Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 87 (2016) 29 – 34

Physics Procedia

44th Annual Symposium of the Ultrasonic Industry Association, UIA 44th Symposium, 20-22 April 2015, Washington, DC, USA and of the 45th Annual Symposium of the Ultrasonic Industry Association, UIA 45th Symposium, 4-6 April 2016, Seattle, WA, USA

# Dynamics characterisation of cymbal transducers for power ultrasonics applications

Andrew Feeney, Fernando Bejarano, Margaret Lucas*

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

**Abstract**

A class V cymbal flextensional transducer is composed of a piezoceramic disc sandwiched between two cymbal-shaped shell end-caps. Depending on the type of piezoceramic, there exists a maximum voltage that can be reached without depolarisation, but also, at higher voltage levels, amplitude saturation can occur. In addition, there is a restriction imposed by the mechanical strength of the bonding agent. The effects of input voltage level on the vibration response of two cymbal transducers are studied. The first cymbal transducer has a standard configuration of end-caps bonded to a piezoceramic disc, whereas the second cymbal transducer is a modified design which includes a metal ring to improve the mechanical coupling with the end-caps, to enable the transducer to operate at higher voltages, thereby generating higher displacement amplitudes. This would allow the transducer to be suitable for power ultrasonics applications. Furthermore, the input voltages to each transducer are increased incrementally to determine the linearity in the dynamic responses. Through a combination of numerical modelling and experiments, it is shown how the improved mechanical coupling in the modified cymbal transducer allows higher vibration amplitudes to be reached.


Peer-review under responsibility of the Ultrasonic Industry Association.

*Keywords:* Cymbal transducer; linearity; high-power; ultrasonics

## 1. Introduction

Flextensional transducers have been in existence for a number of years, primarily being used in underwater and sonar applications since the 1920s (Zhang et al., (1999)). Cymbal transducers are a variation of the flextensional

* Corresponding author. Tel.: +44 (0)141-330-4323.
*E-mail address:* margaret.lucas@glasgow.ac.uk


Peer-review under responsibility of the Ultrasonic Industry Association.
doi:10.1016/j.phpro.2016.12.006

design, and were developed in the early 1990s by Newnham et al. at the Penn State University Materials Research Laboratory (Zhang et al. (2000)). It is only recently that their capabilities in alternative applications and at high amplitudes have being investigated. Presently, the incorporation of cymbal transducers into high-power ultrasonic technology is underdeveloped, primarily because the bonding agent in the configuration imposes voltage or displacement limits at which the cymbal transducer can be driven. This is one of the issues which this paper aims to address.

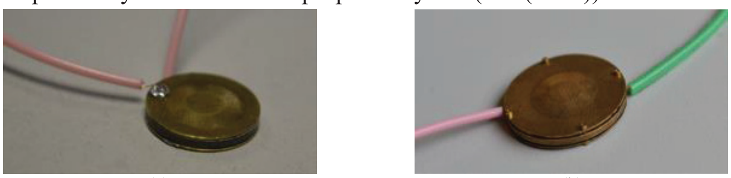
The two most critical aspects of the cymbal design that affect the vibration performance of a cymbal transducer are the cavity dimensions and the thickness of the end-caps (Sun et al. (2005)). The end-cap of the transducer acts as a mechanical transformer, to convert high impedance, low displacement radial motion into low impedance, large axial-flexural motion (Zhang et al., (1999)). In recent years, there has been a significant research effort to expand the range of applications in which cymbal transducers can be used, as well as developing evolutions of the designs for application in different environmental conditions (Newnham et al. (2000)). For example, cymbal transducers have found prominence in energy harvesting (Yuan et al. (2010)). However, the number of applications in which cymbal transducers are operating in commercial devices, despite being of a wide variety, is still limited. Since epoxy is commonly used as the bonding agent, there exists an operating limit of the transducer, where debonding will occur if the input power is too high. Also, because radial motion is converted into large-amplitude flexural motion, robust mechanical coupling should exist between all components (Lin (2010)). The dimensions of the end-caps affect the frequency of the cymbal transducer (Lin (2010)), and improved designs that aim to enhance the mechanical coupling can result in many complex modes being present in the vibration response.

In this paper, two cymbal transducer designs are studied. The first is of the standard design developed by Newnham et al., and the other is based on a design proposed by Lin in 2010 (Lin (2010)), which incorporates a metal ring with the aim of improving mechanical coupling in the transducer, by removing the problems associated with debonding in the epoxy layer. It is evident from the literature that new interest in cymbal transducers is emerging, and that as yet there has not been a fully comprehensive study into the dynamic characteristics of this type of flextensional transducer when driven at higher voltages, particularly with respect to an analysis of linear dynamic response. Additionally, the investigation of the operational limit of these transducers relative to increasing input voltage has not received significant attention. The results of the experimental studies are presented with support from finite element analysis (FEA), which was conducted using Abaqus/CAE Version 6.10 software.

