Finite Element Modeling of Ultrasonic Transducers for Polymer Characterization

Serena De Paolis*, Francesca Lionetto and Alfonso Maffezzoli
Department of Innovation Engineering, University of Salento, Lecce (Italy)
*Corresponding author: Department of Innovation Engineering, University of Salento, Via per Monteroni, 73100, Lecce, Italy. Email: serena.depaolis@unisalento.it

Abstract:

Finite element analysis has been used to model the ultrasonic wave propagation both in a custom made transducer and in the tested polymer sample. The model consists of acoustic (passive elements) and electroacoustic (active elements) transmission lines. The simulation of the acoustic propagation accounts for the interaction between the transducer and the materials in the buffer rods, and the coupling between the electric and mechanical properties of the piezoelectric material.

The simulation results of longitudinal ultrasonic waves propagation in liquid and solid epoxy resin are presented. They have been validated by comparison with the experimental data.

Keywords: ultrasound, piezoelectric transducer, viscoelasticity, polymers, non-destructive evaluation.

1. Introduction

Ultrasonic wave propagation for polymer characterization is a fast, non-destructive and non-invasive technique based on low intensity ultrasound. Its reliability for the high frequency dynamic mechanical analysis of polymers has been widely demonstrated by previous studies of the authors [1-2]. The ultrasonic technique enables to estimate the polymer viscoelastic properties and transition temperatures. In addition, ultrasonic wave propagation can be used to monitor the curing process of thermosetting resins during manufacturing operations and, indeed, constitutes a useful tool during the production of polymer matrix composites [3-4].

The measurement of ultrasonic properties (velocity and attenuation) depends upon generating a dynamic pressure wave into a material of known thickness and measuring the transit time and the amplitude of the emerging acoustic pressure wave. The generation and detection of an acoustic wave is usually accomplished by a piezoelectric transducer assembled in a transducer case of proper dimension, size and material.

Despite the great potential of the ultrasonic technique in analyzing the viscoelastic behavior of polymers, its application has been limited by the inadequate long-term stability of transducers at high temperature and by the lack of commercial equipments especially designed to characterize polymers. Researchers usually build their own setup from commercially available components (piezoelectric crystals, buffer rods, electronic equipments, etc.), which require a fairly good understanding of the underlying physic principles. Many factors, including materials, thicknesses, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer in terms of frequency response, selectivity and sensitivity.

However, the need of reliable ultrasonic devices for high temperatures (around 250°C) is deeply felt in the field of polymers and polymer-based composites. The use of advanced ultrasonic transducers, with new piezoelectric materials and probe geometry, could enhance the detection performances thanks to a higher adaptability to the inspection geometry and a better control of the beam parameters. These advances can be reached only with modeling the ultrasonic propagation in the transducer. Modeling saves time and money by reducing the number of prototypes and laboratory measurements of transducer performances.

Recently, modeling software have being used in ultrasound sensor design. Some of them (circuit simulation software) simulate only the electronic equipment and the piezoelectric disk. Other finite difference software simulate the acoustic field but often do not take into account some aspects like the influence of the electronic equipment and the load of the buffer rods on piezoelectric ceramic [5].

We have used COMSOL Multiphysics in order to model both the acoustic and electric aspects of the generation and propagation of ultrasonic wave in ultrasonic probes, when they are coupled with the sample material. This paper presents the first results of the simulation of an ultrasonic transducer.

The ultrasonic multilayered transducers, composed of both active and passive elements, have been custom made in our laboratory and widely tested with several polymers, both thermosetting and thermoplastic.

The aim of the research is to develop a finite element model able to be a designing tool for optimizing the performance of our custom made ultrasonic transducers for polymer characterization.

2. Geometrical model description

In this work we present a simplified COMSOL model to study the acoustic wave propagation through materials with different acoustic properties. The probe is built by stacking different materials of suitable thickness: a piezoelectric crystal, a back buffer rod and a metallic buffer rod.

The piezoelectric crystal is the active element transforming an electric current to an acoustic pressure field and, vice versa, producing an electric current from an acoustic field. The back buffer rod supporting the crystal has a great influence on the damping characteristics of the ultrasonic transducer and, hence, on its sensitivity and resolution. The buffer rod is a material at the front of a transducer responsible of a time delay between the initial pulse and the front surface reflection. The buffer rod is necessary for several reasons, e.g. near surface resolution, multiplied back reflections, wear resistance, hot surfaces, impedance matching, near field. The model geometry is sketched in Figure 1.

