HiFFUT – A New Class of Transducer

Project Meeting

September 2017

Dr Andrew Feeney

FLEXIM when measuring matters

NATIONAL NUCLEAR LABORATORY

DYNOPTIC

DETECTRONIC FLOW MEASUREMENT AND DATA DELIVERY

WARWICK

EPSRC Engineering and Physical Sciences Research Council
EP/N025393/1

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Agenda

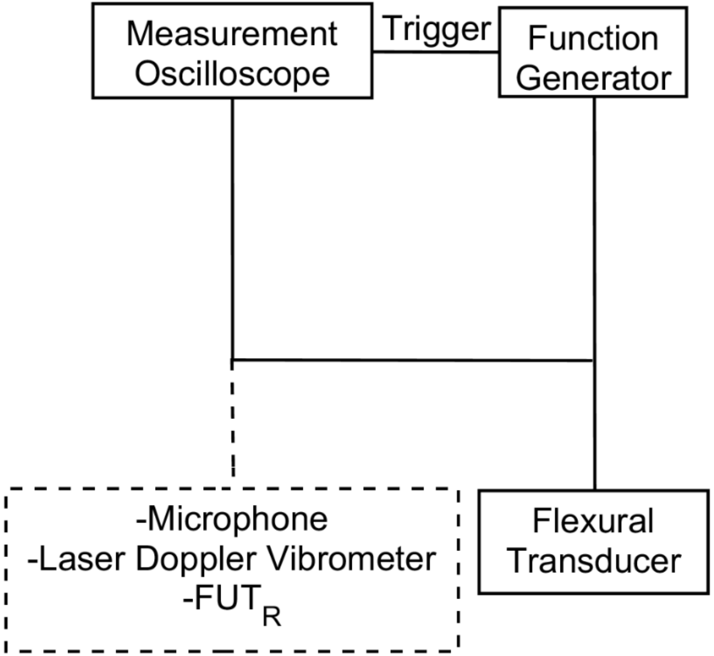
10.00am	Meet at the Department of Physics, University of Warwick.
10.15am	Research update from Andrew Feeney.
10.45am	Contributions from project partners, and review of the work packages and key project deliverables.
11.15am	Demonstrations in the ultrasound laboratories, and presentation from Lei Kang.
12.30pm	Lunch.
1.30pm	Meeting summary and AOB.

The Physics of FUT Behaviour

Included in this update is the following:

- The dynamic performance of flexural ultrasonic transducers, expanding on the research reported in *Applied Physics Letters*.
- As part of this, the development of a robust mechanical analog model, in particular to accurately represent the dynamic characteristics of the build-up to steady-state.
- The nonlinearity in the dynamic response of flexural ultrasonic transducers.
- The first steps in the design and characterisation of a high-frequency flexural ultrasonic transducer for high temperature environments.
- An update on the design and delivery of the pressure vessel.

The experimental setup shown has been used to collect the vibration response data provided in this presentation.



Experimental setup

Online HiFFUT Design Tool

- JavaScript in HTML environment.
- Example graphical user interface is shown opposite.
- The user can input a desired HiFFUT cap membrane diameter and thickness.
- The cap material can be selected, along with the mode of vibration of interest.
- The frequency is returned, in kHz, to three decimal places.
- This is an estimator, which is based on standard plate modes of vibration for an edge-clamped boundary condition.
- Eventually I would like to expand what I have provided on-line by providing guidelines for pressure and temperature considerations, and accounting for compliance in the HiFFUT membrane.

HiFFUT Design Tool

This section provides an expedient and rapid estimator for basic HiFFUT design and operating parameters, for the fundamental axisymmetric operating modes of vibration, and for three common cap materials. This is a predictor based on the vibration modes of an edge-clamped plate, and should be used as a guideline only, since physical device parameters will affect the vibration characteristics of a HiFFUT. The predictor makes use of the equations presented above to generate the operating frequency in each case, and take account of the rigidity of the cap membrane. The higher the rigidity, the less compliant the membrane is, and hence less efficient for propagating ultrasound energy. This is important to consider in the design of HiFFUTs. Note that when specifying the membrane diameter, this does not include the side-wall geometry. Also, the operating mode frequency is calculated in terms of kHz, and so is presented to three decimal places. The estimator is provided below, followed by the supplementary information important for the design and fabrication of HiFFUTs.