## 2. Cymbal transducer fabrication

### *2.1. Cymbal end-cap manufacture*

The fully assembled standard and modified designs used in the experiments are shown in Fig. 1. The modified design is based on the improved cymbal transducer proposed by Lin (Lin (2010)).



(a) (b)

Fig. 1. (a) The standard cymbal transducer; (b) the modified cymbal transducer.

Each cymbal end-cap was cut from brass sheet, and hard PZT (PZT-402) discs of 12.7mm diameter, 1mm thickness were used as the driving element in the assembly. Table 1 shows the dimensions of the cymbal transducer components. The material properties, which were also used in the FEA, are shown in Table 2. The modified cymbal transducer incorporates a brass ring around the PZT disc which improves the mechanical coupling and decreases the stress on the epoxy layer, thereby allowing operation at higher amplitudes. For the modified transducer, the total diameter of the brass end-caps had to be increased from 12.7mm, required for the standard configuration, to 16.7mm, to allow the incorporation of the brass ring in the transducer assembly. However, the cavity dimensions for the modified cymbal transducer end-caps remained the same as those for the standard transducer end-caps, to ensure a similar resonance.

Table 1. Cymbal transducer dimensions, in mm.

| Dimension | Standard design | Modified design |
|---|---|---|
| PZT thickness | 1.0 | 1.0 |
| End-cap thickness | 0.25 | 0.25 |
| Total diameter | 12.7 | 16.7 |
| Base cavity diameter | 9.0 | 9.0 |
| Apex cavity diameter | 4.5 | 4.5 |
| Maximum cavity depth | 0.3 | 0.3 |
| Inner ring diameter | - | 14.7 |
| Outer ring diameter | - | 16.7 |
| Ring thickness | - | 1.0 |

Table 2. Material properties of the cymbal transducer components.

| Component | Young's modulus (E, GPa) | Poisson's ratio (ν) | Density (ρ, kg/m$^3$) |
|---|---|---|---|
| Brass end-caps; ring | 100.6 | 0.35 | 8324.64 |
| Cured epoxy | 2.42 | 0.35 | 1438.15 |

### *2.2. Cymbal transducer assembly*

Bonded joints operate best in a state of shear or compression, and the inhomogeneities in the bonding thickness layer are a result of surface roughness, local menisci, or incomplete adhesive coverage from the curing process, all of which can affect the resonance frequency of the transducer (Ochoa et al. (2007)). Consequently, it should be ensured that during the curing process, pressure is only applied to the end-cap flanges. For the standard cymbal transducer, a layer of insulating epoxy resin (Eccobond®, 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 before the transducer was assembled in a custom rig. The epoxy resin, with a layer of nominally 40μm thick, was left to cure in the assembly at room temperature for 24 hours. The reason that an insulating and not a conductive epoxy was chosen, is that conductive epoxies tend to exhibit lower bonding strength (Zhang et al. (2001)). To ensure electrical contact between the end-cap flanges and the piezoceramic disc, a small solder spot was applied to each flat surface of the PZT. The end-caps of the standard cymbal transducer were bonded directly to the piezoceramic disc, but the modified cymbal transducer included a metal ring bonded to the outer edge of the piezoceramic disc. The modified cymbal transducer assembly required the use of threaded screws, with a diameter of 0.50mm, in order to secure 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.

## 3. Experimental and numerical procedure

An Impedance Gain/Phase Analyzer (Agilent 42941A) was used to measure the impedance-frequency spectra for the transducers, and provided information regarding the resonance frequencies. The transducers were then driven in a series of voltage increments at resonance in order to characterise the relationship between displacement amplitude and frequency, characterise the linearity or nonlinearity of the response, and also to determine the attainable displacement amplitude before debonding occurred. A 1D laser Doppler vibrometer (Polytec CLV) was used to measure the displacement 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.

For this study, Abaqus/CAE Version 6.10 was used for the numerical modelling and simulation of the transducers. The different brass end-caps, the metal ring for the modified transducer, the PZT material and the adhesive bond were included in the model. It has been shown that the response of a cymbal transducer is significantly affected by the adhesive bonds and therefore including the epoxy adhesive layer in the FEA models is essential to ensure a valid comparison can be made between experimental and FEA results (Zhang et al. (2001)).

