ANALYSIS OF SPURIOUS RESONANCES IN SINGLE AND MULTI-ELEMENT PIEZOCOMPOSITE ULTRASONIC TRANSDUCERS

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Abstract 1-3 piezocomposites provide for significant advantages over solid piezoceramic transducers for ultrasound applications, at the expense of introduction of additional spurious resonances. We examine in detail the generation of high frequency inter-pillar (lateral) resonances in 1-3 piezoelectric composites, through experiment and finite element analysis (FEA) with the PZFlex package. These inter-pillar modes are clearly shown to be generated due to Lamb waves propagating through the substrate between pillars, the magnitude of which varies dependent upon magnitude of displacement from the thickness mode vibration and its proximity in the frequency domain.

I. Introduction

Piezoelectric composites are a common method of generating ultrasound, and consist of a piezoelectrically active ceramic component, and a passive, usually polymer, component. The most common type, 1-3 connectivity piezocomposites, are typically manufactured using the dice-and-fill technique first documented by Savakus [1]. While 1-3 piezocomposites offer significant advantages over solid piezoceramic devices, such as increased electromechanical coupling efficiency and better acoustic matching, the new microstructure results in the introduction of additional inter-pillar resonances. Auld [2] and Gururaja [3] compared the generation of inter-pillar resonances to Bragg scattering, usually found in crystal lattices. Auld and Smith [4] compared these modes to Bragg scattering but stated that these resonances may be due to the formation of Lamb waves in the structure – however no significant work was carried out in relation to the type of Lamb wave generated, or the conditions under which it could be sustained. By close examination of both electrical impedance profiles, and surface displacement behaviour, this paper more completely describes the formation of these inter-pillar resonances by Lamb waves, with specific mention made of the type of Lamb wave generated and the Lamb wave velocity dependence on device microstructure. All FEA results presented in this paper are generated using the commercially available package PZFlex, version 1j8.

II. 1-3 Piezoelectric Composites

Three 1-3 piezocomposite devices were constructed, using PZT5H as the piezoceramic, and CY1301/HY1300 epoxy as the polymer, the details of which are listed in Table 1. Device A was designed to be unimodal to ensure any lateral resonances are significantly removed from the fundamental thickness mode in frequency. Devices B and C maintain the same pitch and kerf as Device A, but reduce the thickness, increasing the thickness mode frequency and bringing it closer to that of the inter-pillar resonances, thus making them more apparent.

	Device A	Device B	Device C
Thickness (mm)	**2.5**	**1.4**	**1.0**
Pitch (mm)	**0.726**	**0.726**	**0.726**
Kerf (mm)	**0.282**	**0.282**	**0.282**
Aspect Ratio	**0.178**	**0.315**	**0.44**
Volume Fraction	**37.4%**	**37.4%**	**37.4%**
Centre Freq (MHz)	**0.57**	**1.01**	**1.44**

Table 1: Properties of Piezocomposites

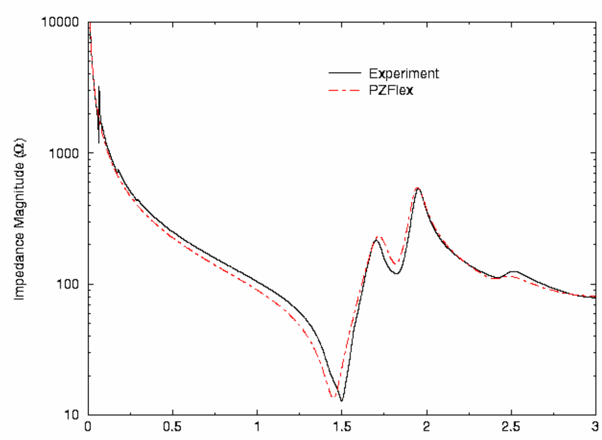

Figure 1: Comparison of Electrical Impedances for Experiment and PZFlex Simulation for Device C

Figure 1 shows the electrical impedance profile of Device C for both experiment and PZFlex simulation, with excellent correlation. The thickness mode resonance can be seen at 1.44 MHz, with the first lateral resonance at 1.8 MHz and the second lateral resonance at 2.4 MHz closely impinging upon it.