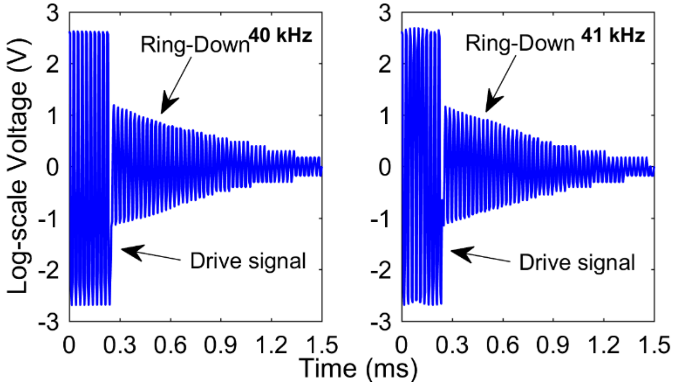
Estimator of HiFFUT Operating Frequency

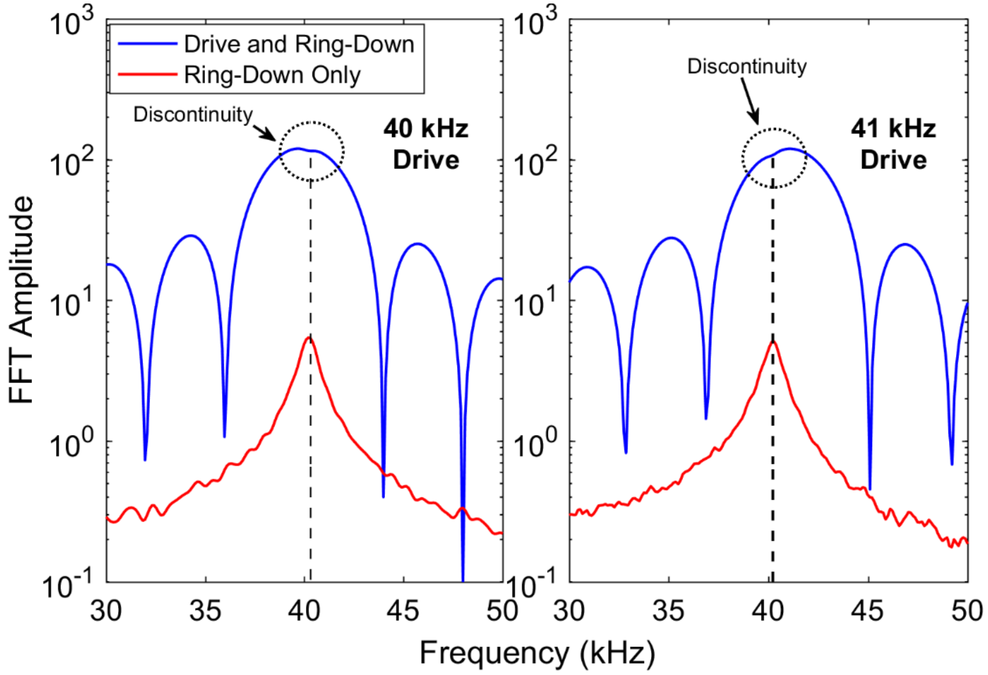
HiFFUT Membrane Diameter (mm):	
HiFFUT Membrane Thickness (mm):	
HiFFUT Membrane Material:	Aluminium ▾
Axisymmetric Mode of Vibration:	(0,0) ▾
Modal Frequency (kHz):	

Calculate | Reset

Resonance Frequency Measurement

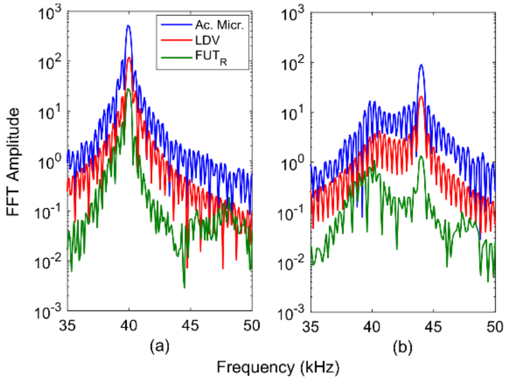
- Measurement of FUT resonance frequency using only an oscilloscope and function generator.
- Two drive frequencies of 40 kHz and 41 kHz are applied to the FUT, at 10 $V_{p\text{-}p}$ and 10 cycles, as burst sine signals.
- The ring-down region in each case is isolated, and analysed separately to the entire responses.
- The FFTs of the amplitude-time responses enable the identification of resonance.

