Experimental Assessment of Periodic Piezoelectric Composite Arrays Incorporating an Anisotropic Passive Phase

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Abstract— This paper discusses the experimental assessment of a number of piezoelectric composite array structures incorporating a novel passive phase exhibiting anisotropic elastic properties. The passive polymer phase has been designed to limit inter-element crosstalk by attenuating lateral propagation across the array aperture. A selection of water coupled linear array coupons, operating with a nominal 400kHz fundamental thickness mode frequency, has been prepared comprising the novel anisotropic passive phase. As a control, comparisons are made to similarly configured devices employing isotropic filler materials. Scanning laser vibrometry and measurements of electrical impedance characteristic on the array substrate demonstrate that the fundamental thickness mode of the devices configured with anisotropic polymer fillers is not contaminated by parasitic modes of vibration. The reasons for this are explained by considering the dispersion characteristics of the substrate. Water coupled hydrophone measurements of array element directivity; transmit voltage response and subsequently efficiency calculations illustrate that the observed reduction in mechanical cross talk has not been achieved at the expense of element sensitivity. Finally, comparisons between the experimental data and the PZFlex derived array responses are made, with good corroboration demonstrated

Keywords-piezoelectric composite array, anisotropic passive polymer phase,

I. INTRODUCTION

Piezoelectric rod/polymer composite arrays are typically configured such that the composite substrate and electrode pattern follow a regular spatial periodicity. This periodicity can contribute to parasitic Lamb mode vibrations across the array aperture [1, 2], interfering with the fundamental thickness mode, leading to a degraded directional response and reduced array sensitivity. The elastic character of the constituent materials is significant and mechanical crosstalk can be limited through selection of a soft, highly attenuating polymer phase. However, this is achieved at the expense of array element sensitivity. Alternatively, design of the substrate such that it operates in a stop-band of the Lamb mode propagation is a viable technique to limit inter-element cross talk [3]. However, this is typically across a narrow spectral range and as such unsuitable for extremely wideband designs.

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A recent finite element modelling study using the PZFlex code [Weidlinger Associates, Mountain View, CA] by the authors [4], demonstrated the benefit of selecting a passive polymer phase exhibiting elastic anisotropy, i.e. a combination of low longitudinal loss and high shear loss. Such materials were found to limit mechanical cross talk in periodic piezoelectric composite arrays without compromising the desired elemental response. This paper exemplifies this concept through the experimental assessment of a range of array coupons comprising polymer fillers with the desired anisotropic elastic character.

It is useful to define the metrics that will be used to assess array performance. In each case the electrical impedance characteristic of the array under consideration was measured to assess vibrational behaviour. This was then corroborated with laser vibrometer [5] measured surface dilation. Finally, the array substrates were housed and matched to a water load and measurements of directivity and transmit voltage response (TVR) as a function of excitation frequency were performed. TVR is the level of the acoustic output from a transducer referenced to one meter per unit excitation voltage and transducer efficiency can be determined by considering the theoretical and experimental TVR [6]. The theoretical TVR can be calculated using Equation (1):

$$TVR_{(Theo)} = 170.9 + DI + \log(G)$$

$$DI = 10\log\left(\frac{31600}{B_v \times B_h}\right) \qquad (1)$$

Where DI is termed the directivity index and B_v and B_h are defined as the vertical and horizontal –3dB beam widths of the transducer, respectively. G is the measured device conductance in water. The experimental TVR is defined in Equation (2)

$$TVR_{(Exp)} = 20\log\left(\frac{V_i}{V_o}\right) - C + 20\log(d) \qquad (2)$$

Where V_i and V_o are the output and the input voltages at a given excitation frequency of the transmitter, respectively; C is the source level of the calibrated receiver and d is the separation of the two transducers. With the theoretical and the experimental TVR, the efficiency is expressed as a percentage and can be calculated from equation (3)

$$Efficiency = 10^{\left(\frac{TVR_{(Exp)} - TVR_{(Theo)}}{10}\right)} \quad (3)$$

The next Section describes the problem of crosstalk in periodic arrays by considering the behaviour of piezoelectric composite array substrates operating in air. Test coupons comprising both isotropic and anisotropic passive phase materials are presented Then, the Lamb wave dispersion behaviour of the composite substrate [1, 2] is used to explain some of the differences observed. In the following Section, the experimental behaviour of the array coupons operating into a water load is discussed in terms of directivity, TVR and efficiency. It is shown that the novel anisotropic materials are more suited to minimising crosstalk whilst maintaining device efficiency. Throughout, the PZFlex finite element code will be employed to analyse each array in terms of the experimental metrics.

