Dynamic Characteristics of Flexural Ultrasonic Transducers

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Overview of Research

- The flexural ultrasonic transducer (FUT) is a sensor used primarily in flow measurement, proximity sensing and industrial metrology.
- Currently FUTs are used at ambient conditions and low ultrasonic frequencies, up to around 50 kHz.

Target Operating Conditions

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.

- Close collaboration with industry.
- A major aim is to design FUTs operational towards 1 MHz.
- FUT resonance frequencies depend on cap material and dimensions.
- The physics of FUT behavior is currently not understood.
- This study demonstrates results from the characterisation of a set of 5 flexural transducers, all nominally identical.

The Flexural Ultrasonic Transducer

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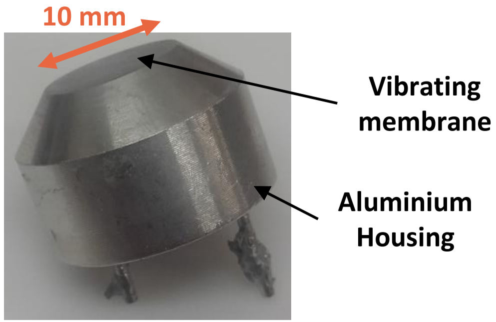
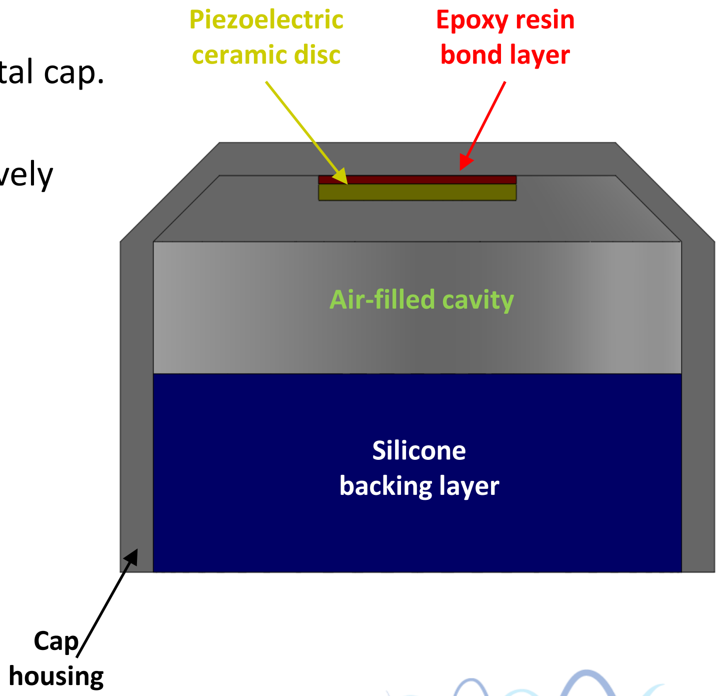
- The flexural ultrasonic transducer is a unimorph device, with a piezoelectric driver bonded to a metal cap.
- The vibration of the piezoelectric element causes bending of the metal cap.
- An advantage of flexural transducers is that the transducer couples efficiently to low-impedance media, operating effectively with relatively low input voltage.
- Flexural transducers have been exploited for a range of applications, including for non-destructive evaluation, and as car-parking sensors.

The FUT of the type analysed in this study (Multicomp)





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Air-Coupled Ultrasound Applications

