Finite Element Study of 2-2 Piezocomposite Transducer with Random Polymer Properties

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ABSTRACT

2-2 piezocomposite materials are widely used for ultrasonic transducers in medical ultrasound imaging and underwater acoustics. An important issue in 2-2 piezocomposite transducer designs is to avoid spurious lateral modes. We proposed a new method to solve the lateral mode problem in this paper. A 30-element 2-2 piezocomposite transducer composed of PZT-5H and five different types of polymers were studied by using ANSYS finite element software. Using a 2-D model of the transducer the electrical admittances were calculated within the interested frequency range. The results show that there is a strong coupling between the thickness mode and the first lateral mode when any one type of polymer is used in the transducer design. However, the lateral mode is greatly suppressed when all of these polymers are used, and the electromechanical coupling coefficient for the thickness mode is also increased. The analysis further shows that the reduction of the lateral mode is only related to the shear velocity of the polymer, while the density and longitudinal velocity of the polymer have little effect on it.

Keywords: ultrasonic transducer, piezocomposite material, finite element analysis, thickness mode, lateral mode, electromechanical coupling coefficient

1. INTRODUCTION

Piezoceramic-polymer composite materials, which combine the high electromechanical coupling coefficient of piezoelectric ceramics and the low acoustic impedance of polymer, have become one of the most important ultrasonic transducer materials for medical imaging and underwater acoustic. Being a biphasic material, the properties of a piezocomposite can be tailored over a wide range by adjusting the material properties and geometric shape of constituting phases. This provides significant technological advantages for the transducer design [1-4].

The piezocomposite materials with 2-2 or 1-3 connectivity are the most commonly used for ultrasonic transducers. However, due to the periodic nature of these composites, there exist undesirable lateral modes, which can couple to the thickness mode to degrade the transducer performance, particularly at high frequencies [5,6]. Such coupling can prolong the pulse length, change the frequency band shape, and reduce the effective thickness electromechanical coupling coefficient. Conventional transducer design will keep the width to height aspect ratio of pitch to 1:2, i.e., the element to be tall and thin to avoid mode coupling. Such fine pitch is not economic and sometimes unfeasible for transducer fabrications. Seeking an approach to reduce the lateral modes while keeping the composite with a coarser pitch can increase the structural stability and reduce the cost.

With rapidly improved computer technology and development of new software, the finite element method (FEM) becomes more and more popular for modeling composite transducers [7-9]. Qi and Cao have performed FEM investigations on the lateral modes of 2-2 piezocomposite transducers [8]. In order to break the periodicity of the composite, they introduced the randomness into the width of the polymer phase. The simulation results show that the undesirable lateral resonance can be sufficiently suppressed. The results were observed later in Yuan's [10] and Perez's [11] experimental work.

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In this paper, we report a new method to solve the lateral modes problem in the 2-2 piezocomposite transducers by combining five different polymers into one composite transducer. The electrical admittances of the 2-2 composite transducers were calculated by using ANSYS finite element software. There is strong mode coupling when one type of polymer is used, while significant lateral mode suppression is observed when all of five polymers are used, and the electromechanical coupling coefficient for the thickness mode is also increased. The analysis further shows that the reduction of the lateral mode is only related to the shear velocity of the polymer.

2. FINITE ELEMENT MODEL

A typical 2-2 piezocomposite material and the coordinate system are shown in Fig. 1(a). The origin of the coordinate is designated to be the center of the piezoceramic. The alternating piezoceramic and polymer phases are perfectly bonded and oriented perpendicularly to x_1 direction; d_c and d_p are the width of the ceramic and polymer phases, respectively. In x_2 direction, the dimension of the piezocomposite transducer is usually much larger than the thickness t. As a good approximation it can be taken as infinite. The operation direction, which is also the piezoceramic poling direction, is along x_3.

