Analysis of Flexural Ultrasonic Transducers for High Frequency Applications

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Engineering and Physical Sciences Research Council

CIU Centre for Industrial Ultrasonics

www.ciu.ac.uk

Overview of Our Research

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- The FUT is currently used primarily for flow measurement, proximity sensing and industrial metrology
- Designed for ambient conditions and low ultrasonic frequencies, up to approximately 50 kHz

How can we adapt FUTs for operation at higher frequencies, in high pressure and temperature environments?

Application	Example Pressure (bar)
Domestic water meters	20
Industrial gas meters	300
Industrial flow meters	300+
Environment	**Example Temperature (°C)**
Oil production	120
District heating	250
Petrochemical	350-450
Power plants	560

Ultimate Goal

The development of high frequency flexural ultrasonic transducers (HiFFUTs), a new class of ultrasonic transducer.

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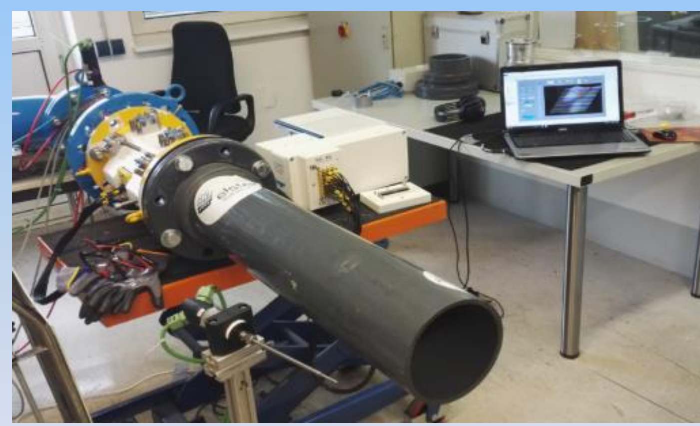
Applications of FUTs

Robotics, Obstacle Avoidance

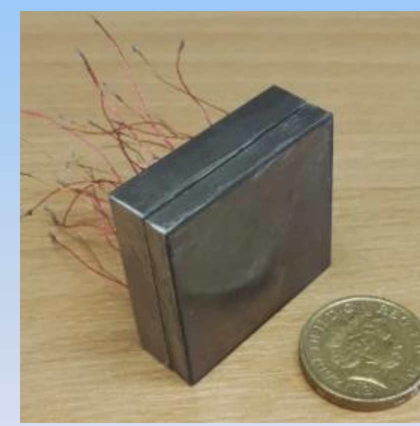
Proximity and Parking Sensors

NDT Inspection

Short-Range Wireless Communication



Flow Measurement and Metrology



Phased Arrays

Applications of FUTs

Robotics, Obstacle Avoidance

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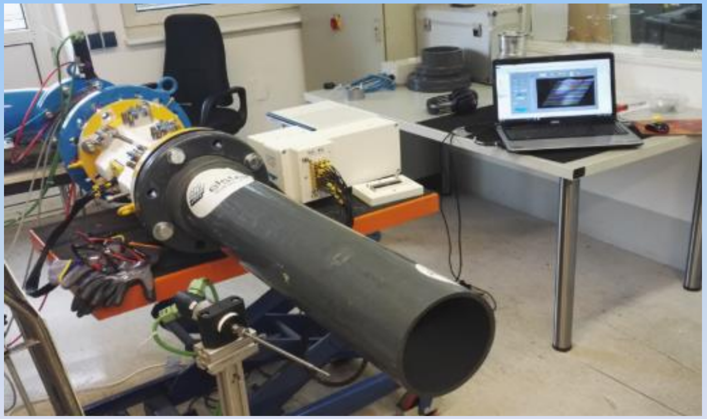
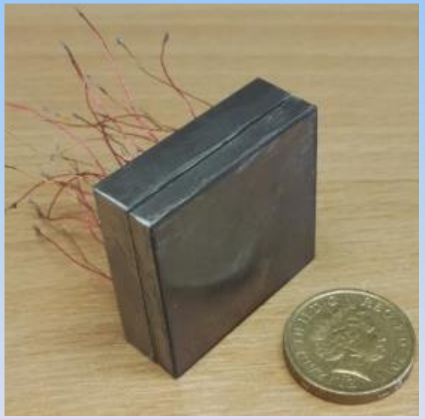
Short-Range Wireless Communication



Flow Measurement and Metrology

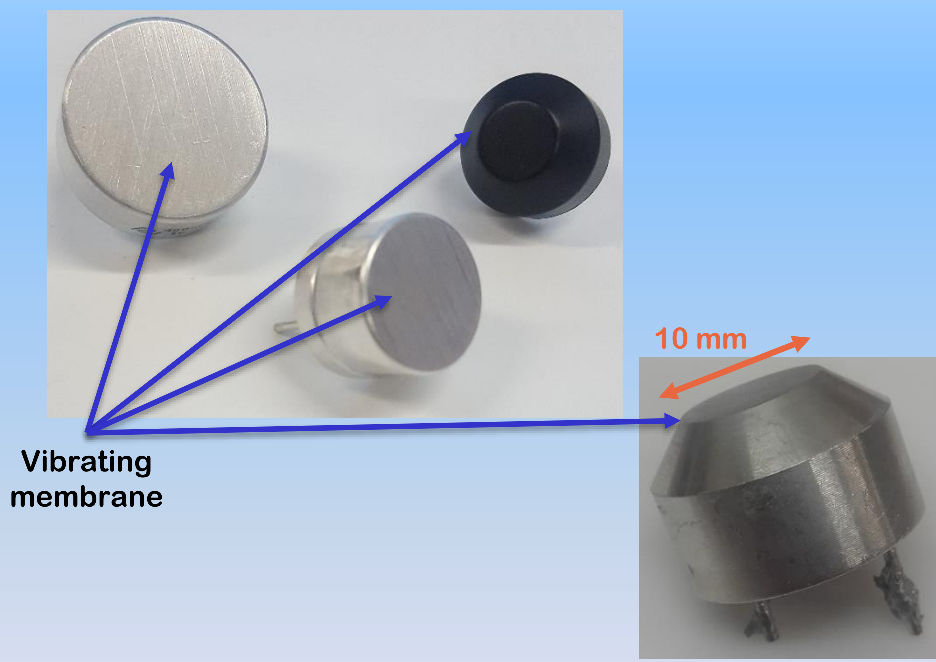


Phased Arrays

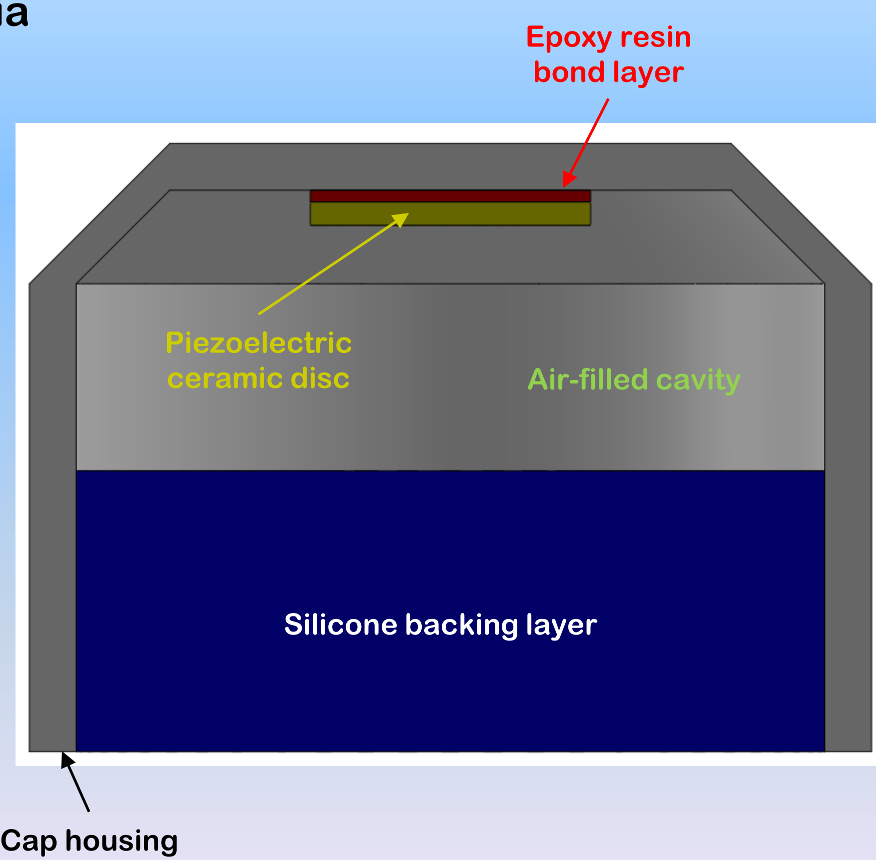
TARGET HIGH FREQUENCY APPLICATIONS FOR OUR HIFFUTs (> 100 kHz)