Robotics, Obstacle Avoidance

NDT Inspection, Phased Arrays

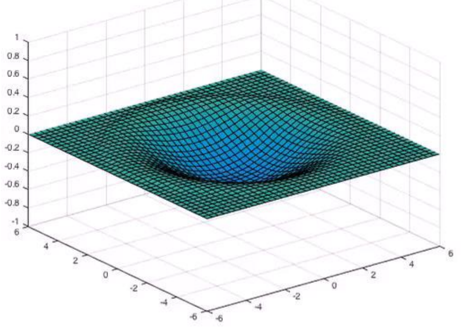
Short-Range Wireless Communication

Parking Sensors

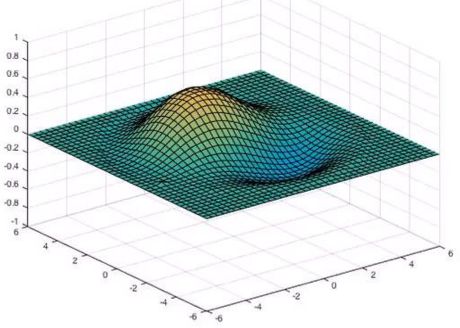
Material Characterisation

Operating Characteristics

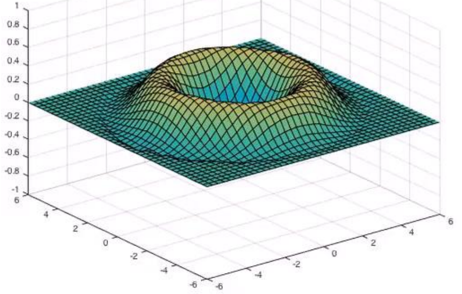
(0,0) Mode



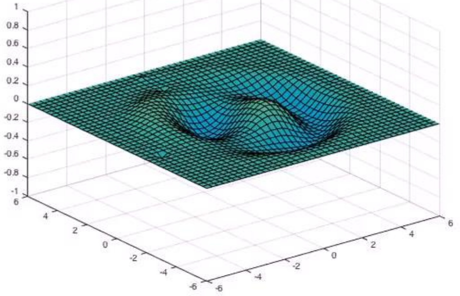
(0,1) Mode

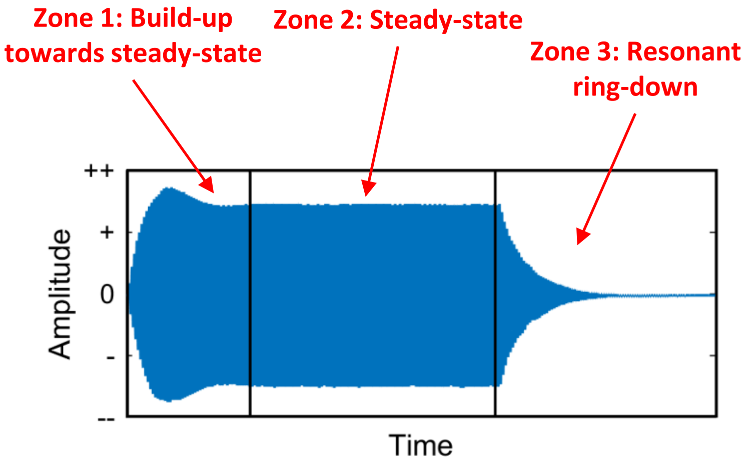


(1,0) Mode



(1,1) Mode





Isolated response regions for an amplitude-time spectrum of a FUT

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Characterisation Methods

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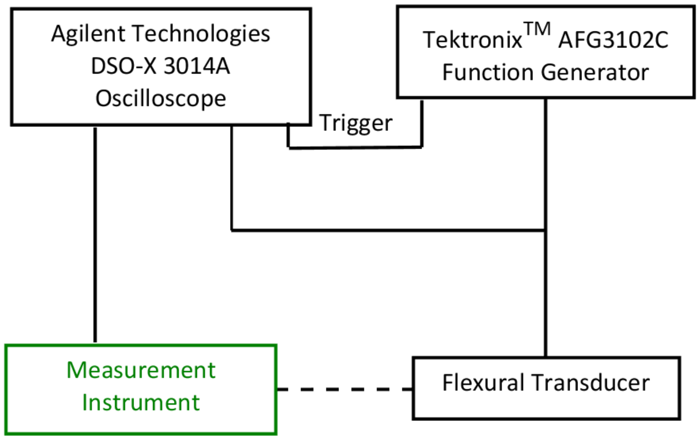
- The experimental setup is shown opposite, and consists of a function generator and oscilloscope with a measurement instrument.
- The function generator is used to provide the input signal to the FUT, and the oscilloscope is used to measure the voltage across the electrical contacts of the FUT. The mechanical vibrations are recorded by the measurement instrument, which can be:

  - An acoustic microphone

  - A laser Doppler vibrometer (LDV)

  - A second FUT
- The response of the transducer can be monitored for different input signal frequencies, amplitudes, and number of cycles.
- All flexural transducers analysed in this study possess a nominal (0,0) mode frequency of 40 kHz.



