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A cymbal transducer for power ultrasonics applications

Fernando Bejarano, Andrew Feeney, Margaret Lucas*

School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

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ABSTRACT

The flextensional class V 'cymbal' transducer has been widely adopted for low power ultrasonics applications, exhibiting high output displacement for low input energy, compared to a single ceramic, when used as an actuator. Despite its performance benefits, the original designs of cymbal transducers have inherent drawbacks for high power ultrasonics applications that require much higher output displacements. Asymmetries introduced during the fabrication process reduce the efficiency of the transducer, and degradation of the bonding layer between the end-caps and the electroactive material can alter the vibration response and ultimately lead to failure. A new design of the cymbal transducer is therefore proposed that delivers high output displacements. A comparison is presented between a cymbal based on the original design configuration and a new cymbal, to demonstrate the effects of input voltage levels on the dynamic characteristics and vibration response of the two different transducers. For the first cymbal the end-caps are directly bonded to the piezoceramic disc using a commercial non-conductive epoxy. The second cymbal incorporates a metal ring bonded to the outer edge of the piezoceramic disc to improve the mechanical coupling with the end-caps, thereby enhancing the operational capability of the device at higher voltages, allowing for excitation of higher output displacements by removing the problems associated with failure in the epoxy layer. This design is demonstrated to be particularly suitable for power ultrasonics applications such as miniature surgical devices, for example as drilling and cutting devices for orthopaedics procedures.

1. Introduction

Flextensional transducers have been in use since the 1920s, primarily in underwater and sonar applications [1]. A class V 'cymbal' flextensional transducer is a variation of the flextensional 'moonie' transducer design, and was developed in the early 1990s [2]. It is composed of a piezoceramic disc sandwiched between two cymbal-shaped metal end-caps, which are bonded directly to the surface of the disc using a suitable adhesive agent. The end-caps transform high impedance, low radial displacement of the piezoceramic disc into low impedance, high axial displacement of the end-caps. The two most critical features of the cymbal design, which directly influence the transducer performance, are the cavity dimensions and the thickness of the end-caps [3,4]. The geometry of the end-caps greatly affects the frequency response of the cymbal transducer and even small asymmetries in the epoxy layer or in the end-caps themselves can result in each metal end-cap exciting a different resonant frequency. Therefore, the vast majority of these devices exhibit a double resonance peak in the frequency response. Although there are many low-power applications for this type of transducer, cymbals have remained largely undeveloped for high-power ultrasonics applications. One of the primary reasons for this is that the bonding material imposes a limit on the output displacement of the end-caps. Previous studies have shown that when the device is driven at high power levels, degradation in the epoxy layer can occur due to high stress concentrations and this can significantly reduce the operating life of the device [5].

In this paper, two cymbal transducer configurations are studied and compared. The first is consistent with the original design developed by Newnham et al. [6], and the other is a modification of a design first proposed by Lin [7]. The latter consists of a piezoceramic disc bonded to a metal ring. The end-caps, which incorporate a larger flange, are attached directly to the metal ring through screws, to improve the mechanical coupling. The two transducers are experimentally characterised using electrical impedance measurements, vibration response measurements and experimental modal analysis (EMA).

Cymbal transducers were first developed as low frequency, moderate-to-high power underwater projectors [3,8] and subsequently as miniature flextensional devices, as hydrophones and

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* Corresponding author. Tel.: +44 1413304323.
E-mail address: Margaret.Lucas@glasgow.ac.uk (M. Lucas).

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microactuators. However, cymbal transducers were limited to shallow water applications, for example at depths less than 200 m, to prevent the hydrostatic pressure imparting permanent deformations on the device end-caps. A new design was proposed to address this limitation, where the end-cap had a concave shape [9], and was named the 'double-dipper' transducer. This concave configuration meant that the transducer could operate under higher pressures, albeit with reduced output displacement. This was one of the first attempts to enhance the design of the cymbal transducer for high power applications.

The simplicity of fabrication of the cymbal transducer allows for tailoring of different resonant frequencies in a single device by introducing small differences between the end-caps [4]. However, this sensitivity to changes in geometric dimensions of the end-caps was found to be a significant drawback in many applications where high efficiency was required. Irregularities introduced in the fabrication of cymbal transducers, such as asymmetries in the epoxy layer and end-cap dimensions, create a double resonance, characterised by a double-peak in the measured frequency response [4,10,11], and this effect appears in approximately 80% of assembled transducers. Several studies have focused on improving symmetry. A screen-printing method was proposed to improve the deposition of the epoxy layer [10], but this only improved the percentage of single-peak devices to approximately 35%. An alternative approach [11] involved tuning one of the end-caps to the same resonance frequency as the other by adding a small mass to the top of the end-cap.

