data from the sample measuring load program and the CAMS data from all F-16 flights it was possible to provide the RNLAF information on the experienced load severity per tail number. From the sample measuring program the severity per mission type, per squadron and per time period is available. By combining this information with the actual mission mix per individual tail number for the same period an individual damage indication can be calculated.

As a damage indicator, the Crack Severity Index (CSI) is in use. This CSI, developed by NLR, is a relative figure: for the F-16 a value of 1.0 means fatigue damage according to the reference usage and loading environment used to generate the current inspection schedule (Fleet Structural Maintenance Plan FSMP). The CSI method takes into account interaction effects between large and small load cycles (or between severe and mild flights). The fatigue damage of a flight is therefore dependent on the severity of the flights flown before.

At first glance one could say that an upscaling of the sample load monitoring program took place; an increase of one to five strain gage bridge locations and fleetwide implementation. However as discussed in chapter 2, the FACE system is fully integrated with other aircraft systems through which by far more flight parameters for airframe , engine and avionics monitoring are available. Moreover the set of measured parameters is not a fixed set, but can easily be changed via the Setup Configuration File (SCF). Figure 9 shows the default SCF used for airframe- and engine monitoring.

In order to cope with the large amount of loads and usage data a drastic change had to be made in collecting, storing and analyzing in comparison with the sample program with a fixed selected set of measured parameters and number of instrumented aircraft. The whole process of data handling has been automated to a large extent. Every night read out measured flight data from one squadron, collected from the Data Recording Cartridges (DRCs) at the squadron's logistic debriefing station (LDS), is automatically sent to NLR. Once a week the relevant operational flight administrative data of all flights is directly extracted from CAMS. Special care has been taken to ensure "secure" data communication.

For storing, managing and processing the recorded raw measured FACE and CAMS administrative data NLR built a tailor made database application with the Oracle relational database package. In the design of the database special attention was given to the flexible way of FACE's handling of a large amount of different signals which was a base requirement for the database as well. Before storing the actual data a large number of checks is performed. Next recorded flights (FACE) are linked to realized flights (CAMS). One must realise that the number of recorded flights will always be less than the number of realized flights even after fleetwide implementation. A 100% data capture is an illusion. It is inevitable that sensors break down, memory cartridges lose data, wiring problems occur etc. Besides the real loss of data it may take a while before actual recorded data becomes available. Initially a DRC was only changed after 25 flying hours, which meant a delay of several weeks in processing the data. Nowadays the DRC is changed after 10 flying hours.

The database became operational with a limited functionality end 2000. In the base functionality <u>all</u> recorded FACE data is stored together with the operational flight administrative data and automatic calculation of the damage severity indicator CSI per tail number for strain gage location FS 325 is implemented. This is done according the sample program methodology since not all aircraft are equipped yet though the number of used measured flights is significant higher and still increasing. For the remaining four strain gage locations discussions with LM Aero are still going on about correct determination of the reference load sequences, which are needed to calculate the correct CSI for these locations. As mentioned before the CSI is a relative figure between the <u>actual</u> measured and the <u>reference</u> usage and loading environment that was used as input by LM Aero for generating the current inspection schedule. Therefore the CSI can be used as an indicative measure for ASIP (Aircraft Structural Integrity Pogram) control points.

Making the measured loads and usage data in combination with the flight operational data easy accessible for routine and ad hoc analysis is one. Another base requirement of the database is that routine status reports for the RNLAF for fleet management purposes should be made available in an “on line” interactive form on a weekly basis. For this specific purpose use is made of the so-called OLAP-tool PowerPlay (On Line Analytical Processing). Characteristic for these kind of tools is the possibility of presenting different sets of results at different levels to the end users, for example air staff, air force bases and squadrons. The end user has the possibility to carry out a limited analysis of the final results to find out why a change took place in for example the usage severity by simply “drilling through” the data. In 2001 a pilot project has started with the RNLAF air staff in presenting the results in such a way for replacing the “old” routine CSI status reports. During this start up phase it has already become clear that in the near future more results will be presented via this way. NLR and the RNLAF discuss on a regular basis how to fully exploit these possibilities for fleet management support.

For the routine engine monitoring program the F-16 Loads and Usage Monitoring Information System functions as the data source for the measured engine parameters and operational flight data. Processing the signals and calculation of the usage severity results done with separate software tools developed at NLR.

4. CONCLUDING REMARKS AND WHAT'S NEXT

- An overview has been presented of the development of the loads and usage monitoring instrumentation for the F-16 of the RNLAF from the ex factory FLR and MSR to the advanced fully integrated FACE system.
- The change from sample based monitoring to fleetwide individual monitoring with FACE has been described and the impact this had on managing, storing data and making final results available.
- As soon as the proper reference load sequences for the remaining four strain gages are released by LM Aero 5 damage severity indicators per aircraft will be presented (indicative for about 40 ASIP control points).
- On short term a switch will be made from the "sample load monitoring methodology" to use of individual measured per aircraft. A "gap filling" procedure is still needed for replacing lost or not yet available data of the flights concerned.
- During the second half of this year a start will be made with collecting new L/ESS recordings for a new update of the Fleet Structural Maintenance Plan by making use of FACE.
- For engine monitoring more detailed recordings are planned and engine results will also be made available via the F-16 Loads and Usage Monitoring Information System.

5. REFERENCES

1. Ottens, H.H., Spiekhout, D.J., Prognosis and Health Management, Air Focus, Summer 2001.
2. Spiekhout, D.J., Loads/Usage Monitoring, RTO Meeting Proceedings RTO-MP-7, Exploitation of Structural Loads/Health Data for Reduced Life Cycle Costs, Brussels, Belgium, May 1998.
3. Spiekhout, D.J., Load Monitoring of F-16 Aircraft of the RNLAF with a Smart Electronic Device, AGARD Conference Proceedings CP-506, Fatigue Management, Bath, United Kingdom, May 1991.

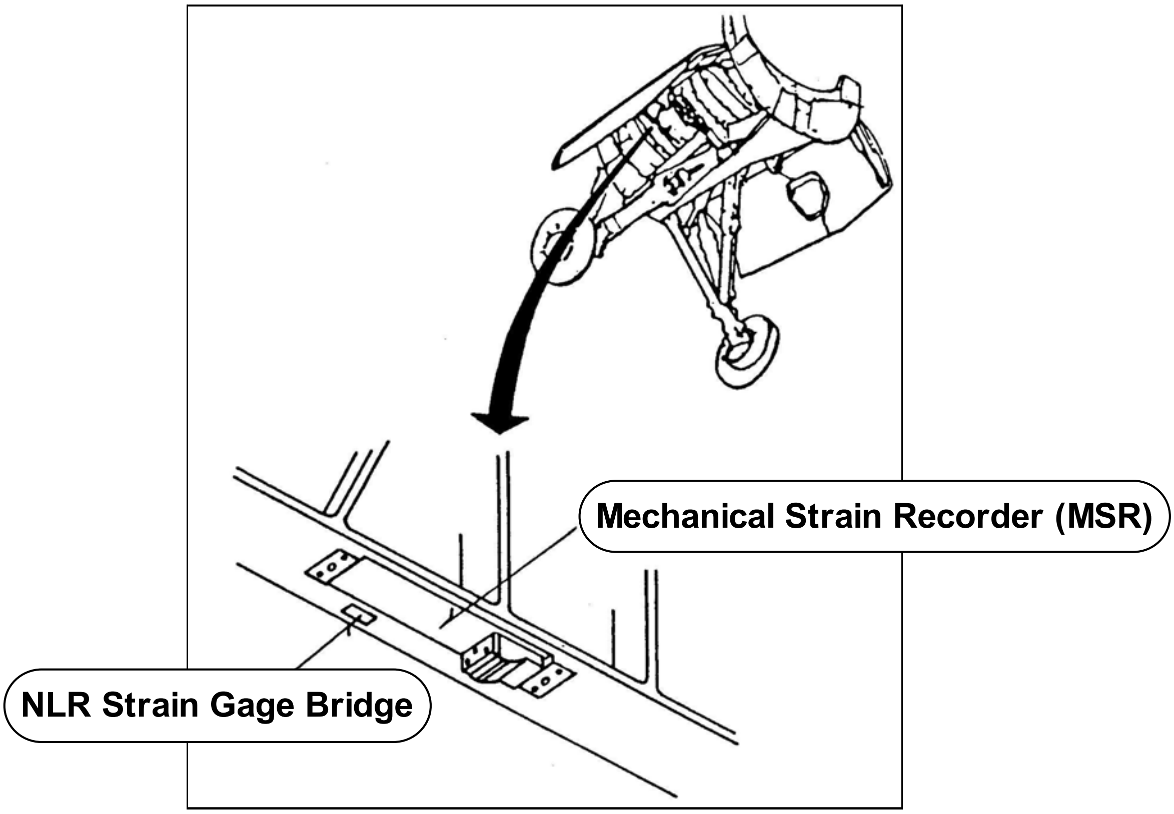


Figure 1: Strain gage bridge and MSR location FS 325.8

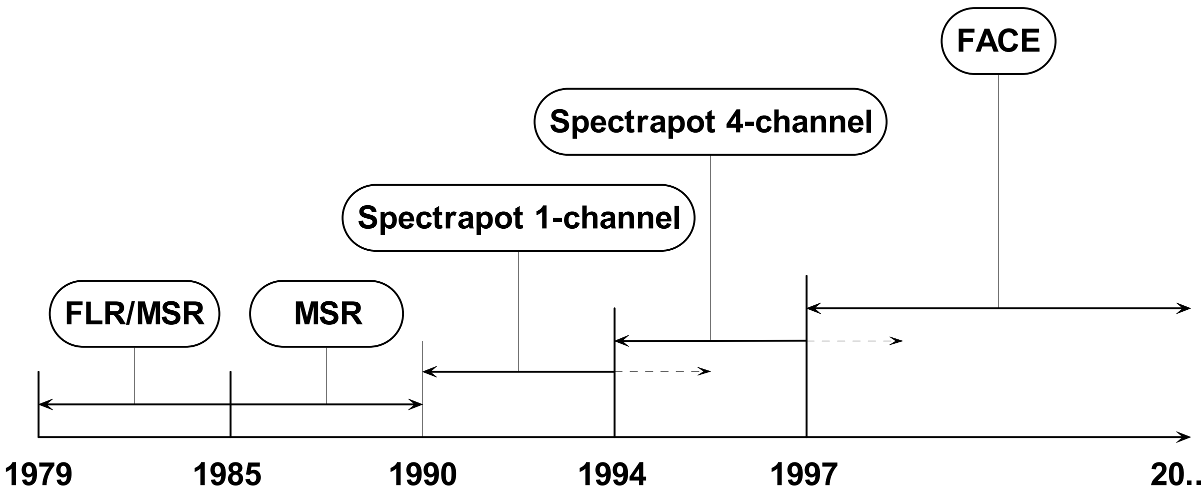


Figure 2: Timeline monitoring instrumentation trhough the years

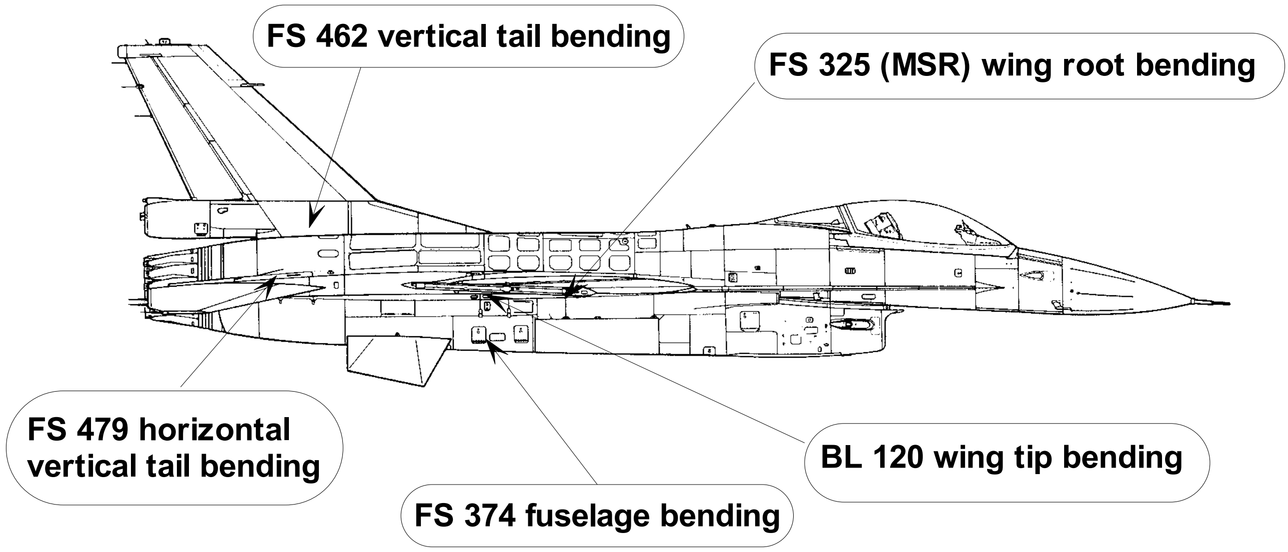


Figure 3: Strain gage bridge locations

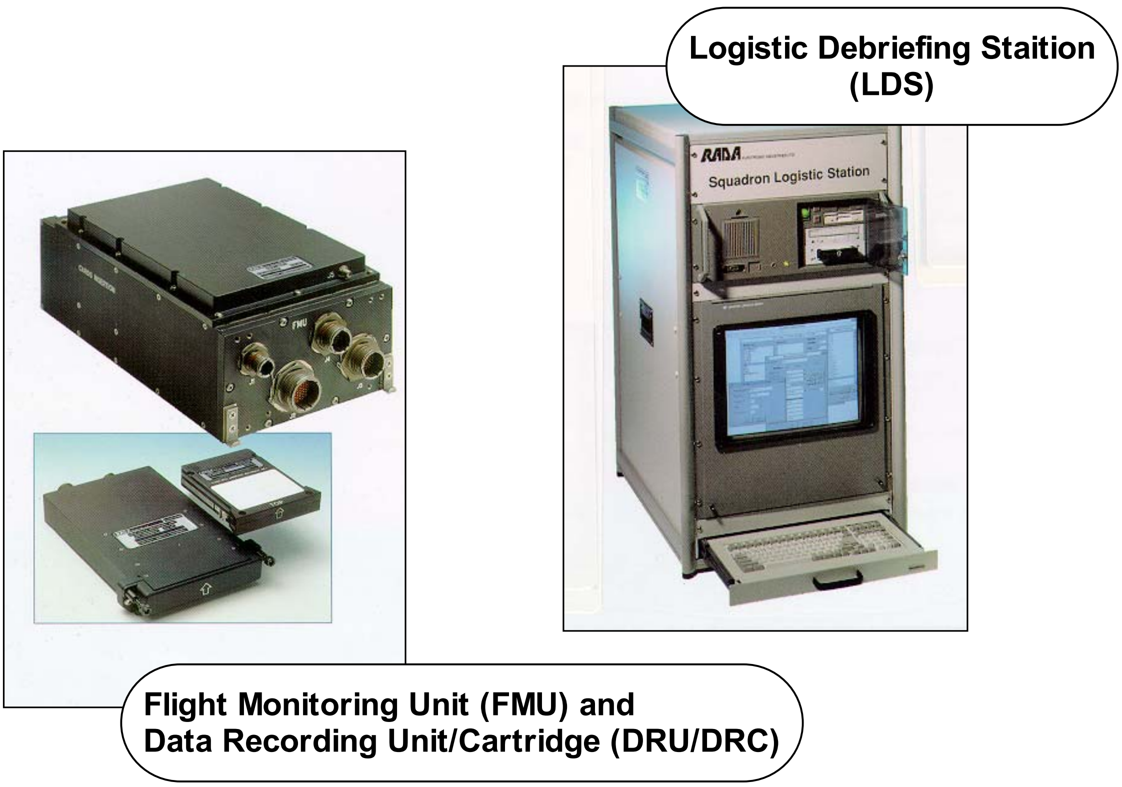


Figure 4: FMU, DRU/DRC, and LDS

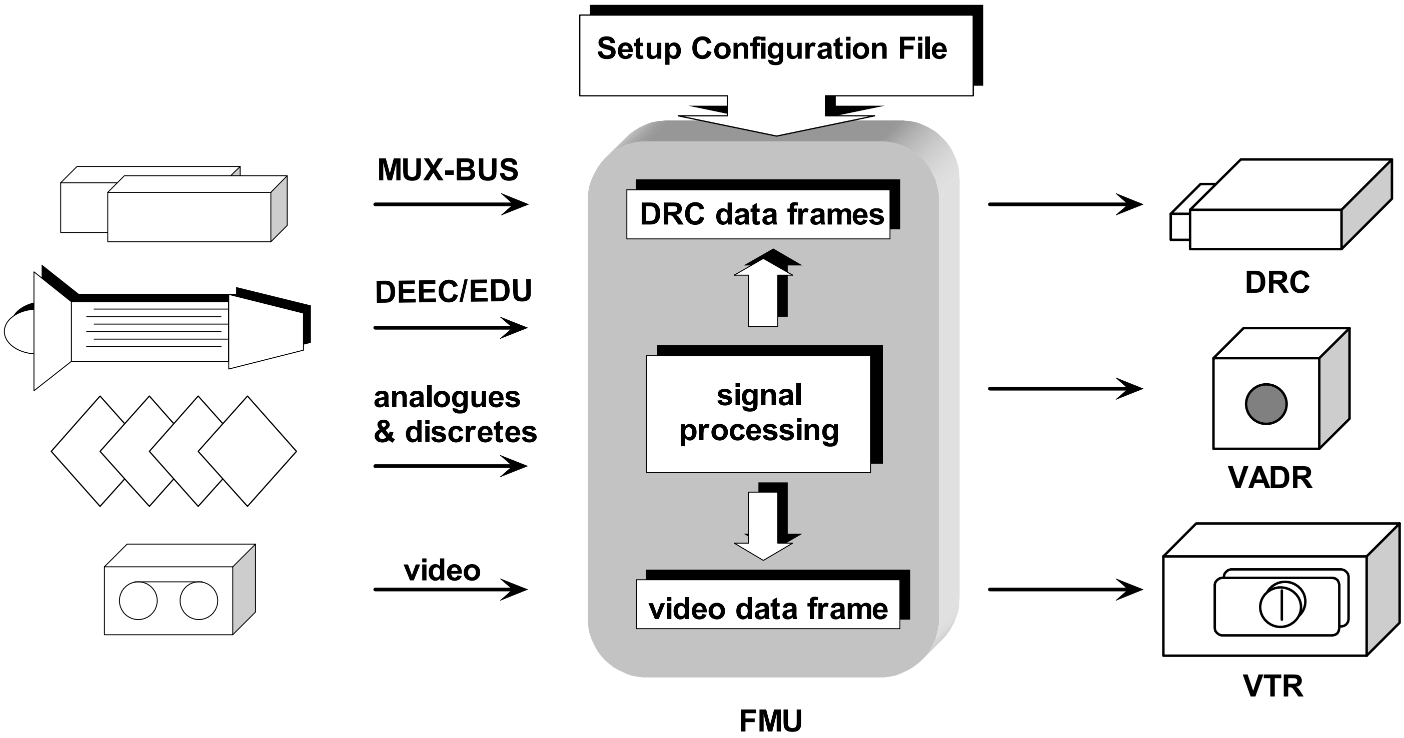


Figure 5: Schematic overview FACE system structure

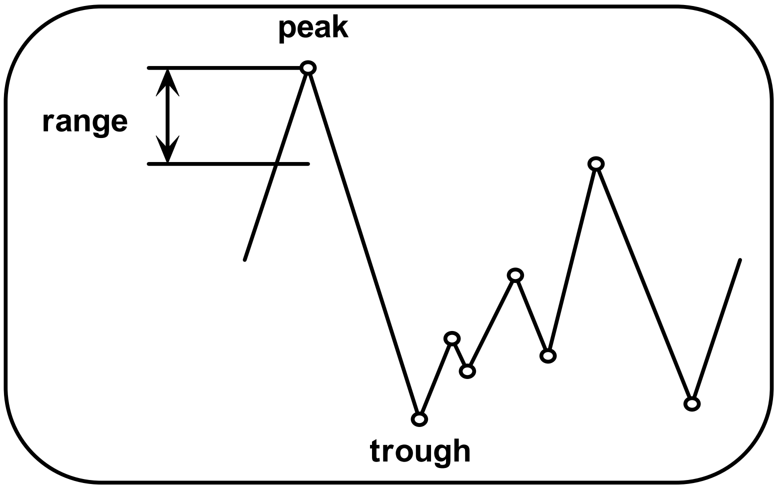


Figure 6: Peak and Trough data reduction algorithm

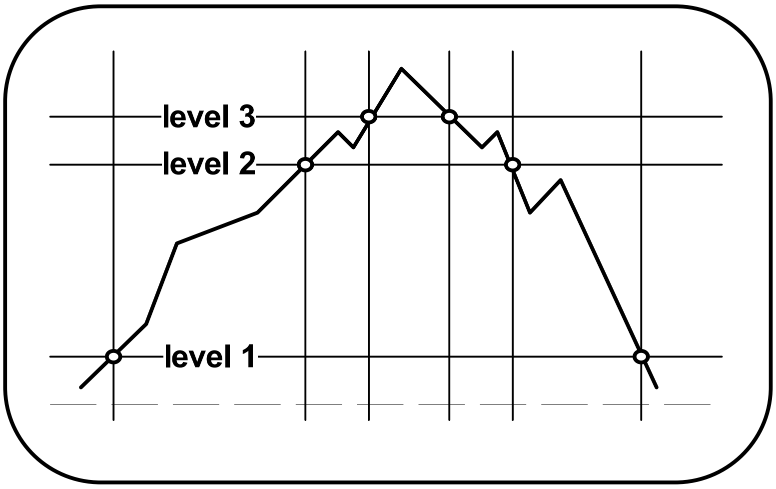


Figure 7: Time at level data reduction algorithm

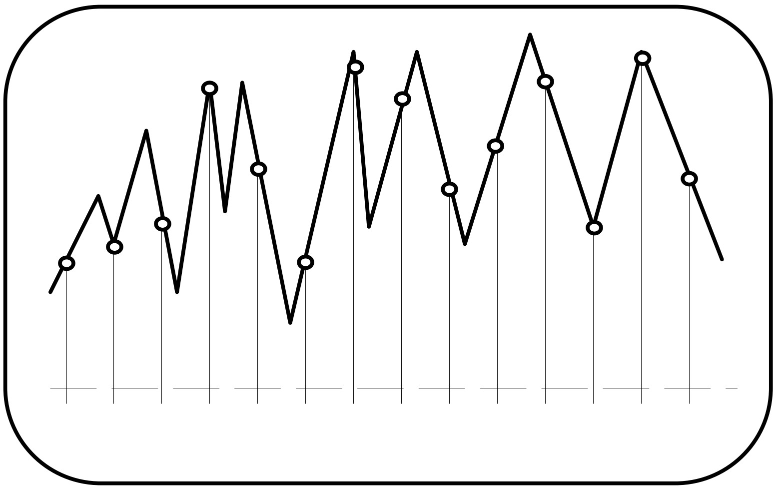


Figure 8: Sample data reduction algorithm

proces	master	slaves	processing algorithm
0	NORMACCEL normal acceleration	-	PAT range filter 0.5G
1	LATACCEL lateral acceleration	-	PAT range filter 0.1G
2	FS325 strain gage center fuselage bulkhead	-	PAT range filter 10 MPa
3	FS374 strain gage keelson center fuselage	-	PAT range filter 10 MPa
4	FS462 strain gage vertical tail attachment	-	PAT range filter 10 MPa
5	FS479 strain gage aft fuselage bulkhead	-	PAT range filter 10 MPa
6	BL120 strain gage outer wing	-	PAT range filter 10 MPa
7	N1 fan speed	-	PAT range filter 2%
8	N2 high compressor speed	-	PAT range filter 2%
9	PLA power lever angle	-	PAT range filter 2%
10	PLA power lever angle	-	TAL level1 17 deg, level2 89 deg
11	NORMACCEL normal acceleration	25	SAMPLE reduction factor 250, NORMACCEL on MUX available with 50 Hz → SAMPLE frequency 0.2 Hz

no	parameter	description	no	parameter	description
1	LATACCEL	lateral acceleration	14	AOA	angle of attack
2	LONGACCEL	longitudinal acceleration	15	Mach	Mach number
3	FS325	strain gage FS 325	16	CAS	calibrated airspeed
4	FS374	strain gage FS 374	17	MMCFDRMW1	configuration
5	FS462	strain gage FS 462	18	FUELWGT	fuel weight
6	FS479	strain gage FS 479	19	Ph	pressure altitude
7	BL120	strain gage BL 120	20	N2	high compressor speed
8	roll	roll-angle	21	PLA	power lever angle
9	pitch	pitch-angle	22	TFAT	true free air stream temp
10	TRHDG	true heading	23	FTIT	fan turbine inlet temp
11	FCCROLLR	roll-rate	24	TT2	inlet total temperature
12	FCCPTHR	pitch-rate	25	N1	fan speed
13	FCCYAWR	yaw-rate			