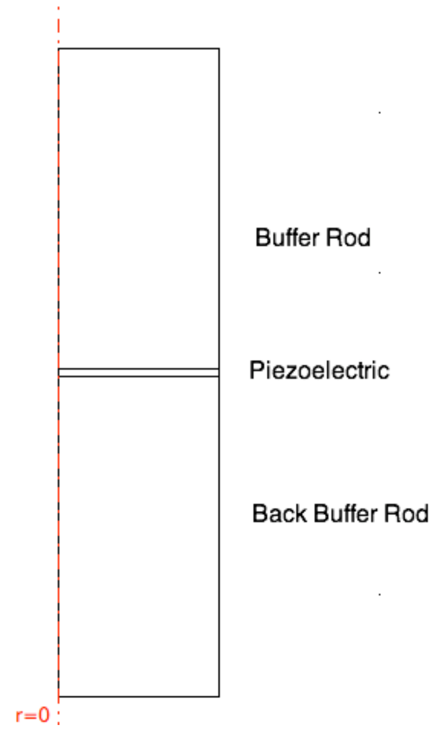

Figure 1. Geometry of the ultrasonic transducer modeled with COMSOL Multiphysics.

3. Use of COMSOL Multiphysics

The ultrasonic transducer has been modeled using the *Piezo Axial Symmetry* and *Pressure Acoustics* application modes, both belonging to the COMSOL Acoustics Module. The *Piezo Axial Symmetry* mode has been used to calculate the vibration mode of an electrically charged piezoelectric material. The *Pressure Acoustics* mode models the propagation of an acoustic wave into different materials, each of them characterized by its own density and sound speed. No damping effect has been considered for this preliminary study.

Only the piezoelectric crystal has been modeled by the *Piezo Axial Symmetry* mode, while the other materials by the *Pressure Acoustics* mode. An axial symmetric geometry has been considered in order to reduce the computational time of simulations.

We have performed a transient analysis and a frequency response analysis for *Pressure Acoustics* and *Piezo Axial Symmetry* mode, respectively, with a time dependent solver.

3.1 The *Piezo Axial Symmetry* mode

The piezoelectric crystal is a commercial modified bismuth titanate, suitable for applications at high temperature. Being the material not present in the COMSOL Material Library, we needed to derive all the piezoelectric properties. The stress-charge form of constitutive piezoelectric properties has been used in the model.

Elasticity matrix $\mathbf{C}_E$:

C^E_{11} (10^{10} N/m^2)	13.6
C^E_{12} (10^{10} N/m^2)	4.78
C^E_{13} (10^{10} N/m^2)	5.36
C^E_{33} (10^{10} N/m^2)	11.76
C^E_{44} (10^{10} N/m^2)	4.76

Piezoelectric coupling matrix **e**:

e_{11} (C/m^2)	0.598
e_{33} (C/m^2)	1.901
e_{15} (C/m^2)	0.667

Relative Permittivity Matrix $\boldsymbol{\varepsilon}_{rS}$:

ε^{rS}_{11}	164
ε^{rS}_{13}	133

Density

ρ (kg/m^3)	7200

The material orientation is in the xz plane, by default.

The piezoelectric crystal has not constraints or load, except for the electrical point of view. A square wave (200 V pulse amplitude and 100 ns pulse width) is applied on the upper surface of the crystal, while the bottom one is grounded. A rise/fall time of 5ns has been considered for the pulse.

The excitation frequency of the piezoceramic crystal is 10 MHz.

3.2 The *Pressure Acoustics* mode

Sound waves in a lossless medium, in absence of outer monopole or dipole source, are governed by the following equation:

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2} - \frac{1}{\rho_0}\nabla^2 p = 0$$

The propagation of acoustic pressure p has been simulated for the materials of buffer rod, back buffer rod and a polymer sample in contact with the ultrasonic probe. The material properties are reported below:

Buffer rod (aluminum):

ρ (kg/m^3)	2700
c_s (m/s)	6300

Back buffer rod (polyimide):

ρ (kg/m^3)	1480
c_s (m/s)	2440

Polymer sample 1 (solid epoxy resin)

ρ (kg/m^3)	1100
c_s (m/s)	2700

Polymer sample 2 (liquid epoxy resin)

ρ (kg/m^3)	1480
c_s (m/s)	1500

The boundary conditions are “axial symmetry” on the z-axis and “sound hard boundary (wall)” on the outside. At the interfaces between the piezoceramic crystal and the neighboring materials (back buffer rod on the bottom side and metallic buffer rod on the upper one) the boundary condition is set to “normal acceleration”. The other interfaces are continuity boundaries, by default.

