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Monolithic class IV type flextensional transducers

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Abstract In this study new type piezoelectric monolithitic low cost underwater and biomedical transducers based on Class IV flextensional transducer design has been introduced. Transducers were produced by using two techniques: fused deposition and extrusion. Besides, finite element analysis (FEA) was used extensively in order to optimize transducer design to achieve broad bandwidth for both transmitting and receiving and engineered vibration modes. Class IV transducers possess resonance frequencies in the range of above 30 kHz to below 150 kHz. Symmetry and design of the transducer, poling patterns, driving and receiving electrode geometries and driving conditions have strong effect on the vibration modes, resonance frequencies.

Keywords Underwater transducer · Biomedical transducer · Monolithic · Class IV flextensional · FEA

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1 Introduction

During the past few years, multimode transducers have been the center of interest in ultrasound technology in order to improve bandwidth which is particularly important in acoustic applications for better resolution [1].

As well the broad bandwidth, one of the most desired properties in advanced acoustic systems is the enhanced directivity. When the size of the transducer is small compared to the acoustic wavelength of interest, the transducer behaves as an acoustic monopole with omnidirectional response. However, this omnidirectional characteristic may create significant problems when a transducer is intended to be used as a projector, or used in an array, that radiates in only one direction. Desired beam patterns are achieved by using some expensive time consuming and cumbersome solution such as with the large buffles or rows of transducers that are spaced and phased carefully [2–5].

Miniaturization is the other important concern in biomedical and underwater transducers. If the radiating dimensions of a projector are less than a wavelength ($ka \ll 1$), a large displacement is required to generate sufficient volume velocity to achieve high source levels. Since the typical strain that can be obtained from a bulk piezoelectric ceramic is limited to 0.1%, amplification mechanisms are required to obtain the necessary large displacements for low frequency projectors.

Moonie and cymbal transducers that are miniaturized version of the traditional flextensional transducers have found many application areas in the recent years [6–10]. Inspiring from these miniaturized versions of flextensional transducers, the study has been started to develop new monolithic piezoelectric ceramic transducer designs, based on flextensional transducer designs, with internal displacement or stress amplification mechanisms that will allow us to

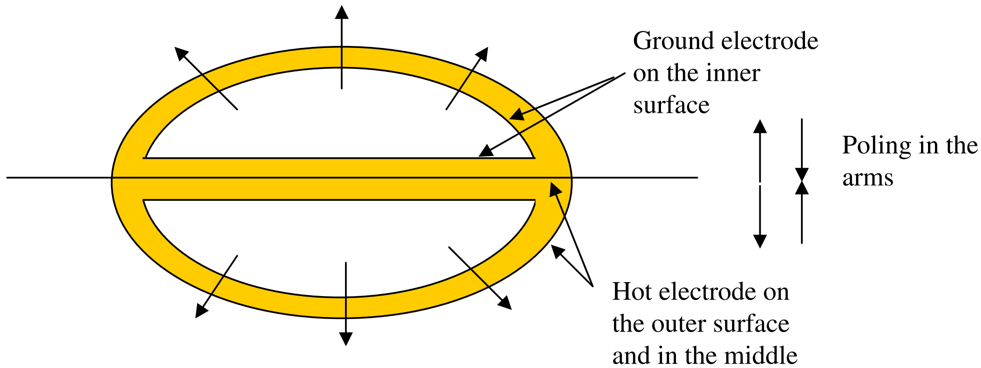

Fig. 1 Cross section of the class IV transducer and possible poling conditions in the shell and in the arm

engineer resonance frequencies, vibration modes and resultant acoustic beam patterns with broadband transmit and receive response. Monolithic structures that combine the functions of two or more narrow band transducers provide many benefits, including additional imaging information at lower cost.

Many flextensional transducers (Class IV, Class VII, outboard class II, class IV hybrid Wagon Wheel, Class I) can benefit from the monolithic design and they are all under study in our research program now. In this paper, Class IV monolithitic transducer is described along with the fabrication and testing procedures. Class IV transducers consist of a metal shell driven by a piezoelectric ceramic stack [11]. They are difficult to manufacture in a reproducible, inexpensive manner. Extruded or injection molded monolithic structures are much cheaper and offer possibility of superior performance. In addition, better performance is expected from monolithic design because they exhibit higher power and larger bandwidth than present day Class IV transducers. It is expected that such monolithic transducers show improved bandwidth and better control of the beam patterns in both send and receive modes.