Figure 9: Default Setup Configuration File

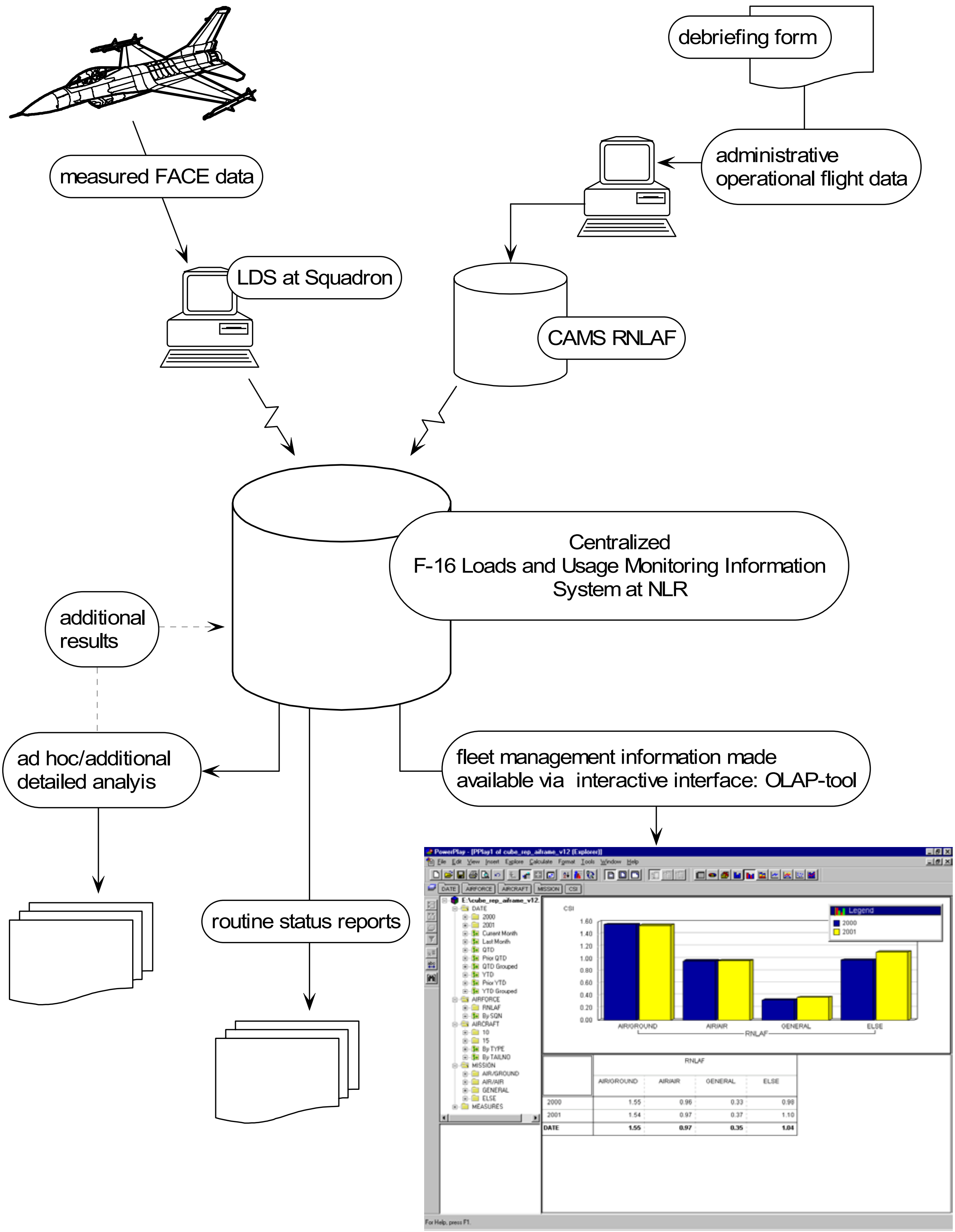


Figure 10: Overview data/information flow

Acoustic Wave Propagation Phenomena Modelling and Damage Mechanisms in Ageing Aircraft

Wieslaw. J. Staszewski
University of Sheffield
Dept. of Mech. Engineering
Mappin Street
Sheffield S1 3JD, UK

Christian Boller
EADS Deutschland GmbH
Military Aircraft
D-81663 München/Germany

ABSTRACT

Aircraft structure integrated health monitoring systems for specifically detecting damage in ageing aircraft is an issue very much discussed over the past years. One of the methods successfully used is acoustic wave propagation. This paper describes the various aspects to be considered in design and application of such systems underlined by some practical examples.

INTRODUCTION

The dramatic events of September 11, 2001 may have led to the conclusion that the problem of ageing aircraft very much discussed in the past would be significantly alleviated. Indeed this slightly seemed to be the case in civil aviation for a few weeks and months but looking a little more into the statistics shows that this is likely to not be the case in the longer term.

To obtain a slight overview regarding numbers of ageing civil and military aircraft currently being around, a summary for some of the typical, mainly Western built aircraft is shown in Tables 1 and 2 given below. The numbers are based on pre September 11 statistical data published in *Flight International* and have been put here in a specific order for better visualisation. As a consequence of post September 11 around one thousand aircraft have been additionally put into storage. Keeping this in mind and the fact that civil aircraft business has again significantly recovered within just 6 months after September 11, it is likely that in the near future a further number of aircraft stored has to be brought back into service because the aircraft manufacturing industry may not have sufficient resources to meet the increasing demand of air transportation through manufacturing of new aircraft. Existing aircraft will therefore still have to continue to fly much longer than initially planned. Very recent announcements say that around 600 aircraft are considered to be put back into service again in 2002 and the old constrained situation of lack in aircraft is expected to back by no later that 2004. The few current numbers for the truly old jets such as 707, DC-8, DC-9, 727, 737-100/200, L-1011 or 747 Classic where 37%, 44%, 74%, 68%, 79%, 62% and 78% of the total built fleet respectively is still in service is just a sign that the ageing aircraft problem will stay relevant for the future.

Aircraft type	Total delivered	Fleet in service 09/01	Ageing aircraft in 1999		
			≥ 15 Years	≥ 20 Years	≥ 25 Years
A300	503	411 (82%)	220 (46%)	60 (12%)	1 (0,2%)
A310	255	218 (85%)	54 (21%)		
707/720	1009	379 (37%)			
727	1831	1247 (68%)	1381 (75%)	1127 (62%)	673 (38%)
737-100/200	1144	901 (79%)	853 (75%)	442 (39%)	222 (19%)
737 CFMI	1988	1971 (99%)	13 (0,7%)		
747-100/SP/ 200/300	724	562 (78%)	490 (68%)	317 (44%)	154 (21%)
757	968	943 (97%)	51 (6%)		
767	840	820 (98%)	109 (14%)		
DC-8	556	243 (44%)	268 (48%)	268 (48%)	268 (48%)
DC-9	976	727 (74%)	776 (79%)	739 (75%)	588 (61%)
DC-10	446	397 (89%)	333 (75%)	276 (62%)	162 (36%)
L-1011	249	155 (62%)	185 (74%)	113 (45%)	60 (24%)
Total	11489	8974	4733 (46%)	3342 (33%)	2128 (21%)

Table 1: Ageing civil aircraft overview

With military aircraft the numbers become even more extreme. Table 2 is just a selection of what is currently flown worldwide. The average age of the US Air Force's (USAF) fleet now stands at around 22 years with the Boeing B-52H, aerial tankers and the Lockheed C-141 having an average age of 39, 37.6 and 34 years respectively. This average age is expected to increase to 25 years in the year 2007 and 30 years in 2020 respectively. The USAF would have to boost aircraft purchases by about 170 a year to reverse the age trend, but this is not the plan, so the ageing aircraft problem will possibly become more severe. Looking at other areas of the world, the problem of ageing military aircraft is even of higher relevance.

Aircraft Type	*First built*	*Total in service 09/2001*	*Life extension until*
BAE Hawk/Boeing T-45 Goshawk	1976	641	
Boeing F/A-18 Hornet/Super Hornet	1978	1762	2019
Boeing B-52H Stratofortress	mid 50ies	94	2045
Boeing 707/C-137/C-18/KE-3	60ies	97	2030
McDonnel Douglas F-4 Phantom	1958	889	
Dassault/Dornier Alpha Jet	1973	289	
Lockheed-Martin F-16	1974	3398	
Northrop T-38	1959	685	2040
Panavia Tornado	1974	746	2018
MiG-21 (incl. licences)	mid 50ies	3324	
L-39/L-39 Albatros/L-159	mid 70ies	2233	

Table 2: Ageing military aircraft overview

The big burden with ageing aircraft is definitely that they have to be maintained much more than new ones, which has been the lesson learned from the Aloha Airlines Flight 243 accident in 1988. Maintenance includes inspection and repair as well as all the engineering being related to it. With regard to ageing aircraft this means:

- Higher inspection effort due to shorter inspection intervals, specifically when the aircraft is designed fail-safe;
- More replacement of components having achieved their end of usage through spare parts;
- Higher engineering effort required due to special repair resulting from non-availability of spare parts.

This paper will be mainly discussing the issue of automating inspection such that the higher inspection required for ageing aircraft can be significantly alleviated. The components being considered for monitoring are specifically those, which are difficult to access due to the increased effort required in dis- and reassembly and which may have to be accessed more often than an inspection plan requests to disassemble the aircraft due to other reasons.

The idea on how to automate such an inspection process is to have a relatively simple sensing device available, which can be easily attached – preferably bonded – onto the component to be inspected. Such sensing devices have indeed already been developed and they are either based on an ultrasonic [1] or eddy current [2] basis respectively, similar to the techniques mainly used for non-destructive testing of aircraft structures. Communication to these sensing devices has been so far done on the basis of wiring but solutions for wireless communication are more and more proposed.

The following paragraphs will describe the methodology used and discuss the available options and the measures to be taken to successfully perform this monitoring process.

METHODOLOGY

The methodology or in other words the strategy of monitoring is extremely important for successful damage detection. The basic factors, which determine the Lamb wave-based damage detection analysis are related to properties of the structure under inspection, transducer schemes, choice of excitation input signal, and appropriate signal processing as reported in [3-13]. Other elements include various aspects related to transducer coupling methods, optimal sensor locations and sensor validation procedures. The last but not least is the hardware used for monitoring, graphical interface and data storage organisation. All these elements are briefly discussed in the current paper.

Real engineering structures under inspection are usually quite complex when compared with simple plates and pipes studied in laboratory conditions and reported in the literature. The complexity of the real components is determined by the variety of joints, stiffeners, rivets, complicated shapes or varying thickness. This causes the entire analysis to be much more complicated and requires an appropriate monitoring strategy.

Acousto-ultrasonic techniques are based on stress waves introduced to a structure by a probe at one point and sensed by another probe at a different position. The first applications of Lamb waves for damage detection used bulky web transducers. It appears that piezoceramics are now the most widely used transducers due to the fact that they can be used as sensors and actuators at the same time. Often piezoceramics can become an integral part of the monitored structure. Examples include: piezoelectric rubbers, paints [14] and Smart Layer sensors [1]. Recent advancements in this area include optical fibre [15] and micro electromechanical systems (MEMS) based sensors [16]. Both types of sensors can be used not only for Lamb wave detection but also for strain measurements. MEMS devices can additionally generate Lamb waves and detect corrosion. A number of different practical aspects need to be considered once choosing transducers for Lamb wave detection. This includes: coupling, connectors and environmental protection. Cold bonding is usually preferred to hot bonding. The process of bonding must be as easy, if not even easier than the strain gauge bonding procedure. Also, bonded sensors are better than embedded due to possible sensor failures and replacements. Reliable connectors and environmental protections are required to prevent sensor failures. Wireless communication is possible with piezoceramic and MEMS sensors. Coupling, connectors and environmental protection are particularly important in the case of optical fibre and piezoceramic sensors.

Different types of signals are used as inputs in acousto-ultrasonic systems including: impulse, sine burst, sine sweep and Gaussian white noise signals [17]. It is considered that the simpler the input signal, the simpler the output signal for damage detection. The choice of input excitation is often a compromise between the amplitude and the mode generation. Low-voltage signals are possible when the input frequencies are within transducer resonance frequencies. This is often associated with intelligent signal processing to remove undesired noise and extract features related to damage. In practice transducers resonance frequencies do not coincide with single Lamb wave mode frequencies. Previous studies show [17-18] that even a simple input signal can lead to complex output signals due to various attenuation and dispersion effects, which are not related to damage. This clearly shows that intelligent signal processing is one of the most important elements of the Lamb wave based damage monitoring strategy.

Once the transducers excitation signals are chosen the question is where to put sensors for optimal damage detection. Recent years have shown considerable progress on the problem of determining the number and location of sensors in engineering structures. This problem requires the application of different optimisation techniques, which includes: *ad hoc* methods, classical deterministic unconstrained and constrained optimisation techniques. More recently, new non-deterministic optimisation methods have been proposed. These are: neural networks, genetic algorithms, evolution strategies, simulated annealing, tabu search and different hybrids of the above techniques as reported in [19-20]. Other new studies include ranking techniques such as mutual information [21].

Sensor architectures need to incorporate validation procedures, which are important to detect sensor failures. This can involve active and passive approaches. In the active approach a signal is sent through the sensor and the transmission characteristic of the sensor can be compared to the expected response using a novelty index. In the passive approach the response probability distribution of the sensor is computed. Subsequent measurements are then inspected to detect outliers, which can indicate sensor failures. There exist a number of algorithms based on statistical analysis and neural networks.

An example for such an acousto-ultrasonic based methodology is shown in Fig. 1. A computer equipped with a signal generation card is used to generate the input signal for the different piezoelectric elements working as actuators. Each of these elements can be addressed using a multiplexer. In a similar way the sensor data is again recorded where the multiplexer then addresses all the different piezoelectric elements working as sensors. The right hand side diagrams show that the output signals are significantly different to the input signals and this not only due to attenuation but also due to reflections from boundaries as well as specifically due to a damage having occurred.

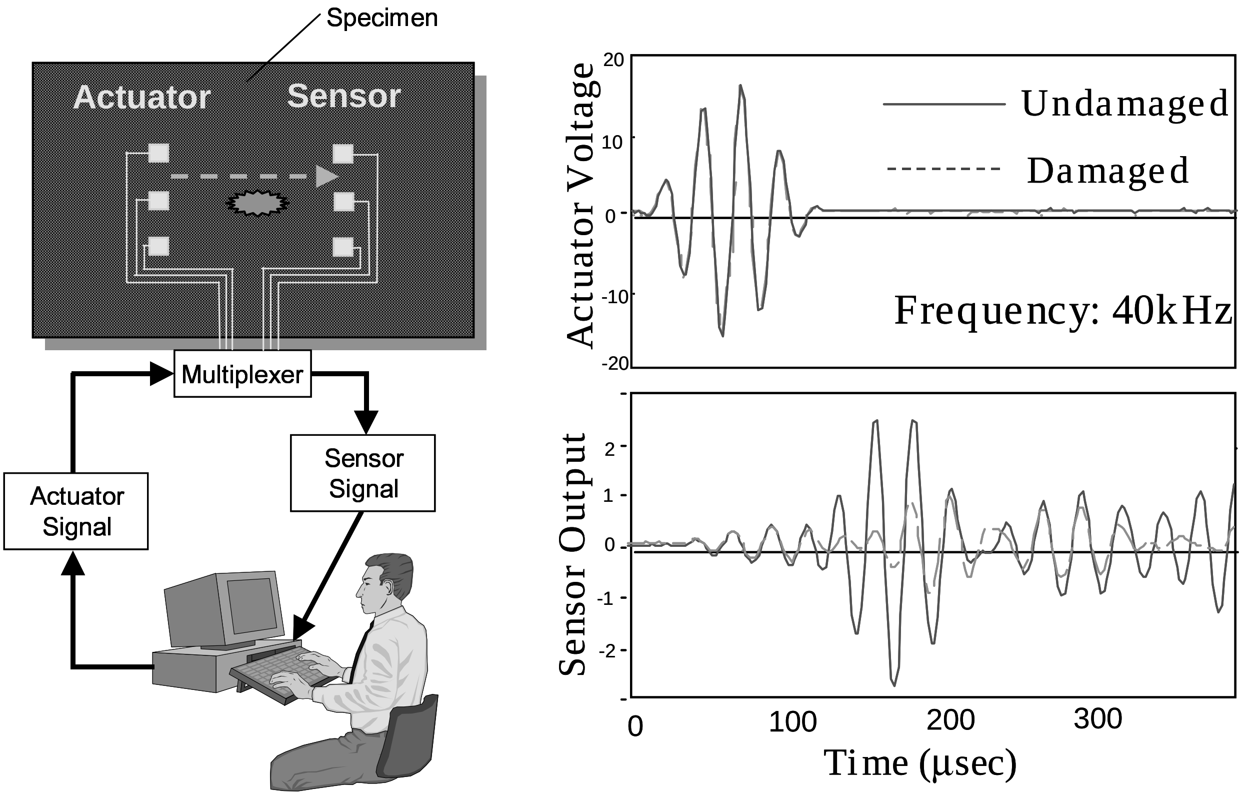


Fig. 1 The acousto-ultrasonic monitoring principle

Monitoring structures in the way shown in Fig. 1 implies that the sensor network is pre-configured on a carrier, where the sensing layer can be easily bonded onto or integrated into the structure to be monitored. An example for such a sensing system realised in hardware is the *Smart Layer*^{TM} which is described and discussed in more detail in [1] and shown as an example in Fig. 2. The layer consists of two Kapton foils, with tiny piezoelectric elements as well as the required electric wiring integrated in between, similar to the way this is done for electronic components. These layers can be either integrated into a composite structure or patched on the outside of any kind of structure (e.g. metallic, polymer, composite, etc.). Smart layers can be configured with that technology allowing to be used for autonomously monitoring damage critical components. A software for generating the input and analysing the output signal is also provided [22].

As can be seen from the different types of *Smart Layer*^{TM} shown in [23], geometry of the layer and position of the different piezoelectric elements very much depends on the geometry of the component to be monitored, and the type, size and location of the damage to be detected. Together with an effective way of sensor signal processing this requires a very well planned sensor system configuration.

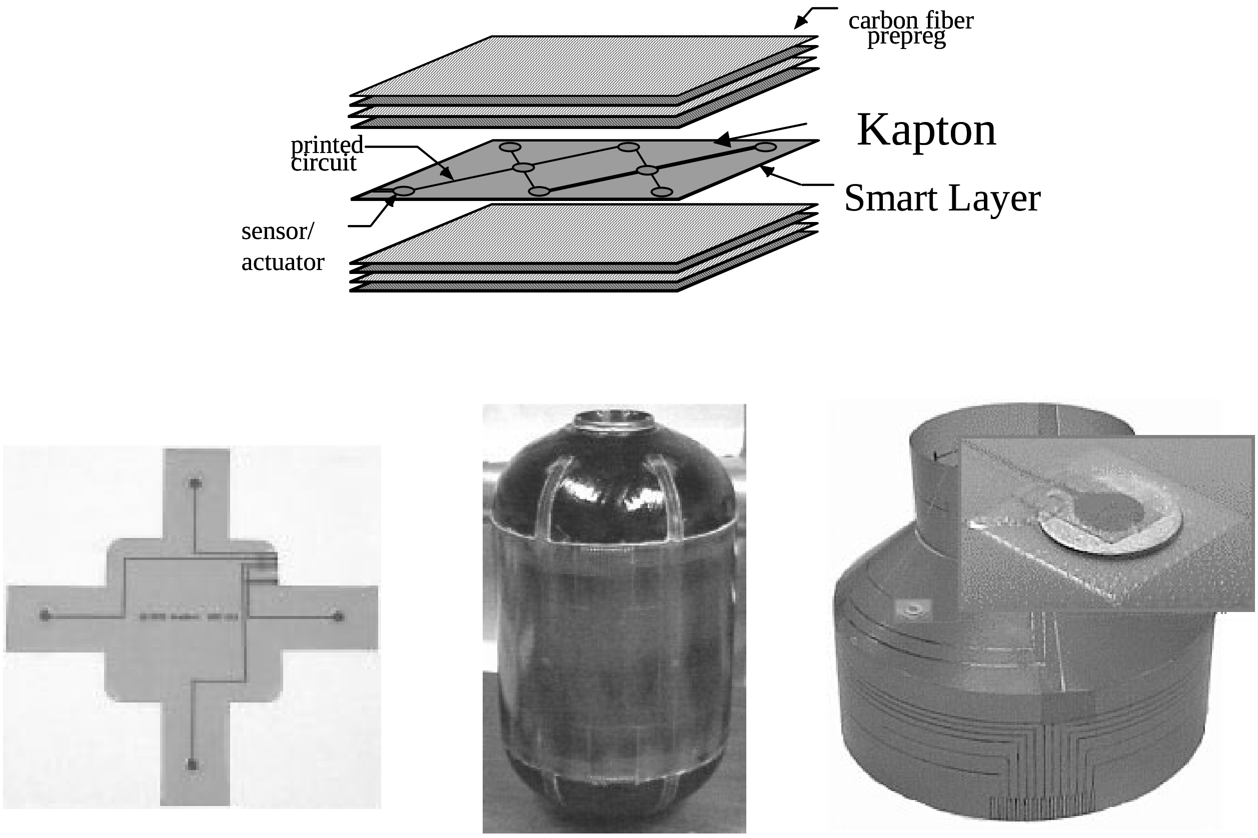


Fig. 2 Principle and configuration of *Smart Layer™* [1, 23]

SIGNAL PROCESSING

Intelligent processing of data and information is an important element of any structural health monitoring system. So far signal processing has been limited to analysing

- Relative amplitude change
- Scattered spectral density damage index
- Wavelet based damage index

The *relative amplitude change* method, which is explained in more detail in [24] takes the difference in maximum amplitudes between the envelopes of the time-domain signal for the undamaged and the damaged stage of the specimen. In the case no damage has occurred between two measurements, this difference has to be basically zero. The larger the difference between the amplitudes of these envelopes turns out to be, the greater the damage identified by the system.

The *scattered spectral density damage index* (SDI) [25] can be seen as an extension of the relative amplitude change method. With SDI the spectrogram of the scattered wave (called ‘scattered spectrogram’) is taken and a damage index is calculated such that the scatter spectral density at the resonant frequency of the structure is integrated over time according to the following equation

$$DamageIndex = \int STFT\{S_{damaged} - S_{undamaged}\}dt = \int P_{scatter}(\omega_0, t)dt$$

where *STFT* denotes the short time Fourier transform of sensor measurements, $P_{scatter}$ the power spectral density and ω_0 the selected frequency or the resonant frequency of the structure respectively.

The *orthogonal wavelet transform analysis,* which is explained in more detail in [26], is an important tool for data compression and feature selection in vibration analysis [27]. The orthogonal wavelet transform decomposes a given function $x(t)$ into a basis of orthogonal wavelet functions $\psi_{m,n}(t)$ following the formula

$$W_{\psi}(m,n) = \int_{-\infty}^{+\infty} x(t)\psi_{m,n}(t)dt$$

For the dyadic wavelet grid the $\psi_{m,n}(t)$ take the form

$$\psi_{m,n}(t) = 2^{-m/2}\psi(2^{-m}t - n)$$

The analysis gives the span of the $x(t)$ function at different resolutions according to wavelet scales and without any redundancy. The basis of the orthogonal wavelet functions is constructed from the dilation equations which can be generally represented as

$$\phi(t) = \sum_{n=0}^{N} c_n \phi(2t - n)$$

where $\phi(t)$ is the so called scaling function, c_n are some numerical coefficients (also regarded as filter coefficients) and N is a number of non-zero c_n coefficients. Scaling functions are used from the following formula

$$\psi(t) = \sum_{n} (-1)^n c_n \phi(2t + n - N + 1)$$

Any arbitrary signal $x(t)$ can be decomposed using wavelets according to the expansion

$$x(t) = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} c_{mn}\psi(2^m t - n)$$

In order to obtain an orthogonal decomposition, scaling functions $\phi(t)$ and c_n coefficients must satisfy certain conditions. The orthogonal basis used here is Daubechies’ wavelets, which is discussed in more detail in [28]. The finite set of ϕ, ψ of functions gives a decomposition of the signal $x(t)$ into so called wavelet levels. Each level m is represented by different wavelet coefficients and gives the contribution to the original signal at different resolution scales (or frequencies). The higher the level, the higher the frequency of the contribution.

