Modeling of 3D electro-mechanical wave propagation in 1-3 piezocomposite based ultrasonic sensors: simulation and experimental comparison

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Abstract
Quantitative modeling tools are important in design and fabrication of ultrasonic sensors with optimum characteristics and reduce the number of experimental efforts. This paper describes a computationally efficient 3D time-domain finite element modeling of electro-mechanical wave propagation in 1-3 piezocompoiste based ultrasonic sensors using the PZFlex (Piezoelectric Fast, large and explicit) software. First, we demonstrate the full 1-3 piezocomposite transducer design, which includes the standard dice-and-fill technique, electrical impedance matching layers, backing materials, electrical circuit of a coaxial cable and the coupling medium. The accuracy of electrical, mechanical and dielectric properties of a piezoceramic material are verified and optimized by comparing the simulated electrical impedance results with experiments, quantitatively. The simulated ultrasonic pulse-echo results are compared with both PiezoCAD transducer modeling result and laboratory experiments and a good quantitative agreement is achieved. Finally, we discuss special applications of ultrasonic sensors in the Oil & Gas industry.

1. Introduction

PZFlex is a 3D finite element analysis (FEA) simulation software, which supports time domain elastodynamic analysis with full electromechanical coupling. This allows simulation of both piezoelectric effects and ultrasonic wave propagation [1]. The FEA modeling was applied to simulate 1-3 composites for underwater imaging arrays and analysed the cross-talk voltage in multi-electroded designs [2]. A review on the theoretical description of FEA for the piezo-acoustic problem was presented in [3], where the simulation result on a virtual prototype of tonpilz transducer device for the low-frequency applications was discussed. The simulation of ultrasonic phased array inspection of austenitic welds using FEM was presented in [4, 5] and the experimentally measured backwall reflection signal of a real transducer was considered as the input excitation pulse at the model's boundary elements. In the present paper, the developed FEA model assumes the real transducer characteristics unknown and it considers both 3D sensor modeling and ultrasonic pulse-echo evaluation. In this work, the validity of developed PZFlex simulation code in modeling and characterization of 1-3 piezocomposite and the pulse-echo response of an in-house developed ultrasonic NDT sensor was investigated quantitatively.

2. Comparison results and discussion

2.1 Piezoceramic characterization

A computationally efficient 3D piezoceramic wafer model was used for the simulation of electrical impedance of a piezoceramic material (PZT-5H). A wide-band ricker wavelet waveform was considered as the input drive function. The piezoceramic manufacturer data was further verified experimentally according to the piezoelectric standard DIN EN-50324 [6]. These optimized elastic, dielectric and piezoelectric properties were used in the simulation. The experimental comparison of simulated thickness-mode electrical impedance is shown in Fig 1(a). A good quantitative agreement between simulation and experiment was achieved.

2.2 1-3 Piezocomposite characterization

In order to simulate 1-3 piezocomposite resonator, a 3D model with epoxy filled kerfs and piezoceramic pillars was considered. In this work, we developed a PZFlex code with full composite manufacturing process including the effect of electrode dimensions and mechanical properties. Both thickness mode and lateral mode resonances of the 1-3 piezocomposite were predicted using the PZFlex simulation (see Fig. 1(b)).

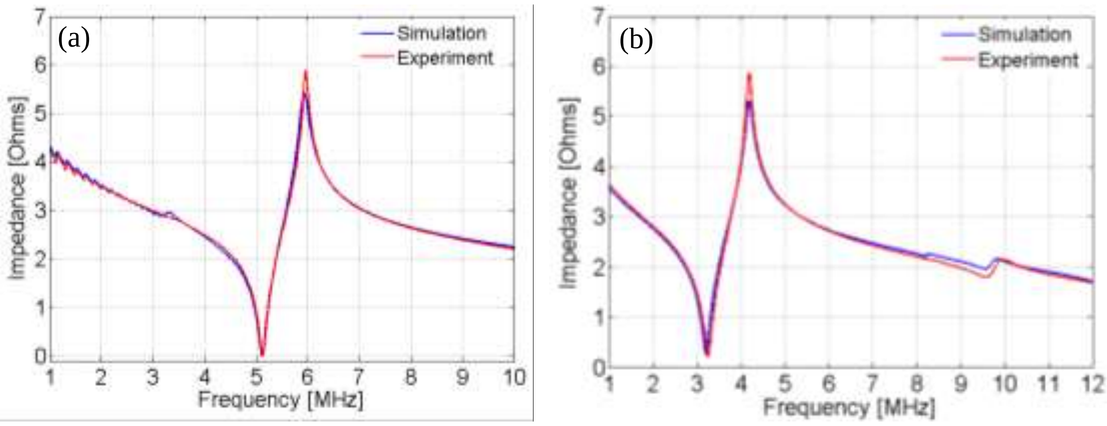

Figure 1. Comparison between the experimental and PZFlex simulated electrical impedance: homogeneous piezoceramic material, (b) 1-3 piezocomposite material fabricated using the dice-and-fill technique.

2.3 Ultrasonic pulse-echo response of a sensor

The time-dependent sound pressure of an ultrasonic sensor at any point inside the medium is calculated using extrapolation methods and time-domain Kirchhoff integral equations. A broad-band excitation waveform was used for the ultrasonic pulse-echo measurements and PZFlex transducer modeling (see Fig.2). A pulse duration of 120ns and an excitation voltage of 30V were considered.

