The Benefits of Operational Modal Analysis of Aircraft and Spacecraft Structures

J. Debille[1], S. Pauwels[1], B. Peeters[1]

1: LMS International , Interleuvenlaan 68, B-3001 Leuven, Belgium

Abstract: In the classical modal parameter estimation approach, the baseline data are Frequency Response Functions measured in laboratory conditions. However real operating conditions may differ significantly. Laboratory modal testing for realistic excitations is often impossible due to practical, economical and safety reasons, which makes that only response data are measurable while the actual loading conditions are unknown. The paper includes applications where modal parameter identification was done in operating conditions for aircrafts and spacecrafts. Through PolyMAX, the LMS modal parameter identification algorithm, with its crystal clear stabilization diagrams, the modal analysis process of highly damped structures and noisy data became straightforward, which enables engineers to fine-tune and update their numerical models.

Keywords: Operational modal analysis, PolyMAX, structural identification,

1. Introduction

In the classical modal parameter estimation approach, the baseline data, which are processed, are Frequency Response Functions measured in laboratory conditions. However, in many applications, the real operating conditions may differ significantly from those applied during the modal test. Therefore the need arises to identify a modal model in these real operational conditions. In many situations input-output FRF measurements are feasible, but the special test setups for artificial excitation of the structure significantly increase the complexity of the test setup. In these cases the response signals not only contain the response due to the artificial excitation, but also a part due to operation of the structure, which is considered unwanted noise and has a negative effect on the quality of the FRF measurements. In many cases, only response data are measurable while the actual loading conditions are unknown, but provide the necessary excitation of the structure. Therefore, the system identification process will need to base itself on response-only data. In this case one speaks of Operational Modal Analysis (OMA).

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2. Operational modal analysis

Operational modal analysis techniques distinguish themselves from operational deflection shapes analysis in that they are able to identify the structural characteristics of the structure by estimating resonance frequencies, damping values and mode shapes and as such are able to separate closely spaced modes. An operational deflection shape is only the operational response of the structure at a fixed frequency and is as such a combination of several modes and forced responses.

Several operational modal analysis techniques have been developed and evaluated of which [1] gives an overview. Recently a new operational modal parameter estimator has been developed of which the theory is described in detail in [1]. The PolyMAX algorithm greatly facilitates the operational modal parameter estimation process by producing extremely clear stabilization diagrams, making the pole selection a lot easier. PolyMAX has also been computationally optimized to analyze large datasets with a broad frequency band up to high model orders.

In the next sections the PolyMAX operational modal parameter estimator is applied to 2 aerospace applications and its results compared to the results from a time domain stochastic subspace identification technique [2]: analysis of aircraft flutter data and analysis of the Ariane 5 launcher during launch. More applications can be found in [3].

3. Flight testing of an aircraft excited by turbulence

In this section the operational PolyMAX method is applied to in-flight aircraft data. At the end of the development cycle, a new aircraft is certified by means of in-flight flutter tests [4][5]. These tests consist of flying the aircraft at different airspeeds and measuring the accelerations at a limited number of locations on the aircraft structure. The scope is to open the flight domain by verifying that the aircraft does not suffer from aero-elastic instabilities such as flutter. Flutter clearance is achieved by both on-line and off-line vibration data analysis encompassing monitoring of signal time histories and spectra, extraction of the eigenfrequencies and damping ratios, and tracking the frequency and damping evolution with increasing airspeed. However, the analysis of in-flight data poses a number of specific challenges that are related to the complex nature of the test article and the difficulty of the test conditions. This section explores the possibilities to enhance the flight data exploitation by using "Operational Modal Analysis". The reason for using modal analysis techniques that do not require input information is that it is difficult to measure the forces from the artificial excitation devices and that these techniques also allow the use of natural turbulences as input.