The variance of the orthogonal wavelet coefficients $W_\psi(m,n)$ is then calculated for all wavelet levels representing different data sets. The combined logarithmic wavelet variance is then used for analysis. The mean vector $\overline{\mu}$ of the logarithmic wavelet variance taken from the wavelet coefficients x_m^n, given by

$$\mu(m) = \frac{1}{N}\sum_{i=1}^{N}\log(\mathrm{var}_i\, x_m^n)$$

is calculated for the data representing the undamaged condition. This vector forms the template for the similarity analysis. The damage index is finally calculated as an Euclidian distance between the template $\overline{\mu}$ and the wavelet variance characteristics $\overline{x} = \log(\mathrm{var}_i\, x_m^n)$, from which the damage is to be evaluated

$$d_{x,\mu}^2 = (\overline{x} - \overline{\mu})^T (\overline{x} - \overline{\mu})$$

where T denotes the vector transpose. The values of damage index from the undamaged condition are used to establish statistics for the expected variations in damage indices. The 95% statistical confidence levels are calculated as $\nu \pm 1.96\sigma$, where ν and σ are mean and standard deviations of the damage indices respectively. The alarm or warning level represents the index value above which it can be considered that damage exists in the structure. A suitable alarm value is $\mu + 4\sigma$, where μ and σ are the mean and the standard deviation of the damage index representing the undamaged condition.

These three signal processing methods mentioned so far have been compared on the basis of experimental results which were obtained on the multi-riveted aluminium panel shown in Fig. 3. Different panels were tested under a full tension constant amplitude fatigue loading with cracks starting from the different rivets. Three strips of *Smart Layer*^{TM} were bonded between the rivet lines and at a 12 cm distance of the rivet lines respectively. The smart layer between the rivet lines was used for actuation, the other smart layers for sensing. The signals were recorded by the piezoelectric elements being on the direct straight path as shown in Fig. 3 as well by the piezoelectric elements being next to them. Measurements with the *Smart Layer*^{TM} as well as with ultrasonic and eddy current method used traditionally for non-destructive testing (NDT) were done at specified intervals during which load cycling was stopped. Measurement with these different methods allowed a comparison between the traditional and emerging monitoring techniques.

A comparison of results obtained with the *Smart Layer*^{TM} and conventional NDT is shown in Fig. 4. Here NDT measurements were taken as the reference by ranking them from the largest down to the smallest crack length and then comparing this ranking with the results obtained with the *Smart Layer*^{TM} and different signal processing procedures using the same ranking procedure.

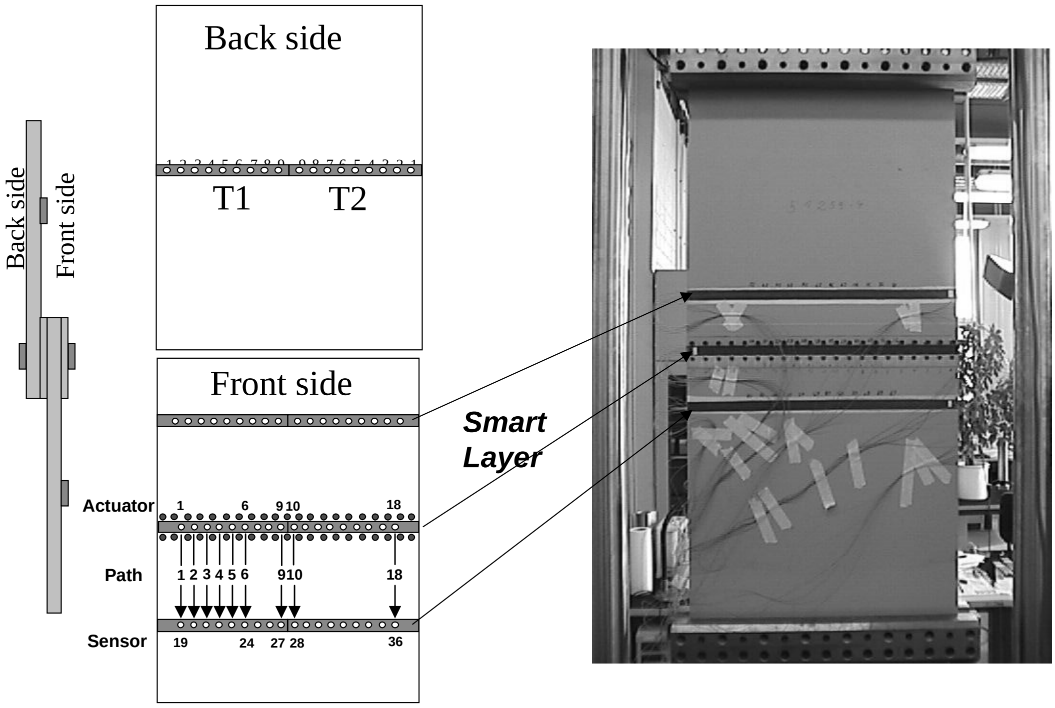


Fig. 3 Testing of riveted panel in fatigue test using *Smart Layer*[TM]

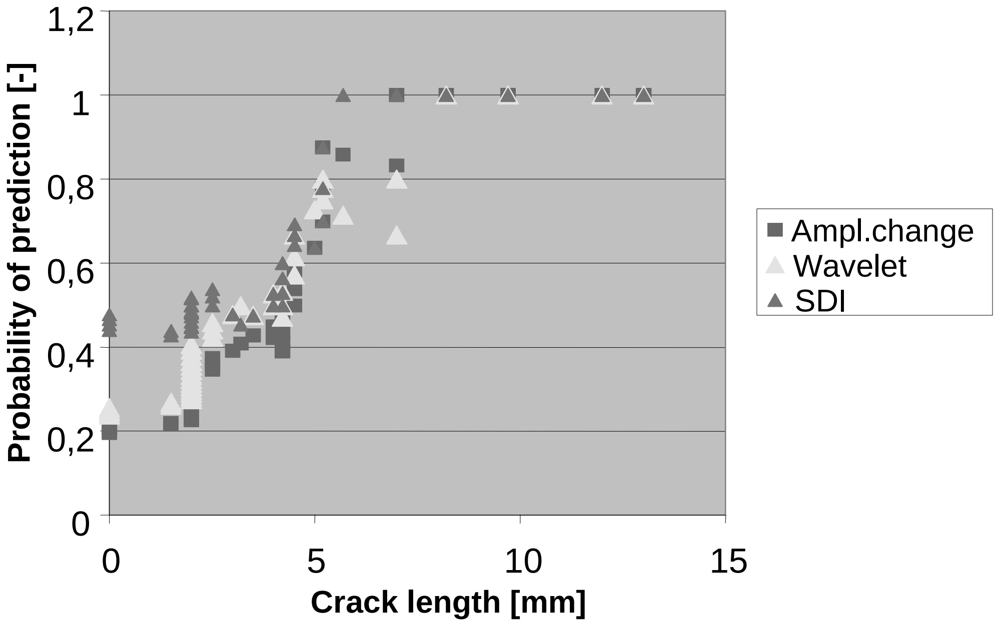


Fig. 4 Probability of crack prediction for the different procedures considered

Adequacy with traditional NDT is achieved according to Fig. 4 when probability of prediction becomes unity. This is the case for all signal processing procedures discussed here for the *Smart Layer*[TM] when cracks are around 8 mm long or more. In a few cases unity goes even down to around 5 mm crack length which proves that slightly improving the signal processing procedure can also remarkably improve the sensitivity of the monitoring system. It is therefore worth looking around what further options are available for improving the result obtained through the sensor signal information. A schematic overview of the sensor signal processing process with further options to be considered is therefore given in Fig. 5.

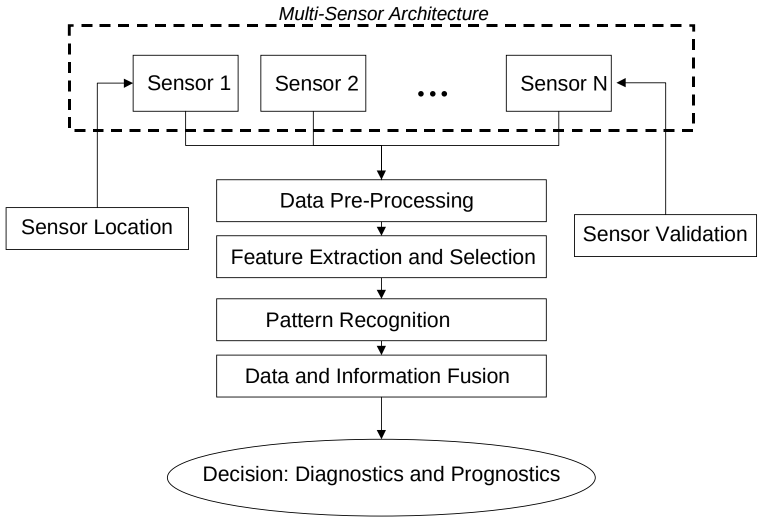


Fig. 5: Chain of sensor signal processing

Data pre-processing is the first element of signal processing. It involves normalization, trend removal techniques, outlier analysis, averaging, smoothing and filtering. Recent developments in this area include wavelet-based denoising procedures.

The process of feature extraction and selection is necessary to enhance damage detection. Feature extraction for damage detection include signature and advanced signature analysis. In order to obtain scalar features signature analysis employs simple feature extraction methods based on data reduction procedures in general. This includes for example statistical spectral moments, physical parameters of the analysed system or modal based criteria. Advanced signature analysis uses sets of features in a form of vectorial or pattern representations, e.g. spectra, envelope and phase characteristics. The past ten years have seen major developments in the area of advanced signature analysis. A number of algorithms based on time-frequency and time-scale procedures have been proposed, as discussed in [20]. Feature selection is a process of choosing input for pattern recognition. The process of selection reduces a number of features for training. Feature selection reduces the dimensionality of feature space either through the process of reducing the number of features, combining features into new features or selecting a subset of features. The terms feature extraction and selection are often used synonymously. It is very important to establish features that are only related to damage and not sensitive to changing environmental/operational conditions. Also, in contrast to *black-box* methodologies, features based on physical knowledge and understanding, find more confidence in the engineering community. Therefore, often feature extraction and selection needs to be combined with appropriate modelling techniques described in the next section.

Features are combined in patterns formed in a vector or matrix notation. The objective of pattern recognition in damage detection is to distinguish between different classes of patterns representing different damage conditions. Classical methods of pattern recognition use statistical and syntactic approaches [29]. In recent years neural networks have been established as a powerful tool for pattern recognition [30]. This includes: Kohonen networks, Multi-Layer Perceptron and Radial Basis Functions. More recently methods of novelty detection have been established [31]. These methods establish a description of normality using features representing undamaged conditions and then test for abnormality or novelty. These methods provide only damage detection level, however they do not require any *a priori* knowledge about damage. Novelty detection methods can incorporate information related to varying environmental and/or operational load conditions.

Sensors are usually deployed in arrays. Multi-sensor architecture improves signal-to-noise ratio, offers better robustness and reliability, and increases confidence in the results. Distributed sensors are also needed for the location and assessment of structural damage. Data gathered from different types of sensor often need to be combined with linguistic and knowledge-based information. There exist a number of different data fusion algorithms within hierarchical levels of processing. This includes physical models, parametric methods, information techniques and cognitive-based models, as reported in [32].

MODELLING

In order to ease the monitoring strategy and/or interpretation of the Lamb wave signals, understanding of the physics behind the acousto-ultrasonic technique is very helpful. Due to complex anisotropy in a structure and piezoelectric effects, an analytical approach is in practice mainly impossible. Various simulation techniques are used to model transducer characteristics, mode generation, wave propagation, damage, and wave interaction with damage. Finite Element (FE) analysis is applied to obtain transducer characteristics and/or transducer coupling effects [33]. Transducer characteristics can also be obtained experimentally, as shown in Fig. 6. This analysis allows transducer operational modes, frequencies and coupling effects to be established.

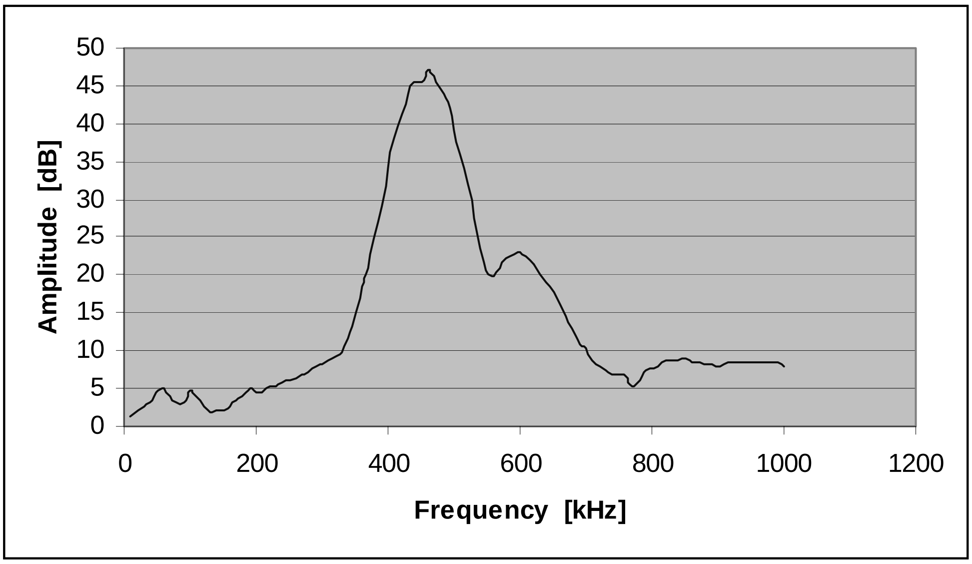


Fig. 6 Transfer function for SMART Layer sensors embedded in a composite panel.

The main problem with Lamb waves is that there is an infinite number of modes, which can propagate in structures. Finite Difference Equations (FDE) [33, 34] and experimental analysis [33] can be used to establish velocity dispersion curves, which are functions of a combined thickness-frequency parameter. These curves indicate frequency ranges for various propagation modes. For most engineering structures, dispersion curves are not easy to obtain in practice. This is due to the interaction of individual Lamb wave modes within a structure of varying thickness.

Most structural health monitoring applications are based on single Lamb wave mode generation and utilise amplitude attenuation and/or mode conversion for damage detection. However, previous studies [17] show that even simple input signals can lead to complex output waves that are difficult to interpret. Therefore, it is important to understand the behaviour of Lamb waves propagating in structures. There are several simulation approaches that give better understanding of the wave propagation modelling. These include: FDE, FE analysis [8, 35, 36], spring lattice model [37, 38] and local interaction simulation approach (LISA) [31-35]. Most of the methods in this area are also related to wave propagation in composite structures but with different boundary condition measurements. Fig. 7 gives a comparative example of LISA wave propagation and experimental results in a complex structure consisting of two piezoceramic, two copper and one oil grease layer [7]. Different approaches are used for damage simulation. The most common approach utilises mass-spring models and FE analysis, as shown in [44]. Examples of Lamb wave interaction with damage can also be found for metallic [45] and composite [40-46] structures.

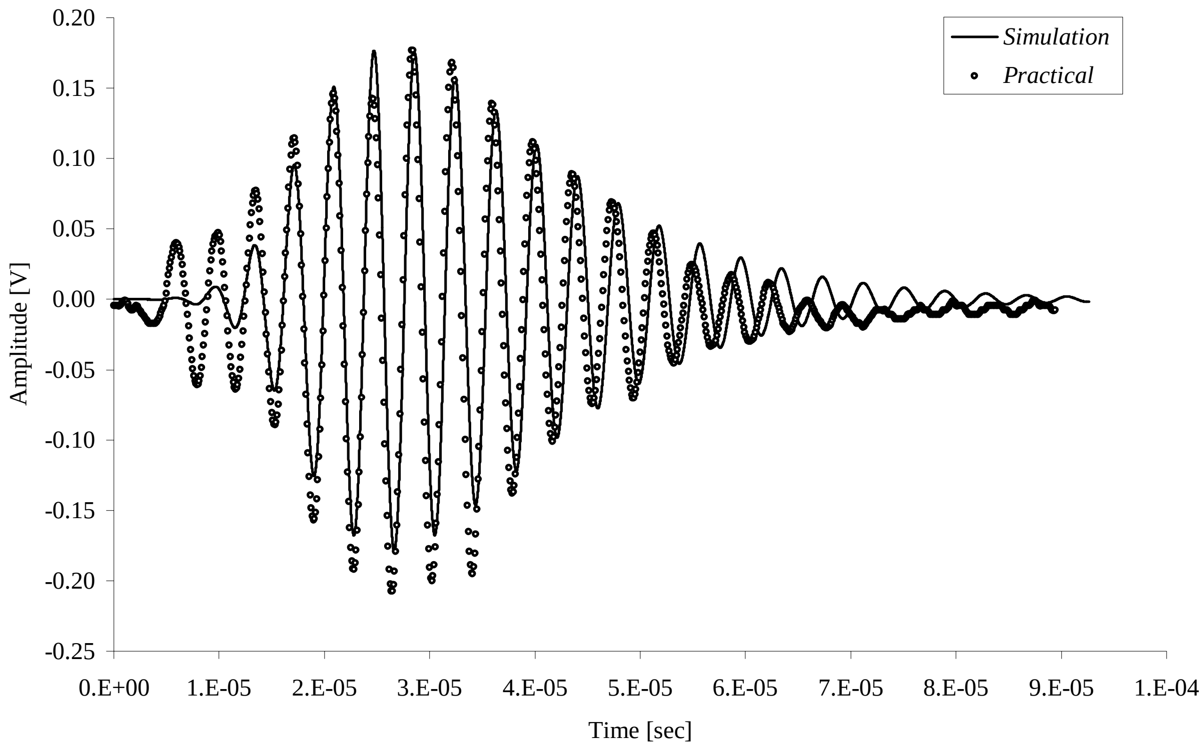


Fig. 7 Comparison between simulated (solid line) and experimental time-domain (dotted line) Lamb wave signals at the sensor [43].

CONCLUSIONS

Development ongoing in structural health monitoring over the past decade has shown that a significant progress has been achieved, starting from concepts derived from the nervous system of the human body with an uncountable number of sensors down to a much more engineering approach derived from wave propagation physics and damage mechanics with a manageable number of discrete sensors. Although nature is a wonderful world for engineering inspiration, it should possibly not be copied for engineering application at a one to one scale. Sensors and sensor systems in nature are of a completely different type. They tend to be very sloppy, have very low reliability, have to go through a learning/training process and can regenerate themselves – to just name a few of their peculiar features. Similar statements can possibly be made with regard to actuators when comparing nature with the engineering world and in control processes may be different too.

Coming back to engineering and structural health monitoring, it is specifically the engineering approach, which has shown that the early vision of bonding a 'sensing plaster' to any location of a structure where damage is expected and which can sense damage initiation and progress at any time, is no science fiction anymore. Technologies for manufacturing the respective sensing hardware are definitely available. What is still not exhaustively determined is the potential sensor signal processing as well as recording strategies can bring in. This is a broad field of which the basics need to be explored and transferred into design guides, which only allow the design engineer to apply structure integrated health monitoring on a broader basis. Modelling wave propagation in structures is one of the very first issues to be tackled in that regard because it allows to better understand the physics behind and to establish the optimisation process with regard to the minimum number of sensors required as well as any schemes of sensor redundancy which only allow to achieve a high level of reliability.

In excess to sensor signal processing there is a very large need for experimental validation and certification of the structural health monitoring systems, which is a further contribution to the overall system's reliability. So far validation has been done on a very limited number of tests only, which were mainly achieved through a lucky symbiosis between structural health monitoring developers and structural testing organisations. Much more of these symbioses will be required to get the broader experience, which only allows to get the respective confidence requested by the certification authorities. The alternative of establishing specific testing programs for validating structural health monitoring systems only would be much more costly and would delay application and drive down motivation and momentum in technological development of those systems significantly.

REFERENCES

[1] Chang F.K., 1998, "Smart layer: built-in diagnostics for composite structures", *Smart Materials and Structures* - Proceedings of the 4th European and 2nd MIMR Conference, Harrogate, UK, 6-8 July, 777-781.

[2] Washabaugh A P, V A Zilberstein, D E Schlicker, Y Scheiretov, D Grundy and N J Goldfine, 2002; *Shaped-field eddy-current sensors and arrays;* Proc. of

SPIE Conf. 4702 Smart NDE and Health Monitoring of Structural and Biological Systems; San Diego/CA
[3] Boller, C. Fundamentals on damage monitoring. In *Smart Structures and Materials: Implication for Military Aircraft of New Generation.* AGARD Lectures Series 205, NATO, 1996.
[4] Doebling, S. W., Farrar, C. R., Prime, M. B. and Shevitz, D. Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics. Technical Report LA-13070, Los Alamos National Laboratories, Los Alamos, NM, 1996.
[5] Lalande, F. and Rogers, C. A. Quantitative non-destructive evaluation research at cimess. In *Proceeding of ICIM'96 and ECSSM'96, SPIE,* 1996, 2779, 106-111.
[6] Cawley, P. and Alleyne, D. N. The use of lamb waves for the long range inspection of large structures. *Ultrasonics,* 1996, 35, 287-290.
[7] Pierce, G. S., Culshaw, B., Philp, W. R., Lecuyer, F. and Farlow, R. Broadband lamb wave measurements in aluminium and carbon/glass fibre reinforced composite materials using non-contacting laser generation and detection. *Ultrasonics,* 1997, 35, 105-114.
[8] Alleyne, D. N. and Cawley, P., Optimization of Lamb Wave inspection techniques. *NDT&E International,* 1992, 25 (C1), 11-22.
[9] Rose, J. L. *Ultrasonic Waves in Solid Media.* Cambridge University Press, 1999.
[10] Achenbach, J. D. *Wave Propagation in Elastic Solids.* New York: North-Holland, 1984.
[11] Auld, B. A. *Acoustic Fields and Waves in Solids.* 2nd ed., Vol. 1 and 2. Malabar, FL:Kreiger, 1990.
[12] Viktrov, I. A. *Rayleigh and Lamb Waves – Physical Theory and Applications*. Plenum., New York. 1967.
[13] Wilcox, P. D., Dalton, R. P., Lowe, M. J. S. and Cawley, P. Mode transducer selection for long range lamb wave inspection. In M. D. Gilchrist, Dulieu-Barton, and K. Worden, editors, *Damage Assessment of Structures, Proceeding of the 3rd International Workshop on Damage Assessment Using Advanced Signal Processing Procedures – DAMAS 99 Dublin, Ireland, 28-30 June, pp.*152-161, Switzerland, 1999. Trans Tech Publications Ltd.S
[14] Egusa S., Iwasawa N., 1993, "Polling characteristics of PZT/epoxy piezoelectric paints", *Ferroelectrics*, **145**, 45-60.
[15] Betz D.2002, "Acousto-ultrasonic sensing using fibre Bragg gratings", MPhil/PhD Transfer Report, Department of Mechanical Engineering, Sheffield University, UK.
[16] Yaralioglu G.G., Badi M.H., Ergun A.S., Cheng C.H., Khuri-Yakub B.T. and Degertekin F.L., 2002, "Lamb wave devices using capacitive micromachined ultrasonic transducers", *Applied Physics Letters*, **78**(1), 111-113.
[17] Staszewski, W. J., Biemans, C., Boller, C. and Tomlinson, G. R.; Crack propagation monitoring in metallic structures using piezoceramics sensors. In P. D. Mangalgiri, A. R. Upadhya, and A. Selvarajan, editors, *Proceedings of the International Conference on Smart Materials, Structures and Systems, Bangalore, India, 7-10 July,* pp. 532-541, New Delhi, 1999. Allied Publishers Ltd.
[18] Doyle, J. F. *Mechanical Engineering Series: - Wave Propagation in Structures.*2nd Ed. Springer, 1997.

