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Piezoelectric modelling using a time domain finite element program

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Abstract

The disconformities in piezoelectric resonators between the electrical and mechanical experimental measurements in frequency resonance and transient modes and the prediction of the one-dimensional models that supports the characterization of them, are well known. The same can be applied to the piezoelectric transducers based on piezoelectric resonators. A finite element analysis of both the resonator and the piezoelectric transducers can help the understanding of the reason of these disconformities.

A finite element modelling program, PZFlex (Weidlinger Associates Inc., Los Altos, CA, USA), has been used to analyse the piezoelectric transducer devices, i.e. isotropic plates, piezoceramic disks, etc. This program uses a mixed explicit–implicit time integration algorithm, which is used to obtain the mechanical, acoustic and electrostatic field solution of the piezoceramic device. Working on the time domain gives advantages on the speed and model size against frequency domain models, thus allowing more accurate models.

This work shows the mechanical and electrical behaviour in transient mode of piezoelectric resonators with standard sizes for metrological purposes and the piezoelectric transducers made with them.

Keywords: Electrical properties; Impedance; Piezoelectric properties; PZT; Finite element modelling

1. Introduction

Piezoelectric devices are a common and widespread method of generating ultrasound. Finite element modelling (FEM) is extensively used in the ultrasound industry to design and validate new prototype piezoelectric transducers. Accurate FEM modelling requires knowledge of the physical composition of the devices, driving conditions and accurate material properties.[1–4] Material characterization is particularly difficult for piezoelectric materials. The finite element program used in this work, PZFlex,[5] has multiple element and material types available, including fully coupled piezoelectric materials, and isotropic and anisotropic elastic solids, in both 2D and 3D dimensions. The piezoelectric transducers consider the full anisotropic material properties. The element order and time integrator are both second order, and linear interpolation is used between elements for field calculations. Single point integration is used. While PZFlex is capable of variable mesh spacing, a regular element spacing was chosen throughout the models. In this work, the PZFlex finite element analysis program has been used to simulate different transducers and its mechanical, acoustic and electrical properties.

All simulations were run on a desktop PC (Dual Pentium IV processor 3 GHz with 3 GHz RAM) under the Windows XP Professional operating system.

2. FEM simulations

2.1. Piezoceramic disk

The first simulation consisted of a piezoceramic disk with a diameter of 25 mm and thickness of 2 mm. For this purpose, a 2D axi-symmetrical piezoceramic model was built. Mesh density was at least 20 elements/wavelength of interest. The driving input function was a single sinusoid wave at 1 MHz frequency. The simulation outputs chosen were the voltage and charge on the piezoceramic active electrodes. The model took few seconds to run. The impedance characteristics of the device were then calculated with the simulation outputs, that is with the piezoceramic voltage and charge.

It is very important to know how long the model should be run. For instance, if we wish to examine a wave interaction with

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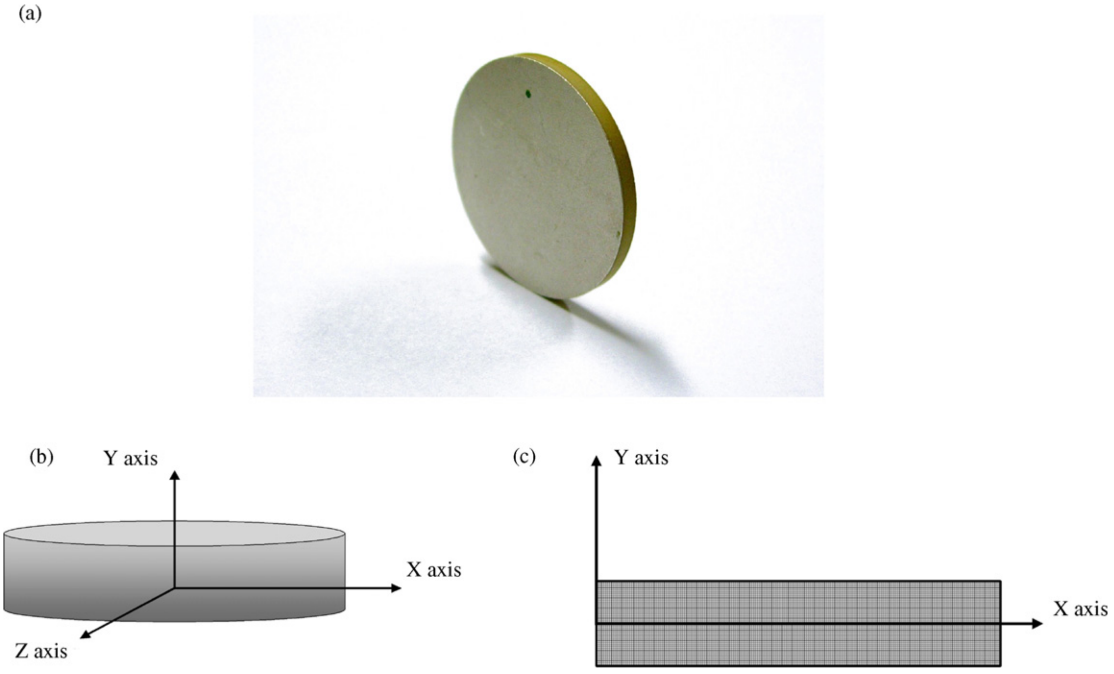

