01 Jan 1990

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Recommended Citation

W. Huebner et al., "Design Considerations for 1-3 Composites Used in Transducers for Medical Ultrasonic Imaging," *Proceedings of the IEEE 7th International Symposium on Applications of Ferroelectrics, 1990*, Institute of Electrical and Electronics Engineers (IEEE), Jan 1990.
The definitive version is available at https://doi.org/10.1109/ISAF.1990.200231

DESIGN CONSIDERATIONS FOR 1-3 COMPOSITES USED IN TRANSDUCERS FOR MEDICAL ULTRASONIC IMAGING

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ABSTRACT

Ceramic polymer piezoelectric composites with 1-3 connectivity have become an important tool in the design and manufacture of thickness mode transducers for medical diagnostic ultrasonic imaging. The major reasons for this are that, relative to piezoelectric ceramics alone, the composite can be designed with higher thickness coupling coefficient, acoustic impedance can be more closely matched to human tissue, and low frequency lateral resonances can be suppressed. These improvements can lead to higher sensitivity and bandwidth in the transducer and reduce ringing due to unwanted modes of vibration.

This paper compares annular array transducers made from ceramics alone to those made with composites to demonstrate the advantages of composites, and examines some of the trade-offs involved in optimizing composite designs for this application. Effects of varying Young's modulus and Poisson's ratio of the polymer phase on coupling coefficient and high frequency lateral resonances of the composite are presented.

MAJOR ADVANTAGES OF 1-3 COMPOSITES

Since their first published application in medical ultrasound transducers in 1984 [1-3], 1-3 piezoelectric composites have come into widespread use as the piezoelectric material of choice for many annular array applications. An excellent summary of the development of the material and its application, including an extensive bibliography, has been written by Smith [4].

One major reason for the use of 1-3 composites is that composites made with PZT's often have a thickness coupling coefficient (kt) as much as 40% higher than the ceramic alone. In a thickness mode transducer, the electrical-acoustical transformation may be viewed as an interface through which energy must pass. kt^2 represents the amount of energy incident upon that interface which is transmitted. The remainder of that energy is reflected and may be absorbed if the electrical terminal is well matched. In this case, kt has little affect on bandwidth, but limits the transmit efficiency. On the other hand, if the reflected energy is re-reflected or caused to resonate, it will be incident upon the interface again and more will be transmitted. In this case, kt will represent a limitation on bandwidth because of the time required for all of the energy to be transmitted. Similar arguments may be made for the receive case. Thus, a high kt represents an opportunity to increase either the sensitivity or bandwidth (or both) of a transducer, depending on the specifics of the design. This is demonstrated in Figure 1 where KLM one-dimensional modeling [5] has been used to predict the performance of two transducers which are identical except for kt.

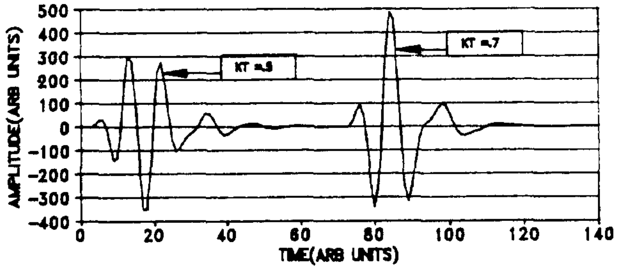
Another major advantage of the 1-3 composite is that its acoustic impedance is considerably lower than that of ceramic. The importance of low acoustic impedance may be understood in the same way as the argument for kt. Acoustic energy which is in the piezoelectric material is incident on the front face and the portions reflected and transmitted depend on how well the acoustic impedances are matched at the interface. Thus, a material poorly matched to the medium will severely limit either sensitivity, or bandwidth, or both, depending on whether the rest of the device is designed to resonate or to absorb energy.

The effects of a poor acoustic impedance match can be alleviated over a limited bandwidth by placing an intervening layer (a quarterwave layer) between the two mismatched materials [6]. In theory, adding enough layers of proper design could eliminate the effect of this mismatch. However, in practice, additional layers usually means additional losses and the existence of low-level reflections which cause long low-level ringdown. This means that acoustic impedance does not have to be reduced to that of the body to be useful since transducers with fewer matching layers have some inherent advantages.

