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INCREMENTAL "MODEL-BUILD-TEST" VALIDATION EXERCISE FOR A 1-D BIOMEDICAL ULTRASONIC IMAGING ARRAY

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Abstract **-** Quantitative validation is critical to the effective utilization of large-scale modeling in advanced biomedical ultrasonic imaging applications. This work describes an incremental "model-build-test" validation exercise centered around a nonproprietary, 5MHz, 1D linear array design. The step-by-step sequence reported here includes piezoceramic slivers, slivers with matching and slivers with both backing and matching. Furthermore, prior to the fabrication process, all the active and passive material components are accurately characterized. PZFlex, an explicit time-domain finite element modeling package, is used to predict the performance of the incremental array components at each stage of the validation exercise. Deviations between experimental results and finite element predictions are identified and subsequently analyzed. Although the manufacturing techniques used do not push the current operational envelope, observed process effects should be relevant to today's devices.

INTRODUCTION

As engineers and scientists in the electronics and materials industries continually redefine the “state-of-the-art”, designers of biomedical ultrasonic imaging systems are faced with the challenge of how to integrate this new technology into their future “state-of-the-art” products. Such systems have the potential for enhanced bandwidth & sensitivity, greater numbers of array elements & data acquisition channels and improved image processing capabilities. Furthermore, it should be possible to package all these enhancements in a smaller and more compact unit than had been previously possible.

Traditionally, the design of the acoustic front-end to such a system was often accomplished via established “rules-of-thumb” and simple analytic one-dimensional transducer models. Unfortunately, this design philosophy is often no longer adequate if all potential performance gains are to be ultimately realized. Consequently, transducer designers and system integrators require comprehensive design and analysis tools to facilitate the design, development and subsequent optimization of future ultrasonic imaging systems.

Over the past couple of years, the computational power offered by desktop computer systems has increased dramatically. Furthermore, the cost of RAM has fallen to the point where it is not uncommon to find desktop computer systems equipped with more than 1GByte of RAM. By employing a computationally efficient finite-element code such as PZFlex[1], it now becomes possible to model the entire ultrasonic array assembly, and not be confined to simpler “unit-cell” types of analysis. However, before large-scale finite element models can be effectively utilized, it is essential that these modeling tools have been fully validated and key implementation issues identified.

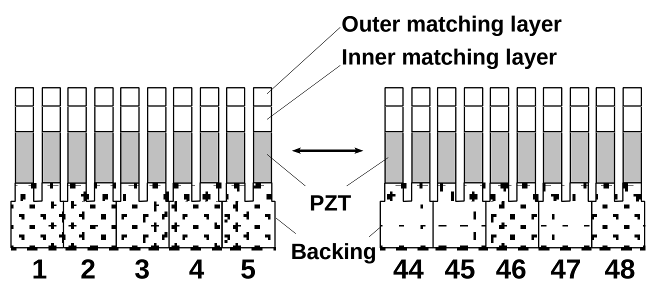

Figure 1 Diagram of validation array assembly (Two PZT slivers per physical array element)

The motivation for this work effort was the need for a well-documented, nonproprietary "primer", that transducer designers can use to establish confidence in, and expertise with, the time-domain finite element modeling paradigm. This paper focuses on a detailed analysis of a non-proprietary, 5MHz, 1D linear array design (see Figure 1). The array’s performance is studied via an incremental analysis and experimental measurements are cross-correlated with PZFlex predictions at all stages of the fabrication process. Through the course of this work, the prerequisite for accurate material characterization is

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emphasized. Consequently, experimental methods are currently being developed and refined for accurately characterizing both the active piezoceramic, as well as the passive matching layer and backing block materials.

APPROACH ADOPTED

The PZFlex validation exercise presented in this paper is centered around the incremental “model-build-test” analysis of an ultrasonic biomedical imaging array. The array is constructed from Motorola 3203HD PLZT[2] and has 48 individual elements, each comprising two sub-elements as shown in Figure 1. A double layered, sub-diced matching layer configuration was adopted for the validation array, with both matching layer materials being provided by Staveley NDT Technologies Inc[3]. The inner matching layer material was Staveley part number ML#107, whilst the outer matching layer was ML#103. A light acoustic backing with an impedance of about 2.5MRayls was attached to the bottom of the device to help promote improved bandwidth characteristics whilst still maintaining reasonable transmit sensitivity.

