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

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41st Annual Symposium of the UIA

San Francisco 2012 April 16-18

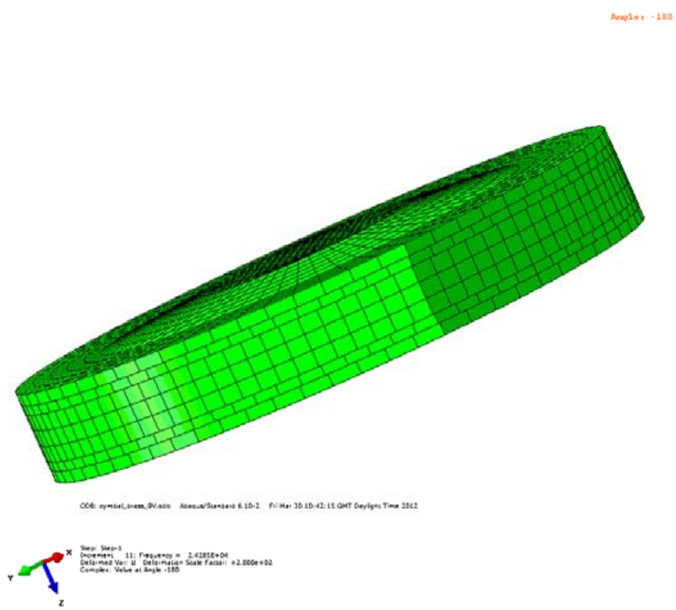
Ultrasonics in bone surgery

Although the first attempts to introduce tultrasonic technology in bone cutting procedures appeared in the 1950's, when researchers applied industrial drilling machines for bone surgery, it was not until 2001 that the first commercial device designed for bone cutting applications arrived on the market - a result of a collaboration between a maxillofacial surgeon, Vercellotti, and Italian company Mectron S.p.A

Piezosurgery® Device. Courtesy of Mectron S.p.A

Langeving transducer from the Piezosurgery® Device. Courtesy of Mectron S.p.A.

Traditional cymbal



High piezoelectric coefficients, high vibrational displacement and acceleration sensitivity at low frequencies, ease of tailoring the desired properties by the choice of the end-cap and driver materials and geometries with cost effective manufacturing are attractive features of the cymbal design.

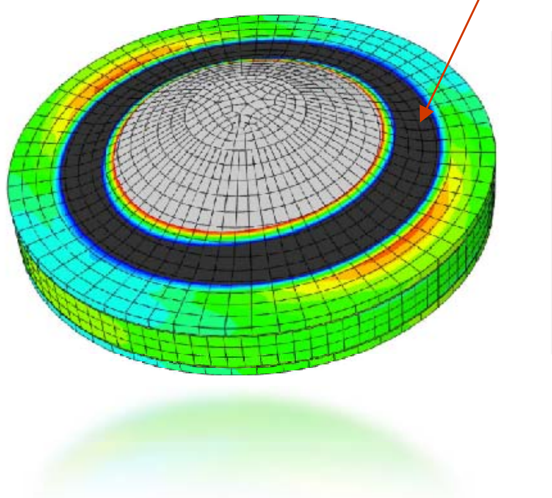
These make this transducer an attractive device for using **in low power applications:** hydrophone, accelerometer, sensors, actuators, motors and sound projector.

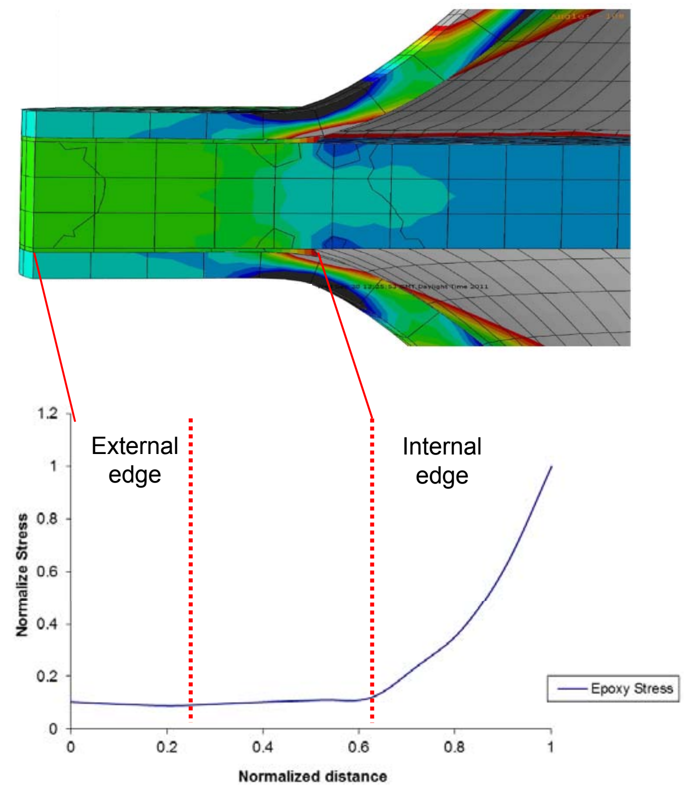
University of Glasgow

Traditional cymbal

When cymbal transducers are use at high power, critical problems appear that can reduce the performance of the cymbals due to high stress and electric concentration points, leading to degradations or debonding phenomena that can drastically reduce the operating life.