II. AIR-COUPLED ARRAY SUBSTRATE BEHAVIOUR

Piezoelectric composite arrays typically comprise a passive polymer phase exhibiting isotropic elastic character. To analyse the problem of mechanical crosstalk in periodic arrays, it is useful to consider two examples comprising such materials, with what can be considered to be the extremes of elastic character. The relevant acoustic properties of four example materials, measured at 500kHz, are detailed in Table 1. Polymer A is a rigid isotropic polymer that has relatively low acoustic loss and a polymer B is soft, flexible isotropic polymer that has relatively high acoustic loss. Polymers C and D are both soft materials that exhibit anisotropy in their acoustic attenuation. These material descriptions refer to the polymer character at 20^{o}C. Each of the polymer materials in Table 1 was configured in a piezoelectric composite array structure with a nominal fundamental thickness mode of 400kHz employing PZ29 [Ferroperm, Kvistgard, Denmark] as the active material. Each of the devices is denoted by the same letter as the passive polymer phase; for example A for the hard, low loss polymer A; and B for the soft, high loss polymer B, etc. The microstructure employed in each case is detailed in Table 2. A 7-element linear array pattern is defined on one face of the array substrate and a monolithic ground plane is deposited on the opposing face. A schematic of the electrode configuration is illustrated in Figure 1.

Considering device A, Figure 2 details the electrical impedance characteristic for element #4 of the array operating in air. Both the experimental and PZFlex derived data are shown and the two data sets are in good agreement. It is clear from Figure 2 that the fundamental thickness mode is contaminated with additional resonant activity. This is a result of extraneous vibration being generated across the array aperture as a result of the periodicity of the composite substrate and the electrode pattern [1, 2].

TABLE 1 ACOUSTIC PROPERTIES OF EXAMPLE ISOTROPIC FILLER MATERIALS MEASURED AT 500KHZ

Polymer	**A**	**B**	**C**	**D**
Longitudinal velocity, ms^{-1}	2512	1500	1533	1584
Shear velocity, ms^{-1}	1175	747	385	498
Longitudinal attenuation, dBm^{-1}	139	825	80	104
Shear attenuation, dBm^{-1}	356	6063	7062	8669

TABLE 2 MICROSTRUCTURE OF PIEZOELECTRIC COMPOSITE ARRAY

Composite Substrate Thickness	3.83mm
Lateral Dimensions	30mm x 30mm
Kerf	0.23mm
Saw Pitch	0.69mm
Array Element Width	1.9mm
Array Element Pitch	2.4mm

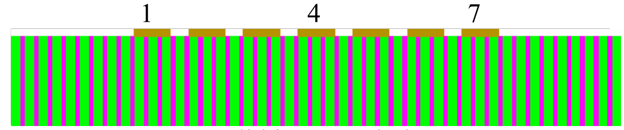


Figure 1 Schematic diagram of electrode configuration in the array substrate

This is further evidenced in the surface dilation across the array aperture. Element #4 of the array was electrically excited with a 10V_{pp}, 20 cycle tone burst, centred on the impedance minimum of the array, whilst the motion of the front surface of the array is monitored using a scanning laser vibrometer [5]. The surface displacement data for device A are shown in Figure 3(a) and it is clear that significant surface motion is observed outwith the area of the central (#4) electrode. This will lead to narrowing of the directivity response of the array and will be discussed further in Section IV. It is important to note the displacement magnitude of the array element, 7nm in the case of device A.

To demonstrate the difference in array behaviour arising from the soft, attenuating polymer filler, the surface displacement data for device B is shown in Figure 3(b). From Figure 3(b) the array is shown to only be displacing in the central area under the excited electrode with a magnitude of 2.8nm. Importantly, the fundamental thickness mode of the array has not been corrupted by parasitic vibrations, as was observed for device A. However, the magnitude of the surface vibration has been reduced which will have ramifications on the acoustic output of the device. Both of these effects result from the higher attenuation exhibited by polymer B, damping out both the desired element response and the unwanted modes of vibration. The electrical impedance characteristic of device B, not shown here for reasons of brevity, also demonstrates the uni-modal character of this device.

Considering the composite arrays configured with the anisotropic polymer materials, Figure 4 details the electrical impedance characteristic of device C operating in air, as again the PZFlex derived data are also shown. The two data sets are found to be in good general agreement, both indicating uni-modal operation, and as such free from additional modes of vibration. However, the loss in the experimental data is higher than that predicted by the FE model. The electrical impedance characteristic of device D is not shown but it exhibits the same uni-modal response. Further evidence of this uni-modal nature can be seen in the surface displacement profiles of devices C and D, shown in Figure 5.