The analysis was performed on a Polish PZL 28, Bryza, which is a twin propeller aircraft derived from the An-28 and used for SAR as well as standard transport purposes. The aircraft was first extensively tested by means of a detailed Ground Vibration Test (GVT), describing the vibration response by means of 180 measurement points (measured in 3 directions). Then a series of flight tests was scheduled. For these, the measurement grid was limited to 30 vibration response locations where accelerations were measured in 3 directions. The vibrations were the structural response to the natural operational excitation, being mainly the turbulent air-flow. No artificial excitation was applied. Since only 36 data measurement channels were available, 5 flights were executed to collect all necessary data. For each flight, 6 common signals were measured: 4 flight parameters (airspeed, motor speed, temperature, altitude) as well as 2 common reference accelerations, one on a wing, one on a rear rudder (Figure 1). This left 30 additional signals per flight. During each flight, a sequence of pre-defined speeds and altitudes was executed, resp. from 225 km/h to 350 km/h and from 2000 m to 4000 m. The excitation during the 5 flights was very similar, as well in terms of excitation level as frequency content. This provided a consistent data set, as can be seen from the comparison of the power spectra of the references in Figure 2.

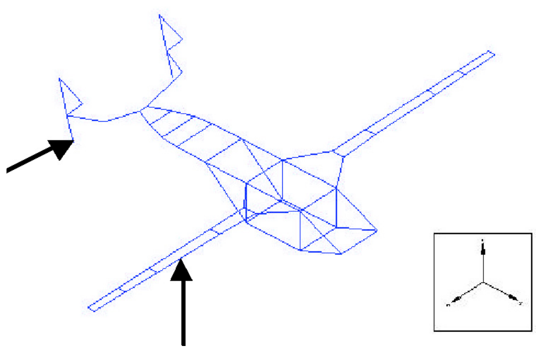

Figure 1: Geometry model of the aircraft and common reference points measured in all flights

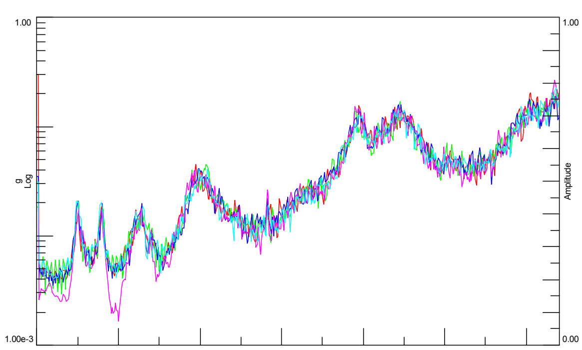

Figure 2: Reference signal autopower spectra for different flights

Before starting the analysis, the original data needed to be "cleaned" to compensate for large DC disturbances, low-frequency drift and some spikes. No filtering was applied for the 28 Hz peak caused by the engine, but the knowledge of the engine speed allowed to afterwards remove this pole from the modal parameters (it was also characterized by a very low damping value). From the response accelerations, the modal parameters were extracted. Both the time domain Stochastic Subspace Identification and the PolyMAX techniques were used. Figure 3 compares the stabilization diagrams of both techniques in the same frequency band. When using stochastic subspace identification, a larger number of non-physical poles are identified at higher model order. The PolyMAX stabilization diagram is much clearer, making the pole selection easier.

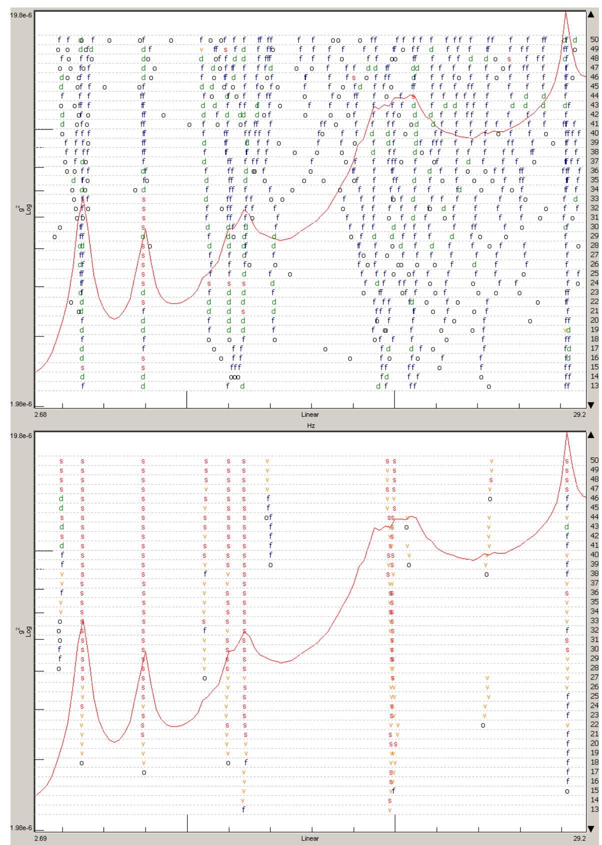

Figure 3: Stabilization diagram obtained by the time domain Stochastic Subspace Identification (top) and the PolyMAX technique (bottom) on the flight data