## 4. Results

The red line in Fig. 2 shows the single resonance which was observed for the standard cymbal transducer after assembly. It is clear that the condition of the applied bond between the two end-caps can result in the appearance of a second cavity resonance frequency (Ochoa et al. (2006)), where a single resonance response is reported to occur in only around 20% of fabricated cymbal transducers (Ochoa et al. (2002)).

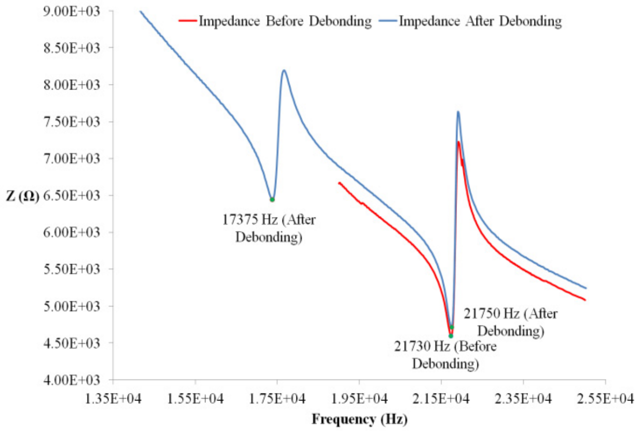



Fig. 2. Impedance-frequency spectra, pre- and post-debonding, of the standard brass cymbal transducer.

The single resonance is an indicator of a high level of symmetry between end-caps, and high quality mechanical coupling. The blue line, measured after transducer operation at increasing voltage levels, illustrates how debonding affects the impedance of the transducer, where energy is now shared between two distinct resonance responses which are caused by an asymmetry between the end-caps of the transducer. The measured displacements at which debonding occurs are shown in Fig. 3, compared with numerical data from FEA.

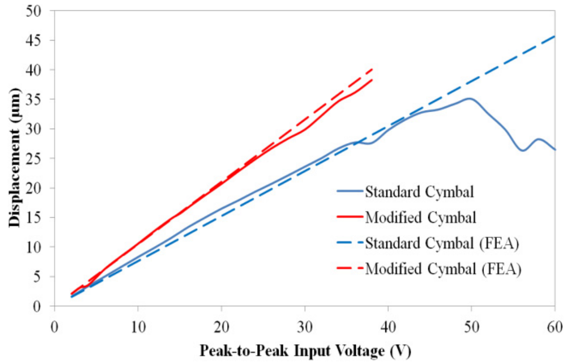
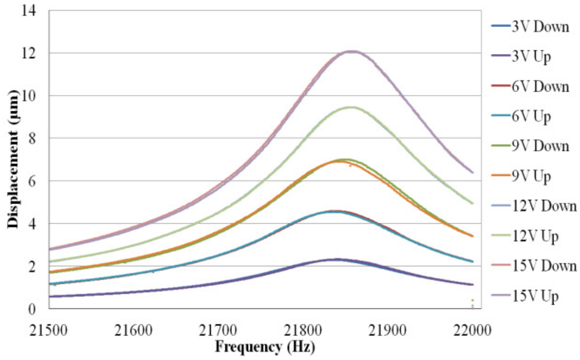
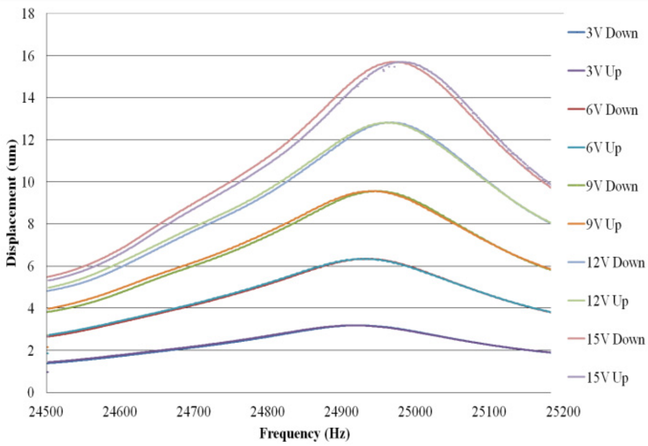



Fig. 3. Driving of the transducers at increasing input voltage.

The driving of the transducers to high voltages was conducted with the intention to demonstrate that the modified cymbal transducer could operate at higher amplitudes. The results in Fig. 3 show that probable debonding in the standard cymbal transducer was detected for an input voltage of 50V, achieving a displacement amplitude of 35μm. The modified cymbal transducer reached a displacement amplitude of 38μm at an input voltage of 38V, and had the potential to be driven at even higher voltages. However, the precise displacement amplitude or input voltage at which debonding occurs cannot be determined from this analysis, because a micro-crack in one or both of the epoxy resin bond layers could be initiated at a displacement amplitude lower to that which causes the transducer to fail. Despite this, the method used to obtain the experimental results shown in Fig. 3 enables a general comparison between transducers to be made, showing that the modified cymbal transducer can be operated at higher displacement amplitude for a specified input voltage. The linearity of the vibration response of each transducer was also characterised, the results of which are shown in Fig. 4.




