MULTILAYERED PIEZOELECTRIC COMPOSITE TRANSDUCERS

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Abstract – *Multilayer piezoelectric materials present themselves as a suitable technology for the development of sub 100kHz transducers. A variety of different configurations have been proposed, including stacked 2-2, 1-3 and 3-1 connectivity configurations. Historically multilayer devices designed for low frequency of operation have comprised uniform layer thickness through the height of the device. The potential for extended bandwidth through the use of non-uniform layers through the thickness dimension has been investigated. In addition commercially available stacked ceramic mechanical actuators have been investigated. A combination of theoretical and experimental assessment has been employed to evaluate each transducer technology. Selection of the passive phase for these multilayer devices is critical. Typically, these devices operate in the high power regime and as such selection of the passive polymer material is crucial - thermal stability coupled with thermal conductivity would be a virtue. To this end a number of polymer materials possessing the appropriate thermal properties have been investigated.*

I. INTRODUCTION

Multilayered piezoelectric composites present a viable approach for the manufacture of sub 100kHz sonar transducers. A number of different composite configurations have been explored, including 1-3, 2-2 and 3-1 connectivites. Manufacture of multilayer devices based upon 1-3 and 2-2 connectivites has been found to be problematic. Each layer is manufacture individually and once surface electrodes have been applied the layers are bonded together to produce the stack structure. This approach can lead to problems associated with precise alignment of the microstructure in the thickness dimension [1]. 1-3 connectivity designs have been investigated employing stiffening layers in between the active layers to address this problem [2]. However increased complexity of manufacture and poor performance under high drive conditions were observed [2]. A more suitable approach is the 3-1 connectivity stack device, examples of which are shown in Figure 1.

In this type of device the piezoelectric ceramic is bonded together prior to machining and since the ceramic material remains connected is all three dimension the continuity of the surface electrode is retained. Moreover, the polymer filled saw cuts, shown in blue in Figure 1, contribute to the mechanical integrity of the structure - Bonding of the layer is no longer taking place at the interfaces between layers but through the full height of the stack. These multilayer devices typically have uniform layer thickness for example considering a device comprising *n* layers where each layer has a thickness d the overall thickness *D* of the stack will be the product of *n* and *d*.

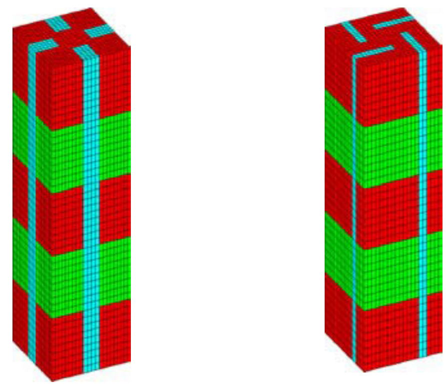

Figure 1 *Examples of the 3-1 Connectivity, (a) notch type pillar and (b) spiral type pillar*

The use of non-uniform layer thickness in the height of a stack can result in some interesting vibrational behaviour. Consider a standard 3 layer uniform stack structure possessing alternate poling where $D = 3d$. The impulse response of such a structure would yield a resonance at the fundamental frequency f_0, which is related to the total transit time of the structure. In addition, the odd harmonics of the fundamental would be observed at $3f_0$, $5f_0$ etc.

Now consider the non-uniform structure, in this case $D = d_1 + d_2 + d_3$ and for example $d_1 = 2d_2 = 4d_3$. In this configuration additional impulses are observed. They result from the different electric fields in the layers and the incomplete cancellation of the waves of force generated at the interfaces between layers. In addition to the fundamental resonance being observed at f_0, even and odd harmonics are observed at $2f_0$, $3f_0$, $4f_0$ etc. The exploration of stacked structures possessing non-uniform layer thickness should present a viable approach for the manufacture of wideband multilayer devices.

In the proposed application, the stack devices, of either uniform of non-uniform layer thickness, are to be arranged in an array, essentially forming a large 'Super 1-3' connectivity device. Each pillar of the super 1-3 will be a 3-1 connectivity stack surrounded by a suitable polymer material. Selection of the appropriate polymer material to act as the passive filler for these stacked devices is most important. These devices are expected to operate in the high power regime and as such the polymer materials that are to be utilised should benefit from some degree of thermal stability. Indeed, the ability for the polymer to provide a thermal pathway for the dissipation of heat would be an obvious advantage. To this end, the elastic and thermal properties of a number of polymer materials possessing high glass transition temperature (T_g) and enhanced thermal conductivity have been investigated and will be discussed in Section II.