[19] Staszewski W.J., Worden K. and Tomlinson G.R., 1996, “Optimal Sensor Placement for Neural Network Fault Diagnosis”, Proc. of the ACEDC'96, PEDC, Plymouth, UK..
[20] Staszewski W.J., 2000 “Advanced data pre-processing for damage identification based on pattern recognition”, *International Journal of Systems Science, **11**, 1381-1396.*
[21] Wong C.S. and Staszewski W.J., 1998, “Mutual Information approach to sensor location for impact damage detection in composite structures”, The International Conference on Noise and Vibration Engineering ISMA-23, Leuven, Belgium, 16-18 September, 1417-1422.
[22] Lin M, X Quing, A Kumar and S Beard, 2001: *SMART Layer and SMART Suitcase for Structural Health Monitoring Applications*; Proc. of SPIE Smart Structure and Materials Symp., Newport Beach/CA
[23] http://acellent.net
[24] Beard S. and F.-K. Chang, 1997: *Active Damage Detection in Filament Wound Composite Tubes Using Built-In Sensors and Actuators;* J. of Intell. Mat. Syst. & Struct., Vol. 8, S. 891 – 897
[25] Ihn J-B, F-K Chang and H Speckmann, 2001: *Built-in Diagnostics for Monitoring Crack Growth in Aircraft Structures*; in Proc. of Damage Assessment of Structures (DAMAS 2001), Cardiff/Wales, Key Engineering Materials, Vols. 204-205, Trans Tech Publ., pp. 299 – 308
[26] Mallat S, 1998: *A Wavelet Tour of Signal Processing,* Academic Press, San Diego
[27] Staszewski W J, 1998: *Wavelet based Compression and Feature Selection for Vibration Analysis;* J. of Sound and Vibration, **211**, No. 5, pp. 735-760
[28] Staszewski W J and K Worden, 1999: *Wavelet analysis of time series: coherent structures, chaos and noise;* Internat. J. of Bifurcation an Chaos, Vol. 9, No. 3, pp. 455-471
[29] Schalkoff R., 1992, *Pattern Recognition. Statistical, Structural and Neural Approaches,* John Wiley & Sons, Inc., New York
[30] Bishop C.M., 1995, *Neural Networks for Pattern Recognition*, Clarendon Press, Oxford.
[31] Worden K., 1997, “Structural Fault Detection Using a Novelty Measure”, *Journal of Sound and Vibration*, **201**(1), 85-101.
[32] Klein L. A., 1999, *Sensor and Data Fusion Concepts and Applications*, second edition, SPIE Optical Engineering Press, Bellingham, Washington.
[33] E. Moulin, J. Assaad and C. Delebarre, 1997, “Piezoelectric transducer embedded in composite plate: Application to Lamb wave generation.”, *Journal of Applied Physics*, **85**(5), 2049-2055.
[34] Lowe M.J.S., 1995, “Matrix techniques for Modelling ultrasonic waves in multilayered media”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **42**(4), 525-542.
[35] Díaz, S. and Soutis C., *2000, “*Structural integrity monitoring of CFRP laminates using piezoelectric devices”, ECCM9, European Conf. Composite Materials, June.
[36] Díaz, S. and Soutis C., 2001, *“*Real-time nondestructive evaluation of fibre composite laminates using low-frequency Lamb waves*”,* submitted to the *Journal of Acoustical Society of America*.

[37] Delsanto, P.P. and Mignogna, R. B., 1998, "A spring model for the simulation of the propagation of ultrasonic pulses through imperfect contact interfaces", *Journal of Acoust. Soc. Am.,* **104**(5), 1-8.

[38] Yim, H. and Sohn, Y., 2000; Numerical simulation and visualization of elastic waves using mass-spring lattice model, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* **47** (C3), 549-558.

[39] Delsanto, P P, Mignogna, R. B, Scalerandi, M. and Schechter, R. S., 1998, "Simulation of ultrasonic pulse propagation in complex media", *New perspectives on problems in classical and quantum physic*s, *Part II, Acoustic Propagation and Scattering Electromagnetic Scattering,* 51-74.

[40] Delsanto, P. P., Perego, G., Scalerandi, M. and Zoccolan, D., 1999; Efficiency of different ultrasonic surface waves for subsurface flaws detection, *Review of Progress in Quantitative Nondestructive Evaluation,* **18**, 127-133.

[41] Delsanto, P. P., Whitcombe, T., Chaskellis, H. H. and Mignogna, R. B., 1992, "Connection machine simulation of ultrasonic wave propagation in materials. I: The one-dimensional case", *Wave Motion*, **16**, 65-80.

[42] Delsanto, P. P., Schechter, R. S., Chaskellis, H. H., Mignogna, R. B. and Kline, R., 1994, "Connection machine simulation of ultrasonic wave propagation in materials. II: The two-dimensional case", *Wave Motion*, **20**, 295-314.

[43] Lee B.C. and Staszewski W.J., 2002, "Local Interaction Modelling for Acousto-Ultrasonic Wave Propagation", Proceedings of the SPIE's 9th International Symposium on Smart Structures and Materials, Conference on Modeling Signal Processing and Control in Smart Structures, San Diego, California, 17-21 March.

[44] Krawczuk M and Ostachowicz W M, 1992, "Parametric Vibration of a beam with crack", *Archives of Applied Mechanics*, **62**, 463-473.

[45] Lee B.C. and Staszewski W.J., 2002, "Modelling of acousto-ultrasonic wave interaction with defects in metallic structures", International Conference on Noise and Vibration Engineering ISMA 2002, Leuven, Belgium, 16-18 September.

[46] Alleyne D.E. and Cawley P, 1992; The interaction of Lamb waves with defects, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **39**(3), 381-397.

MEASUREMENT DEVELOPMENT TECHNOLOGIES FOR
HEALTH MONITORING APPLICATIONS

Arnd Reutlinger; Roland Graue
Kayser-Threde GmbH, Wolfratshauserstr. 48, 81379 Munich, Germany

Abstract

Major cost driver of aircraft operation are scheduled maintenance events. The significant reduction of aircraft operation costs while maintaining the high levels of safety and reliability can be achieved by different approaches:

- Improvements of the vehicle and vehicle subsystem design for life time cycle extension or longer maintenance intervals
  - Reduction of loads or load effects respectively
  - Higher load resistance through better materials and design
- Improvements of vehicle and vehicle subsystem operations
  - Accommodation of consumable subsystems, LRU's and components
  - Maintenance on Demand by Health Monitoring instrumentation

Several subsystems and components have been identified for redesign to improve performance, to reduce loads or the load effects respectively. The learning curve in the aviation propulsion development in the last 50 year shows, that new materials and design have increased considerably the engine reliability, lifetime which has reduced also costs.

The major amount of maintenance tasks is restricted to inspection of the components and subsystems. In military aviation up to 80% of maintenance time is spent for labor intensive assessment of component conditions according to prescribed time and load dependent intervals. Therefore, the know how about the conditions after load cycles on system and component level concerning life consumption or limit exceedances could save maintenance costs. A promising approach to reduce operational costs while maintaining a high level in safety and reliability is an integrated Health Monitoring System (HMS).

HMS encompasses the determination of the structural and functional integrity during all life cycle phases with adequate measurement and inspection techniques. Integrated load monitoring composed of a network of sensors and innovative data processing allows the assessment of subsystem/component condition after each cycle. The load history can be translated to damage due to limit exceedences and degradation/wear due to life consumption in case of damage tolerant structural design. On ground, advanced NDI verifies structural integrity on the basis of abnormal behavior during load cycles.

Many research and development approaches for HM can be found in literature, but only little applications are reported. On major reason is, that HM does interfere with stringent aircraft safety rules. Furthermore, existing measurement technologies are partially not suitable for HM application due to high weight, sensitivity to EMI (electronic sensors), low longterm behavior (strain gages) or due to new materials like composites. Conventional NDI technologies like C-scan and Eddy current have a low performance when applied to composites. Applications of thermocouples for engine HM and strain gauges for structural HM are reported. Nevertheless, the determination of loads during flight plays a minor role.

Several promising technologies in instrumentation, either NDI and flight instrumentation, and data processing have reached a maturity and performance level which fulfils the technological needs for advanced HM. Several candidate technologies have been investigated in system and technology studies in the context of the German TETRA and the European FESTIP (ESA) program.

Though intensive breadboarding, the feasibility of HM with sensor networks and advanced NDI could be verified. The investigation

included prototype development and flight application on board of NASA's X-38. Objective of this programs was the verification of HM for future reusable space transportation systems which summarize the most stringent performance requirements for aerospace systems at all.
An extensive literature survey has been carried out to identify candidate technologies with a high degree of maturity. Following technologies have been selected for technology development programs:

- Lock-In Infrared Thermography (IRT) for cracks and delamination detection in composites
- Laser Shearography for detection of structural degradation
- Acoustic Emission for online material damage determination
- Fiber Optic Sensor Network for multiplex strain and temperature measurement (load monitoring)

Introduction

HM is a rather new system task and there is no universal valid definition of HM tasks, objectives or processes available. In literature several references concerning HM technologies and applications can be found under the key words:

- (Structural) load monitoring
- Health and usage monitoring
- Integrated vehicle health monitoring
- Preventive/informed maintenance
- Health Management
- Validation instrumentation

Most of the literature describes technology developments or system concept studies about single sensor technologies and applications (e. g. load monitoring) on component and subsystem level. Many references can be found concerning HM requirements and functional architecture on system level.

Generally, the HM process is defined as the determination of the functional and structural integrity status of technical systems. The combination and diagnose of various sensor data enables the early detection of failures, failure functions and operational overloads.

There are literally hundreds of non-recurrent functions to be performed for an operational HMS, such as in data acquisition, data analysis, model development, component life usage tracking, maintenance, etc. From a functional architecture viewpoint, all these operational functions require timely access to relevant information in a usable form. This relevant "Health" information can than be used to trigger countermeasures based on the system condition, e. g. the reduction of loads during operation or scheduling of maintenance events.

The provision of this "relevant information" via suitable measurement and diagnostic technologies is a major technology development need of HM. In previous system and concept studies such as FESTIP (Future European Space Investigation Program, ESTEC) and TETRA (Technologies für Future Space Transportation, DLR Bonn) KT has identified the required technologies for future Reusable Launch Vehicles (RLV). In a next step, selected technologies have been investigated in cooperation with research partners on a breadboard level. Two technologies were identified for on-board application as passenger experiments on the U.S. re-entry demonstrator X-38. A first generation diagnose system was developed for post flight analysis on ground to assess the reliability and functionality of HMS. Advanced NDI has also been successful applied to ceramic composite material, which are used for the Thermal Protection System (TPS). First commercial spin-off's of the conducted technology development programs have been achieved.

In the following, the most promising measurement technologies are described in detail. Although all development activities have been focused on RLV requirements, those technologies have high potentials for aircraft application or even have been applied in aircraft technology programs respectively

Fiber Optic Sensor

A Fibre Optic Sensor with Bragg Gratings measures strain and temperature by means of wavelength shifts due to tensile stress on a Bragg grating. Bragg gratings are locally inscribed in the light guiding core of optical fibers using transverse UV laser illumination, which increases locally the refractive index of the fiber core, in a fringe pattern with periodicity L linearly related to the Bragg wavelength λ_B (Fig. 1):

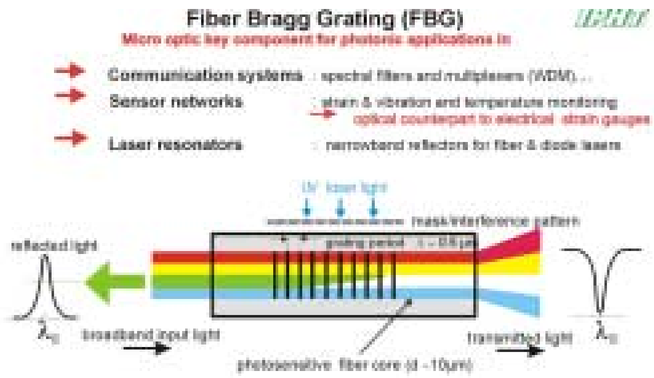


Fig. 1 Functional characteristic of fiber Bragg gratings

A super-luminescence diode as light source provides a broadband input signal in the fiber. When passing a Bragg grating, the light is reflected within the pre-selected narrow wavelength band around λ_B and read-out by a optical demodulation device, either spectroscopic or interferometric. Slight shifts in the reflected wavelength are proportional to temperature T or to strain ε or stress σ respectively which acts on the fiber at the grating location. Dependent on the fixation of the fiber to the structure, either floating or attached to the surface, local thermal or mechanical loads can be determined.

One of the main advantages of the fiber optic sensor is the multiplexing feature using one single fibre with various Bragg Grating without interference between the single measurement points. Due to the small fiber diameter (200 µm), the fiber sensor can be embedded into composite materials. Therefore, a complete primary structure, e. g. a tank, can be monitored with one single unit with a total system weight of 5 kg (sensor and signal processing unit – fig. 2).

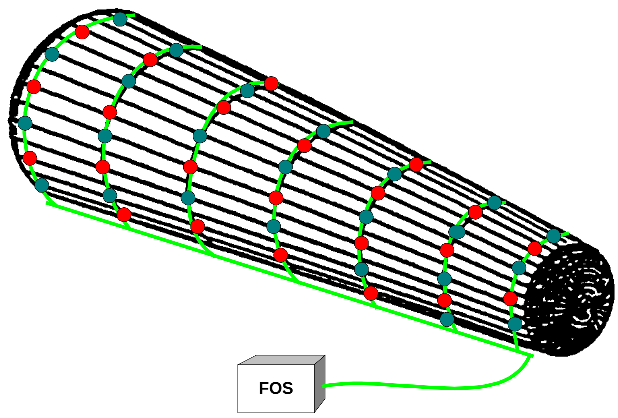


Fig. 2 Fiber optic sensor for tank monitoring

The challenging features of the fiber optic sensor technique based on Bragg Gratings are summarised in the following:

- Negligible cross sensitivity (strains in orthogonal directions) in comparison to strain gauges
- Long term stability at operation in hostile environments (chemicals, EMI, radiation, high temperature)
- Lightweight, small cross sections, robust and easy to implement
- Embeddability in composite materials (smart structures)
- Remote, electrically passive sensors with ideal galvanic separation (no spark ignition of flammable gases or explosive substances)
- Long signal transmission lines, almost loss-free
- Minimized harness (spatially multiplexed sensor networks)
- Measurement of local load distributions (discrete sensor points) along the same optical fiber or several multiplexed fibers, i.e. implementation of nervous system
- Potentials for low cost production

Development Status

Several measurement systems with Bragg gratings are commercially available for laboratory and initial applications in industry. For aerospace application commercial FOS systems are not yet available due to the environmental conditions, design requirements and flight vehicle interfaces.
The following applications of FOS provided by KT can be addressed:

- X-38

A first generation FOS measurement system for space application was designed and developed in the context of the German TETRA project (TEchnologies for future space TRAnsportation) by KT. The objective of this development within TETRA was to verify the feasibility to built a ruggedized, very simple, stationary FOS with limited performance characteristics (sample rate 1 Hz, 12 sensor, reduced resolution for strain and temperature monitoring).

Through intensive development tests, environmental conditions, interface problems like fibre attachment (embedding, bonding), separation of thermally and mechanically introduced loads and other technical concerns could be addressed and solved. The ruggedized FOS prototype which is already qualification tested according to space requirements (fig. 3) will fly on board of the X-38 Crew Rescue Vehicle (NASA).

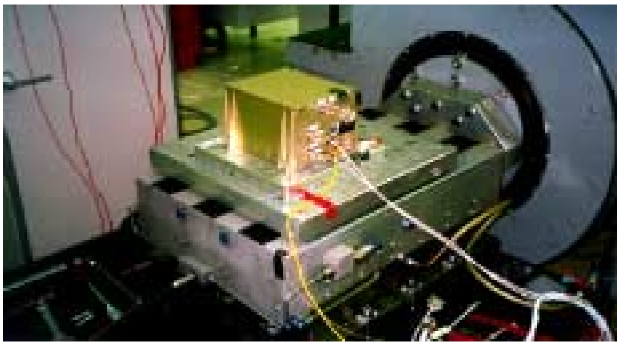


Fig. 3 X-38 fiber optic sensor on the shaker during verification

- CargoLifter CL 75 Aircrane

CargoLifter is a German company, based in the south east of Berlin, which develops airships for the point-to-point transport of heavy loads for up to 160 metric tons. In the context of the development of a technology demonstrator, the “CL 75 Aircrane”, KT developed a temperature monitoring system for the determination of the temperature distribution inside the envelope (fig. 4).

The FOS design for the CL 75 Aircrane bases on the existing FOS designed for space application on board of X-38. For the CL75 Aircrane the FOS system has been adapted to weather conditions (water tightness), lightning protection and to the different mechanical interface.

The fiber harness is divided into an internal and an external fiber section. The internal fiber is the actual sensor array fiber with the Bragg gratings which measures the temperature distribution inside the CL envelope. The 2 internal fibers are attached to a pulley system which spreads from the lower envelope side to the centre top.

Fig. 4 Side view of the CL 75 Aircrane during integration, diameter of the envelope is 60m

The fibre optic sensor prototype for the CL75 Aircrane has a total of 20 temperature measurement points with 10 measurement points per sensor array. The temperature range is from –20°C to +50°C with a resolution of ±0.5°C. The sample rate is 1 Hz. Measurement data are transmitted to the Aircrane data handling system via a RS422 interface.

- SME LET

In the context of the LET-SME initiative lead by ESTEC the existing fibre optic sensor measurement performance has been improved. Primary objective was the evolution from a stationary system with a long response time to a fully dynamic sensor enabling 1000 Hz sampling rate with an excellent strain and temperature resolution. This feature allows to measure directly dynamic loads (e.g. strain) to determine structural integrity instead of ambiguous computations from accelerometer data. Furthermore, the amount of measurement points was increased from 12 up to 50 and several features have been optimised

Current Activities

- Composite cure monitoring

Real-time cure monitoring of composite material is very important to improve the fabrication process of advanced composites. With conventional methods it is very difficult to monitor the cure process online. A fiber embedded between plies provide a unique opportunity to process the flow of the resin and the curing process in real time.

- Solar Sail

The application of optical fiber sensors at the CFRP booms of the Solar Sail (fig. 5) is considered due to the lightweight feature of FOS. The functional intention is the measurement of the boom bending during operation.

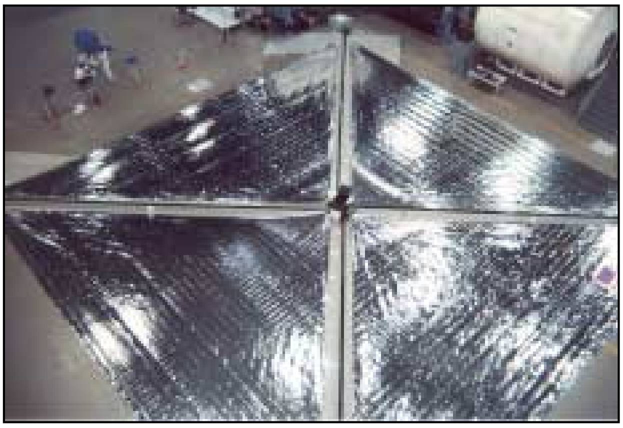


Fig. 5 Solar Sail Boom

- Aerostatic Monitoring and Control System

The satisfactory performance of the FOS in the CL 75 Aircrane by our customer CargoLifter has been proved by the assignment of a development contract for the actual CL 160 airship in December 2001.

The next generation FOS will monitor a total of 50 measurement points distributed inside the envelope. For safety reason a basic temperature system based on conventional temperature sensors will also be installed. If the FOS proves to be reliable in regard to airship regulations and improves the CL160 operation capabilities, the sensor will be part of the CL 160 standard instrumentation (fig. 6).

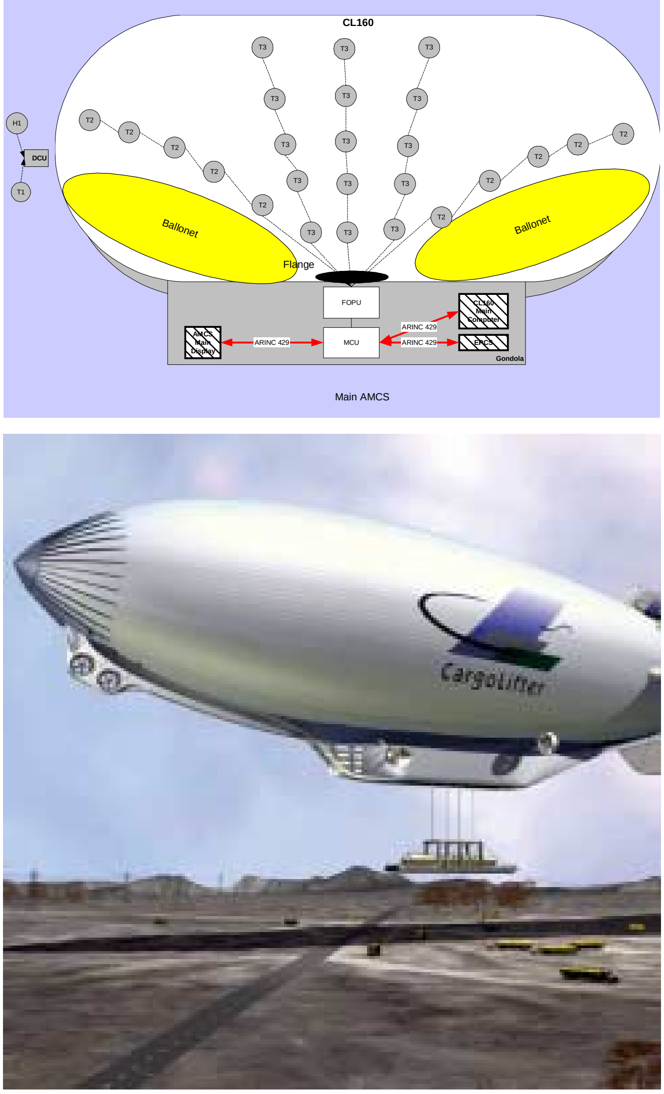


Fig. 6 Scheme of FOS integration in the CL160

- Structural Health Monitoring

In the context of the German ASTRA program (Ausgewählte Technologien für zukünftige Raumtransporter), a continuation of the RLV technology development activities from TETRA, the feasibility of structural HM with fiberoptic sensors on subsystem level shall be demonstrated. Therefore, a structural element, representative for primary RLV structures, has been selected in co-operation with MAN Technology, Augsburg. A composite watertank (fig. 7) from the Airbus family will be equipped with up to 50 FOS sensor for temperature/strain measurements and conventional instrumentation for comparison measurements. Based on FEM analysis and load distribution the measurement points will be determined. The small dimensions of the watertank allow the introduction of loads with reasonable expenditure. Via repeated load scenarios the structural integrity shall be decreased. The investigations will be carried out at the LLB (Institute for Lightweight Structures, Technical University Munich). The data processing concerning life consumption and remaining lifetime shall be supported by NDI.

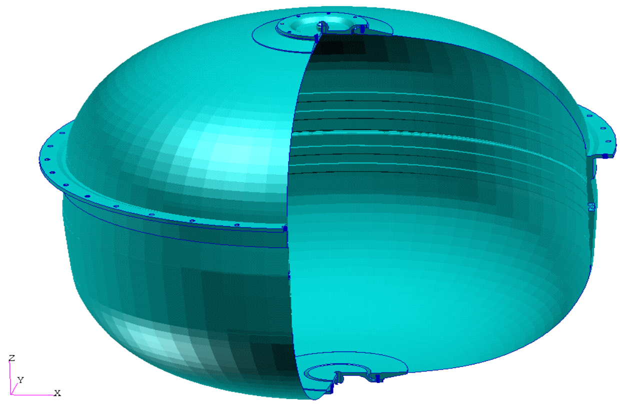


Fig 7 Airbus watertank
(courtesy of MAN Technology)

Acoustic Emission

When subjected to high thermal and mechanical loads cracks emerge or continue growth in materials, specially composite materials such as the C/SiC matrix. Continuous crack growth weaks the material strength, but is admissible within limitations. These cracks emit a characteristical acoustic emission signature featuring high power amplitude (up to 100 dB in case of composites) in a high frequency range (from 20 to 1000 kHz). With an Acoustic Emission (AE) sensor, this signatures can be filtered out and distinguished from environmental vibroacoustics. The accumulated AE events can be used for material degradation assessment. Fig. 8 illustrates the AE course of a specimen (carbon reinforced ceramic) under quasistatic load up to fracture.

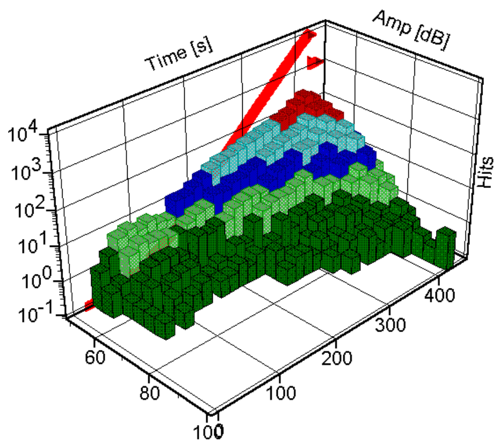


Fig. 8: AE course during quasi-static loading

In the context of TETRA, Kayser-Threde has developed an AE sensor for structural integrity control of the hot TPS up to 1600°C. The AE sensor consists of the of a piezo-ceramic sensor as sensor element, a waveguide to guide the AE from the hot structure to the piezo sensor (temperature max.: 120°C) and a signal processing unit.

