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Resonance modes in the Standard piezoceramic shear geometry: A discussion based on finite element analysis*

L. Pardo[1]; M. Algueró[1] and K. Brebøl[2]

[1] *Instituto de Ciencia de Materiales de Madrid (ICMM).*
Consejo Superior de Investigaciones Científicas (CSIC). Cantoblanco 28049- Madrid (Spain)
[2] *Limiel ApS. Langebæk. (Denmark)*

Abstract. Several authors developed methods for the complex characterization of piezoceramics from complex impedance measurements at resonance. Alemany et al. developed an automatic iterative method, applied and reported in a first publication to four modes of resonance: (1) the length extensional mode of a thickness poled rectangular bar; (2) the length extensional mode of long rods or rectangular bars, length poled; (3) the thickness extensional mode of a thin plate and (4) the thickness shear mode of a thin plate. In a second publication it was reported the application of the method to (5) the radial mode of a thin disk, thickness poled, the most mathematically complex geometry. The (2), (3), (4) and (5) modes of resonance are sufficient for the purpose of the determination of the full set of complex elastic, dielectric and piezoelectric coefficients of piezoceramics, a 6mm symmetry material. This work presents the results of the FEA modeling of a thin plate based on the characterization of a commercial ceramic. The comparison of the experimental resonance spectra and the FEA results obtained for elastically, dielectrically and piezoelectrically homogeneous samples is presented and discussed. The complex characterization for the first time of the shear mode of a new lead-free piezoceramic is also shown.

1. INTRODUCTION

The modeling and design of piezoelectric devices by, among others, finite element analysis (FEA), rely on the accuracy of the coefficients of the active material used, commonly an anisotropic poled piezoelectric ceramic[1].
The description of the material parameters by complex values[2] ($P^* = P' - iP''$) is a convenient way to separately account for the dielectric, piezoelectric and mechanical losses ($\tan\delta = P''/P'$). The origin of the losses in ferroelectric ceramics has been analyzed in numerous works[3,4]. Several authors have developed methods for the complex characterization of piezoceramics from complex impedance measurements at resonance, whose validity has been discussed elsewhere[5]. According to the IEEE standard[6] three sample shapes and four modes of resonance, as mentioned in the abstract, are sufficient for the purpose of the determination of the full set of complex of coefficients of the piezoceramic. Alemany et al. developed an automatic iterative method applicable to all[7,8].
The application of this method to the full complex characterization of a Navy II type PZT-based commercial piezoceramic (PZ27 of Ferroperm Piezoceramics A/S) has been recently published[9]. This allows the modeling by FEA of the electromechanical resonances of samples of a given geometry. Aiming at a better understanding of the modes of the resonance for the shear plate and also to state the validity of the characterization carried out using resonators with sample shapes and aspect ratios according to IEEE Standard, this work presents the results of the FEA modeling of the Standard shear resonator used in the characterization of this PZT-based commercial piezoceramic. The comparison of the experimental resonance spectra of the resonators and the FEA results obtained for elastically, dielectrically and piezoelectrically homogeneous ceramic items here modelled is presented and discussed.