Figure 4 shows some typical measured cross spectra compared with spectra synthesized from the modal parameters. The main modes, as found during the GVT, were also identified from the in-flight data, but at slightly different frequencies. The mode shape results for the mode around 5 Hz are shown in Figure 5, clearly indicating the asymmetric bending of the main wings and stabilizers. Figures 6 and 7 show the evolution of resonance frequencies and damping values as a function of airspeed, which is the main objective of flight tests.

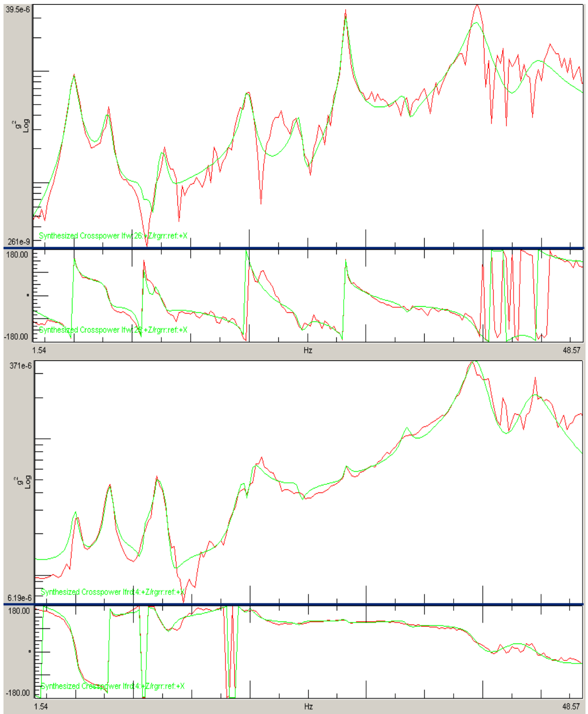

Figure 4: **Comparison of measured (red/black) cross spectra with cross spectra synthesized from the identified modal parameters (grey/green). (Top) Point on wing; (Bottom) Point on tail.**

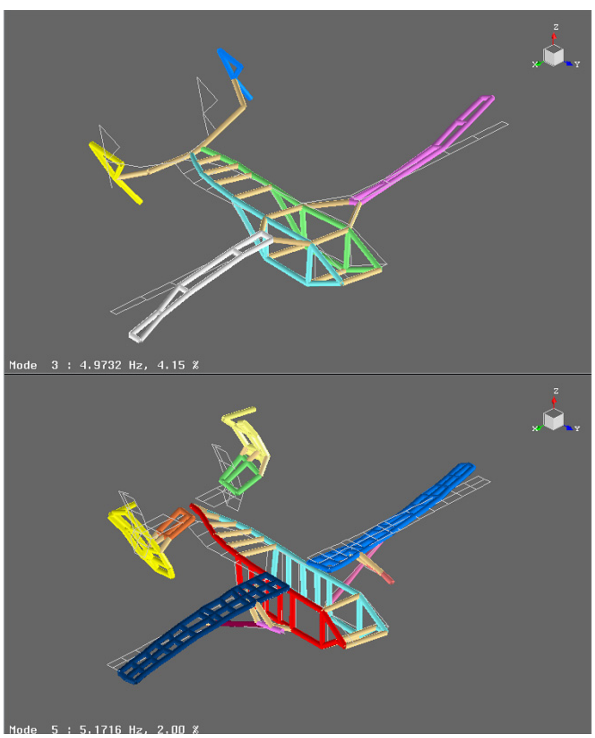

Figure 5: Asymmetric bending mode of main wings and stabilizers around 5 Hz. (Top) mode from flight data; (Bottom) mode from ground vibration test.

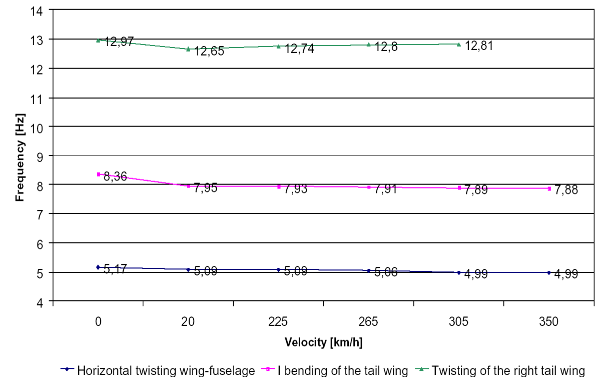

Figure 6: Evolution of natural frequencies with increase of the flight velocity [7].

