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A cymbal transducer for power ultrasonics applications

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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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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

The displacement of the end-caps in a cymbal transducer is generated by the combination of a flexural and rotational motion.

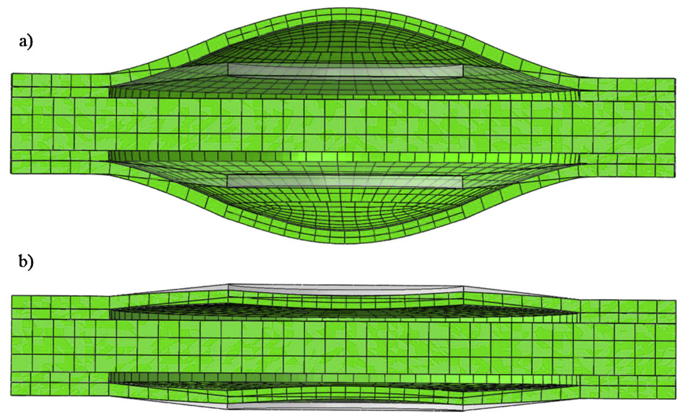

Fig. 1. FE model of the cymbal transducer showing (a) expansion and (b) contraction motion half-cycles of the end-caps.

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

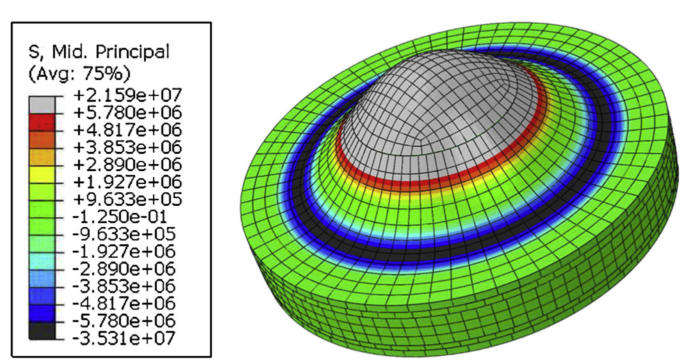

Fig. 2. Stress (Pa) distribution in the end-cap when the cymbal is driven at the cavity resonance frequency.

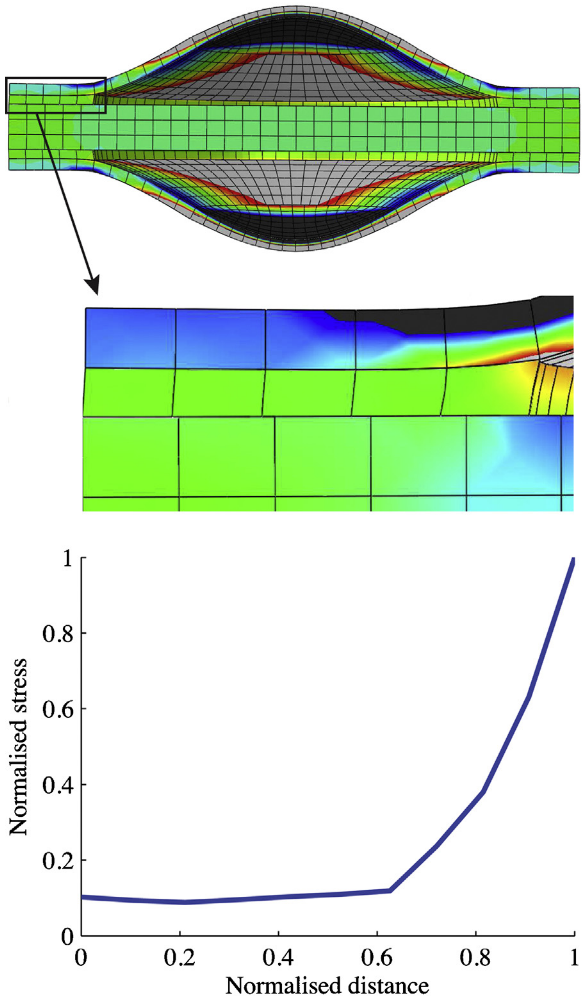

Fig. 3. FE model prediction of the normalised stress distribution along the length of the epoxy layer.