Figure 2 shows the KLM modeled waveforms for two transducers with single quarterwave layers. The transducers are identical except that one piezoelectric (left) has the acoustic impedance of a soft PZT (36 MRayls), and the other has the acoustic impedance of a typical composite (9 MRayls). Backing and quarterwave impedances are appropriately scaled. The unit with high acoustic impedance is lower in sensitivity and bandwidth.

The third major advantage of the 1-3 composites is that they can be designed to operate in a very pure thickness mode over a fairly large bandwidth even for transducer elements with lateral dimensions

FIGURE 1: EFFECT OF KT ON TRANSDUCER PERFORMANCE



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only a few times their thickness. Most PZT's have strong lateral coupling coefficients so that resonances associated with the lateral dimensions are strong. The harmonics of these couple with the thickness mode and create distorted transmit and receive spectra. 1-3 composites can be designed so that the thickness mode is located within a stop band for lateral propagation, thus causing lateral waves to be rapidly attenuated. Even if the design does not place the thickness mode in the stop band, lateral coupling is dramatically reduced. Figure 3 shows impedance plots of a ceramic disk (left) and a 1-3 composite disk (right). The noisy appearance at the left side of the ceramic plot is due to lateral modes.

Figure 4 shows a time waveform comparison for an outer annular array ring made with PZT to one made with a PZT/polymer 1-3 composite. The long ringdown for the annular array made with ceramic is due to radial mode interference.

This has been the primary driving force behind the acceptance of 1-3 composites for annular arrays since the outer elements of equal area arrays are often only a few times as wide as they are thick.·

IDEAL COMPOSITE PERFORMANCE

In order to maximize the transducer performance which can be achieved from composite technology, it is desirable to control kt, acoustic impedance, stop band location, dielectric constant, and mechanical losses. Optimization of the first four parameters will be considered here. Ideal performance for the composite would consist of kt = 1, acoustic impedance = 1.7 MRayl (an estimate of the acoustic impedance for human skin), a stop band centered at the thickness mode frequency, the resonance frequency associated with second stop band, often referred to as ftl, at roughly twice the thickness mode frequency, and a dielectric constant which brings the real part of the tuned electrical impedance for each element close to that required for proper interfacing with the electrical circuitry. For many medical transducers, this means being matched to coax cables with characteristic impedance of 50 to 75 Ohms. A general rule of thumb is that the capacitive reactance of an element at its design frequency ought to be of the same order of magnitude as the final required electrical impedance.

As we shall see below, it is not reasonable to optimize both the kt and the acoustic impedance simultaneously. Given that, the next most ideal case would be the same as that given above, but with acoustic impedance that can be easily matched with a single quarterwave layer made from a common low impedance matching material such as epoxy. This implies that acoustic impedance is ideal at about 10 MRayls.

OPTIMIZATION

Six parameters can be identified which dominate the performance of the 1-3 composites with evenly spaced square posts and an isotropic filler. These are: k33 and dielectric constant for the piezoelectric ceramic; two independent elastic parameters of the polymer Young's modulus (E) and Poisson's ratio (σ) will be used here; and two independent geometric parameters. Although several choices exist to describe the geometry, we will use ceramic volume fill and center-to-center post spacing here.

One approach to the selection of the six parameters is as follows: Select a volume fill which will yield the optimum acoustic impedance for a given design. Select a piezoelectric ceramic which has an appropriate dielectric constant with the highest available k33 since this will be the upper limit on possible kt. This leaves the moduli of the polymer and center-to-center spacing yet to be determined in optimizing kt and the stop band structure.

In order to gain insight into how to optimize kt, we convert E and σ into isotropic stiffness matrix components C11, C12, and C44 and use the Smith-Shaulov approach [7] which has been verified experimentally for composites with close post

FIGURE 2: EFFECT OF PIEZOELECTRIC ACOUSTIC Z ON TRANSDUCER PERFORMANCE

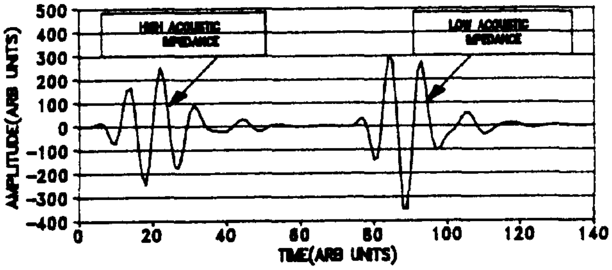


FIGURE 3: ELECTRICAL IMPEDANCE CERAMIC DISK AT LEFT SHOWS MANY RADIAL MODES (COMPOSITE AT RIGHT SHOWS FEW)