At the resonance frequency of the cavity mode, high stress concentrations appear at the inner edge of the epoxy layer adjacent to the cavity of the end-cap. When the stress due to the flextensional and rotational movement of the end-cap reaches the tensile strength of the epoxy, micro-cracks appear in the bond layer leading to degradation of the coupling [5]. This imposes a limit on the maximum output displacement of the device. Subsequent studies, attempted to reduce the stress in the epoxy layer by introducing slots in the end-caps [12]. These transducers exhibit higher output displacements, but with a reduction in the resonance frequency depending of the number of slots introduced.

Cymbal transducers generally exhibit high Q but low efficiency, due to being small in size compared to their wavelength at resonance in water [13]. Therefore, in order to achieve a desirable directivity and source level, cymbals are commonly incorporated into array formations. Another configuration, which allows for excitation of higher displacement while avoiding failure of the bonding layer, involves fabrication of multi-stacked cymbals coupled in series [6,14], although this configuration results in a low resonance frequency, dependent on the number of coupled devices. However, by simply stacking actuators in series, the strain in the actuation direction is not improved by more than around 2–3%. Other studies have also investigated the capability of transducer arrays to obtain larger output displacements, one such example utilising Class IV transducers with hierarchical cellular structures in order to obtain a significant improvement in the total displacement [15].

One of the most recent studies regarding application of the cymbal transducer to higher power applications [7] demonstrated that a modification to the coupling mechanism resulted in a transducer which could be operated at higher power through a configuration that incorporated a metal ring connected to the end-caps. This allowed for the necessary enhancements to the dynamic behaviour without significantly increasing the overall size of the device.

2. Stress considerations in cymbal transducer design

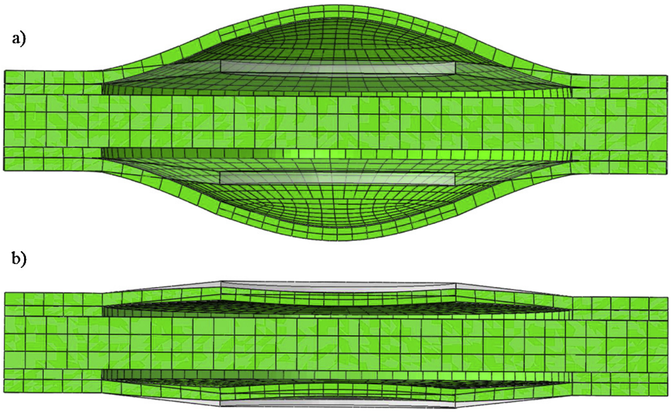

Fig. 1. FE model of the cymbal transducer showing (a) expansion and (b) contraction motion half-cycles of the end-caps.

The displacement of the end-caps in a cymbal transducer is generated by the combination of a flexural and rotational motion. Due to its geometry and operational mode, there are consequently regions in the end-cap which are subjected to high stress. The areas of highest stress include the region at the edge of the cavity, where the epoxy layer is in contact with the end-caps [5]. Fig. 1 shows the displacement maxima of the expansion and contraction half-cycles of the end-caps as predicted by a finite element model run in Abaqus. The resulting stress distribution on the surface of the end-caps when driven at the cavity resonance frequency is shown in Fig. 2.

For high power applications, a cymbal transducer will operate in resonance, at the resonant frequency of the cavity mode of vibration. In resonance, the high displacement of the end-caps increases the stress at the inner edge of the adhesive bond layer, as shown in the finite element prediction in Fig. 3, which plots the axial stress component. When this stress exceeds the tensile strength of the epoxy, failure occurs, often after only a small number of cycles [5]. Since the epoxy is not a high strength adhesive suitable for high power applications, and its use is recommended in cymbals excited at frequencies away from resonance to avoid transducer failure, it is necessary to improve the mechanical coupling between the piezoceramic disc and the end-caps.

3. Cymbal design for increased end-cap displacement amplitude

A new design of the cymbal transducer was proposed [7] which solved a number of the drawbacks of the original design for high power applications. In this new configuration, the piezoceramic disc that generates the radial vibration is substituted for a combination of a piezoceramic disc and a metal ring, to which the end-caps are fixed directly via a number of screws. The radial

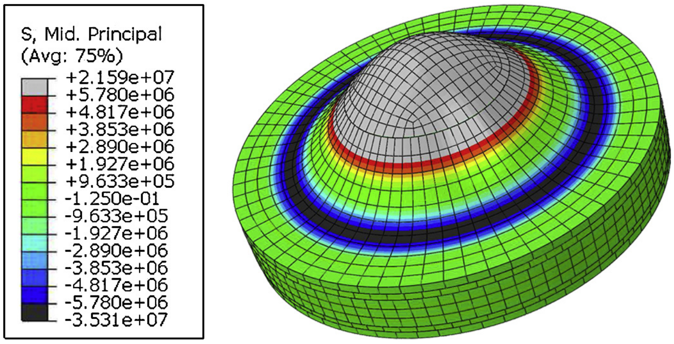

Fig. 2. Stress (Pa) distribution in the end-cap when the cymbal is driven at the cavity resonance frequency.