2 The transducer design

The Class IV transducer is the most well known, understood and widely used of the flextensional transducer configurations. It consists of bar stack held in compression by a thick elliptical convex shell (Fig. 1). The small velocity imparted at the ends of the stack is converted into a larger velocity at the major faces of the ellipse. Thus, both the radiation resistance and effective mass of the water load transform to larger values. This provides the designer improved efficiency and increased bandwidth. Better performance is expected from monolithic design of Class IV because they can exhibit higher power and larger bandwidth. The shell can be poled and driven from inside to outside or vice versa. By poling and driving different sections of these transducers separately, new vibrations modes can be obtained and acoustic radiation beam patterns can be engineered (Fig. 1). The geometry of the Class IV transducer is described in Table 1. Two different cases are considered: half and full class IV (Fig. 2(a) and (b)). Full Class IV is made in two halves to permit versatility in electroding and poling the arms.

3 Class IV fabrication and testing

The Class IV monolithic ceramic transducer design has been prepared by extrusion process and Fused Deposition Ceramics (FDC) techniques. Commercial Lead Zirconate Titanate (PZT=$Pb(Zr,Ti)O_3$) piezoelectric ceramic compositions were used in both processing methods, that are described in ref [12, 13] and [14] respectively. For extrusion process, the feed material is prepared by mixing ceramic powders with organic binders. This method has given the full transducer (Fig. 3(a)). The Fused Deposition of Ceramics is a Solid Freeform Fabrication technique where a net-shaped green ceramic body is built in a layered fashion. To build a 3-D part, a corresponding Computer Aided Design (CAD) file is initially generated and sliced mathematically into several thin layers with thickness of

Table 1 Dimensions of the class IV monolithic transducer.

	Dimensions
Length (mm)	12.3
Thickness of the shell (mm)	1.5
Thickness of the arms (mm)	3
Inner big axis (mm)	7.75
Inner small axis (mm)	4.75
Outer big axis (mm)	8.75
Outer small axis (mm)	5.75

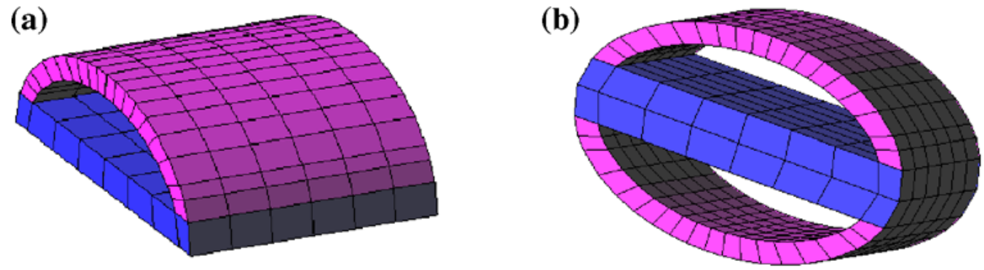

Fig. 2 (a): half class IV and (b): full Class IV

25–250 μm. The FDC method gives two halves of the transducer (Fig. 3(b)).

The organics are burned out at between 300 and 700 °C, followed by a sintering step between 1,200 and 1,400 °C. After firing, the appropriate surfaces are coated with electrode metal through sputtering, painting or dipping. Wire leads are then attached to the electrodes and the ceramic is poled.

The resonance and antiresonance frequencies, the electromechanical coupling coefficients and quality factors were determined using impedance spectroscopy. Underwater performance was evaluated in an anechoic water tank at Penn State's Applied Research Laboratory. The tank has the approximate dimensions of 5.5 m depth, 5.4 m width, and 7.9 m length.

4 Finite element modelling

The experimental results were compared with those calculated using the ATILA finite element code, that was created by the Institut Supérieur d'Électronique et du Numérique (ISEN) France and is specifically designed to solve problems of elastic, piezoelectric, magnetostrictive, and electrostrictive materials radiating in a fluid. It can provide information concerning prestresses, and the behavior under hydrostatic pressure (static analysis), together with the various resonant modes and their associated coupling factors (modal analysis), the in-air or in-water impedance and displacement field, the transmitting voltage response, free field voltage sensitivity, and directivity beam patterns and dynamic stresses (harmonic analysis) [15].

5 In air results

5.1 Half transducer

Numerical and experimental analyses have been performed on the half Class IV transducer and the corresponding impedance spectrum is presented on Fig. 4(a), when only the shell is active, on Fig. 4(b) when only arms are active, and on Fig. 4(c) when both shell and arms are active. A good agreement is observed between the finite element results and the experiments. In the numerical model, losses are not taken into account because they are not well known. Therefore, numerical peaks are sharper than experimental ones. A precise analysis of the displacement field at the frequencies of the peaks gives the vibration modes. When only shell is active, around 36 kHz, the displacement field drawn on Fig. 5 shows that mainly a bending mode is excited, whereas at higher frequency, a width mode (80 kHz) is excited.

