Characterization and modelling of 3D piezoelectric ceramic structures with ATILA software.

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Abstract

In this paper, correspondence between ATILA simulated and measured values of two piezoelectric ceramic structures; bulk and RAINBOW actuators were determined. Modelling began by creating a 2D wire-model of the structures, after that the 3D model was created and simulation parameters were introduced (electric potentials, polarizations, and boundary conditions). Harmonic type analyse was used in the simulations. Results obtained from the simulations contained information about displacements in the z-axis direction.

Displacements of the structures showed nonlinearity as a function of electric field in measured values. Accordingly, effective piezoelectric coefficients (ie. d_{31}, d_{33}) calculated from electric field and displacement changed nonlinearly. However, displacement results acquired from simulations are linear, since ATILA program uses a linear approach for calculation. This causes the modelling results to differ from the measurement results, especially when large voltages were used.

The problem was solved by modifying the constant parameters used in the simulations. In this paper, relative permittivity K_{33}, piezoelectric coefficient d_{33} and approximated piezoelectric coefficient d_{31} were used to obtain more accurate modelling results corresponding to the measurement results.

The differences of the z-axis displacements between modelling (using original material parameters) and measurement results with bulk and RAINBOW actuators were 6.5-17.7 % and 6.0-27.9 % respectively. With modified material parameters the differences were 1.1-1.6 % and 3.1-8.5 % respectively.

Keywords: ATILA; actuators; PZT; piezoelectric properties

1 Introduction

Different active materials and new actuator applications need thorough modelling before practical experiments are reasonable to be made. Modelling programs facilitate and speed up the designing and development of the new structures, especially optimization. Changes to different applications (ie. size and shape) and those effects to the whole structure can be predicted, which also eases the optimization.

Characteristics of the modelled structures are strongly dependant upon material specific parameters. In modelling softwares, parameters and modifications for designs can be altered easily and quickly. When designing the function of the component, different modelling softwares can be used also for problem-solving, particularly when perceiving the problem is difficult or nearly impossible otherwise.

Aim of this paper is to define correspondence between ATILA simulated and measured values of the piezoelectric ceramic structures. Also frames for reliable simulation using ATILA software were determined. The modelled structures were: Bulk and RAINBOW actuator.

2 Experimental

The displacement measurement system used based on Michelson's Interferometer. The z-axis displacement of the piezoelectric actuators top surface compared to interferometers detector was measured[1-2]. Material of the bulk actuator was PZT-5H. The RAINBOW actuator was manufactured from a commercial PZT-5A bulk disc (Morgan Electro Ceramics)[3-4]. The voltage signal used in measurements was sinusoidal with offset value of $V_{p-p}/2$ and frequency of 100 Hz (bulk actuator) and 10 Hz (RAINBOW actuator).

ATILA software used in this paper was developed in the acoustic department of ISEN France, primarily to model actuators and transducers used in underwater applications[5-6]. ATILA software uses FEM (Finite Element Method) when calculating modelled structures. The software version used was 5.2.2 and it functioned in Windows XP environment.

The modelling of all the structures began with making a 2D wire-model, which was further processed into a 3D model. Also the necessary data needed for FEM calculation was introduced, such as: used materials and parameters, boundary conditions, polarizations and excitation signals. In the simulations; harmonic type analysis was used and Cartesian polarization with Euler angles 0, 90, 0 (a, band g respectively)[6] was applied to the materials; hence the positive voltage was applied to the top surface of the structure and the ground to the bottom surface.

For a piezoelectric material, ATILA assumes that it belongs to the crystalline class 6mm (hexagonal)[6]. The material properties needed for FEM calculations are presented in table 1. Materials used in simulations and real structures were commercial and material properties were acquired from material manufacturers[7]. Some material parameters were modified during the modelling process; the modified parameters are listed accordingly in context of each case.

2.1 Bulk actuator

In measurement, the bulk actuator was clamped with a metal pivot (diameter of 2 mm), which was attached to the bottom surface of the actuator[2]. The diameter of the bulk-actuator was 10 mm and thickness 500 µm. The voltage values used in measurements and simulations were 100 – 1000 V.

Piezoelectric coefficient d_{33} shown in table 2 were calculated from the displacement measurement results with formula 1.

In modelling, the actuator was clamped from the bottom surface of the clamping area so that displacements in the x-, y- and z-axis directions in that surface were zero. Two sets of simulations were calculated and compared to the measuring results. In the first set, the material parameters used were from the material manufacturer (table 1). In the second set, the previously measured piezoelectric d_{33} values (table 2) were used.

2.2 RAINBOW actuator

The RAINBOW actuator rested freely from the edges against the measurement jig. The electric field values used in the measurements and simulations were 0.5 – 1.25 kV / mm. Electric field values were calculated using minimum piezoelectric ceramic thickness (300 µm) at the center of the actuator (fig. 1). The relative permittivity in the polarization direction

(K_{33}) of the RAINBOW actuator was also measured as a function of electric field using Radiant RTV6000HVS equipment. Measured relative permittivity values of the RAINBOW actuator can be seen in table 3.