Several tests on specimen and the X-38 nose cap qualification model have been carried out. Objective of this test was to find a coherence between the accumulated AE and the structural integrity of the specimens. The test specimens have been subjected to thermal and mechanical loads under simulated environmental conditions (vacuum, low partial pressure). The tests have been performed stepwise to distinguish specific loads and their affects upon the material. The prior picture illustrates the AE course under stepwise increased static load. Characteristic AE parameters are the amplitude of the hits and the number of hits in a fixed time window. A rough estimate for life consumption is the augmentation of amplitude and hits shortly before fracture of the specimen. The characterisation of structural integrity via AE is simple when the specimen is only subjected to a unique load case. In case of overlapping load cases (shear, stress, compression, buckling, thermal loads, etc.) the assessment is more difficult and only qualitatively. A further complexity increasing item is the design of the test item itself. Simple rectangular specimens experience only little disturbances through AE reflections, attenuation through composite matrix and long distances and time-shift phenomena (same event is counted two times because of different wave propagation modes).

Next figure 9 illustrates the nose skirt of the X-38. During re-entry, two AE sensors will record the AE of the C/SiC structure. For structural integrity assessment complementary parameters will be recorded such as strain, temperature and trajectory parameters.

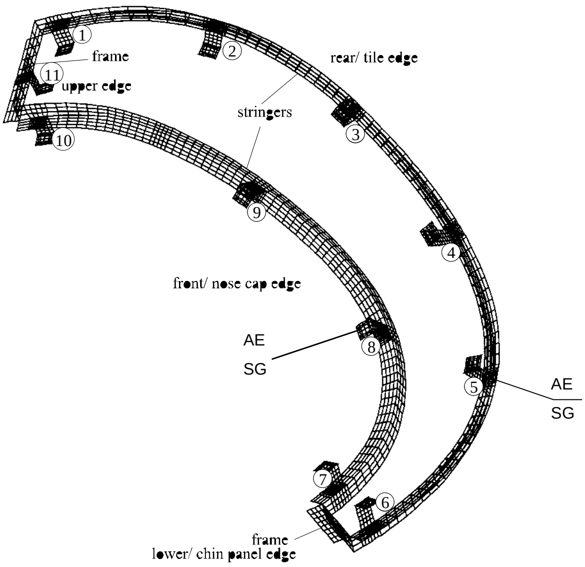


Fig. 9 Nose skirt with AE sensor positions

The nose skirt qualification model has also been instrumented with AE and subjected to mechanical and thermal loads. Next figure 10 shows the AE signals in relation to the temperature of the nose skirt qualification model in the cooling down phase.

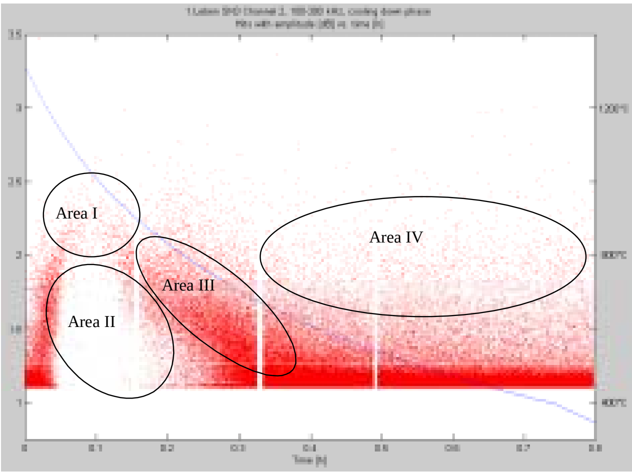


Fig. 10 Acoustic emission signals during cooling down phase

The AE signal graph can be divided in four characteristical areas:

- Area I: High density of high amplitude hits at high temperature (1200°C – 900°C)
- Area II: "White area", no single hit events extractable which means a long lasting burst without interruption
- Area III: Decreasing AE amplitude but many hits at decreasing temperature (900°C – 600°C)
- Area IV: Lingering sound (from 600°C to ambient)

Note: The figure provides the AE lists with amplitude [dB] versus time [h]. Additionally the cooling down curve (temperature [°C] versus time [h] is given).
All this areas have been quantified for the 5 test runs (2 pre test, 3 repetitive re-entry tests, carried out at a re-entry test chamber at IABG, Munich) and compared with each other. Although this assessment is very qualitative, deviations in the AE signature could be found. The AE increased considerably from the pre-test to the first re-entry test run due to the higher thermal loads. This has been expected due to the presumption that AE only emerges in case of micro-damage. Once a structure has experienced the highest load, the AE decreases to an ongoing wear level . In case of the nose skirt, we discovered an increase of the AE between first and second re-entry tests which indicates that the nose skirt has experienced further damage. A further interesting outcome of the investigation is the lingering sound in the cooling down phase. Most AE events occur in this phase, when the structure has cooled down to 600°C up to environmental temperatures. This phenomena is related to the reduction of internal strain forces due to deviating transversal and orthogonal thermal extension coefficients in the composite matrix. The AE in this phase indicate, that most structural damage occur in area 4.

NDI Technologies

The identification of critical conditions in primary structures is a complex task with regard to the coherence of the involved components, assembly and affecting mechanical and thermal loads. Thorough knowledge about stationary/in-stationary and

regular/irregular system conditions is mandatory. Statistical evaluation of test data obtained in test runs and during operations or analytical investigations have to be performed in order to identify all significant critical conditions.
The fault events involved in the course of critical condition do not always have the same linear or temporal size. Subsequently, these different sizes result in different sample rates of the concerning measurands. The temporal course of crack propagation, for example, is relatively continuous until shortly before failure event of function. Measurands, whose temporal course is short (some missions only) and not critical, do not necessarily need to be monitored in-flight. The division of monitoring task in in-flight and on-ground (between loads) monitoring results from the varying fault events.

Load monitoring can not determine directly flaws such as cracks and delaminations. Only when the size of the flaw has reached a dimension which changes the characteristics of the structural response the flaw might be detectable. Such suspicious indications must be investigated and assessed with suitable on-ground (between load cycles) measurement systems. Non-Destructive-Inspection methods such as X-ray, C-scan, etc. have been proven to identify flaws in different kind of materials during maintenance and inspection. For a complete HMS therefore the complementary investigation of the structural integrity with inherent (on-line) load monitoring and off-line verification with NDI is mandatory.

Non destructive inspection (NDI) tools, successfully applied in many industrial fields, have demonstrated their substantial importance for structural integrity assessment of critical components. Standard NDI methods such as Eddy current and C-Scan have a low performance when applied to composite materials. Therefore, the potential of innovative ground based NDI methods have been investigated. Typical defects such as matrix/Fiber cracks, delaminations, impact damages had to be detected with sufficient reliability and resolution. Either coupon tests or in-situ tests of complete subassemblies have been performed. The investigated methods were:

- Lock In IR-Thermography
- Dynamic Phase Shift Laser Shearography

Lock In Infrared Thermography
Thermal inspection techniques determine inhomogenities inside materials on non steady thermal conductivity processes stimulated by well defined pulse or periodic heating of the inspected objective. In contrast to pulse excitation the Lock In Infrared Thermography (IRT) works with a steady, sinusoidal heat or ultrasound excitement, which produce a harmonic heat wave inside the material. Local thermal inhomogenities such as flaws, delamination, cracks and anisotropies inside the material reflect the steady thermal wave. The local time delay between heat flux and temperature distribution provide a phase shift on the surface of the inspected object. The phase image is recorded by specially adapted infrared camera system. This NDI technique was successfully applied to the X-38 TPS material (carbon Fiber reinforced ceramics). The flight hardware was investigated prior to load cycles and after in order to determine changes in the material properties (fig.11).

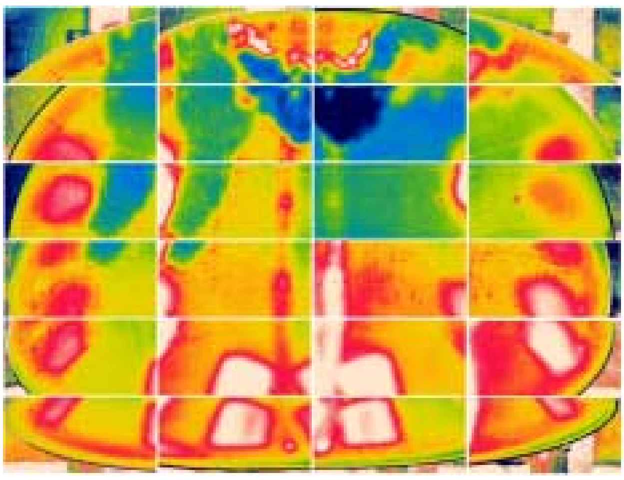


Fig. 11: Lock-In Infrared Thermography image of the X-38 nose cap, delaminations are blue colored (courtesy DLR,Stuttgart)

Laser Shearography (LSG) detects changes in the surface of a stress component with a single laser beam to unprecedented levels of precision and reliability. The technology no longer needs an optical bench to find small flaws in large composite structures. LSG illuminates the test objective with a single beam, which reflects off points on the surface to create a speckle pattern. Special optics shear the image of the surface by focusing light from adjacent speckles onto individual pixels of a camera. The intensity of light at each point in the sheared speckle pattern is the sum of light reflected from two points a few millimetres apart on the surface of the object. When introducing load into the test objective, by heating or with a local applied vacuum, the speckle intensity is modulated proportional to the in-plane strain distribution. LSG is applied for finding defects in curved panels from the Ariane 5 rocket or examine helicopter blades from Eurocopter. Next figure 12 illustrates the strain distribution caused by a delamination in a C/SiC panel.

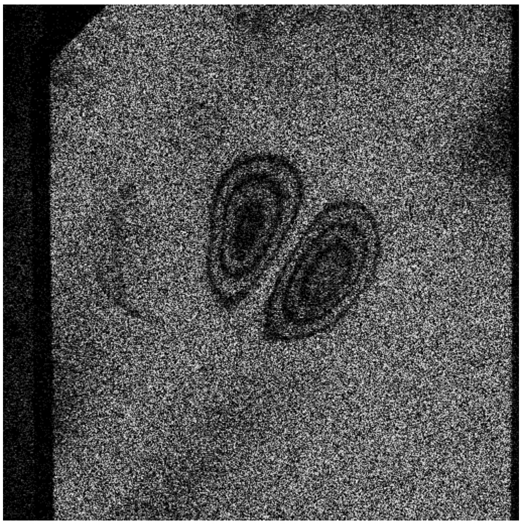


Fig. 12 Examples of Laser-Shearographic Measurements, strain deviation indicates a delamination in a C/SiC panels (courtesy DLR,Stuttgart)

The application of those advanced complementary dynamic methods provides significant gain in terms of resolution, environmental in-sensitivity, in situ applications, etc. compared to the more conventional Pulse IR-Thermography and Shearography methods and enable even a quantitative indication of defects. The achieved functional performance is mandatory for the required reproducibility and efficiency (minimized efforts for large area scanning).
The major advantage of both technologies is the application on site. The test coupons and thrust frame demonstrator can be investigated on the testbed without the need of dismounting or additional laboratory equipment. Scanning can be performed from one side only, though only visible access to the structure under investigation is required.

HMS Platform

Also in the context of ASTRA, a HMS platform is currently under development (fig. 13). The HMS platform will improve the measurement performance of both NDI technologies and allow the correlation of them. Innovative image processing algorithm will filter erroneous data from environmental conditions, correct misalignment, etc, all features which have required a lot of expertise in recording and which where related to a low reproducibility and low reliability.
The HMS platform shall be applied to scan the test coupons and thrust frame demonstrator for flaws between loading. All required hardware and software can be brought to the testbed and be operated with minor impact on the test setup. Such kind of impact would be visible access to the test objects, dependent on object size scanning time up to one day and sufficient space at test site for handling of NDI system. Before the actual application, the HMS platform had to be trained (test survey) to the used materials (not more than 2 materials).
The output of the HMS platform is a reliable and reproducible scan of the material or object under investigation. Potential cracks and delamination shall be detected and quantitatively assessed. After each single load cycle flaw propagation can be determined and be used for assessment of structural integrity.

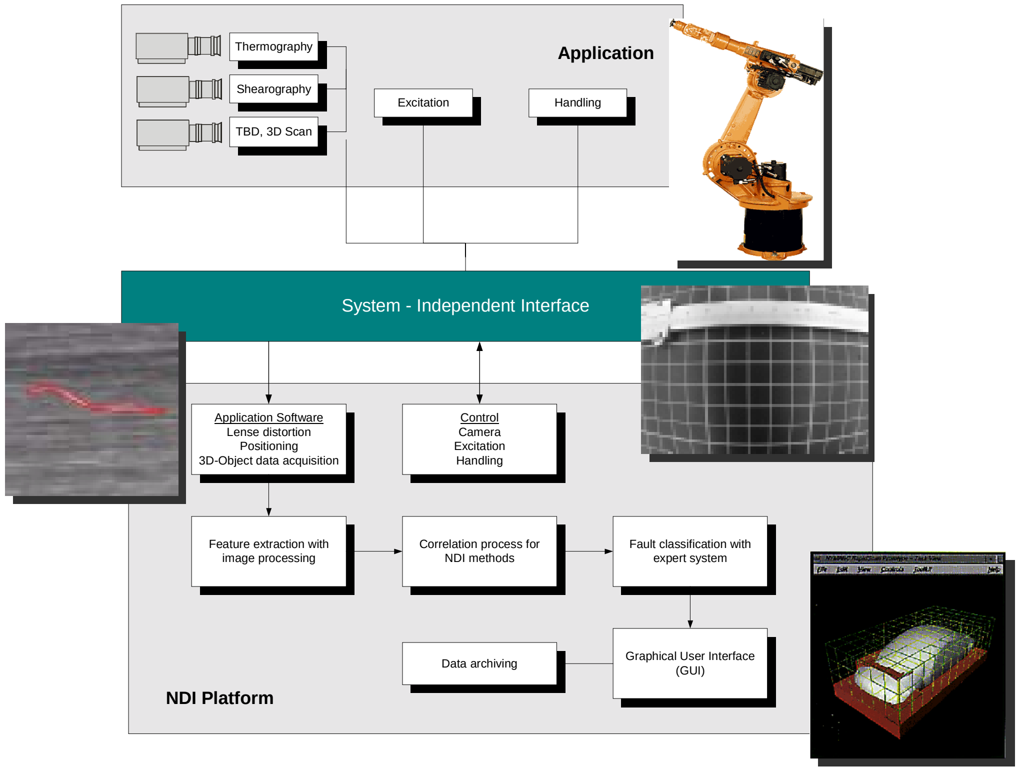


Fig 13 Functional architecture of the HMS platform

Exhaust Plume Spectroscopy
When engine components experience wear due to degradation or failure, material particles may be entrained in the gas/liquid flow. The particles are burning with the propellants in the combustion chamber. When leaving the engine via the nozzle, the particle emission can be monitored by absorption/emission spectroscopy. The existence of particles of a degrading component provides an early warning compared to conventional measurement.
In the ASTRA program a breadboard for optical plume spectroscopy shall be designed and manufactured and applied at injection system test bed (ASTRIUM) and turbine test stand of the LFA (Institute of Propulsion System, Technical University Munich)

Conclusion

All the in this document describes HM measurement technologies have been developed and investigated for application on future reusable launchers. Due to the high loads and stringent lightweight requirements do RLV systems require HM functions to keep operational costs down. In the case of the Space Shuttle, refurbishment costs are so high, that expandable rockets are even cheaper. To avoid this contradiction of reusability and higher costs, future RLV will be equipped with advanced HM systems.
Reduction of operational costs is also an important issue for aircraft. Many research and development activities prove that HM plays a major role for the improvement of aircraft operations.
The investigations of the described measurement technologies proved the feasibility to apply advanced sensors to save mass, to increase the number of measurement points or measurement performance. All technologies have a high maturity level and can be easily applied for commercial operations.

Many potential applications of HM technologies have been identified in aviation, power and plant engineering. A first commercial spin-off of the fiber sensors could be realized with the application for the CargoLifter CL 75 Aircrane. For the future we intend to find more applications for the existing technologies in aviation and other industrial branches and furthermore to broaden and deepen our technology base.

Acknowledgements

The development of the HM technologies contained in this article have been funded by DLR-Bonn, Bavarian State, ESTEC, Cargolifter and internal development and research resources of KT. Furthermore we like to thank our partners for the good cooperation during the development and test work.

- TETRA partners (DLR-ST, MT, ASTRIUM)
- ASTRA partners (DLR-BO, MT)

References

1. I. Latka; W. Ecke; B. Höfer; R. Willsch; A. Reutlinger; C. Luffman; "Optical Fiber Grating Gas Temperature Sensor Network in Airship", OPTO 2002, Erfurt

2. R. Graue; A. Reutlinger; "Structural Health Monitoring for Future Launchers: Results from Breadboarding and Prototype Development"; Structures and Technologies – Challenges for Future Launchers; CNES; 2001, Strasbourg

3. R. Graue, A. Reutlinger, Importance and Methods of Structural Health Monitoring for Future Launchers, Cost F3, 2000, Madrid

4. J. Fox, T. Gormley, Informed Maintenance for Next Generation Reusable Launch Systems, IAF-00-V.5.09, 51st International Astronautical Congress, 2000, Rio de Janeiro

5. S. Cook, D. Dumbacker, NASA's Integrated Space Transportation Plan, IAF-00-V-0.3.01, 51st International Astronautical Congress, 2000, Rio de Janeiro

6. R. Graue, A. Reutlinger, X-38 Structural Health Monitoring, IAF-00-I-0.4.02, 51st International Astronautical Congress, 2000, Rio de Janeiro

7. H. Mosebach, A: Hönle, A. Stichternath, E. Gabriel, X-38 Vehicle Analysis Data Recording System (VADR), AAAF, 1999, Arcachon,.

8. R. Graue, A. Reutlinger, Health Monitoring Flight Demonstration on Board X-38, AAAF, Atmospheric Re-entry Vehicles and Systems Symposium, 1998, Arcachon

9. R. Graue, M. Krisson, M. Erdmann, Integrated Health monitoring Approach for Reasonable Cryogenic Tank Structures, AIAA-98-1593, International Space Planes and Hypersonic Systems and Technology Conference, 1998, Norfolk

THE TOPOLOGY OF AIMS DATA TRANSFER STRUCTURES

Mr David Jesse

BSc CEng MIEE MIMechE MRAeS

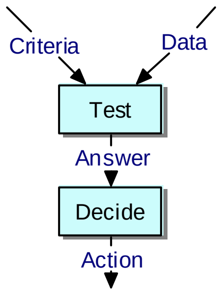
Flight Data Services Limited

14 Brookmeadow
Fareham
Hampshire
PO15 5JH
United Kingdom

www.flightdataservices.com

THE MONITORING PROCESS

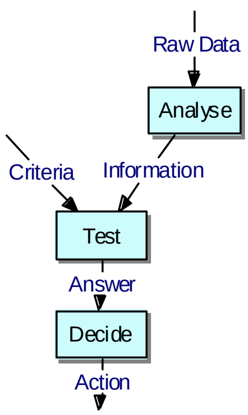
This presentation starts by examining the most basic form of monitoring. Here we have a piece of data and some criterion used together in a test. The result of that test will usually be binary in nature. For example, if I wanted to boil an egg, the criterion is that the water should be boiling. If I look at the water and see bubbles, then the result of my visual test will be that the water is boiling. I then make a decision to put the egg into the water and the action is straightforward (unless I drop the egg!).



This is a trivial example, but is used to illustrate that we have started from a very basic starting point.

DATA PREPARATION

It's not usually possible to gather data as readily as described in the opening example. If I get out of the kitchen and back into the air, we can consider the case of a glider pilot looking for rising air. The variations in air pressure that he seeks to tell him that he is going up rather than down are very small, and he certainly can't tell them by the changes in pressure on his eardrums. We therefore need some means of converting the Raw Data (static air pressure) into meaningful information (rate of climb).



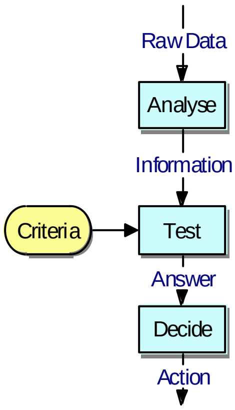
The pilot can then recognise if he is rising as fast as he needs to – his criteria may vary, depending upon the circumstances - and act to turn the glider into the thermal.

You might argue that this is a control function, but in many ways, monitoring and control have close parallels and there is a large degree of overlap.

TEST CRITERIA

When we examine monitoring functions, it is more commonplace for the criterion for a test decision to be fixed. Particularly in the engineering field, it is usual for the test values to be defined by the aircraft manufacturer or such like. Alternatively, the criteria may be quasi-static. For example, if a number of airlines are going to compare OFDM data for a part of their operation, it is necessary for them to agree upon the criteria and to all use the same test techniques for the resulting answers to be meaningful.

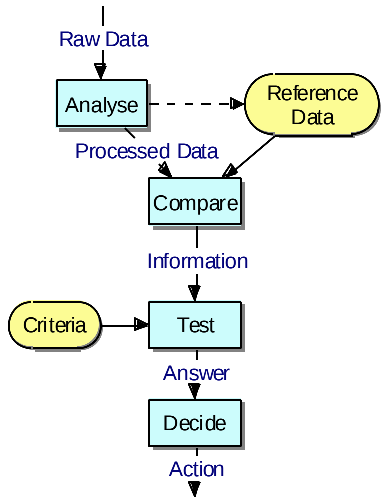
I have adopted a consistent symbology for these diagrams, with entities on the arrows, processes in rectangular boxes and storage as ovals, as shown in this next development of the topology.



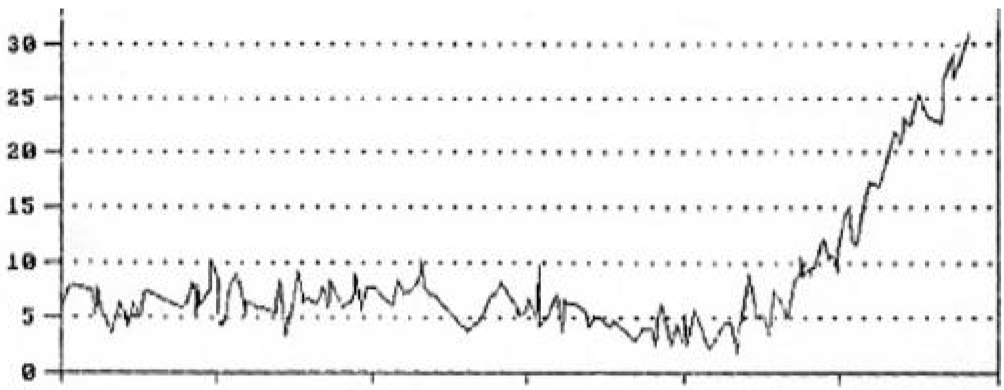
This is a good representation of many on-aircraft monitoring functions. Aircraft with multiple attitude references typically have a monitor that analyses the difference between the sources of attitude data and if the difference is excessive, alerts the pilot. At this point the pilot decides what to do by following the Flight Manual procedures and takes the appropriate action. Notice that the action may also be the wrong action, such as shutting down the wrong engine, or the decision may be to take no action.

DATA ANALYSIS

Data can be assessed against static criteria in many cases however we can obtain better (by which I mean more sensitive, more meaningful or more timely) information through the use of Reference Data Sets. These can be simply looking at a gauge long enough to see if the oil temperature is rising fast or slowly, comparing the engine readings with readings from an earlier flight or looking through records for a trend over many flying hours.



The key element of Reference Data is that it is derived from the same data as used in the core monitoring process, and so provides an element of feedback (or feedforward) to improve the usefulness of the data. As an example, here is a trend with flying hours as the timebase. This graph is actual aircraft data, and may be recognisable to some of you. The key thing is that, without knowing what this parameter represents or what the scales are, you can see that something is happening in the latter third of the graph by comparing individual values against the historical record.



THE NEED TO ESTABLISH COMPLETE TREND DATA

While Reference Data is invaluable in increasing the sensitivity of the monitoring functions, it brings with it significant data management problems. No longer do we have a system that you can turn on and get predictable results. We now have a case where the results rely upon the history of operation and the Answers will be different from one instance to another.

MILITARY CONSIDERATIONS

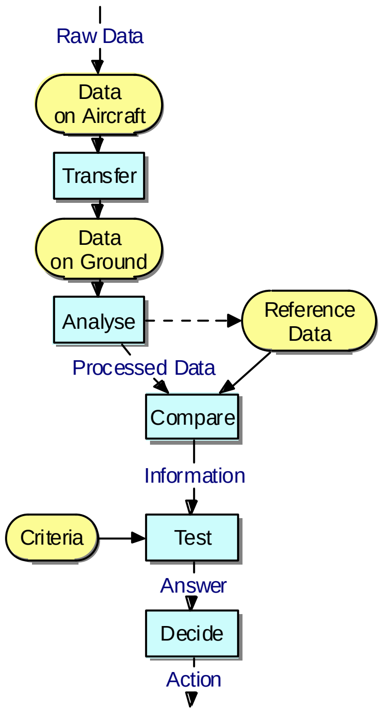
Military operators often prefer, for sound operational reasons, for the aircraft to be "self contained" and capable of operating with minimal support infrastructure. In these cases Reference Data is usually gathered on the aircraft and stored within the avionics system. The prognostic system is then able to use that aircraft's historical data to estimate the hours that can be flown before maintenance is required. This "maintenance free operating period" philosophy is becoming a requirement for new aircraft or system upgrades. The problem arises when equipment on the aircraft suffers a malfunction. If all of the available data is lost, then either the newly installed equipment will give a sudden monitoring change or procedures have to be put in place to provide redundancy in the data storage.