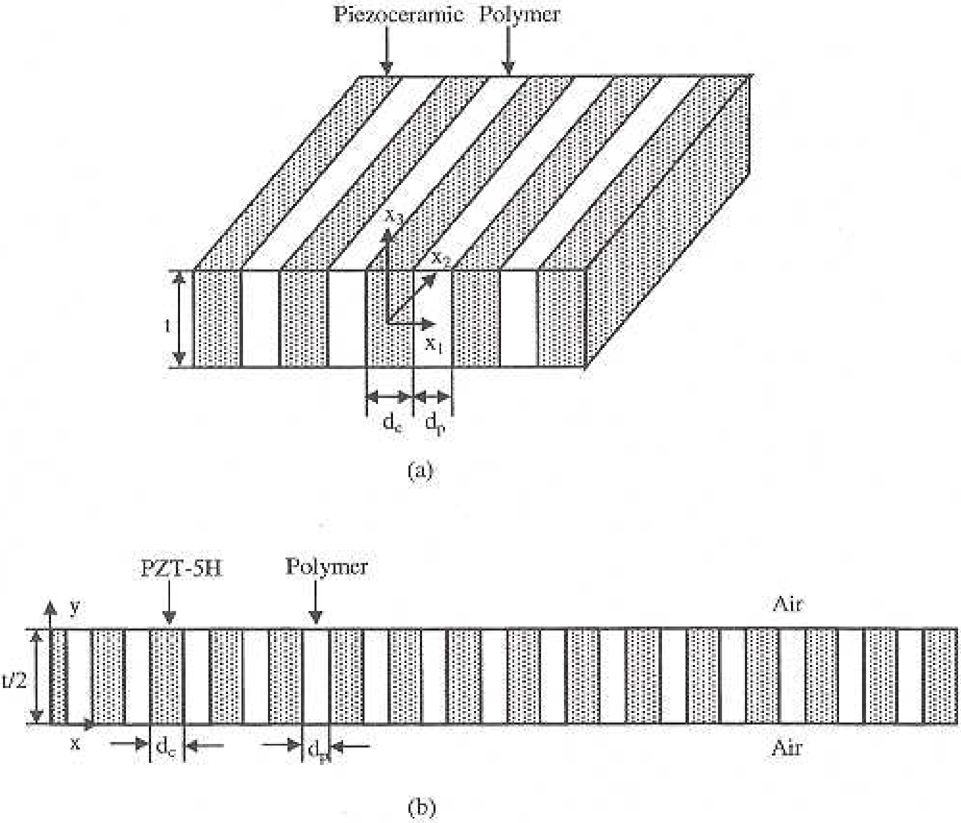

Figure 1: (a) The geometry of the 2-2 piezocomposite and the coordinate system. (b) 2-D model used in ANSYS for calculating the electronic admittance of 2-2 piezocomposite

The polymer is homogeneous and isotropic, but the piezoceramic is anisotropic with a uniaxial symmetry with respect to the x_3 axis. Materials properties used in the piezocomposite analysis in this paper are given in Table I. The Rayleigh damping is used to define the damping effect in our numerical analysis. In ANSYS software, the Rayleigh damping matrix [C] is given by $\alpha[M] + \beta\,[K]$, where [M] is the mass matrix and [K] is the stiffness matrix. In our study, mass damping is ignored ($\alpha = 0$) and stiffness damping is taken as a constant within the interested frequency range. Therefore, the damping ratio $\xi = \beta\omega/2$ is assumed to be proportional to frequency. This may not reflect the real situation. We could also define the damping ratio ξ as a constant in ANSYS software. However, only one global damping ration can be defined in ANSYS. Errors will be introduced if there is more than one type of materials, such as composite materials.

TABLE 1

Material Properties Used For the 2-2 Piezocomposites in the Investigation

PZT-5H

Piezoelectric constants (C/m^2)			Dielectric constants (ε_{ij})		Density (kg/m^3)	Rayleigh damping (s)
e_{15}	e_{31}	e_{33}	ε_{11}	ε_{33}	ρ	β
17.1	-6.3	23.5	1470	1700	7500	$2*10^{-10}$

Elastic constants ($*10^{10}$N/m^2)

C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}
13.0	8.3	8.8	12.1	2.3	2.3

Polymers

	Density ρ (kg/m^3)	Young's modulus E (N/m^2)	Poisson ratio σ	Rayleigh damping β (s)
1	1100	$3.49*10^{9}$	0.35	$2*10^{-9}$
2	1060	$2.64*10^{9}$	0.35	$2*10^{-9}$
3	1160	$4.35*10^{9}$	0.37	$2*10^{-9}$
4	1030	$1.78*10^{9}$	0.38	$2.5*10^{-9}$
5	1010	$1.45*10^{9}$	0.4	$2.5*10^{-9}$

