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A THEORETICAL AND EXPERIMENTAL INVESTIGATION INTO MULTILAYERED PIEZOELECTRIC COMPOSITE TRANSDUCERS

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Abstract – *The behaviour of a number of 3-1 connectivity piezoelectric composite plate transducers is presented. The fundamental thickness mode resonance of such devices is found to be contaminated by lateral resonant activity; this is evidenced in the measured and predicted electrical impedance profile and the surface displacement data at the fundamental thickness mode. Measurements taken on the 3-1 devices infer that they are not acting as true composites. In addition to this the finite element technique is applied to a number of stacked 3-1 and 1-3 connectivity devices to predict the mechanical Q-factor, and hence bandwidth, as a function of polymer filler properties.*

I. INTRODUCTION

Piezoelectric composite transducers possess distinct advantages for certain underwater sonar applications. A controlled combination of active and passive materials can improve mechanical matching to a water load and also extend bandwidth when compared with standard piezoelectric ceramic designs. Specific configurations, such as the 1-3 arrangement, can extend electromechanical coupling by up to 50%, due to a reduction in the lateral clamping of the active phase. Such advantages are well documented in the literature [1-3] and indeed, 1-3 piezoelectric composites are now routinely employed in many high frequency sonar applications. Extrapolation of this technology to lower frequency bands (less than 100kHz) has not been straightforward, mainly due to the difficulty in obtaining efficient piezoelectric ceramic materials of sufficient thickness. An alternative solution is to utilise composite stacks, providing the additional advantage of improved transducer sensitivity, which theoretically can increase in proportion to the number of active layers in the stack. However, the requirement for precise alignment of the microstructure through the full height of the stacked device can be difficult when the 1-3 configuration is employed [4]. Alternative designs that involve the insertion of intermediate stiffening layers [5] between the active components, introduce increased manufacturing complexity and problems with robustness under high drive conditions [5].

One possible way to circumvent these difficulties is the 3-1 configuration [5], whereby the individual piezoelectric ceramic layers are bonded together, prior to dicing into the ceramic and filling with a suitable passive agent, as indicated in Figure 1.

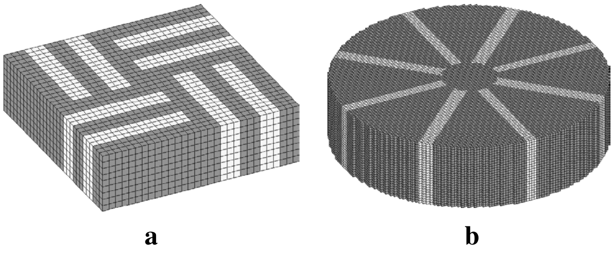


Figure 1 *3-1 connectivity piezoelectric composite designs, (a) square design and (b) radial design*

This maintains the advantages of low electrical impedance (facilitating electrical driving), sensitivity and strength, since the passive material will promote structural integrity. However, in both cases, the surface displacement can be non-uniform, precluding true composite operation. Moreover, it is unclear if the bandwidth advantages of a composite structure can be realised and critically, the ability to influence device operation via adjustment of volume fraction is likely to be restricted.

This paper compares the relative performance of 1-3 and 3-1 piezoelectric composite transducers, using a combination of finite element modelling and experimental assessment. Firstly, the relative performances of single composite plates are compared, from the perspective of intrinsic mechanical wave interaction and vibration uniformity across the radiating aperture. Since the 1-3 structure is already well documented; different 3-1 plate configurations, intended to operate at the fundamental thickness mode, are simulated using the PZFlex [6] code. The electrical impedance and surface displacement characteristics are then compared with experimentally measured data and this is then used to predict the radiated beam profiles of the sample devices. Secondly, multi-layer stacks, whereby the fundamental resonance of the stack is much lower than any individual lateral resonances, are simulated. The differences between 1-3 and 3-1 operation are highlighted for two conditions - when each stack is operating in free space and also when the devices are subject to a polymeric loading on all lateral sides and operating directly into a water load. The influence of the passive materials on performance indicators such as bandwidth and sensitivity is also noted.

II. SINGLE LAYER PIEZOELECTRIC COMPOSITE PLATES

Adopting the configuration shown in Figure 1a, four different 3-1 plates were manufactured, with ceramic/filler volume fractions ranging between 40% and 47%. The active ceramic material was PZ26, supplied by Ferroperm [7], and the filler CY1301/HY1300 [8], with each device possessing dimensions 18mm (square) and 1.8mm in thickness. Table 1 details the microstructure of each device.

