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Characteristics of piezoceramic and 3–3 piezocomposite hydrophones evaluated by finite element modelling

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Abstract

The transducer characteristics of hydrophones manufactured from porous 3–3 piezocomposites are compared with dense piezoceramic disc hydrophones using finite element modelling. Due to the complex porous structure of the 3–3 piezocomposites, a real-size 3-dimensional model was developed while a 2-dimensional axisymmetric model was constructed for the simple dense disc hydrophone. The electrical impedance and receiving sensitivity of the hydrophones in water were evaluated in the frequency range 10–100 kHz. The model results were compared with the experimental results. The sharp resonance peaks observed for the dense piezoceramic hydrophone were broadened to a large extent for porous piezocomposite hydrophones due to weaker coupling of the structure. The receiving sensitivity of piezocomposite hydrophones is found to be constant over the frequency range studied. The flat frequency response suggests that the 3–3 piezocomposites are useful for wide-band hydrophone applications.

Keywords: Piezoceramics; Piezocomposites; Porous structures; Modelling; Hydrophones; Underwater acoustics

1. Introduction

Piezocomposite materials have drawn considerable attention in recent years due to their potential application in ultrasonic and underwater transducers [1,2]. Piezocomposites have potential for higher electromechanical coupling coefficients, lower acoustic impedance, higher piezoelectric voltage constants and higher hydrostatic coefficients compared to conventional dense materials. In addition, by changing the ceramic/polymer volume fractions, the material parameters of a composite transducer can be altered to meet specific requirements for different applications [3]. Piezocomposites exist in various connectivities [4], with 0–3 [5], 1–3 [6], 2–2 [7] and 3–3 [8] being the most common for transducer applications.

The 1–3 piezocomposite system has been studied extensively and various modelling and experimental studies have been reported in the literature [9,10]. Although, 1–3 composites are highly useful

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for transducer applications, their production can be relatively expensive [6]. The 3–3 piezocomposites are a possible alternative, with comparable material properties and a relatively simple method of synthesis [8,11]. Experimental studies on 3–3 piezoelectric structures indicate that they have a higher hydrostatic figure-of-merit [12–14] compared to dense PZT hydrophones of similar design [8,15,16]. In certain cases, depending on the method of synthesis, 3–3 piezocomposites are found to also exhibit a degree of 0–3 connectivity for intermediate ceramic volume fractions (i.e., areas of isolated porosity). The material properties of these composites with mixed connectivities (0–3 and 3–3) have been evaluated using theoretical models [17–19]. Theoretical models have also been proposed to study the material properties of pure 3–3 piezocomposites [20], including optimisation techniques and homogenisation methods which have been used to find effective properties of piezocomposites [21–23].

While these models exist, the transducer characteristics of these materials have not been studied extensively and finite element modelling (FEM) offers a simple and effective tool. FEM studies on 1–3 piezocomposite transducers have been reported [20], where a single unit cell of the composite has been modelled (such as a single ceramic pillar). The assumption is that it represents the entire piezocomposite structure, since the structure is periodic. Although these models can give material parameters such as piezoelectric d and g coefficients, to considerable accuracy, they are inadequate to evaluate the lateral-mode resonance of a transducer of finite dimensions. Hence, full and real-size 3-dimensional FEM studies are necessary to evaluate the device characteristics of piezocomposite hydrophones. This is even more important for porous structures, such as the 3–3 piezocomposites, since the microstructure can be less periodic with percolated and non-percolated porosity.

In this work we have developed finite element models of dense PZT and porous 3–3 PZT hydrophones which allow the impedance and receiving sensitivity of the hydrophone as a factor of frequency to be calculated. The model results are validated by experimental studies and are presented in this paper.

2. Finite element model

The hydrophones were modelled by finite element analysis using the ANSYS 5.7 package to calculate the free-field voltage sensitivity and electrical impedance as a function of frequency. An axisymmetric model was used for the dense PZT hydrophones and a full 3-dimensional model was developed for the porous PZT hydrophones due to their more complex and less symmetrical structure. The thickness and diameter of the discs were 4 and 40 mm, respectively.