Figure 2 shows the predicted thickness direction displacement magnitude on the transducer surface against frequency, both in the centre of the ceramic pillar and in the polymer. The thickness mode can be easily seen, as can the first and second inter-pillar resonances. Table 2 lists the magnitude of these resonances relative to the thickness mode for all three devices. As the thickness mode approaches the inter-pillar modes in frequency, the laterally resonant modes increase in strength significantly – e.g, the first lateral resonance is 17.7 dB stronger in Device C than Device A.

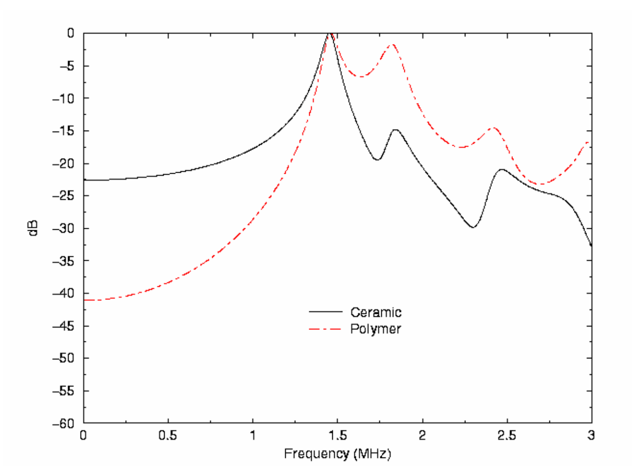

Figure 2: Normalised Surface Displacement against Frequency for Device C

	Device A	Device B	Device C
1st Lateral Resonance (dB)	**-19.5**	**-8.3**	**-1.8**
2nd Lateral Resonance (dB)	**-23.1**	**-23.0**	**-14.8**

Table 2: Magnitude of Lateral Resonances for Piezocomposite Devices

In addition, the surface displacements at the inter-pillar resonances were predicted by PZFlex. These were then compared to those obtained experimentally via a scanning laser vibrometer, and an example result is shown in Figures 4a and 4b for the first inter-pillar resonance, and 5a and 5b for the second inter-pillar resonance. An expanded 2 by 2 pillar section of the composite is shown, and is detailed in Figure 3. The PZFlex displacement plots also draw a border around the ceramic for simpler identification.

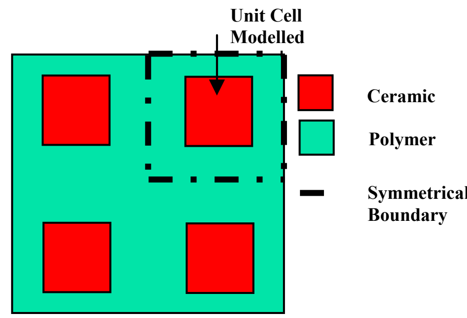

Figure 3: Diagram of Section of 1-3 Piezocomposite Modelled and Shown in Figure 4

There is clearly a distinct pattern of surface behaviour for each mode, that PZFlex predicts well. These patterns diverge significantly from the ideal 'piston-like' displacement of a device, with significant variation in both magnitude and phase of displacement. It is clear why such resonant modes can be detrimental to device performance. By considering the piezoelectric composite microstructure we can postulate the mechanism by which these shapes are created. Effective 'lines of force' are generated when the monolithically electroded 1-3 piezoelectric composite is activated and all the ceramic pillars compress and expand in phase. Figure 6 illustrates how for the first inter-pillar resonance, columns of pillars act as such a line, with an effective wavelength equal to d_0, the saw pitch. For the second inter-pillar resonance, although the distance between a ceramic pillar and its nearest neighbour on a diagonal is $\sqrt{2}d_0$, the distance between each 'line' is $d_0/\sqrt{2}$ [5]. Thus the wavelength of the second inter-pillar resonance is $d_0/\sqrt{2}$. Obviously, additional 'lines' would exist at right angles to those shown in the diagrams. That is, the structure is doubly periodic. It would be expected, therefore, that for the first inter-pillar resonance of a composite that waves would propagate normal to the transducer edges, while for the second resonance they would propagate in a 'diagonal' manner. By the nature of the driving force, Lamb waves will be generated [6]. An additional complication of the Lamb waves is that their velocity, is dependent upon the type of Lamb mode and the frequency-thickness product (FTP) of the plate. The FTP is defined as the product of the plate thickness with the operating frequency. Figure 7 shows the phase velocities against FTP for the two fundamental antisymmetric (a_0) and symmetric (s_0) modes for hardset epoxy – these are termed *dispersion curves*.

