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Optimisation of a cymbal transducer for its use in a high-power ultrasonic cutting device for bone surgery

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Abstract

The class V cymbal is a flextensional transducer commonly used in low-power ultrasonic applications. The resonance frequency of the transducer can be tailored by the choice of end-cap and driver materials, and the dimensions of the end-caps. The cymbal transducer has one significant limitation which restricts the operational vibration amplitude of the device. This is the limit imposed by the mechanical strength of the bonding agent between the metal end-cap and the piezoceramic driver. Therefore, when there is an increase in the input power or displacement, the stresses in the bonding layer can lead to debonding, thereby rendering the cymbal transducer ineffective for high-power ultrasonic applications. In this paper, several experimental analyses have been performed, complemented by the use of Abaqus/CAE finite element analysis, in order to develop a high-power ultrasonic cutting device for bone surgery using a new configuration of cymbal transducer, which is optimised for operation at high displacement and high input power. This new transducer uses a combination of a piezoceramic disc with a metal ring as the driver, thereby improving the mechanical coupling with the metal end-cap.

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Keywords: Cymbal transducer; transducer design; high-power; ultrasonic bone surgery

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1. Introduction

Although the first attempts to introduce the ultrasonic technology in bone cutting procedures were made by Catuna in 1952, with a drilling device for dentistry (Mathieson (2012)), it was not until 2001 when the first commercial device

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designed for bone cutting applications was available. The Piezosurgery® device, which is the result of a collaboration between a maxillofacial surgeon, Vercellotti, and the Italian company Mectron S.p.A (Vercellotti (2004)), is based on a Langevin transducer, and is optimised for driving cutting inserts for a range of surgical procedures. Many studies have been conducted on the performance of the Piezosurgery® device, in order to understand how to improve the mechanical and clinical efficacy of the system.

The cymbal transducer was developed at the Materials Research Laboratory, Penn State University, and patented by Newnham and Dogan in 1998 (Dogan et al. (1997)). The transducer is a class V flextensional-type, consisting of an electroactive driver in the form of a piezoelectric ceramic ring or disc, poled in the thickness direction, sandwiched between two shallow-shell metal end-caps. The end-caps serve as mechanical transformers for conversion and amplification of the relatively small radial displacement of the piezoelectric ceramic into a much larger axial flexural motion normal to the surface of the end-caps. Each end-cap possesses a shallow cavity on the inner surface, the dimensions of which significantly influence the resonance frequency of the transducer. There is significant opportunity for a new generation of miniaturised bone cutting devices to be developed, based on modifications to the cymbal transducer configuration.

In the traditional cymbal transducer design, the piezoelectric ceramic disc and the metal end-caps are bonded together using a high-strength epoxy. Therefore, the conversion of the radial displacement of the piezoelectric ceramic (poled in thickness direction) to the flexural-rotational displacement of the metal end-caps depends exclusively on the mechanical coupling of this bonding agent. The cymbal transducer has been widely adopted for low-power applications, but the mechanical coupling was found to be a critical limitation when the cymbal was driven at high voltages or high displacements (Ochoa et al. (2006); Ochoa et al. (2007)).

In 2010, Lin developed a modified design of the cymbal transducer in which a metal ring was used to enclose the piezoceramic driver using a thermal expansion/contraction method (Lin (2010)). The end-cap, with a larger flange in order to accommodate the metal ring, was then affixed directly to the metal ring through a bolted interface, thereby improving the mechanical coupling by eliminating the epoxy resin bond layers. Since the cavity dimensions can be controlled, this new cymbal transducer could be designed to exhibit approximately the same resonance frequency as a cymbal transducer of the traditional design, but with the capacity for operation at higher displacement amplitudes before failure. The new cymbal transducer is shown in Fig. 1(a). For the purposes of this study, the mechanical coupling was adapted from that used by Lin. Epoxy resin was used to fill the gap between the outer edge of the piezoceramic disc and the inner surface of the metal ring. This is shown in Fig. 1(b).

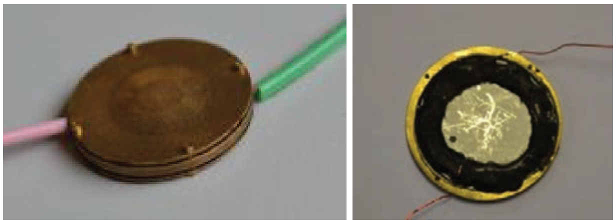

(a) (b)

Fig. 1. (a) The new cymbal transducer; (b) the coupling between the PZT disc and metal ring.