Finite element analysis is the most powerful tool available today in designing piezocomposite transducers. It can handle complex structures with irregular boundaries. The finite element software package ANSYS was used for the present study. A 2-D model of a 30-element 2-2 piezocomposite, as shown in Fig.1 (b), is constructed for the simulations, considering the dimension in the x_3 direction is much larger than the thickness. Due to symmetry, only the up right quarter of the piezocomposite is studied, i.e., the left and bottom sides of the model are lines of symmetry. The right side boundary is free. A constant potential difference is applied to the top and bottom sides of the model to specify the electrical boundary condition. The meshing scheme is to maintain at least 10 elements per wavelength. The electrical admittance of the piezocomposite transducer within the interested frequency range was calculated by using the harmonic analysis in ANSYS, which is used to study the mode coupling effect.

3. RESULTS AND DISCUSSION

First of all, five 2-2 piezocomposite transducers, each transducer is composed of PZT-5H piezoceramic and one type polymer from the list on Table I, have been studied by using ANSYS. In order to study the mode coupling effect, we have designed the transducers with coarse pitch size so that the first lateral resonance frequency is very close to the fundamental thickness resonance frequency. The calculated electrical admittance curves of these transducers are shown in Fig. 2(a)-(e). The strong mode coupling effect can be easily seen from the peak overlapping on all of these curves.

