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A miniaturized class IV flextensional ultrasonic transducer

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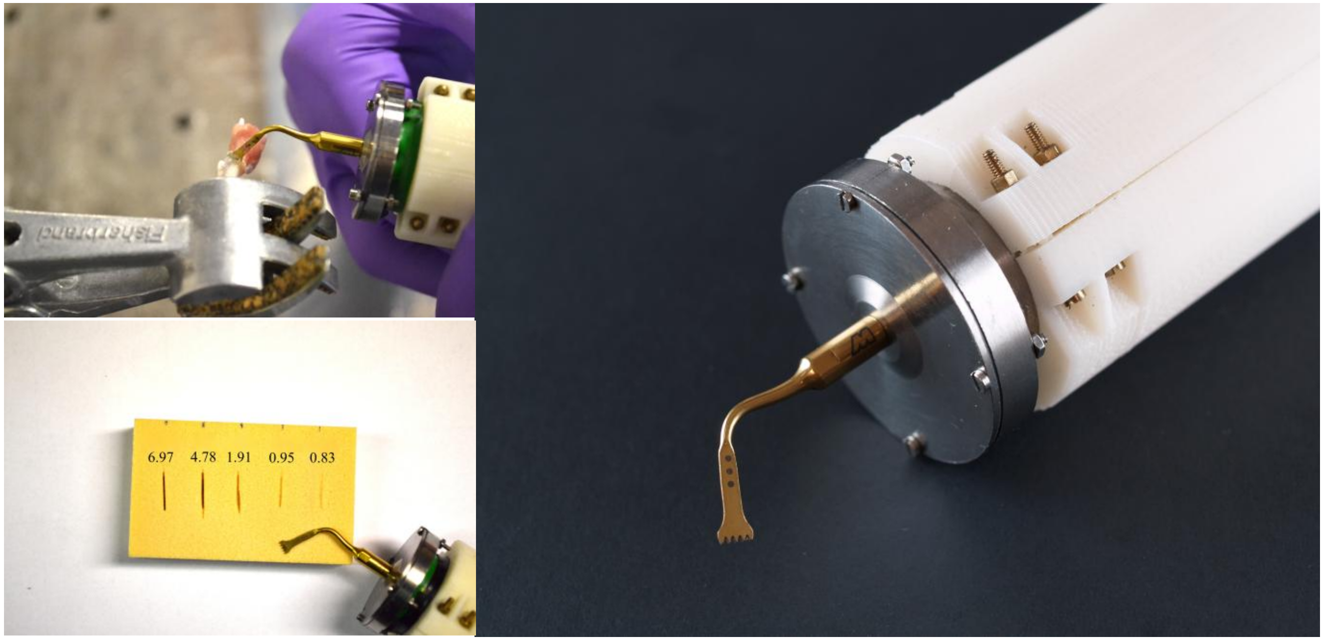
Investigation Motivation

Miniaturisation of piezoelectric transducers has recently been studied for power ultrasonic cutting (Bejarano 2014).



The device was based on a class V flextensional transducer design called the cymbal transducer.

It is postulated that the performance and optimisation of a miniaturised transducer can both be improved by employing a parametric design process.

Flextensional Transducers

Transducers which are capable of significantly amplifying motion of the driver through a flexural-extensional behaviour.

Seven principal classes have found popularity:

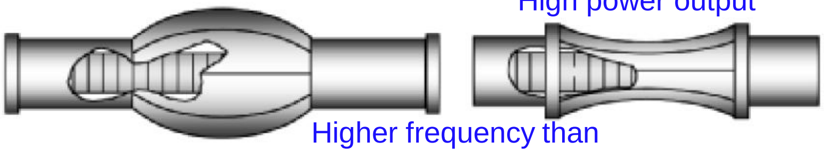
Class I

Short, cylindrical end-sections

Low frequency

Omnidirectional radiation

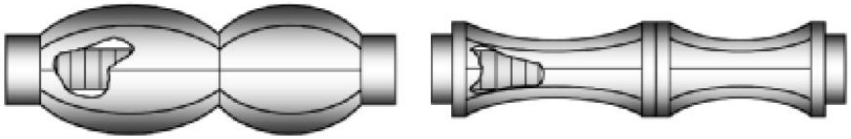
Class II



High power output

Higher frequency than class I: ≈ 1-15kHz

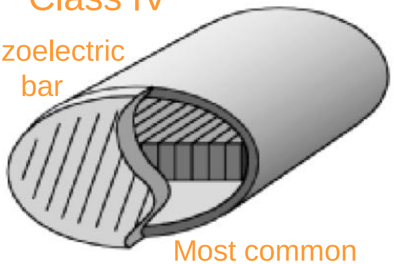
Class III



Different resonance for each shell

Broadband

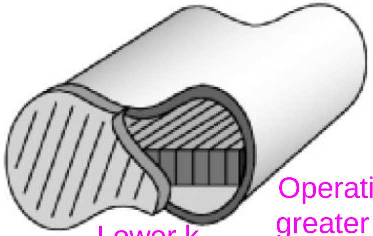
Class IV



Piezoelectric bar

Most common

Class VII

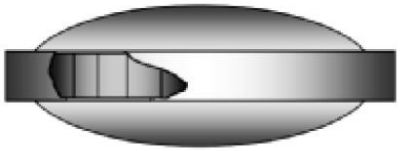


Omnidirectional radiation

Operational at greater depths

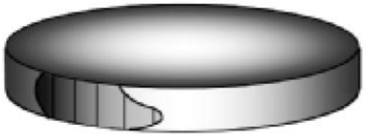
Lower k_{eff} than class IV

Class V



Adapted into popular moonie and cymbal transducers

Class VI

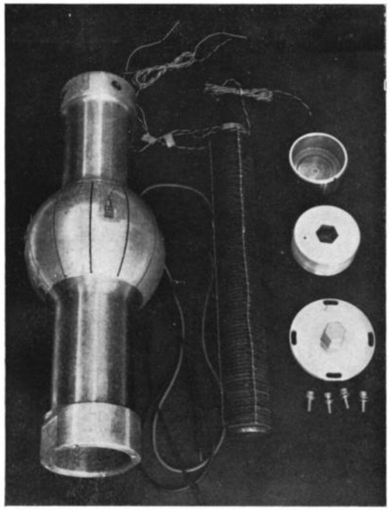


Concave shell

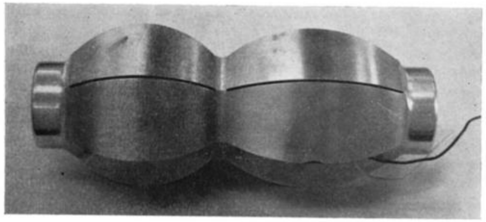
Operational at greater depths than class V