Device	Kerf (mm)	Pitch (mm)	Ceramic Volume Fraction
1	0.4	0.76	0.51
2	0.8	1.16	0.40
3	0.4	0.76	0.45
4	0.5	0.86	0.47

***Table 1** Constructional Parameters of the Single Layer 3-1 Connectivity Piezoelectric Composites to be Studied*

A comparison between the measured and simulated electrical impedance characteristics, in the open air environment, are shown in Figure 2 and 3 for devices 2 and 3 respectively.

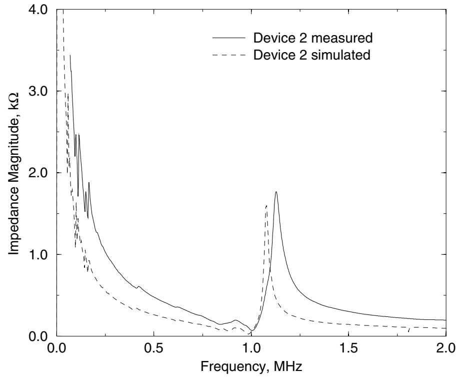


***Figure 2** Measured and Simulated Electric Impedance Response for Device 2*

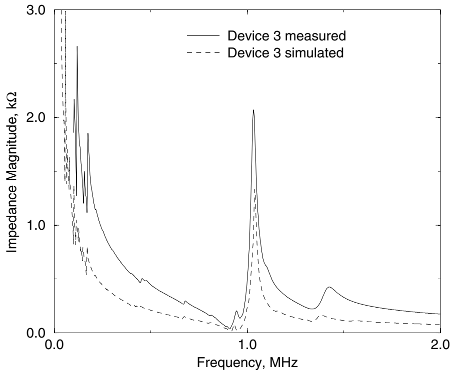
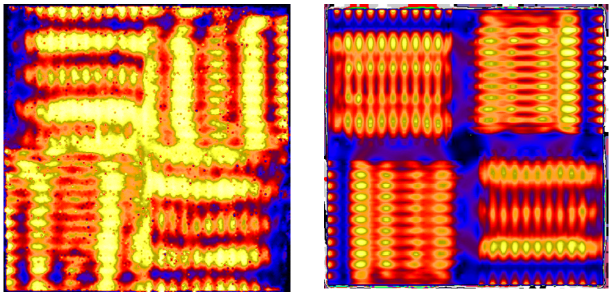


***Figure 3** Measured and Simulated Electric Impedance Response for Device 3*

Although the experiment and simulation data are in good agreement, it is clear that the devices possess quite different impedance spectra and that in both cases the fundamental thickness resonance is contaminated by the presence of unwanted resonant modes. From the simulated impedance characteristics, the electromechanical coupling coefficients were estimated to be 0.44 and 0.45 for the 45% and 40% devices respectively.

In a 1-3 composite structure, comprising identical materials, with similar microstructure and volume fractions, unimodal behaviour around the fundamental thickness resonance would have been anticipated, with coupling coefficients in the region of 0.65 in both cases. Moreover, the bulk longitudinal wave velocity in the thickness direction was estimated to be 4060m/s and 3717m/s for devices 2 and 3, respectively. Comparing this with the expected velocities for a similar 1-3 configuration, both would be in the region of 3500m/s. These results indicate that the 3-1 piezoelectric composite devices are not behaving as true composite materials.

In the 1-3 structure, the major source of unwanted modal vibration arises from standing Lamb wave patterns, introduced by the periodicity of the composite lattice [1, 9]. Standard techniques for reducing their influence include the introduction of aperiodicity and the adoption of sufficiently fine spatial scales to remove unwanted resonances beyond the spectrum of interest [4]. The 3-1 structure is much more complex in that additional resonances are introduced as a result of Lamb wave propagation along the ceramic fingers and also throughout the central ceramic stock. Some of these modes are largely confined within the ceramic material and as a result, are difficult to eradicate via damping from the filler phase. Consequently, the 3-1 configuration will always comprise additional resonant modes that are liable to corrupt the fundamental thickness mode when operating as a plate or disc transducer. All of the sample devices manufactured during the course of the present work demonstrated similar behaviour.