The maximum stress appear in the epoxy layer





Traditional cymbal

Experimental results for a traditional cymbal

Dimension:

PZT disc

PZT hard class 1

Diameter: 12.7 mm

Thickness: 1 mm

End cap

Material: brass

Cavity diameter: 9 mm

Apex diameter: 4.5 mm

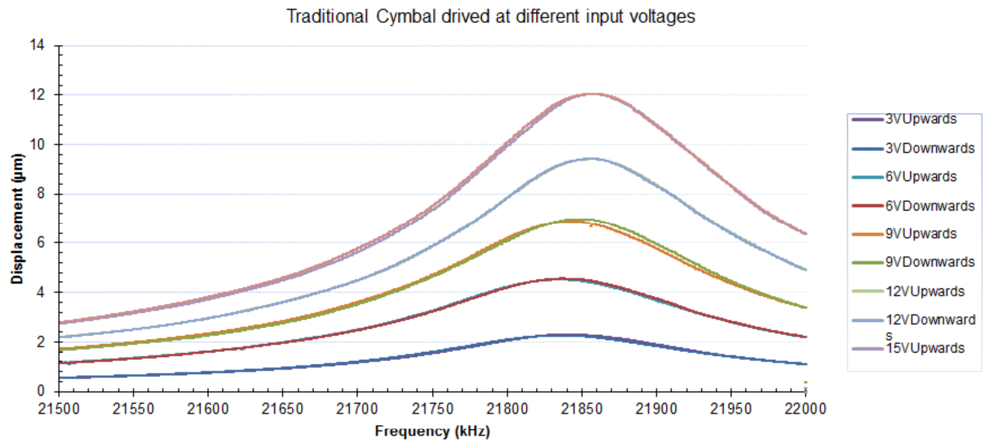
Cavity depth: 0.3 mm

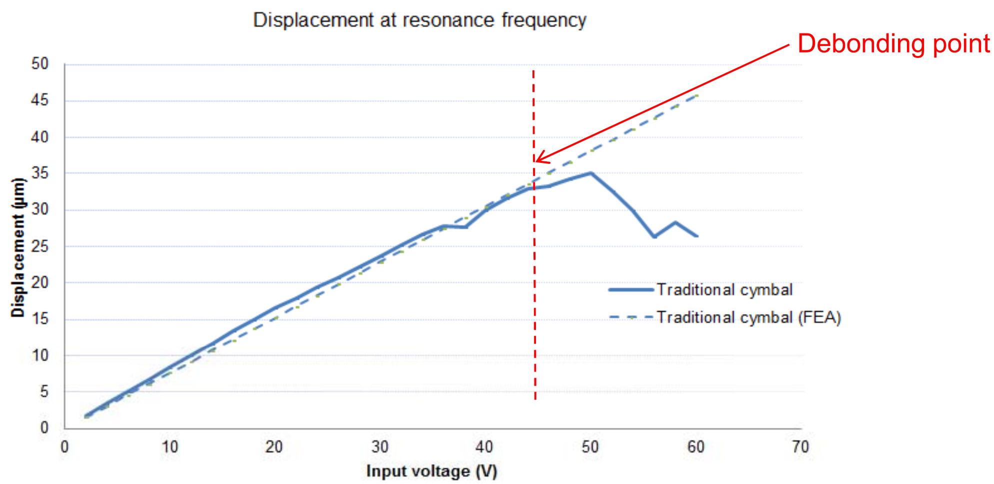
Epoxy layer

Eccobond 45LV

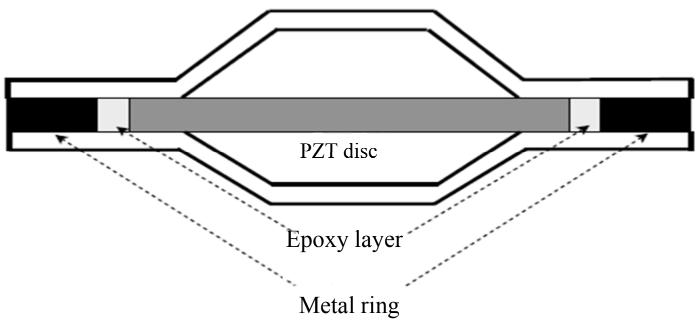
Thickness: 0.2 mm

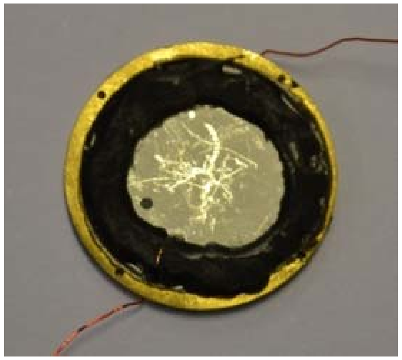
Traditional Cymbal	Resonance frequency (Hz)
Experimental analysis	21850
FEA analysis	24280