Transducers driven using either magnetostrictive or piezoelectric driver materials

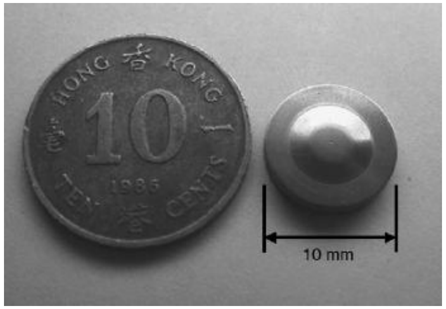
Flextensional Transducer Applications



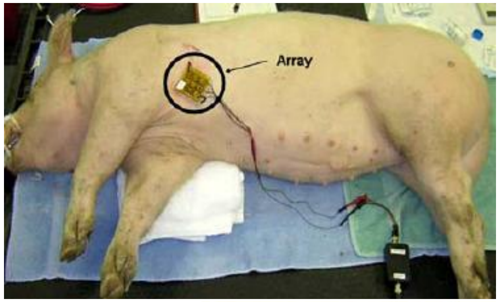
Underwater class II transducer (Royster, 1970)

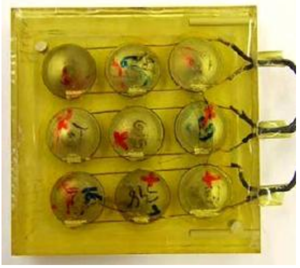


Underwater class III transducer (Royster, 1970)



Miniaturised actuators (Lam et al., 2006)



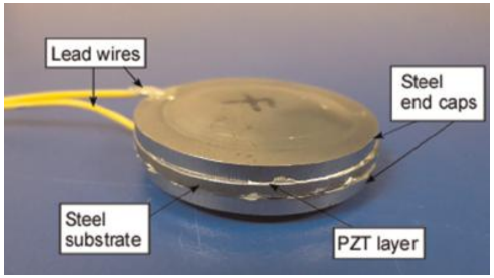


Transdermal drug delivery (Park et al., 2007)

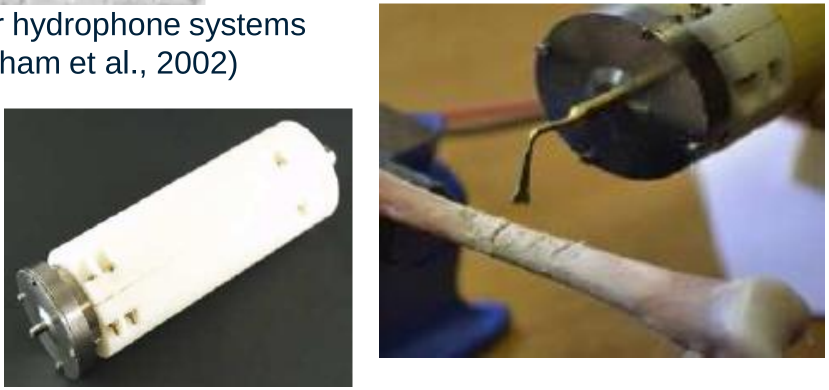
The original class V as a sonobuoy (Royster, 1970)

Underwater hydrophone systems (Newnham et al., 2002)

Flextensional modified for high amplitude (Lin, 2010)



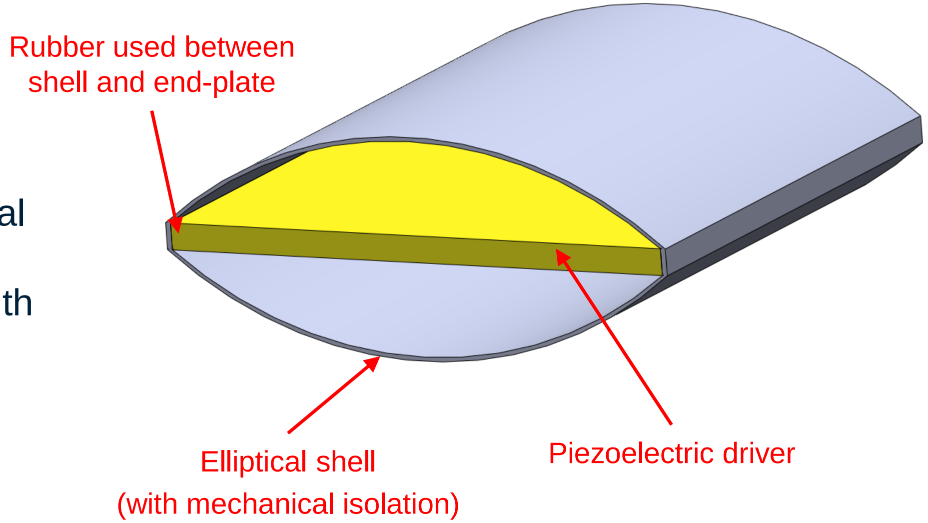
Energy harvesting (Mo et al., 2012)



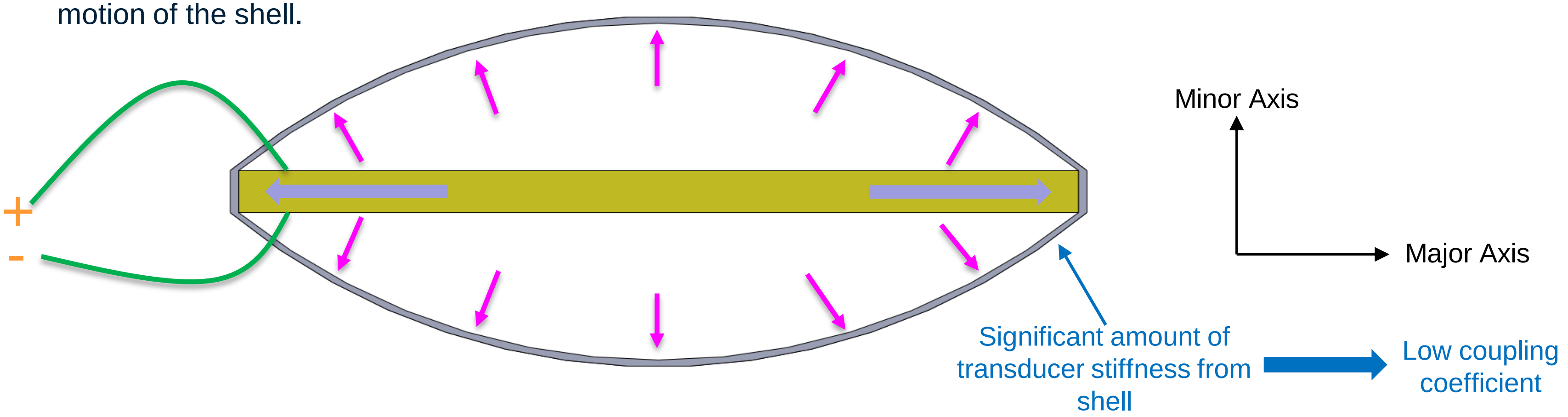
Surgical cutting application of a modified cymbal transducer (Bejarano et al., 2014)