Experimental setup

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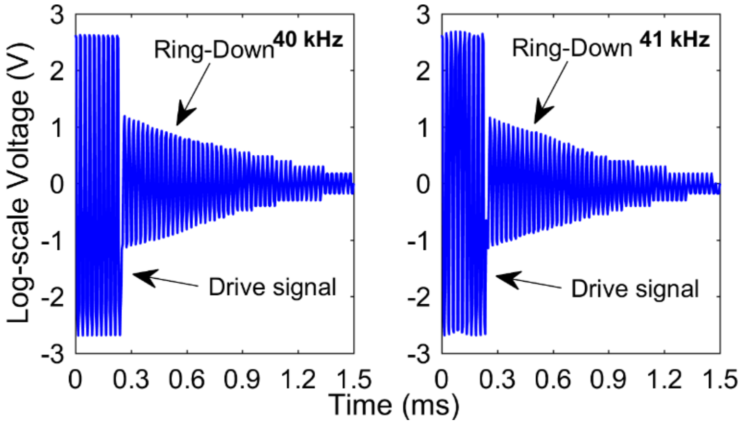
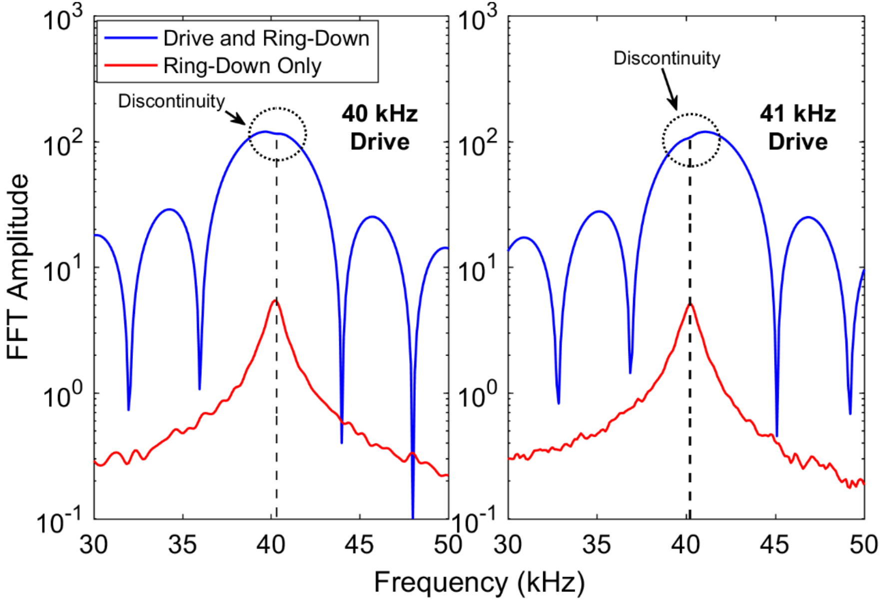
Resonance Frequency Measurement

- Measurement of FUT resonance frequency using only an oscilloscope and function generator.
- Two drive frequencies of 40 kHz and 41 kHz are applied to the FUT, at 10 $V_{p\text{-}p}$ and 10 cycles, as burst sine signals.
- Discontinuities in the FFTs of the amplitude-time responses indicate resonance, due to the phase difference between the driving signal and the vibration displacement of the membrane.