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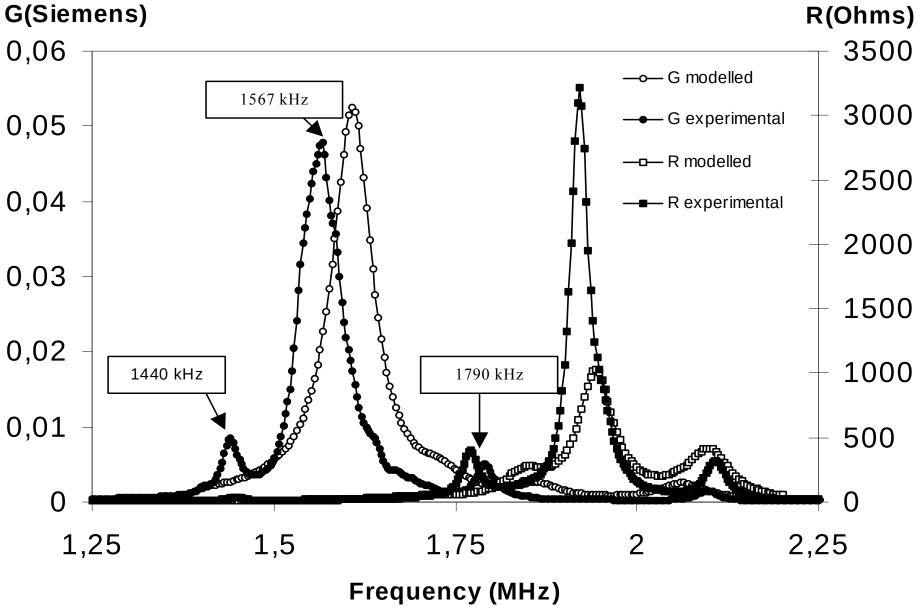

Figure 1. Experimental and FEA simulated resistance, R, and conductance, G, for the fundamental thickness shear resonance of the thin plate of PZ27

2. EXPERIMENTAL PROCEDURE

The simulations were done using a finite element software, ATILA[10] version 5.2.4, especially developed for active materials. A Standard shear plate of thickness t=0.59 mm, width for poling w=5.9 mm and length L= 5.9 mm was modeled, based on a full complex matrix of coefficients for the PZ27 piezoceramic. This matrix and the measured spectra were published in reference 9.

3. EXPERIMENTAL RESULTS AND DISKUSSION

Figure 1 shows the experimental and modeled spectra of a thickness shear resonance mode in the thin plate. The agreement in the frequencies is reasonable (deviation ≈2.5%). However, the height of the R and G FEA modeled peaks is not well reproduced.

The obtained real part of the piezoelectric coefficient of PZ27 from shear resonance is lower[9] (d_{15}=396 pC.N^{-1}) than the figure (d_{15}=500pC.N^{-1}) stated in the manufacturer catalog , which is obtained from direct measurements on accelerometers working with shear elements. A similar result was obtained[11] for Motorola 3203HD piezoceramic. The resonance method with such standard shear geometry gave k_{15}=61%, whereas the manufacturer states k_{15}=72% as catalog value[12]. Aurelle et al.[13] already stated that there is an aspect ratio dependence of the coefficients obtained with the standard shear

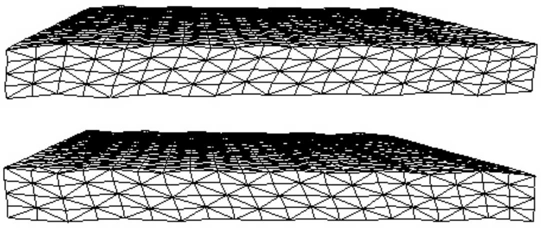

Figure 2. FEA simulated shear item in the two positions of the maximum shear displacement for the mode of motion at the shear series resonance (f_2=1570kHz),. Displacement is exaggerated.

sample, due to clamping. It is clearly observed in Figure 2 that the sample is dynamically clamped. This can be understood as the origin of the underestimation of the shear coefficients for the Standard shear sample.

Secondary resonance peaks appearing at the resonance spectra near the main resonances are commonly observed (Figure 1) and often related to material inhomogeneities. But the results of the FEA, corresponding to an elastically, dielectrically and piezoelectrically homogeneous item shows that in fact this explanation is doubtful. Secondary modes can be clearly observed in the FEA simulated R curve at frequencies in good agreement with the measured ones. In the G curve they appear as soft shoulders of the main peak. Secondary peaks take place due to the occurrence of non-shear modes at f_1 = 1440 kHz and f_3 =1790 kHz (Figures 3 and 4) near the shear resonance mode in such a sample geometry and dimensional ratios. At f_3=1790 kHz (Figure 4) a composition of a thickness shear and an asymmetrical Lamb wave modes of motion with perpendicular propagation directions can be seen, whereas at f_1=1440 kHz (Figure 3) even more complex modes of motion are found.