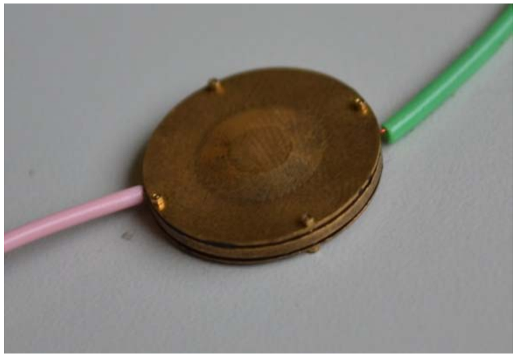




New Cymbal

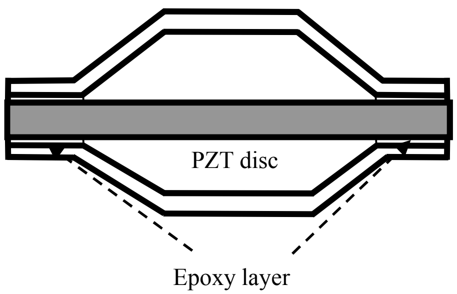


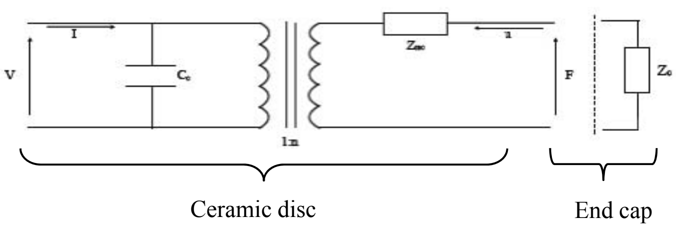




In 2010 Shuyu Lin developed a new design for the cymbal transducer, where the piezoceramic driver that generates the radial vibration, is substituted for a combination of a piezoceramic disc coupled, by means of an epoxy layer, to a metal ring. The end caps are fixed directly to the metal ring through some screws. The radial movement is transformed to a higher flextensional displacement through 2 mechanical couplings. This cymbal solves the problem of critical stress concentrations since the mechanical coupling between end cap and metal ring can be strong enough to drive the device at high power.

Electromechanical analysis



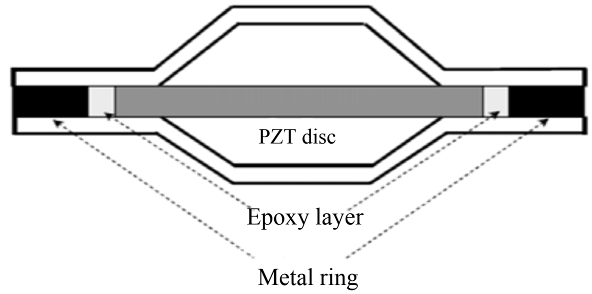


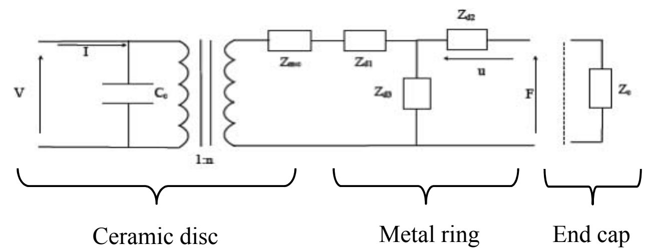
$$V_n(t) = V(t) \cdot n$$

$$u(t) = \frac{V_n(t)}{Z_{mc} + Z_c}$$

$$D(t) = \int u(t)dt = \int \frac{V_n(t)}{Z_{mc} + Z_c} dt$$

$$f_r = \frac{n^2}{2\pi \cdot C_c \cdot [Z_{mc} + Z_c]}$$





$$u(t) = \frac{V_n(t)}{Z_{mc} + Z_c + \left[Z_{d1} + Z_{d3} + \frac{(Z_{mc} + Z_{d1}) \cdot (Z_{d3} + Z_c)}{Z_{d2}} \right]}$$

$$D(t) = \int u(t)dt = \int \frac{V_n(t)}{Z_{mc} + Z_c + \left[Z_{d1} + Z_{d3} + \frac{(Z_{mc} + Z_{d1}) \cdot (Z_{d3} + Z_c)}{Z_{d2}} \right]} dt$$

$$f_r = \frac{n^2}{2\pi \cdot C_c \cdot \left[Z_{mc} + Z_{d1} + \frac{Z_{d2}(Z_{d3} + Z_c)}{Z_{d2} + Z_{d3} + Z_c} \right]}$$

New cymbal

Experimental results for the new cymbal

Dimensions of the driver part:

Metal ring

Material: Brass

Thickness: 1 mm

Outer diameter: 16.7 mm

Inner diameter: 14.7 mm

Epoxy ring

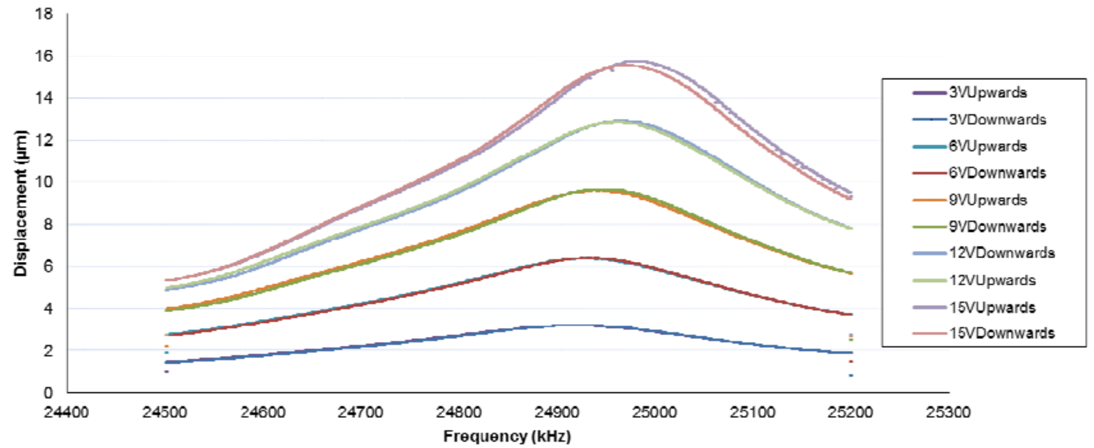
Eccobond 45LV

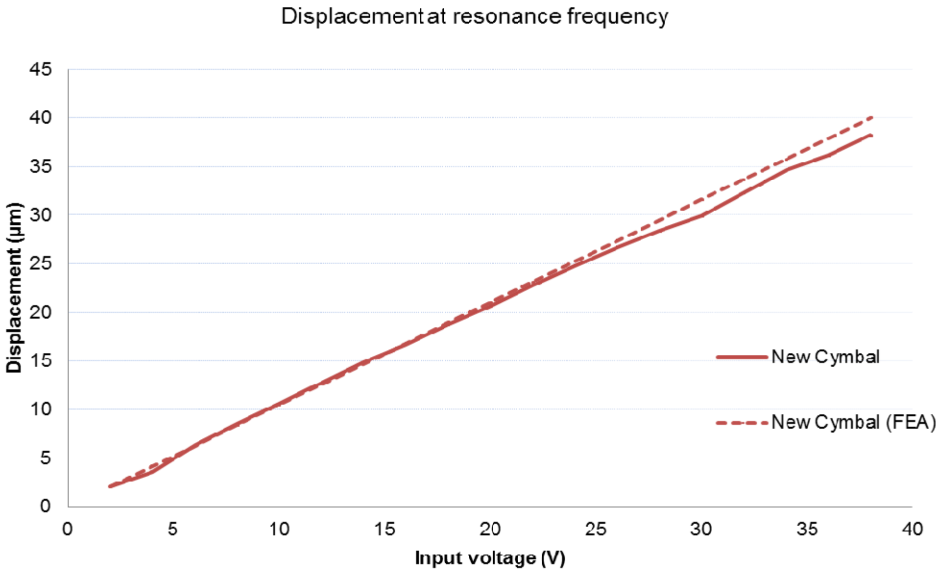
Thickness: 1 mm

Outer diameter: 14.7 mm

Inner diameter: 12.7 mm

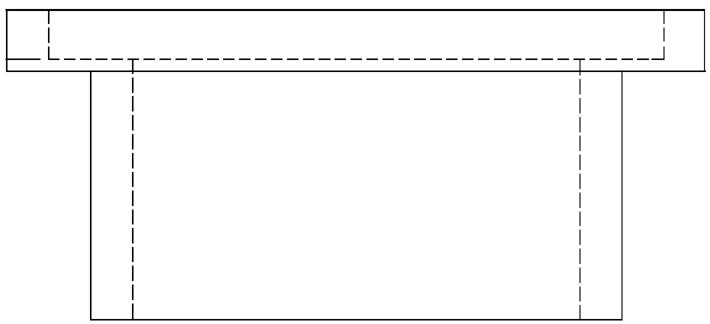
New Cymbal	Resonance frequency (Hz)
Experimental analysis	24920
FEA analysis	25416