The Flexural Ultrasonic Transducer

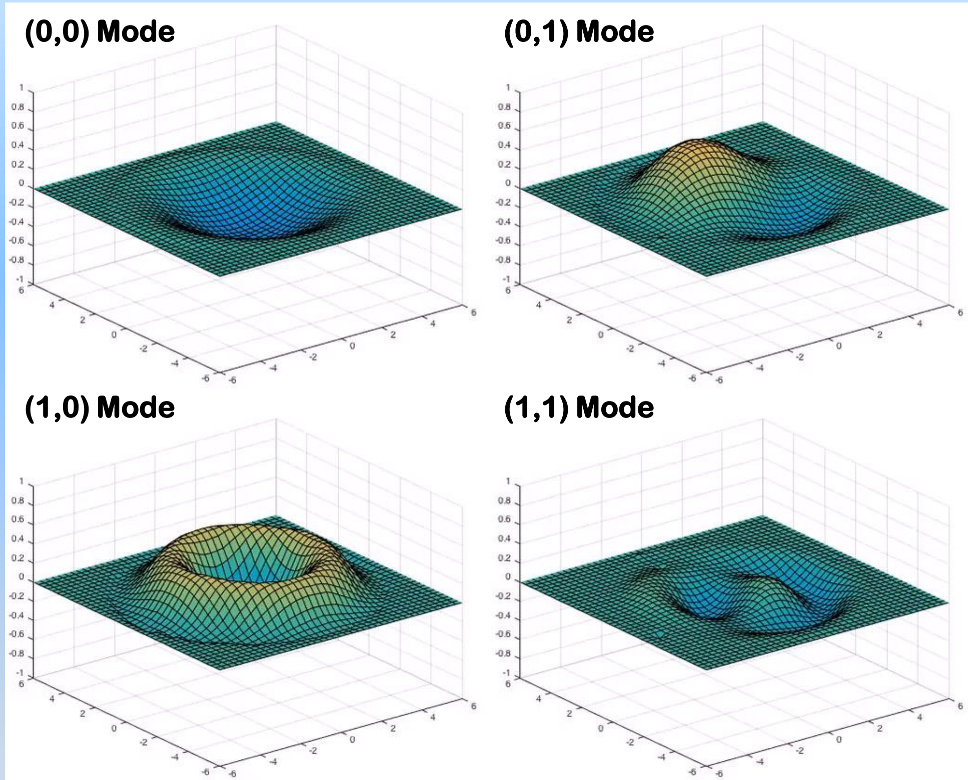
- Unimorph device
- Piezoelectric driver bonded to a metal cap
- Vibration of the piezoelectric causes metal cap bending
- Efficient coupling to low-impedance media