5.2 Full transducer

Numerical and experimental analyses have been performed on the full Class IV transducer and the corresponding impedance spectrum is presented on Fig. 6, when both shell and arms are active. A good agreement is observed between the finite element results and the experiments. Once again, numerical peaks are sharper than experimental ones, because losses are not taken into account in the modeling. The displacement field at 25 kHz is presented on Fig. 7 and shows that a bending mode is excited. It is similar to the displacement field presented on Fig. 5, but with one more

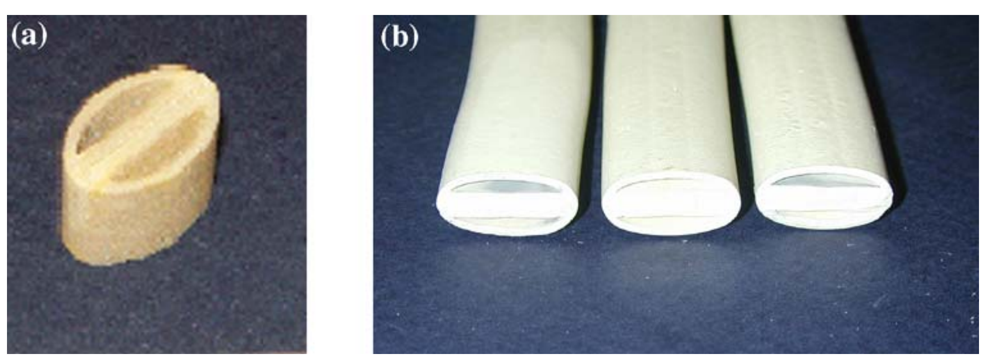

Fig. 3 Class IV monolithitic transducer (a) fabricated by extrusion, (b) fabricated by FDC