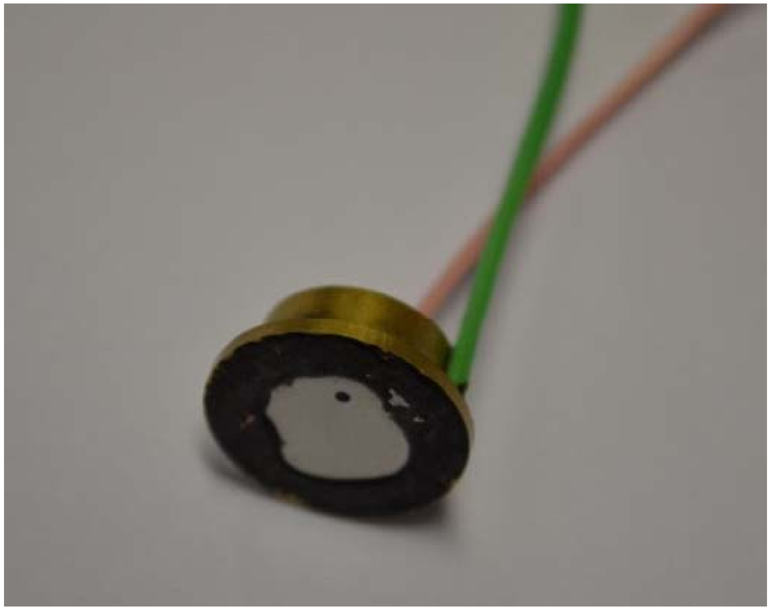


Prototype cutting device

This prototype is based on the design of the new cymbal. The transducer has only one end cap and has a back shell where the piezoelectric driver is placed, bonded with insulating epoxy resin. The metal end cap is attached directly to the shell. This part makes it easier to use the device and gives more stability to the whole prototype. The cutting tip is attached on top of the end cap.



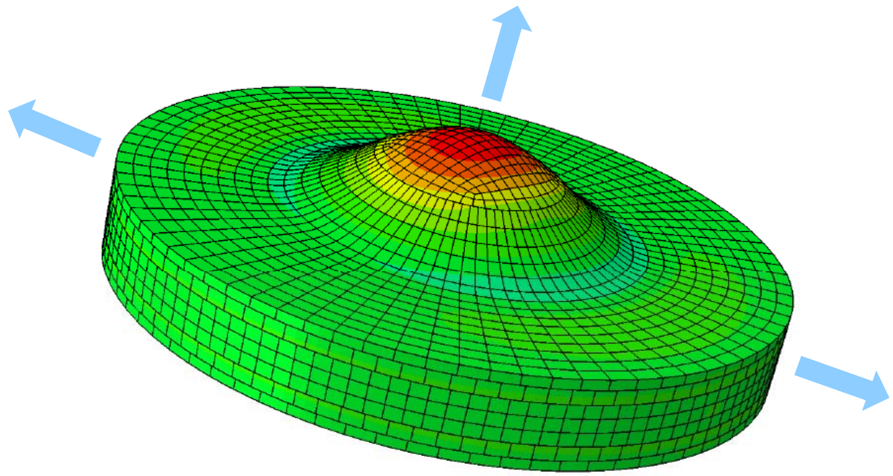
Sketch of the back shell

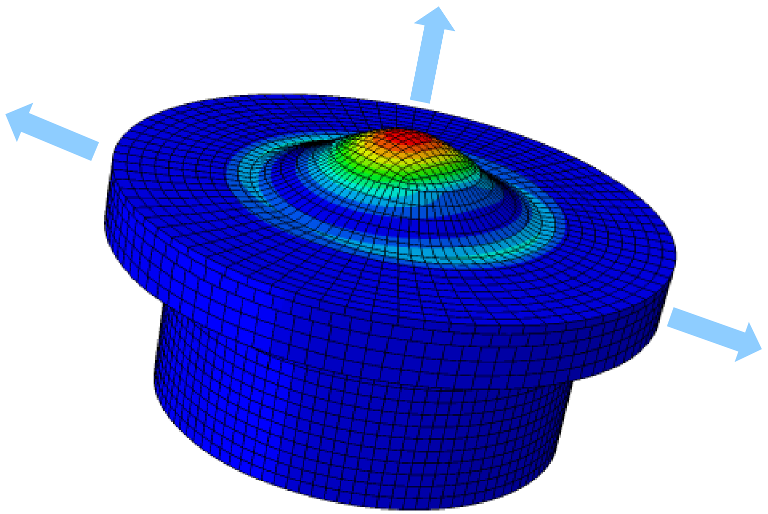


Prototype cutting device

The design of the whole transducer is optimised to transfer the radial movement of the piezoelectric disc directly to the metal end cap, so at the resonant mode of the cavity the device exhibits a pure axial movement as is shown in the traditional cymbal transducer.

The resonance frequency is determined by the dimensions of the cavity. With the same end cap, this device should have approximately the same resonance frequency as the new cymbal transducer.

