UNIDIMENSIONAL MODELING AND CONSTRUCTION OF A 1-3 PIEZOELECTRIC COMPOSITE TRANSDUCER

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Abstract. *In many applications, such as medical imaging and nondestructive testing, broadband ultrasonic transducers capable of producing short pulses are required. Combining a piezoelectric element and a passive polymer to form a piezoelectric composite allows the development of transducers with high bandwidth and sensitivity, and low radial coupling. This work presents the modeling and construction of an ultrasonic transducer using a 1-3 piezoelectric composite. A simple physical model is used to calculate the effective properties of the composite. This model can be applied when the lateral spatial scale of the composite is sufficiently small so that the composite can be treated as an effective homogeneous medium. The effective properties are used in a distributed matrix model to calculate the electrical impedance of the composite. It is used the dice-and-fill technique to construct a 1-3 lead zirconate titanate(PZT)/epoxy 800 kHz, 20 mm diameter composite. The simulated results of the electrical impedance are compared with the experimental results measured by an impedance analyzer equipment. Finally, the ultrasonic transducer is constructed using the piezoelectric composite. The impulse response of the transducer is measured and compared with the theoretically obtained using the distributed matrix model. The experimental results show excellent agreement with the simulated ones.*

Keywords: ultrasonic transducer, piezoelectric, composite

1. Introduction

Ultrasonic piezoelectric transducers are widely used in medical applications, materials characterization and nondestructive testing. These applications require ultrasonic transducers with high bandwidth and sensitivity. The bandwidth of a transducer is inversely related to the pulse duration and hence to the number of cycles in each pulse. The sensitivity is related to the output acoustic pressure at a given input voltage and vice versa. To increase the bandwidth, and, consequently to reduce the ringing of the transducer, is commonly used a highly damped backing with an acoustic impedance similar to that of the piezoelectric element. Unfortunately, the use of a highly damped backing reduce the sensitivity of the transducer. Another problem that arises in the tradicional transducer design is the radial vibration modes of the piezoelectric element. These radial modes are responsible for the non-uniform velocity distribution on transducer face. A transducer with high bandwidth and sensitivity, and low radial coupling can be made using a piezoelectric composite material. A piezoelectric composite material is basically the combination of piezoelectric ceramic and polymer. The bandwidth of an ultrasonic transducer depends on the difference between the specific acoustic impedance of the piezoelectric element and the propagation media. To achieve a high bandwidth, the piezoelectric element must have an acoustic impedance close to that of the propagation media. In this work, acrylic is used as the propagation media. The specific acoustic of acrylic is 3.24 MRayls, while the impedance of a piezoelectric element is approximately 35 MRayls. Consequently, when an ultrasonic wave that propagates in the piezoelectric media reaches the interface with acrylic, most of the energy is reflected, and consequently the bandwidth of the transducer is reduced. The sensitivity of an ultrasonic transducer is determined by the electromechanical coupling constant and the internal losses of the transducer. In a piezoelectric composite the acoustic impedance is reduced, and the electromechanical coupling constant is increased.

In this work, the effective properties of a 1-3 piezoelectric composite is calculated using a simple physical model (Smith and Auld, 1991). The effective properties are used in a distributed matrix model (Lamberti *et al.*, 1987 and Lamberti *et al.*, 1997) to calculate the electrical impedance of the composite and the impulse response of an ultrasonic transducer. The theoretical electrical impedance and the impulse response are compared with those obtained experimentally.