In this study, a prototype device for ultrasonic bone cutting surgery is proposed, adapted from the cymbal transducer design shown in Fig. 1. The adapted device comprises only one end-cap with a supporting back-shell in which the piezoceramic driver is fixed in place with insulating epoxy resin. The metal end-cap is attached directly to the back-shell with a bolted connection. The design of the whole transducer is optimised to transfer the radial movement of the piezoelectric disc directly to the metal end-cap, so that in resonance the device exhibits an axial vibration motion. Experimental data is supported in part by numerical simulations using Abaqus/CAE finite element analysis (FEA) software.

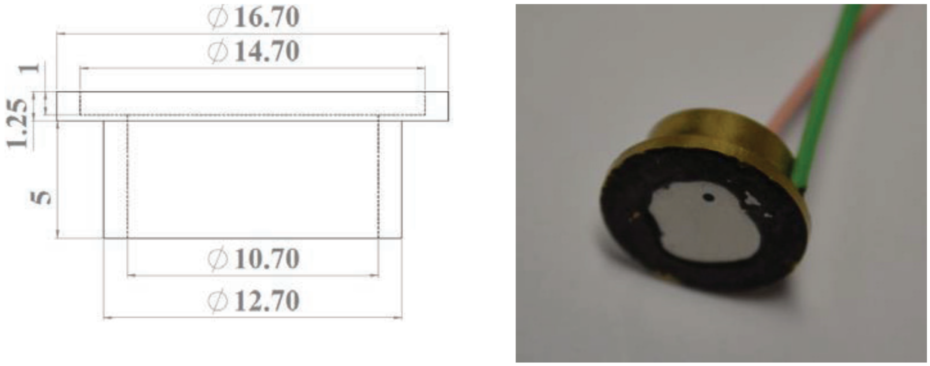
2. Fabrication considerations

Two devices were fabricated for this research, consisting of the new cymbal transducer adapted from that proposed by Lin, and a novel cutting prototype. The end-cap material of both devices was brass, with a thickness of 0.25mm. Instead of a commonly used stamping and shaping process to form the end-caps using a hardened steel die set, the end-caps were cut from a sheet in order to reduce residual stresses. The piezoelectric driver in each was a hard PZT (PZT-402) disc of 12.70mm diameter and 1.0mm thickness poled in the thickness direction. Key dimensions of the end-caps for both devices are shown in Table 1.

Table 1. End-cap dimensions.

End-cap dimension	Size (mm)
Total diameter	16.70 ± 0.03
Base cavity diameter	9.0 ± 0.20
Apex cavity diameter	4.50 ± 0.10
Maximum cavity depth	0.30 ± 0.03

For the cymbal transducer, a metal ring was fabricated with an inner diameter of 14.70mm and an outer diameter of 16.70mm. The total thickness was 1.0mm to match the thickness of the piezoceramic disc. In order to ensure an impedance-match between different assembly components, the material selected for the metal ring and the back-shell for the cutting device was brass, the same as the end-cap. The back-shell of the prototype consisted of three parts, comprising a metal ring (with inner diameter of 14.70mm, an outer diameter of 16.70mm, and a thickness of 1.0mm), joined to a cylinder of 10.7mm inner diameter, 12.70mm outer diameter, and 5mm thickness, via a sheet layer of 0.25mm thickness. The dimensions of the back-shell are shown in a schematic in Fig. 2(a), and the fabricated back-shell is displayed in Fig. 2(b).



(a) (b)

Fig. 2. (a) The back-shell of the new prototype with dimensions in mm; (b) assembly of the PZT disc and the back-shell.

The epoxy resin used for the devices was Eccobond® 45LV (Emerson & Cuming), at a ratio of three parts 45LV epoxy resin to one part 15LV resin hardener. This non-conductive epoxy also acts as isolating agent, and prevents short-circuiting. Threaded bolts and nuts are necessary to secure the end-caps to the metal ring and back-shell of the cymbal transducer and the prototype cutting device respectively. Each device contained four brass bolts of 0.35mm thread diameter and nuts of 0.50mm diameter.

