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A miniaturized class IV flextensional ultrasonic transducer

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Abstract

The class V transducer has found popularity in a diverse range of applications such as surgical and underwater projection systems, where high vibration amplitude for relatively low piezoceramic volume is generated. The class IV transducer offers the potential to attain even higher performance per volume than the class V. In this research, a miniaturized class IV power ultrasonic flextensional transducer is proposed. Simulations were performed using PZFlex finite element analysis, and electrical impedance analysis and experimental modal analysis were conducted for validation, where a high correlation between simulation and experiment has been demonstrated.

Peer-review under responsibility of the Ultrasonic Industry Association.

Keywords: Class IV transducer; flextensional; power ultrasonic; experimental modal analysis; finite element analysis

1. Introduction

The class IV transducer is a form of flextensional transducer which has found success in many low-frequency underwater applications (Chen and Yu, 2013). Although notable early research on the class IV transducer was conducted in the 1960s, for example using a piezoceramic driver by Toulis, the first recorded occurrence of a class IV flextensional transducer was in a patent filed in 1936 by Hayes (Rolt, 1990). A class IV flextensional transducer consists of a magnetostrictive or piezoelectric driving stack, typically in the form of a bar, which vibrates longitudinally to drive an oval shell configuration. The vibration of the driving element causes a combined flexural

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and extensional motion of the shells to produce high amplitude motion. Materials commonly used to fabricate the shells for underwater applications include steel, high-strength aluminium and glass reinforced plastic (GRP), while materials such as PZT-4, PZT-8, and PMN are popular piezoelectric driver materials.

The cymbal transducer, which was successfully miniaturized and adapted from the class V configuration by Newnham et al. (Zhang et al., 1999), has recently been used to create a prototype for orthopedic surgery (Bejarano et al., 2014). Despite the success of this device, it is anticipated that the achievable output amplitude per unit volume of piezoceramic will be greater by using a class IV configuration. In this investigation, the traditional class IV transducer design has been modified to enable future development of miniaturized power ultrasonic devices. The oval shells have been replaced with end-caps which include flanges to affix directly to the piezoceramic bar using an epoxy resin. A schematic of the traditional class IV flextensional transducer, and the modified design, are shown in Fig. 1.

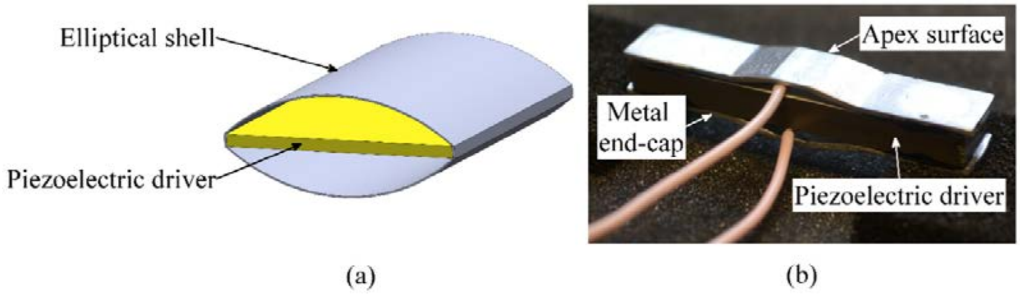

Fig. 1. (a) Schematic of the traditional class IV flextensional transducer; (b) the modified and miniaturized class IV flextensional transducer.

The apex surface of each end-cap has been included to provide a mechanism for the attachment of an end-effector, such as a cutting blade, as shown in Fig. 1(b). To ensure device stability when an end-effector is connected to the transducer during operation, a high level of amplitude uniformity on the end-cap apex is required to minimize the likelihood of nonlinear and autoparametric responses. Furthermore, a robust mechanical coupling mechanism is also required to join the end-cap to the piezoceramic element in order for the device to withstand high stresses induced by elevated operational amplitudes. Recent investigations into adapting flextensional transducers for high-power applications have been conducted, such as the design and fabrication of devices based on the class V cymbal transducer (Bejarano et al., 2014, Lin, 2010), which eliminated epoxy resin bond layers to improve mechanical coupling, and also the modification of the class IV transducer by employing a monolithic configuration (Hladky-Hennion et al., 2008). However, the performance of the monolithic form of the class IV transducer has not yet been fully evaluated for its suitability to high-power applications.

