Vibration characterisation of cymbal transducers for power ultrasonic applications

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Abstract. A Class V cymbal flextensional transducer is composed of a piezoceramic disc or ring sandwiched between two cymbal-shaped shell end-caps. These end-caps act as mechanical transformers to convert high impedance, low radial displacement of the piezoceramic into low impedance, large axial motion of the end-cap. The cymbal transducer was developed in the early 1990’s at Penn State University, and is an improvement of the moonie transducer which has been in use since the 1980’s. Despite the fact that cymbal transducers have been used in many fields, both as sensors and actuators, due to its physical limitations its use has been mainly at low power intensities. It is only very recently that its suitability for high amplitude and high power applications has been studied, and consequently implementation in this area of research remains undeveloped. This paper employs experimental modal analysis (EMA), vibration response measurements and electrical impedance measurements to characterise two variations of the cymbal transducer design, both aimed at incorporation in ultrasonic cutting devices. The transducers are fabricated using the commercial Eccobond 45LV epoxy adhesive as the bonding agent. The first cymbal transducer is of the classic design where the piezoceramic disc is bonded directly to the end-caps. The second cymbal transducer includes a metal ring bonded to the outer edge of the piezoceramic disc. The reason for the inclusion of this metal ring is to improve the mechanical coupling with the end-caps. This would therefore make this design particularly suitable for power ultrasonic applications, reducing the possibility of debonding at the higher ultrasonic amplitudes. The experimental results demonstrate that the second cymbal design is a significant improvement on the more classic design, allowing the transducer to operate at higher voltages and higher amplitudes, exhibiting a linear response over a practical power ultrasonic device driving voltage range. The results also show that the device can be accurately tuned using finite element modelling and that the cymbal exhibits a modal response as predicted by the finite element models.

1. Introduction
Flextensional transducers have been in existence for a number of years, primarily being used in underwater and sonar applications since the 1920’s [1]. Cymbal transducers are a variation of the flextensional ‘moonie’ transducer design, and were developed in the early 1990’s by Newnham et al. at the Pennsylvania State University Materials Research Laboratory [2]. Although there are many applications for this transducer in low power applications, the incorporation of cymbal transducers into high-power ultrasonic technology is underdeveloped. One of the major reasons for this is that the bonding material imposes a natural limit at which the cymbal transducer can be driven.

The two most critical aspects of the cymbal design, from a dynamic and vibration response perspective, which directly impinge on the transducer performance, are the cavity dimensions and the
thickness of the end-caps [3]. The end-cap of the transducer is used as a mechanical transformer, to convert high impedance, low displacement radial motion into low impedance, large axial-flexural motion [1]. A cymbal transducer has a high output vibration displacement amplitude and is sensitive to acceleration changes [4]. However, for the same materials and design, when the devices are used at high power, critical problems occur that can reduce the reliability of the cymbal due to high stress and electrical concentration points leading to degradations or debonding phenomena that can reduce drastically the operating life of the device [5].

The geometrical dimensions of the end-caps greatly affect the frequency response of the cymbal transducer and, due to this, the vast majority of cymbal transducers present a double resonance peak in the frequency response, as even small asymmetries in the epoxy layer or in the end-caps result in each metal cap being resonant at a different frequency. This effect reduces the efficiency of the whole transducer.

Since epoxy is commonly used as a bonding agent, there exists a finite limit for the performance of the transducer based on the components in the system, and therefore debonding will occur if the excitation level is too high. Because of the limitation imposed by the components of the system, such as the epoxy layer and the fact that radial motion is converted into large-amplitude flexural motion, strong mechanical coupling must exist between all components for its use in high power applications.

In 2010 Shuyu Lin developed a new design of the cymbal transducer suitable for high power applications in which the driver part consist of a ceramic disc bonded to a metal ring [4]. The end-cap, with a larger flange, is then attached directly to the metal ring through screws, increasing the mechanical coupling and reducing the stress in the epoxy layer.

The literature presents many studies, such as the work of Naidu et al., which describe the results of numerically-computed modal analyses of cymbal transducers [6], but this investigation utilises experimental modal analysis (EMA) to complement the numerical models in order to identify the differences in the operational mode of these devices. In this paper, two cymbal transducer designs are studied. The first is of the traditional design developed by Newnham et al., and the other is based on a design proposed by Shuyu Lin in 2010. The results of the experimental studies are presented along with finite element analysis (FEA) results obtained using Abaqus finite element software.

2. Cymbal transducer fabrication

2.1. Cymbal end-cap manufacture
The traditional and new designs used in the experiments are shown in Figure 1 and Figure 2.

![Figure 1. Schematics of the traditional device (left) and new device (right).](image1)

![Figure 2. Traditional device (left), new device (centre), new device with end-caps removed (right).](image2)
Each cymbal end-cap was cut from a 0.25mm thick brass sheet and the piezoelectric elements were hard PZT (PZT-402) discs of 12.7mm diameter and 1mm thickness. Table 1 shows the dimensions of the cymbal transducer components. The new cymbal transducer incorporates a brass ring around the PZT disc which increases the mechanical coupling in the device and decreases the stress in the epoxy layer, thereby allowing operation at higher amplitudes. The dimensions of the brass end-caps are modified to allow the incorporation of the brass ring, as shown in Table 1. The cavity dimensions for the new cymbal transducer design remained the same as those in the traditional configuration, since the resonance frequency is largely influenced by this geometry.