a **b**

***Figure 4** Surface Displacement Profiles of Device 1, (a) experimentally measured and (b) FE simulation*

Clearly, the presence of modal activity close to the fundamental resonance will influence the surface displacement characteristics and the transducer beam profile. Beam profile uniformity is also expected to be compromised in a 3-1 structure due to the non-uniform nature of the ceramic finger arrangement. Figure 4 shows the theoretical and experimentally measured surface displacement profiles of another sample 3-1 plate, similar to that shown in Fig 3, but with the width of the central ceramic stock increased by

8%. Both sets of data are in reasonable agreement and it is apparent that the displacement pattern is non- uniform across the radiating aperture of the device. Figure 5 shows the axial beam profile when operating into water, extrapolated from measured and simulated surface displacement data.

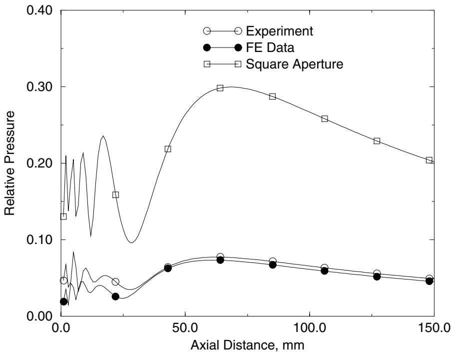


***Figure* 5** *Extrapolated Axial Beam Profile of Device 1 Operating into Water*

The profile anticipated from a uniformly vibrating aperture is superimposed on the data for ease of comparison. As would be expected, the axial beam response of the 3-1 transducer illustrated in Figure 4 is quite poor when compared to uniformly radiating aperture.

III. MULTILAYERED PIEZOELECTRIC COMPOSITE COLUMNS

The PZFlex finite element code was utilised to simulate the electrical and mechanical response of a number of stacked piezoelectric composite configurations to assess the relative performance of the 1-3 and 3-1 connectivity designs.

In each case, the composite comprises 60% ceramic volume fraction and has the lateral dimensions of 9mm square. Each layer is 5.25mm in thickness and each stack comprises 5 layers. Table 2 details the stacked devices investigated. The simulated response of each composite device was compared to the simulated response of a ceramic pillar 9mm square having the same layer and thickness dimensions as the piezoelectric composite stack devices, this is represented by Device A in Table 2.

Device	Polymer Filler	Connectivity
A	N/A	N/A
B	CY1301/HY1300	1-3
C	CY1301/HY1300	3-1
D	CY208/HY956	1-3
E	CY208/HY956	3-1

***Table* 2** *Device Composition*

The electrical impedance and conductance of each device was simulated in free space. The composite devices were simulated with two different polymer filler materials. Table 3 gives the longitudinal (V_l) and shear (V_s) velocities, together with the longitudinal (α_l) and shear wave (α_s) attenuation, of the two resin systems. These data were measured at 500kHz using a through transmission methodology [10, 11].

	CY1301/HY1300	CY208/HY956
V_l, ms^{-1}	2512	2000
V_s, ms^{-1}	1175	747
Density, kgm^{-3}	1149	1165
Poisson's Ratio	0.36	0.42
α_l, dBm^{-1}	139	825
α_s, dBm^{-1}	356	6063

***Table* 3** *Mechanical Properties of the Vantico Epoxy Resins Measured at 500kHz*

The simulated impedance profiles are shown in Figures 6 and 7. Figure 6 depicts the simulated electrical impedance response of devices A, B and C and Figure 7 illustrates the simulated conductance of devices A, D and E. From Figure 5 it can be seen that each device possesses a single fundamental thickness mode resonance of approximately 50kHz. In each case there is also some minor lateral activity at approximately 100kHz in the case of the composite devices and at 140kHz in the case of the pure ceramic stack.