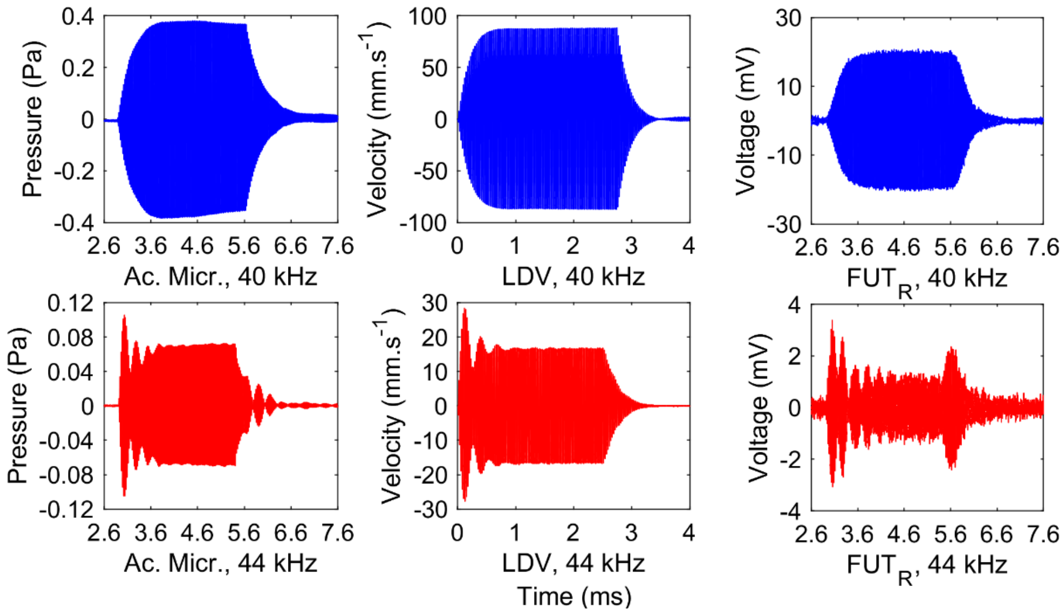




Methods of Characterisation

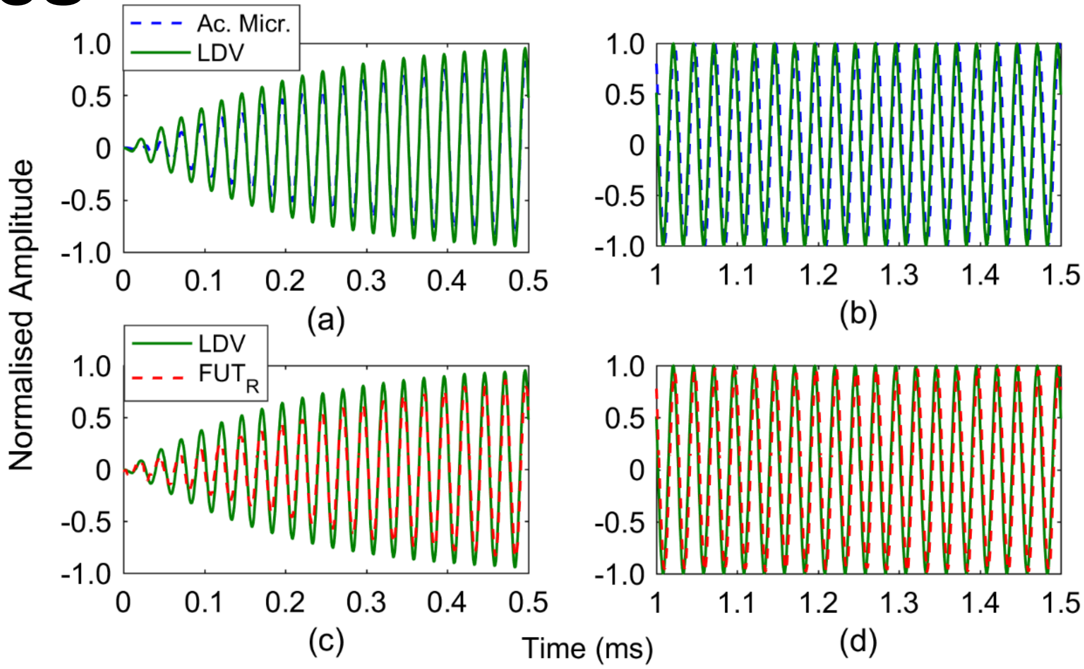
- Three methods of FUT characterisation are shown opposite.
- Two drive frequencies of 40 kHz and 44 kHz are applied to the FUT, at 10 V_{p-p} and 110 cycles, as burst sine signals.
- 40 kHz is at resonance, and 44 kHz is off resonance, in the (0,0) mode.
- The oscillating nature of the build-up to the steady-state region gives some information about proximity to resonance.





Signal Similarities

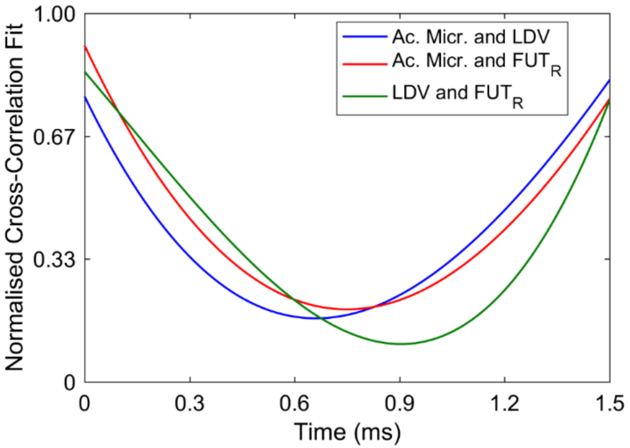
- There is little difference between the signal shapes for the acoustic microphone and LDV.
- Similarly, the LDV and FUT_R display an almost identical shape profile in the response signals.
- Any difference between the comparison of the vibration responses with the LDV method can be identified most prominently at the initiation of the amplitude-time response, just after switch-on. This is particularly noticeable for the acoustic microphone in this case, where the mass inertia of the capacitive membrane takes a small amount of time to oscillate sinusoidally.

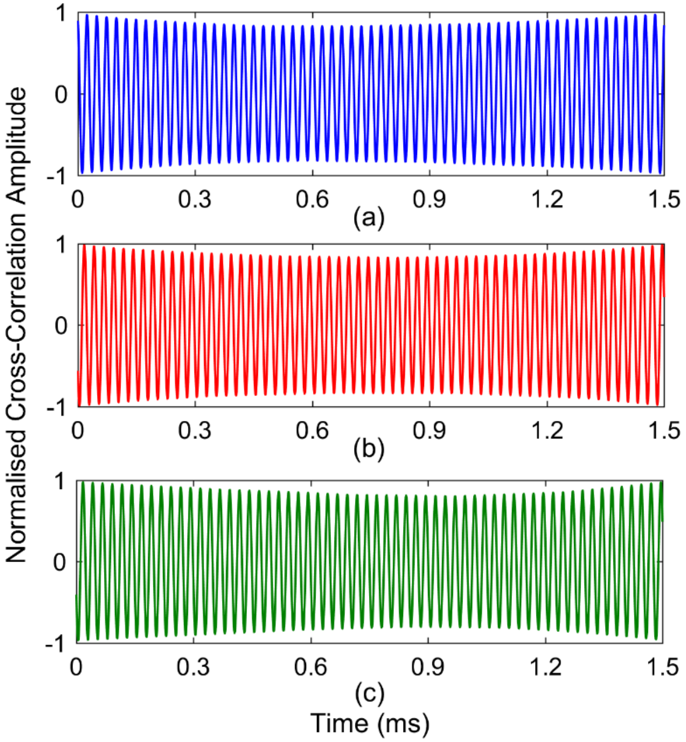


(a) and (c) show the Region 1 amplitude-time spectra, and (b) and (d) show steady-state. These results are time-shifted to enable comparison.