This research outlines the design and fabrication of a miniaturized class IV type flextensional transducer with modified end-caps for power ultrasonic applications. The finite element analysis (FEA) software, PZFlex, is used to design the transducer before the experimental validation of the model is conducted using a vibration characterization process, comprising electrical impedance measurements (Agilent 4294A impedance/gain phase analyzer) and experimental modal analysis (EMA) using 3-D laser Doppler vibrometry (Polytec CLV).

2. Finite element analysis

A set of dimensions for a high performance class IV type transducer were calculated from an iterative simulation process using the FEA software PZFlex. A Navy Type I piezoceramic plate was chosen as the driving element of the transducer (Ferroperm Hard PZ26, Meggitt A/S), while stainless steel 316 was selected as the transducer end-cap material. A skewed structure grid was used to accurately represent the end-cap structure, while shell elements minimized the time step of the explicit solver, increasing computation efficiency. In PZFlex software, the damping is usually applied in the material model definitions and is dependent on frequency. The PZ26 plate was modelled as a continuum material, where the damping was applied as a Q of 200. The model of the transducer used for the simulations in PZFlex is shown in Fig. 2.

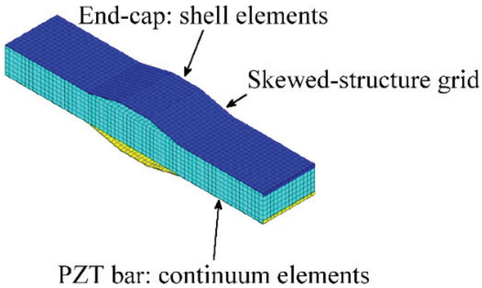

Fig. 2. The miniaturized class IV transducer PZFlex simulation model.

3. Transducer fabrication

Two transducer end-caps were fabricated using the dimensions determined from the numerical simulation process. The end-caps were machined from a stainless steel 316 sheet to a width of 10mm, where the material was principally chosen for its suitability for use in surgical devices. The end-cap schematic is shown in Fig. 3, where all dimensions are in millimeters.

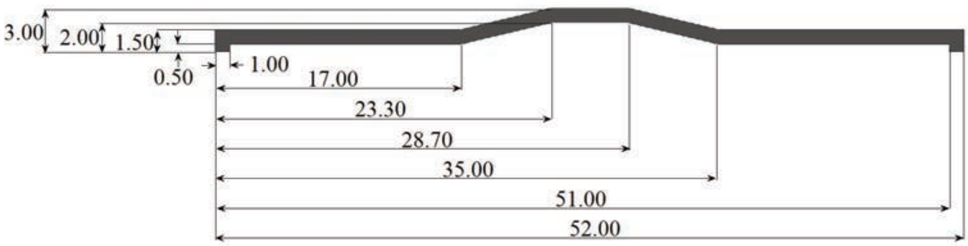

Fig. 3. Schematic of the transducer end-cap, where the dimensions are in millimeters.

Small protrusions, each of 0.5mm in height, were included at the ends of each end-cap to maximize the energy transfer between the piezoceramic bar and the end-cap and also to help secure the piezoceramic in place during manufacture. The PZT plate, poled in the thickness direction, was machined into a bar with a length of 50mm, width of 10mm and thickness of 5mm. Copper wire connections were soldered to the electrode surfaces of the bar.

The mechanical coupling of the transducer was produced using an insulating epoxy resin adhesive (Eccobond 45LV High Strength, Ellsworth Adhesives Ltd.). For high-power applications, high bond strength and fatigue resistance are required to reduce the chance of failure in operation. It is common to employ an insulating epoxy resin, due to its relatively high strength compared to conductive epoxy resins (Zhang et al., 2001). The epoxy resin was composed of three parts resin to one part catalyst (15LV). Air bubbles in the epoxy mixture should be minimized before application, as their inclusion can reduce the strength of the bond. These can be eliminated by thorough mixture of the resin components prior to deposition. The epoxy resin was deposited on to the 16mm-long flange surfaces of each end-cap. A transducer fabrication rig was assembled to assist in the controlled deposition process. The precise deposition of epoxy resin is critical, and it is vital to avoid epoxy resin setting on the end-cap surfaces around the cavity, as this can significantly affect the vibration response of the end-cap, and hence the response of the transducer.