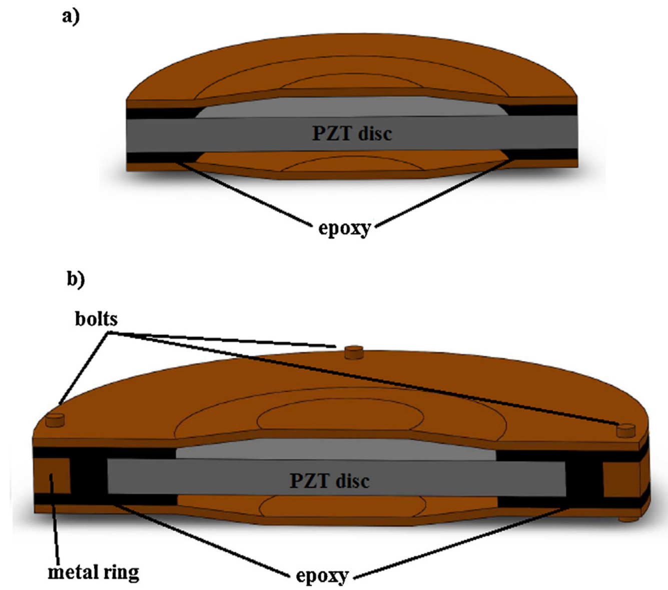

Fig. 4. Schematics of the (a) original and (b) new cymbal transducer design.

movement is transformed into a high flextensional displacement through these two mechanical couplings. Since there is now no epoxy layer between the end-caps and the piezoceramic disc, it is possible to drive the transducer at higher voltages to excite higher displacement amplitudes without compromising performance of the device.

Two different methods for coupling the piezoelectric ceramic disc with the metal ring have been proposed [7]. For the first method, a metal ring with a smaller inner radius than the piezoceramic disc is used. The metal ring radius is then expanded by heating, the piezoceramic disc is placed inside, and then the ring is cooled quickly to produce a strong mechanical coupling. The piezoceramic disc is now pre-stressed in the radial direction. For the second method, a metal ring with a larger radius than the piezoceramic disc is used and the disc and ring are bonded by an epoxy layer. For both of these metal ring and piezoceramic disc configurations, the resulting cymbal transducer operates at a considerably lower resonant frequency than the original cymbal design; in the absence of a direct bonded connection between the inner edge of the end-cap cavity and the ceramic, the effective cavity diameter is larger.

An improvement of this configuration is proposed in order to design and characterise a cymbal transducer specifically aimed at high power applications where the cymbal operates in resonance at the cavity mode frequency. Fig. 4 shows a schematic of the basic configuration of the original and new cymbal transducer. As well as the mechanical connection of the ring and end-caps via four threaded bolts, an epoxy layer bonds the end-caps and the piezoceramic disc. The coupling between the ceramic disc and the metal ring is also achieved via an epoxy layer, to prevent any radial pre-stress acting on the ceramic, and thus enabling effective transmission of the radial vibration movement from the piezoelectric disc to the metal ring. The coupling of the end-cap and metal ring via threaded bolts leads to a more rigid end-cap flange. Because of this, it is expected that the base edge of the cavity allows for a rotational movement, which should slightly reduce the stress in the epoxy layer. Although the improved mechanical coupling does not entirely solve the adhesion degradation problems that were shown to affect the original cymbal transducers, it does enable the transducer to be operated at considerably higher powers and higher displacements at approximately the same resonance frequency. The new device similarly operates with the piezoceramic disc poled in the thickness direction to generate a radial vibration which is transmitted to the metal ring, from which the radial movement is transformed into flextensional displacement of the end-caps.

Another advantage of this new design is the improvement in the control of transducer assembly. The use of threaded bolts means that the end-caps can be much more accurately aligned with the piezoceramic disc. This reduces asymmetries in the assembled transducer, reducing the likelihood that the transducer resonance frequency response will exhibit a double-peak.

4. Transducer fabrication process

In most studies reported in the literature, end-caps are produced from sheet metal by punching. Whilst this is a highly repeatable process for precise, high volume production, there are some drawbacks. Accuracy of the cavity dimensions is paramount in ensuring an efficient transducer, however punching results in the edge between the inner cavity and the flange becoming rounded. Consequently, when the epoxy resin is deposited a portion can escape into the inner cavity area, with the resulting asymmetry affecting the vibration response. An alternative is to cut the end-caps, so there is no rounded edge thus reducing, but not eliminating, the chance of epoxy resin entering the cavity. For both end-cap production processes, however, epoxy resin entering the cavity area remains as a significant disadvantage of the original cymbal transducer design.