2. Unidimensional modeling of 1-3 piezoelectric composite transducers

A piezoelectric composite material with 1-3 connectivity consist of a periodic array of small, finely spaced piezoelectric posts extending through the thickness of the resonator and surrounded on the sides by a polymer (Papadakis *et al.*, 1999). A schematic representation of a 1-3 piezoelectric composite material is presented in Fig. 1.
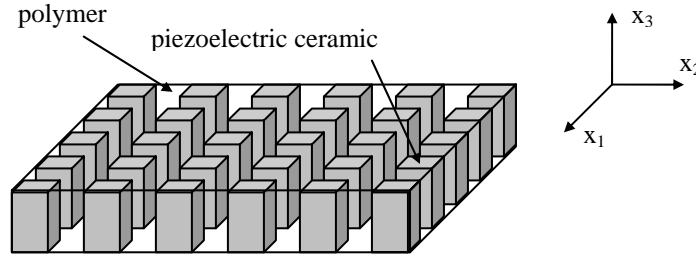

Figure 1. Schematic representation of a 1-3 piezoelectric composite material.

The behavior of a piezoelectric material is described by its constitutive equations (Kino, 1987). In this work, it is considered that the lateral dimensions of the piezoelectric material is much larger than its thickness. In this case, we can assume that the lateral displacements of the piezoelectric plate are small, then the unidimensional constitutive equations can be used to model the thickness behavior of the piezoelectric material. To describe the thickness behavior of a piezoelectric composite material, it is assumed that the lateral dimensions of each unit cell is small compared with its thickness. In this case the composite is modeled as homogeneous medium with a set of effective material properties. The homogenized constitutive equations of a 1-3 piezoelectric composite plate is given by (Smith and Auld, 1991):

$$\overline{T}_3 = \overline{c}_{33}^E \overline{S}_3 - \overline{e}_{33} \overline{E}_3 \tag{1}$$

$$\overline{D}_3 = \overline{e}_{33} \overline{S}_3 + \overline{\varepsilon}_{33}^S \overline{E}_3 \tag{2}$$

where $\overline{T}_3$ is the longitudinal stress, $\overline{S}_3$ is the longitudinal strain, $\overline{E}_3$ is the electric field and $\overline{D}_3$ is the electric displacement. The subscript 3 indicates the component direction of these properties, and the bar above the variables indicates the average value. The notation used in Eq. (1) and (2) is according to the IEEE Standard (IEEE, 1996). The variables $\overline{c}_{33}^E$, $\overline{e}_{33}$ and $\overline{\varepsilon}_{33}^S$ are, respectivelly, the homogenized elastic stiffness constant at constant electric field, the homogenized piezoelectric constant, and the homogenized permittivity at constant strain of the 1-3 piezoelectric composite. These homogenized properties are given by (Smith and Auld, 1991):

$$\overline{c}_{33}^E = \delta \left[c_{33}^E - \frac{2\tilde{\delta}\left(c_{13}^E - c_{12}\right)^2}{\delta\left(c_{11} + c_{12}\right) + \tilde{\delta}\left(c_{11}^E + c_{12}^E\right)} \right] + \tilde{\delta} c_{11} \tag{3}$$

$$\overline{e}_{33} = \delta \left[e_{33} - \frac{2\tilde{\delta} e_{31}\left(c_{13}^E - c_{12}\right)}{\delta\left(c_{11} + c_{12}\right) + \tilde{\delta}\left(c_{11}^E + c_{12}^E\right)} \right] \tag{4}$$

$$\overline{\varepsilon}_{33}^S = \delta \left[\varepsilon_{33}^S - \frac{2\tilde{\delta}\left(e_{31}\right)^2}{\delta\left(c_{11} + c_{12}\right) + \tilde{\delta}\left(c_{11}^E + c_{12}^E\right)} \right] + \tilde{\delta} \varepsilon_{11} \tag{5}$$

where δ is the volume fraction of piezoelectric ceramic and $\tilde{\delta}$ corresponds to the volume fraction of polymer. In Eq. (3), (4) and (5), the elastic and dielectric constants of the ceramic phase are easily distinguished from those of the polymer phase by the superscripts *E* and *S*.