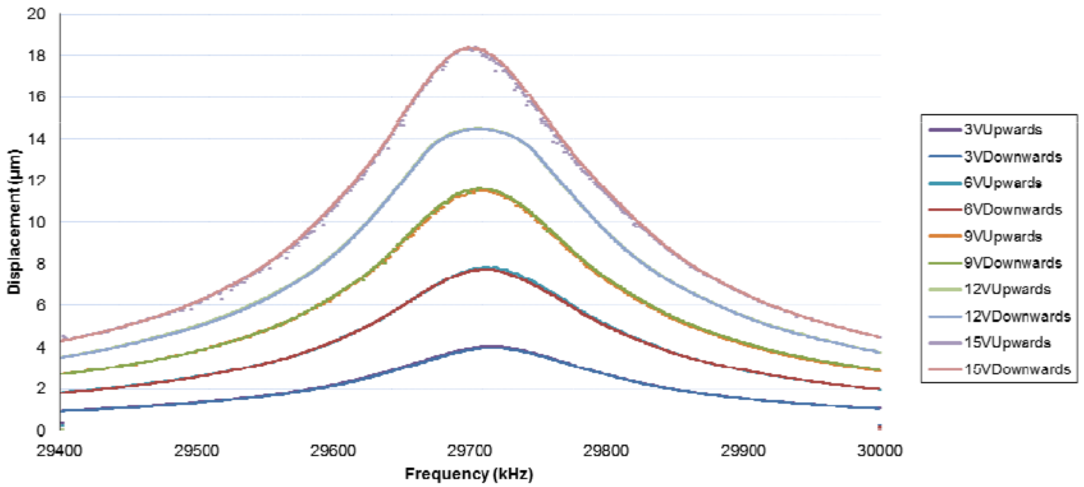


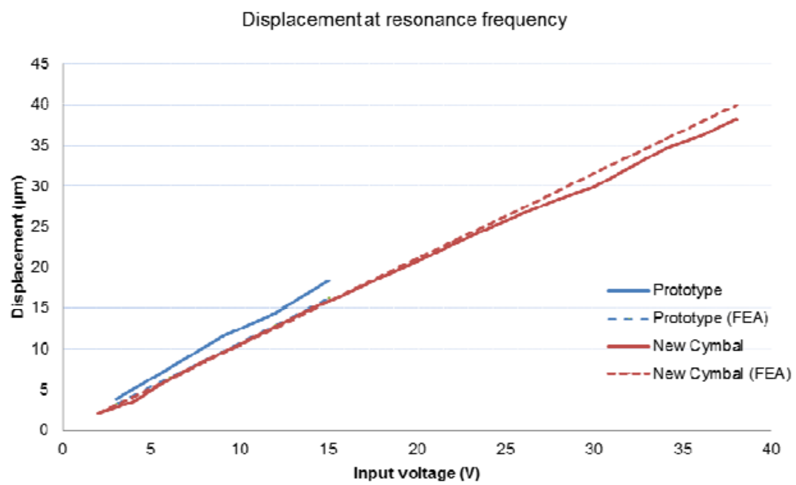


Prototype cutting device

Experimental results for the prototype

Prototype	Resonance frequency (Hz)
Experimental analysis	29712
FEA analysis	28028