In this study, the cymbal end-caps were cut from a 0.25 mm-thick brass sheet. Table 1 lists the dimensions of the components

Table 1
Cymbal transducer dimensions (all units in mm).

Dimension	Original design	New design
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
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

used for both cymbal transducers, one based on the original cymbal design and one based on the new design incorporating a metal ring. It can be noticed that the dimensions of the brass end-caps for the two transducers must differ to allow for incorporation of the brass ring, but the cavity dimensions remain the same in order to allow consistency of the cavity mode resonance frequency.

Hard PZT 402 piezoceramic discs (Piezo Kinetics) were used for both transducers. For the original cymbal transducer a layer of Eccobond insulating epoxy resin (Emerson & Cuming), at a ratio of three parts epoxy resin to one part resin hardener, was deposited between each end-cap flange and the piezoceramic disc to form a 40 μm thick epoxy layer. After careful assembly of the device in a custom rig, the epoxy resin was left to cure at room temperature for 24 h. The reason that an insulating and not a conductive epoxy was chosen is that conductive epoxies tend to have lower bonding strength [10]. To ensure electrical contact between the end-cap flanges and the piezoceramic disc, a small solder spot was applied to each surface of the PZT disc and wires were welded on to the surface of the end-cap flanges. The new cymbal assembly required threaded bolts and nuts, with a head diameter of 0.50 mm and thread diameter of 0.35 mm, to fix both end-cap flanges to the metal ring. The gap between the PZT and the metal ring was filled with epoxy resin at a thickness of 1 mm. The end-caps were bonded with the ceramic disc and metal ring using a layer of insulating epoxy. During the curing process the bolts were used to help achieve improved symmetry through a controlled realignment of the end-caps and piezoceramic disc, through small adjustments to the different bolts. For this transducer, a vital function of the epoxy layer is also the electrical isolation of the metal end-caps from the electrodes of the piezoceramic disc, as both end-caps are connected via the metal ring. The electrical wires were welded directly to the ceramic surfaces through two holes on the outer face of the metal ring. For this reason, it was not necessary to apply solder spots to the piezoceramic in the new cymbal transducer. The two assembled transducers are shown in Fig. 5.

5. Experimental procedure and results

Experiments were undertaken to characterise and compare the two transducers. Electrical impedance measurements were recorded for the purposes of quality verification of the device assembly, and also as a method of determining the level of symmetry of the transducer, a single-peak frequency response being an indicator of acceptable symmetry. A 1D laser Doppler vibrometer (LDV) measured the displacement amplitude response of the end-caps of both transducers for a range of input excitation voltage levels, and experimental modal analysis (EMA) was undertaken using a 3D LDV to measure the modal frequencies and mode shapes.

The experimental results also allowed for verification of numerical models using Abaqus FEA software. For the finite element models, steady-state dynamic analysis was performed to predict the displacement amplitude of the end-caps under different input

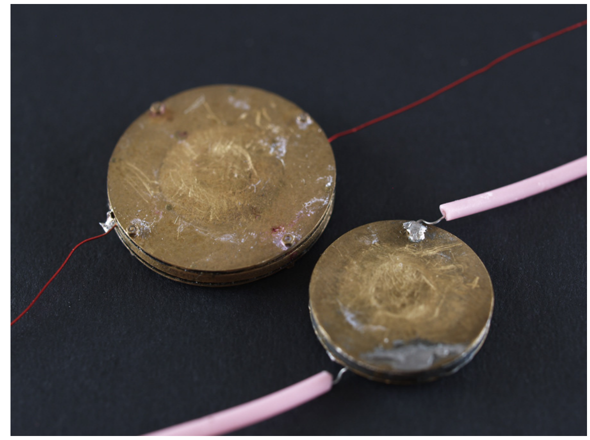

Fig. 5. Assembled cymbal transducers based on original (right) and new (left) designs.

excitation voltages and to calculate the modal frequencies and mode shapes of the transducers.