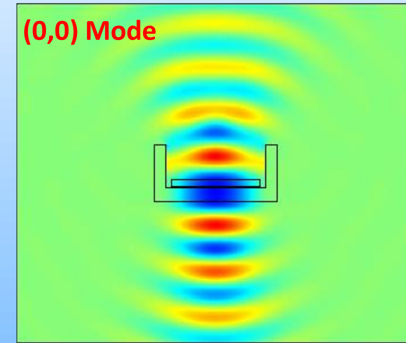


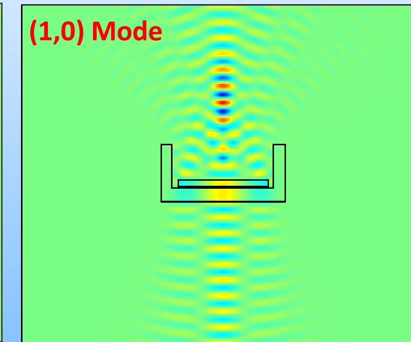
Aluminium 40 kHz FUT

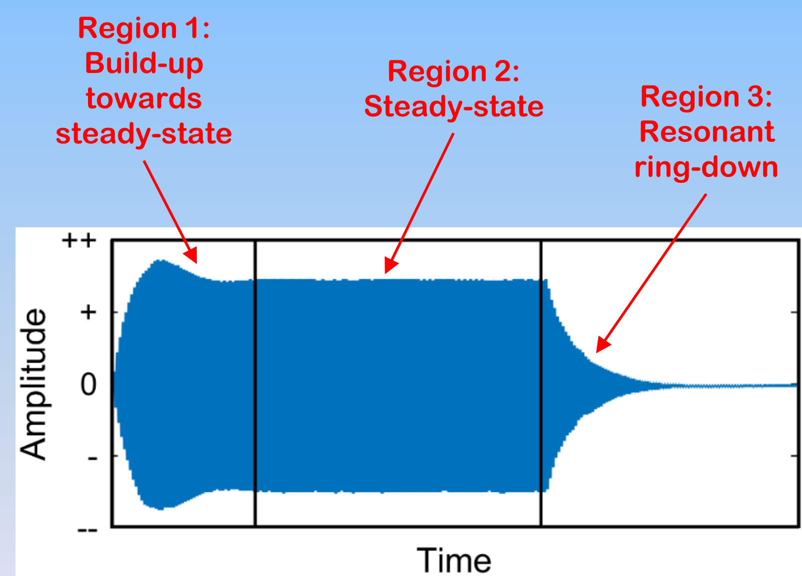


Operating Characteristics









Isolated Response Regions

Dynamic Characterisation

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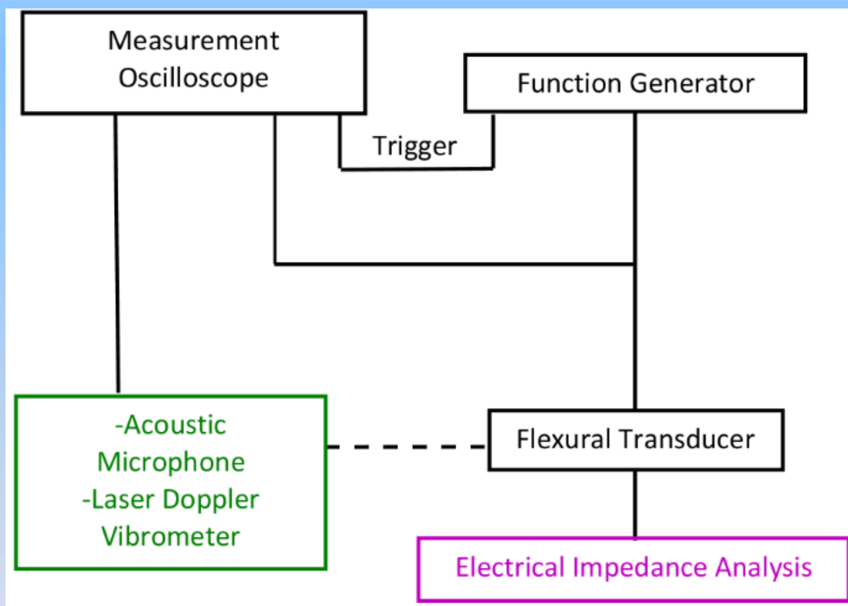
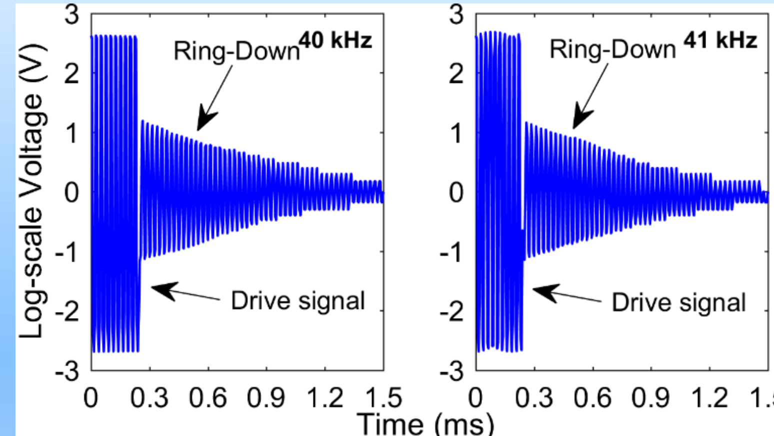
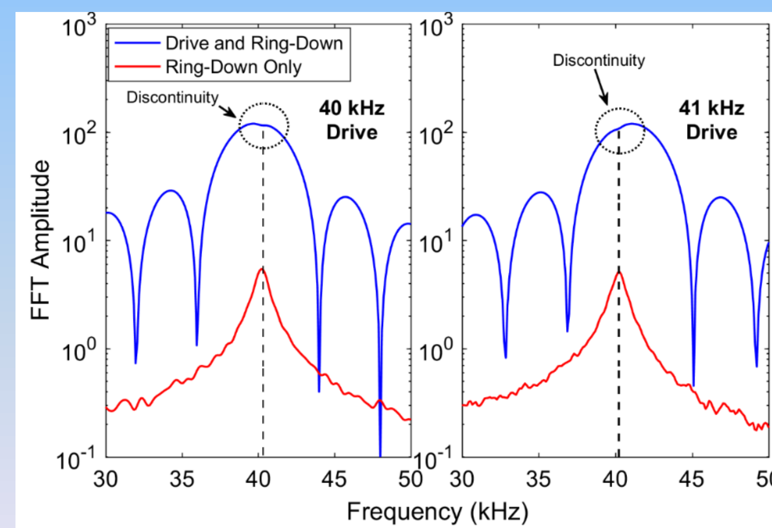
- FUTs characterised with acoustic microphone, LDV, or a receiver FUT
- Function generator and oscilloscope can be used for rapid resonance check

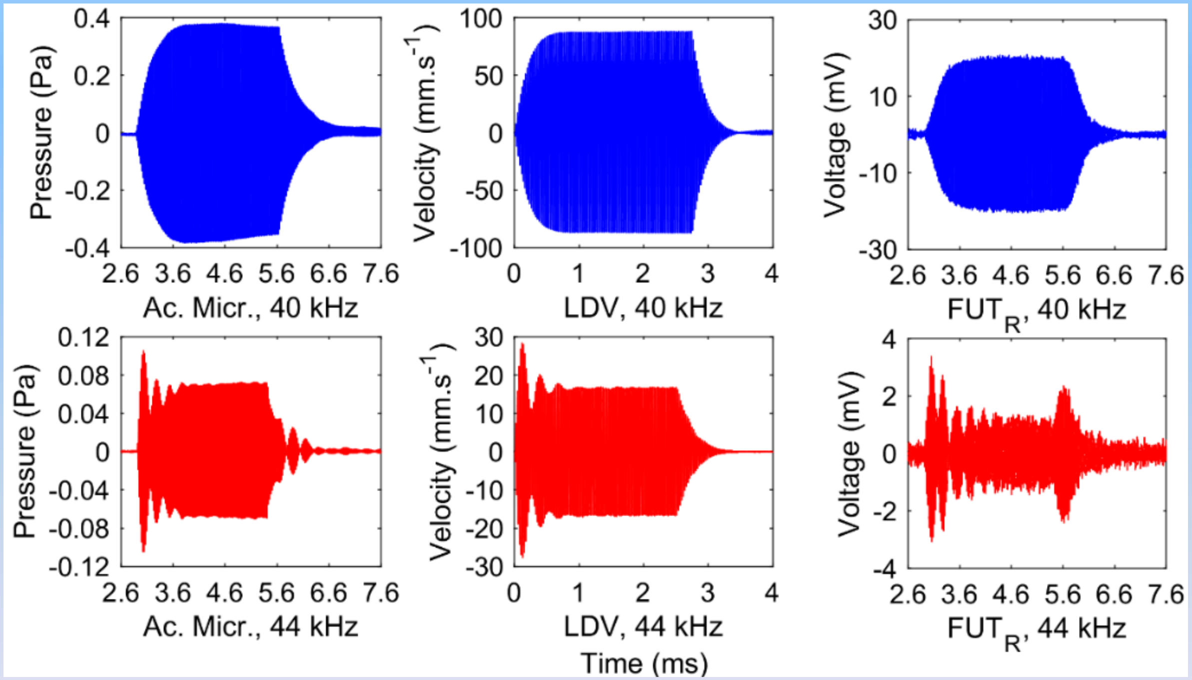


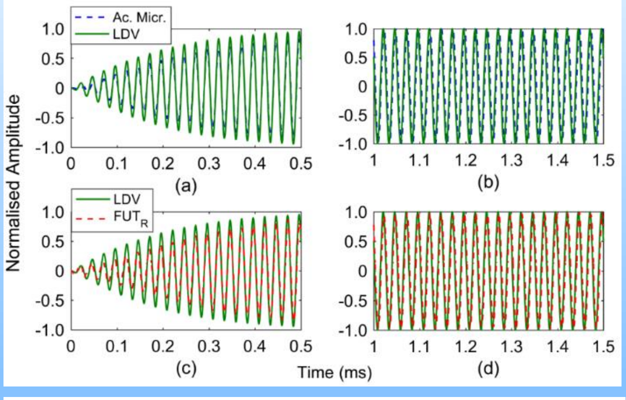


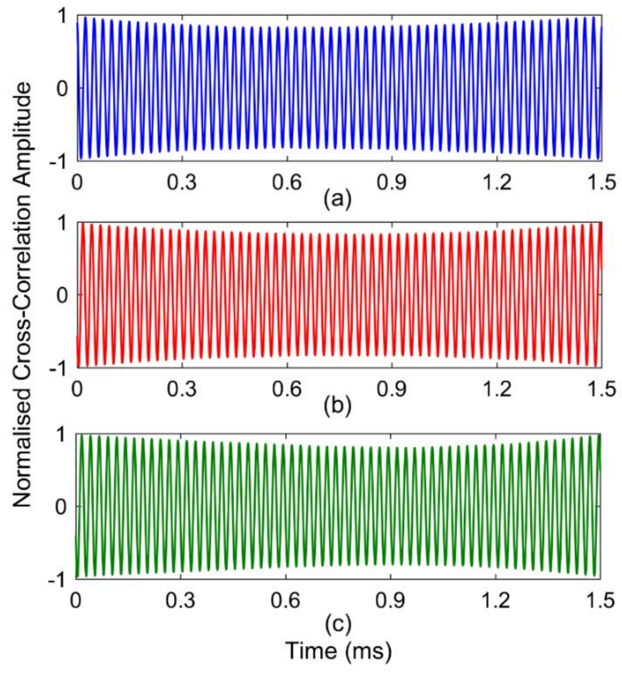


Dynamic Characterisation

- Resonance and off-resonance responses of the FUT measured
- Cross-correlation of responses at 40 kHz and 110 cycles computed