To calculate the electric impedance of a 1-3 piezoelectric composite and the impulse response of an ultrasonic transducer is used the distributed matrix model (Lamberti *et al.*, 1987 and Lamberti *et al.*, 1997). In this model the piezoelectric plate is modeled as a three-port system with one electric and two mechanical ports. Basically, the

transducer consists of a layer of a 1-3 piezoelectric composite material and a backing layer of Tungsten/epoxy composite. This transducer is modeled according to Fig. 2.
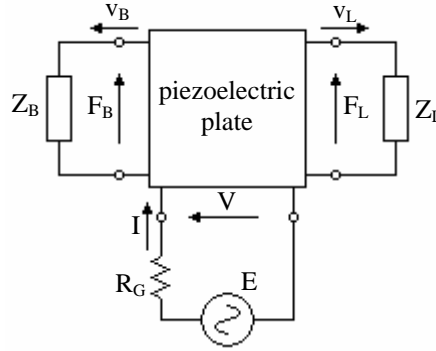

Figure 2. Transducer modelling as a three-port system.

In Figure 2, V is the voltage across the piezoelectric ceramic, I is the electric current, R_G is the internal impedance of the voltage generator E, Z is the specific acoustic impedance, F is the mechanical force and v is the velocity on the interface. The subscript B corresponds to the backing of the transducer, while the subscript L corresponds to the propagation media. The transducer backing has a high attenuation and therefore can be modeled as a semi-infinite medium. The transducer shown in Fig. 2, whose rear surface is terminated with the backing impedance Z_B, is described by the following relation (Lamberti $et\ al.$, 1997):

$$\begin{pmatrix} V \\ I \end{pmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{pmatrix} F_L \\ v_L \end{pmatrix} \tag{6}$$

where:

$$A_{11} = \frac{\left(\dfrac{l}{A\bar{e}_{33}}\right)\left(\cos(kl) + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)\right) - \dfrac{\bar{e}_{33}}{A\bar{Z}_C\omega\bar{\varepsilon}_{33}^S}\sin(kl)}{\cos(kl) - 1 + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)} \tag{7}$$

$$A_{12} = \frac{\left(\dfrac{j\bar{e}_{33}}{\omega\bar{\varepsilon}_{33}^S}\right)\left(2\cos(kl) - 2 + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)\right) + \left(\dfrac{\bar{Z}_C l}{\bar{e}_{33}}\right)\left(\dfrac{Z_B}{\bar{Z}_C}\cos(kl) + j\sin(kl)\right)}{\cos(kl) - 1 + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)} \tag{8}$$

$$A_{21} = \frac{\left(\dfrac{j\omega\bar{\varepsilon}_{33}^S}{\bar{e}_{33}}\right)\left(\cos(kl) + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)\right)}{\cos(kl) - 1 + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)} \tag{9}$$

$$A_{22} = \frac{\left(\dfrac{j\omega\bar{\varepsilon}_{33}^S}{\bar{e}_{33}}\right)\left(AZ_B\cos(kl) + jA\bar{Z}_C\sin(kl)\right)}{\cos(kl) - 1 + \dfrac{jZ_B}{\bar{Z}_C}\sin(kl)} \tag{10}$$

where l is the thickness of the piezoelectric composite material, k is wavenumber, ω is the angular frequency, A is the area of the ceramic surface, and $\overline{Z}_C$ is the effective acoustic impedance of the composite material given by:

$$\overline{Z}_C = \sqrt{\left(\overline{c}_{33}^{\,E} + \frac{\left(\overline{e}_{33}\right)^2}{\overline{\varepsilon}_{33}^{\,S}} \right) \overline{\rho}} \tag{11}$$

where $\overline{\rho}$ is the effective density of the composite and is calculated through the mixture rule:

$$\overline{\rho} = \delta\rho^c + \tilde{\delta}\rho^p \tag{12}$$

where ρ^c is the density of the piezoelectric material and ρ^p is the density of the polymer. To calculate the electric impedance of the piezoelectric composite material, it is assumed that the specific acoustic impedance of the rear and the front surface of the ceramic are zero. In this case, $Z_B = Z_L = F_2/Av_2 = 0$, and the electric impedance Z^e is given by:

$$Z^e = \left(\frac{l}{j\omega A \overline{\varepsilon}_{33}^{\,S}} \right) \left[1 - \left(1 - \frac{\overline{c}_{33}^{\,E}}{\overline{c}_{33}^{\,E} + \frac{\left(\overline{e}_{33}\right)^2}{\overline{\varepsilon}_{33}^{\,S}}} \right) \frac{\tan\left(\dfrac{kl}{2}\right)}{\left(\dfrac{kl}{2}\right)} \right] \tag{13}$$