The mesh size has been adapted to every acoustic subdomain in order to properly resolve the wavelength. The maximum dimension of the mesh has been set on a value corresponding to 1/5th of the acoustic wavelength in each material.

4. Results

The model has been solved in the range 0-8μs, with a step of 10ns. The simulated pressure fields at different times are shown in Figures 2-4.

At time 0.2 μs (Figure 2), the pressure wave has been just generated by the piezoelectric ceramic. It is propagating in a small area of the aluminum buffer rod and has not yet reached the polymer sample.

At time 1.1 μs (Figure 3), the acoustic wave is propagating all through the aluminum buffer rod. It is also possible to distinguish the backward reflections through the back buffer rod.

At time 1.9 μs (Figure 4), the simulation lasts long enough to observe the perturbation also in the polymer sample.

The pressure is not constant along the diameter of the piezoceramic active element but it decreases with the radial direction. Moreover, the intensity of pressure wave is decreasing during its path through different materials.

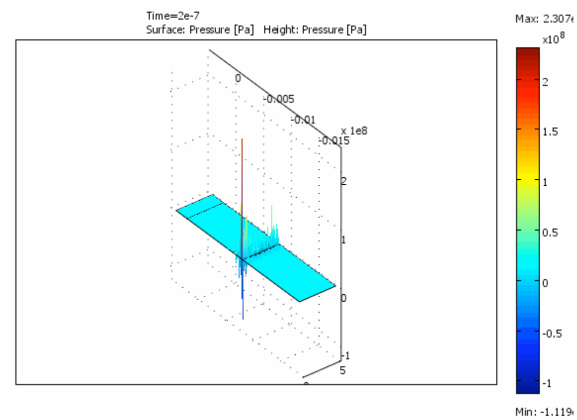

Figure 2. Acoustic pressure at time 0.2 μs.

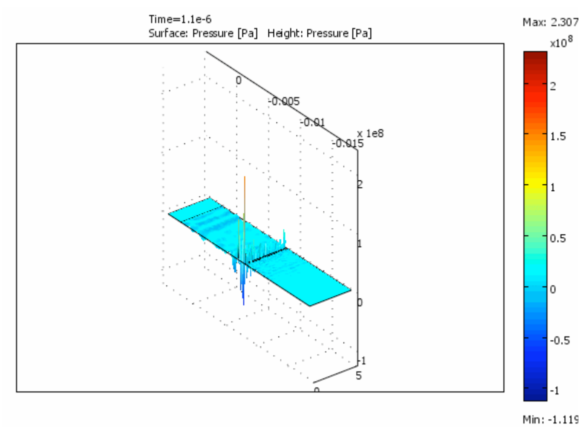

Figure 3. Acoustic pressure at time 1.1 μs.

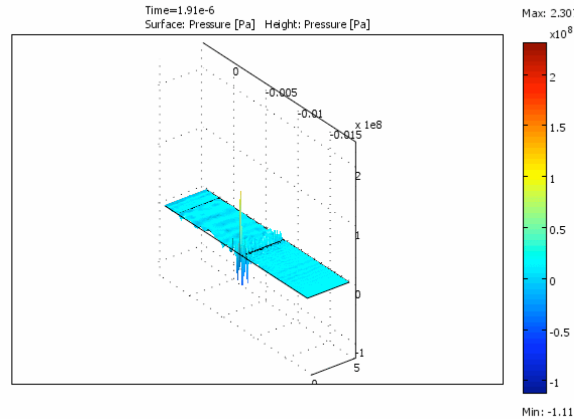

Figure 4. Acoustic pressure at time 1.9 μs.

The simulated echo for a sample of solid epoxy resin of 1 mm thickness is reported in Figure 5. The use of a back buffer rod produces a shorter response by reducing the ringing following the initial excitation of the piezoelectric element.