The radius of the RAINBOW actuator was 12.5 mm, thickness 500 µm, minimum thickness of the active material 300 µm in the center and height 700 µm in the center. In the bottom of the actuator was a 200 µm thick (in the center) reduced lead layer which started from 1 mm of the edge of the actuator. The 2D wire-model of the RAINBOW actuator can be seen in fig. 1.

The piezoelectric material of the actuator was PZT-5A. Passive material was elastic material LEAD, Properties of the reduced lead layer were assumed to be as pure lead[3] (table 1). Clamping was applied from the edge of the actuator so that displacement in z-axis direction in that edge was zero.

Four sets of simulations were calculated and compared to the measurement results. In the first set; material parameters used were from the material manufacturer (table 1). Measured relative permittivity K_{33} shown in table 3, were used in the second set of simulations.

New piezoelectric coefficient d_{31} values were approximated from the first set simulation results. Simulated z-axis displacements were compared to the measured results, from which a percentual difference was calculated. The acquired percentual differences were used to calculate new d_{31} values (ie. if the difference was 5.98 %, the new d_{31} value was 5.98 % larger than the original one). The approximated d_{31} values are shown in table 4.

In the third set, the approximated piezoelectric coefficient d_{31} values (table 4) were used. In the fourth set, both the measured relative permittivity values (table 3) and the approximated d_{31} values (table 4) were used.

3 Results and discussion

Displacements of the actuators changed nonlinearly as a function of electric field in measurements. Therefore, effective piezoelectric coefficients (ie. d_{31}, d_{33}) calculated from voltage and displacement (formula 1) change nonlinearly. When calculating displacements, ATILA program uses constant material parameters for all electric field values (linear approach). This causes modelling results to differ from the measurement results, especially when large voltages were used.

By adjusting the original parameters used by ATILA program, correspondence between modelling results and measuring results improved. Using measured d_{33} values, in the case of the bulk actuator correspondence improved significantly, as can be seen in figure 2.

The four sets of modelling results of the RAINBOW actuator compared to measuring results can be seen in figures 3-6. The simulation results of the RAINBOW actuator improved significantly, especially when modified d_{31} or both modified d_{31} and modified K_{33} values were used, which can be seen in figures 5 and 6, respectively.

4 Conclusions

Linear approach of the ATILA software caused simulation results to differ from measured results, especially when large voltages were used. Using measured /calculated material parameters and also values approximated with feedback calculation, correspondence between modelling and real results improved significantly. The differences of the z-axis displacements between modelled (using original material parameters) and measured results with bulk and RAINBOW actuator were 6.5-17.7 % and 6.0-27.9 % respectively. Using modified material parameters the differences were 1.1-1.6 % and 3.1-8.5 % respectively.

Acknowledgements

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Figure Captions

Figure 1. The 2D wire-model of the RAINBOW actuator.

Figure 2. Measured and modelled results of the z-axis displacement of the PZT-5H bulk actuator.

Figure 3. Measured and modelled results of the z-axis displacement of the PZT-5A RAINBOW actuator. (using original material parameters in simulation).

Figure 4. Measured and modelled results of the z-axis displacement of the PZT-5A RAINBOW actuator (using modified K_{33} values in simulation).

Figure 5. Measured and modelled results of the z-axis displacement of the PZT-5A RAINBOW actuator (using modified d_{31} values in simulation).

Figure 6. Measured and modelled results of the z-axis displacement of the PZT-5A RAINBOW actuator (using modified d_{31} + K_{33} values in simulation).

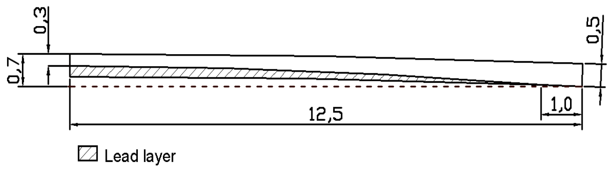

Figure 1.

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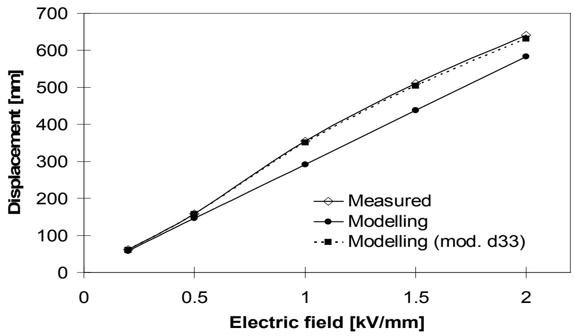

Figure 2.