Fig. 1. (a) Piezoceramic disk, (b) 3D model of the simulated piezoceramic disk and (c) 2D model.

a target in a solid material, we have to allow enough time for the wave to propagate through the material and reach the target. However, this problem becomes a little more difficult when we are dealing with piezoelectric transducers and we are looking to determine the operational impedance of the device. In this instance, we must wait for the charge to ring down in the device. By plotting the results as they are computed, voltage or charge on the active electrodes of the device, we can see how the model is reacting and optimize the run simulation time.

In Fig. 1(a), the simulated piezoceramic disk is shown. The three-dimensional 3D disk, Fig. 1(b), is reduced to a 2D model with axi-symmetry along the *Y*-axis, Fig. 1(c).

Fig. 2 shows the real part of the electrical impedance of the simulated piezoceramic disk compared with the experimental results obtained with a disk of the same dimensions and material properties. Several attempts were made to adjust the model to the experimental results varying the different material properties of the simulated piezoceramic disk. The experimental electrical impedance of the piezoceramic disk was measured with a HP 4194 Impedance/Gain-Phase Analyzer. It can be seen that the FEM results agree very well with the experiments. The resonant frequencies can be now determined by observing the main picks in the plots. With these resonant frequencies, the model can be re-run to calculate the displacement mode shapes. Fig. 3(a) shows the displacement mode shape of the simulated piezoceramic disk at 1 MHz frequency and phase of 0.00°. It can be seen that there is a superposition between the radial and thickness resonant modes. The displacement mode shape in the case of a phase shift of 180° is depicted in Fig. 3(b).

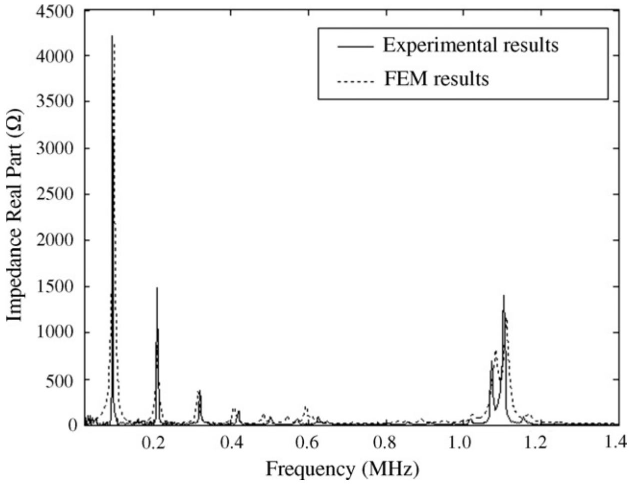

Fig. 2. Real part of the electrical impedance of the simulated piezoceramic disk compared with the experimental results.