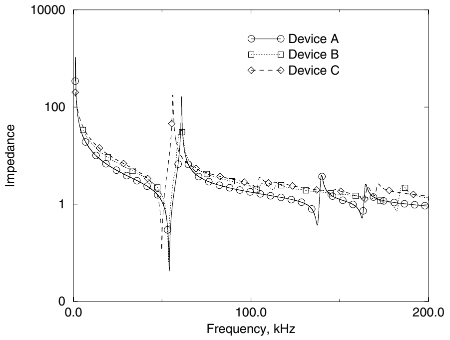


***Figure* 6** *Comparison of the simulated electrical impedance characteristic of devices A, B and C*

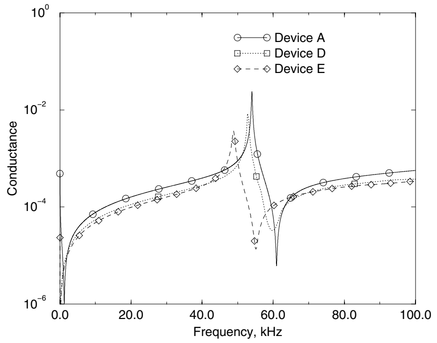


***Figure* 7** *Comparison of the simulated conductance of devices A, D and E*

Again the effects of the polymer filler are evidenced by the reduction in magnitude of the conductance peak at the frequency of electrical resonance. In addition the peak is broadened somewhat. The electromechanical coupling coefficient and Q factor were calculated for each of the simulated responses, these data are presented in Table 4. As expected the Q-factor reduces in proportion to the polymer filler and its relative hardness.

Device	Electromechanical Coupling Coefficient	Q Factor
A	0.502	266
B	0.501	112
C	0.498	105
D	0.502	51.9
E	0.502	42

Table 4 *Simulated electromechanical coupling coefficient and Q Factor*

To further investigate the effect of polymer loading the devices were simulated surrounded by a polymer filler to asses the effect of the filler and any subsequent ancillary materials that would be required to marinise these devices. In each case the simulations were performed with the front face of the device water loaded. Figure 8 illustrates the simulated conductance for devices A, B and C when surrounded by the hard setting polymer CY1301/HY1300.

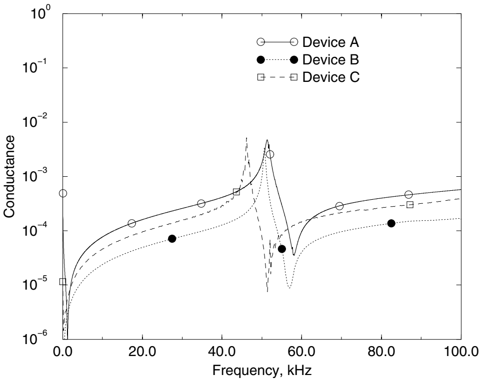


Figure 8 *Simulated conductance of devices A, B and C when subject to polymer and water loading.*

The Q-factors were calculated to be 118, 74 and 94 for device A, B and C, respectively, when surrounded by the hard polymer. Where the soft setting CY208/HY956 was simulated surrounding the devices the Q-factor was calculated to be 30 for each case except for device D; which had a Q-factor of 20.

Comparing the three stack technologies the calculated Q-factors have been found to be a function of the polymer properties. Surrounding each device with the same polymer produced similar results. When each device was surrounded by hard setting polymer, the Q-factor ranged from 74 to 118. In the case of the stacks each being encapsulated by the soft setting polymer, irrespective of the polymer used in the composite stacks, the Q-factor spanned the range 20-30.

It would be simplistic to consider utilising such a strategy to reduce the Q-factor of stacked piezoelectric composite devices. This work serves to demonstrate that the polymer filler is not sufficient to significantly reduce the Q-factor of the stack. The incorporation of soft setting polymer in such a structure would pose problems. Firstly, the material is likely to vibrate anti-phase to the active stack element. Secondly the stacked piezoelectric composite devices are designed to operate in a high power regime and the encapsulation of the active element in a thermally insulating medium would only serve to accentuate the problems of excess temperature on the active element [12].

Recent work in area of extending the useful temperature range of the piezoelectric composite has identified a number of high glass transition temperature materials. These materials have low acoustic loss and as such would not be useful in reducing the Q-factor of the stacked devices presented in this paper.

IV. CONCLUSIONS

This paper has demonstrated the thickness mode resonance in 3-1 connectivity plate transducers can be contaminated with additional resonant activity. This is thought to be a result of Lamb wave activity in the ceramic fingers. The measured and predicted surface displacement data of the 3-1 plate transducer has demonstrated the existence of such modes. In the case of the stacked devices it has been shown that irrespective of the composition of the stacked device surrounding the stack with a high loss polymer will serve to reduce the Q-factor. However this approach has significant drawbacks where high drive powers are to be used to excite the stack device.

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