The accuracy of finite-element analysis is ultimately dependant upon the accuracy of the dielectric, piezoelectric and elastic properties used to simulate the model’s constituent materials. Consequently, in the course of this work, particular emphasis is placed on material characterization issues since these will largely determine the validity and accuracy of the end result.

Piezoceramic properties are obtained via the application of curve-fitting techniques to IEEE standard resonator measurements[4]. The material properties are then cross-checked by comparing the experimental impedance responses for the IEEE standard resonators with the corresponding PZFlex predictions. Matching layer and backing properties are obtained via a combination of through-transmission water tank measurements [5] and measurements made with a pair of contact shear-wave probes.

Once all the active and passive materials have been accurately characterized, the response of the entire array assembly is initially considered in terms of the response of its incremental components. Currently, the experimental results are confined to electrical impedance measurements, however, future experiments will include transmit, pulse-echo and surface displacement measurements. This type of incremental “model-build-test” sequence permits transducer models to be developed which describe the transducer at each distinct stage of the manufacturing process. Consequently, deviations between

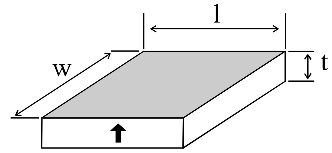

Figure 2
Thickness extensional (TE)
w>10t, l>10t
w=l=7.5mm, t=0.5mm

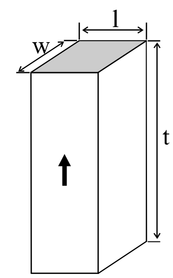

Figure 3
Length extensional (LE)
t>5w, t>5l
w=l=1.0mm, t=5.0mm

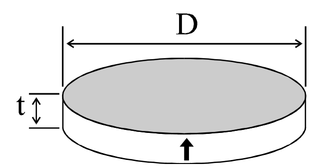

Figure 4 Radial (RAD)
D>20t; t=0.5mm, D=10.0mm

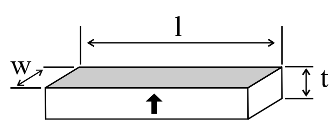

Figure 5
Length thickness (LTE)
w<3t, l>10t, l>3w
w=1mm, l=7.5mm, t=0.5mm

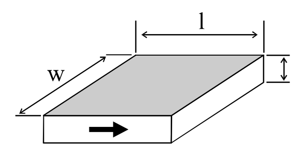

Figure 6
Thickness shear (TS)
w>10t, l>10t
w=l=7.5mm, t=0.5mm

experimental results and finite element predictions can be more readily analyzed and the transducer models refined as appropriate, ie. sources of accumulative error can be minimized.

The following section describes the techniques which were used to fully characterize the active and passive materials components of the validation array. Subsequent sections deal with the performance of the incremental array components and their correlation with finite element predictions.

MATERIAL CHARACTERIZATION

The IEEE standard on piezoelectricity[6] identifies certain geometrical shapes which may be used to facilitate the measurement of a material’s elastic, dielectric and piezoelectric properties. For piezoelectric materials, there are 5 standard resonator geometries as shown in Figures 2 to 6. These resonator samples are specifically designed so as to isolate certain types of resonant behavior. Consequently, it is possible to measure those material properties which are strongly coupled to a particular resonant mode (Table 1 shows the material properties which can be extracted from each resonator). The equations used to determine the material properties (as given in the IEEE piezoelectric standard [6]) have idealized derivations, and assume that the material is lossless. In practice, all real materials possess certain loss mechanisms, and hence the calculated properties will be subject to certain inaccuracies. A refinement to this method has been developed by researchers at the Royal Military College of Canada and employs curve fitting techniques to more accurately determine a material's properties. The software package, PRAP[4], was used to perform this analysis, and the extracted material properties for Motorola 3203HD PLZT are also given in Table 1.