There are also many attractions for airlines to have on-board monitoring system, because degradation of mechanical and avionic systems can be identified in flight and the necessary spares and maintenance crew can be readied at the next port of call to minimise aircraft down time.

DATA TRANSFER

In most forms of monitoring that require sophisticated diagnostic techniques and perhaps expert analysis, it is preferable to transfer the data to the ground and process the data on a ground-based system. This permits high power, low cost computers to be used and the algorithms can be adapted and refined without incurring the burdens that are placed on avionics software.

There is also much to be said for making difficult engineering decisions when the aircraft is on the ground as there is usually less stress involved than making the decisions when the aircraft is airborne.



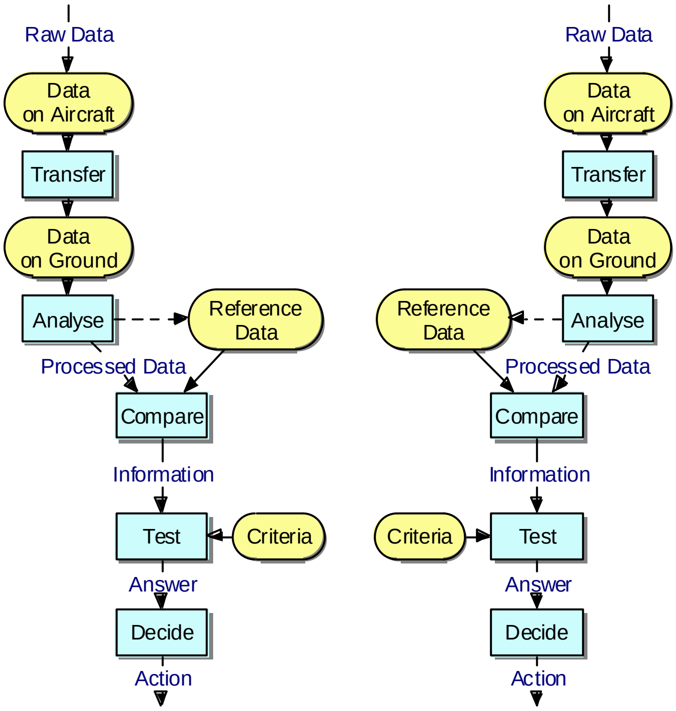
Here we have the familiar on-board data storage, usually a Quick Access Recorder, and a Data Transfer process.

DIVERSIONS

When an airline has a very simple route structure, it may be possible for the aircraft to all land back at the main operating base at the end of the day and for a single analysis station to cater for all of the data. However, as soon as there are two analysis stations (either because the airline has two operating bases or because they fly to a distant airport and need to analyse data there) a problem of synchronising two sets of data arises.

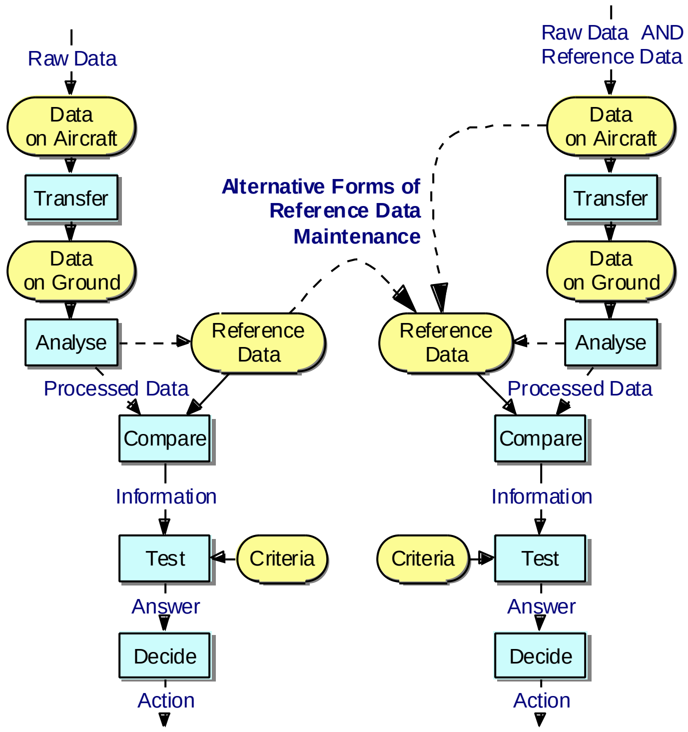
It is this problem of managing Reference Data Sets at multiple locations that makes the aircraft monitoring system different from most other monitoring systems.

Let me illustrate this by initially drawing the previous diagram as two mirror images.



Clearly, the criteria for testing will be the same in both locations, and so maintaining these to be the same is usually a straightforward configuration control problem. More difficult is the Reference Data. If an aircraft can land at either airport, it is essential that the Reference Data Sets are kept in step with each other so that the results of the analysis are the same. Imagine the problem if, for example, an engine trend illustrated a problem in Paris, but that the problem went away whenever the aircraft landed at Rome!

There are two options for managing this issue. Either data has to be passed between the Reference Data Stores directly, or the aircraft can carry it's own Reference Data to update the computer prior to analysis. "Pulling yourself up by the boot laces" so to speak.



There are advantages and disadvantages to both of these Reference Data Maintenance schemes. Connecting between analysis computers is a good option for establishing a complete data trend in all locations and does not require an aircraft to download for the data to be updated. This is particularly significant for specialists who might need to browse data on a computer away from an operating base.

However, as an aircraft can be diverted in mid-flight, it is not possible to predict which analysis computer will need fresh Reference Data and so this process cannot be relied upon to provide the required data under all circumstances, unless it is implemented as a continuous, automatic function.

COMPLEXITY

So far, I have only shown an example involving two analysis computers. The problems of maintaining valid Reference Data Sets on multiple computers grow as the number of computers grows and where there is any difficulty in transferring the data from one analysis computer to another. I know of cases where two computers a few miles apart were almost always out of step with each other because there was no direct connection, and data transfer was by making a tape and driving from one airfield to the next, whereas an Australian operator managed to keep his computers perfectly synchronised even though they were some 2,600 km apart, just using modems to transfer Reference Data Sets.

There is a price to be paid for maintaining concurrency of multiple analysis computers. This is seen in the manpower, data transfer costs and software costs to implement this type of arrangement.

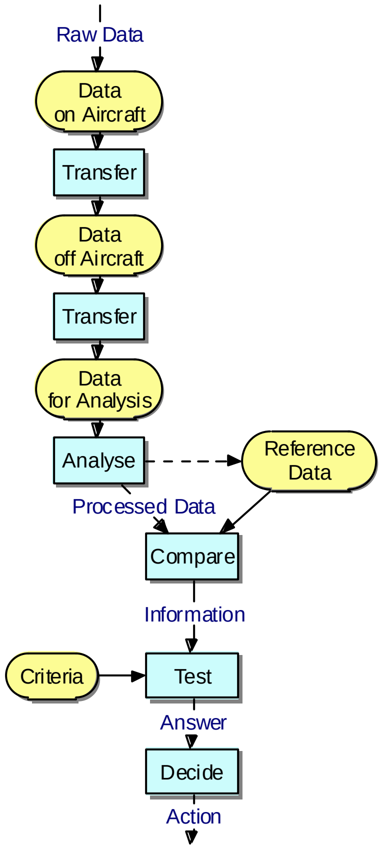
EXPERTISE REQUIREMENTS

There are three types of expertise required to operate, maintain and develop aircraft monitoring systems. So far, we have referred to a decision maker, who will typically be an Engineering Manager or Flight Safety Officer, who decides what action to take within the airline. He collates the "Answers" from the monitoring system with other information to make a final decision, and carries responsibility for the selected action. Secondly, there are the designers who specified the analysis algorithms in the first place. A third group are the system operators who run the system on a day-to-day basis.

No matter how small the number of aircraft for which data is being analysed, we see an almost organic process whereby one or two people will be nominated to run the system. Almost without exception, they find that this takes more time than they expected. As their degree of knowledge and understanding grows, they become the in-house "experts" and the task of data analysis grows until a small department has been formed. Whether this is by intention or evolution depends upon the organisation, however this has been seen so often as to be almost a rule.

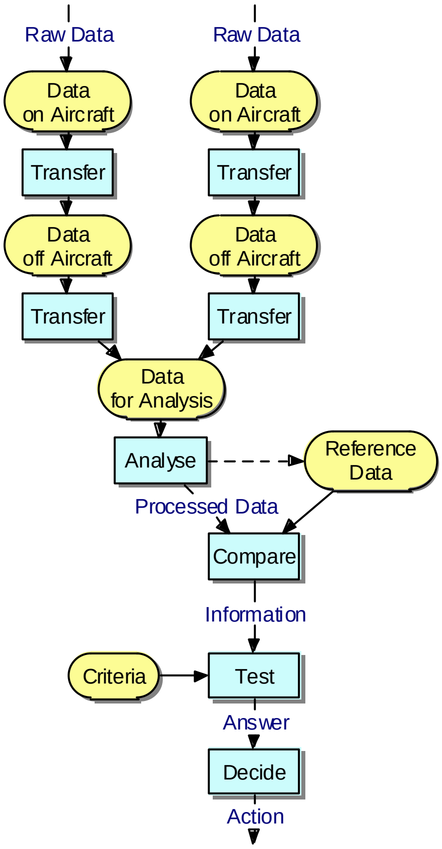
When an operator decides to set up a monitoring system, they will estimate the manpower required to operate the system. This is often under-estimated drastically. For example, at the recent Lisbon conference, one operator had started with an allocated one day per month to analyse data from about 12 aircraft. On average, in the UK, one full-time analyst handles 11 aircraft so this airline underestimated the task by a factor of about 20!

One solution to this is to bring data from a large number of aircraft into a central point and, in so doing, centralise the expertise needed to obtain good information from the data. To achieve this, we need to go back a step and reorganise the system topology. Let us look back at the basic, single analysis process situation and add another stage of data transfer:



This is more realistically what happens, as the data will have been transferred off the aircraft and buffered in some way before being analysed.

Using this structure, we can now add a second aircraft without the need to duplicate the core analysis functions:



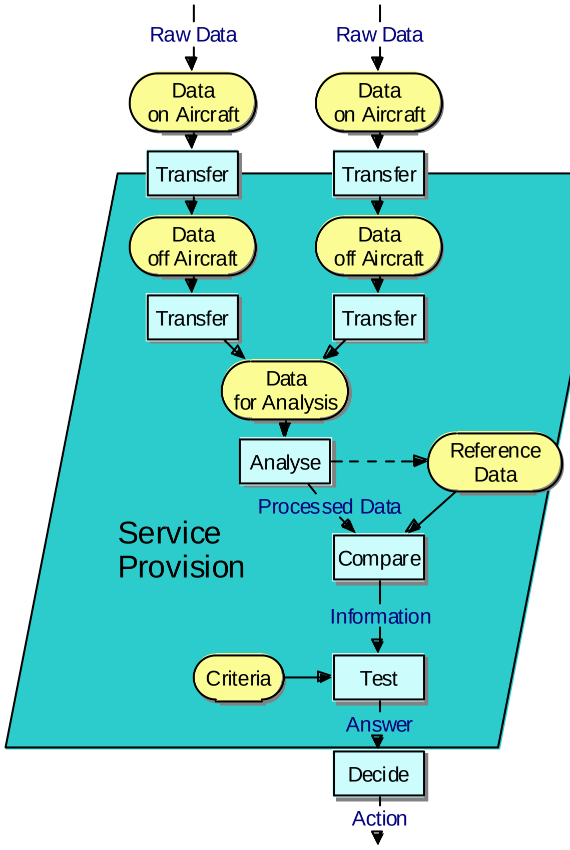
If the "Data off Aircraft" to "Data for Analysis" is implemented using the Internet we now have a system where aircraft from anywhere in the world can have the data analysed at a single analysis computer.

Transferring large quantities of flight data across the Internet may appear difficult, but there are two factors that make this easier. Firstly, ARINC flight data has certain characteristics that mean that the file sizes can be reduced significantly at the same time as the data is encrypted for secure transfer, and secondly, higher speed connections to the Internet are now more commonly available. As an example, the standard flight data recording from a 12-hour flying day can be transmitted over plain telephone lines in about 40 seconds and in as little as 16 seconds when using ADSL.

There are concerns about the reliability, privacy and security of Internet data transfer, particularly if the data could be identified as relating to a specific flight and therefore to a specific crew. These concerns also relate to individual and corporate use of the Internet, for example the use of credit cards on-line or transmitting proprietary data. In response to these concerns, some sophisticated security technologies are now available. Point-to-point tunnelling technology and 128-bit data encryption are examples of the techniques that can be used to provide the necessary high levels of data security.

PROVISION OF ANALYSIS BY SERVICE PROVIDERS

It is with the introduction of Internet data transfer that it becomes a realistic possibility for an airline to elect to pass the data analysis task to a third party. A good OFDM Service Provider will have the expertise required to set up and operate the OFDM system for an airline and to manage the configuration of the Criteria and Reference Data Sets, thereby saving the airline from developing this expertise in-house.



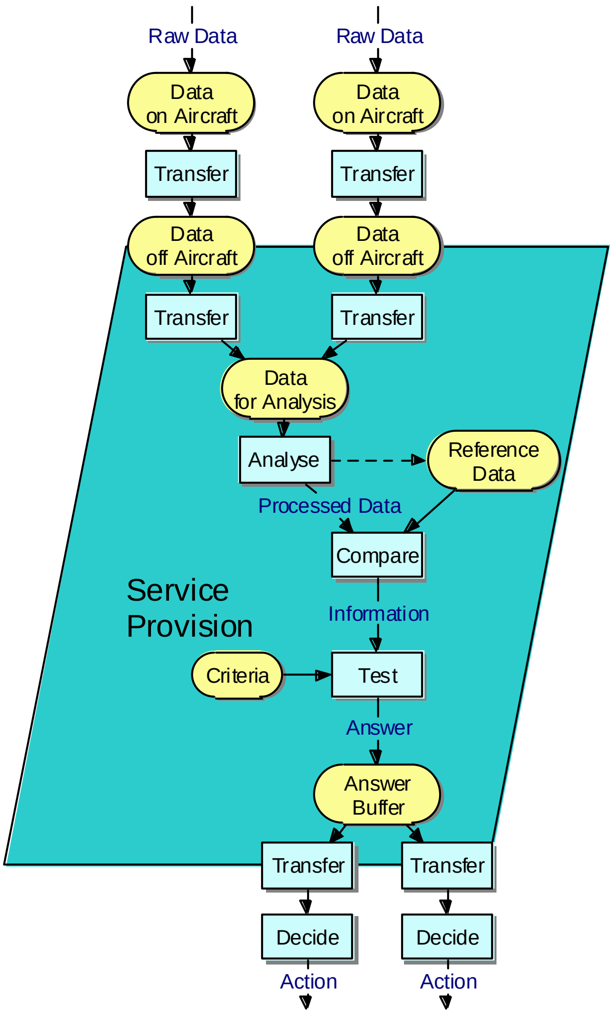
Furthermore, there are some advantages to a small airline that are not directly related to the system topology, but rather to the integration of the OFDM process to the rest of the airline. Two examples cited by the International Federation of Air Line Pilots' Associations (IFALPA) are the inability of small airlines to separate Flight Safety from Flight Operations matters, and the difficulty to preserve the anonymity of aircrew within the airline. Both of these are easier to manage if the data analysis is separated from the organisation and carried out off site by specialists who do not know the airline personnel.

TIMELINESS AND DISPERSION OF ANSWERS

The important practical effect of separating the analysis process from the aircraft is that the results of analysis are no longer adjacent to the maintainers and operators of the aircraft. If the decisions relate to short-term maintenance actions, this can be a real problem and delays in data transfer may make this topology unsuitable in these cases. For example, this topology could be used for engine trending, but may be inappropriate for engine exceedance reporting.

For most flight safety related issues, however, a short delay is not a problem because decisions are not made at the aircraft. We are therefore in a position of transferring the "Answer" from the analysis to the person responsible for making a decision – in the case of an OFDM system, the airline's Flight Safety Officer.

Many airlines like the FSO to be an active line pilot and so it is unlikely that he will be sitting at his desk when the results of the analysis process become available. For these reasons, we need to include a buffer for results and a means of remotely accessing the Answers.

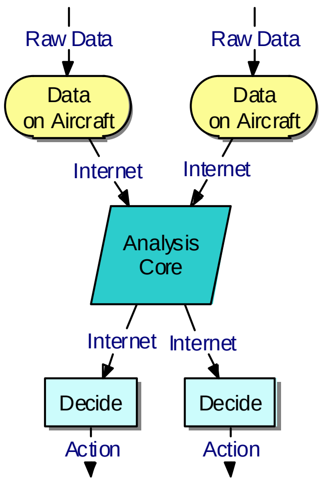


DECISION MAKING IN MULTIPLE LOCATIONS

As you can see, I have jumped forward a stage by assuming that there will in fact be multiple potential "customers" for the results of the data analysis and that therefore this type of system will have to cater for many decision makers. Engineering, operations and flight safety are the obvious candidates in this regard.

Furthermore, there are some operators who have operations and engineering centres not just in different buildings but in different airports. Clearly, if the system includes the ability to transfer answers to each decision maker, this is not a problem, however the system must incorporate adequate security and segregation facilities so that users can only access the information they are authorised to see.

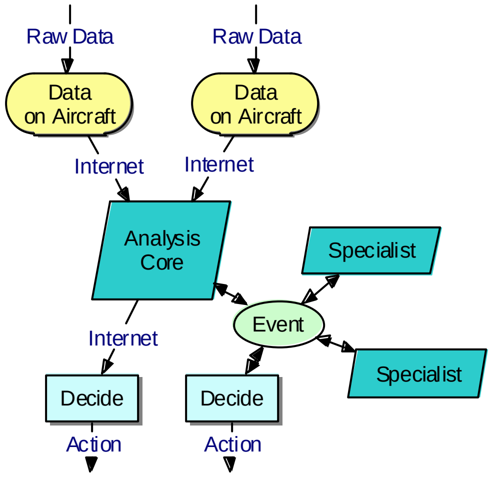
In the same way that one can use the Internet to gather data from the aircraft, so it can be used to transfer data to the decision makers. If the core part of the analysis is condensed diagramatically, we have a system diagram like this:



Here, the aircraft data collection and decision making processes have been isolated from the "mechanical" task of converting raw data into analysed facts.

THIRD PARTY EXPERTISE

There are some highly specialised areas of analysis and diagnostics where an operator needs to obtain the advice of particular companies or individuals. For example, engine performance trend prediction and helicopter transmission defect identification. Here, the rapid and efficient transmission of data allows these "third tier" experts to be involved in the support of the aircraft. I have, in fact, been involved in cases where the operator, analysis service provider, diagnostics specialist and aircraft manufacturer were all working collaboratively to determine the nature of a problem and agree upon the best course of action.



This level of support requires a clear understanding of the responsibilities and roles of the parties involved. The efficiency and speed of such a network also relies upon established lines of communication and a high degree of personal understanding between the parties involved, however, the cost, time and effort involved can be repaid many times over.

OPERATIONS ACROSS MULTIPLE TIME ZONES

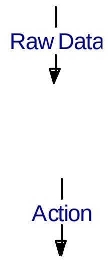
As a result of buffering and separating the download / analysis and decision making processes, some time delays have inevitably been introduced. As mentioned before, these may be unacceptable, and this is particularly likely to be the case for engineering uses of the data.

On the other hand, for operators who have global reach, it can be useful to allow these processes to occur at different times. Inclusion of data from differing parts of the world into the Comparison process can give greater insights and improve the quality of information derived form the original data.

CONCLUSIONS

By examining the monitoring process from a Systems Engineering standpoint, we have seen that many different data flow topologies are available. Some of the advantages and disadvantages of these have been examined.

The common thread of all the systems we have discussed is the need to convert raw data into actions.



From my experience, all the worst monitoring systems were designed by starting with the raw data and asking what processing could be done to make something from this. All the best monitoring systems are designed by identifying the actions that will be taken and building backwards to develop a system with the correct characteristics to support the Decision Makers.

We all want aircraft to fly safely and efficiently, and those of us attending this Symposium believe that aircraft monitoring is a valuable tool to achieve this goal. I hope this presentation has given you some ideas about the alternative topologies for a monitoring system that will help you to fly more safely.

An Approach to the Analysis of Data from Aircraft Integrated Monitoring Systems and Flight Simulators Intended to Support the Development of Agents Assisting the Assessment and Diagnosis of Man/Machine Interactions

Frank Köster[1] und Klaus Mehl[2]

[1]Carl-von-Ossietzky-Universität Oldenburg ◦ Fachbereich Informatik ◦ Abteilung Informationssysteme ◦ Escherweg 2 ◦ 26121 Oldenburg ◦ eMail.: frank.koester@offis.de
Tel.: +49 441 - 9722 211 ◦ Fax: +49 441 - 9722 202

[2]Carl-von-Ossietzky-Universität Oldenburg ◦ Fachbereich ◦ Psychologie ◦ 26111 Oldenburg

Abstract

In this paper we sketch our approach to the analysis of data from aircraft integrated monitoring systems and flight simulators by applying techniques from the field of knowledge discovery in databases.

To analyze these data which are multivariate time series, we developed a knowledge discovery technique based on a parallel evolutionary algorithm—the data mining system EA-MOLE. The application of EA-MOLE aims at the extraction of useful and explicit knowledge from the processed data. This knowledge, for example, covers criteria or combinations of such criteria to early detect flight situations which may lead to extreme or dangerous outcomes (e.g. abandoning a landing approach).

Furthermore, insights gained by the application of EA-MOLE can support the development of "intelligent" agents. These agents, in the future, can assist pilots or trainers to (online) assess and diagnose individual performance in real flight situations or training sessions in flight simulators. Thus, they can support safety in real flight situations as well as they can be useful to assess training progress or to determine the individual need of a trainee for additional specialized training.

1 Introduction and Overview

In the year 1998 the International Journal of Aviation Psychology devoted a special issue to the topic of simulation training ("Simulation and Training in Aviation", Vol. 8, No. 3, 1998). In the preface, Salas, Bowers & Prince (1998) formulated the central question: "How can simulation optimize learning and skill acquisition in aviation environments?" In this same issue an article by Salas, Bowers & Rhodenizer (1998) called for "a rational use of simulation to support aviation training". From our point of view, this paper in some ways is intended as a response to that call and describes our approach to support the "rational use" of simulation in aviation training. But our approach seems to be more general; it offers the possibility to support the development of agents assisting the assessment and diagnosis of man/machine interactions not restricted to training purposes.

We use data (recorded as multivariate time series), which can be supplied by aircraft integrated monitoring systems or special software components of interactive training simulators, as a foundation to gain explicit knowledge about criteria useful to evaluate the behavior of a pilot (assess and diagnose) or to predict the outcome of special flight situations (e.g. the landing approach). Currently, the data we use are derived from a personal computer-based flight training device and includes detailed information about rudder operation, power settings, NAV and COM frequency settings, as well as flight position data etc.

Following, Section 2 gives a short introduction to an area of research known as Knowledge Discovery in Databases. In our work, the interactive and multistage process of knowledge discovery in databases describes a framework for the application of a special data mining system which is based on an evolutionary algorithm—the data mining system EA-MOLE. Originally, EA-MOLE was developed for applications in environmental epidemiology (cf. Köster et al., 2000; Köster & Sonnenschein, 1999); but this (general) tool for the analysis of multivariate time series could be easily adapted for applications in aviation (cf. Köster, 2002). Section 2.1 introduces the algorithmic core of EA-MOLE. Additional, Section 2.2 provides more technical information about the data mining system. In Section 3 we discuss a case study to demonstrate the application of EA-MOLE. Section 4 contains some ideas for practical applications of the results gained by the application of EA-MOLE (agents assisting the assessment and diagnosis of man/machine interactions). Finally, Section 5 contains some conclusions and plans for future work.

2 Knowledge Discovery in Databases and Data Mining

Knowledge Discovery in Databases (KDD) is an interactive and multistage process for the exploration of large databases. In the common literature one usually finds characterizations of this process comparable to the following definition suggested by Fayyad et al.:

> "KDD is the nontrivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data." (Fayyad et al., 1996—pages 40-41)

During this process, five phases are distinguished: *Selection*, *Pre-processing*, *Transformation*, *Data Mining*, and *Interpretation* (cf. Fig. 1).