3. Device characterisation

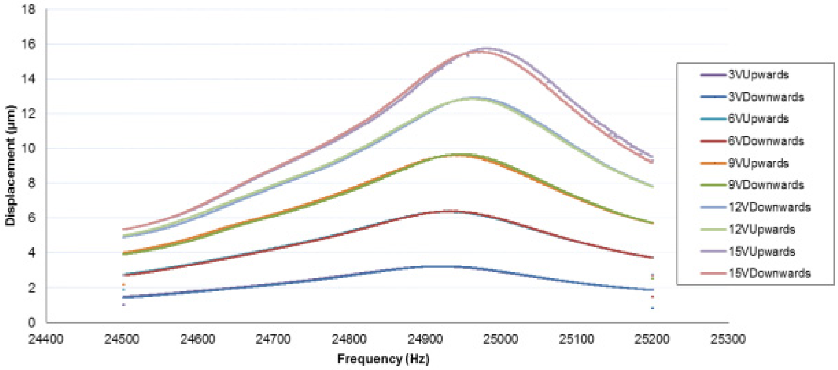
3.1. Vibration response of the devices

The impedance-frequency spectra of the devices were recorded with an Impedance Gain/Phase Analyzer (Agilent 42941A) in order to identify the resonance frequencies. Using this information, the displacement amplitude was measured in a small frequency range around the operational resonance frequency of each device in bi-directional sweeps using a 1D laser Doppler vibrometer (Polytec CLV) with a LabVIEW acquisition system and a signal generator, with a burst-sine signal applied. To support the experimental data, numerical models were produced using FEA. The resonance frequencies of the devices are shown in Table 2 and compared with the FEA results.

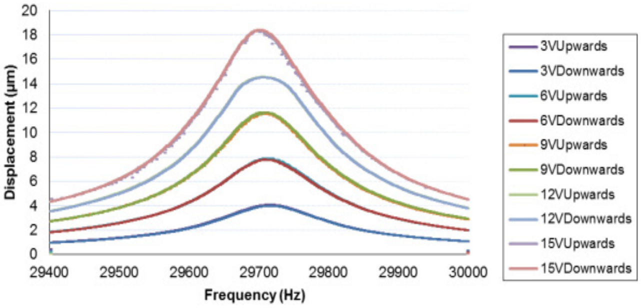
Table 2. Resonance frequencies of the different devices, in Hz.

Device	Experimental	FEA
New cymbal	24920	25416
Prototype	29712	28028
Prototype with insert	8370	8406

There is a very close correlation between the experimental and numerical data for each device, including the prototype device with a cutting insert attached. This level of correlation means that the finite element method can be used with a high level of confidence in the design of prototype devices based on the cymbal transducer. Using this information, the laser Doppler vibrometry method was used to measure the displacement amplitude for increasing input voltage for both the new cymbal transducer and the prototype device, and the results are shown in Fig. 3.



(a)



(b)

Fig. 3. Displacement of the (a) new cymbal transducer; (b) new prototype, for different input voltages.

The results in Fig. 3 show that the displacement amplitude for a given input voltage is almost the same for both the new cymbal transducer and the prototype device, showing the influence of the cavity dimensions on the displacement amplitude. The inclusion of a back-shell as a replacement of one of the transducer end-caps has not significantly affected the displacement amplitude response, where a similar level of energy is transferred from the piezoceramic to the vibrating end-cap in each case. However, there is a difference in the resonance frequency between the devices, where it is higher in the prototype device. The back-shell of the prototype device is a stiffer constraint than the metal ring of the cymbal transducer, which contributes to the higher resonance frequency.

3.2. The prototype device in operational cutting mode

In the prototype device, the cutting insert is attached directly to the apex surface of the end-cap via a threaded connection. This device can operate in two different ways, either in resonance or in non-resonance. In resonance mode the device operates with a cutting insert tuned at the same resonance frequency as the prototype, and in non-resonance mode the cutting insert has a different resonance frequency than the prototype, where the entire device operates at an independent resonance frequency. In the resonance mode, it is necessary to design the total length of the cutting insert to be half-wavelength ($\lambda/2$), in order to resonate at the same frequency as the prototype. A slight change in the dimensions of the cutting insert produces a notable reduction in the resonance frequency of the entire device. The prototype device developed for this study has been designed to operate in a range of frequencies between 25kHz and 30kHz, which means that the $\lambda/2$ length of the cutting insert should be very large in comparison with the dimensions of the prototype, in order to resonate at the same frequency. The consequence of this is that the resultant cutting device design will operate with a relatively low displacement amplitude due to the large mass fixed to the vibrating end-cap. In the non-resonance mode, the entire prototype device will operate at a resonance frequency much lower than that of the prototype, due the effect of adding the cutting insert mass. In this mode, a slight change in the length and shape of the cutting insert does not contribute a significant change to the resonance frequency, and the displacement amplitude achieved is higher, due to the small cutting insert relative to the large end-cap.

This study focuses on the non-resonance mode, in order to identify the effect of the cutting insert on the resonance frequency of the device. A commercial cutting insert (IM2A®) developed by Mectron S.p.A was affixed to the prototype, in this case using commercial adhesive. This cutting insert was made of steel with a total length of approximately 35mm. The IM2A® cutting insert and complete prototype device are shown in Fig. 4.