5.1. Impedance and modal analysis

An impedance gain/phase analyzer (Agilent) was used to measure the impedance spectra which are shown in Fig. 6. The measurements give a clear indication of asymmetry present in the transducer based on the original design, where a double-peak is present in the response spectrum in Fig. 6(a). The cymbal exhibits a double resonance, a symmetric and an asymmetric mode characterised by out-of-phase and in-phase motion of the two end-caps respectively [10,16].

In order to verify these modes of vibration, an experimental modal analysis (EMA) was carried out using a 3D LDV and data acquisition hardware and software (DataPhysics SignalCalc, ME'scopeVES) [17]. The mode shapes from the EMA are shown alongside the corresponding results from the finite element analysis in Figs. 7 and 8.

Since the achievable displacement of the cymbal transducer is highly dependent on the geometry of the cavity [3], if there is

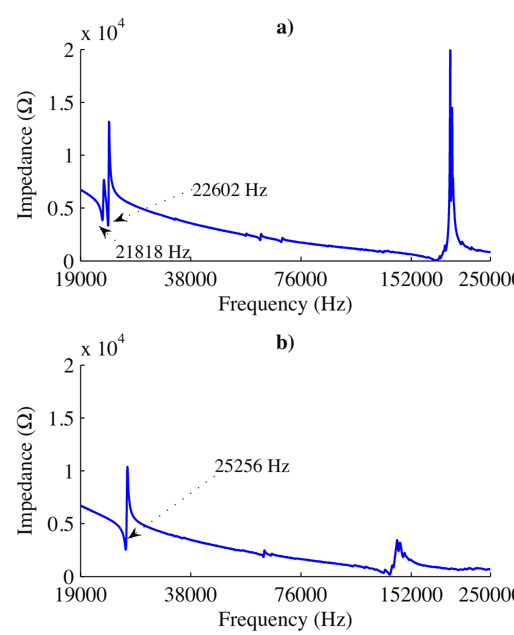

Fig. 6. Impedance spectra of the (a) original and (b) new transducer design.

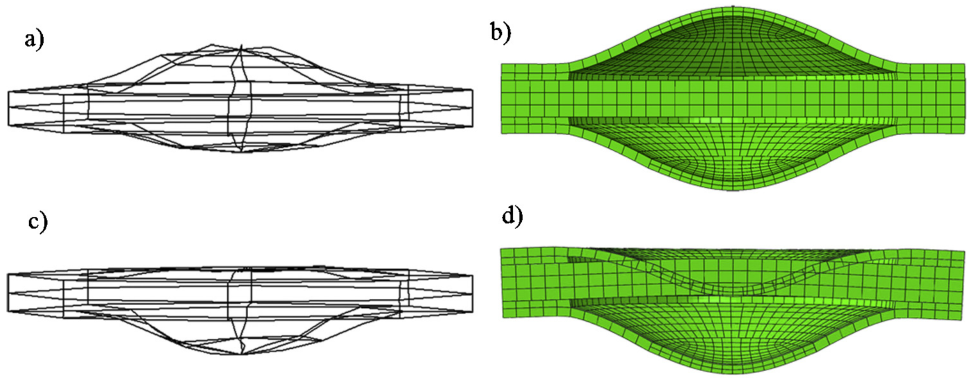

Fig. 7. Mode shapes from (a), (c) EMA and (b), (d) FEA of the original cymbal transducer for the (a), (b) symmetric and (c), (d) asymmetric cavity mode.

asymmetry then the displacement of each end-cap is different. Consequently, for each mode in the double resonance, there is one end-cap which exhibits higher output displacement than the other. The asymmetry also introduces bending responses in the piezoceramic disc resulting in undesirable stress that can reduce the operational life of the transducer. In Fig. 6 the double-peak observed in the response of the original cymbal transducer exhibits a different impedance peak magnitude for the two frequencies, and this is consistent with the different vibration amplitude of each end-cap as observed in the EMA results in Fig. 7. From Figs. 6(b) and 8, it is shown that for the new transducer a single-peak resonance is exhibited, corresponding with symmetric vibration amplitude of the end-caps.