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, not unexpected due to the method of response measurement.





Cross-correlation of the signal spectra at 40 kHz and 110 cycles, for (a) the acoustic microphone and LDV, (b) the acoustic microphone and the FUT_R, and (c) LDV and the FUT_R

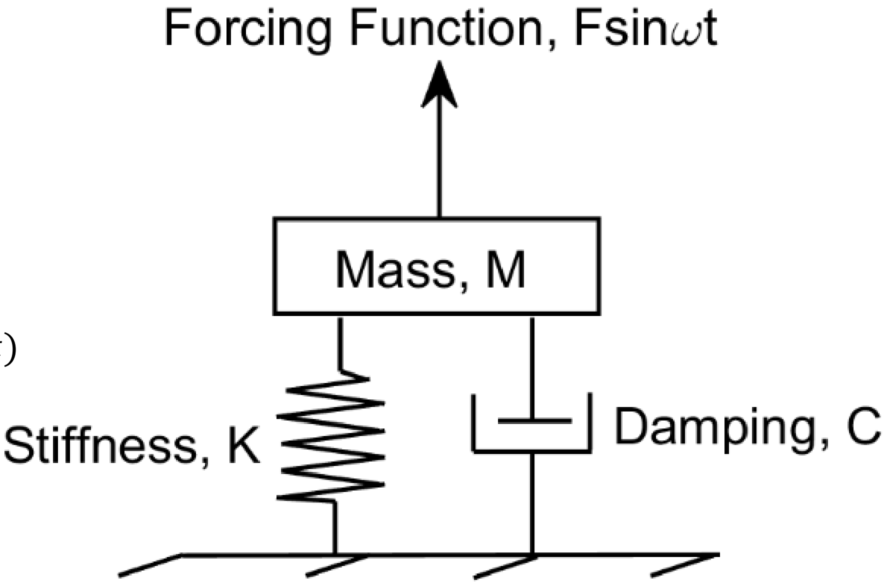
The Mechanical Analog Model

- The mechanical analog model schematic is shown opposite.
- The relationships provided below are taken from the previous research presented.
- The focus of the mechanical analog model for this phase of the research is on the Region 1 response.

Region 1 $$M\ddot{x} + C\dot{x} + Kx = Fsin\omega t.H(t_0 - t)$$

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

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



Analog schematic of the transducer

Correlation of Analog and Experiment

- The following assumptions are made, including an underdamped vibration response:

$$H = 1 \ for \ 0 < t \leq t_0$$

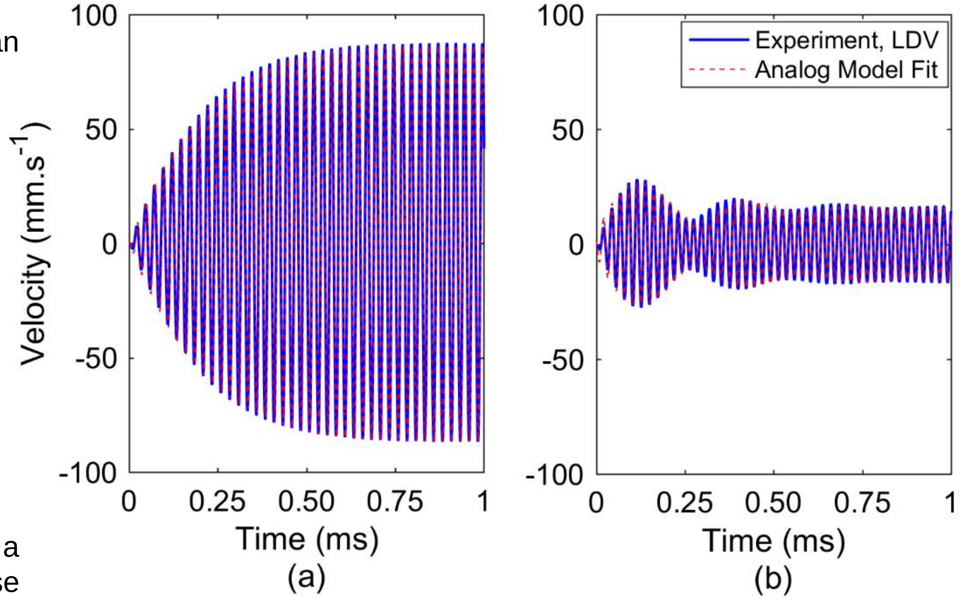
$$C^2 < 4MK$$

- The solution for the equation of motion is derived as:

$$x(t) = F_+ e^{-\alpha t}(cos\bar{\alpha}t + isin\bar{\alpha}t) + F_- e^{-\alpha t}(cos\bar{\alpha}t - isin\bar{\alpha}t) + \sqrt{A^2+B^2}(\sin(\omega t + \Phi))$$