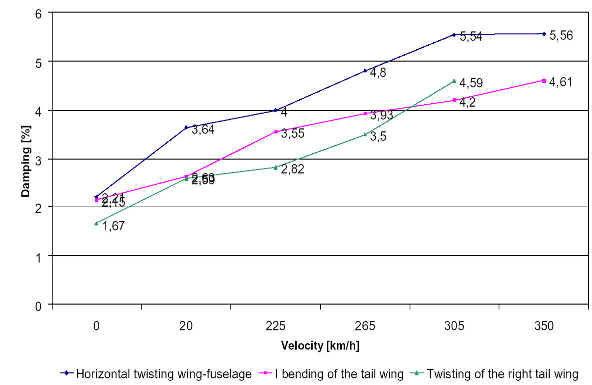

Figure 7: Evolution of damping ratios with increase of flight velocity [7].

4. Modal characterisation of the Ariane 5 launcher

Objective of the data analyses was to identify the modes of the main constituents of the European ARIANE 5 launcher during the initial launch phase. Operational modal analysis was applied to the time response data acquired on the launcher during flight number 501, which only lasted about 39 seconds due a failure of the inertial reference system. In total, about 100 accelerations were mounted on different constituents of the launcher such as the booster segments, the booster skirts JAR and JAV, the booster attachments DAAR and DAAV, the LH2 and LOX tanks in the main cryogenic stage, the VULCAIN and AESTUS engines and the MMH and N204 tanks in the EPS stage (see figure 8) [6] [8].

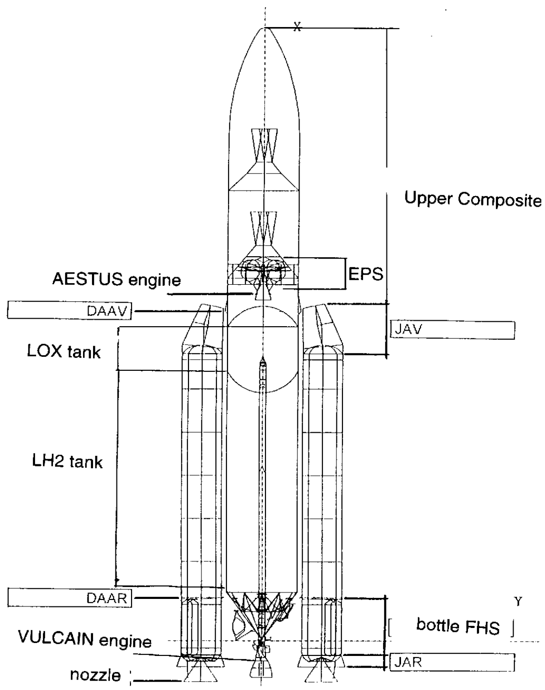

Figure 8: The main constituents of the Ariane 5 launcher

The data were recorded via a telemetry measurement system. As different data recording systems were used, the available time response data had quite different characteristics. Although all data channels were synchronized with respect to a common time to, the data of each channel was slightly non-equidistant due to rounding-off errors (10µs) and due to the nature of the used data sampling and telemetry system (e.g. transmission losses due to antenna masking). In addition, the data channels were sampled at different sampling frequencies and were characterized by different time offsets from the common time to. Therefore, a preprocessing step was first performed to convert them to a consistent response database. Without going too much in detail, following steps were performed:

- Conversion of the non-equidistant data to an equidistant time axis on the basis of a cubic spline interpolation.
- Resampling of the equidistant data to a common sampling rate. As the conversion factor was typically not an integer, the resampling consisted of a fixed upsampling with a factor 15 and subsequently, a linear interpolation in order to reach the new sampling rate. The filters used during resampling were designed such that they had a maximum ripple of 0.01dB in the passband and a minimum attenuation of 50dB for mirrored spectrum bands.
- Zero-mean adjustment of the signals

In addition to these steps, the preprocessed response signals were visually inspected. Dropouts due to transmission losses of the telemetry system (e.g. masking of the antennas) or spikes (e.g. engine ignitions) were manually adjusted.