This paper employs the PZFlex finite element code in the analysis of the 3-1 connectivity stack structure and its application to the super 1-3 type device. In each case the bandwidth of the device is assessed, by determining the mechanical Q-factor. In addition the potential for improved device bandwidth by employing non-uniform layer thickness in the height of the stack structure is explored. Finally the use stacked ceramic mechanical actuators as the active component within a super 1-3 connectivity device is investigated.

II. Passive Polymer Materials

Previous work on single layer devices has shown that the use of a polymer filler material possessing a high T_g coupled with increased thermal conductivity will impart some temperature stability to the piezoelectric composite device [3]. To this end, a number of thermosetting epoxy resin materials have been investigated. The longitudinal and shear wave velocities have been measured by a through transmission time of flight technique, together with the measured attenuation of each wave type. These data are detailed in Table 1 for three virgin epoxy resins and Table 2 details the properties of the polymer modified with thermally active filler materials.

Polymer	A	B	C
V_l (m/s)	2513	2342	2000
V_s (m/s)	1175	1094	747
ρ (kg/m^3)	1149	1150	1165
Z (Mrayl)	2.86	2.69	2.33
α_l (dB/m)	139	174	825
α_s (dB/m)	356	243	6063

Table 1 *Elastic Properties of the unfilled polymer materials under investigation measured at 500kHz*

Polymer	D	E	F	G
V_l (m/s)	2925	3377	2813	2636
V_s (m/s)	1494	1780	1464	1345
ρ (kg/m^3)	1503	2292	2007	1673
Z (Mrayl)	4.40	7.74	5.65	4.41
α_l (dB/m)	176	96	174	174
α_s (dB/m)	363	252	400	382

Table 2 *Elastic Properties of the filled polymer materials under investigation measured at 500kHz*

The three materials in Table 1 are unfilled epoxy resins, supplied by Vantico [4]. Polymer A is Vantico CY1301/HY1300, a hard setting polymer resin with a T_g of 60°C. Polymer B is MY750/HY956/DY062, a high temperature material with a glass transition temperature of 151°C. Finally CY208/HY956 is a high loss soft setting polymer. Table 2 details the elastic properties of the high temperature materials that have been investigated in this paper. Materials D and E are Stycast 2651–40 and Stycast 2850FT [5] respectively; polymer D is mica filled and E is loaded with alumina. These materials are very highly loaded with their respective thermally active additives making them elastically stiff, albeit imparting excellent thermal conductivity. An obvious corollary is that the high loading of these materials, polymer E in particular, leads to them being highly viscous in the uncured state. This may lead to problems in manufacture of piezoelectric composites possessing fine spatial scale.

To counter the problem of increased viscosity of materials containing particulate additives, materials F and G were both manufactured within CUE. Each is loaded with a thermally active material to impart thermal conductivity to the high T_g resin B. However, the formulation is controlled such that viscosity of the blended material in the uncured state does not increase excessively. F is a blend of polymer B and 30% v/v alumina. Material G is a blend of polymer B with 24% v/v aluminium nitride.

In addition to the elastic properties, the thermal properties of the polymer materials have been measured and are reported elsewhere [3]. As was stated previously, both of the highly loaded polymers, D and E are very effective thermal conductors exhibiting high thermal conductivity and diffusivity when compared to an unloaded epoxy resin. Comparing polymers B, F and G the addition of the thermal active particulate has served to increase the thermal conductivity and diffusivity [3].

III. Piezoceramic Stacks

Piezoceramic stacks are a fairly simple multilayered device, Figure 2 shows the comparison between theory and experiment for the unloaded impedance response of a 5 layer stack manufactured from Ferroperm PZ26 ceramic material [6] having lateral dimensions of 9mm square and an overall height of 37mm.

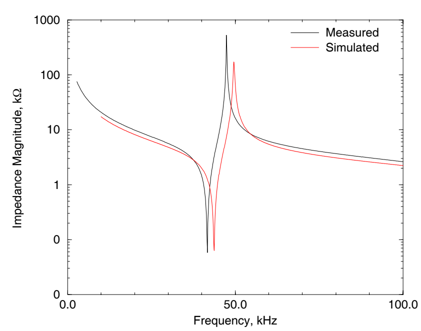

Figure 2 *Comparison of theory and experiment for the electrical impedance of a 5 layer piezoelectric ceramic stack*

The measured and simulated data are in good agreement, the measured and predicted values for k_t being equal at 0.513 and the measured and predicted values of Q being 238 and 231 respectively. Since this is a ceramic only stack, the Q value is quite high and can be reduced by firstly cutting into the stack to produce the 3-1 connectivity; further reductions on the value of Q can be made by encapsulating the resulting composite in polymer. Figure 3 illustrates the unloaded impedance of a 75% notch type 3-1 connectivity device encapsulated in hard setting polymer A. It is clear from Figure 3 that the simulated and measured data are in good agreement. The Q-factor in this case was found to be 96.