The Class IV Transducer

- Idea originated by Hayes in 1936
- Toulis developed a class IV transducer in the 1960s with a piezoceramic driver
- Traditionally fabricated using an oval or elliptical shell
- For underwater applications, steel, high-strength aluminium or GRP are the most common shell materials
- The most popular drivers are PZT-4, PZT-8, Terfenol-D or PMN



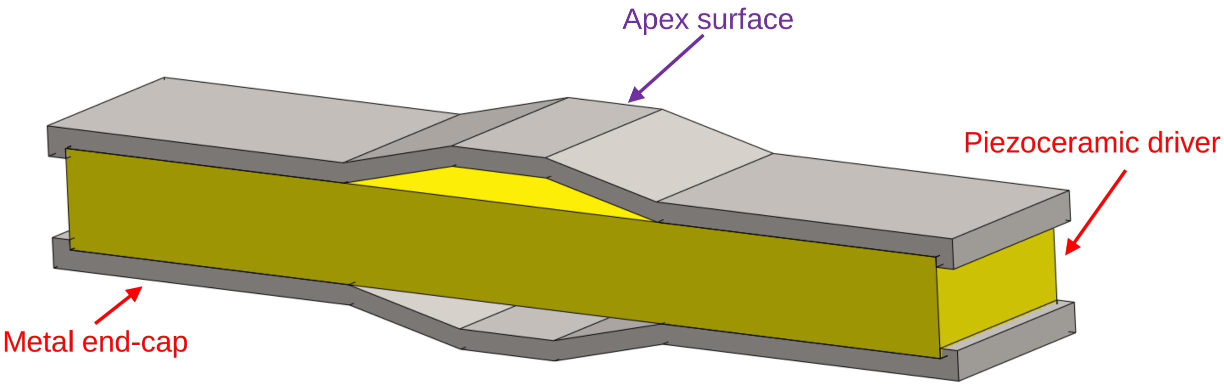
Conversion of high impedance, low displacement extensional motion of piezoceramic into high amplitude extensional motion of the shell.

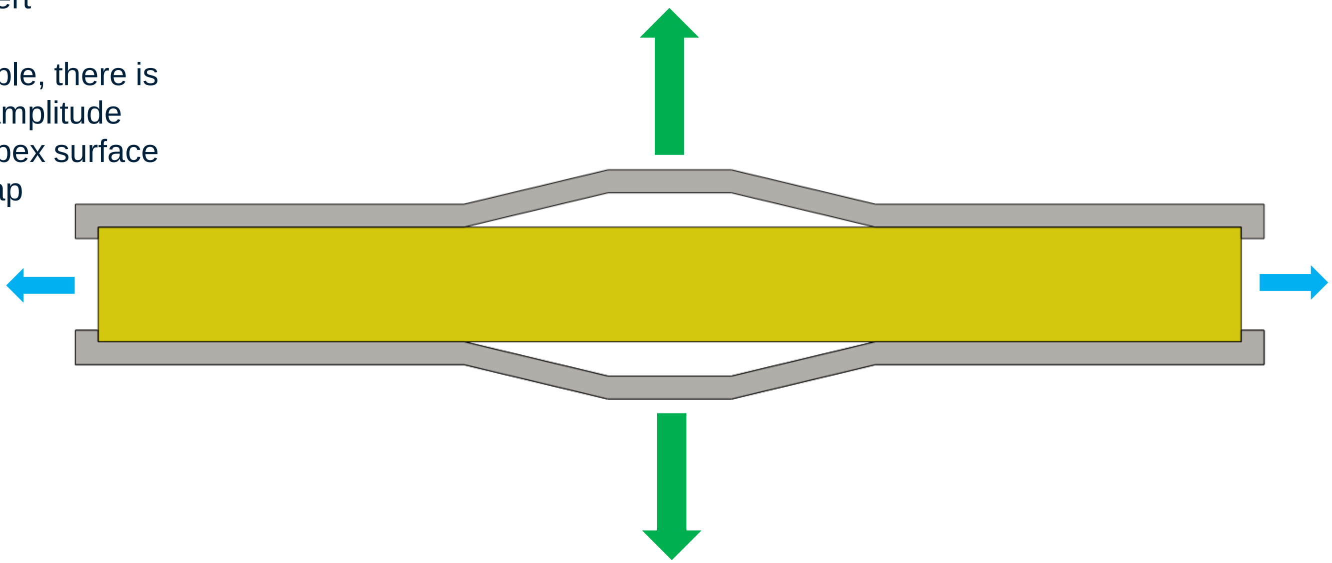


Transducer Design

In this research, the class IV configuration and operating principle has been utilised, but with slight modification of shell geometry.

- Future objective is to be able to drive an attachment or end-effector for a power ultrasonic application, for example a surgical cutting insert
- To make this possible, there is a requirement for amplitude uniformity on the apex surface of the metal end-cap





Conversion of high impedance, low displacement extensional motion of piezoceramic into low impedance, high displacement axial motion of the end-caps.