The wavelength of a Lamb wave can therefore be expressed as Equation 1a

$$\lambda = \frac{V_{phase}}{f} \qquad V_{phase} = \lambda f \qquad \textbf{1 a,b}$$

here λ is the Lamb wave wavelength, v_{phase} is the appropriate phase velocity, f is the operating frequency. The phase velocity of a material can be determined, for any particular wavelength, by drawing a line as defined by Equation 1b.

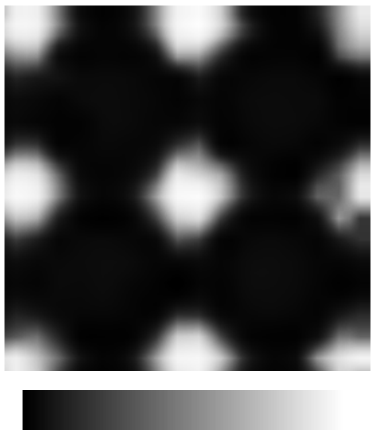

Figure 4a: First Lateral Resonance (1.8MHz) Experimental Displacement.

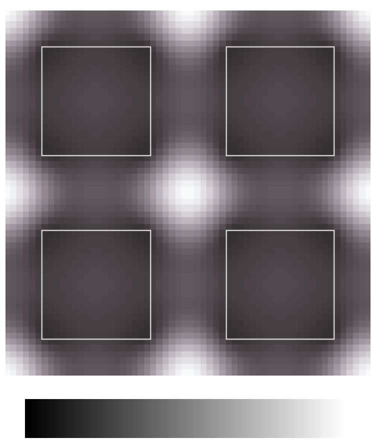

Figure 4b: First Lateral Resonance (1.8MHz) PZFlex Displacement.

The x-coordinate at which the line crosses the curve for each mode type (a_0 or s_0) is the FTP for that mode, while the y-coordinate is the phase velocity. Figure 7 demonstrates how this would be done for a 1mm thick Ciba-Geigy CY1301/HY1300 (hardset) polymer plate, with forcing function spacing of 2 mm. This arrangement could result in an a_0 mode of frequency 455 kHz and phase velocity 889 ms^{-1}, and an s_0 mode at 800 kHz with a phase velocity of 1580 ms^{-1}.

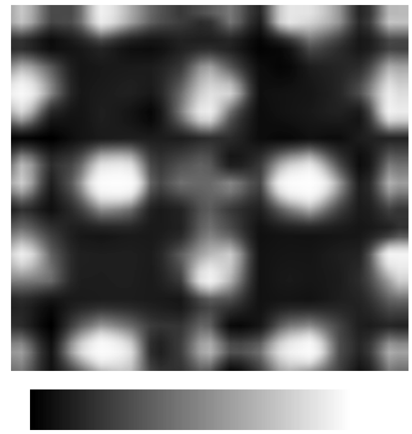

Figure 5a: Second Lateral Resonance (2.4MHz) Experimental Displacement.

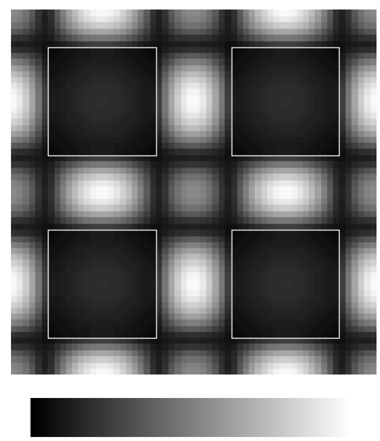

Figure 5b: Second Lateral Resonance (2.4MHz) PZFlex Displacement.