2.2. *Three-layer piezoelectric stack transducer*

In this case, a 3D model composed of three square plates (7 mm lateral side and 0.5 mm thickness) of identical piezoceramics (layers) was developed. These piezoceramics were bonded together with the poling in the alternating directions. This model can also be implemented as a 2D model but for visualization purposes a 3D model has been chosen. The ground electrode is placed along the bottom layer and between the top and the central layer, while the active electrode is placed at the top layer and between the central and bottom layers. The active electrodes are connected to an ideal voltage source by a resistor. The value of the resistor has been chosen to enable a rapid return to steady state. The device is symmetrical about two axes, *X* and *Z*, consequently, symmetry conditions were applied allowing to model only a quarter of the device. Mesh chosen was 15 elements/wavelength and at least 4 elements through piezoceramic

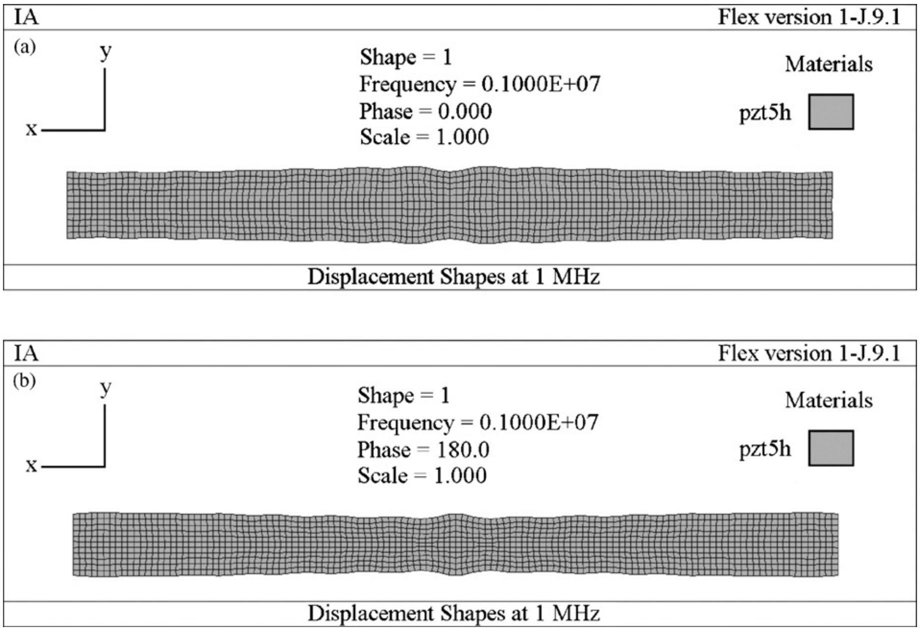

Fig. 3. Displacement mode shapes at 1 MHz frequency. (a) Phase 0 and (b) phase 180.

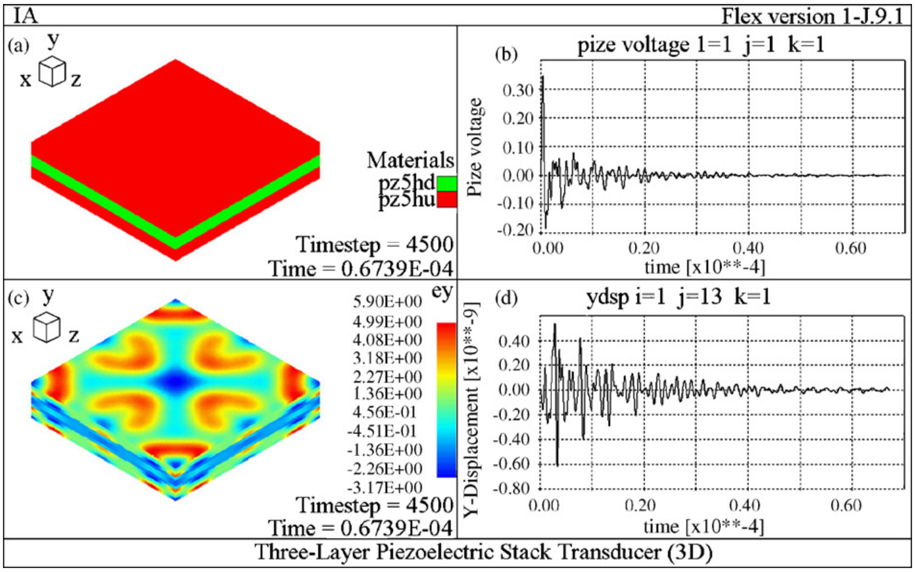

Fig. 4. (a) Materials plot of the multilayer transducer, (b) voltage time-history on active electrodes, 67 μs length, (c) electric fields of the multilayer transducer in the Y direction and (d) *Y*-displacement–time-history of the multilayer transducer, 67 μs length.