Comparison of Measurement Methods

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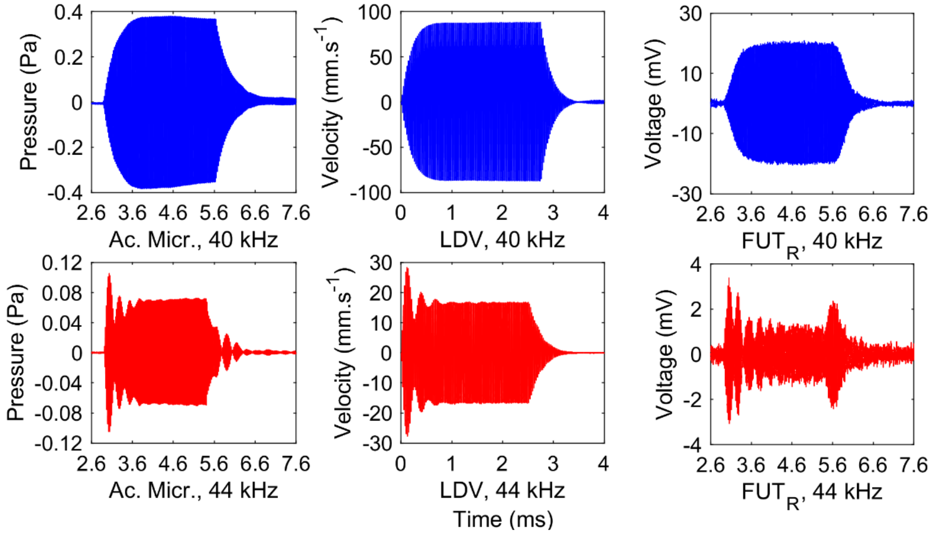
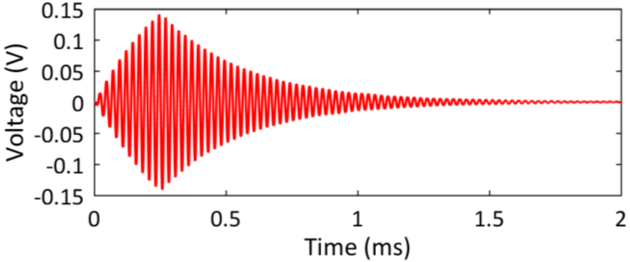
- Three methods: An acoustic microphone (BK 4138-A-015), a laser Doppler vibrometer (LDV, Polytec OFV-5000), and a second FUT acting as a receiver.
- Burst sine signals at 10 $V_{p\text{-}p}$ are applied, at 40 kHz (the (0,0) mode) and 44 kHz (off-resonance).
- The amplitude oscillation and overshoot of the build-up to steady-state indicates proximity to resonance.
- Too few cycles in the drive signal prevents the generation of the steady-state.





Drive frequency of 40 kHz, 10 cycle burst sine signal

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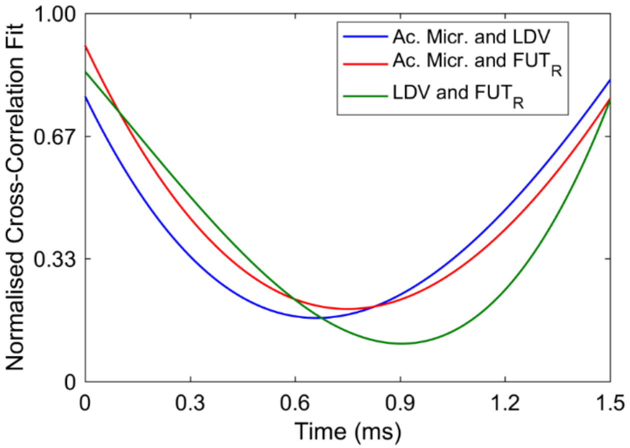
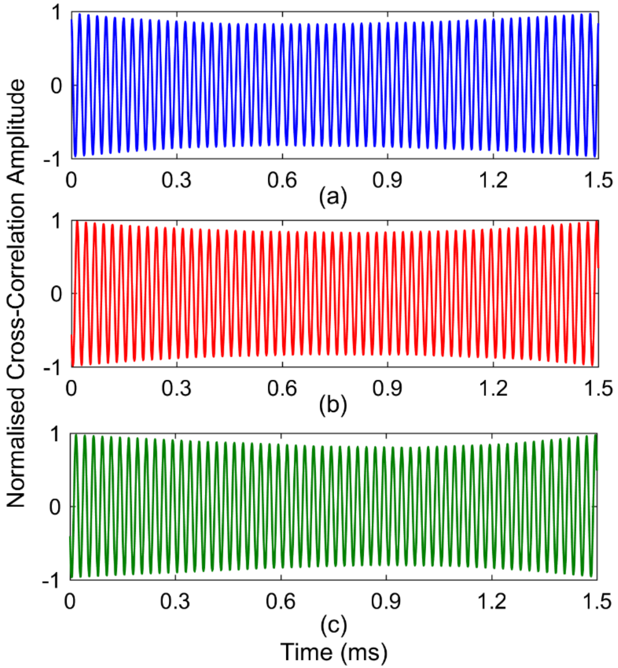
Cross-Correlation

- The cross-correlations were calculated to determine the signal similarity between different characterisation methods.
- The transition from Region 1 into steady-state was studied.
- 3rd order polynomials fitted to the absolute magnitude responses.
- The acoustic microphone and FUT_R show the greatest similarity. One explanation is that these methods both measure far-field, whereas LDV optically records membrane motion.