2.1. Hydrophones using dense PZT discs

Owing to the rotational symmetry of the dense PZT disc hydrophone it was modelled using 2-dimensional axisymmetric harmonic analysis. The model and the finite element mesh are shown in Fig. 1. Axisymmetric coupled-field elements were used for the active material. The model includes the PZT element, a copper film electrode, a polyurethane encapsulant and the surrounding fluid (water) medium. A small section of the fluid medium, which was in contact with the structure, was assigned with acoustic elements capable of handling fluid–structure interactions. In all other elements in the fluid, the displacement degree of freedom (d.o.f) has been suppressed. This reduces the memory requirement and the computing time. The outer boundary of the fluid mesh contains infinite acoustic damping elements. This ensures that the acoustic waves are not reflected at the boundary, simulating the infinite extent of the fluid medium. In order to obtain good numerical accuracy, the size of the mesh has been kept very small compared to the dominant wavelength of the sound waves in PZT and water.

The voltage d.o.f for the nodes lying on the top electrode surface of the PZT disc were coupled and the bottom electrode surface nodes were also coupled. The pressure d.o.f for the nodes on all outer surfaces are coupled, which removes diffraction effects at high frequency. Two different boundary conditions are applied in the present studies. For electrical impedance measurement, the outer surfaces of the transducer are stress-free and a known potential difference (V) was applied between the

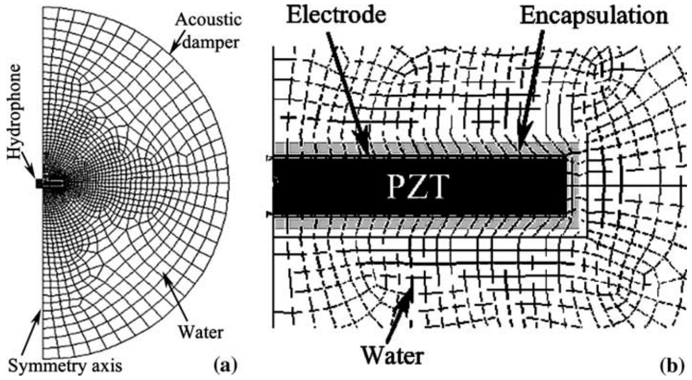

Fig. 1. Axisymmetric finite element model of a dense PZT hydrophone (a) and details of the model (b). Acoustic damping elements are placed at a distance of 300 mm from the acoustic centre.

electrodes. The impedance was calculated from the charge collected at the electrodes. In the case of the receiving sensitivity measurement, an acoustic wave of known pressure P (located on the transducer centre axis) excites the surfaces of the transducer from the fluid medium and the voltage generated at the electrodes is determined. In order to achieve far-field conditions, the point source of sound waves is placed at a distance of 300 mm, which is sufficiently away from the hydrophone, compared to the appropriate wavelength under consideration [23]. Harmonic analysis with no damping was performed in the frequency range 10–100 kHz. The properties of the ceramic, electrode and encapsulation are in Table 1.

Table 1
Material parameters used in the model calculations

I. PZT [26]
(a) Elastic coefficients (10^{10} N m^{-2})
c^E_{11}: 12.6, C^E_{12}: 8.0, c^E_{13}: 8.4, c^E_{33}: 11.7, C^E_{44}: 2.3, c^E_{66}: 2.4
(b) Piezoelectric coefficients (C m^{-2})
e_{31}: −6.5, e_{33}: 23.3, e_{15}: 17.0
(c) Density (kg m^{-3}): 7500
(d) Dielectric constant $(\varepsilon^S_{33}/\varepsilon_0) = 1470$; $(\varepsilon^S_{11}/\varepsilon_0) = 1700$
II. Electrode (copper)
(a) Density (kg m^{-3}): 8250
(b) Young' s modulus (GPa): 110
(c) Poisson's ratio: 0.34
III. Encapsulation (polyurethane)
(a) Density (kg m^{-3}): 940
(b) Young's modulus (MPa): 2.0
(c) Poisson's ratio: 0.45
IV. Fluid (water)
(a) Density (kg m^{-3}): 1000
(b) Velocity of sound (m s^{-1}): 1460