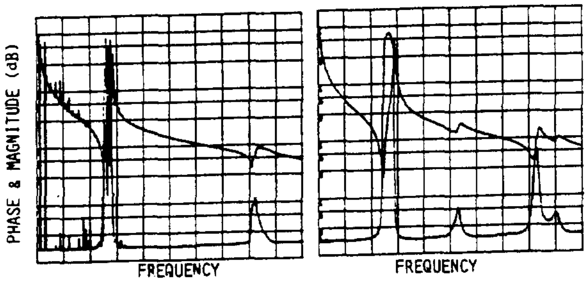
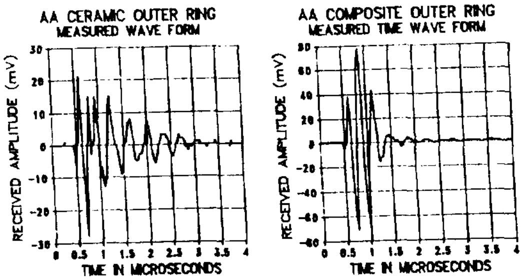


FIGURE 4



spacing [8]. For reference, a table of moduli for epoxy blends ranging from very stiff to very flexible is included as Table I. This data was taken in the MHz range at room temperature. Note that E can easily be made to vary from 1 to 6 GPa while Poisson's Ratio varies from .27 to .43.

Figure 5 shows the calculation of kt for PZT5H ceramic using polymer with several values of E, holding σ constant at .375. Using a flexible polymer clearly optimizes the coupling with the effect being most dramatic at low ceramic volume fill.

Figure 6 shows the calculation of kt for PZT5H ceramic for several values of σ, holding E constant a 6 GPa. Figure 7 is the same except that E is held constant at 1 GPa. It can be observed that for stiff polymers there is an advantage in having a low σ, but there is only *a little improvement for* σ <.3. In flexible polymers, σ is even less critical.

The reason that kt is higher for flexible polymer and for low σ is that the lateral expansion of the post which is responsible for the higher coupling in composite is not severely clamped by the polymer. For stiff polymers, the lateral post clamping can be reduced somewhat if σ is low. For soft polymers, the lateral post clamping is small so variations in σ have less effect. This is true at all volume fills. Also, picturing the composite on receive and considering the polymer and posts to act as springs in parallel, one can see that the amount of energy which goes into the ceramic is reduced when the amount of force required to compress the polymer approaches the force required to compress the ceramic. Only the energy going into the posts can be converted to the electrical domain so unconverted force spent on compressing the polymer represents unconverted energy. This accounts for the drop-off of kt at low volume fills and the more drastic drop-off for composites made with stiff polymers.

An approach to solving for the waves which propagate laterally in 1-3 composite plates made of isotropic materials has been outlined by Auld and Wang [9]. Bloch-Flouquet analysis is used and solutions are expanded in a basis of Lamb wave modes which propagate in the effective media. Full analysis is tedious and is not very practical as a design tool. The simplest analysis presented compares measured ftl for two-dimensional composites with frequencies calculated using the lowest order symmetrical Lamb wave dispersion curve for a one-dimensional composite assuming equal stress on the polymer and ceramic. ftl is assumed to be the frequency corresponding to a wavelength equal to the center-to-center spacing.

Figure 8 shows ftl predicted for σ = .375 and varying E between 1 and 6 GPa. Lowering E tends to drop ftl significantly. Figure 9 shows ftl for E = 6 and varying σ. Lowering σ also drops ftl but the effect is small. The effect of σ on ftl for flexible polymer is equally small.

The only way to significantly increase ftl for the soft polymer is to decrease the center-to-center spacing and kerf width. Although this presents *no problems in the simple theory presented so far,* reducing center-to-center spacing, post width, and