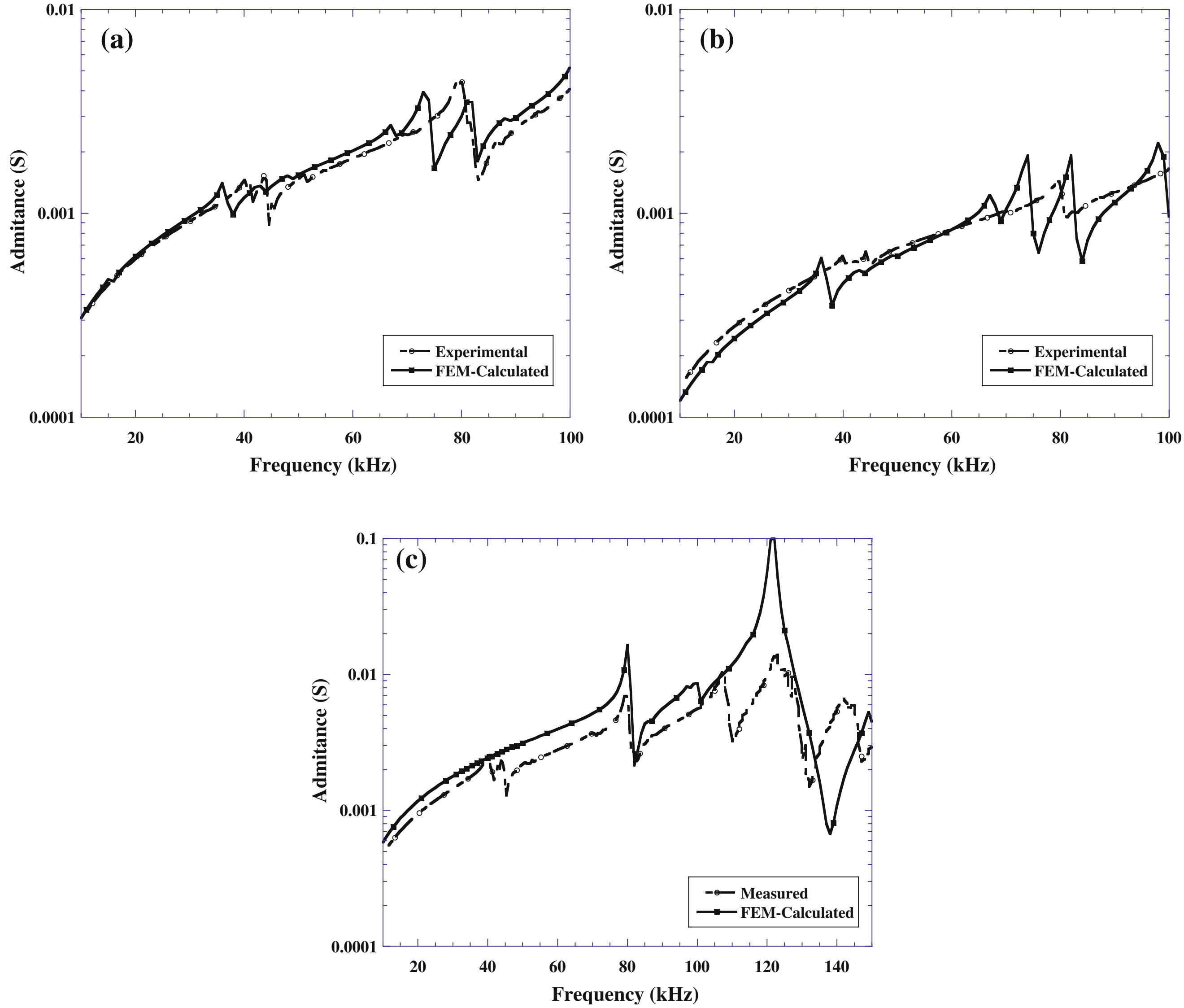

Fig. 4 In air impedance of Half Class IV: (a) Only active shell (b) only active arms (c) shells and arms are active

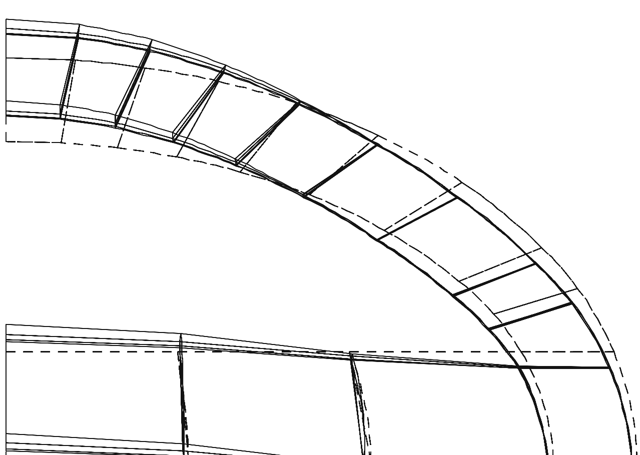

Fig. 5 Displacement field of the half transducer at 36 kHz, showing a bending mode. Cross section view. Dashed lines are the rest position. Due to symmetry, only half structure is meshed

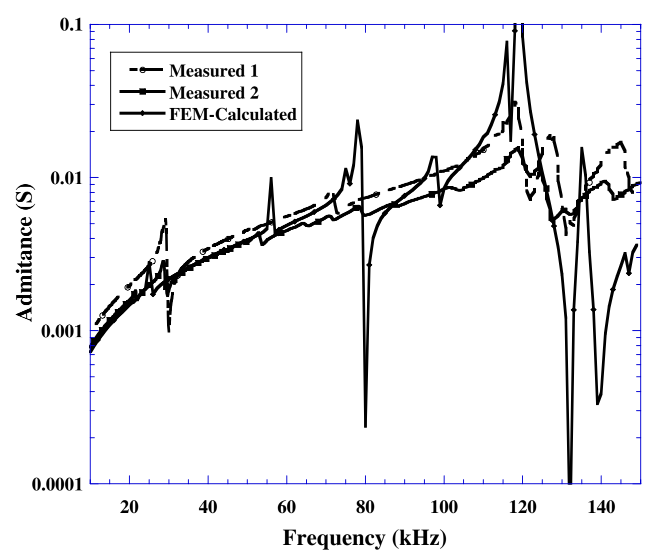

Fig. 6 Full Class IV. In air impedance-shells and arms are active

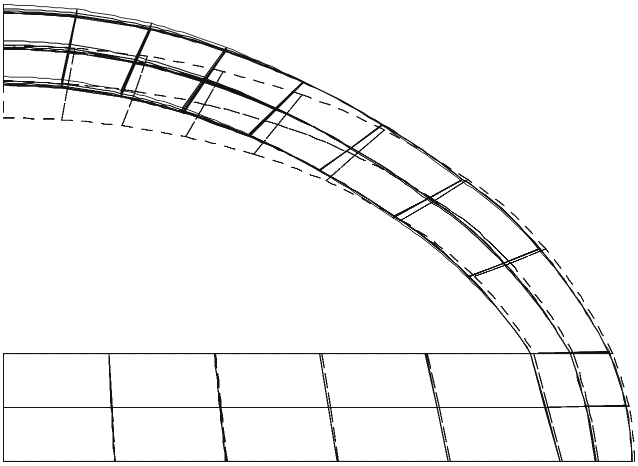

Fig. 7 Displacement field of the full transducer at 25 kHz, showing a bending mode. Cross section view. Dashed lines are the rest position. Due to symmetry, only a quarter of the structure is meshed

symmetry plane. At higher frequencies (56 and 78 kHz), higher order of bending modes are excited. At 119 kHz, the vibration corresponds to a length motion of the shell but the arm doesn't move so much.