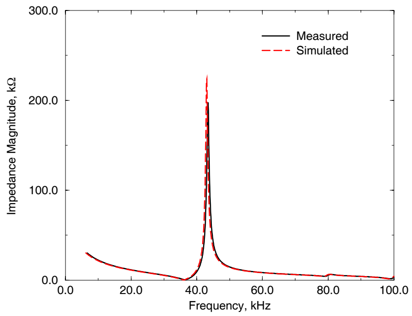

Figure 3 *Comparison of theory and experiment for the electrical impedance of a 3-1 connectivity stack encapsulated in CY1301/HY1300*

Figure 4 details the comparison between theory and experiment for the air loaded impedance for a spiral type 3-1 connectivity stack encapsulated in soft setting polymer C. Again the measured and simulated data are in good agreement and as would be expected for a soft polymer, the Q factor of this material in air is 8. It is clear then that the PZFlex models that have been used to simulate these structures are accurate and as such introduce a high degree of confidence in the results of the next phase of the study.

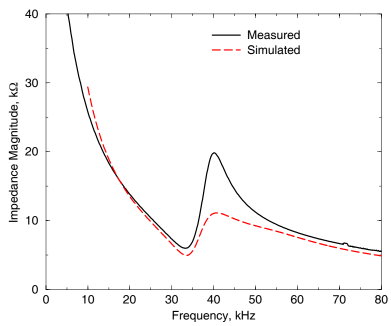

Figure 4 *Comparison of theory and experiment for the electrical impedance of a 3-1 connectivity stack encapsulated in CY208/HY956*

IV. PZFlex Simulation of Super 1-3 Structure

It is expected that the stacked pillars that have been evaluated so far will be employed as individual pillars in the large device wherein the over connectivity is 1-3. PZFlex has been employed to investigate such a structure to predict the bandwidth of the devices when matched to water. The notch type pillar possessing 75% volume fraction was simulated in a unit cell model using PZFlex. A selection of polymer materials has been investigated, with particular emphasis on the thermally conductive materials, both commercially available and those formulated within CUE. In each case the device was simulated with a matching layer manufactured from the Al_2O_3 filled material, polymer F in Table 2 operating in to a water load. Figure 5 illustrates the calculated Q-factor for a selection of the polymers under study. As would be expected the soft lossy material, polymer C, has yielded the lowest Q-factors. However, the use of the high T_g thermally conductive materials has also given rise to relatively low Q-factors in spite of their elastic stiffness and low mechanical loss.

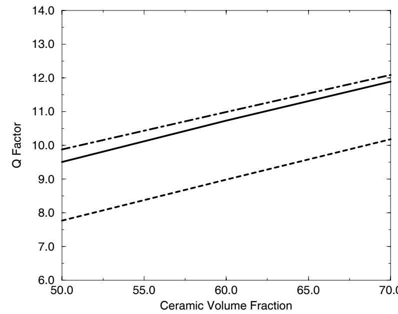

Figure 5 *PZFlex calculated Q-Factor as a function of ceramic volume for the notch type pillar (solid) Polymer A (dashed) Polymer C (dot-dashed) Polymer G*

V. Non-Uniform Layers

The PZFlex finite element code was used to explore this type of device. A 5 layer device was investigated, as detailed in Table 3, where layer 1 is the rear face and layer 5 is the front face.

Layer Number	Thickness (mm)
1	4.77
2	2.39
3	4.77
4	9.55
5	19.10

Table 3 *Layer thickness of device X*

Figure 6 illustrates the theoretically determined normalised pressure response of a ceramic only pillar having the layer thicknesses detailed in Table 3 operating into a water load. Figure 6 also shows the theoretically determined normalised pressure response of a similarly configured piezoelectric ceramic stack with uniform layer thickness. It is clear from Figure 6 that the device is operating with a fundamental frequency of 39kHz; the second and third harmonics of this resonance are also present.