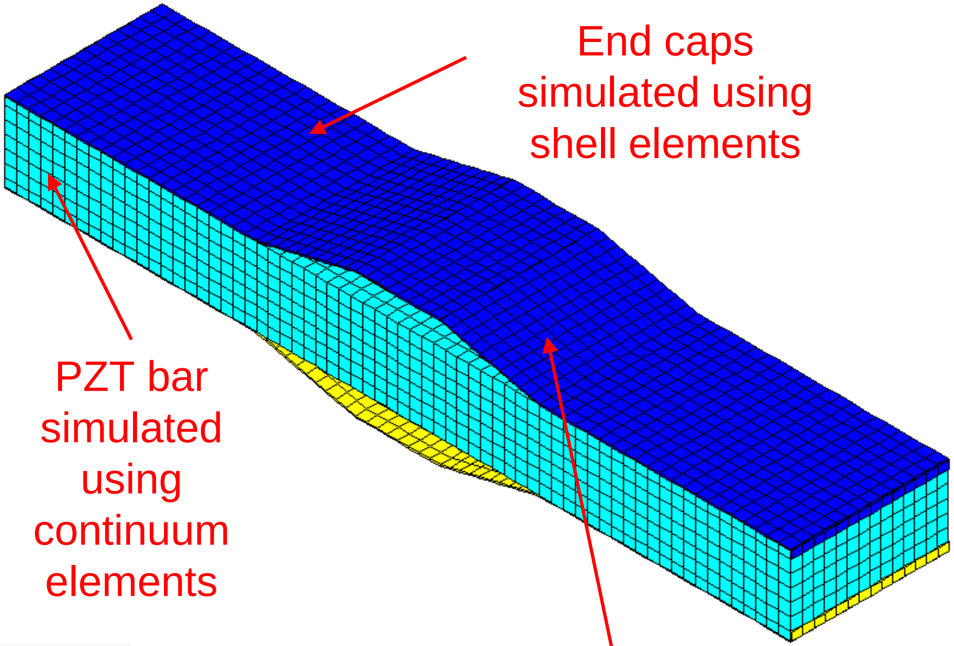
Objectives

The objectives for this study are:

- Miniaturisation of a class IV type flextensional transducer
- Exploitation of the length mode of a piezoelectric ceramic bar
- Maximisation of the ratio of amplitude of vibration to the volume of the piezoelectric ceramic bar
- Establish foundations for the design of a class IV type flextensional transducer for power ultrasonic applications
- Numerical simulation used in the design and optimisation of the transducer, enabling fast and efficient design assessment
- Experimental vibration characterisation used to compare with the simulations

Numerical Simulation

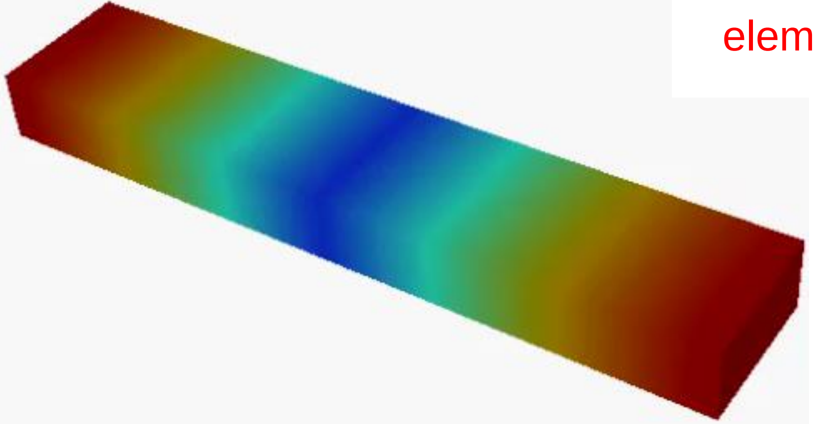
- PZFlex is a Finite Element package specifically design for simulating ultrasonic transduction and wave propagation
- An explicit time domain solver is used to allow rapid simulation of very large transient problems
- A hybrid electro-mechanical solver allows fully coupled simulation of piezoelectric devices



End caps simulated using shell elements

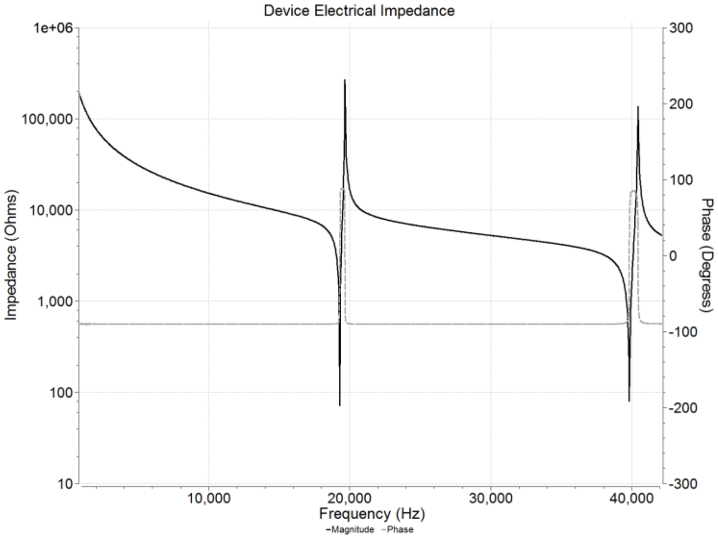
PZT bar simulated using continuum elements

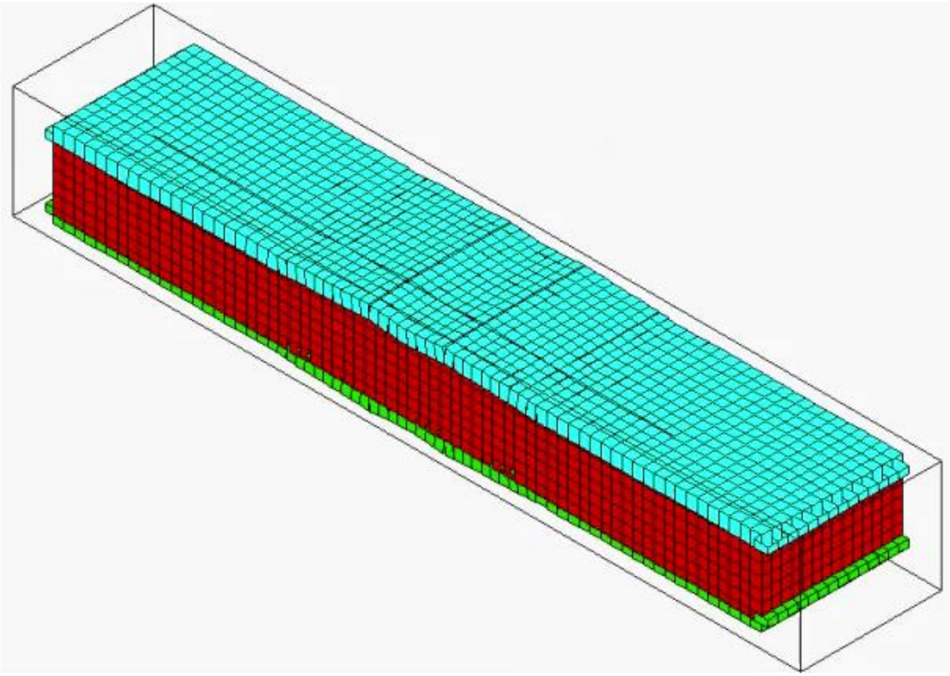
Skewed structured grid accurately recreated end-cap structure