The transfer function *TF* of the transducer operating in the pulse-echo mode is given by (Lamberti *et al.*, 1987):

$$TF = \frac{2R_G A Z_L}{\left[A_{11} A Z_L + A_{12} + R_G \left(A_{21} A Z_L + A_{22} \right) \right]^2} \tag{14}$$

The echo impulse response is obtained through the inverse Fourier transform of the transfer function *TF*.

3. Transducer fabrication and characterization

The first step in the design of the ultrasonic transducer is the fabrication of the 1-3 piezoelectric composite material. To fabricate this material, the dice-and-fill technique was used (Smith, 1989). A ceramic disk of lead zirconate titanate (PZT-5A) with a diameter of 20.0 mm and a thickness of 2.0 mm was cut in one direction using a dicing machine (Buehler® Isomet 4000) with a 150 μm thick blade. The unit cell of the composite is shown in Fig. 3. The grooves of the ceramic were filled with epoxy (GY 279 with hardner HY 951 in a mixing ratio of 10:1). The epoxy was supplied by Huntsman®. To avoid air bubbles, the epoxy was degassed in a vacuum chamber for approximately 5 minutes. The ceramic with polymer was put in an oven for 2 hours at a temperature of 50 °C. After that, the composite was cured at room temperature for 24 hours. A second set of cuts perpendicular to the first direction was made using the same procedure. It was used a sandpaper to remove the excess of polymer of the piezoelectric composite material. This procedure reduced the thickness of the composite to 1.85 mm. Figure 4 shows a photograph of the piezoelectric composite material. After remove the excess of polymer, the electrodes of the composite were made using a conductive silver ink.
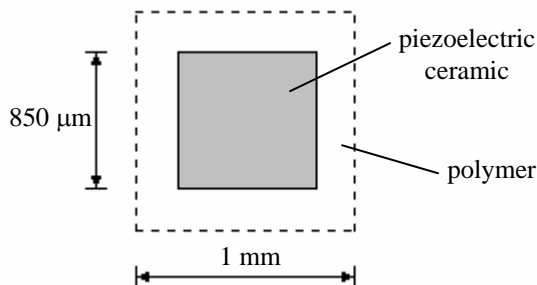

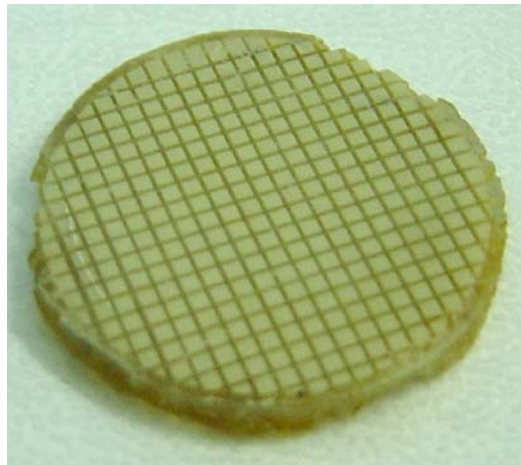Figure 3. Unit cell of the constructed piezoelectric composite.