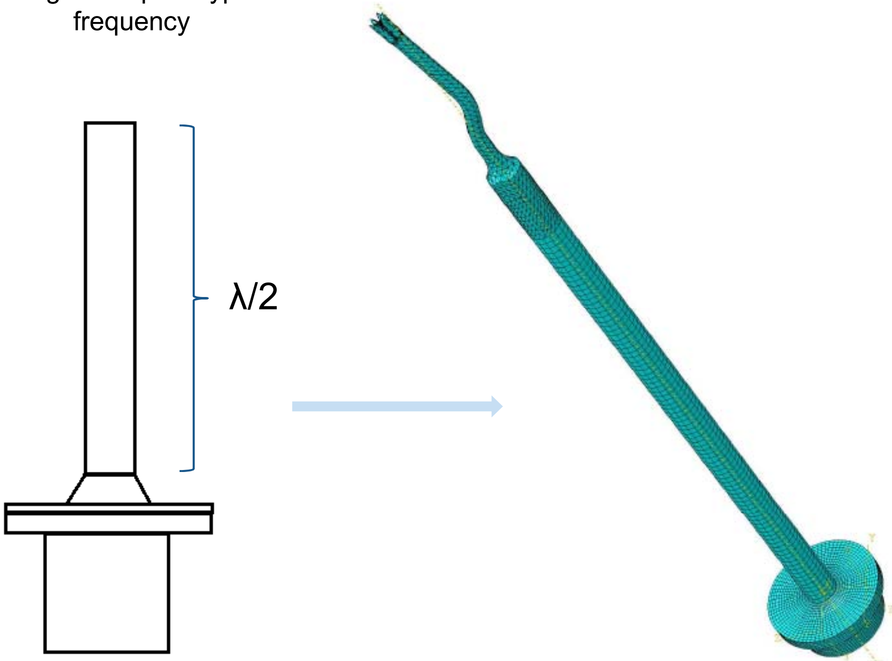


Prototype cutting device

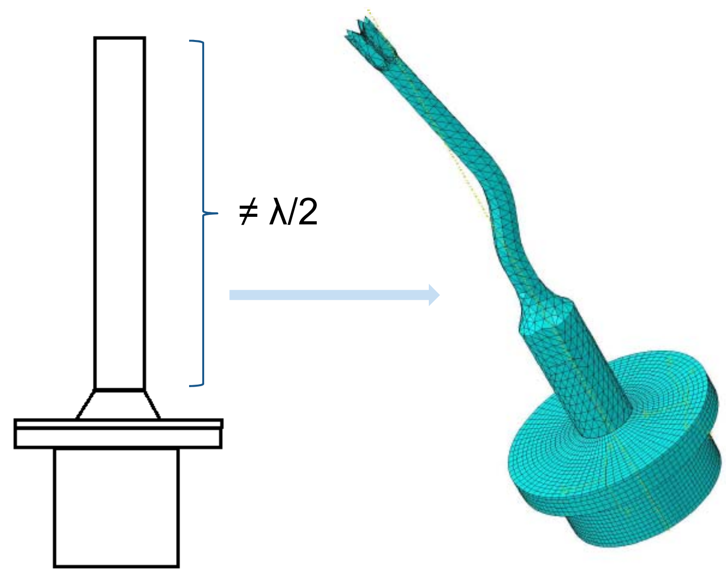
This device can operate in two different ways: In resonant mode, with a blade tuned at the same resonant frequency as the prototype, or in not-resonant mode, in which the blade has a different resonant frequency than the prototype and the total device works at an independent resonance frequency.

In resonant mode it is necessary to design the total length of the blade at λ/2 to resonate at the same frequency as the prototype. Due to the small dimensions of the prototype and the low ultrasonic frequency, the length of the cutting tip necessary to tune it with the prototype resonance frequency is large, so the resultant device has a low displacement.

Device working at the prototype resonance frequency

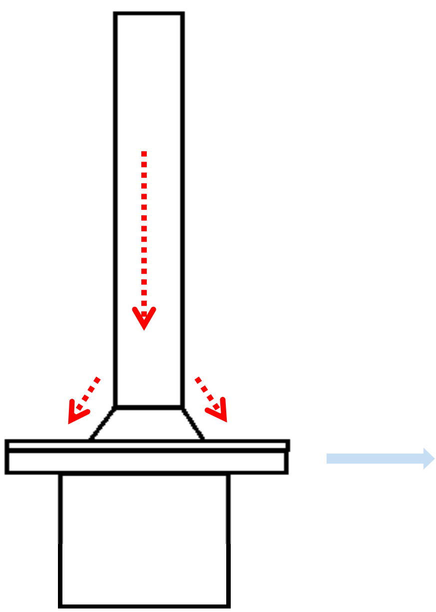


Device working at a different frequency from the prototype resonance frequency

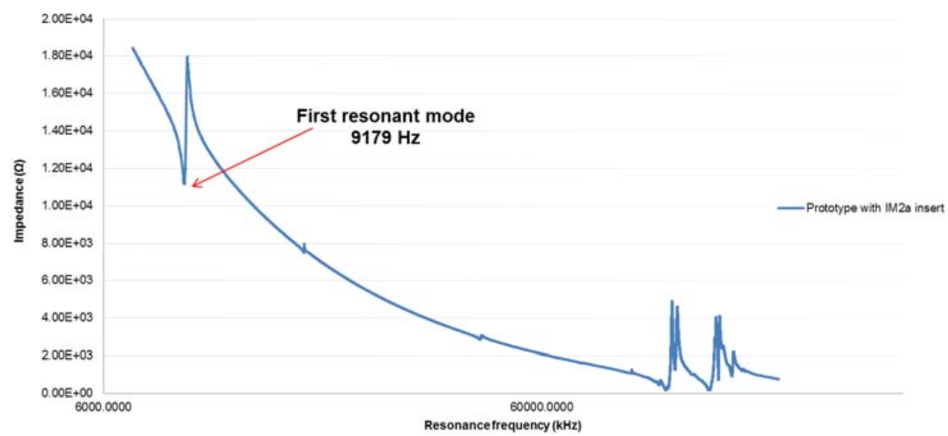


Prototype cutting device

In not-resonant mode, the blade has an arbitrary dimension, in this case as small as possible. The total device will work at a different resonance frequency, much lower than the resonance frequency of the prototype, due to the effect of the tip mass. In this mode a slight change in the length and shape of the blade does not have a big effect on the resonance frequency, and due to the relatively small dimensions of the blade, this exhibits a much better ratio of displacement/input voltage than the tuned device.