5.2. Vibration response characterisation

The two transducers were driven over a range of voltage increments across a narrow frequency band centred at the resonance frequency of each device. The cymbals were excited through upwards and downwards frequency sweeps in order to observe any nonlinearities in the displacement–frequency responses. A 1D LDV was used to measure the displacement amplitude response from the centre of each end-cap. Excitation was via a burst-sine wave with 2–4 s intervals between bursts, with the interval selected depending on the voltage level. This ensured that transducer heating was minimised for the duration of an experiment and any measured response characteristics such as frequency shifts were not associated with heating of the piezoceramic. The resulting measured displacement amplitude responses of the two transducers are shown in Fig. 9. Fig. 9(a) and (b) illustrate the maximum displacement response measured for the two end-caps, hence (a) records the response in the symmetric mode and (b) records the response in the asymmetric mode in the case of the original cymbal transducer.

By comparing Fig. 9(a) and (b) with (c) and (d) it is possible to observe the result of improved symmetry in the fabricated new cymbal transducer, both from the excitation of a single mode at 25.3 kHz (the symmetric mode) and also from the more consistent displacement amplitudes measured on the two end-caps.

However, for the new cymbal transducer, the constraint of the metal ring results in a lower displacement amplitude at resonance (Fig. 9(c) and (d)) than for the transducer based on the original cymbal design (Fig. 9(a) and (b)). In the new cymbal configuration, the driver comprises both the piezoceramic disc and the metal ring, such that there are lower effective piezoelectric coefficients than for a piezoceramic disc driver alone. For a piezoceramic disc, the piezoelectric coefficient d_{33} is the strain in the polarisation axis (i.e. perpendicular to the plane of the disc) per unit electric field applied in the axis of polarisation, and the coefficient d_{31} is the strain in a direction perpendicular to the axis of polarisation (i.e. in the plane of the disc) per unit electric field applied in the axis of polarisation. The coefficient d_{33} is related to the displacement that the ceramic can attain in the axial direction, and the coefficient d_{31} relates to the displacement in the radial direction. For high power ultrasonics applications, large values of piezoelectric coefficients are required. The axial and radial displacements of the drivers of the two transducers were measured as an indicator of the difference between the d_{33} and d_{31} coefficients respectively for the two transducers. From these measurements the d_{33} for the new transducer is 13% lower than for the original design, whilst the d_{31} reduction is 38%. The measured difference in axial displacement of the end-caps is 37% between the two transducers (Fig. 9), where end-cap displacement is largely influenced by the d_{31} coefficient. These results mean that, for high power ultrasonic devices, the new cymbal transducer needs to be driven at a higher input power than the corresponding original transducer to achieve the same displacement amplitude.

The degree of hysteresis in the displacement–frequency response is also an important measure of transducer performance, especially when accounting for mechanical losses. When part of the energy in the device is dissipated internally, there can appear regions of high stress, heat and electrical concentration in the piezoceramic that exhibit as nonlinearities in the measured displacement, one consequence of which is hysteresis. The degree of hysteresis is defined as [18]:

$$\Delta H\% = \frac{100\Delta X}{X_{\max}} \tag{1}$$

where X_{max} is the displacement at the location of maximum electric field, where the highest hysteresis region is generated, and ΔX is the difference in displacement between the paths of the upwards and downwards frequency sweeps at the half-maximum of the

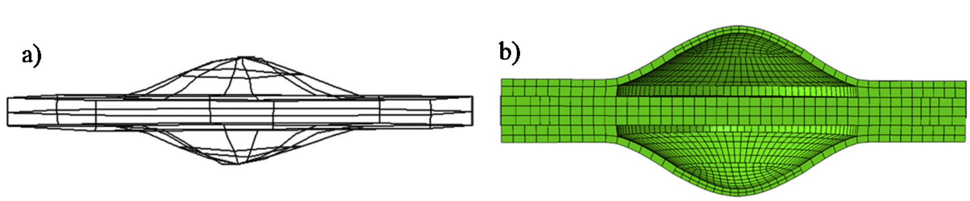

Fig. 8. Mode shape from (a) EMA and (b) FEA for the cavity mode of the new cymbal transducer.