The IEEE resonators shown in Figures 2 to 6 were modeled in PZFlex using the measured material properties given in Table 1. Figures 7 to 10 show the correlation between the experimental electrical impedance response and the corresponding PZFlex predictions for a selection of these resonator samples.

The in-air impedance response for the thickness extensional mode resonator (TE) is shown in Figure 7. It may be clearly seen that there is excellent agreement between the experimental result and the PZFlex analysis. Moreover, the simulated response correctly predicts the spurious modal activity lying between the electrical resonance at 4.1MHz and the mechanical resonance at 4.7MHz. These spurious resonances are due to lateral

Material Constant	Resonator	Value	
		Real	Imag
s_{11}^E (m^2/N) x 10^{-11}	RAD, LTE	1.55	-0.043
s_{12}^E (m^2/N) x 10^{-11}	RAD	-0.446	0.018
s_{13}^E (m^2/N) x 10^{-11}	calculated	-0.819	0.025
s_{33}^E (m^2/N) x 10^{-11}	LE	1.94	-0.046
s_{55}^E (m^2/N) x 10^{-11}	TS	3.92	-0.13
s_{66}^E (m^2/N) x 10^{-11}	calculated	3.992	-0.122
c_{33}^D (N/m^2) x 10^{11}	TE	1.743	0.017
d_{13} (C/N) x 10^{-12}	RAD, LTE	-294	11.7
d_{33} (C/N) x 10^{-12}	LE	584	-17.7
d_{15} (C/N) x 10^{-12}	TS	600	-30.0
e_{33} (C/m^2)	TE	22.15	-1.081
ε_{11}^T (F/m) x 10^{-8}	TS	2.14	-0.130
ε_{33}^T (F/m) x 10^{-8}	RAD, LTE	3.01	-0.081
ε_{33}^S (F/m) x 10^{-8}	TE	1.02	-0.067
k_{33}	LE	0.763	-0.004
k_{13}	LTE	0.435	-0.010
k_{15}	TS	0.611	-0.003
k_p	RAD	0.703	-0.006
k_t	TE	0.542	-0.011
ρ (kg/m^3)	-	7800	-
Q_m	TE	90	-

Table 1: Measured properties for Motorola 3203HD

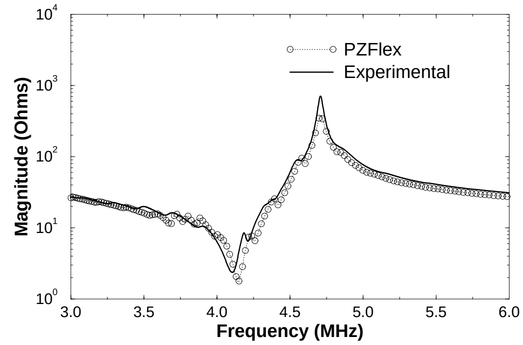

Figure 7 Impedance magnitude response for thickness extensional mode resonator (TE)

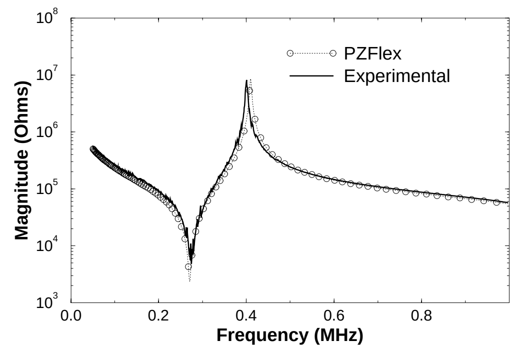

Figure 8 Impedance magnitude response for length extensional mode resonator (LE)

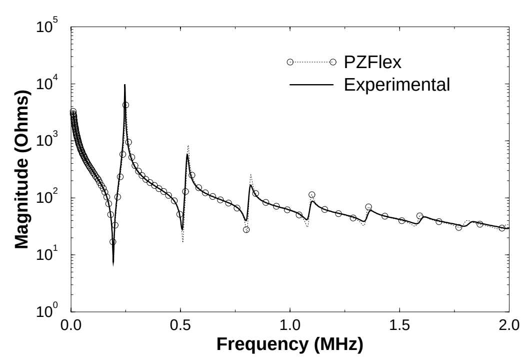

Figure 9 Impedance magnitude response for radial mode resonator (RAD)