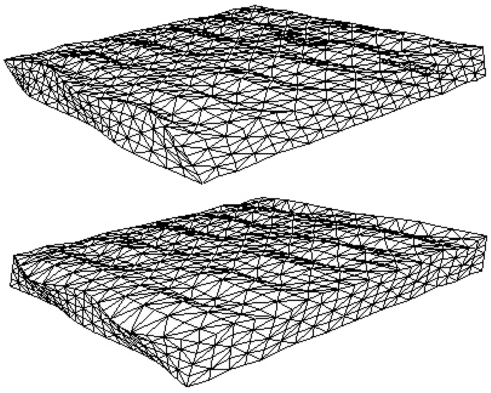

Figure 3. FEA simulated shear item in the two positions at maximum displacement for the mode of motion at f_1= 1440 kHz. Displacement is greatly amplified.

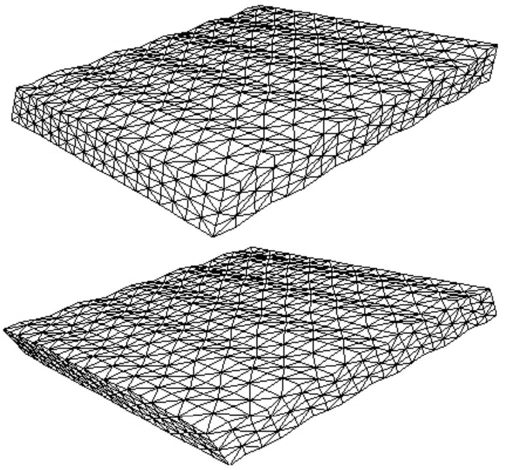

Figure 4. FEA simulated shear item in the two positions at maximum displacement for the mode of motion in the neighborhood of the thickness shear resonance at f_3=1790 kHz.

Although not reported here in detail, FEA results[14] also show the well-known fact that at the thickness resonance of the thin disk the mode of motion does not follow a simple piston like scheme. On the contrary, there is a shear stress pattern in the modelled item. Thus the low values of the shear coefficients result in differences of the frequencies determined by FEA with respect to the experimental ones (Exp. values: f_s=2494 kHz, f_p=2784 kHz ; FEA values f_s=2405 kHz, f_p= 2661kHz). However the understimated coefficients do not have a great influence on the modelling of the resonances of the purely dilatational modes of the length resonance of the longitudinally poled long bar and the planar mode of the thin disk[14] (Lenghth mode: exp. values: f_s= 71.0 kHz, f_p= 91.8 kHz ; FEA values f_s= 70.9 kHz f_p=91.4 kHz. Radial mode: exp. values: f_s= 53.5 kHz f_p= 62.3 kHz ; FEA values f_s= 53.7 kHz f_p= 62.9 kHz).

The substitution of the standard thickness shear plate geometry is at present under study and will be reported separately. The preliminary results of measurements on our choice for a shear geometry yielded a d_{15}=(526 – 18i)pC.N^{-1}, closer to the actual value of PZ27.

In the characterization of a commercially available lead-free material[15], Ferroperm PZ61, the Standard shear geometry provides a value of d_{15}=(54-1i)pC.N^{-1}, whereas the iterative method applied to our choice for a shear geometry, yields d_{15}=(118-5i)pC.N^{-1}.

4. CONCLUSIONS

Using a full set of material coefficients, including losses, of a Navy II type PZT-based commercial piezoceramic, a modelling by 3-D FEA of a shear element having dimensions as recommended by the IEEE Standard was carried out. FEA results reproduce the resonance frequencies of the shear mode, and reveal the type of motion involved. The secondary modes of resonance are also reproduced in the homogeneous shear item modeled, indicating that they cannot be related with previously assumed inhomogeneities in the material. FEA results also show the origin of the underestimation in the standard shear sample of the k_{15} electro-mechanical coupling coefficient and d_{15} piezoelectric coefficient of the material to be the dynamic clamping of such a geometry.

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