Mathematical Analog Model

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- **Relationships governing the three response regions separately are:**

Region 1 $M\ddot{x} + C\dot{x} + Kx = F\sin\omega t.\,H(t_0 - t)$ [Ref]

Region 2 $M\ddot{x} + C\dot{x} + Kx = F\sin\omega t$

Region 3 $X(t) = Fe^{-\zeta\omega_n t}\cos(\omega_d t + \theta)$

- **The equations for Region 2 and Region 3 are familiar. For Region 1:**

$H = 1$ for $0 < t \leq t_0$ and $C^2 < 4MK$

- **The full solution is:**

$$x = N_P\, e^{-at}(\cos\bar{a}t + i\sin\bar{a}t) + N_N\, e^{-at}(\cos\bar{a}t - i\sin\bar{a}t) + \sqrt{G_1{}^2 + G_2{}^2}(\sin(\omega t + \theta))$$

- **Or simplified, with the real part of the equation:**

$$\mathbf{x = N\,(e^{-\alpha t}\cos\bar{a}t) + R(\sin(\omega t + \theta))}$$

Ref S. Dixon, L. Kang, M. Ginestier, C. Wells, G. Rowlands, and **A. Feeney**, "The electro-mechanical behaviour of flexural ultrasonic transducers," *Applied Physics Letters*, vol. 110, no. 22, p. 223502, 2017.

Correlation of Analog and Experiment

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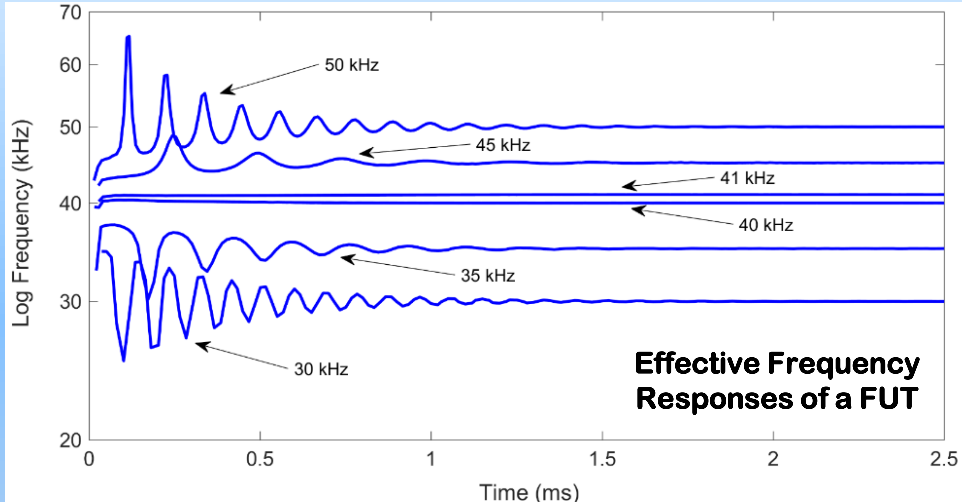
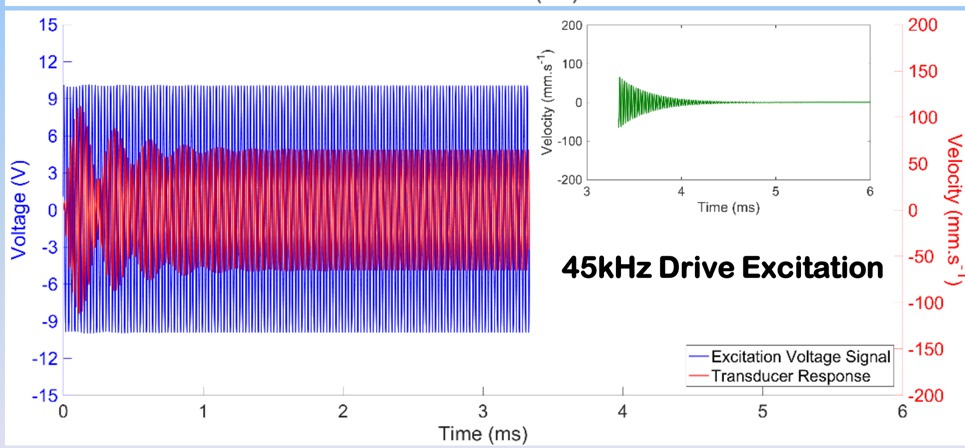
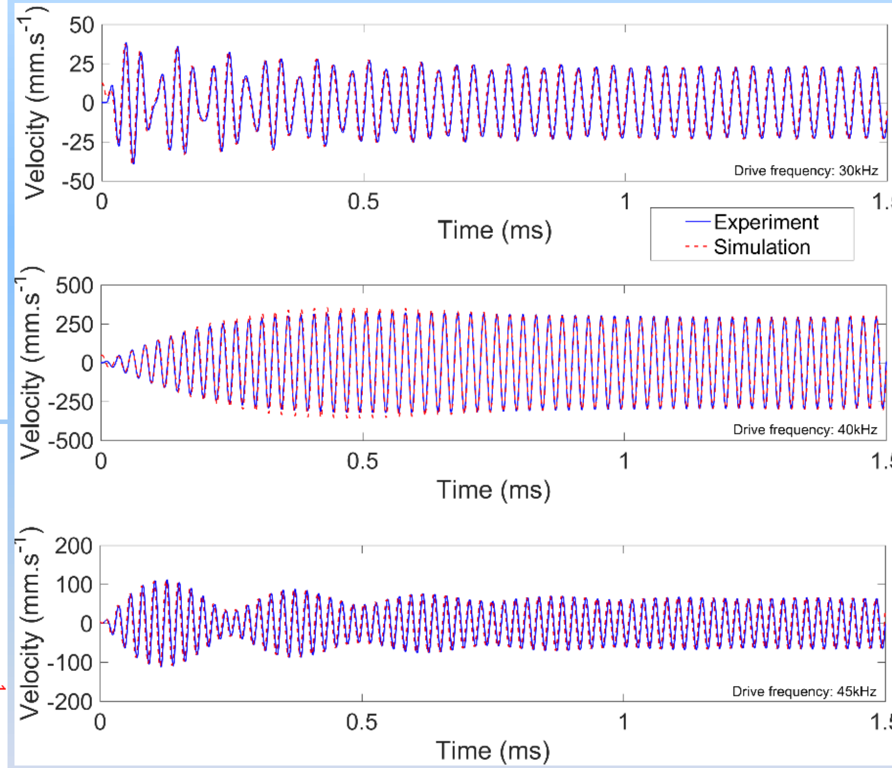
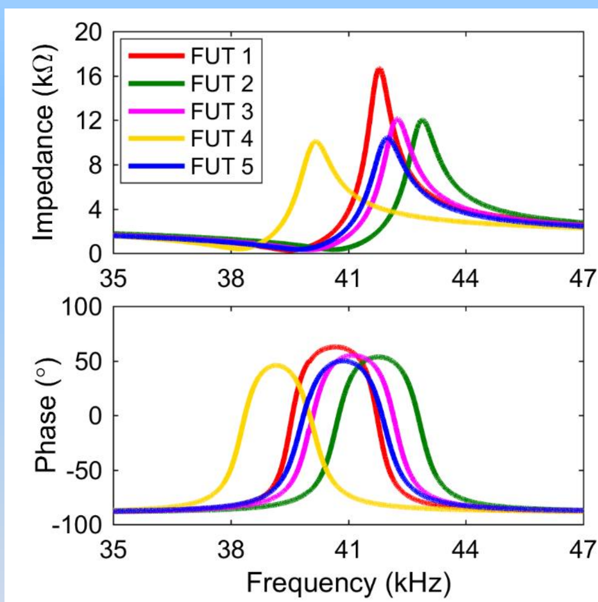