Figure 4. Photograph of the 1-3 piezoelectric composite material

It was measured the electric impedance of the piezoelectric composite using an impedance analyzer (HP4194A) before constructing the ultrasonic transducer using this composite material. A schematic representation of the ultrasonic transducer is shown in Fig. 5. The backing of the transducer was made using a epoxy/Tungsten composite with a volume fraction of Tungsten of 20 %. To construct the backing was used Araldite Professional Adhesive and Tungsten (Aldrich Co.) with particle size of 12 μm. This backing material has a specific acoustic impedance of 6 MRayls. No matching layer was used in the construction of the transducer prototype.
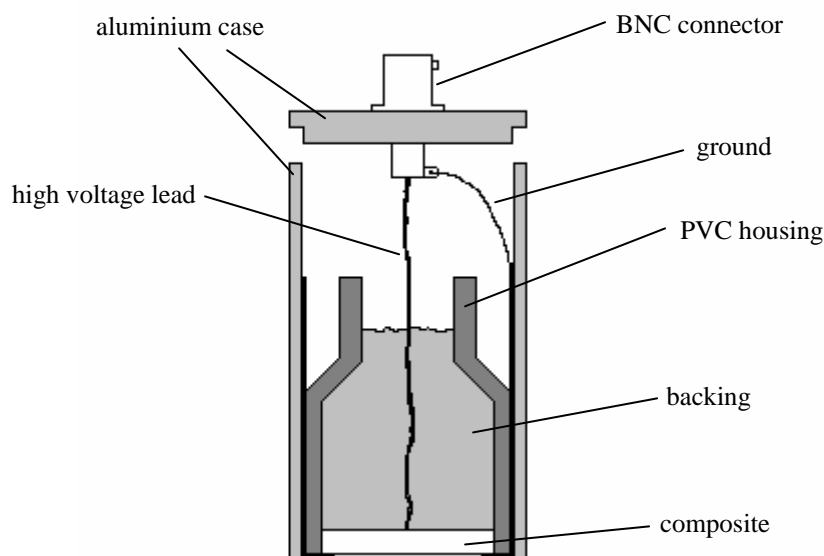

Figure 5. Schematic representation of the ultrasonic transducer

The echo impulsive response of the transducer was measured by coupling the ultrasonic transducer to an acrylic block with a thickness of 42 mm. This acrylic block has a specific acoustic impedance of 3.24 MRayls. The experimental result was obtained using a pulse/receiver (Panametrics 5072PR) operating in pulse-echo mode. The echo signal was acquired by a computer with a data acquision board (Signatec PDA12 – 125 MHz).

4. Results

The properties of the polymer and the PZT-5A are presented in table 1. In this table, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the permittivity of free space. The effective properties of the 1-3 piezoelectric composite shown in Fig 4 were calculated using Eq. (3), (4), (5) and (12). As shown in Fig. 3, this composite has a volume fraction of ceramic δ of 72.25 %. The electric permittivity ε_{11} of the polymer is very small compared to that of the piezoelectric ceramic, and therefore can be

neglected in the calculation of the effective electric permittivity $\bar{\varepsilon}_{33}^{S}$. The effective properties of the piezoelectric composite material are shown in table 2. According to Eq. (11), the specific acoustic impedance of PZT-5A is 33.5 MRayls. In the piezoelectric composite material, the acoustic impedance is reduced to 22.4 MRayls. This decrease in the acoustic impedance is responsible for the increase of the bandwidth of the ultrasonic transducer.

Table 1. Material properties.

Piezoelectric ceramic	PZT-5A
c_{11}^{E} $(10^{10}$ N/m^2)	12.1
c_{12}^{E} $(10^{10}$ N/m^2)	7.54
c_{13}^{E} $(10^{10}$ N/m^2)	7.52
c_{33}^{E} $(10^{10}$ N/m^2)	11.1
e_{31} (C/m^2)	-5.4
e_{33} (C/m^2)	15.8
$\varepsilon_{33}^{S}/\varepsilon_0$	830
ρ^{c} (Kg/m^3)	7750
Polymer	GY 279 / HY 951
c_{11} $(10^{10}$ N/m^2)	0.704
c_{12} $(10^{10}$ N/m^2)	0.422
ρ^{p} (Kg/m^3)	1126.8

Table 2. Effective material properties of the 1-3 piezoelectric composite material.