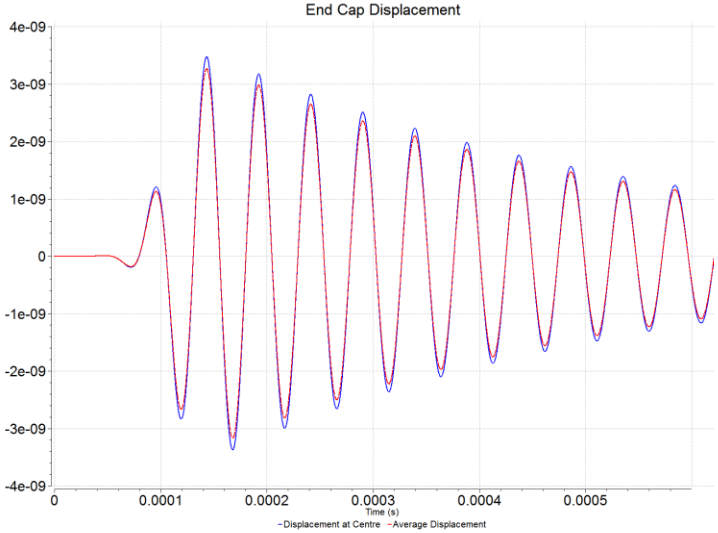


Numerical Simulation

- Simulating using time domain FEA allows a range of outputs to be produced which can be directly compared to experiment
- Results show modal displacement at 19.3kHz (bottom left), electrical impedance (top right) and cap displacement (bottom right)
- Comparing cap displacement at the centre to the average across the face provides a way of measuring dilation quality



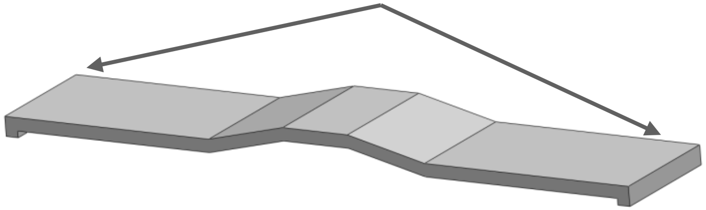


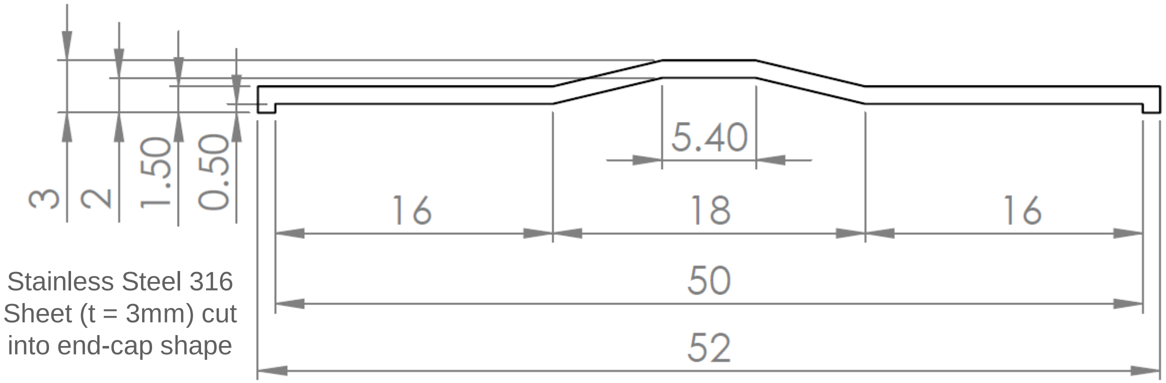


Transducer Fabrication

Flanges included at the end:

- Analogous to the traditional end-plates for a class IV
- Used here to increase energy transfer between piezoceramic and end-cap
- Also helps to secure piezoceramic in place

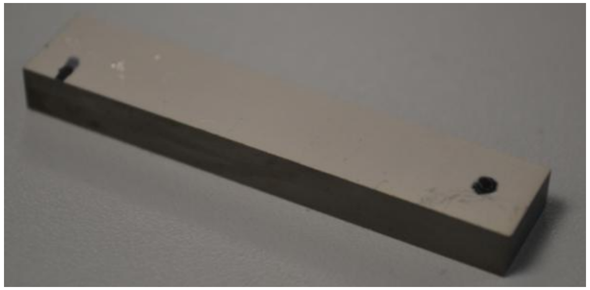




Stainless Steel 316 Sheet (t = 3mm) cut into end-cap shape

Size of each end-cap, with all dimensions in mm

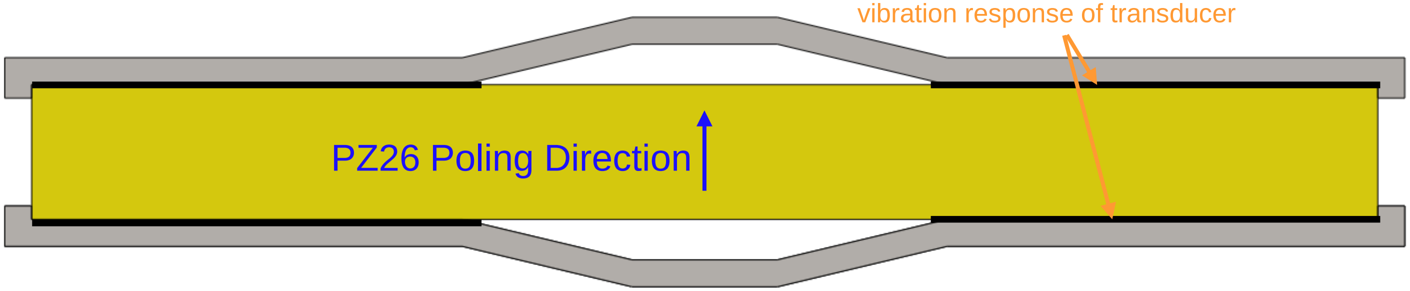
Ferroperm Hard PZ26 plate (Navy Type I), 50x50x5 mm (Meggitt A/S)