6 In water results

In-water performance of the Class IV transducer was measured and modeled using a 3D mesh and the ATILA-EQI coupling to incorporate fluid domain. For the modeling of the immersed structure, the solid structure is meshed using the finite element method, and then it is coupled to an integral equation formulation to account for the acoustic radiation problems [16]. Figure 8 presents the numerical and experimental TVR, in the direction of the short axis

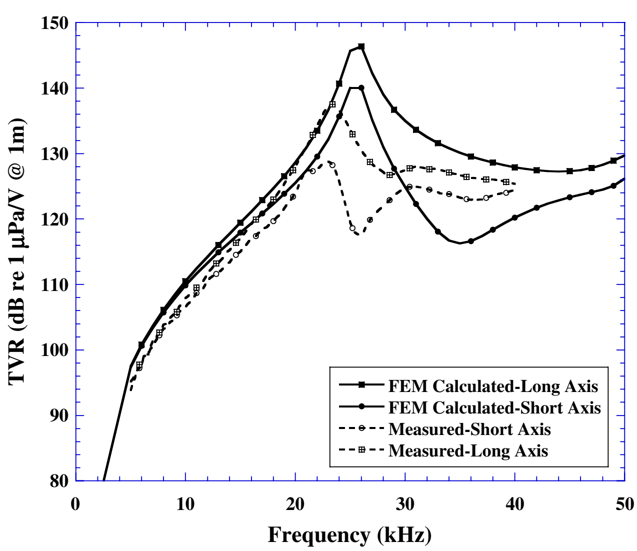

Fig. 8 Frequency variations of the TVR for the Class IV transducer, in the short axis and long axis directions

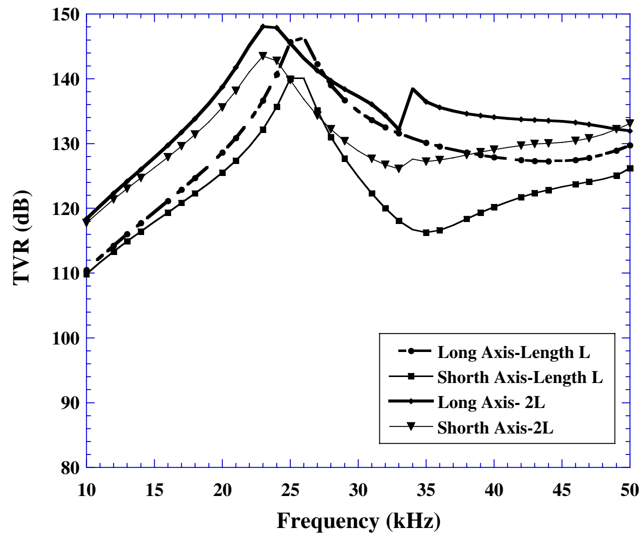

Fig. 9 Frequency variations of the TVR for the Class IV transducer, in the short axis and long axis directions, for two different lengths (12.3 and 24. 6 mm)

and in the direction of the long axis of the transducer. In both directions, the shape of the curves is correct but the experimental level is lower than the numerical values. This is probably due to the polyurethane cap, or the potting or other unknown material property differences. Longer samples have been numerically tested (Fig. 9) and have shown that a better TVR level is obtained, whereas the frequency of the main maximum is lightly shifted towards a lower frequency. Figure 9 gives a way to find the accurate geometry of the class IV transducer with a view to obtain a given performance.

7 Conclusion

Compared to standard flextensional transducers, multimode monolithic transducers are much less expensive because far less assembly is required and there are no glue bonds. In this study, two prototyping techniques were employed to fabricate monolithic class IV piezoelectric transducers from piezoelectrically active materials. The manufactured samples had a range of diameters and wall thickness with complex internal structures. Monolithic transducers make multimode operation possible for better underwater projector and receiver performance, wider bandwidth, beam shaping and many interesting applications in nonlinear acoustics.

Finite-Element Modeling has accurately predicted most resonance modes and transmission levels and has allowed the refinement of designs for various transducer topologies, cross-sections and symmetries. The Class IV type monolithic transducer has been studied in details and highest TVR values can be obtained by increasing the length of the transducer.

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