2.2. Hydrophones from porous PZT discs

The porous PZT has an intricate structure that cannot be analysed using a 2-dimensional model, therefore a 3-dimensional model has been developed. In modelling the 3–3 piezocomposites, it has been a general practice to model only a unit cell of the structure, assuming that it is representative of the entire piezocomposite structure. However in certain cases, the results of the unit cell model deviate from the actual values, especially in the determination of resonance frequencies [25]. The unit cell model may yield correct resonance frequencies of the thickness-mode vibrations, whereas it fails to yield lateral-mode resonance frequencies if the lateral dimensions of the transducers are finite. Further, it leads to difficulties when a periodic boundary condition in the x–y plane is not applied. In the case of transducers with finite dimensions, the resonance frequency corresponding to the dimension in the z-direction depends also on the dimensions in the x- and y-directions [25]. Hence, we have performed the first finite element analysis of a real-size 3-dimensional model of the porous PZT hydrophone, despite the requirement of large computer memory size and a prolonged computing time involved.

A typical porous 3–3 piezoceramic structure and the representative finite element model used for the ceramic component of the 3–3 piezocomposite

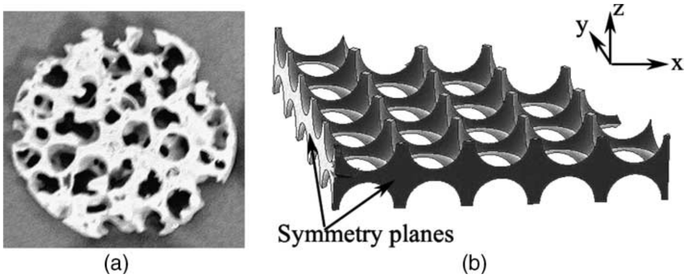

Fig. 2. Structure of a porous PZT disc (diameter of hydrophone is 40 mm) (a) and representative FEM image (b).

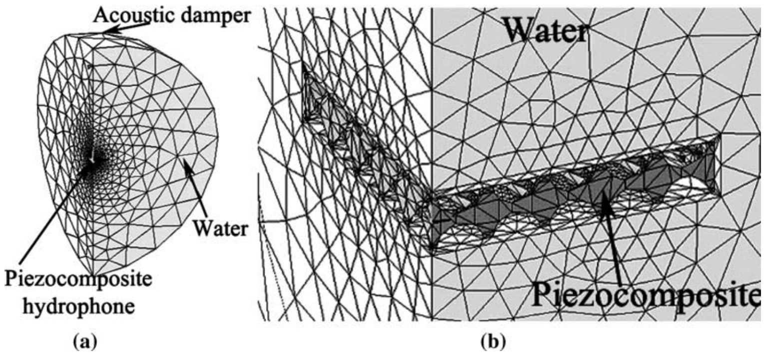

Fig. 3. 3-Dimensional finite element model of a porous PZT hydrophone (a) and details of the model (b).

hydrophone is shown in Fig. 2. The complete model is shown in Fig. 3. One fourth of the geometry is modelled to reduce computational time and the fact that the symmetry planes at the edges of the model are relatively pore free (Fig. 2b), which allows the boundary conditions to be easily applied. The model ceramic volume fraction of the disc (22 vol.%) and the pore size where chosen to be similar to the ceramic component used to construct the experimental hydrophone (Fig. 2). The receiving sensitivity and electrical impedance are evaluated using two successive analyses imposing the same boundary conditions described for the dense hydrophone. The properties of the ceramic phase in the model are those of the dense material (Table 1).