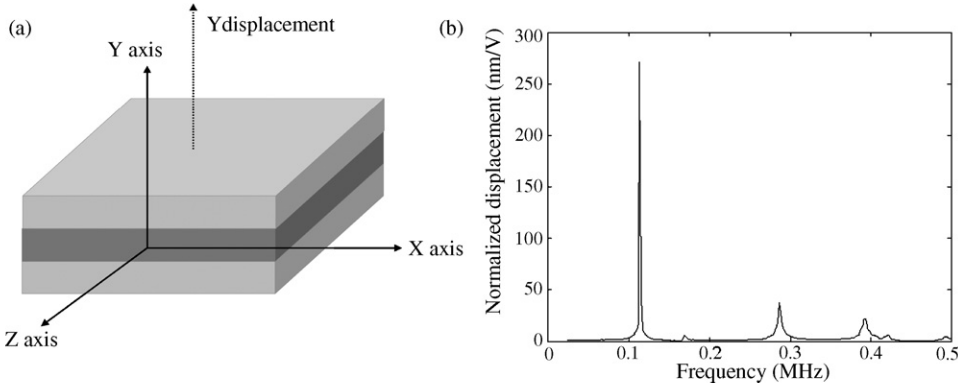

Fig. 5. (a) Scheme of the multilayer transducer and displacement direction and (b) normalized displacement magnitude at top centre of the multilayer transducer.

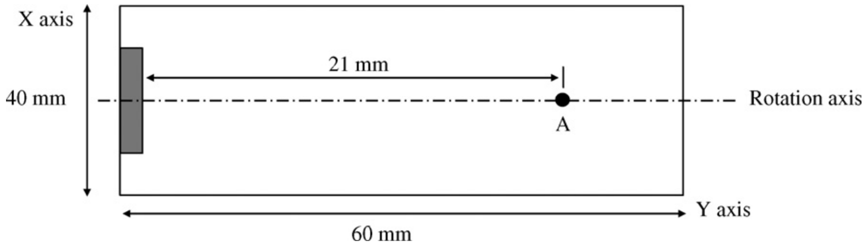

Fig. 6. Schematics of the model of the piezoceramic disk surrounded by water.

thickness. The driven signal was a single cycle sinusoid of 1 MHz frequency. Simulations took 5 min to run.

In Fig. 4, a multiple snapshot with several outputs of the model is depicted. In Fig. 4(a), a plot of the 3D model developed for the stack transducer is depicted. The different materials used in the model are plotted in different colours for identification purposes. Fig. 4(b) shows the time-history signal of the voltage on the active electrode for a simulation time of 67 μs. The electric fields of the device for the same simulation time as before can be seen in Fig. 4(c). Finally the *Y*-displacement at the top centre of the multilayer transducer is depicted in Fig. 4(d).

A scheme of the simulated stack transducer with the displacement direction, *Y*-axis, at the top centre of the stack can be seen in Fig. 5(a). Fig. 5(b) shows the response in the frequency domain of the simulated transducer normalized to the voltage on the active electrode. This normalized response can be calculated by dividing the displacement–time-history signal (Fig. 4(d)), between the voltage–time-history signal (Fig. 4(b)).

2.3. Transducer pressure response

The model for the piezoceramic disk is now extended so that the transducer is surrounded by a water medium. The pressure field in the water for the resonant frequency of the device is calculated. The pressure response from the transducer at a distance point, A, is determined. Mesh chosen was 15 elements/wavelength through *X*-axis and 30 elements/wavelength along *Y*-axis. Driving signal was one single cycle sinusoid of 1 MHz frequency. Simulations took 5 min to run.

We can see in Fig. 6, the scheme of the modelled transducer surrounded by water. As in the model of the piezoceramic disk, this model has also axi-symmetry with its rotation axis, *Y*-axis. Absorbing boundaries were also set to the model to avoid unwanted reflections travelling back from the water medium.

Fig. 7 depicts the response from the transducer measured at point A whereas Fig. 8 shows an image of the pressure field generated by the waves propagating through the water and the time-history signal of the piezoceramic charge at 42 μs.

Having all the snapshots at each calculated propagation time, it is immediate to create the directivity pattern of the transducer as shown in Fig. 9 where it is represented the maximum pressure field at each fluid point in front of the transducer.