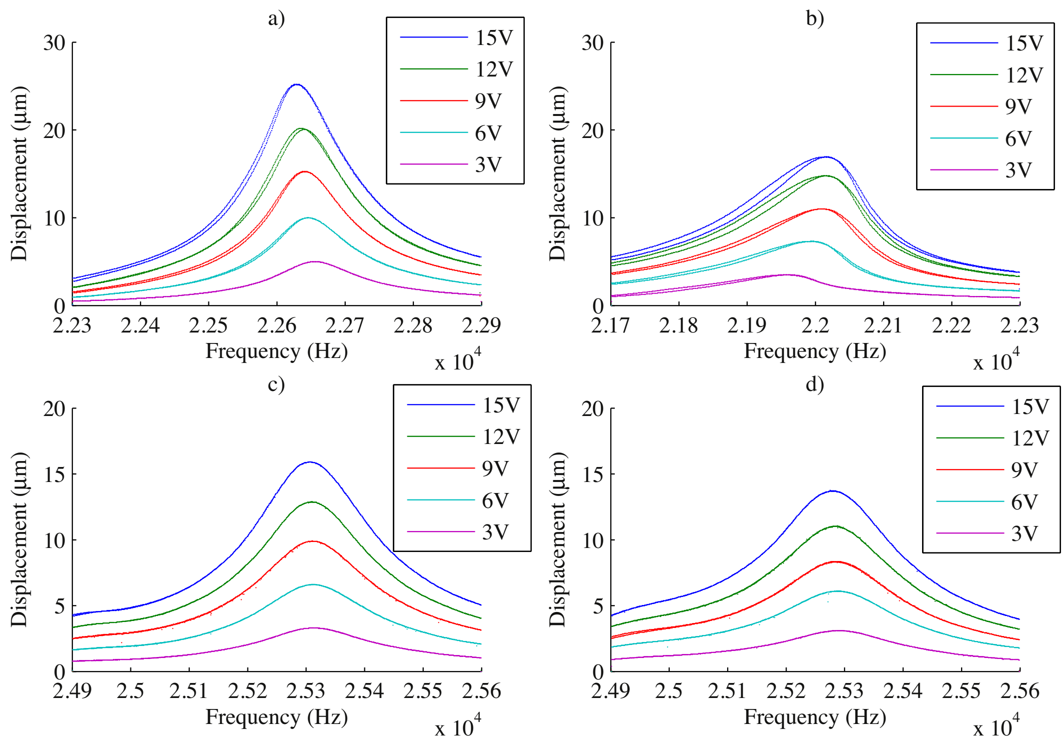

Fig. 9. Vibration displacement response of the (a), (b) original and (c), (d) new cymbal transducer for each end-cap.

applied electric field. The degrees of hysteresis calculated from the data measured at the maximum voltage level used in this study for the original and new design of transducers are recorded in Table 2.

Low hysteresis is calculated for the new cymbal transducer design, in part due to the high level of symmetry achieved in its fabrication. The result is a transducer with a more linear response, over the range of excitation voltages adopted in this study. This is evidenced by the highly symmetric response curves measured from both end-caps in the responses for the upwards and downwards frequency sweeps and the constant resonance frequency maintained across measurements from both end-caps and across the excitation voltage range. The responses for the upward and downwards frequency sweeps coincide in Fig. 9(c) and (d), as compared with the slightly different upwards and downwards frequency responses in Fig. 9(a) and (b). As well as the higher degree of hysteresis associated with the original cymbal in Fig. 9(a) and (b), nonlinear responses are also exhibited as a shift in resonance frequency across the voltage range; a reducing frequency for one end-cap and an increasing frequency for the other.

5.3. Failure test

Through the same measurement methodology as described in Section 5.2, it was possible to determine the displacement amplitude achieved before failure of the transducer occurred. The two cymbal transducers were driven at increasing voltage levels and the results are shown in Fig. 10.

The cymbal transducer based on the original design reached a displacement of around 50 μm, above which the displacement amplitude dropped due to failure of the bonding layer. This failure is characterised by the appearance of micro-cracks in the epoxy layer in the vicinity of the cavity. The new device reached a displacement of around 90 μm before a drop in displacement was measured. This demonstrates the significant advantage of the new cymbal transducer, which can be driven at higher voltage levels to attain higher end-cap displacements through the improved mechanical coupling and symmetry of the device.

Table 2
Degree of hysteresis for the original and new cymbal transducers.