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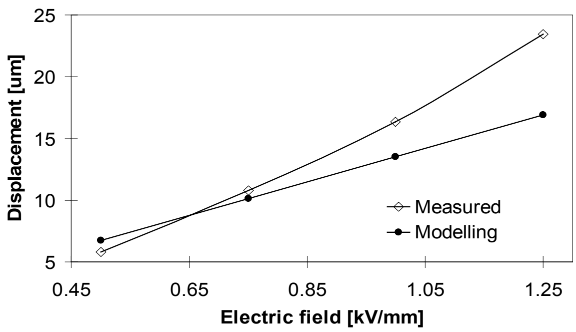

Figure 3.

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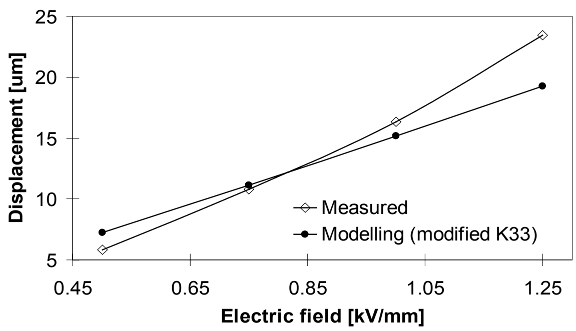

Figure 4.

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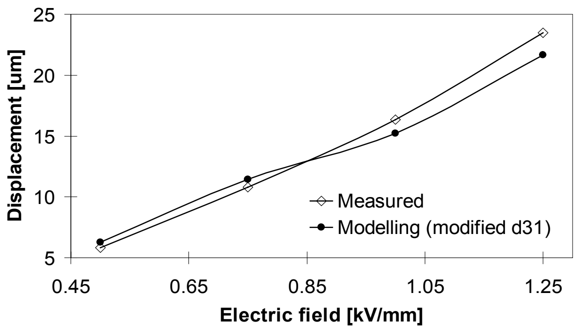

Figure 5.

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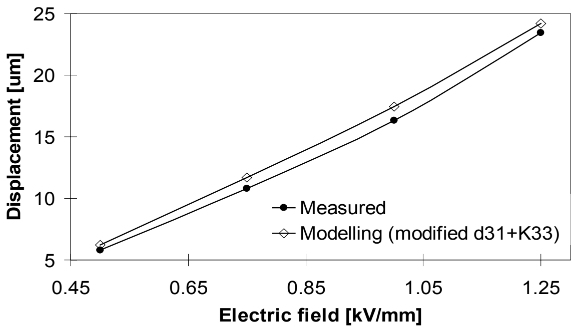

Figure 6.

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Table Captions

Table 1. Material properties of piezoelectric materials PZT-5H, PZT-5A and elastic material LEAD.

Table 2. Calculated d_{33} values of the bulk actuator.

Table 3. Measured relative permittivity K_{33} values of the RAINBOW actuator.

Table 4. Approximated piezoelectric coefficient d_{31} values.

Material	Elastic compliance coefficients [m^2/N x 10^{-12}]					
	s_{11}	s_{12}	s_{13}	s_{33}	s_{44}	s_{66}
PZT-5H	16.5	-4.78	-8.45	20.7	43.5	42.56
PZT-5A	16.4	-5.74	-7.22	18.8	47.5	44.28
	Density [kg/m^3]	**Piezoelectric coefficients [m/V x 10^{-12}]**			**Relative permittivity**	
		d_{31}	d_{33}	d_{15}	$\varepsilon_{11} / \varepsilon_0$	$\varepsilon_{33} / \varepsilon_0$ (K_{33})
PZT-5H	7500	-274	593	741	1700	1470
PZT-5A	7750	-171	374	584	916	830
	Density [kg/m^3]		**Young's Modulus [N/m^2]**		**Poisson's ratio**	
LEAD	11100		1.6E+10		0.45	

Table 1. Esa Heinonen, Jari Juuti and Seppo Leppävuori

Voltage [V]	**Displacement [x 10^{-9} m]**	**d_{33} values [m/V x 10^{-12}]**
100	62	620
250	159	636
500	355	710
750	510	680
1000	641	641

Table 2. Esa Heinonen, Jari Juuti and Seppo Leppävuori

Electric field [kV/mm]	Relative permittivity K_{33}
0.5	1776
0.75	2597
1.0	3922
1.25	6155

Table 3. Esa Heinonen, Jari Juuti and Seppo Leppävuori

Electric field [kV/mm]	Original d_{31} value [m/V x 10^{-12}]	Difference in displ. [%]	New d_{31} value [m/V x 10^{-12}]
0.5	-171	-16.28	-143
0.75	-171	5.98	-181
1.0	-171	17.23	-200
1.25	-171	27.94	-219

Table 4. Esa Heinonen, Jari Juuti and Seppo Leppävuori

Legends to Formulas

Formula 1.

η_3 = displacement in the polarization direction (m)

U_3 = voltage in the polarization direction (V)

$$d_{33} = \frac{\eta_3}{U_3} \tag{1}$$

Formula 1. Esa Heinonen, Jari Juuti and Seppo Leppävuori