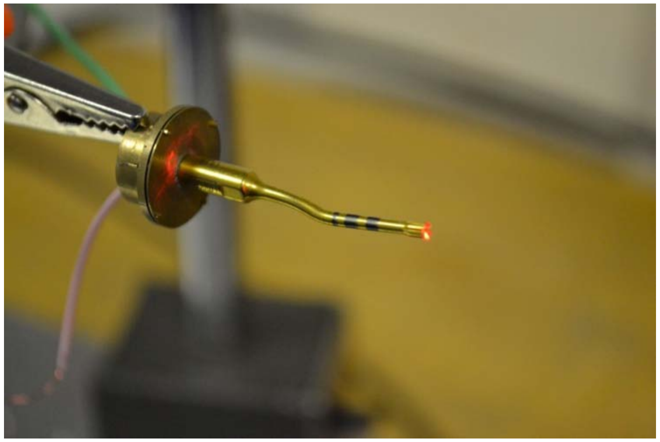
↓ Resonance frequency

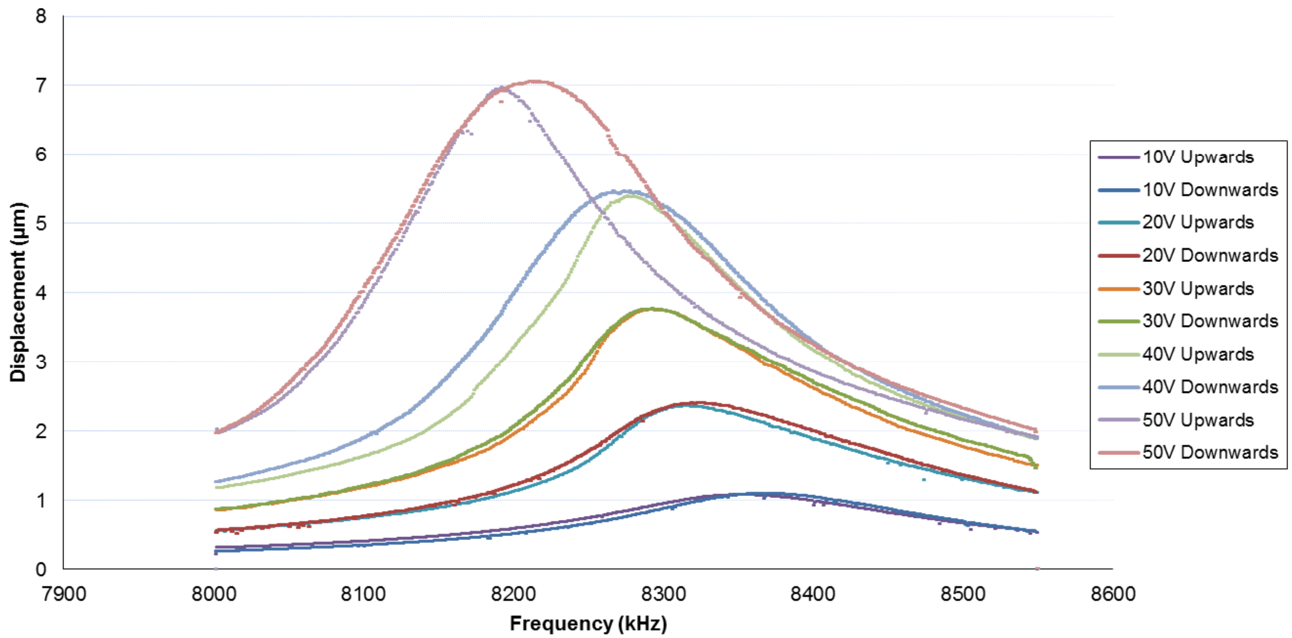


Prototype cutting device

Experimental results for a non-tuned cutting device at the resonance frequency of the prototype

Cutting device	Resonance frequency (Hz)
Experimental analysis	8370
FEA analysis	8446





Conclusions

- The new cymbal solves the problem of coupling between the end cap and piezoceramic of the traditional cymbal. The mechanical coupling between both can be as strong as our application requires.
- The design of the new cymbal will reduce or eliminate the double-peak response in the spectrum of the transducer, since the control of symmetry of the whole device is easier of to achieve.
- A novel device for use as the driver of an ultrasonic cutting device has been proposed. It is a variant of the new cymbal optimised to accommodate a mass (cutting tip). In order to transmit the maximal energy to the cutting tip it is necessary to choose carefully the materials for the different parts to ensure a match of impedances. With this device we can reach high displacement with low input power.
- There are two different ways to design the final cutting device:
  - tune the cutting tip to resonate at the prototype resonance frequency, in this case the displacement is low and slight changes in the shape of the cutting tip results in the final prototype losing its operational mode,
  - use an arbitrary length of cutting tip, where the prototype has a low resonance frequency, much less dependant on the shape of the cutting tip, increasing the output amplitude. In order to have a prototype working at a specific resonance frequency it is important that the design of the prototype compensates for the reduction in the resonance frequency due to the tip mass.

Acknowledgments

The authors would like to thank **Mectron S.p.A.** for providing the cutting tip for this paper, **Andrew Mathieson** of the Power Ultrasonics Research Group, University of Glasgow, for experimental advice, and the **Engineering and Physical Sciences Research Council** (Grant EP/G046948/1) for the funding and support of this project.

Thank you very much for your attention