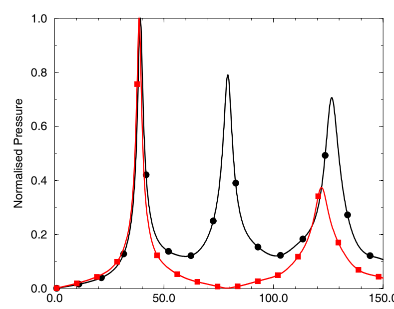

Figure 6 *Theoretically determined normalised pressure output from device X, (●) non-uniform layer thickness (■) uniform layer thickness*

This type of design shows potential for the manufacture of multi resonance low frequency transducers. When considering such a non-uniform layer structure within a composite a very wideband response is predicted using PZFlex. Figure 7 details the theoretically determined response of a 30% ceramic volume fraction super 1-3 device possessing non-uniform layer thickness attached to a backing block and acoustically matched operating into water. For completeness the theoretical pressure response of a similarly configured device with uniform layer thickness is included in Figure 7. It is clear from Figure 7 that the use of non-uniform layer structures in super 1-3 type device opens up the potential for very wideband operation of these low frequency devices. It is this type of stack configuration that is being investigated within CUE for sub 100kHz transducer applications.

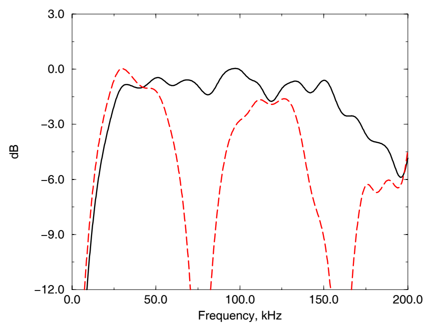

Figure 7 *Theoretically determined pressure response of a 30% ceramic volume fraction Super 1-3 device backed and matched operating into water, solid line is non-uniform layer thickness dashed line is uniform layer thickness*

VI. Stacked Ceramic Mechanical Actuators

Another application of multilayered piezoelectric devices is in the manufacture of stacked ceramic mechanical actuators. Typically these devices have very many thin layers and as such have very low electrical impedance. In addition it is not uncommon for these devices to produce surface displacement in the micron range when subject to electrical excitation. They are manufactured from green state ceramic powder with electrodes screen printed between each layer of the actuator. The actuators are then co-fired and poled to achieve the alternate poling. The individual actuators can then be stacked to produce a stacked ceramic mechanical actuator (SCMA). Figure 8 details the comparison between theory and experiment for electrical impedance of a 14 layer SCMA manufactured from Ferroperm PZ26 [7, 6]

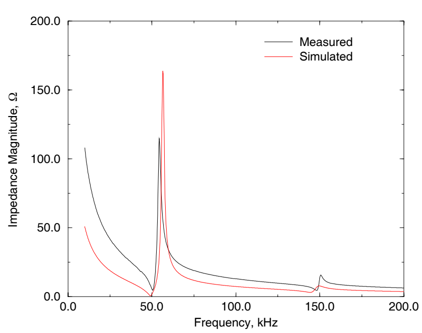

Figure 8 *Comparison of theory and experiment for electrical impedance response of a 14 layer SCMA*

It is clear that the theory and experiment are in good agreement. The use of SCMA as the active element within a large 1-3 connectivity device has been investigated using PZFlex. Figure 9 details the simulated conductance response of a water-loaded 14 layer SCMA based super 1-3 employing polymer F as the encapsulant and matching layer operating into a water load; the calculated Q-factor in this case is 3.4.

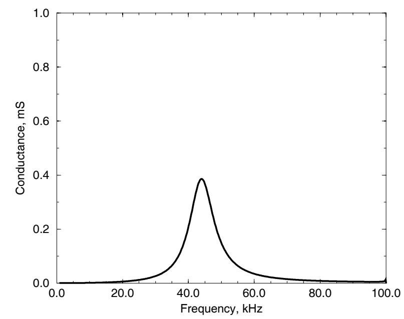

Figure 9 *PZFlex simulated conductance response from a water-loaded super 1-3 comprising a 14 layer SCMA as the active element*

As has already been stated the SCMA devices afford very low electrical impedance, due to the high number of thin layers utilised in their construction; this is coupled with very large surface displacements.

VII. Concluding Remarks

This paper has explored a number of multilayer piezoelectric materials for the development of sub 100kHz transducer technology. In general, the use of uniform layer thickness through the height of the stack has been demonstrated experimentally and theoretically using PZFlex. Low values of mechanical Q-factor have been calculated for each of the technologies employing uniform layer thickness. In addition the use of non-uniform layer thickness has demonstrated the potential for the manufacture of very wideband low frequency transducers.

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