| Dimension       | Traditional design (mm) | New design (mm) |
|-----------------|-------------------------|-----------------|
| PZT Thickness   | 1.0                     | 1.0             |
| End-Cap Thickness | 0.25                   | 0.25            |
| Total Ø        | 12.7                    | 16.7            |
| Base Cavity Ø  | 9.0                     | 9.0             |
| Apex Cavity Ø  | 4.5                     | 4.5             |
| Max. Cavity Depth | 0.3                    | 0.3             |
| Ring Inner Ø   | N/A                     | 14.7            |
| Ring Outer Ø   | N/A                     | 16.7            |
| Ring Thickness | N/A                     | 1.0             |

2.2. Cymbal transducer assembly
For the traditional cymbal transducer a layer of insulating epoxy resin, Eccobond® from Emerson & Cuming, at a ratio of three parts 45LV epoxy resin to one part 15LV resin hardener, was applied to the flange of each end-cap and left to cure at room temperature for 24 hours. The layers were approximately 40μm thick. The reason that an insulating and not a conductive epoxy was chosen is that conductive epoxies tend to have lower bonding strength [7]. To ensure that electrical contact could be achieved between the end-cap flanges and the piezoceramic disc, a small solder spot was applied to each surface of the PZT. The end-caps of the traditional cymbal transducer were bonded directly to the piezoelectric disc, but the new cymbal transducer includes a metal ring bonded to the outer edge of the piezoceramic disc. The new cymbal assembly required the use of threaded screws, with a head diameter of 0.50mm and thread diameter of 0.35mm, to fix the metal ring to both end-cap flanges. The gap between the PZT and the metal ring was filled with epoxy resin at a thickness of 1mm. In the device constructed by Shuyu Lin, there was no epoxy resin present between the end-caps and the ceramic. Because of that, the device had a lower resonance frequency [4]. In this investigation, epoxy resin has been included between the end-caps and the ceramic in the new design to enable vibration at a similar frequency to that of the traditional design. The inclusion of the bolts adds strength at the points of highest stress concentration in the epoxy layer. Two traditional cymbal transducers and one new device were assembled.

3. Device characterisation
The devices were driven over a range of voltage increments at resonance to characterise the response with the aim of identifying whether the transducer could be excited for high power applications in a range where a linear response was exhibited. The characterisation also aimed to determine the output displacement amplitude achievable before debonding occurred. A 1D laser Doppler vibrometer (LDV) was used to measure the output amplitude response. A burst-sine wave was applied with 2-4s between
bursts depending on the voltage level, and all stated voltages are peak-to-peak. EMA was then conducted using the 3D LDV and DataPhysics SignalCalc acquisition software.

For the numerical analysis, Abaqus/CAE v6.10-2 was used. For the FEA model, steady-state dynamics analyses were performed using different input voltages as boundary conditions. The model is composed of elements of approximately 0.4 mm in size to ensure that optimal results are returned.

4. Experimental results

4.1. Dynamics characterisation

The displacements for both cymbal transducers are shown in Figure 3. The resonance frequency should match, but any discrepancy can come from the epoxy bonding layer and the tolerances in the fabrication process. Also the effect of the bolts improving the mechanical coupling of the system in the new device enables a more efficient transfer of energy from the driver to the metal end-cap. Also, differences in the strength of the coupling can lead in a variation in the resonance frequency.

In order to observe the differences in the behaviour of both devices at high displacements, the cymbal transducers were driven at different voltages to demonstrate that the new design can operate at higher amplitudes. In Figure 4 the results of the experiment are shown.

In the traditional cymbal transducer the maximum displacement is 32µm. Above this point, the device lost its performance due to debonding. However the new device reached 38µm and had the potential to achieve even higher displacements.
4.2. Experimental modal analysis

A frequency response function from the experimental modal analysis is shown in Figure 5. For the traditional design, it is very difficult to control the thickness and uniformity of the epoxy layer. One consequence of this loss of symmetry is the appearance of a double-peak in the response spectrum, as seen in Figure 5, meaning each end-cap vibrates at a different resonance frequency. The total energy of this mode is shared between these two frequencies. The new cymbal design advances the assembly procedure by improving the controllability of the epoxy layer. Also, the bolts allow a correct alignment of the end-caps with the ceramic surface. The results of the EMA of the new cymbal design show a single resonance peak, indicating considerably improved symmetry and increasing the output response.

![Figure 5. Frequency response of the traditional cymbal transducer (left) and new cymbal (right).](image)

The mode shapes and associated frequencies from the EMA and finite element modal analysis are shown in Figures 6 and 7. It can be seen that there is a good agreement between the numerical and experimental results for frequencies and mode shapes, where the small differences can be attributed to the fabrication process of the different transducers.

![Figure 6. EMA (left) and FEA (right) of the traditional cymbal transducer.](image)

\[ f_{r,1} = 22945 \text{ Hz}, \; f_{r,2} = 23566 \text{ Hz} \]

\[ f_r = 24280 \text{ Hz} \]
5. Conclusions
In this paper two different designs of the cymbal transducer have been studied. In the new design, the mechanical coupling of the end-caps with the driver part of the transducer enables the device to be driven at higher excitation levels and displacements, and reduces the stress on the end-caps due to bending modes of the cavity. It is clear that even though the new design incorporates additional components of bolts and metal ring, the device exhibits the same cavity resonance mode as the traditional design.

Experimental results have demonstrated that the performance of the new cymbal transducer is similar to the traditional cymbal transducer, preserves the advantages of this design and solves the drawbacks in the power limitation imposed by debonding of the epoxy layer. The improvement in control of the fabrication of the new transducer, that allows significantly improved symmetry to be attained, removes the appearance of a double peak in the cavity mode frequency response, and therefore enables considerably improved resonance performance of the transducer.

Both the increased displacement amplitude capabilities and improved symmetry control of this cymbal transducer configuration mean that it can now be incorporated in high power ultrasonic applications for the first time.

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