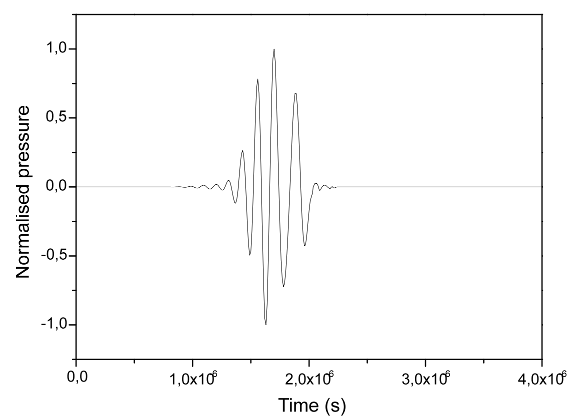

Figure 5. Simulated pressure wave in a sample of solid epoxy resin (1 mm thickness).

In Figure 6 are reported the echoes related to two different sample polymers, liquid and epoxy resin. As expected, the echoes start at different time cause of different value of ultrasonic velocity through the sample polymers.

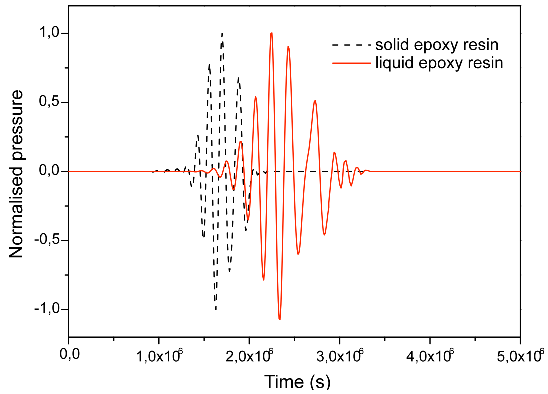

Figure 6. Comparison of the simulated echoes in different polymer samples (1 mm thickness).

In Figure 7 a comparison between the echo obtained by the experimental equipment and that one simulated is reported. The two echoes are very similar, but the simulated one presents more oscillations (ringing). Further work will consider damping effect by using the Acoustic-structure interaction mode of the Structural Mechanics Module. In this way we hope to reduce the ringing phenomenon and get a signal more similar to the real one.

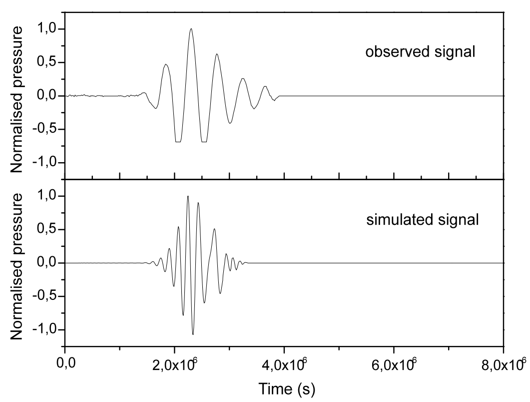

Figure 7. Comparison between a real and a simulated pressure wave signal in a sample of liquid epoxy resin (1 mm thickness).

5. Conclusions

This paper present the first results of the mathematical modeling of ultrasonic wave propagation in a simple domain like that reported in Figure 1. Our aim is to understand the mechanism underlying propagation of acoustic waves through interfaces between materials with different acoustic impedance.

We are planning to extend the model to more complex geometries like those of our custom-made ultrasonic transducers and to handle the acoustic–structural interaction.

Future work will consider the effect of several backing materials and their thickness on the transducer bandwidth and, consequently, on its sensitivity and resolution. Moreover, the effect of the material and size of buffer rod will be investigated.

In addition we would like to simulate the echo responses arising from propagation through different polymeric materials. We expect to be able to simulate the transducer response to changes in the polymer viscoelastic behaviour as a consequence of a temperature change or a chemical reaction.

6. References

1. F. Lionetto, F. Montagna, A. Maffezzoli, Ultrasonic dynamic mechanical analysis of polymers”, *Applied Rheology*, **15**, pp.326-335 (2005).

2. F. Lionetto, A. Maffezzoli, Polymer characterization by ultrasonic wave propagation, *Advances in Polymer Technology*, **27**, 63-73 (2008).

3. F. Lionetto, A. Maffezzoli, Relaxations during post-cure of unsaturated polyester networks by ultrasonic wave propagation, dynamic mechanical and dielectric analysis, *Journal of Polymer Science Part B: Polymer Physics*, **43**, 596-602 (2005).

4.F. Lionetto, A. Tarzia, A. Maffezzoli, Air-coupled ultrasound: a novel technique for monitoring the curing of thermosetting matrices, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **54**, 1437-1444 (2007).

5. J. van Deventer, One dimensional modeling of a stepdown ultrasonic densitometer for liquids, *Ultrasonics*, **42**, 309-314 (2004).