- Taking the real part, and assuming $\sqrt{A^2+B^2} = \bar{E}$, we get a solution used to generate the numerical vibration response of the FUT:

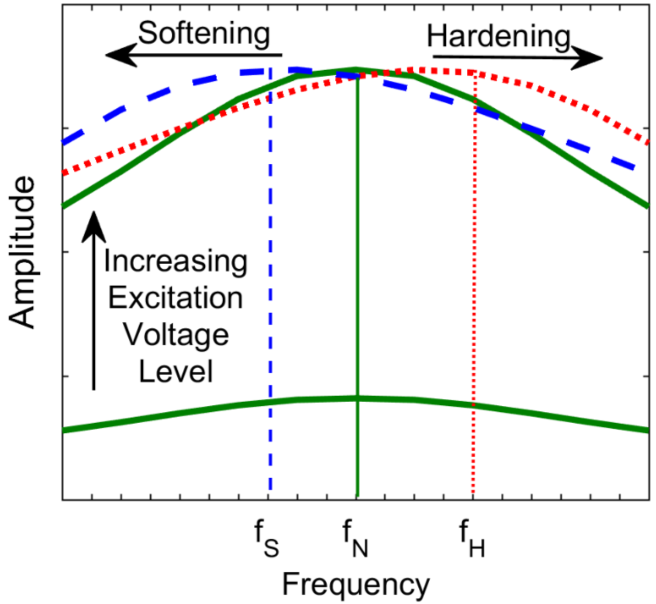
$$\boldsymbol{x(t) = (F_+ + F_-)(e^{-\alpha t}cos\bar{\alpha}t) + \bar{E}(sin(\omega t + \Phi))}$$



Correlation between experimentally obtained LDV data and numerical output from the mechanical analog model, for drive frequencies of (a) 40 kHz, and (b) 44 kHz

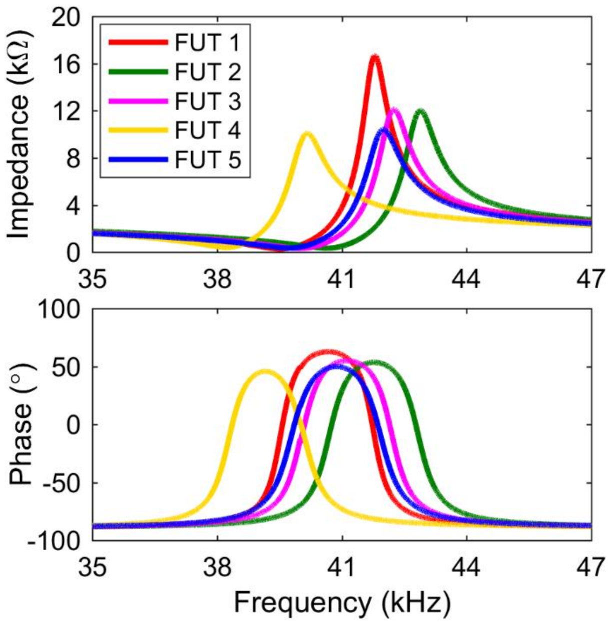
Dynamic Nonlinearity in FUTs

- The green trace in the chart opposite shows a linear response with respect to excitation amplitude. There is no apparent change in the centre resonance frequency, f_N.
- A change in resonance frequency in response to increasing amplitude can take place. A reduction in resonance is called a softening nonlinearity, where f_N approaches f_S. A hardening nonlinearity is exhibited as an increase in resonance frequency, where f_N approaches f_H.
- Hardening nonlinearities may be observed in systems with particular material properties causing a stiffening of the vibrating system. One example source would be materials such as shape memory alloys which exhibit stress-induced phase changing properties in certain conditions. Epoxy resins might be another good example.