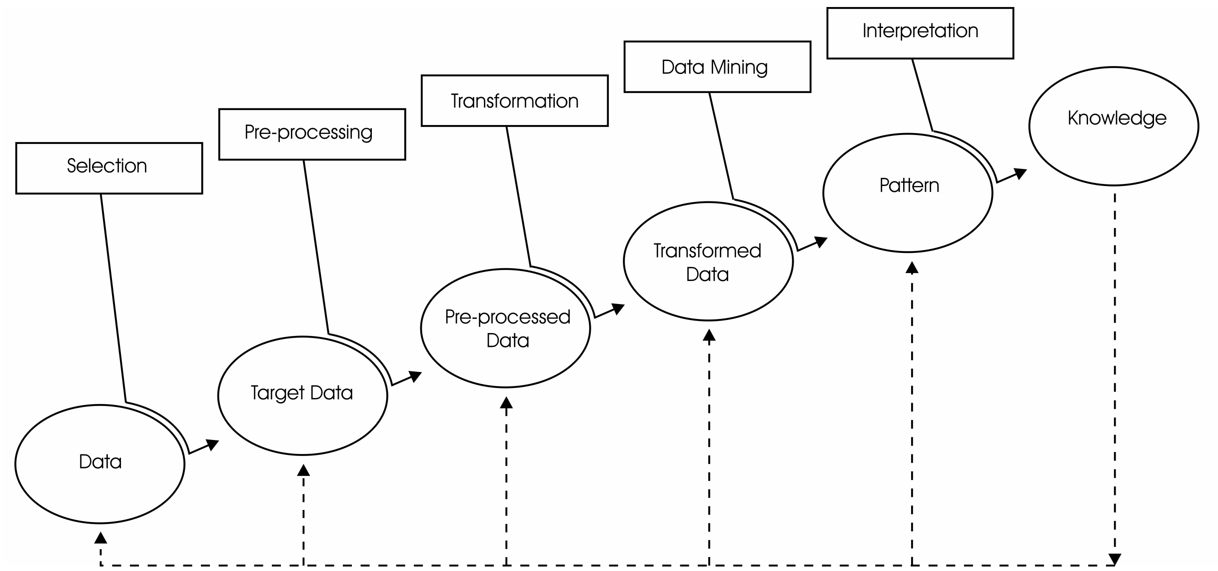


Figure 1: The process of KDD

Within the first three phases an initial database is created to process in the 4th phase (data mining). The identified patterns are interpreted with respect to the area of application and carefully checked for plausibility in the final phase[1].

[1] For further information on this topic refer to publications by Fayyad et al. (e.g. Fayyad et al., 1996) or to the report by Woods & Kyral (1997).

In the data mining phase "intelligent" algorithms (e.g. see the report by Holsheimer & Siebes (1994) or the book by Ester & Sander (2000) for an overview) are applied to rummage through the transformed data in order to detect significant patterns. A more generic definition of data mining is given in the report by Woods & Kyral:

> "[Data mining is] the automated analysis of large or complex data sets in order to discover significant patterns or trends that would otherwise go unrecognised." (Woods & Kyral, 1997—page 6)

2.1 An Application of Evolutionary Algorithms to Data Mining: EA-MOLE

The way our data mining technique works, is related to the theory of natural evolution introduced by the naturalist Charles R. Darwin (1968)—an evolutionary algorithm. This superclass of algorithms consists of several more or less sharply separated specializations (Michalewicz, 1999). These are for instance the class of genetic algorithms (Holland, 1975) or approaches to evolutionary and genetic programming (Fogel, 1995; Koza, 1992)—to name only some "main streams" in this area of work. In more detail, the basic principle of our approach to data mining in time series can be assigned to the last-mentioned two classes (Köster, 2002; Köster et al., 2000).

2.1.1 Algorithmic Principle of EA-MOLE

A population of so-called γ-individuals performs an evolution driven forward by the principle of "the survival (and selection) of the fittest". The γ-individuals are composed of a set of different metrics and functions (e.g. based on descriptive statistics, differential equations, wavelets (e.g. see Louis et al., 1998), or fuzzy graphs (e.g. see Berthold & Hand, 1999—pages 282-292)) which are presently arranged in a special tree-based classifier.

A γ-individual is called "fit", if it, for instance, can be used to distinguish operating data of successful approaches from operating data of unsuccessful approaches. These classifiers can't be determined by one step. Within EA-MOLE classifiers with a high classification accuracy gradually emerge within an evolutionary process. The current fitness of each γ-individual is computed by a quality function which defines the goal of the evolution. To allow (new) γ-individuals to increase their fitness, the two genetic operators *crossover* (recombination) and *mutation* (alteration) are used to create and modify γ-individuals (cf. Fig. 2).

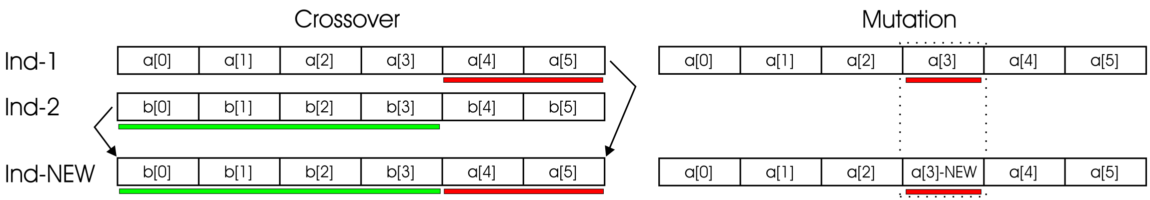


Figure 2: The genetic operators crossover and mutation

Within the current implementation of the data mining system EA-MOLE the γ-individuals can be seen as hypotheses about possible cause-and-effect relationships hidden in the processed data. The fitness of the γ-individuals grows with the evolution of generations within the evolutionary algorithm—the quality of the hypotheses about cause-and-effect relationship grows in the same way.

Figure 3 shows the general structure of an evolutionary algorithm: This figure shows a population of γ-individuals (in this special case) all containing a unique tree-based classifier. Furthermore, these γ-individuals all have different fitness values which influence their chance to be selected as the basis for a next generation of γ-individuals generated by the application of the two genetic operations mentioned above.

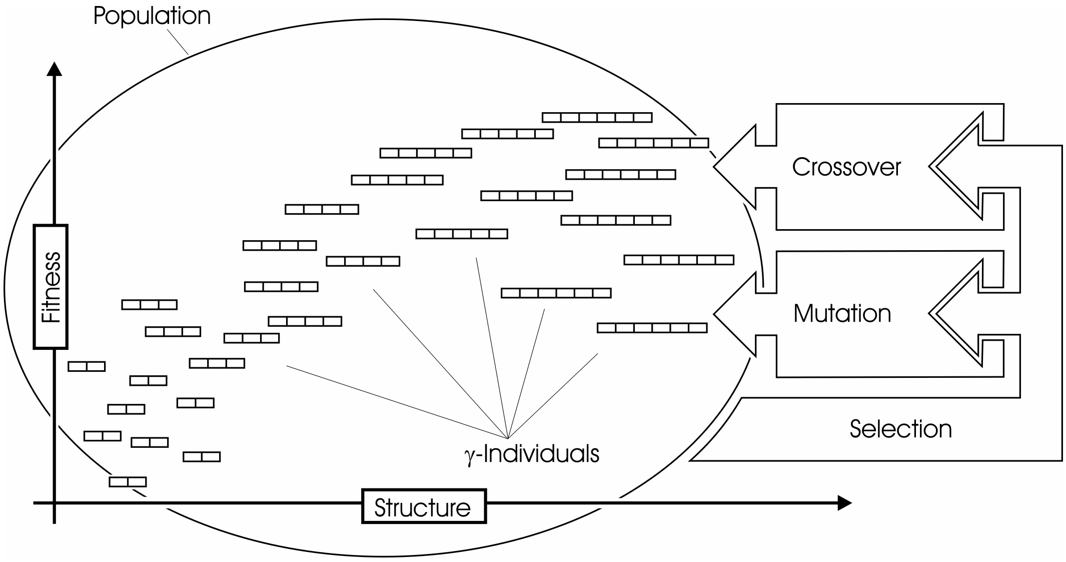


Figure 3: General structure of an evolutionary algorithm

2.1.2 Goal of EA-MOLE

For the application to data mining in sets of multivariate time series our evolutionary algorithm "works on" the following tasks to increase the γ-individuals' fitness:

→ select the most significant time series from the processed data (e.g. select time series which could be useful criteria to identify critical flight situations),

→ find the most important characteristics within the time series (e.g. describe significant phenomena within the selected time series, which could be explanations for the occurrence of critical flight situations which may lead to extreme or dangerous outcomes),

→ explore the most important coherences within the processed database (e.g. describe significant coherences in courses of selected time series, which could be explanations for the occurrence of critical flight situations),

→ indicate if the last-mentioned most important characteristics and coherences "act protective" or not (e.g. indicate the case that a special behavior is typical for an experienced pilot), and

→ present the γ-individuals in a comprehensible and interpretable way (e.g. reduce their size by simplification of the tree-based classifiers).

2.2 Brief Technical Information about EA-MOLE

The entire data mining system EA-MOLE consists of a core tool for data mining in sets of multivariate time series, and some additional utilities for the transformation of datasets processed with EA-MOLE, the parameterization of analysis runs, and for the interpretation/evaluation of gained results (Köster, 2002).

The core of the data mining tool is based on an evolutionary algorithm (cf. Sect. 2) and is available for different single- and multiprocessor computer systems (UNIX, LINUX, and UNICOS/*mk*).

The efficient parallel implementation for multiprocessor computer systems reduces the runtime of the evolutionary algorithm (cf. Hoffman, 1991) and enables us to process very large databases. Some features of the current implementation of EA.MOLE are mentioned in the following list (for further information refer to the PhD thesis of Köster (2002)):

→ The software design of EA-MOLE allows the easy integration of available domain knowledge.

→ The application of integrated domain knowledge and the analysis process itself can be adjusted by different parameters which are organized in a parameter file.

→ EA-MOLE enables the user to access selected status information via the internet by sending defined messages to the running program.

→ The data mining tool generates electronic mails to inform a user about the current state of the data mining process (e.g. the current progress of the analysis or the current "worst"/"best" γ-individuals).

→ It is possible to continue a previously interrupted data mining process.

The development of EA-MOLE was supported by the John von Neumann-Institute for Computing (NIC—at the Research Center Jülich in Germany). The NIC enables us to use the CRAY-T3E computer system available at the research center in Jülich.

3 Case Study: Application of EA-MOLE

To demonstrate that EA-MOLE is a valuable tool for the analysis of data from aircraft integrated monitoring systems and flight simulators, we first integrated a recording option into a so-called Personal Computer-Based Flight Training Device (PCATD). This "test bed" enables us to record a total of 57 operating parameters (with a resolution of 3 Hertz). In principle, it was possible to record all relevant information over time; including rudder operation, power settings, NAV and COM frequency settings, as well as flight position data etc. The data obtained from the PCATD was made available for further analysis in a simple file-based data collection.

3.1 Scenario

The exercise and scenario used to obtain data for this case study was situated near the city of Oldenburg in northern Germany—to be precise, on the STAR (Standard Terminal Arrival Route) on runway 15 of the Hamburg Airport (EDDH). The starting point of the exercise was inside the missed approach traffic circuit of runway EDDH 15 at the Hamburg-Finkenwerder Airport (EDHI). Figure 4 shows the flight route (thick black line). Participants took off from EDHI, ascended with runway heading to an altitude of 1000ft, executed a right curve, in order to intercept Radial 160 inbound ELBE VOR. The ascent was continued until the plane reached an altitude of 3000ft. After the plane flew over ELBE VOR, the flight continued along the STAR on the radial 034 outbound over the ELBE VOR until it reached a distance of 11.1 DME LBE. At this point, the pilot executed a right curve in order to intercept the ILS EDDH 15. At 10.4 DME ALF the pilot began the descent to the ILS. The pilot was instructed to pass over the outer marker at an altitude of 1400ft and the middle marker at 231ft (cf. Fig. 4—outer marker and middle marker).

If the runway was not visible after flying over the middle marker, the pilot was instructed to follow the missed approach procedure.

The participants in this case study consisted of two groups: (1) experienced pilots who were familiar with the airplane used in the simulation (a Piper PA-28)[2], and (2) devotedly enthusiastic "PC pilots" with no flight experience whatsoever. All pilots were given a thorough introduction to the task to be performed as well as extensive instruction in the use of the simulator. The person conducting the experiment observed the flights on a control monitor and simulated the ATC using a normal headset. The analysis included only the data of those pilots who were able to complete at least 5 flights along the outlined route. Ultimately, data from a total of 137 flights was available for the analysis with EA-MOLE and evaluation.

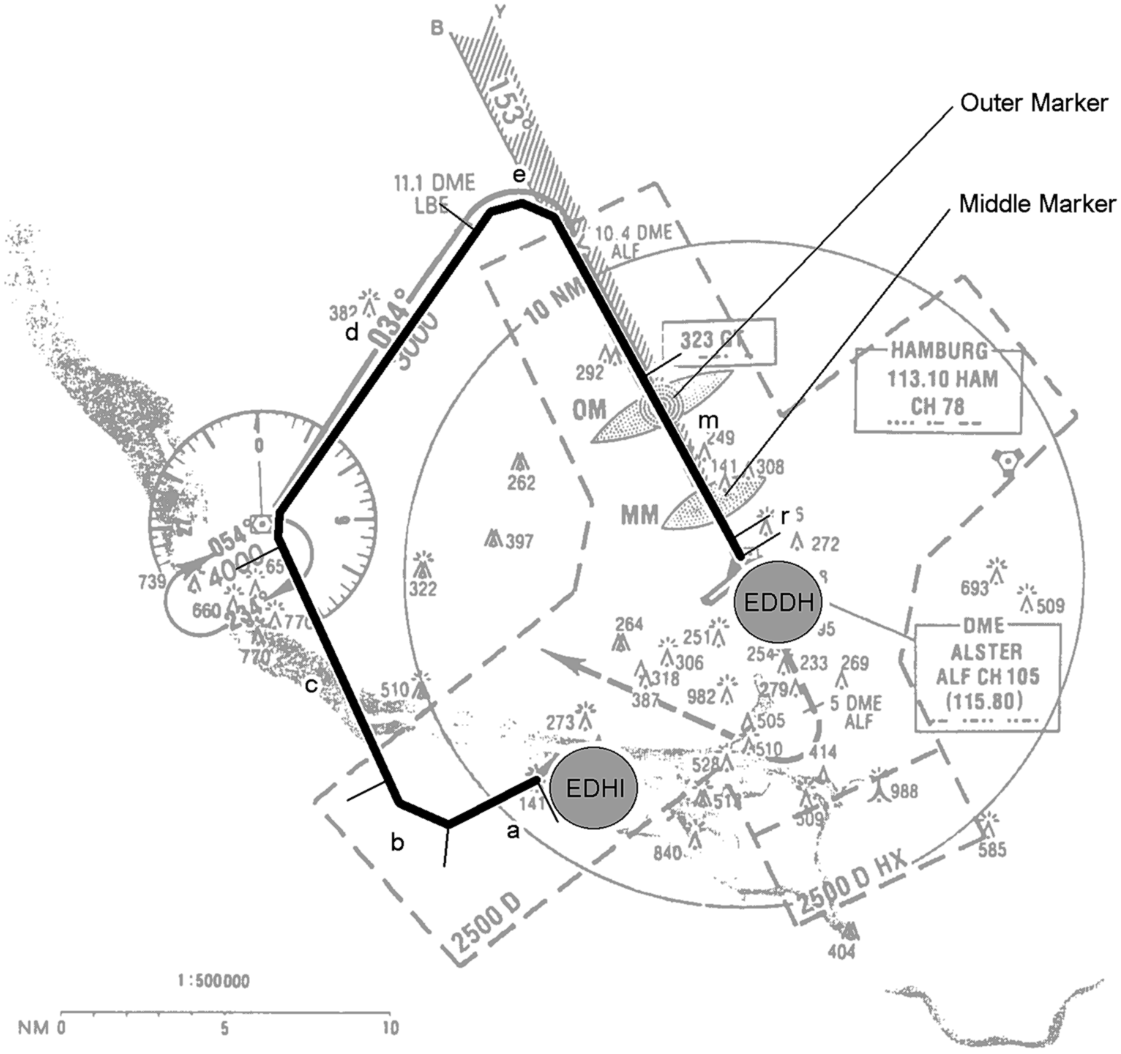


Figure 4: The flight route of the training task from EDHI to EDDH (Northern Germany)

The starting point for the application of EA-MOLE (see Sect. 3.2), was a clear distinction between successful and unsuccessful approaches[3]: In the case at hand, the prescribed altitudes at the outer marker (1400ft) and at the middle marker (231ft) allowed for tolerance ranges of 1350-1500ft and 200-275ft, respectively. If the simulated approach was executed within the tolerance range, the flight was considered successful. Approaches at altitudes outside the tolerance range were considered unsuccessful.

[2] The most experienced pilot had an ATPL—approximately 20 000 flight hours.
[3] Although more differentiated distinctive criteria could be applied as well.

3.2 Results

First, EA-MOLE was used to analyze operating data from 80 randomly selected flights (out of the total of 137). The determined γ-individuals can effectively distinguish between successful and unsuccessful approaches to EDDH (according to the criteria mentioned above—outer marker: 1350-1500ft; middle marker: 200-275ft).

In this first step, we analyzed only data from the m-section of each flight (cf. Fig. 4). Figure 5 shows the classification accuracy of one single γ-individual with a remarkable fitness.

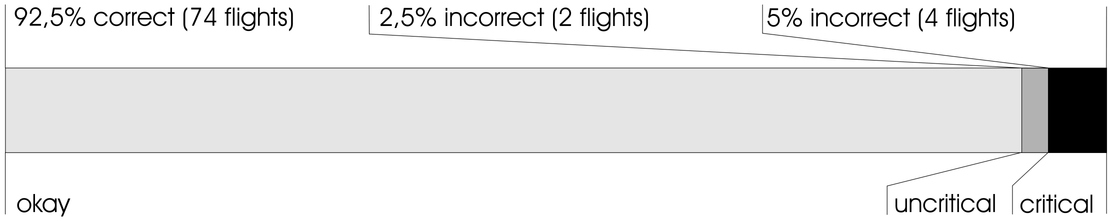


Figure 5: Quality of one single γ-individual (m-section (80 approaches))

The percentage of correct classifications is 92.5% (74 of the 80 approaches are classified correctly). Within Fig. 5, the incorrectly classified flights are divided into two categories: A classification was considered "uncritical" if a flight which had actually been successful was mistakenly classified as "unsuccessful". In contrast, if a flight which had actually been unsuccessful was mistakenly classified as "successful", this was considered a "critical" misclassification.

In a further step, which was intended to "validate" the result determined by EA-MOLE, the γ-individual from Fig. 5 was applied to data from 30 (unknown) approaches to EDDH—again we consider only data from the m-section of each flight. These data was not included in the set of the 80 previously processed approaches. Figure 6 shows the classification accuracy of the selected γ-individual applied to these 30 unknown approaches to EDDH.

The classification accuracy shown in Fig. 6 is comparable to the result shown in Fig. 5: 90% of the processed approaches are classified correctly.

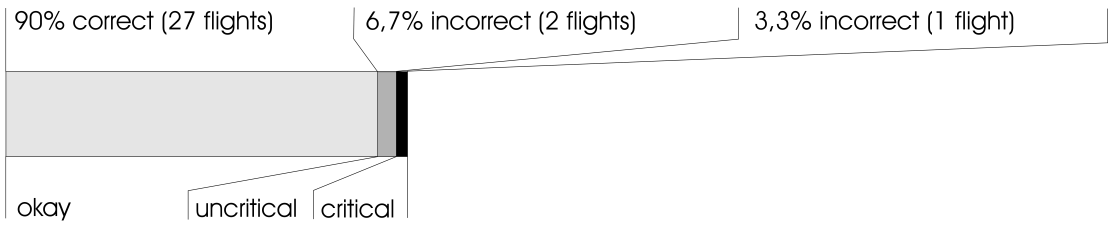


Figure 6: Application of the γ-individual to data from 30 approaches to EDDH (m-section)

In addition to the previously discussed findings, we validated those exemplary results in a cross-validation procedure (Berthold & Hand, 1999—pages 56-57). The cross-validation procedure enables us to show that the γ-individuals determined by the application of EA-MOLE are structurally stable. Furthermore, their fitness values are just as stable as their structure (cf. Köster, 2002).

In a next step, we used the γ-individual from Fig. 5/6 for the prognosis of the outcome of different flights. For that purpose, we applied the γ-individual to data from the a-b-c-sections (cf. Fig. 4) of 80 flights: For each flight, we applied the γ-individual to the mentioned portion of data. The resultant classification was compared to the real outcome of each processed flight (according to the criteria mentioned above—outer marker: 1350-1500ft; middle marker: 200-275ft).

Figure 7 shows the result of the application of the selected γ-individual to data from 80 a-b-c-sections: 81.25% of the 80 flights are classified correctly (65 flights); a total of 18.75% of the flights are misclassified.

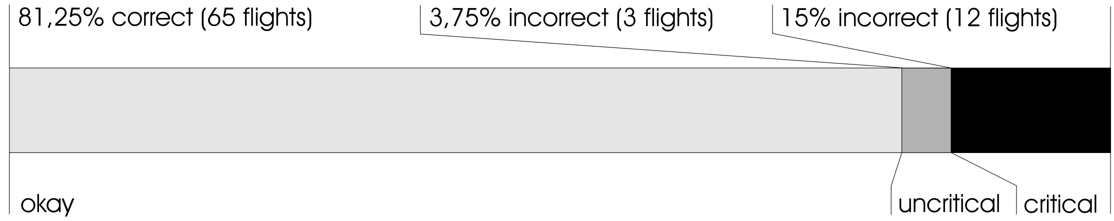


Figure 7: Prognosis of the outcome of 80 flights (a-b-c-section)

Moreover, the quality of the classification accuracy shown in Fig. 5 to Fig. 7 can be increased beyond the mentioned values by the application of a set of γ-individuals which is merged into a so-called *Team of γ-individuals* (for further information refer to the PhD thesis of Köster (2002)).

The results shown in Fig. 5/6 and (in particular) Fig. 7 could be a first indication of a strong standardization within the human interactions with the simulation of the virtual airplane. Apparently, this standardization can be "exploit" by the γ-individuals. From the perspective of a psychologist, for this application this wasn't obvious.

4 Application: Agents Assisting the Assessment and Diagnosis of Man/Machine Interactions

Individuals performance should be measured in real flight situations and training sessions to acquire information for many purposes: Especially such as (1) immediate feedback to a pilot/trainee or instructor, (2) performance diagnosis, (3) performance assessment and grading.

The approach discussed in this paper, seems to be a useful foundation for various applications in aviation. Following, this section sketches two ideas to utilize the γ-individuals gained by the application of the data mining system EA-MOLE.

First, the γ-individuals' classification accuracy offers a possibility for the (online) assessment of individuals' (pilot/trainee) performance. Such information can be useful in real flight situations and should provided to pilots to indicate situations which may lead to extreme or dangerous outcomes. Furthermore, such information can be valuable within training sessions for the following reason: Based on the prognosis of the γ-individuals a training session can be adapted to correspond to the individual needs of a trainee—increase or decrease current demands with respect to the individuals' competence or capabilities, respectively. In this context it must be empathized, that the knowledge gained by the application of EA-MOLE enables a pilot or an instructor to extract a set of (explicit) criteria which forms the foundation of the assessment/classification. In particular, this is an major advantage of EA-MOLE compared to artificial neuronal networks (ANN) (Ritter et al., 1991) which are "black boxes". Compared to ANN, the output of EA-MOLE requires no extensive deciphering.

For instance, 16 (explicit) criteria was identified/selected and merged into the γ-individual applied in the previous section (cf. Fig. 5 to Fig. 7). Beyond this, EA-MOLE established an inter-criteria ranking and provides detailed information about the identified criteria (→ phenomena). The already mentioned set of metrics and functions (one foundation of the γ-individuals—cf. Sect. 2.1.1) can be seen as a key to access these information.

Thus, the γ-individuals not only offer the classification. Additionally, the concept of the γ-individuals offers the possibility to asses/diagnose individuals' performance with regard to each single criterion. Figure 8 shows the un-aggregated values of all 16 criteria (single factors influencing the classification) for a "best practice"-pilot compared to a more or less unexperienced trainee. This is, for instance, the ability of a pilot/trainee to control the height of the flight, which is coded by the second pair of bars (2) in Fig. 8. The criteria 1, 8, and 12 are concerning the heading of the airplane; criterion 9 concerns the airspeed. It is obvious, that there are noticeable differences for the criteria 1, 2, 8, 9, and 12. Because we also have these detailed information about the criteria/phenomena, we are possibly able to intervene critical flight situations well directed.