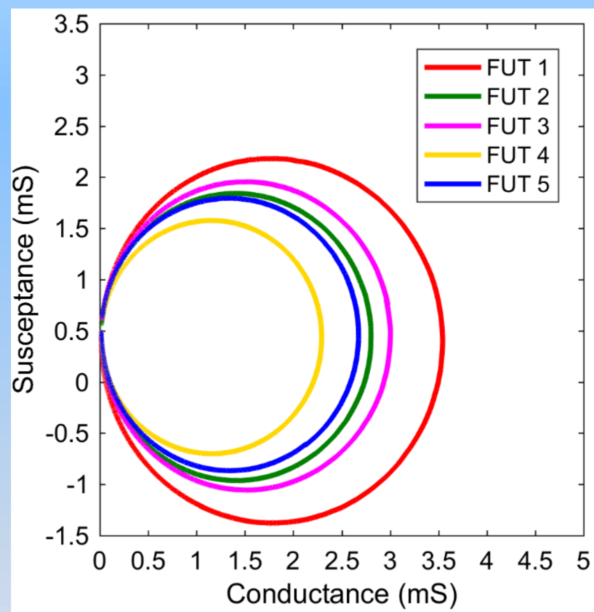


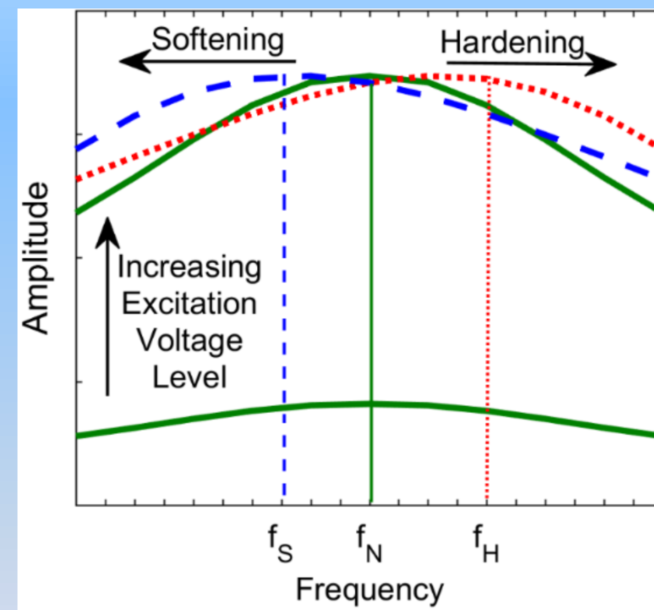


Dynamic Nonlinearity

- Sample of 5 aluminium FUTs analysed
- Electrical properties measured
- LDV used to assess nonlinearity







Dynamic Nonlinearity

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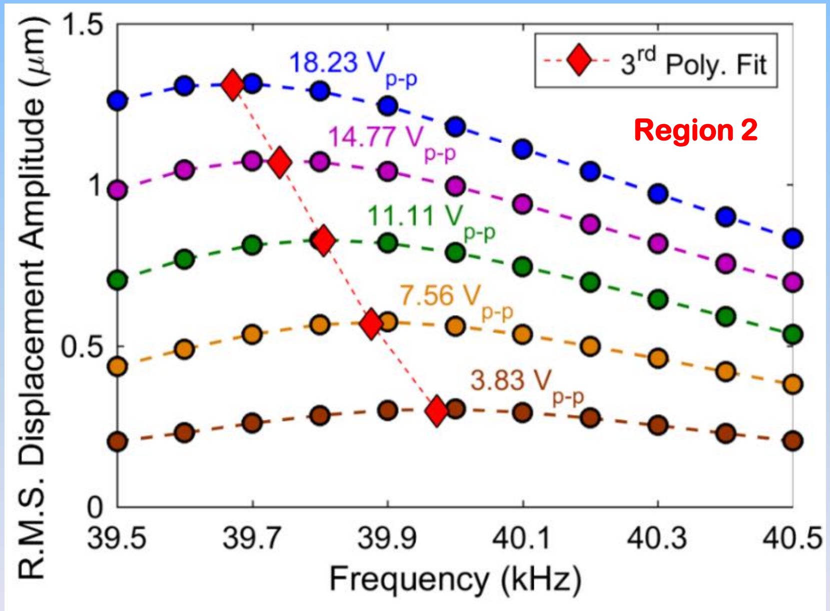
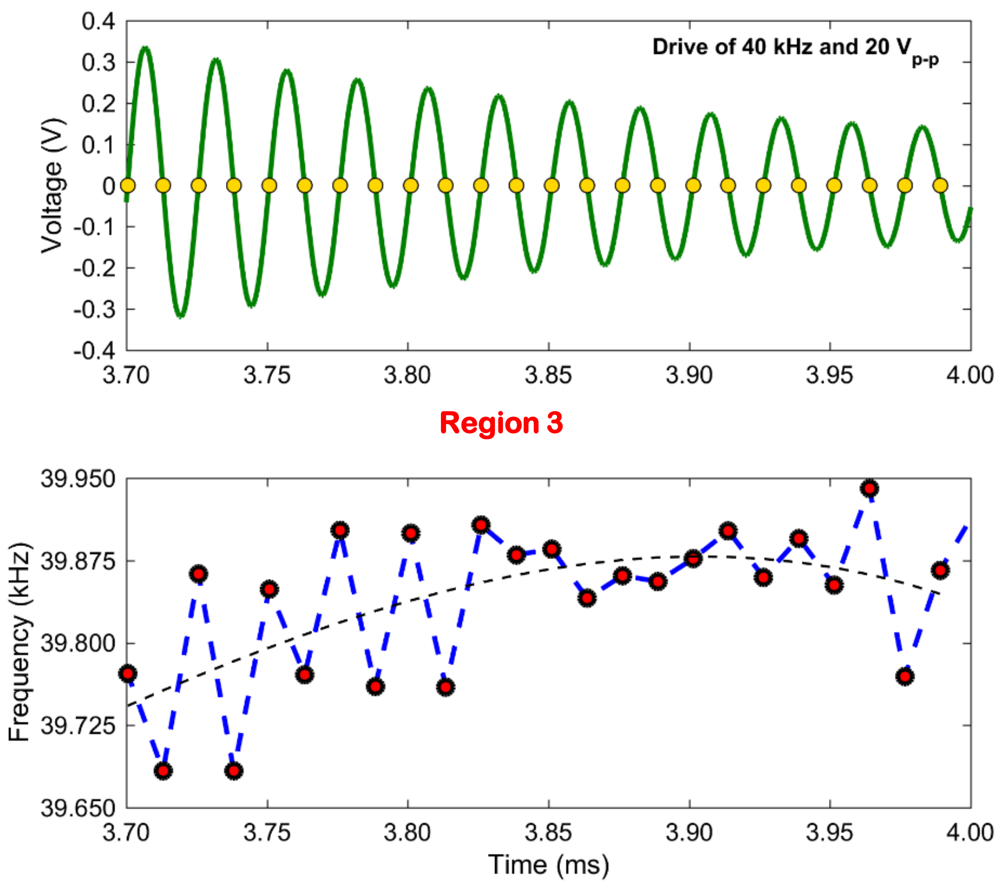
- FUTs driven around resonance with burst sine signals
- Steady-state and resonant decay isolated
- Zero-crossings calculated for nonlinearity in Region 3