In this paper, the extraction of the suspension modes of the fuel tanks in the EPS stage is detailed. Hereto, both the stochastic subspace identification technique and the new PolyMAX method was applied to 8 preprocessed signals measured at the bottom of the 4 tanks in different directions. The sampling rate of the preprocessed signals equaled 93.4Hz. Figure 9 depicts some of the measured time signals. It illustrates the non-stationary behavior of the excitation and shows that the strongest responses occur around 7.3 sec, when the launcher lifts off. A detailed inspection revealed a small shift of the autopower spectra peaks as function of time, suggesting a small effect of the mass decrease due to fuel consumption on the modal parameters. In order to better understand this, it was decided to perform the output-only modal analyses for the following 4 time data segments:

S1	S2	S3	S4
6-14s	14-26s	26-36s	6-36s

Note that segments S1 and S4 include the time responses around 7 seconds when the boosters are ignited and the main excitation occurs.

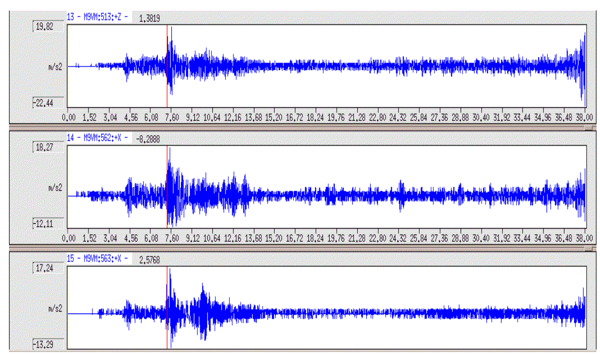

Figure 9: Time signals measured on the fuel tanks in the EPS stage

The stabilization diagram for the data segment S1, from the stochastic subspace technique is compared with the one from PolyMAX in figure 10. Again the PolyMAX stabilization diagram is much clearer,, making pole selection easier. The quality of the modal model can be verified by overlaying the crosspower functions calculated from the measured data with the crosspowers synthesized from the estimated modal parameters (Figure 11).

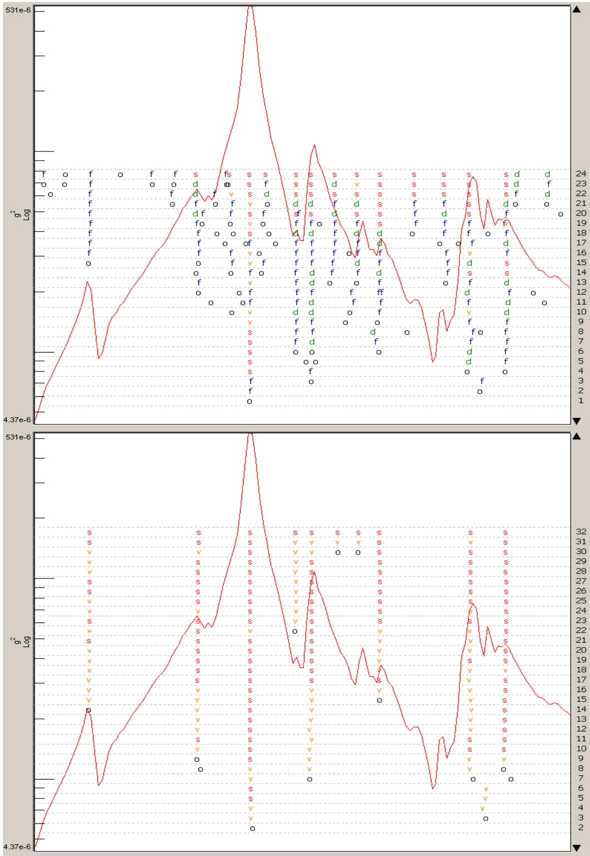

Figure 10: Stabilization diagrams for the suspension modes of the fuel tanks in the EPS stage (data segment S1). (Top) time domain Stochastic Subspace Identification; (Bottom) PolyMAX.