	Piezoelectric composite
$\bar{c}_{33}^{E}$ $(10^{10}$ N/m^2)	4.99
$\bar{e}_{33}$ (C/m^2)	13.87
$\bar{\varepsilon}_{33}^{S}/\varepsilon_0$	620
$\bar{\rho}$ (Kg/m^3)	5912

The electric impedance of the composite was calculated using Eq. (13). Figure 6 shows the comparison between the experimental electric impedance of a 20.0 mm diameter, 2.0 mm thickness piezoelectric ceramic disk, the impedance of the composite material with the same diameter and thickness of 1.85 mm, and its theoretical electrical impedance. In the ceramic impedance curve, one can see that there are many peaks associated to the radial vibration modes of the ceramic disk. These peaks reduce in intensity as the frequency increases but they interfere with the thickness mode, causing a non-uniform velocity distribution on the transducer face. In a piezoelectric composite material, the peridocity is responsible for the reduction of the radial modes of the disk, generating a smoother impedance curve. The theoretical impedance curve shows excellent agreement with the experimental curve. The theoretical curve was obtained by an unidimensional model, and therefore, cannot predict the existence of radial modes. This limitation is not particularly important in the modeling of a piezoelectric composite, because the radial modes are strongly reduced. The thickness of the composite material is smaller than that of the piezoelectric ceramic. In this case, the ressonance frequency of the composite should be higher than that of the piezoceramic, however, in a composite, the longitudinal velocity is reduced, and consequently, the ressonance frequency is reduced too.

Figure 7(a) shows the comparasion between the theoretical and experimental echo impulse responsed of the ultrasonic transducer coupled to an acrylic block with a thickness of 42 mm. Figure 7(b) shows the comparison between the theoretical and experimental transfer functions of the transducer operating in the pulse-echo mode. The experimental impulse response was obtained by a data acquision board, while the theoretical one was obtained by calculating the inverse Fourier transform of the transfer function shown in Fig. 7(b). The experimental transfer function was obtained through the Fourier transform of the experimental echo signal. Figure 7(b) shows only one peak in the transfer function, however, theoretical transfer function calculated using the distributed matrix model has many peaks. In the theoretical model, both attenuations of the composite material and acrylic were not considered. In the experiment, the higher vibrational modes die out, resulting only in the first axial mode. Therefore, only the first peak of the transfer function was used to calculate the theoretical echo impulse response of the transducer.
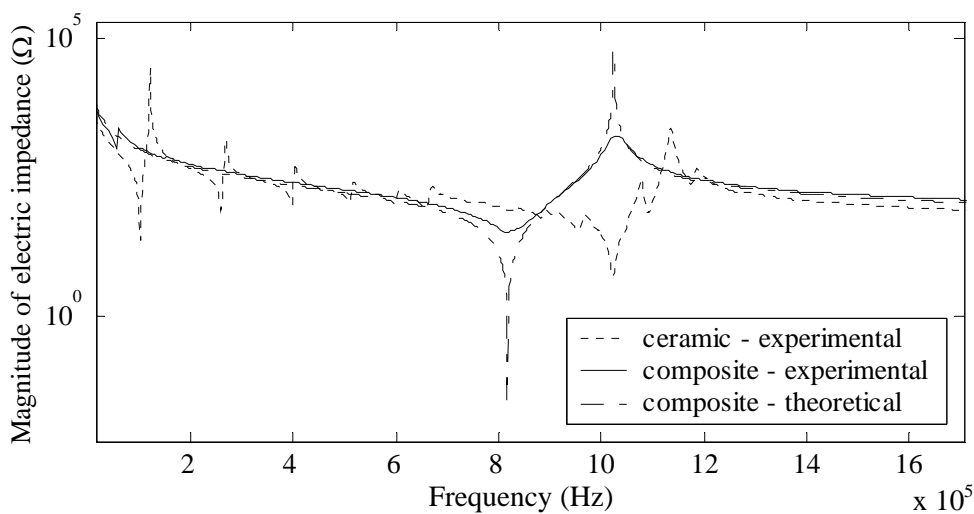
Figure 6. Comparasion between the electric impedance of the piezoelectric ceramic disk and the piezoelectric composite material.