Dynamic Nonlinearity

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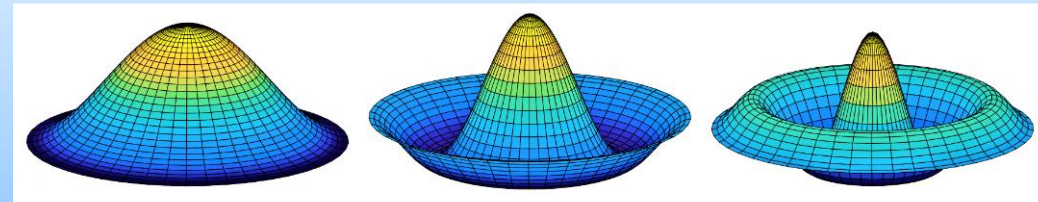
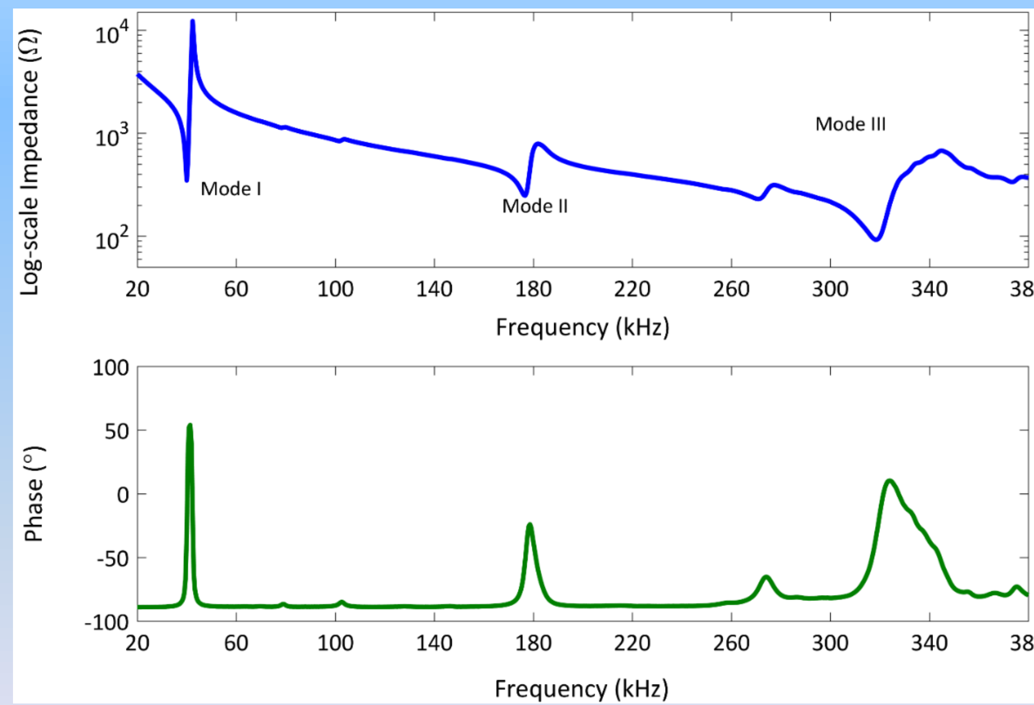
- Dynamic properties of five FUTs summarised
- Characteristics variable between nominally identical FUTs

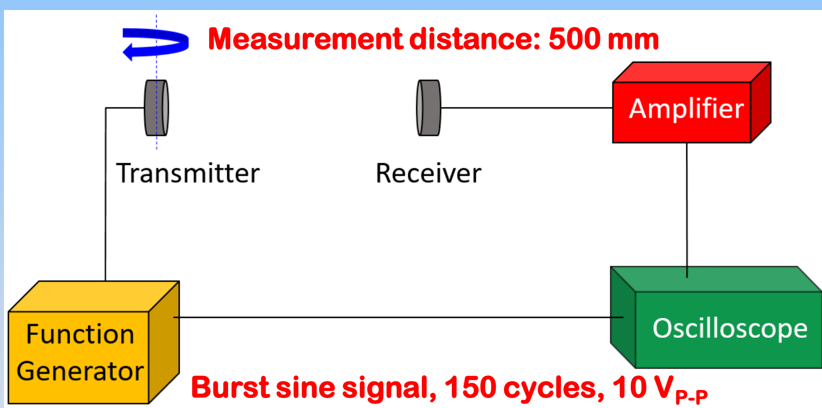
	Electrical Impedance analysis			Laser Doppler Vibrometry	
FUT	Coupling Coefficient k^2	Quality Factor Q_M	Resonance Frequency f_r (kHz)	f_r, nom. 4 V_{p-p} (kHz)	f_N - f_S (Hz) nom. 4 to 20 V_{p-p}
1	0.33	71.01	39.51	40.00	300
2	0.32	56.13	40.64	41.00	200
3	0.33	56.71	39.97	40.40	200
4	0.31	54.17	38.23	37.90	200
5	0.32	49.75	39.72	40.10	200
Mean	0.322	57.55	39.59	39.66	220
Standard Deviation	0.007	7.16	0.88	0.90	40

High Frequency Operation

- Propagation of ultrasound in air
- Efficient driving mechanism required
- Bespoke amplifier adopted
- Two FUTs, one as a transmitter, one as a receiver, both with a (0,0) mode of 40 kHz







High Frequency Operation

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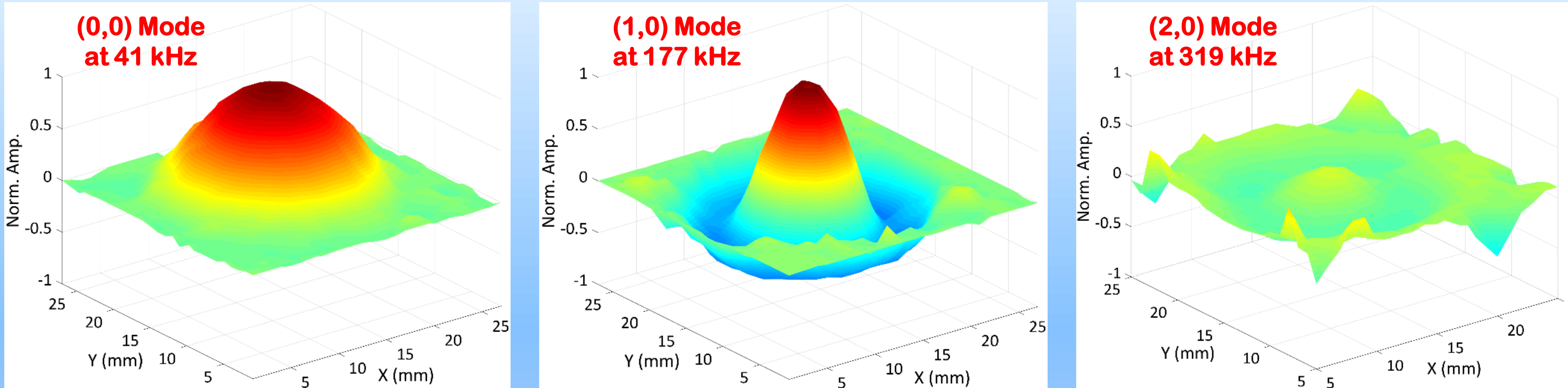
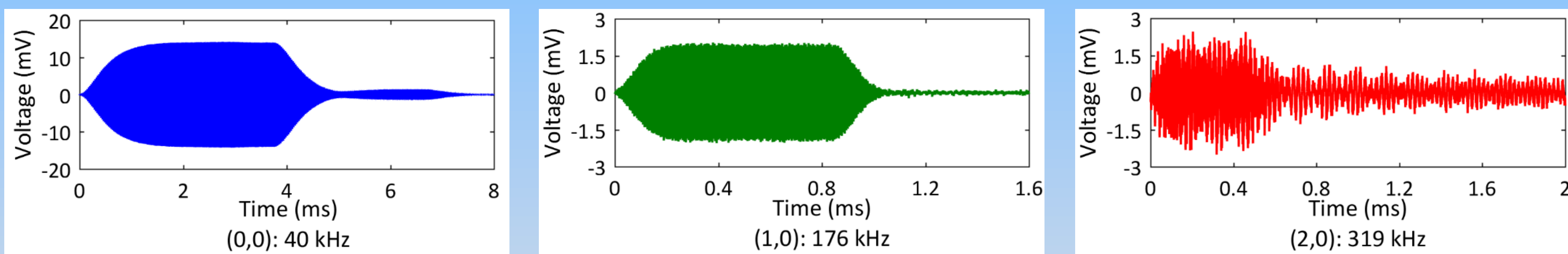
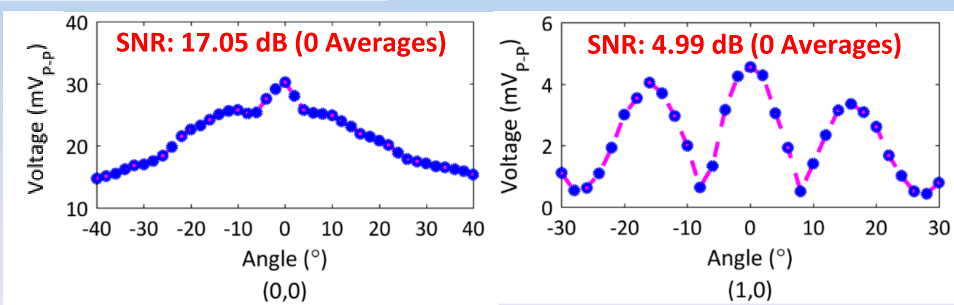