4. Experimental vibration analysis

The impedance-frequency spectrum of the transducer was generated using an impedance gain/phase analyzer (Agilent 4294A). Fig. 4 shows the impedance-frequency spectrum for the transducer beside the impedance trace predicted via FEA.

The impedance-frequency spectrum measured from the fabricated transducer exhibits a mode of vibration around 14kHz which does not appear in the simulation results. However, a mode around 20kHz has been measured which correlates well with the FEA predictions. Furthermore, the impedance magnitudes predicted by the FEA simulation do not closely match the experimental data, and in particular the impedance magnitudes of the numerical results are much higher than those found from experimental measurements. This is likely to stem from the absence of the epoxy resin bond layers in the numerical model which are known to damp the system. Additionally, the response of the transducer measured at 40kHz does not closely correlate with the simulation, and suggests delamination has occurred in the transducer. This phenomenon could be studied through the use of ultrasonic microscopy.

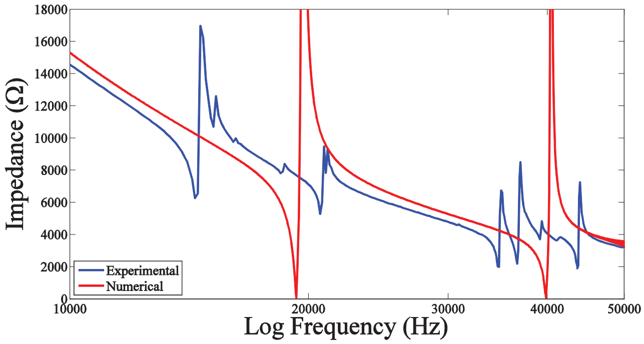

Fig. 4. Impedance-frequency spectrum of the transducer, showing both numerically-simulated (red) and experimentally-measured (blue) results.

Experimental modal analysis (EMA) is a vibration analysis technique which enables modal parameters, such as mode shapes and associated resonant frequencies, of a vibrating structure to be identified. To conduct EMA, a 3-D laser Doppler vibrometer (Polytec CLV) was used to measure vibrational responses of the device. Data acquisition software SignalCalc, (Data Physics) was used to collect the vibrational responses in the form of frequency response functions (FRFs), while post-processing software ME'ScopeVES (Vibrant Technology, Inc.) allowed the identification and visualization of the resonant frequencies and modes of vibration. The vibration response of the transducer was recorded across 90 discrete points located on the surface of the transducer.

Fig. 5 illustrates representations of the two principal modes of vibration (I and II) identified using ME'Scope, for the transducer. The extension of the bar can be seen to cause high amplitude motion of the end-caps.

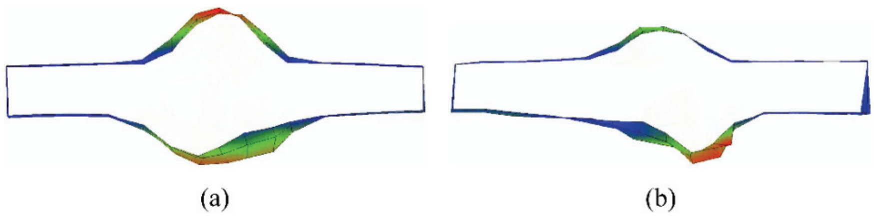

Fig. 5. Deformed representations of the transducer mode shapes identified using EMA, where cool and warm colors represent low and high vibration amplitude respectively, showing (a) mode I and (b) mode II.

The resonant frequency of mode I was measured to be 14322Hz, while the resonant frequency of mode II was measured to be 20401Hz. It is evident that the mode shapes are very similar. The occurrence of mode I at 14322Hz is likely symptomatic of the transducer fabrication process, as there was no correlation with the FEA data for this mode of vibration. The epoxy resin deposition is very difficult to control, in particular to ensure a uniform thickness while preventing epoxy resin entering the cavity. Even very minor asymmetry between the epoxy resin bond layers can cause a secondary mode to appear in the vibration response of the transducer. There have been concerns regarding the suitability of adhesives such as epoxy resin in the assembly of cymbal transducers for high-power applications (Zhang et al., 2001), and this is likely also applicable to class IV type configurations. Despite its high strength, epoxy resin is not recommended for inclusion in high-power ultrasonic devices, due to the poor deposition control, and the likelihood of cracking or failure at high stresses. In addition, asymmetry in the transducer configuration can arise from the differences in dimensions between the end-caps, particularly around the cavities. Precise end-cap manufacture is also vital.