Since the wavelength is determined by the forcing function spacing (d_0 and $d_0/\sqrt{2}$), it is apparent that the first two mode frequencies generated by the Lamb modes will be

$$f_{L1} = \frac{v_{phase}}{d_0} \qquad f_{L2} = \frac{\sqrt{2}v_{phase}}{d_0} \qquad \textbf{2 a,b}$$

Rather than approaching the shear wave velocity of the medium, the phase velocity of the fundamental Lamb modes approaches the *Rayleigh* velocity at high values of FTP. An effective approximation for the Rayleigh wave velocity (v_R) can be found in Achenbach [7] and is typically 90-95% of the shear wave velocity. Rayleigh wave velocity is 1062 ms^{-1} , and shear wave velocity is 1150 ms^{-1} , for hardset epoxy.

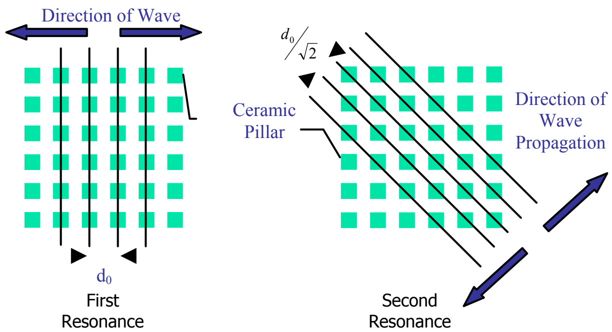

Figure 6: Generation of Inter-Pillar Resonances

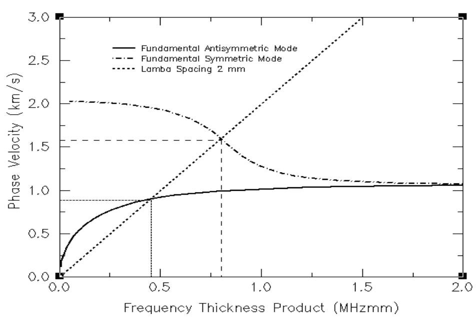

Figure 7: Dispersion Curve of Fundamental Modes for a Polymer.

This close similarity in magnitude between the Rayleigh wave velocity and the shear wave velocity has allowed confusion to exist as to the mechanism for the generation of the inter-pillar resonances. Since a piezocomposite is not a homogenous material, generation of dispersion curves by analytical means is not a simple procedure. For simplicity, an estimate of the phase velocity of a 1-3 piezoelectric composite can be made using the following equation

$$v_{phase} = v_{RPOLY} + (VF^2)(v_{RCER} - v_{RPOLY}) \qquad \mathbf{3}$$

Where v_{RPOLY} is the Rayleigh wave velocity in the polymer, v_{RCER} is the Rayleigh wave velocity in the ceramic, and VF is the ceramic volume fraction, ranging from 0 to 1. This approximation will only hold true in cases where the Lamb wave propagates short distances. Note that the phase velocity calculated is always greater than the lowest velocity in the constituent materials. This 'effective v_{phase}' is only valid for inter-pillar modes in piezoelectric composites, where each Lamb wave propagates a single wavelength before being 'reinforced' by the action of an adjacent ceramic pillar. In cases where the Lamb wave travels multiple wavelengths before 'reinforcement', such as in multi-element arrays on piezocomposite substrates, the effective phase velocity is likely to be reduced by the mass loading of the ceramic on the polymer. Given the entirely symmetrical structure and drive conditions of the piezoelectric composite, the Lamb wave is usually be the fundamental symmetrical wave (s_0). It is important to note that the 'driving force' behind the inter-pillar resonances is the thickness mode displacement of the piezoelectric composite. The inter-pillar resonances require this displacement to be generated, and so while these resonances will always exist, they will only become prominent when their frequencies approach those of the fundamental thickness mode and its harmonics.

IV. Conclusions

Inter-pillar modes in 1-3 connectivity piezoelectric composites are due to s_0 Lamb wave mode generation. These modes may be identified from the device impedance and displacement response, measured experimentally or predicted using FE methods. In multi-element piezoelectric composite structures, the propagating mode travels at a velocity below that of the constituent material with the lowest velocity, while inter-pillar Lamb wave propagation occurs at a velocity between that of the two component materials. The lateral modes thus induced only couple strongly when their frequency is approximate to that of a strong thickness mode or its harmonics. Element and pillar spacing, and material properties, are critical to the frequencies and magnitudes at which these resonant modes occur.

V. Acknowledgements

The authors would like to thank T. McCunnie and R. O'Leary for their assistance, and the ONR for funding for this research.

VI. References

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