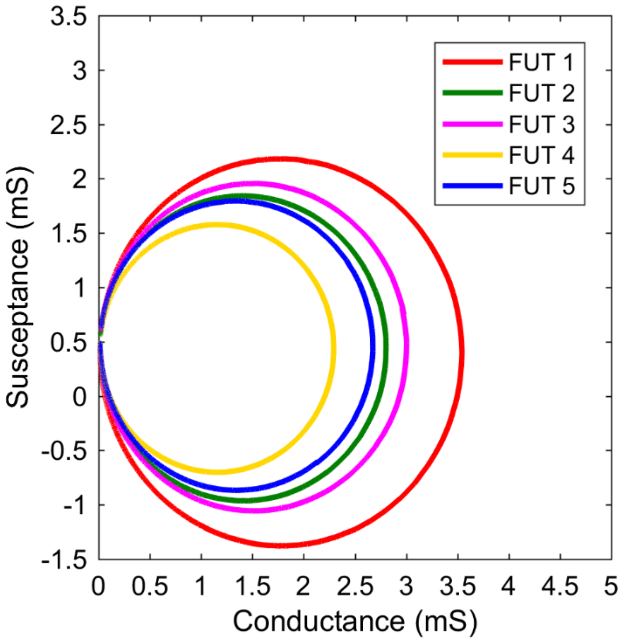


Softening and hardening nonlinearities, compared to linear response

Electrical Impedance Analysis



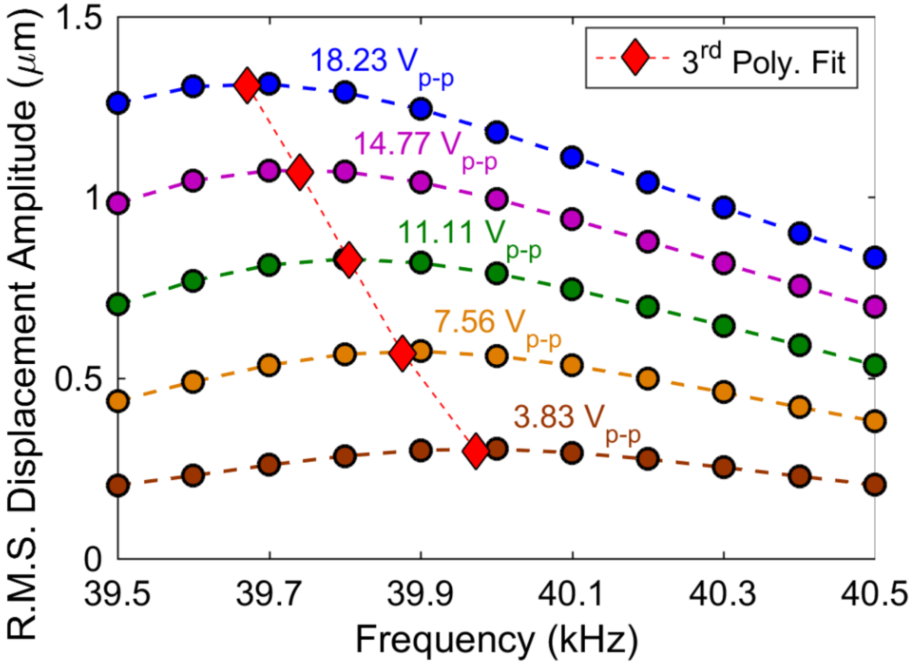
Impedance and phase spectra for five FUTs



Admittance loops for five FUTs

Dynamic Nonlinearity at Steady-State

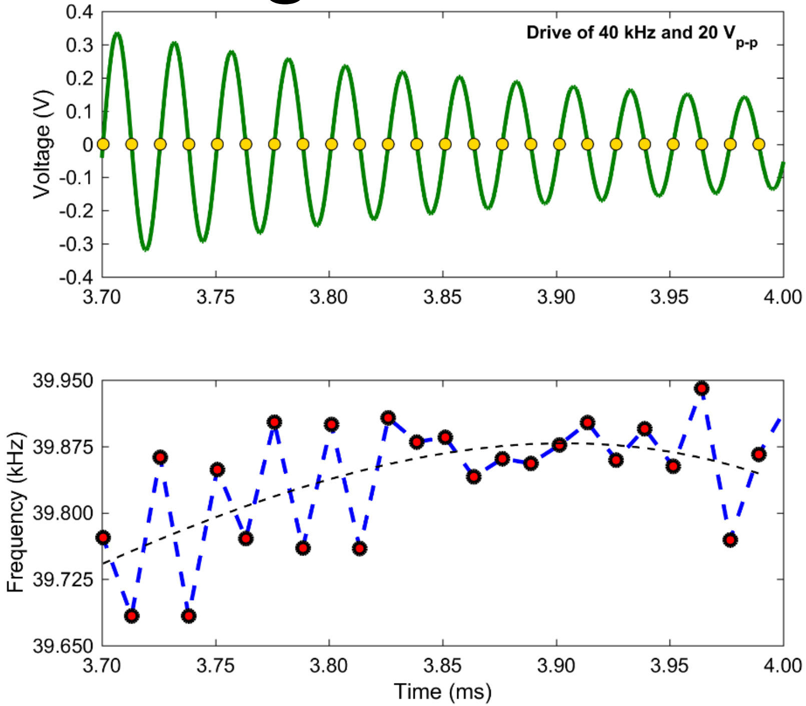
- One of the FUTs (FUT 1) was driven at a range of frequencies around resonance, itself determined from the electrical impedance analysis.
- The FUT was driven at nominal 4 V increments from 4 $V_{p\text{-}p}$ to 20 $V_{p\text{-}p}$, with a burst sinusoidal wave signal of 150 cycles.
- The amplitude-time response was measured for each driving frequency and voltage, using the LDV system.
- The steady-state region in each response spectrum was isolated, and the root mean square (R.M.S.) magnitudes were calculated.
- The difference between the resonance frequency at 3.83 $V_{p\text{-}p}$ and 18.23 $V_{p\text{-}p}$ has been measured to be approximately 300 Hz. The results demonstrate a clear nonlinearity in the dynamic response, where there is a reduction in frequency as the vibration amplitude is increased.
- The trend-lines for each data set are included for clarity.



Amplitude-frequency response of the FUT at steady-state

Dynamic Nonlinearity at Ring-Down

- The R.M.S. method cannot be used in the analysis of the ring-down region, due to the frequency component of the amplitude term.
- The results shown indicate the ring-down response of 20 V_{p-p} and 40 kHz drive, at resonance.
- Ring-down has previously been modelled as exponential decay. For this analysis, the ring-down region was isolated, and the exponential decay removed.
- The zero-crossing points were calculated in the remaining signal (top chart).
- The frequency magnitudes over the time window were then computed (bottom chart).
- The results demonstrate that the ring-down frequency is not constant, indicating the presence of dynamic nonlinearity in the vibration response.