(a)




(b)

Fig. 4. Vibration response of the (a) standard brass cymbal transducer; (b) modified brass cymbal transducer.

From the experimental study into the linearity of the vibration response of each transducer, the resonance frequency and displacement of the standard cymbal transducer were found to be 21838Hz and 12μm, and 25136Hz and 16μm for the modified cymbal transducer. This was expected, because the modified cymbal transducer has a stiffer and improved mechanical coupling via the metal ring. The comparison between numerical and experimental data for each transducer is shown in Table 3.

Table 3. Resonance frequency comparison, in Hz.

| Transducer | Numerical | Experimental |
|---|---|---|
| Standard, at 3V | 24280 | 21838 |
| Modified, at 3V | 25416 | 25136 |

There is a high level of linearity in the vibration response of each transducer, where there is no significant shift of resonance frequency measured, as input voltage is increased. Furthermore, a good correlation between numerical and experimental data has been obtained, as shown by the data in Table 3. The resonance frequency is also sensitive to very small changes in the cavity dimensions and these differences will often be a result of small amounts of ingress of the epoxy and tolerances on the end-caps. This study has shown that the modified cymbal transducer can be operated at higher vibration amplitudes compared to the standard cymbal transducer configuration, with a linear vibration response.

## 5. Conclusions

This study has demonstrated that the modified cymbal transducer design allows higher vibration amplitudes to be reached. The standard cymbal transducer reached a displacement amplitude of approximately 35μm, whereas the modified design attained around 40μm, with the potential for higher achievable displacement amplitude. The frequency response also remained linear over the 3-15V range for both transducers. However, further study is required to assess the ability of both transducer types to sustain their respective amplitudes over a significant period of time. Furthermore, greater understanding of the effect of the epoxy bond layer and dimension tolerances is required in order to optimise transducer design. Generally, the modified cymbal transducer has shown promise for power ultrasonic applications, with a good level of agreement between experimental and numerical data.

## Acknowledgements

The authors would like to thank Dr Andrew Mathieson of the School of Engineering, University of Glasgow, for experimental advice, and the Engineering and Physical Sciences Research Council (Grant EP/P50418X/1) for the funding and support of this project.

## References

Zhang, J., Hughes, W.J., Bouchilloux, P., Meyer Jr., R.J., Uchino, K., Newnham, R.E., 1999. A class V flextensional transducer: the cymbal. Ultrasonics 37, 387–393.

Zhang, J., Hughes, W.J., Meyer Jr., R.J., Uchino, K., Newnham, R.E., 2000. Cymbal array: a broadband sound projector. Ultrasonics 37, 523–529.

Sun, C.L., Guo, S.S., Li, W.P., Xing, Z.B., Liu, G.C., Zhao, X.Z., 2005. Displacement amplification and resonance characteristics of the cymbal transducers. Sensors and Actuators A: Physical 121(1), 213–220.

Newnham, R.E., Zhang, J., Meyer R., 2000. "Cymbal transducers: a review," In Applications of Ferroelectrics, ISAF 2000. Proceedings of the 2000 12th IEEE International Symposium, vol. 1, 29–32.

Yuan, J., Shan, X., Xie, T., Chen, W., 2010. Modeling and improvement of a cymbal transducer in energy harvesting. Journal of Intelligent Material Systems and Structures 21(8), 765–771.

Lin, S., 2010. An improved cymbal transducer with combined piezoelectric ceramic ring and metal ring. Sensors and Actuators A: Physical 163(1), 266–276.

Ochoa, P., Pons, J.L., Villegas, M., Fernandez, J.F., 2007. Effect of bonding layer on the electromechanical response of the cymbal metal-ceramic piezocomposite. Journal of the European Ceramic Society 27(2-3), 1143–1149.

Zhang, J., Hladky-Hennion, A.C., Hughes, W.J., Newnham, R.E., 2001. Modeling and underwater characterization of cymbal transducers and arrays. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 48(2), 560–568.

Ochoa, P., Pons, J.L., Villegas, M., Fernandez, J.F., 2006. Advantages and limitations of cymbals for sensor and actuator applications. Sensors and Actuators A: Physical 132(1), 63–69.

Ochoa, P., Villegas, M., Fernández, J.F., 2002. Resonant frequency response of cymbal transducer. Ferroelectrics 273(1), 321–326.