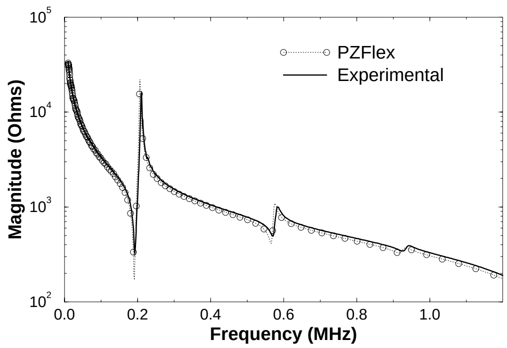

Figure 10 Impedance magnitude response for length thickness extensional mode resonator (LTE)

modes which are supported by the resonator's physical geometry. If these parasitic modes are too strongly coupled to the resonance of interest, the extracted material properties will be inaccurate. The TE resonator used in the current work effort was specifically chosen such that its dimensions fully satisfy the guidelines laid down in the IEEE piezoelectric standard. Since the other resonators have greater modal separation, their impedance response curves appear cleaner and more unimodal. In all cases (Figures 8 to 10) PZFlex is once again seen to accurately predict the devices' impedance characteristics.

It is important to note that a given set of IEEE standard resonators will provide material properties which were measured over a range of different frequencies. For example, the TE resonator provides c^D_{33} at 4.7MHz whereas the LTE resonator yields d_{13} at 200kHz. Typically, all the material properties will exhibit some degree of frequency dependence, however, with care, it is possible to select a set of properties which give consistent results over a wide range of frequencies. Indeed, PZFlex models using the properties shown in Table 1, are seen to demonstrate excellent correlation over the frequency range 100kHz to 6.5MHz.

The validation array considered in this paper has a double matching layer and light acoustic backing attached to its upper and lower surfaces respectively (see Figure 1). Accurate characterization of these passive materials is as important as that of the piezoceramic if the PZFlex analysis is to yield accurate results. The material properties which need to be measured are longitudinal-wave velocity & attenuation, and shear-wave velocity & attenuation.

Longitudinal velocity and attenuation measurements are relatively straightforward and may be accomplished via a simple through-transmission experiment. Unfortunately, measurement of the shear properties is typically much more difficult and potentially less accurate. Shear properties are normally obtained by attaching a pair of shear wave transducers to opposites sides of a test specimen and propagating a shear wave through the sample. Unfortunately, it often proves difficult to get good coupling of energy between the transducers and the sample, hence the measured values are subject to considerable inaccuracies. Furthermore, these measurements are typically narrowband and hence the results are only valid over a narrow range of frequencies.

Professor Junru Wu from the University of Vermont is currently developing a wide-band through-transmission water tank characterization technique[7] for passive isotropic materials. Longitudinal measurements are based on time of flight measurements, whereas shear results are obtained by rotating the test specimen to its critical angle. At this angle, the incident plane wave in the water will undergo mode-conversion at the test specimen interface and propagate through the test sample as a shear-wave. At the opposite face, the shear wave mode-converts back to a longitudinal wave in the water. This is a wide band measurement technique and is capable of providing both velocity and attenuation data over a wide range of frequencies.

Using the characterization techniques described in [5], the measured material properties for the matching layers and backing block are given in Table 2. For the case of the piezoceramic material, the same batch of 3203HD PLZT was used for both characterization and array fabrication. Unfortunately, at this point in time, the matching layer samples from the "fabrication" batch of material have not yet been fully characterized. Consequently, the data provided in Table 2 is for an earlier batch of material, however, the properties should be representative of the actual matching layer properties. Furthermore, as the characterization methods described in [7] are refined further, more accurate material properties will become available.