Device	End-cap 1	End-cap 2
Original cymbal	2.93%	4.19%
New cymbal	0.07%	0.12%

5.4. Vibration behaviour with an added mass

To evaluate the new design of the cymbal as a transducer for high power ultrasonics applications, it is necessary to investigate its incorporation into a device for a typical application. For many high power applications, such as ultrasonic drilling or cutting, the transducer must be able to actuate an attached mass, such as a

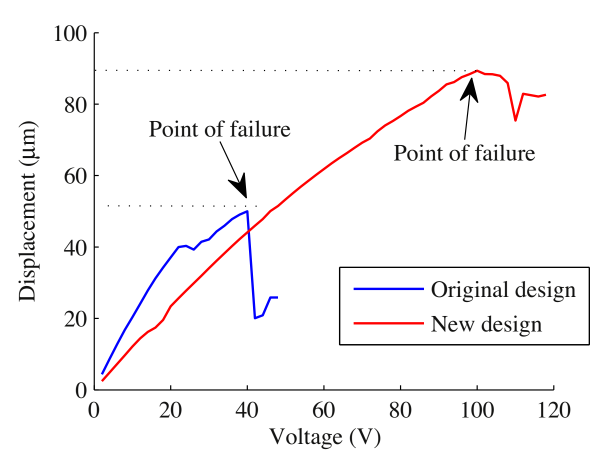

Fig. 10. Displacement amplitude of the original transducer and new transducer for increased excitation voltage.

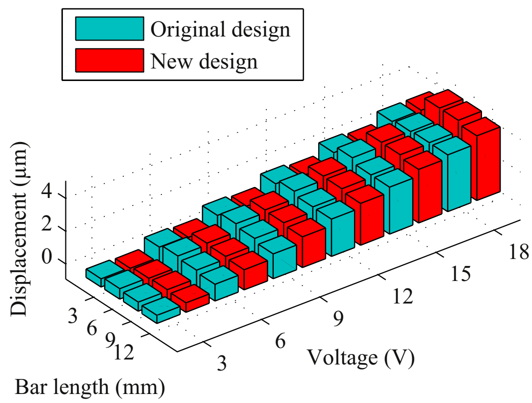

Fig. 11. Vibration responses of the original and new designs with different masses added for different input voltages.

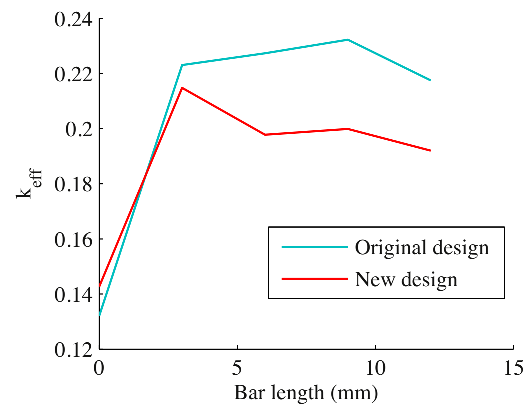

Fig. 12. Variation of the k_{eff} parameter of the original cymbal and new cymbal design transducers, with different added mass.

drill-bit or blade, and therefore a circular cylindrical bar was adopted in this study as a generic added mass. In order to maintain symmetry, equal masses were added to both end-caps. The addition of a mass constrains the axial movement of the end-cap and an additional force also acts on the piezoceramic disc, thereby affecting its radial movement. It is therefore important to understand the effects of these constraints on the vibration displacement response in developing new devices based on these transducers.

Experiments were conducted, again using the same method as described in Section 5.2. The material for the cylindrical bars was stainless steel and bars were of lengths of 3 mm (mass: 0.39 g), 6 mm (mass: 0.74 g), 9 mm (mass: 1.14 g), and 12 mm (mass: 1.48 g). Fig. 11 shows the displacement at resonance measured on the free end of each bar for a series of incremented excitation voltage levels.

It can be observed that, for both transducers, when a mass is added the displacement is significantly reduced compared to the end-cap displacements achieved in Fig. 9. However, the length of the bar, and therefore size of the mass, has very little effect on the displacement and, for the range of added masses, the displacement is very similar for both transducers. These results indicate that both transducers exhibit a similar response, despite the fact that the ceramic disc in the new cymbal transducer is constrained by the metal ring.