Nonlinearity in the ring-down region, with the calculated zero-crossings

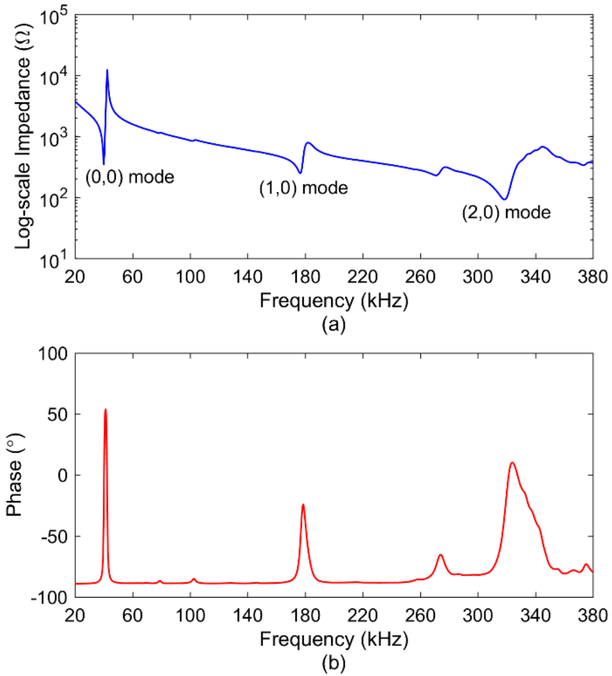
Dynamic Properties of FUTs

	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

Dynamic properties of five flexural transducers

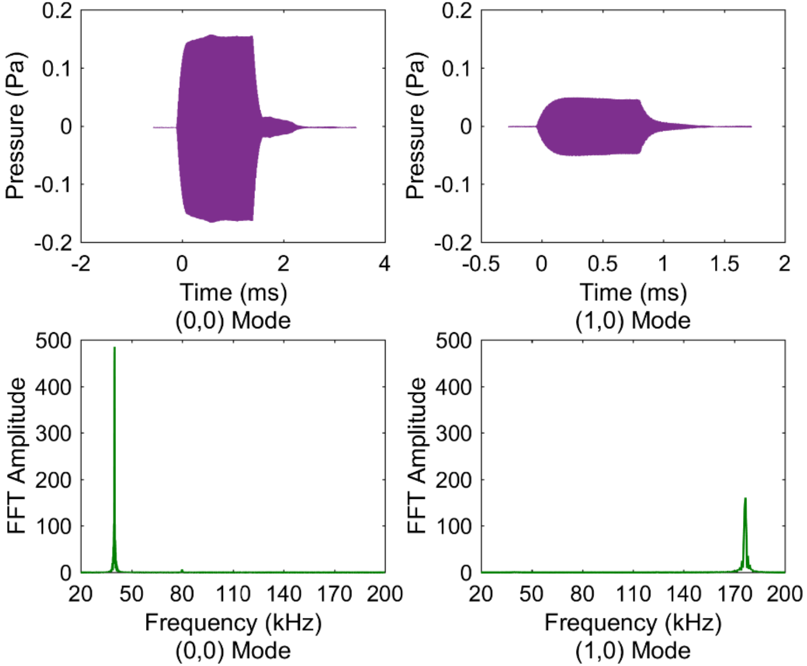
Operation of FUTs at High Frequency

- The vibration response of FUT 3 was investigated in more detail.
- The on-line design tool was used to estimate the (0,0), (1,0) and (2,0) modal frequencies. The approximate FUT dimensions are a cap membrane diameter and thickness of 10 mm and 0.4 mm respectively. The material is aluminium. The predicted frequencies are 40.2 kHz, 156.6 kHz, and 350.8 kHz.
- Electrical impedance measurements show frequencies of 39.97 kHz, 176.36 kHz, and 318.76 kHz. Note very minor changes in dimensions applied to the on-line design tool can generate closer approximations, but detailed FUT dimensions were not available.