$$SNR = 20\log_{10}\frac{V_{RMS,SIGNAL}}{V_{RMS,NOISE}}$$

HiFFUT Design: Operating Modes

- FUT membrane equivalent to an edge-clamped thin plate
- Differential equations used to approximate the normal mode frequencies

$$D\nabla^4 w(\boldsymbol{r},t) + \rho \frac{\partial^2 w(\boldsymbol{r},t)}{\partial t^2} = 0$$

Transverse Displacement

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

Rigidity

$$\omega = \left(\frac{\lambda}{a}\right)^2 \sqrt{\frac{D}{\rho}}$$

Angular Modal Frequency

- Mode frequencies dependent on plate geometry and material
- Online design tool designed, available on project website
- Estimated mode frequencies instantly generated for different materials, including custom

HiFFUT Design Tool

Estimator of HiFFUT Operating Frequency

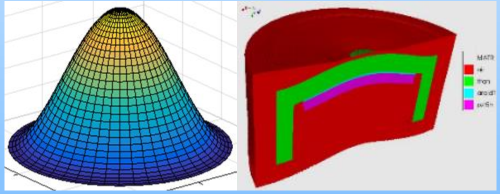
HiFFUT Membrane Diameter (mm):	
HiFFUT Membrane Thickness (mm):	
HiFFUT Membrane Material:	Titanium ▾
Density (kg/m^3):	
Young's Modulus (GPa):	
Poisson's Ratio:	
Axisymmetric Mode of Vibration:	(0,0) ▾
Modal Frequency (kHz):	

Calculate Reset

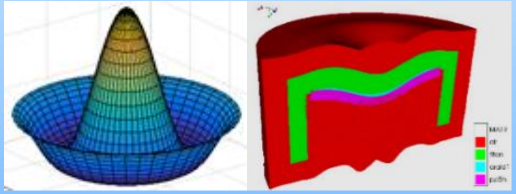
https://warwick.ac.uk/fac/sci/physics/research/ultra/research/hiffut/

HiFFUT Design: Finite Element Analysis

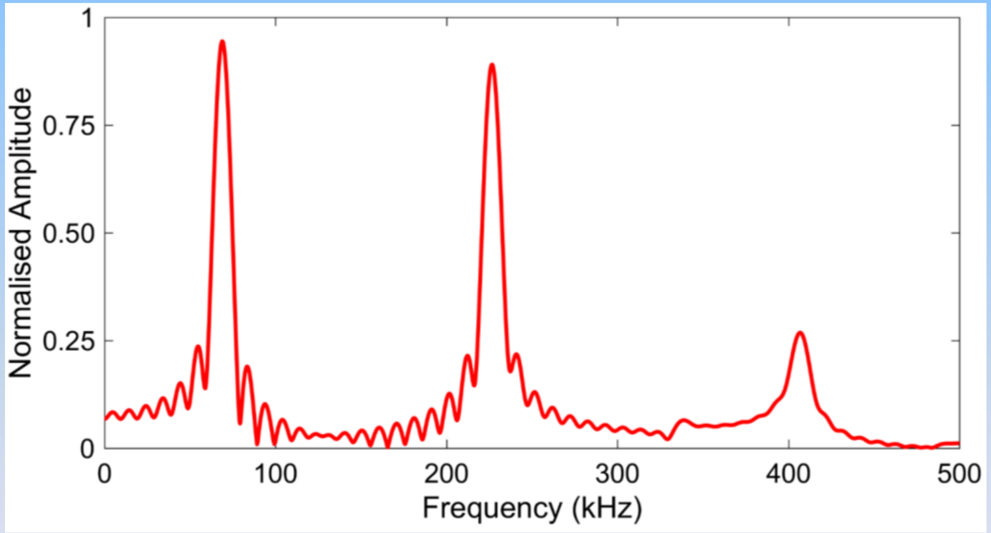
We use PZFlex® finite element analysis software for simulating performance.