Material Constant	ML#103	ML#107	Backing
v_L (ms^{-1})	1220	3950	2180
v_S (ms^{-1})	2430	2170	1115
ρ (kg/m^3)	1130	1901	987
α_L ($dB.cm^{-1}$@1MHz)	3	3	9.5
α_S ($dB.cm^{-1}$@1MHz)	6	6	20

Table 2: Measured properties for the matching layers and acoustic backing

INCREMENTAL ARRAY SAMPLES

A diagram showing the complete array assembly is given in Figure 1, however, in this paper, the analysis is restricted to the set of incremental array components shown in Figure 11. Each of these samples corresponds to half an individual array element, and was fabricated using the same techniques which will be used to construct the final array. Consequently, any process dependent effects should also be observed in the incremental samples.

The first step of the validation exercise is to confirm that the PZFlex finite-element predictions for each of these sub-units agrees with experimental values. Figure 12 shows both the experimental (——) and simulated (o·····o) electrical impedance response curves for Sample-1. At various stages throughout the fabrication process the piezoceramic slivers are subject to elevated temperatures. Although, the samples were repoled after dicing to minimize depoling effects, the samples were subsequently heated to 70°C to "age" the ceramic and improve temporal stability. This artificial aging process can be expected to slightly depole the ceramic and hence 5% depoling was assumed. From the cross-plotted results shown in Figure 12 excellent correlation between experiment and simulation may be seen. In particular, the impedance magnitudes and the resonant frequencies are both seen to correlate well. Figure 13 shows the response for Sample-2 (single 320µm sliver of 3203HD with a 160µm ML#107 matching layer). In this figure, the curve denoted (——) shows the experimental result, however, there are 2 simulated responses. The first curve, (- - - -), was obtained using the nominal matching layer properties given in Table 2, whereas the second simulated curve (o·····o) used velocities in the matching layer which were reduced by about 10%. Furthermore, a 10µm bondline was also included in the calculation. It may be clearly seen that the modified properties give much better correlation with experiment than the original nominal values. It was mentioned earlier that the matching layer properties were not obtained from the same batch of material that used for fabrication. This material is currently being fully characterized and it is anticipated that the new properties will further improve the correlation with experiment. Sample-3 adds a 70µm outer matching layer to the Sample-2 configuration. The impedance characteristics for this device are shown in Figure 14 and the simulated result with bondlines and modified material properties is seen to compare well with the experimental result. It is interesting to observe that small changes in matching layer properties (longitudinal or shear) and the thickness of the bondline can have a considerable impact on overall device response. This once again emphasizes the requirement for rigorous material characterization and accurate experimental measurements. Samples 4 & 5 correspond to the addition of the backing block to Samples 2 & 3