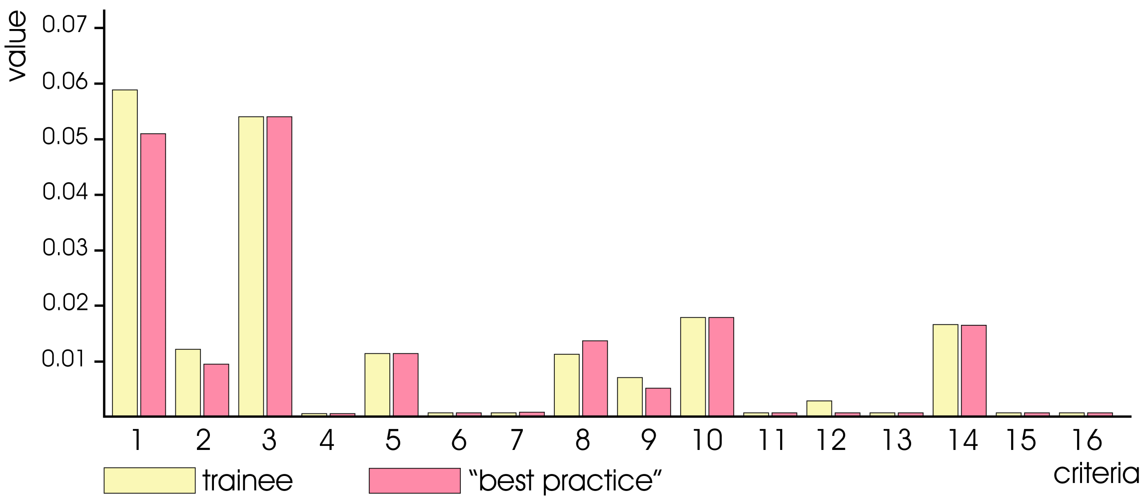


Figure 8: "best practice"-pilot (reference) compared to a trainee

In a next step, we plan to develop "intelligent" (software) agents assisting the assessment and diagnosis of man/machine interactions. The core of these agents will be based on teams of γ-individuals or the knowledge embodied in these structures gained by the application of EA-MOLE.

6 Conclusion

It must be emphasized that the outlined procedure is based on an analysis of operating data, not performance data. In other words, it is to be used for purposes in aviation (real flight situations and training), where deficits are recorded and evaluated. It can indicate which skills need to be optimized or heedful observed, and/or what additional training is necessary, enabling pilots/trainees to preserve/meet prescribed performance standards.

Besides the improvement of the results gained by the application of EA-MOLE and the integration of these results into an agent-based tool, we are currently involved in developing different additional evaluative possibilities (possibly based on techniques form machine learning (Michalski et al., 1998)). These activities could lead to a further improvement in using the γ-individuals as a basis for agents assisting the assessment and diagnosis of man/machine interactions. A proof-of-concept prototype for such an agent-based tool should be available at the end of this year.

REFERENCES

M. Berthold and D.J. Hand (Hrsg.) (1999). *Intelligent Data Analysis – An Introduction*. Springer Verlag.

C.R. Darwin (1968). *The Origin of Species: By Means of Natural Selection or The Preservation of Favoured Races in the Struggle for Life*. Oxford Univ. Press – London, a repr. of the 6th ed.

M. Ester and J. Sander (2000). *Knowledge Discovery in Databases – Techniken und Anwendungen*. Springer Verlag.

U. Fayyad, G. Piatetsky-Shapiro, and P. Smyth (1996). *From data mining to knowledge discovery in databases*. AI Magazine, 17:37-54.

D.B. Fogel (1995). *Evolutionary Computation: Towards a New Philosophy of Machine Intelligence*. IEEE Press, Piscataway, NY.

J.H. Holland (1975). *Adaption in Natural and Artificial Systems*. University of Michigan Press, Ann Arbor.

M. Holsheimer and A.P.J.M. Siebes (1994). *Data Mining: The Search for Knowledge in Databases*. Centrum voor Wiskunde en Informatica (CWI), P.O. BOX 94079, 1090 GB Amsterdam, The Netherlands, REPORT CS-R9406.

F. Hoffmeister (1991). *Scalable Parallelism by Evolutionary Algorithms*. In M. Grauer and D.B. Pressmar (eds.), *Parallel Computing and Mathematical Opimization*. Springer Verlag, pages 177-198.

F. Köster (2002). *The Analysis of Simulations by using Methods from Knowledge Discovery in Databases*. In German: *Analyse von Simulationsmodellen mit Methoden des Knowledge Discovery in Databases*. Dissertation, Carl-von-Ossietzky-Universität Oldenburg (Fachbereich Informatik).

F. Köster, R. Radtke, B. Westphal, and M. Sonnenschein (2000). *Combining Methodical Procedures from Knowledge Discovery in Databases and Individual-Oriented Simulation – Data Mining in Time Series*. Proceedings of the *International Symposium on Medical Data Analysis 2000*, Springer Verlag.

F. Köster and M. Sonnenschein (1999). *An Approach to the Creation and Validation of Hypotheses about Cause-and-Effect Relationships in Individual-Oriented Models by Knowledge Discovery in Databases*. In J.G. Anderson and M. Katzper (eds.), *1999 Medical Sciences Simulation Conference*. SCS, pages 139-144.

J.R. Koza (1992). *Genetic Programming: On the Programming of Computers by Means of Natural Selection.* Complex Adaptive Systems, MIT Press, Cambridge, MA.

A.K. Louis, P. Maaß, and A. Rieder (1998). *Wavelets – Theorie und Anwendungen*. Teubner Verlag.

Z. Michalewicz (1999). *Genetic Algorithms + Data Structures = Evolution Programs*. 3rd, Revised and Extended Edition.

R.S. Michalski, I. Bratko, and M. Kubat (1998). *Machine Learning and Data Mining – Methods and Applications*. John Wiley & Sons Ltd.

H. Ritter, K. Schulten, and T. Martinez (1991). *Neuronale Netze – Eine Einführung in die Neuroinformatik selbstorganisierender Netze*. Addison-Wesley.

E. Sales, C.A. Bowers, and L. Rhodenizer (1998). *It is not how much you have but how you use it: toward a rational use of simulation to support aviation training*. The International Journal of Aviation Psychology, 8(3), 197-208.

E. Salas, C.A. Bowers, and C. Prince (1998). *Special issue on simulation and training in aviation*. The International Journal of Aviation Psychology 8(3), 195-196.

E. Woods and E. Kyral (1997). *Ovum Evaluates: Data Mining*. Ovum Evaluates, Ovum Ltd.

THE I-22 IRYDA POWER PLANT
EXPERT AIDED CODITION MONITORING SYSTEM

R.Kudelski[1], J. Pintara[2], R. Szczepanik[3], M. Witoś[4]

1, 3, 4 – Air Force Institute of Technology, 01-494 Warsaw, str. Ks. Boleslawa 6 Poland
2 – Aviation Institute, 02-256 Warsaw, str. Aleja Krakowska 110/114 Poland

ABSTRACT

The paper presents complex expert aided condition monitoring system of I-22 Iryda power plant which consists of two K-15 turbojet engines. The system consists of two-level diagnostics concept. First on-board monitors the fundamental parameters changes as well as their trends. The second level is basically ground system and enables multidirectional analyses. The system generally complies with on condition maintenance philosophy. Simultaneously the system supports save flying, reduces the maintenance costs and increases the operational readiness of the aircraft. The general architecture of the system is given. The compressor first stage blades vibration spectrum monitoring system as a diagnostic subsystem is described.

1. GENERAL ARCHITECTURE OF THE SYSTEM

1.1. Parameters describing the technical status of K-15 engine

The crucial issue to built any good diagnostic system is to define optimal number of engine performance parameters which can identify:

- all real, constructional – technical characteristics of the engine,
- all faults identification processes,
- weak points in engine structure,
- the operational-phase strategies,
- frequency and scope of maintenance and the health/maintenance status inspestions,
- the routine maintenance and the pre-planned repairs,
- the emergency repair practice,
- overhaul frequency and upgrade extent,

The goal of such system is to present – in some suitable form – a packet of characteristics and rates of the operational process to facilitate a set of rational principles of the process management to be laid, and right decisions to be made.

The following parameters were taken to describe the technical status of K-15 engines:

Analogy data:

a) frame data: ambient temperature, flight altitude, indicated flight speed,
b) engine data: rotational engine speed, exhaust gases temperature and pressure fuel injection pressure ($P_{pal} - P_{cz}$), fuel atomizers pressure, total compressor pressure, vibration velocity amplitude, oil pressure, oil temperature in oil tank, temperature and pressure behind the compressor t_2, P_2, fuel flow metering, position of throttle lever, value of current (from ALAE box)
c) two – status data: engine number – engine ID as eight – bit word: the air valves status, starting fuel feeding valve voltage, minimal oil level in tank, fuel filter blocking, minimal fuel pressure value, icing, starter – generator feeding voltage.

1.2. Basic characteristics in K-15 engines maintenance process

1. The engine starting cycles number,
2. The venting cold engine starting number,
3. The hot engine starting cycles number,
4. Working hours of engine starting procedure relay,
5. Engine starting time on the ground,
6. The flights number metering,
7. The engine air shut – down cases number,
8. The engine air re – light cases number,
9. The total engine working hours (including ground runs),
10. The total engine flying hours,
11. The total engine working hours from start to stop,
12. The take off engine life consumption time,
13. The cruise engine life consumption,
14. The number of cases of exceeded, acceleration engine time,
15. The number of deceleration engine time violations,
16. Surges number,
17. Number of cycles consumed,
18. Oil consumption,
19. Oil quantity in oil tank,
20. n_{max} exceeded cases number,
21. Total n_{max} exceeded cases time,
22. $n > 102\%$ cases number,
23. Total $n > 102\%$ cases number time,

24. $T_{c4} > T_{c4max}$ cases number,

25. Total $T_{c4} > T_{c4max}$ cases number time,

26. Vibration velocity amplitude exceeded cases number,

27. Total vibration velocity amplitude exceeded cases time,

28. $T_{ol.max}$ violences number,

29. Total $T_{ol.max}$ violences time,

30. The starting engine cycles number with $T_{ol} < T_{ol\ min}$.,

31. Total starting engine cycles number with $T_{ol} < T_{ol\ min}$ time,

32. $P_{ol} > P_{ol.dop}$ cases number,

33. Total $P_{ol} > P_{ol.dop}$ cases number time

34. $P_{ol} > P_{ol.min.}$ with n > nbj; n = nbj cases number,

35. Total $P_{ol} > P_{ol.min.}$ with $n > n_{bj}$; $n = n_{bj}$ cases number time,

36. Engine rotation time after shut down,

37. Engine working hrs with min. oil level,

38. Engine working hrs with fuel filter blocked,

39. Engine working hrs with min. fuel pressure before PLT-14 pump,

40. Total engine working hrs in icing condition,

41. Chip detection time.

The total accumulated maintenance engine parameters (from start of maintenance to defined moment of it).

1. The starting cycles quantity,
2. The cold cycles quantity,
3. The hot starting cycles quantity,
4. Flights number,
5. Air engine shut – down cases number,
6. The re lights number,
7. Total engine life time consumption value,
8. Total ground engine life time consumption value,
9. Total air engine life time consumption value,
10. Total exceeded acceleration time cases number,
11. Total exceeded deceleration time cases number,
12. Total surges number,
13. Total surges appearance time,
14. LCF number,

15. Total LCF number,
16. Total n > 100% time,
17. Total n > 102% time,
18. Total $t_{c4} > t_{c4\ max.}$ Time,
19. Total vibration velocity amplitude max. Value time,
20. Total $T_{ol} > T_{ol.max}$ time,
21. Total $T_{ol} > T_{ol.min}$ time,
22. Total $P_{ol} > P_{ol.nax}$ time,
23. Total $P_{ol} > P_{ol.nin}$ time,
24. Total engine working hrs with min. level of oil,
25. Total engine working hrs with fuel filter blocked,
26. Total engine working hrs with min. fuel pressure before PLT-14 pump,
27. Total engine working hrs in icing conditions,
28. Chip detection conditions engine working hrs.

1.3. Estimation criteria of engine technical status

Diagnostics is comparative to measuring process based on compare of the real object to the model. So that is why the parametric description of the model engine is so important to get precision and success of the whole diagnostics procedure with good sensitivity.

First we have to built proper reliability faults and failures criteria basing on which the computer program can conclude the technical status of the engine. According to our experience this status should be estimated both: in static and dynamic conditions.

1.3.1. Not fit to fly criteria (examples)

- $t_{c4} > t_{c4\ max}$ during start and $n \geq n_{bj}$,
- $V_x > V_{xdop}$,
- $t_{ol} > t_{ol\ max}$ with $n \geq n_{bj}$,
- $P_{ol} < P_{ol\ max}$ with $n \geq n_{bj}$,
- $P_{ol} > P_{ol\ max}$,
- $P_{pal} < P_{pal}$ with $n \geq n_{bj}$,
- $P_{pal} > P_{pal}$ max,
- $I_o < 0$ with n < n nom. $t_{c4} < t_{c4\ dop}$ (failure of ALAE)

1.3.2. Engine failure criteria in static engine performance conditions (examples)

- $t_{p1} > t_{pm} > t_{p2}$ (wrong time of starting relay box),

- $t_{ol} > t_{ol\ max}$ (to low oil temperature),
- $v_x > v_{x\ max}$ (exceeded level of vibration),
- $h_1 > h_{1\ max}$
- $t_{c4} > t_{c4\ max}$ (to high temperature on engine idling range)

1.3.3. Engine failure criteria in engine dynamic conditions performance (examples)

- $t_{c4} < t_{c4\ shut-off}$ (engine shut off during acceleration),
- $Q/p_{c2} > (Q/p_{c2} + 300)$ according algorithm – wrong performance of the engine during acceleration and deceleration process,
- $t_{starting} > t_{max}$
- $t_2 > t_{z\ max}$ (to long time of exceeded n_{max} during acceleration).

2. DESCRIPTION OF THE DIA-K-15 ON-BOARD SYSTEM ARCHITECTURE AND PERFORMANCE

The composition and performance of the system shows fig.1.

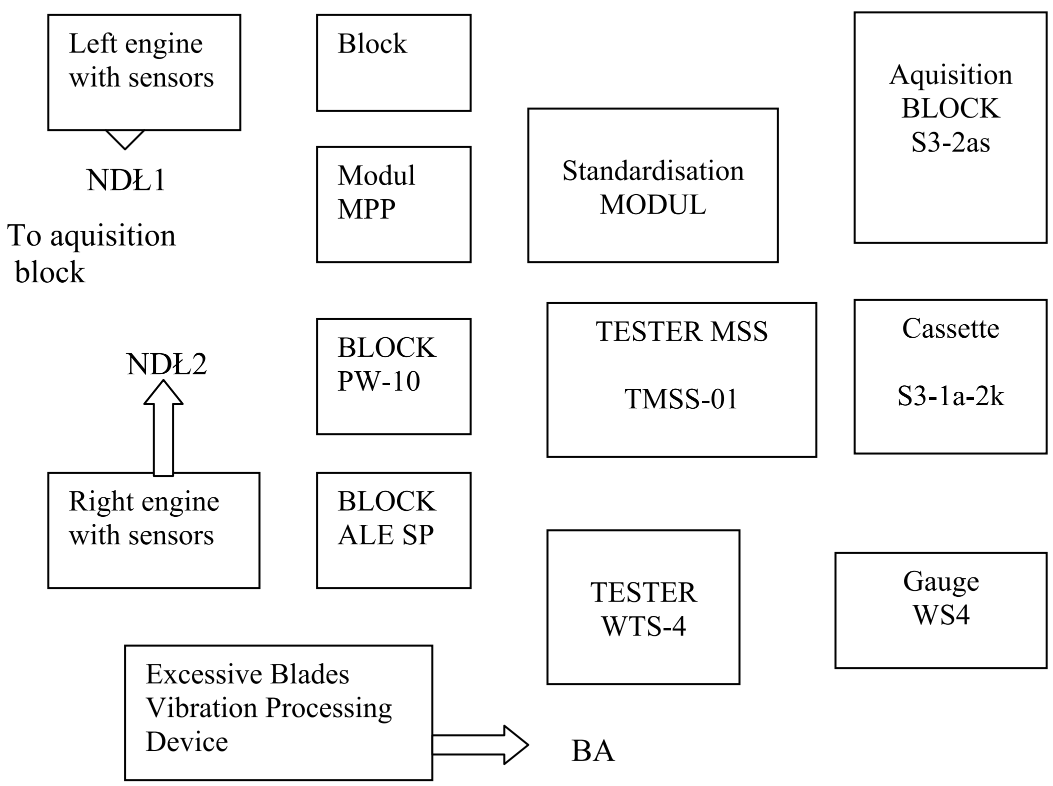


Fig.1. The composition of the DIA-K15 system

The system consists of:

- sensors and gauges which are installed by factory on the engine,
- the I stage compressor blade vibration system,
- standard measuring devices: two ALAE blocks which provides signal “n” and I_o (rotational speed and current value), two channel block PW – 10/2 monitor velocity vibration amplitude of engines
- standard measuring devices: two ALAE blocks which provides signal “n” and I_o (rotational speed and current value), two channel block PW – 10/2 to monitor velocity vibration amplitude of engines,
- additionally designed specialized modul: MPP, MSS and BA (accordingly modul of frame parameters, sensor signals standardization modul and acquisition block which register and refers analog and two – status parameters to both 8-bits engines numbers. BA block has also the analyze – registering system to transmit failure signals to cockpit gauge WS4,
- the portable solid memory cassette to reload the data to ground computer,
- two testers TMSS and WTS-4 for checking the proper function of the system.

Function of the board aircraft system starts with feeding the system with electrical power . The system first performs self checking and hext displays presence of exceeded values of parameters from previous flight if any.

2.1. The ground DIA-K15 system architecture and performance.

The composition of the ground part of the system is shown on fig. 2.

It consists of:

- data modul,
- PC computer with data modul interface,
- Monitor,
- Printer,
- Program “Silnik”,
- Program “DIA-K15”

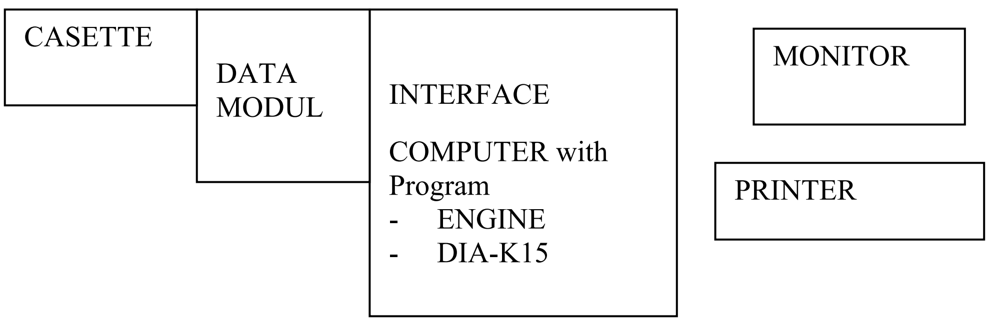


Fig.2. Block scheme of ground part of DIA-K15 system

The performance of the system is based on reading the data from the last flight and numerate it to allow its identification in future with monitor displaying. System DIA-K15 consists of eight program moduls illustrated on fig. 3.

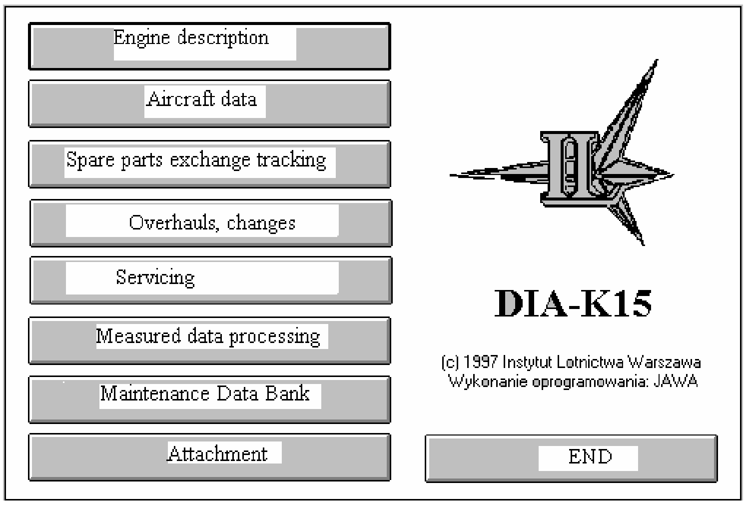


Fig. 3. Program moduls of DIA-K15 systems

System allows within its moduls (see Fig. 3):

Overhauls, changes Modul:

Contents overhauls data and any design changes which are put in two specifications:

- overhauls,
- changes

Servicing Modul:

Servicing list data are given in tables including informations about:

- technical inspections of engine installations,
- boroscop inspections,
- adjustment works,
- oil parameters

Measured Data Processing Modul:

allows following functions:

1. Putting the model data obtained from engine manufacturer into system.
2. Determination the relation between code data and real measured parameters.
3. Data processing
   - measured parameters changes presentation during engine run,
   - engine performance phase definition,

- engine characteristics presentation,
- engine technical status estimation.

Maintenance Data Bank Modul:

allows:

- storing and protection of measured and processed data after each flight,
- trending observations,
- parameters deviations

Engine Description Modul:

allows:

- to read the engine manuals from the computer display,

Aircraft Data Modul:

Gives the information about:

- the technical – operational aircraft data,
- the user data,
- entry maintenance data: aircraft number, data of maintenance beginning, number of the engines installed

Spare Parts Exchange Tracking Modul:

Gives the information in two tables set

- engines rotations,
- engines raports

Attachments Modul:

This modul allows implementing to aircraft data bank all informations possessed outside the DIA-K15 system like:

- engine technical status estimations during periodical visual inspections,
- some results of experimental tests and investigations,
- some technical expertises

4. THE SUBSYSTEM SPŁ-2B/S2-3AS ARCHITECTURE AND PERFORMANCE WITHIN THE DIA-K15 SYSTEM

The system is analogous to system described in the paper "Condition Monitoring System Based on Non-Interference discrete-phase compressor blade vibration measuring method" included in 20th AIMS Conference Proceedings . Garmisch May 22 – 25. 2000. The method is based on discrete blade vibration amplitude measurement and its numerical response analysis referred to the jest engine technical condition analysis. The described method is used in some units of Polish Air Force as SNDŁ-1b/SPŁ-2b SO-3 jet engine diagnostic system. This engine powers polish TS-11 "Iskra" training aircraft.

5. SUMMARY

Demonstrated diagnostic system DIA-K15 creates tool for engine technical status estimation. It can create the basic chain on condition maintenance diagnostics procedures of K-15 and any similar to K-15 turbo-jet engines.

6. REFERENCES

[1] Boliński, Stemlaszczyk. Eksploatacja silników turbinowych. Wydawnictwo Komunikacji i Łączności 1981.

[2] Cempel, Tomaszewski. Diagnostyka Maszyn. Radom 1992.

[3] Diagnostics and Engine Condition Monitoring. Materiały z konferencji AGARD North Atlantic Treaty Organization Advisory Group For Aerospace Research and Atlantic Development 1974.

[4] Niziński, Pelc. Diagnostyka Urządzeń Mechanicznych W.N.T – 1980.

[5] Norma onromma NO-15-A801. Diagnostyka techniczna płatowca i silnika.

[6] Opis silnika K-15.

[7] Pintara. System Diagnostyczny Silnika K-15 stanowiącego napęd samolotu szkolno-bojowego IRYDA. Prace Instytutu Lotnictwa nr 151, część I, 1997.

[8] Sprawozdanie Nr 16/34/98 z pracy pt. Badania stoiskowe prototypu systemu diagnostycznego SPŁ-2b/S2-3as. Wyd. wew. ITWL – niepublikowane.

[9] Szczepanik, Witoś. Komputerowy system diagnostyczny silników odrzutowych bazujący na dyskretno-fazowej metodzie pomiaru drgań łopatek. Prace Instytutu Lotnictwa Nr 152.1/1998.

[10] Tymczasowa Instrukcja Użytkowania i Obsługi Silnika K-15. Warszawa 1994.

[11] Witoś. Diagnozowanie stanu technicznego łopatek sprężarki turbinowego silnika spalinowego metodą bezdotykowego pomiaru drgań. Rozprawa doktorska. ITWL. Warszawa 1994.

[12] Condition Monitoring System Based On Non-Interference Discrete-Phase Compressor Blade Vibration Measuring Method. Proceedings of the 20th Symposium Aircraft Integrated Monitoring System Ragmisch-Partenkirchen. Germany, May 22 – 25.2000.