Figures 6 and 7 show that a piezoelectric composite transducer can be modeled by calculating the effective properties of the composite, and using these results in the matrix model to calculate the electric impedance and the impulse response of the transducer.
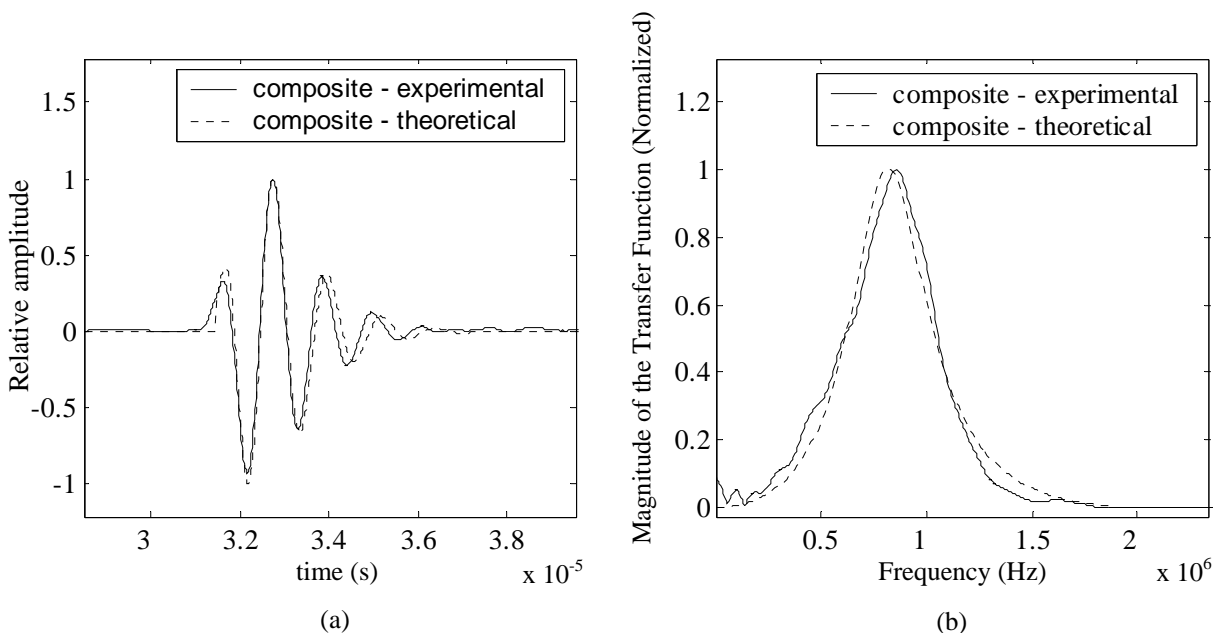

Figure 7. Comparison between theoretical and experimental results. (a). Echo impulse response. (b). Transfer function

5. Conclusion

A simple physical model was used to calculate the effective properties of a 1-3 piezoelectric composite material. These properties were used in a distributed matrix model to obtain the electric impedance of the composite and the echo impulse response of the ultrasonic transducer frabricated with this composite. To validate the theoretical results, a piezoelectric composite material was fabricated using the dice-and-fill technique. This composite was used in the construction of an ultrasonic transducer. The electric impedace of the composite was obtained experimentally through an impedance analyzer and the echo impulse response of the transducer was measured. Theoretical and experimental results show excellent agreement, showing that the ultrasonic transducer can be modeled by the distributed matrix model.

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