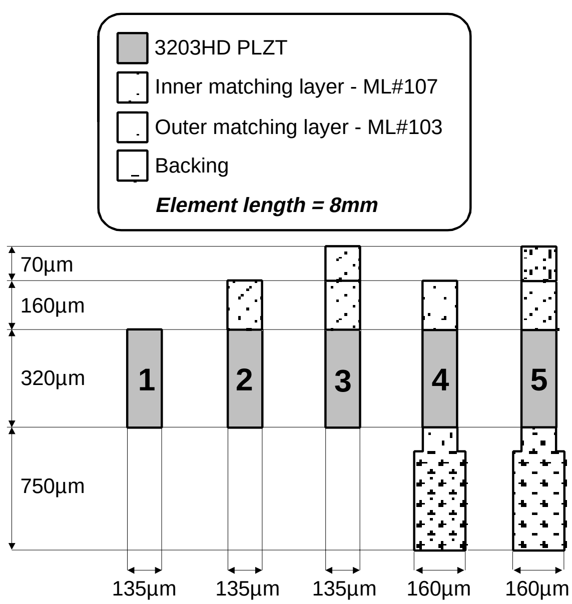

Figure 11 Diagram of incremental array components

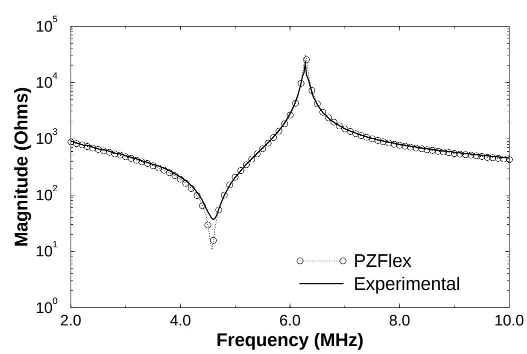

Figure 12 Electrical impedance response of Sample-1

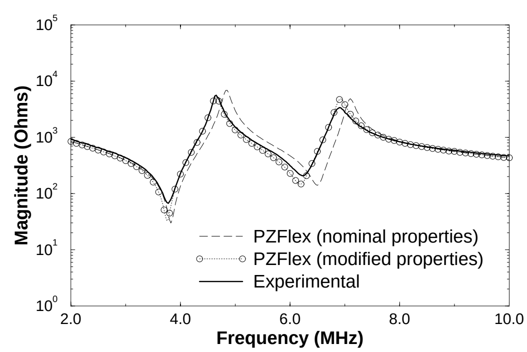

Figure 13 Electrical impedance response of Sample-2

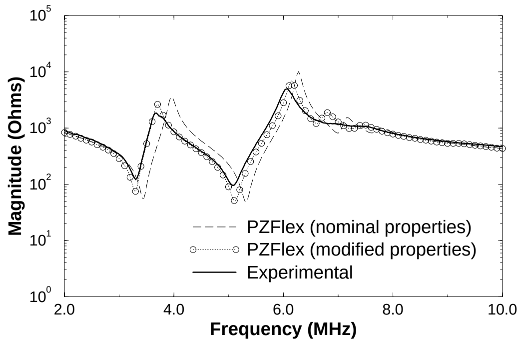

Figure 14 Electrical impedance response of Sample-3

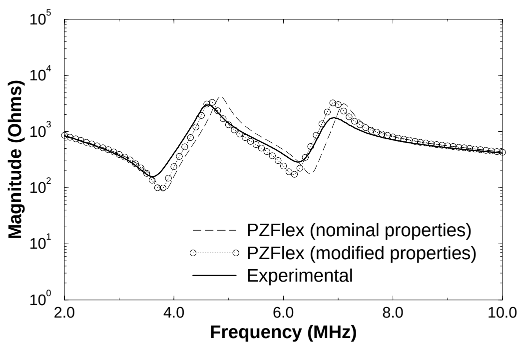

Figure 15 Electrical impedance response of Sample-4

respectively. Although, the impedance response curves for these two samples (Figures 15 & 16 respectively) compare reasonably well with the PZFlex predictions, the correlation is not as good as for the cases without a backing. This can be partly attributed to the omission of the "Flex-Circuit" used to make electrical connection to the lower side of the piezoceramic slivers. The increased thickness due to the Flex-Circuit would serve to reduce the resonant frequency. This will be included in later analyses and will be reported on at a later date.

CONCLUSIONS

This paper has presented an incremental validation exercise to demonstrate the scope and validity of the PZFlex code for the design of biomedical ultrasonic arrays. Excellent agreement between experiment and theory was demonstrated, thus confirming the accuracy of the modeling strategy employed.

Accurate material characterization has been shown to be a fundamental and integral part of finite-element analysis. The properties of passive polymers can vary significantly from batch to batch and hence rigorous characterization and strict process control must be enforced.

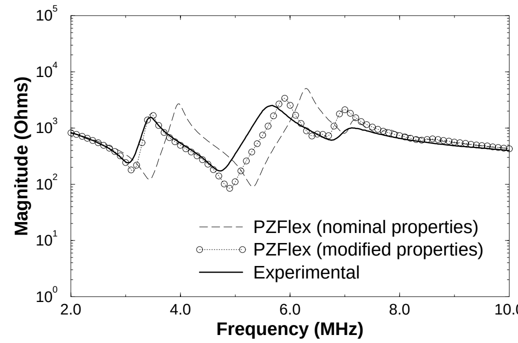

Figure 16 Electrical impedance response of Sample-5

In future work, the complete 1-D linear array assembly will be fabricated and subsequently fully characterized. Additional experimental measurements will include electrical impedance response, laser interferometer surface displacement measurements, cross-coupling between elements, transmit response and pulse-echo sensitivity.

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