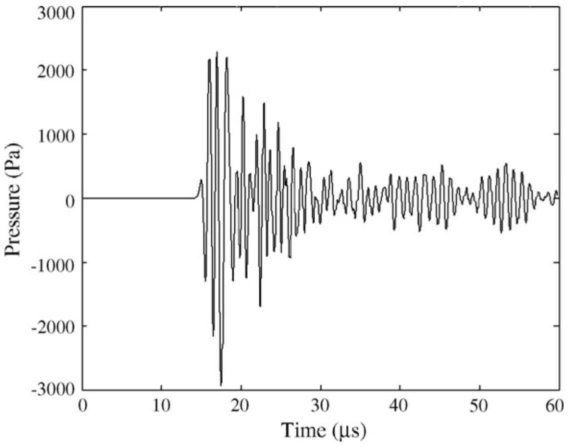

Fig. 7. Transducer response measured at point A.

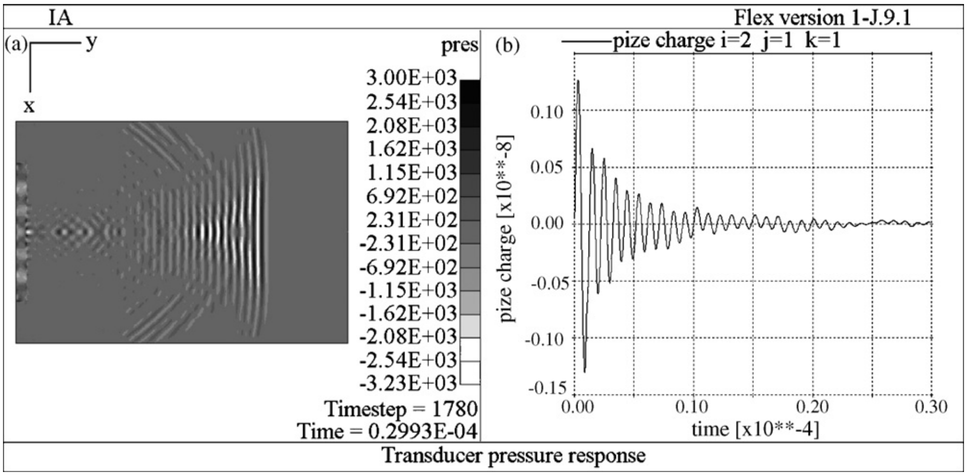

Fig. 8. (a) Pressure field and (b) piezoelectric time-history charge, 42 μs length.

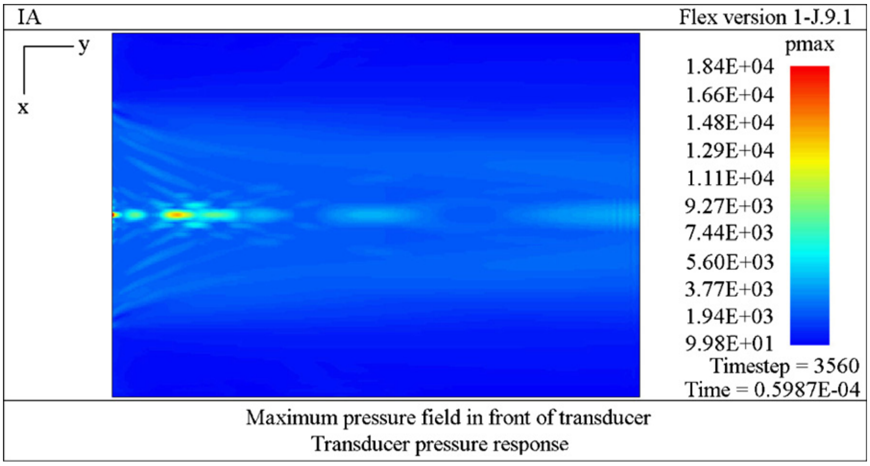

Fig. 9. Maximum pressure field in front of transducer.

3. Conclusions

It has been demonstrated how useful is a finite element modelling approach in time domain to calculate elastic piezoelectric and acoustic performances of piezoelectric components. The main advantage of this approach is the speediness of the models concerning time variables as, for instance, propagation fields maintaining high accuracy.

Acknowledgements

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