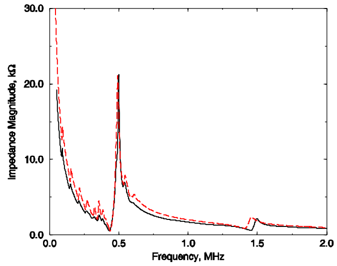
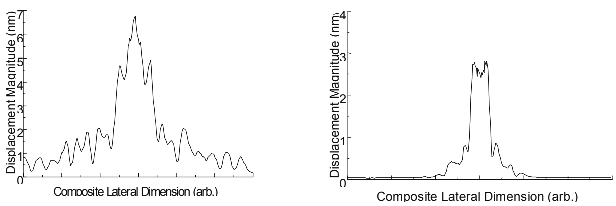


Figure 2 Comparison of experimentally measured (solid) and PZFlex derived (dashed) air loaded electrical impedance characteristic of element #4 of device A



a b

Figure 3 Experimentally measured surface displacement profile of element #4 for (a) device A and (b) device B

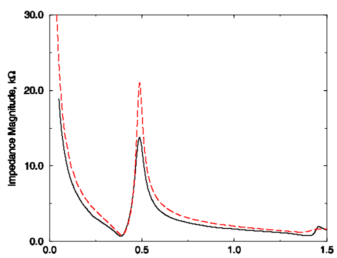
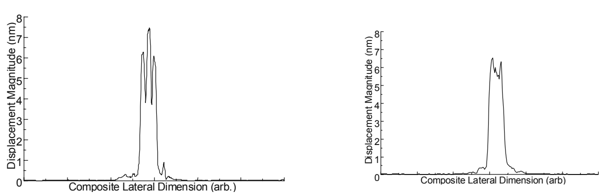


Figure 4 Comparison of experimentally measured (solid) and PZFlex derived (dashed) air loaded electrical impedance characteristic of element #4 of device C



a b

Figure 5 Experimentally measured surface displacement profiles of element #4 of (a) device C and (b) device D

From Figure 5 it can be seen that both of the devices configured with the anisotropic polymers are only displacing under the area defined by the central array element. The anisotropic polymer filler has attenuated the parasitic modes. Importantly, the magnitude of the surface displacement has not been affected, device C has a maximum displacement magnitude of 7.5nm and device D has a maximum displacement magnitude of 6.5nm. When compared with the surface displacement profile of device A shown in Figure 3(a) it is clear that the eradication of the unwanted modes of vibration has not been achieved at the expense of element displacement.

III. ARRAY SUBSTRATE DISPERSION BEHAVIOUR

Following the analysis of Hayward and Hyslop [1, 2], a 2-dimensional finite element model was configured in PZFlex to analyse the dispersion characteristics of the array substrates. The dispersion curves, plotted in phase velocity–frequency space, for device A, are shown in Figure 6. Three modes are predicted; the zero order anti-symmetric and symmetric modes, a_0 and s_0 respectively, and the first order symmetric mode (s_1) Lamb waves. The line of constant wavelength, the dashed line shown in Figure 6, relates to the 2.8mm centre-to-centre (c-c) spacing of the elements in the array. The load line intersects the dispersion data at three frequencies, corresponding to 210kHz, 480kHz and 530kHz. The first of these modes is the a_0 mode and is weakly coupled due to the symmetrical nature of the excitation voltage. The other frequencies can be attributed to the s_0 and s_1 modes. Inspection of the impedance characteristic of device A in Figure 2 shows that these frequencies are apparent. These modes have been introduced by the periodicity of the array elements and, in the case of device A, are strongly coupled to the fundamental thickness mode.

The dispersion data for device C, plotted with a load line of constant wavelength, is shown in Figure 7 where only two modes are predicted, the a_0 and s_0 modes. Due to the lower shear wave velocity of the polymer employed in device C, the modes exhibit significantly lower phase velocity and the attenuation in the polymer has lowered the cut-off frequency.

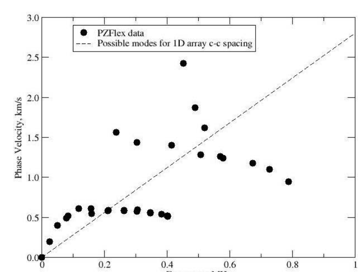


Figure 6 PZFlex predicted dispersion characteristics for device A. The dashed line represents a load line corresponding to the array element centre-to-centre spacing

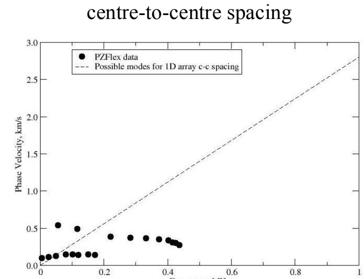


Figure 7 PZFlex predicted dispersion characteristics for device C. The dashed line represents a load line corresponding to the array element centre-to-centre spacing

The line of constant wavelength intersects the modes at 45kHz in the case of the a_0 mode and 160kHz in the case of the s_0 mode. In both of these modes are well separated from he fundamental thickness mode and are weakly coupled since examination of the relevant electrical impedance data, shown in Figure 4, does not indicate any modes corresponding to these frequencies. Careful examination of the phase of the electrical impedance characteristic (not shown) is required to identify these very weakly coupled modes.