3. Experimental

In order to validate model results, hydrophones were manufactured from dense and 3–3 materials of the same dimensions and geometry. Dense PZT discs were made by compacting the PZT-5H powder and sintering at 1200 ° C for 2 h. Porous PZT structures were made by replicating polyethylene foams with PZT slip, followed by sintering at 1200 °C. These structures can be considered as 3–3 piezocomposites with no polymer based second phase (a PZT–air composite). The ceramic volume fraction of the porous structure was 22% (as in the model). The thickness and diameter of the discs were 4 and 40 mm, respectively (as in the model). The top and bottom surfaces were fully electroded by applying silver paint and the discs were polarised in the thickness direction at an electric field of 2 kV mm^{-1} and at 110 °C. Hydrophones were electroded using copper, assembled and encapsulated with polyurethane rubber to make it waterproof. The free-field voltage sensitivity was measured in a water tank using an impulse technique [24] in the frequency range 10–100 kHz and electrical impedance was measured in air using a Solartron Impedance Analyser (model 1260).

4. Results and discussion

Two types of hydrophones with dense and porous piezoceramic discs (of the same geometry) are considered for the present analysis. In the finite element model, the applied pressure for receiving sensitivity calculation is 1 Pa and the applied potential for impedance calculation is 1 V.

The electrical impedance spectrum for the dense piezoceramic hydrophone in the frequency range 10–100 kHz obtained by FEM and experimental studies are shown in Fig. 4. It can be seen from the figure that there is a good agreement between the model and the experimental results. The resonance peaks observed at around 50 kHz correspond to the fundamental radial mode of vibrations. The impedance data for the porous 3–3 piezocomposite hydrophone obtained by FEM and experimental studies are shown in Fig. 5 showing in both cases that the resonance peaks have completely disappeared, indicating weak coupling of the structure.

Fig. 6 shows the free-field voltage sensitivity in water for the dense PZT hydrophone obtained by the finite element model and experimental studies. The polyurethane rubber (1 mm thick) used for encapsulating the hydrophone has an acoustic impedance close to that of water and hence is assumed to be acoustically transparent. It can be seen from the figure that the sensitivity curve is flat for frequencies below 50 kHz. The radial mode

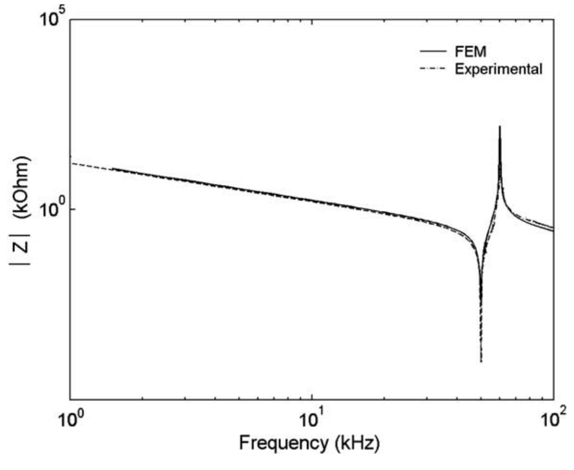

Fig. 4. Electrical impedance spectrum of dense PZT hydrophone.

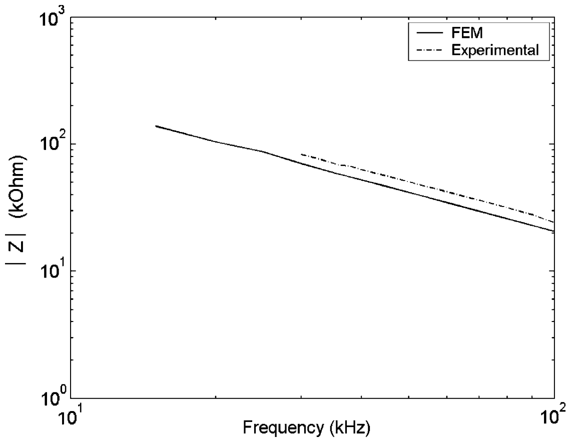

Fig. 5. Electrical impedance spectrum of porous PZT hydrophone.