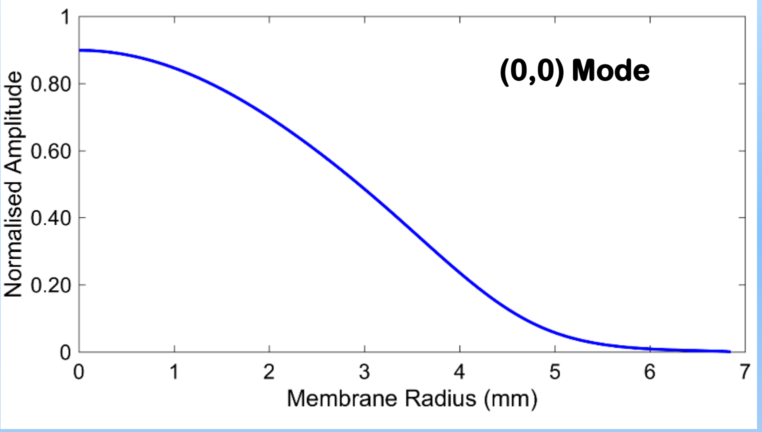


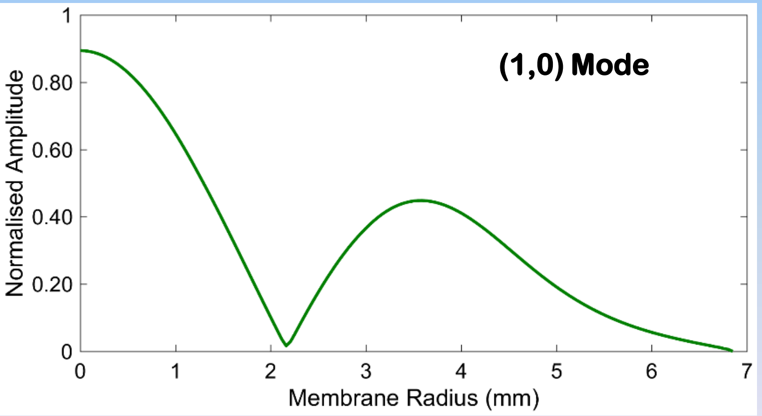
(0,0) Mode at 69.35 kHz



(1,0) Mode at 246.57 kHz







High Temperature Piezoelectric HiFFUTs

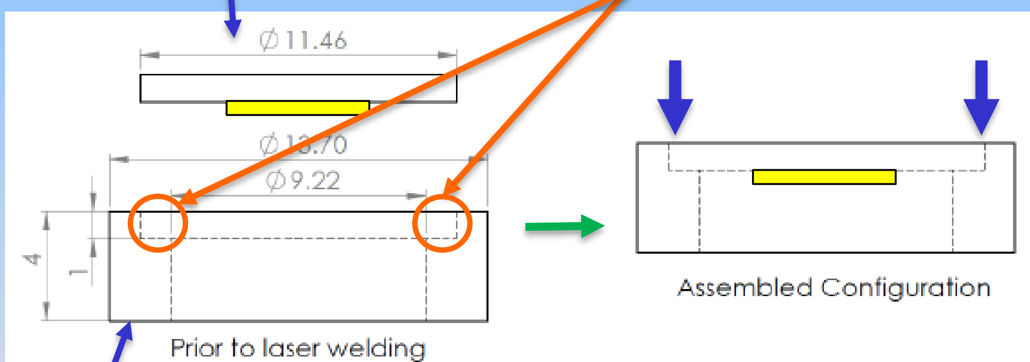
- Custom pressure rig used to bond components
- High temperature epoxy resin: EPO-TEK® 353ND
- Titanium (Grade 2 ASTM) cap
- PZ46 bismuth titanate (BiT) ceramic (Meggitt)

Side-wall

Laser-cut membrane

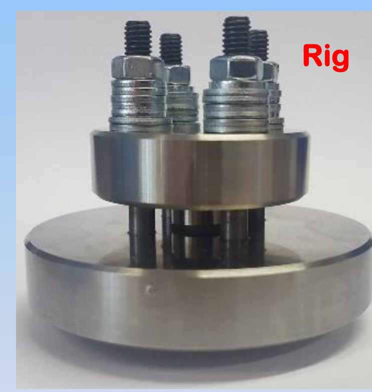
Disc, cut from Ti sheet, with BiT ceramic bonded on top, forming the membrane

Recess cut into tubing

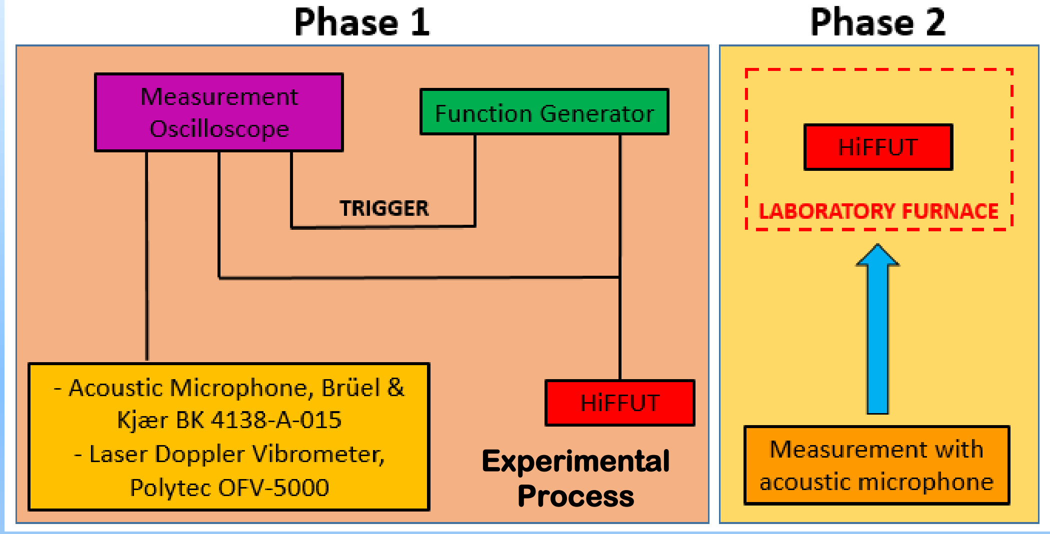


Titanium tubing for side-wall

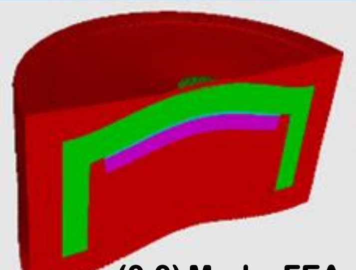
Cap Components for Laser Welding



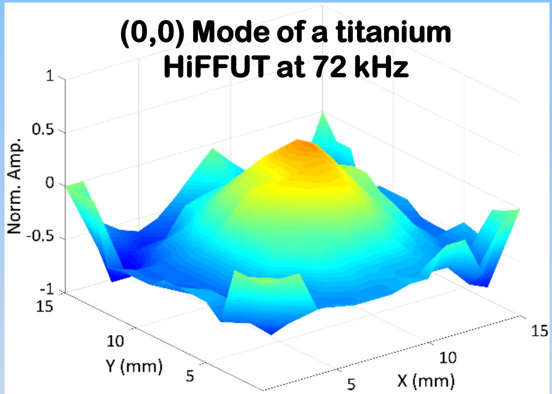
High Temperature Piezoelectric HiFFUTs

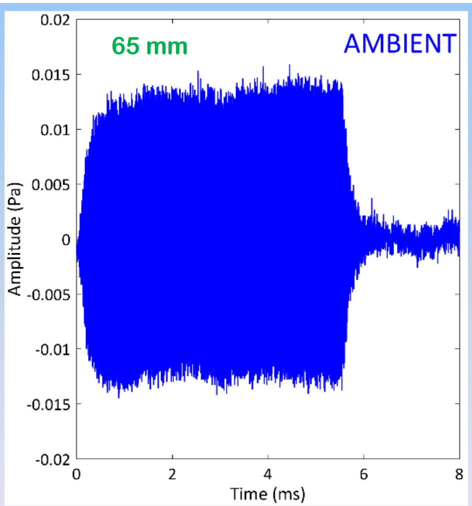


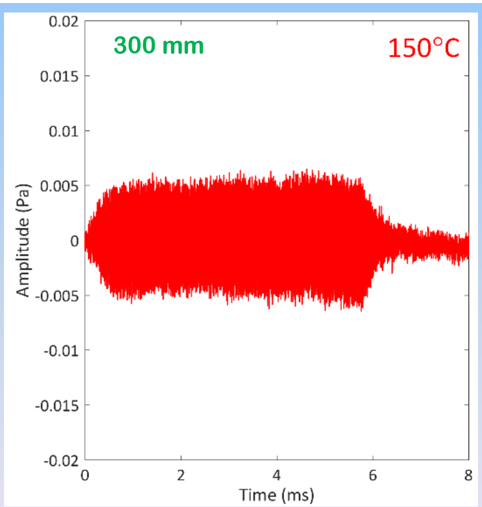
Titanium HiFFUT



(0,0) Mode, FEA







Burst Signal of 400 cycles at 20 V_{P-P}

Resonance frequency at ambience: 73 kHz

Resonance frequency at 150°C: 68 kHz

Summary

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- FUTs are efficient and low cost
- Prototypes show potential for operation at high temperature and frequency
- HiFFUTs for hostile environments, including high pressure, are in development
- Industrial collaboration is ongoing for assessment of prototypes

Acknowledgement

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