Cross-correlation of the signal spectra at 40 kHz and 110 cycles



The Mechanical Analog Model

- The FUT can be modelled as a mass supported by a spring-dashpot in parallel, and subject to a forcing function.
- 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. 1

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:

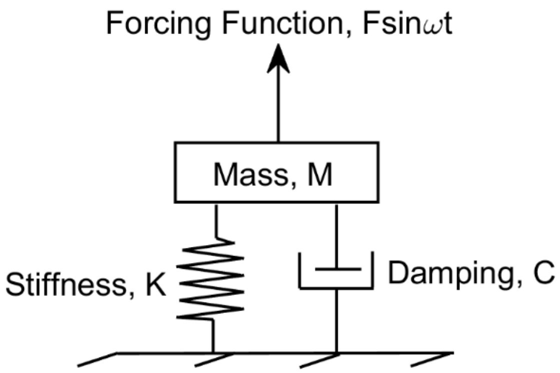
$H = 1 \text{ for } 0 < t \leq t_0$ and $C^2 < 4MK$

- 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:

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



Analog schematic of the FUT

Ref. 1 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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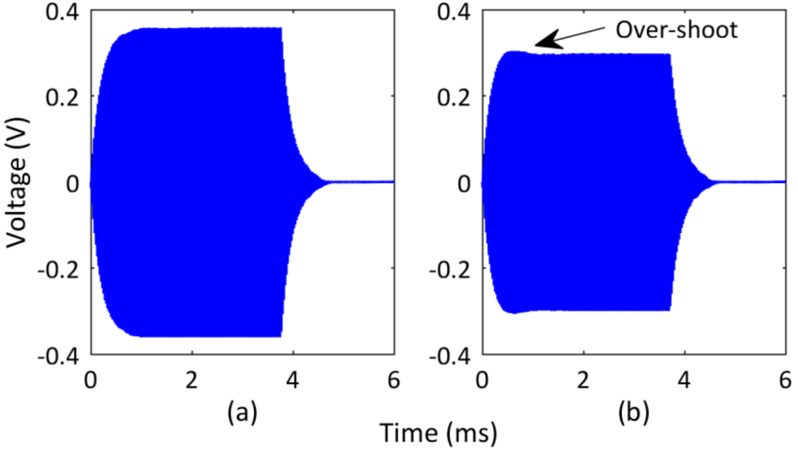
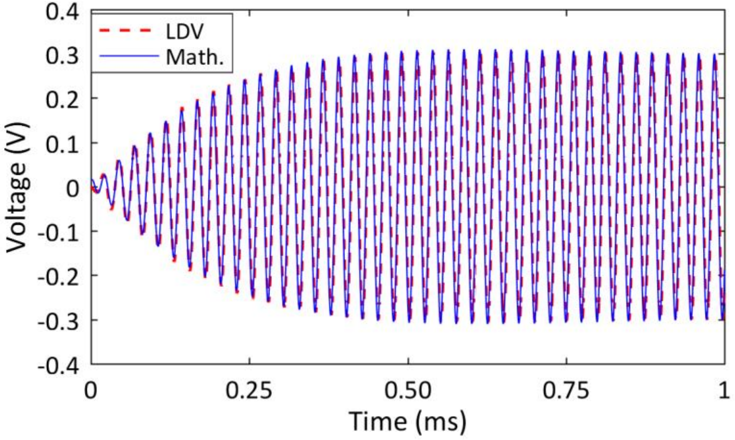


Amplitude-time spectra from LDV for drive frequencies of (a) 39.9 kHz (close to resonance), and (b) 40.5 kHz (off-resonance)



Amplitude-time spectra at 40.5 kHz in the first zone, from LDV and the mathematical model

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

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Summary and Future Research

Summary

- The amplitude-time response of flexural ultrasonic transducers can be discretized into three zones.
- These zones have helped in the development of a mathematical analog model.
- Multiple characterisation methods have been outlined for the experimental analysis of FUTs.

Future Research

- Development of FUTs which operate in axisymmetric modes at multiple frequencies, above 100 kHz.
- Design FUTs suitable for hostile environments, in particular with respect to high pressure and temperature.
- Investigate the dynamics of the FUT at higher excitation amplitude levels.

Acknowledgement

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