The mechanical coupling factor, k_{eff}, is an indicator of the amount of electrical energy that is transformed into mechanical energy, and is therefore related to the mechanical losses and efficiency of the device. The mechanical coupling factor can be calculated from the relationship between the frequencies of resonance (f_{r}) and antiresonance (f_{a}), given by:

$$k_{\mathrm{eff}}^2 = \frac{f_{\mathrm{a}}^2 - f_{\mathrm{r}}^2}{f_{\mathrm{a}}^2}. \tag{2}$$

In Fig. 12, the variation in the mechanical coupling factor, k_{eff}, for both devices with different bar masses is shown. In the case of the new cymbal we might expect higher mechanical losses as a result of the three different mechanical couplings influencing the motion of the piezoceramic disc and end-caps; epoxy layer, metal ring and fixing bolts. Additionally, we might expect that the losses are increased for this transducer with increasing added mass to the end-caps as a result of the additional load affecting all three couplings, rather than only the epoxy layer as in the case of the original transducer. However, the results in Fig. 12 exhibit a similar behaviour for both transducers, indicating that the losses are not significantly increased for the new cymbal.

5.5. Development of an orthopaedic surgical device

Based on this new cymbal transducer, a novel prototype for a miniaturised ultrasonic orthopaedic surgical device has been developed. This device has only one end-cap and a back shell within which the piezoceramic driver is bonded with insulating epoxy resin. The metal end-cap is attached directly to the back shell using threaded bolts and epoxy. Additionally, the end-cap incorporates a threaded stud allowing attachment of a range of different cutting blades. The design of the whole transducer, shown in Fig. 13, is optimised to transfer the radial movement of the piezoceramic disc directly to the metal end-cap, so that in the cavity resonant

a

b

Fig. 13. Orthopaedic device based on the new cymbal transducer design (a) showing blade attachment and handle, and (b) cutting chicken femur bone with a commercial blade attached.

mode the transducer exhibits a pure axial movement, consistent with the traditional cymbal transducer. Initial lab based trials have demonstrated promising performance of the device, realising precise cuts in animal bones using a commercial cutting blade designed by Mectron s.p.a. (Fig. 13(b)).

6. Conclusions

Two different designs of a cymbal transducer have been studied. In the new transducer, the mechanical coupling of the end-caps with the piezoceramic driver enables the device to be driven at higher excitation levels and therefore higher displacements. The new design incorporates additional components of threaded bolts and a metal ring, but exhibits the same cavity resonance mode as the cymbal transducer based on the original design. The experimental results have demonstrated that the performance of the new cymbal transducer preserves the advantages of the traditional design, including high axial displacement for small radial displacement of the disc and constancy of end-cap displacement with increasing added mass. The new transducer also addresses the limit on excitation level, imposed by debonding of the epoxy layer in the original design. The improvement in the control of fabrication of the new transducer allows significantly improved symmetry to be attained, eliminating the double-peak in the cavity mode frequency response, and thereby improves the resonance performance of the transducer. Both the increased displacement amplitude capability and improved symmetry of this cymbal transducer configuration mean that it is better suited to applications in high power ultrasonics than the original design. This is demonstrated by successful lab based cutting trials on chicken femur using a cymbal transducer incorporating a commercial cutting blade.

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Biographies

Fernando Bejarano obtained a degree in Telecommunications Engineering in 2005, specialising in sound and imaging, from the University of Extremadura (Spain). In 2009 he was awarded a Masters degree in Acoustical Engineering from the Polytechnic University of Valencia (Spain). In 2010 he started his PhD in the Ultrasonics Group in the School of Engineering at the University of Glasgow. His research is focussed on the development of a miniaturised ultrasonic cutting device for surgical procedures based on the class V flextensional cymbal transducer.

Andrew Feeney studied for a MEng degree in Mechanical Engineering at the University of Glasgow, which he obtained in July 2010, before embarking on a PhD at the same university as part of the Ultrasonics Group in the School of Engineering, working in the field of power ultrasonics. His research is primarily concerned with novel transducer design and the study and implementation of smart materials in ultrasonic transducers for the development of tunable devices.

Margaret Lucas studied for a BSc(Eng) in Mechanical Engineering at the University of Aberdeen and for a PhD in High Power Ultrasonics at Loughborough University. She was appointed to a Lectureship in Mechanical Engineering at Loughborough University in 1990 and moved to the University of Glasgow in 1996, where she is currently Professor of Ultrasonics and Deputy Head of the School of Engineering. Margaret leads the Ultrasonics Group, with research interests across medical, industrial and space applications of high power ultrasonics.