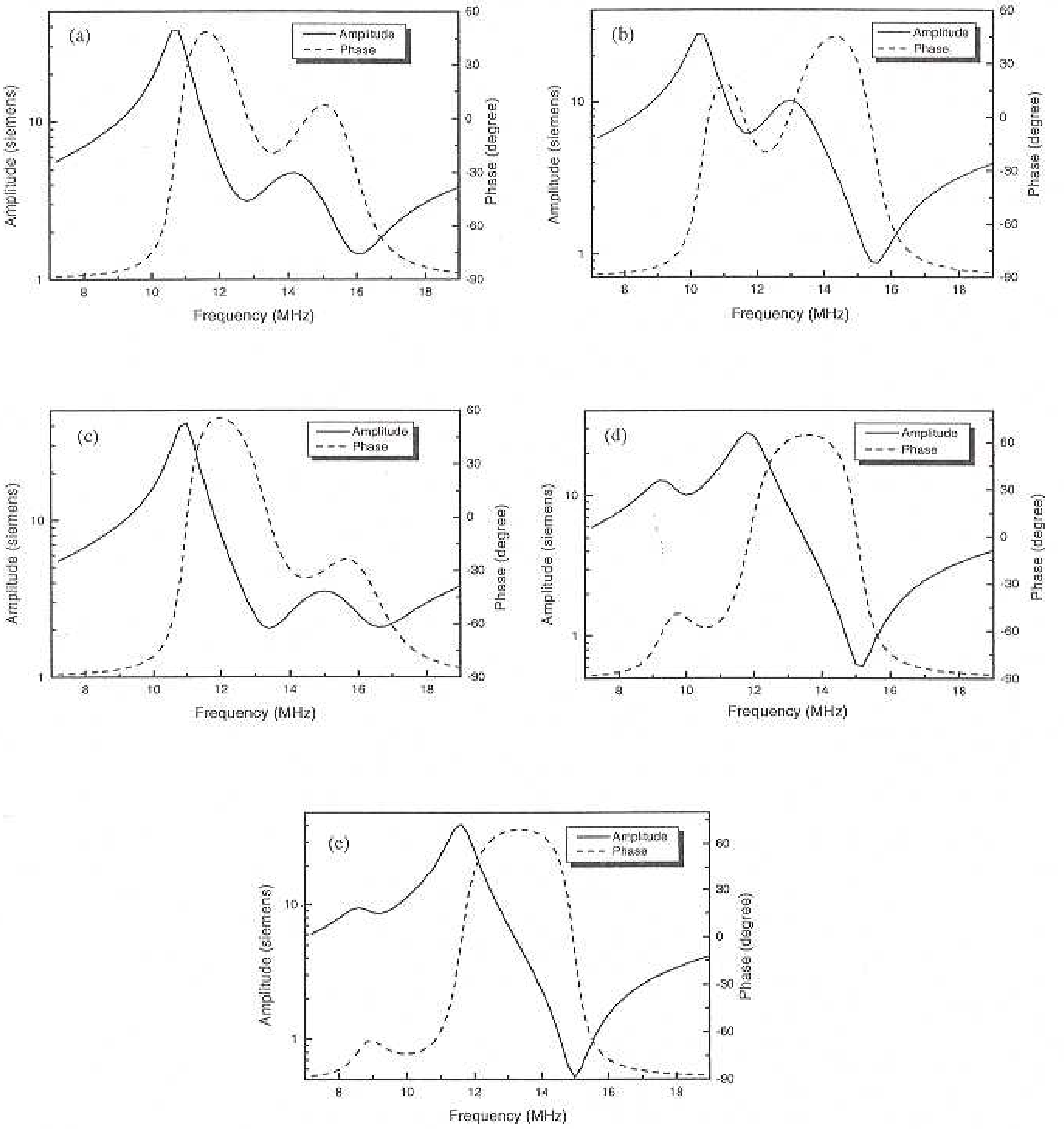

Figure 2: The electrical admittance curves of the piezocomposite transducers composed of (a) PZT-5H and polymer 1, (b) PZT-5H and polymer 2, (c) PZT-5H and polymer 3, (d) PZT-5H and polymer 4, and (e) PZT-5H and polymer 5.

Then, a new piezocomposite transducer, as shown in Fig. 3, was designed. It has the same geometric parameter as the transducer in Fig.1 (b), but all five polymers are used and they are distributed evenly in the transducer. Figure 4 shows the electrical admittance curve of the new transducer calculated by using ANSYS. It is apparent that admittance peak corresponding to the first lateral mode is practically suppressed. This may be understood as the following: the period in the lateral dimension is increase 5 times, which will suppress the lateral resonance to much lower frequency, so that the it will be away from the thickness resonance.

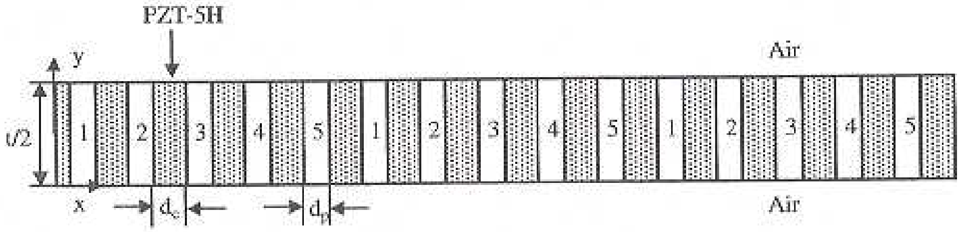

Figure 3: 2-D model for the new 2-2 piezocomposite combining PZT-5H and five different polymers. Here the numbers 1, 2, ..5 represent the polymers in Table 1.

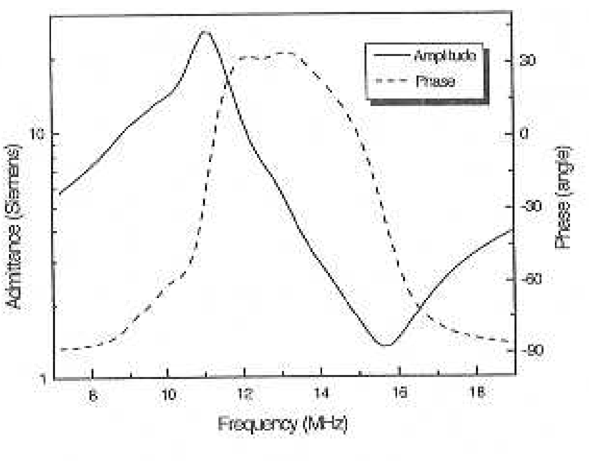

Figure 4: The electrical admittance curve for the new piezocomposite transducer composed of PZT-5H and five different polymers

We can also find, compared to the electrical admittance curves in Fig. 2, the antiresonance frequency of the thickness mode in the new transducer is shifted upward, while the resonance frequency lies almost at the average frequency position of the transducers in Fig. 2. According to IEEE Standard [12], k_t can be obtained by measuring the antiresonance and resonance frequencies (f_a, f_r) with the equation

$$k_t^2 = \frac{\pi}{2}\frac{f_r}{f_a}\tan\left(\frac{\pi}{2}\frac{f_a - f_r}{f_a}\right) \tag{1}$$

The values of k_t in Fig. 2 are 0.59, 0.51, 0.62, 0.65, and 0.66, respectively, and k_t in Fig. 4 is 0.74. This means that the electromechanical coupling coefficient for the thickness mode k_t is increased in the new piezocomposite transducer when more than one polymer materials are used. Since k_t represents the energy transformation between acoustic vibration and electric signal, the increased k_t shows the energy loss to the lateral mode is recovered back to the thickness mode.