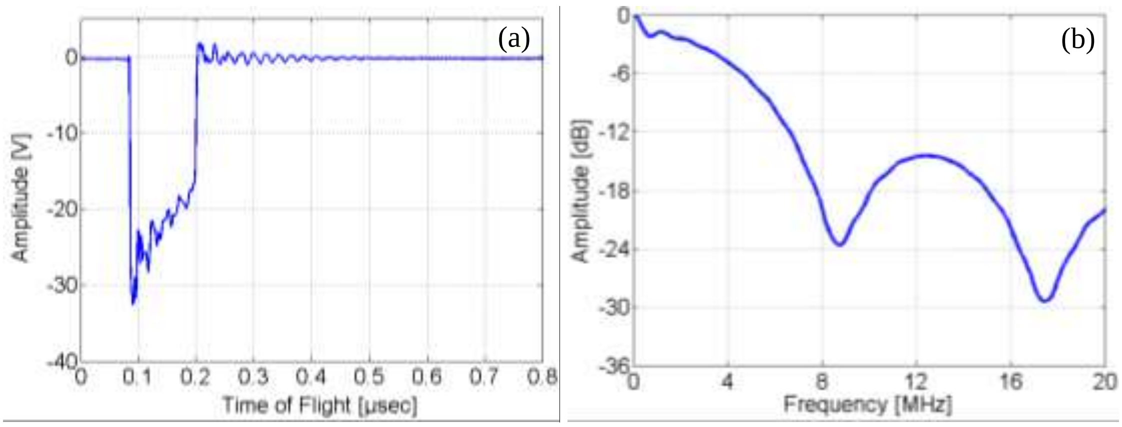

Figure 2. Excitation waveform used for the ultrasonic pulse-echo measurements: (a) time-domain signal, (b) Fast Fourier Transform of the excitation signal.

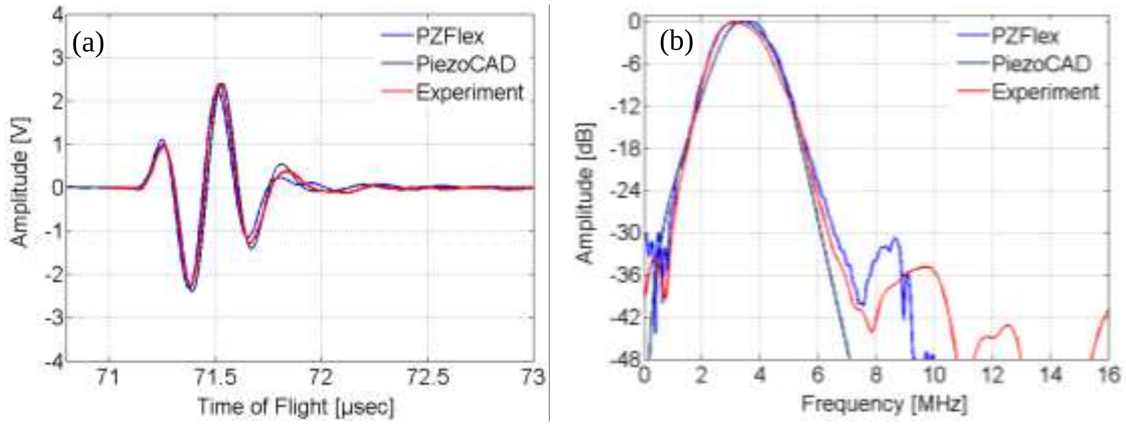

Figure 3. Comparison between the experimental, PZFlex and PiezoCAD simulated ultrasonic pulse-echo response of the 1-3 piezocomposite based ultrasonic sensor: (a) time-domain signal, (b) normalized Fast Fourier Transform of the signal.

The simulated ultrasonic pulse-echo signal and its frequency spectrum using PZFlex and PiezoCAD modeling were well agreed with the experimental result (see Fig. 3). In the high frequency region (>8MHz), minor deviations in the simulation result can be observed. A quantitative comparison between simulated and experimental results at 6dB amplitude fall is summarised in Table1. In the current simulation, the reflector material is considered as rigid. As a future work, the single element sensor model will be extended for ultrasonic phased array applications including the acoustic properties of a real reflector.

Table 1. Comparison between simulated and experimental ultrasonic transducer characteristics

Probe Parameter (at -6dB level)	PZFlex	PiezoCAD	Experiment	Error [%]	
				PZFlex	PiezoCAD
Lower cut-off frequency [MHz]	2.24	2.37	2.29	2.2	3.5
Upper cut-off frequency [MHz]	4.62	4.63	4.54	1.8	2
Center frequency [MHz]	3.43	3.5	3.42	0.3	2.4
Bandwidth [%]	69	65	66	4.5	1.5

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References

1. PZFlex Finite Element Solutions: Wave propagation, Piezoelectric and Ultrasonic applications, User Manual, 2014, https://pzflex.com/
2. GL Wojcik, DK Vaughan, V Murray and J Mould, "Time-domain modeling of composite arrays for underwater imaging", IEEE Ultrasonics Symposium Proceedings, pp 1027-1032, 1994.
3. NN Abboud, GL Wojcik, DK Vaughan, J Mould, DJ Powell and L Nikodym, "Finite Element Modeling of Ultrasonic Transducers", SPIE Conf. Proc., pp 1-24, 1998.
4. J Dobson, A Tweedie, G Harvey, RO Leary, A Mulhoolland, K Tant and A Gachagan, "Finite element analysis simulations for ultrasonic array NDE inspections", AIP Conf. Proc. 1706, pp 1-14, 2016.
5. G Harvey, A Tweedie, C Carpentier, P Reynolds, "Finite element analysis of ultrasonic phased array inspections on anisotropic welds", AIP Conf. Proc. 1335, pp 1-8, 2011.
6. Piezoelectric Properties of Ceramic Materials and Components, DIN EN 50324-1-3, 2002.
7. Piezoelectric Transducer Modeling using the Modified KLM Model: PiezoCAD, User Manual, Sonic Concepts, 2013, http://sonicconcepts.com/