IV. Water Loaded Array Behaviour

Hydrophone measurements of directivity and TVR were performed in water for each array. The subsequent data was then used to calculate the device efficiency as described in Section I. Each array substrate was contained in a waterproof housing and a front-face matching layer, comprising polymer A, was added. The measured beam directivity for each device is shown, together with the PZFlex derived response, in Figure 8. The beam directivity of device A is not uniform and a number of minor side lobes are observed. Considering the beam directivity of device B an improvement in the directional response has been observed, the directivity is symmetrical about the main axis and exhibits a wider beam width than device A. A similar response, in terms of increased beam width, is observed for both devices C and D. The –3dB beam widths and the TVR measured at 400kHz for each of the arrays is summarised in Table 3.

Considering the data for device A shown in Table 3, the narrow beam directivity that results from the inter-element crosstalk is evident. However, since this material is isotropic and low loss it exhibits a high TVR value, 150dB re 1µPa/V, and an efficiency of 22%. The soft, lossy material that comprises device B has resulted in broader vertical beam width and a measured TVR of 151dB re 1µPa/V. However, the larger conductance value of this device results in a higher value of theoretical TVR, 162dB re 1µPa/V in this case, hence the lower efficiency calculated for device B. It is clear from Table 3 that the both anisotropic polymers result in wider vertical beam widths. The measured TVR data shown in Table 3 indicate that the isotropic materials, devices A and B, both exhibit higher measured TVR values than their anisotropic counterparts, device C and D. This fact is counterbalanced by the larger beam widths measured by devices C and D and the major factor in the higher efficiency values for these devices.

V. Concluding Remarks

This paper has discussed the problem of inter element cross talk in periodic composite arrays making reference to key transducer characteristics such as beam directivity, TVR and efficiency. It has been demonstrated that by configuring the piezoelectric composite to incorporate a passive polymer phase exhibiting anisotropy in the acoustic loss, element crosstalk can be significantly reduced without affecting device efficiency. Lamb wave dispersion data have shown that the novel anisotropic polymers have a lower cut-off frequency for these parasitic modes of vibration.

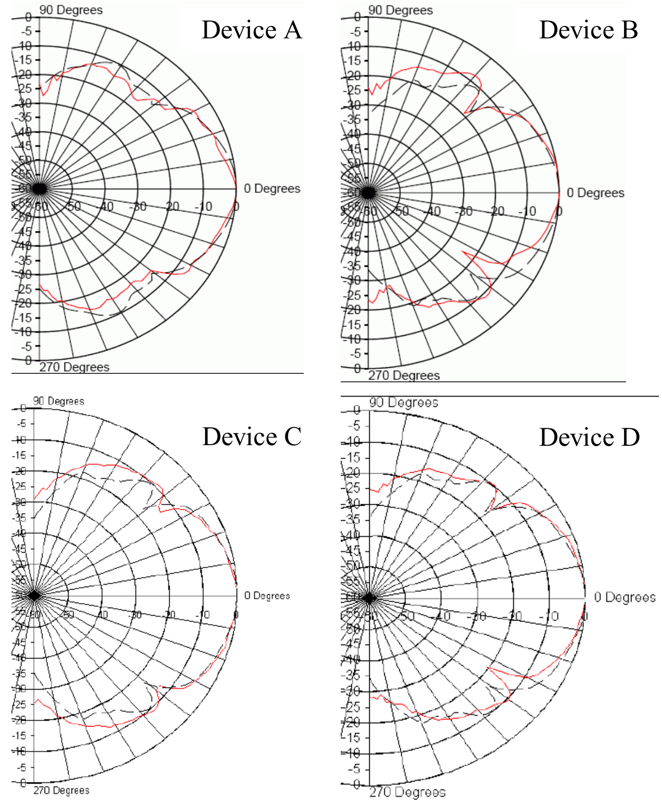


Figure 8 Comparison of measured (solid) and PZFlex derived (dashed) beam directivity for each of the arrays.

Table 3 Measured Beam Directivity, TVR and Efficiency data for each Array at 400kHz

Device	A	B	C	D
Vertical beam width	26	36	43	42
Horizontal beam width	5.5	6.0	6.0	6.5
Measured TVR, dB re 1µPa/V	150	151	147	149
Theoretical TVR, dB re 1µPa/V	156	162	155	156
Conductance, mS	0.17	0.94	0.22	0.30
Efficiency, %	22.0	7.9	18.9	21.8

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