The results shown in Fig. 6 provide a comparison of the measured mode shape of the fabricated transducer with that simulated using PZFlex. The mode shapes are very similar, with only a 5.4% discrepancy between measured and simulated resonant frequencies.

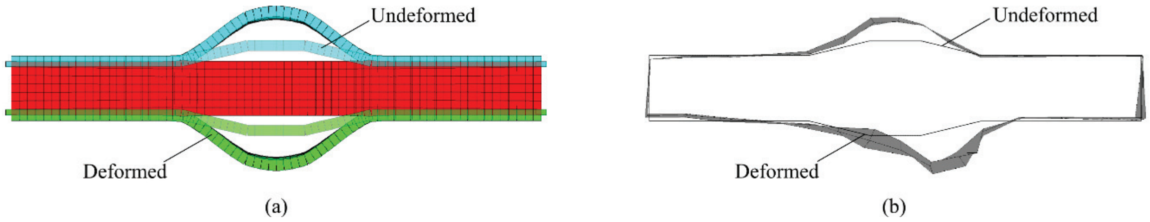

Fig. 6. (a) Cavity mode of vibration at 19300Hz from FEA; (b) cavity mode of vibration at 20401Hz from EMA.

As shown in Fig. 7, it has been demonstrated that a relatively uniform output amplitude has been achieved across the apex surface of the top end-cap. This satisfies one of the original objectives of the investigation, and shows the potential for this class of device to be exploited in a wide range of applications. For example, an end-effector could be attached to the transducer, reducing the likelihood of modal coupling and other nonlinear behaviors.

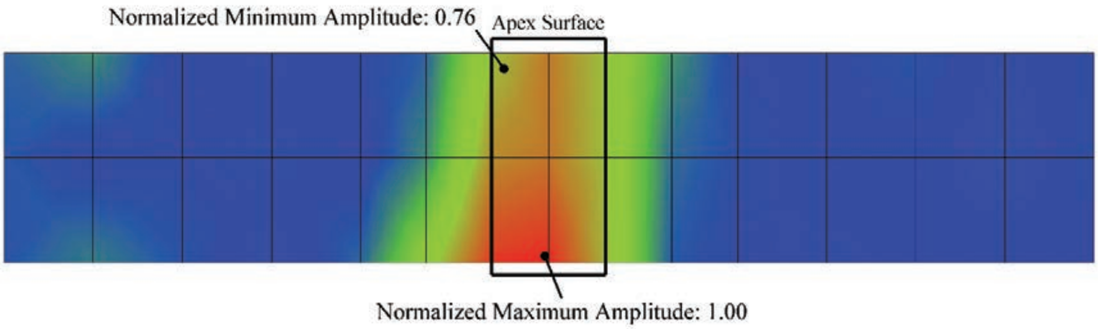

Fig. 7. Normalized amplitude across the surface of the top end-cap.

The class IV transducer has been successfully miniaturized, and despite the fact the epoxy resin bond layers do not appear to be suitable for this type of device, this research has shown that there are clear opportunities for the future development of power ultrasonic devices based on the class IV flextensional design.

5. Conclusions

This research has demonstrated the successful miniaturization and modification of a class IV type flextensional transducer for power ultrasonic applications. PZFlex was used to generate a design specification, from which a transducer was fabricated and experimentally characterized. Similarities between FEA predictions and experimental measurements were found relating to the cavity mode of vibration around 20kHz. However, a mode of vibration was identified experimentally which was not found using FEA. The appearance of this mode of vibration has been attributed to the adhesive deposition and asymmetry between the epoxy resin bond layers. It is anticipated that this research will lead to the development of flextensional devices with improved performance per volume of piezoceramic, for example with respect to displacement amplitude, and which will be suitable for a wide range of applications, from underwater acoustics to surgery.

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