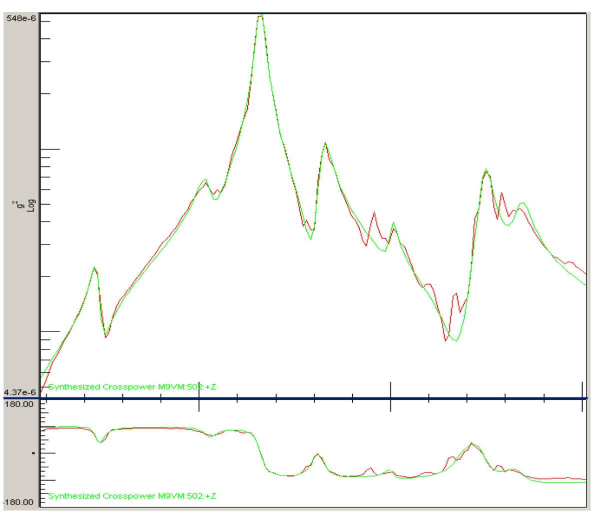

Figure 11: Comparison of measured (red/black) cross spectra with cross spectra synthesized from the identified modal parameters (grey/green) of one of the points measured on the fuel tanks in the EPS stage.

A simple geometry consisting of 4 nodes corresponding to the bottom of each tank was defined for the mode shape animation. Figure 4 depicts the mode shape for a suspension mode of the tanks, identified for data segment S1. It shows a strong longitudinal motion of the bottom of the fuel tanks with a 180 degrees phase shift for 2 tanks.

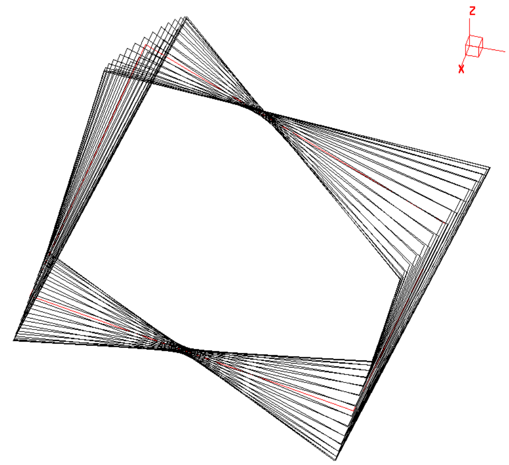

Figure 12: Mode shape of a suspension mode of the fuel tanks

In a next step, the evolution of the natural frequency of the modes for the time data segments S1, S2, S3 and S4 was studied. Figure 6 shows the relative change in natural frequency. The results found for segment S1 were taken as reference as for this data segment, the modes were excited the best. Figure 6 reveals a small frequency increase from segment S1 to segment S3, probably due to the mass decrease. The natural frequency for segment S4 that combines S1, S2 and S3 is very similar to S1. Interesting to note is that the damping ratio identified for segment S4 was about 20% higher than for S1, which can be explained by the small natural frequency shift over the segments S1, S2 and S3.

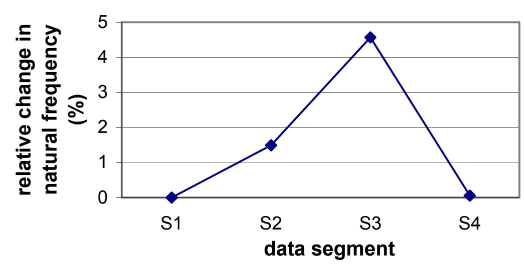

Figure 13: Relative change in natural frequency of a mode for data segments S1, S2, S3 and S4

5. Conclusion

This paper showed that Operational Modal Analysis has developed and reached a mature state with advanced parameter estimation algorithms, high-quality data acquisition systems, commercial software implementations, and very relevant industrial applications. The new PolyMAX modal parameter estimator makes the analysis easier by generating very clear stabilization diagrams. This reduces errors in the pole selection and increases confidence in the resulting modal models. Industrial applicability of the new PolyMAX method has been shown on aircraft flight data and data from the Ariane 5 launcher.

6. Acknowledgement

This work was carried out in the frame of the EUREKA project E!3341 FLITE2 (Flight Test Easy - Extension) which is conducted in cooperation with V.U.Brussels (B), K.U.Leuven (B), Lambert Aircraft Engineering (B), INRIA (F), Sopemea (F), Onera (F), Airbus (F), Dassault (F), AGH (PL), ILOT (PL), PZL Mielec (PL). The financial support of IWT-Vlaanderen is gratefully acknowledged. The authors acknowledge the contribution of their colleagues to this work.

6. References

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