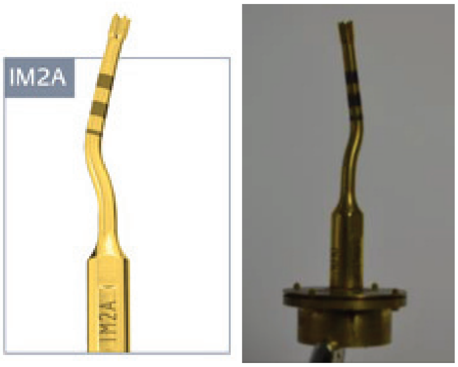
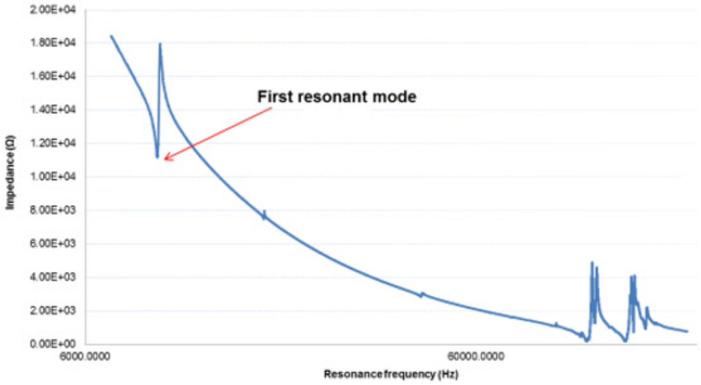
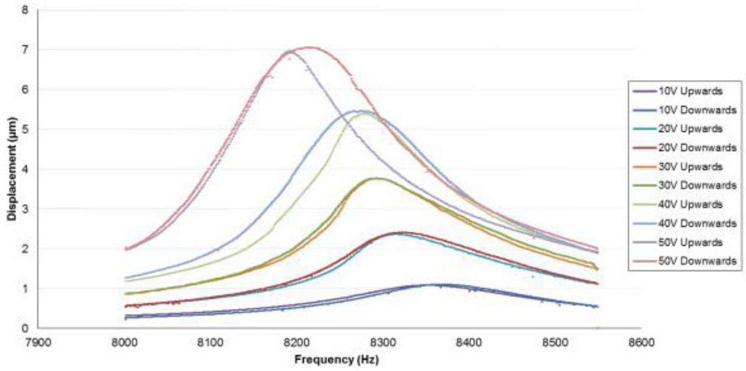


Fig. 4. (a) The IM2A® insert, courtesy of Mectron S.p.A.; (b) the complete device assembly.

The impedance-frequency spectrum and the displacement amplitude response of the prototype device with cutting insert attached were measured using the techniques described in Section 3.1. The impedance frequency spectrum is shown in Fig. 5(a). The displacement amplitude response as a function of frequency is shown in Fig. 5(b), where instead of an input voltage range of 3V to 15V used to characterise the devices as shown in Section 3.1, a range of 10V to 50V was used instead. The displacement amplitude of the prototype device was measured at the base of the cutting insert. A reduction in resonance frequency of almost 20kHz has been measured, which is in agreement with the FEA prediction shown in Table 2. This decrease in resonance frequency is due to the added mass of the cutting insert.



(a)



(b)

Fig. 5. (a) Impedance spectrum of the ultrasonic cutting device with IM2A® insert attached; (b) displacement amplitude of the prototype cutting device for different input voltages.

The results in Fig. 5(b) show that as input voltage is increased, a softening nonlinearity in the vibration response is observed, as a reduction of resonance frequency as the input voltage is increased. Furthermore, above an input voltage of 30V, the difference in displacement amplitude response between upward and downward frequency sweeps also becomes more pronounced. The nonlinearity in the vibration response of the prototype device is a phenomenon that requires much further study, but the appearance of nonlinear behavior in piezoceramics at high vibration amplitude levels has previously been reported (Mathieson (2012)). Despite the nonlinear response of the prototype device, there is clear opportunity for the development of a novel range of ultrasonic cutting devices which are based on the cymbal transducer configuration.

4. Conclusions

A prototype device for ultrasonic bone cutting procedures has been developed, based on an improved design of the traditional cymbal transducer. The mechanical coupling of the end-cap with the driver part of the transducer through a metal ring configuration allows the device to be driven at higher input voltages and displacements. Both the new cymbal transducer and a prototype device were fabricated for analysis. The devices were found to exhibit the same cavity resonance mode as the traditional cymbal transducer, with a single operational resonance frequency. The experimental results demonstrated that the vibration response of the prototype device is similar to that of the traditional and new cymbal transducers, maintaining a high level of energy transmission from the piezoceramic driver to the end-cap, but that the new cymbal transducer and prototype devices can be operated at higher displacement amplitudes than the traditional cymbal transducer. Close correlation was also found between experimental and numerical data. A prototype device with a cutting insert attached was also analysed, showing that for operation in the non-resonance mode the design of the prototype device should focus on tailoring the resonance frequency to compensate for the added mass from the cutting insert. Further research will focus on developing a new generation of ultrasonic cutting devices based on the cymbal transducer design.

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