FIGURE 5: EFFECT OF YOUNGS MODULUS ON KT
Poisson's Ratio = .375

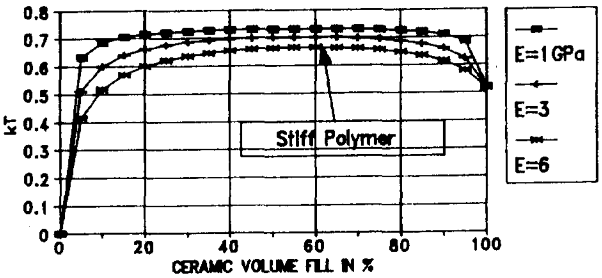


FIGURE 6: EFFECT OF POISSON'S RATIO ON KT
YOUNG'S MODULUS = 6 GPa

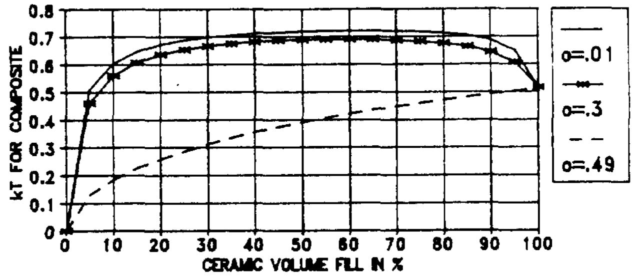


FIGURE 7: EFFECT OF POISSON'S RATIO ON KT
YOUNG'S MODULUS = 1 GPa

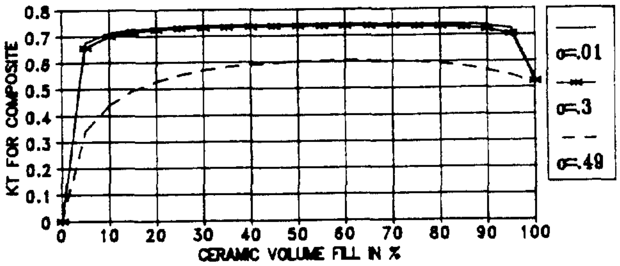


TABLE I

EPOXY	YOUNG'S MODULUS, E (GPa)	POISSON'S RATIO, σ
75% DER 331*1 25% DER 736 + DEH 26	5.95 (stiff)	.343
25% DER 331, 75% DER 736 + BAPP	4.09	.381
Spurrs Epoxy*2	3.71	.274
100% DER 332 + T310	2.92	.385
100% DER 736 + T310	1.47 (flexible)	.430

TRADEMARKS: *1 Dow Corning *2 Polysciences post width to thickness ratio can have many adverse effects in practice. Therefore, selection of proper elasticity for the polymer represents a trade-off of high kt versus the need for fine spacing. It is almost always beneficial to have low σ in the polymer since it increases kt and doesn't drop ft1 very much, but the payback in kt is minimal if reasonably flexible polymers are chosen.

CONCLUSIONS

1-3 piezoelectric composites are currently widely applied in the design of medical ultrasonic annular array transducers. The main reasons for this are high kt and low acoustic impedance which lead to sensitive broadbanded performance and a reduction of lateral mode effects in the thickness pass band. Six major parameters can be identified which may be varied to optimize the performance. Selection of ceramic type and volume fill can usually be made in a fairly straightforward manner. Determining the best polymer properties and periodicity is more complicated. Using Smith-Shaulov theory to predict kt, it is found that flexible polymer always yields better coupling. Using the Auld Wang 1-D Lamb wave approach, it is shown that the use of flexible polymer also requires finer spacing of the composite. Because of the cost and other practical considerations, this is a trade-off which the composite designer must take into account.

FIGURE 8: EFFECT OF YOUNG'S MODULUS ON FT1
POISSON'S RATIO = .375

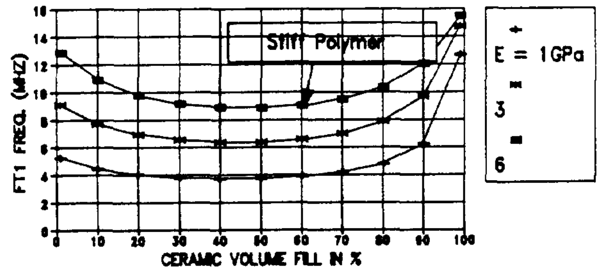
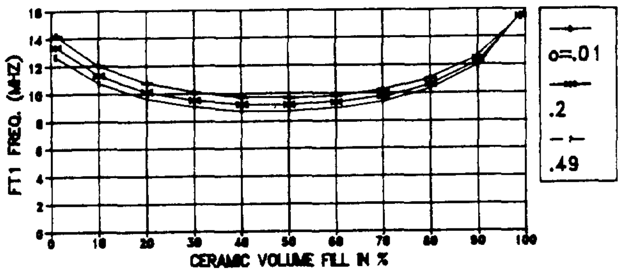


FIGURE 9: EFFECT OF POISSON'S RATIO ON FT1
YOUNG'S MODULUS = 6GPA



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