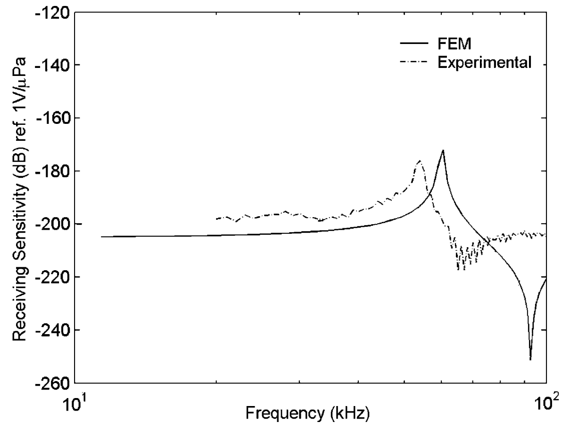

Fig. 6. Receiving sensitivity of dense PZT hydrophone as a function of frequency.

resonance appearing in both the experimental and modelling results is not generally desirable for hydrophone applications, since it limits the operating range of frequency. An ideal hydrophone has a constant receiving sensitivity over a wide frequency range. The resonance peaks can be shifted beyond the operating range by carefully selecting the dimensions of the active elements, but cannot be entirely eliminated in the case of dense PZT transducers.

Fig. 7 shows the receiving sensitivity of the 3–3 piezocomposite hydrophones obtained by FEM and experimental studies, which both show a flat frequency response compared to the dense

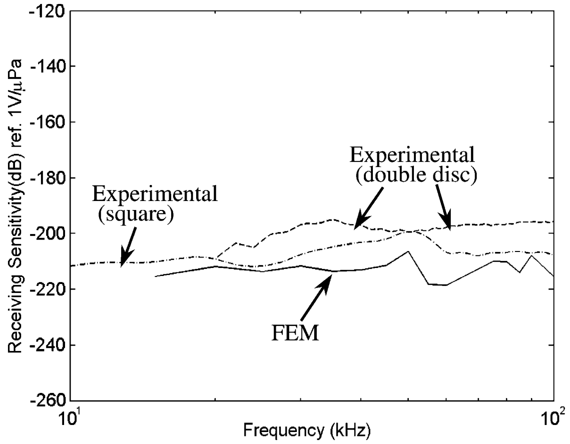

Fig. 7. Receiving sensitivity of porous PZT hydrophone as a function of frequency.

hydrophone. The experimental data is collected for a hydrophone with square shaped active element and a hydrophone assembly with two discs electrically connected in parallel. The sensitivity value for a single element hydrophone is found to be around −210 dB (re. 1 V μPa^{-1}) and is constant in the frequency range studied. The double-disc hydrophone shows sensitivity values above −200 dB. These values are comparable to those reported (−200 to −205 dB) for single-element hydrophones with 75% porosity at 100 kHz measured experimentally [13]. A 3 × 3 array of porous piezoceramic hydrophone, however, shows a higher sensitivity of −193 dB below resonance [8].

It can be seen from the figures that the resonance peaks corresponding to the radial mode vibrations are very prominent for dense PZT (Fig. 6) and have weakened to a large extent for the 3–3 piezocomposite (Fig. 7) which is due to the weak coupling of the porous structure. The sensitivity response is found to be flat over a wide frequency range. This is particularly advantageous as these hydrophones can be used for wide-band applications and offers a possibility of using 3–3 piezocomposites in large-area hydrophone arrays.

5. Conclusions

Axisymmetric and 3-dimensional finite element models have been developed to characterise dense piezoceramic and 3–3 piezocomposite hydrophones, respectively. Since the unit cell model is inadequate to fully evaluate piezocomposite transducers of finite dimensions, a real-size FE model has been used which includes greater detail of the porous structure. The electrical impedance and the receiving sensitivity of the hydrophones in water evaluated by the FE models agree well with the experimental results. This suggests that the transducer design parameters can be optimised using modelling to achieve the required performance. The broadening of resonance peaks of porous piezoceramic hydrophones results in a flat frequency response and indicates that the 3–3 piezocomposite hydrophones can be used for wide-band applications. Further models could be developed to model microstructural effects, such as pore size/volume fraction, pore distribution, percolation of pores etc. to investigate the factors that result in the transition from a highly coupled structure (as with the dense PZT) to the weakly coupled structure (as with the porous structure).

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