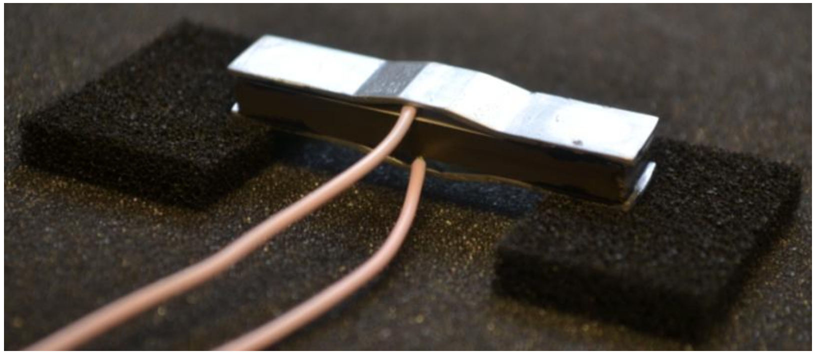
PZ26 sliced to the desired dimensions of 50x10x5 mm

Transducer Fabrication

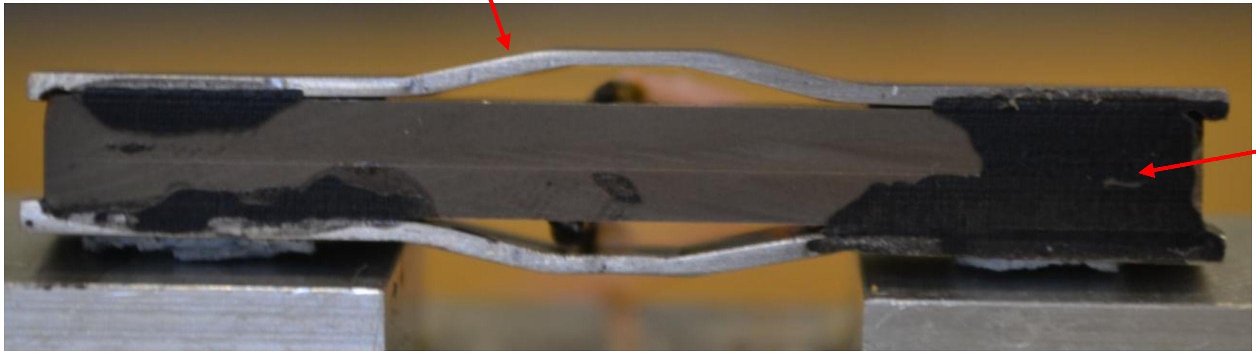
Eccobond 45 LV High Strength Insulating Epoxy Resin (Ellsworth) deposited to surface of PZ26 bar, and left to cure with the transducer in a rig at room temperature for 24 hours



Asymmetry between the epoxy resin bond layers can cause other modes to appear in vibration response of transducer



No epoxy resin in transducer end-cap cavities

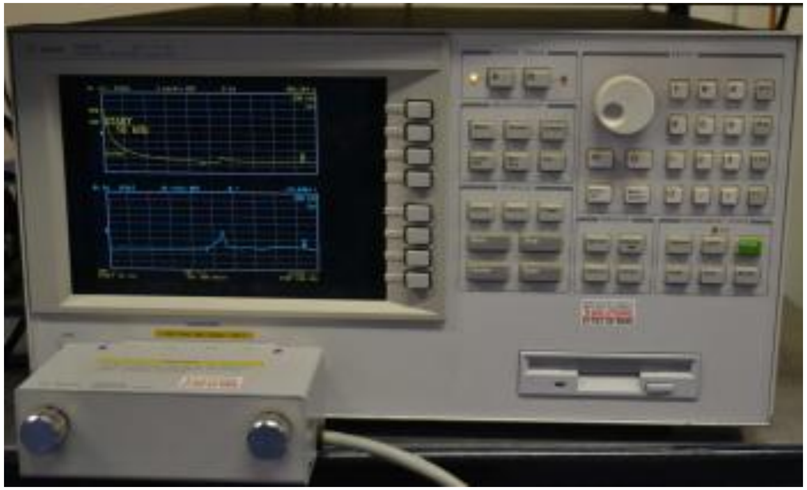


Extra epoxy resin for removal post-cure

Vibration Characterisation Process

Two experimental characterisation methods used to compare to the FEA.

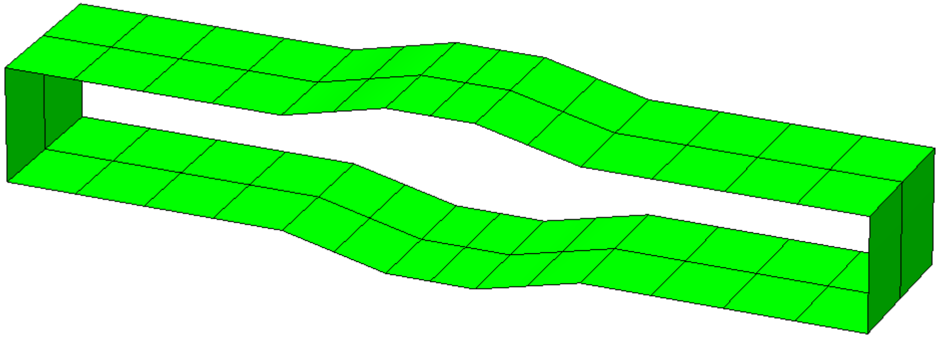
Electrical impedance measurement (Agilent 4294A Impedance Gain/Phase Analyzer)



Impedance-frequency spectrum generated:

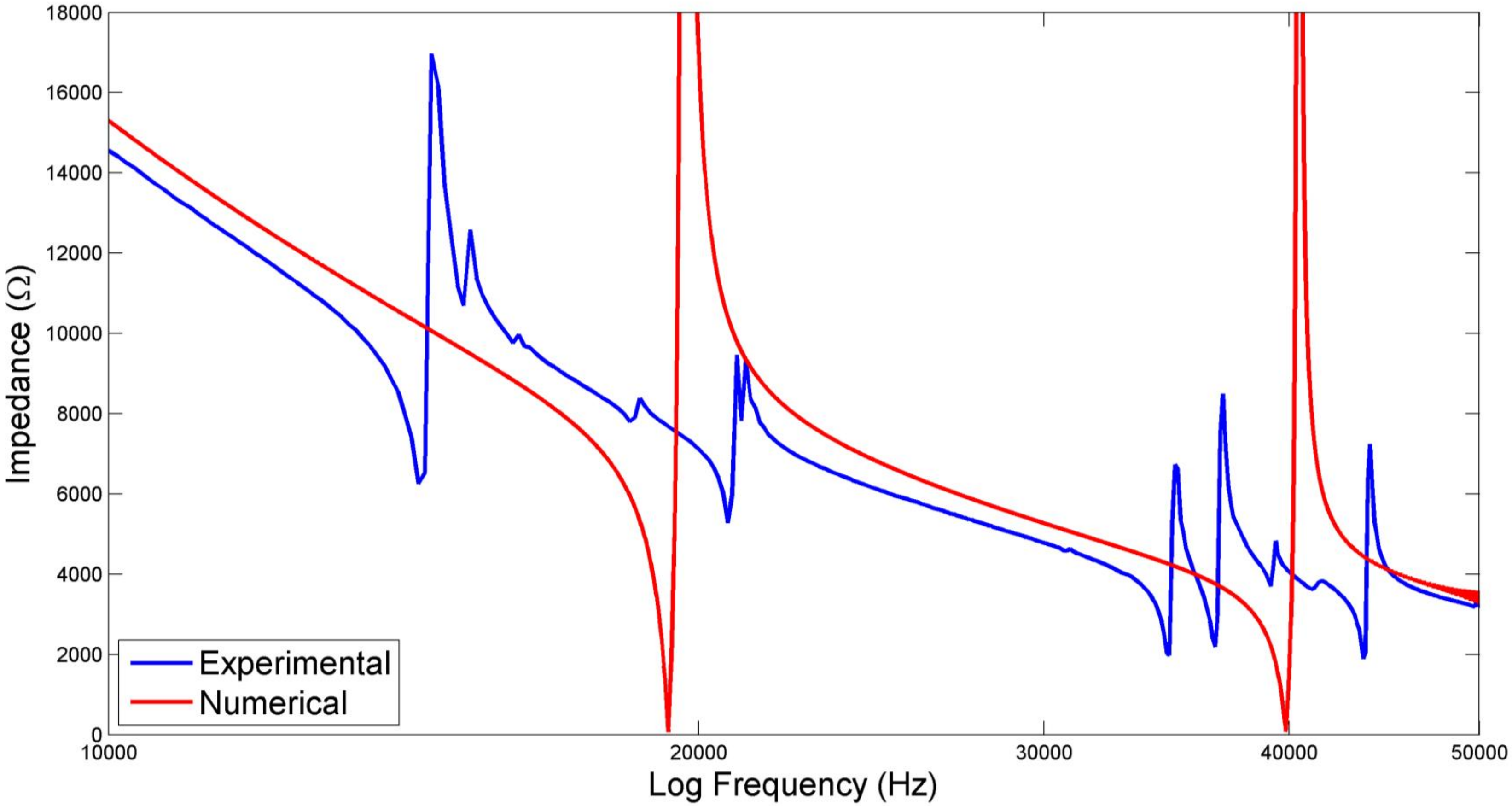
- Helps determine frequency of fundamental operating mode
- Can be used to check short-circuiting in the transducer
- Results can be compared directly with the PZFlex output

Experimental Modal Analysis (EMA), Polytec 3-D LDV with DataPhysics SignalCalc acquisition software, processed with ME'ScopeVES



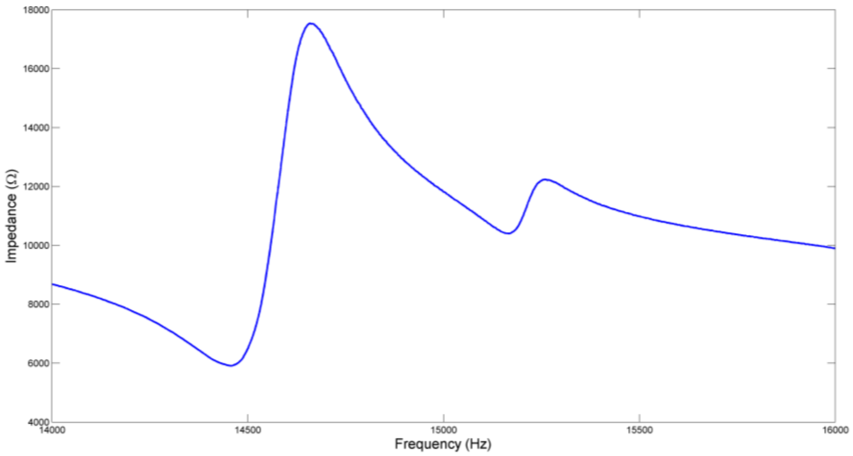
- EMA is used to determine the dynamic properties of a vibrating structure, and can be used to validate FEA simulations
- Mode shapes, associated resonant frequencies, and FRFs are all obtainable using this method
- Laser Doppler vibrometry used to perform EMA, based on small size of transducer

Impedance-Frequency Spectrum

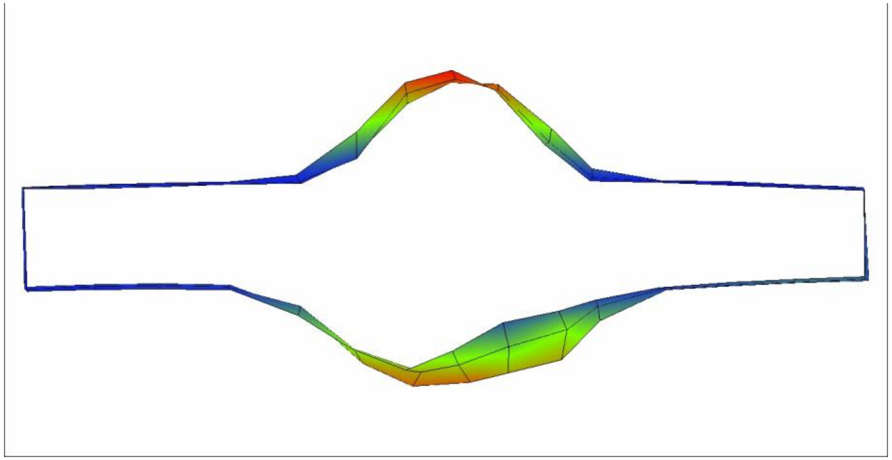


- Mode at 14kHz has appeared in experimental results
- Numerical and experimental frequencies similar around 20kHz and 40kHz
- Device fabrication likely contributing to appearance of 14kHz mode