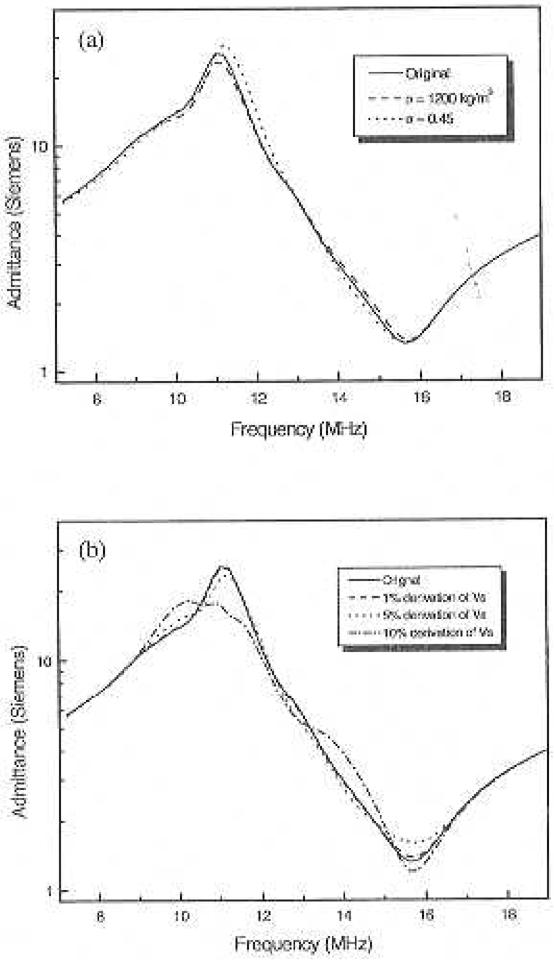

Figure 5: The electrical admittance curves of the new transducer with some changes in the properties of the polymers

The effect of material properties of polymer on the electrical admittance curve of the new composite is investigated. First, the densities of all polymers were set to 1200 kg/m^3. The corresponding electrical admittance curve is shown in Fig. 5(a) as the dashed line, while the solid line is for the original transducer using the densities given in Table I. We can easily find that the two curves are almost the same. Next, the effect of the longitudinal velocity was investigated. In order to keep the Poisson ratio σ in the reasonable range, we set its value of all polymers to 0.45, instead of setting the longitudinal velocity to an arbitrary value. Then the longitudinal velocity v_L can be obtained from the equation

$$v_L = \sqrt{(G + \frac{G}{0.5-\sigma})/\rho} \tag{2}$$

Where G is the shear modulus and ρ is the density. The dotted line in Fig. 5(a) shows the calculated electrical admittance curve, which is also almost the same as the original curve. It is known that the shear velocity is closely related to the lateral resonance frequency, so we performed more detailed study on the effect of shear velocity. Fig. 5(b) shows the electrical admittance curves corresponding to the shear velocities with 1%, 5%, and 10% derivation from the original values. The mode coupling effect can be observed again when the shear velocity derivates 10% from the original value. Since the shear velocity is the only material parameter needed to take care, this makes the selection of the polymer for reducing the mode coupling effect much easier.

4. SUMMARY AND CONCLUSIONS

In this paper, a new 2-2 piezocomposite transducer design is analyzed using ANSYS, which is made of PZT-5H plates and five different types of polymers. The electrical admittance of the transducer was calculated and the results show that the lateral resonance mode is practically suppressed in the new composite transducer. While the mode coupling effect is very strong when only one type of polymer is used. The electromechanical coupling coefficient for the thickness mode is increased in the new transducer to almost the k_{33} value of PZT-5H. The effect of density, longitudinal velocity and shear velocity of polymer on the electrical admittance were investigated by using ANSYS simulation and it was found that the lateral mode appeared again when the shear velocity has 10% derivation from the original value, while the density and longitudinal velocity of the polymer have little effect on the reduction of the mode coupling.

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