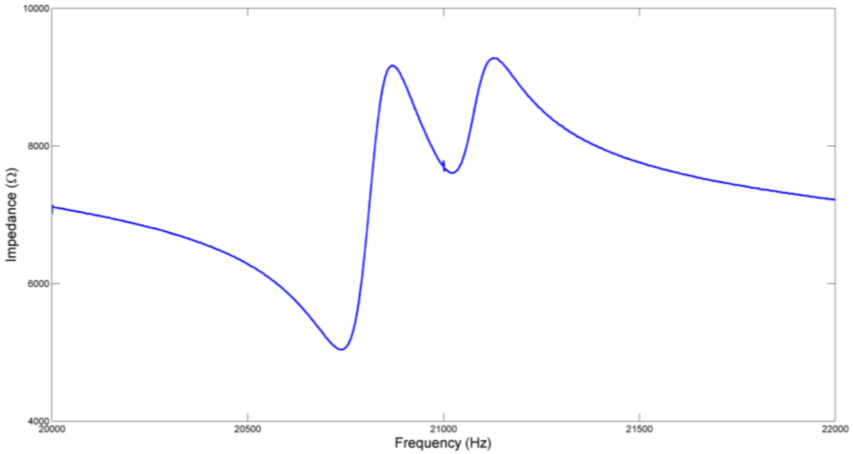
Experimental Modal Analysis



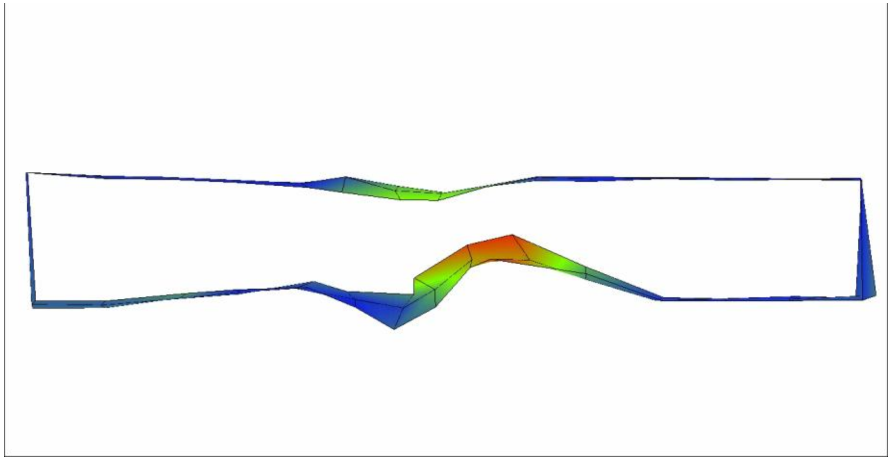
14449Hz



14322Hz

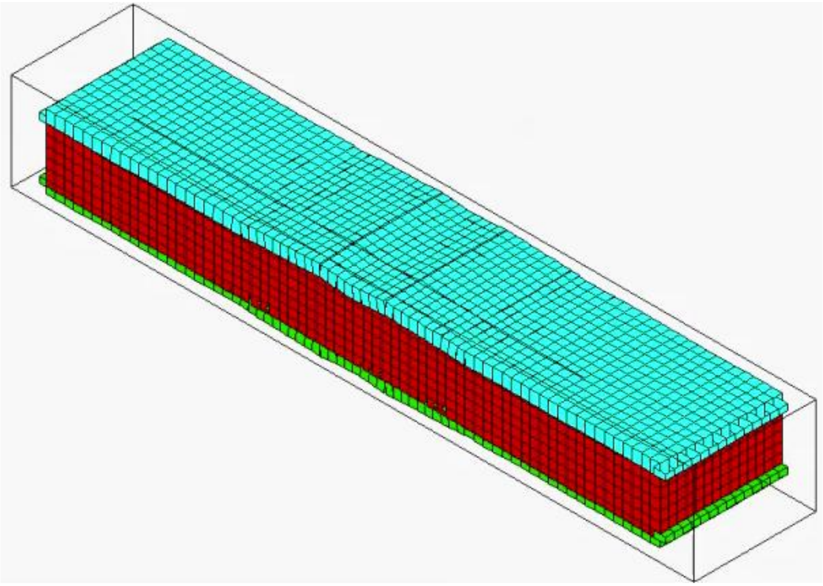


20733Hz

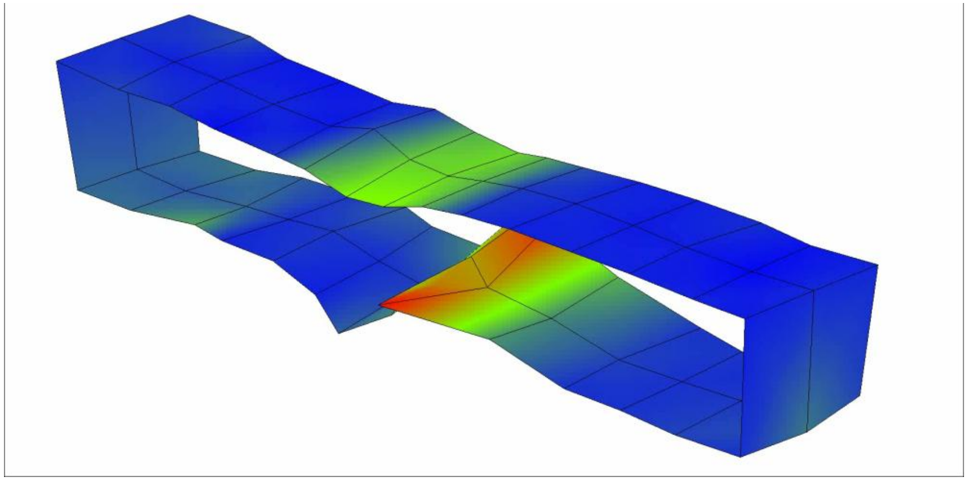


20401Hz

Numerical and Experimental Modal Results



Numerical: 19300Hz



Experimental: 20401Hz

The outcomes of this investigation include:

- Successful miniaturisation of a class IV type flextensional transducer
- Effective use of PZFlex finite element analysis for the design of a class IV type flextensional transducer
- Correlation between numerical and experimental results has been achieved, although a separate mode of vibration was identified from experiment
- The mechanical coupling remains a problem, in addition to precise manufacture of end-caps. Both of these areas require further investigation
- The design process which has been adopted in this study can be utilised to improve on the design of devices based on the class IV or flextensional transducer configuration, to develop high-performance power ultrasonic devices

Acknowledgement

The investigators would like to thank Dr Richard O'Leary at the Centre for Ultrasonic Engineering at the University of Strathclyde, Glasgow, UK, for help with the cutting of the piezoceramic.