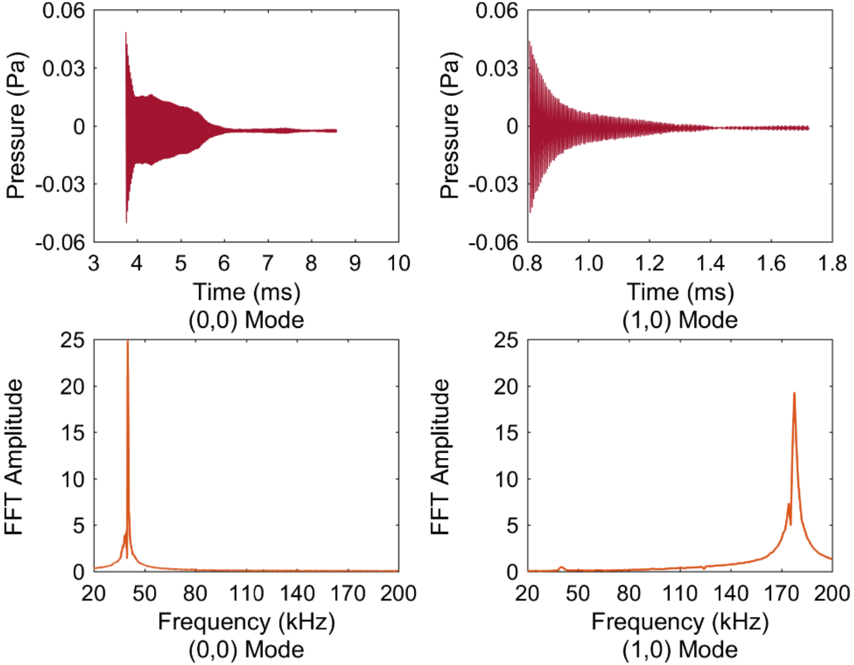


Impedance-frequency and phase-frequency measurements of the FUT

Acoustic Microphone Measurement

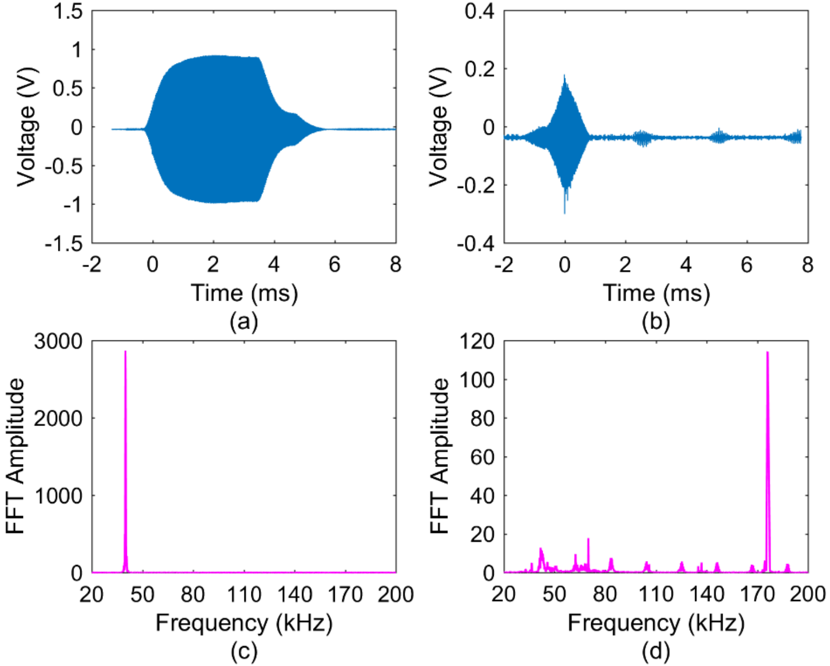


Vibration response measurements of the (0,0) and (1,0) modes using an acoustic microphone

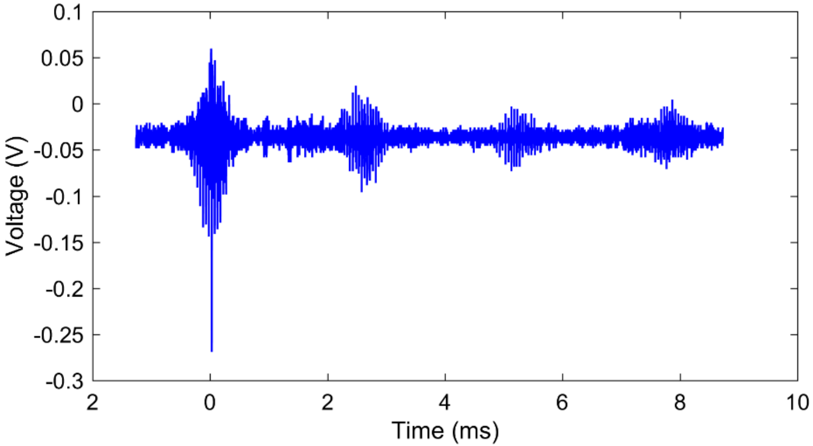


Vibration response measurements of the (0,0) and (1,0) mode ring-down regions using an acoustic microphone

Measurement with an Additional FUT

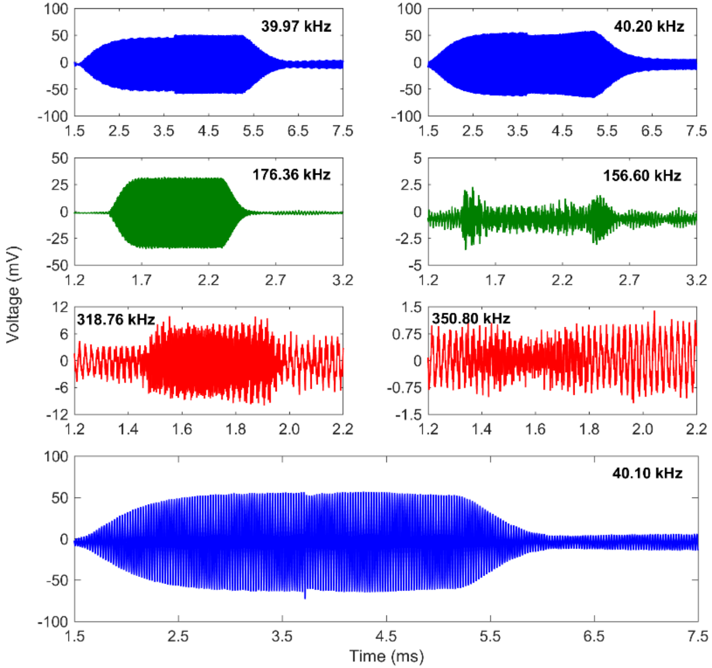


Vibration response measurements of the (0,0) and (1,0) modes using an additional FUT



Suspected (2,0) mode detected with a FUT, driving the transmitting FUT at 318.76 kHz

Higher Order Mode Measurement

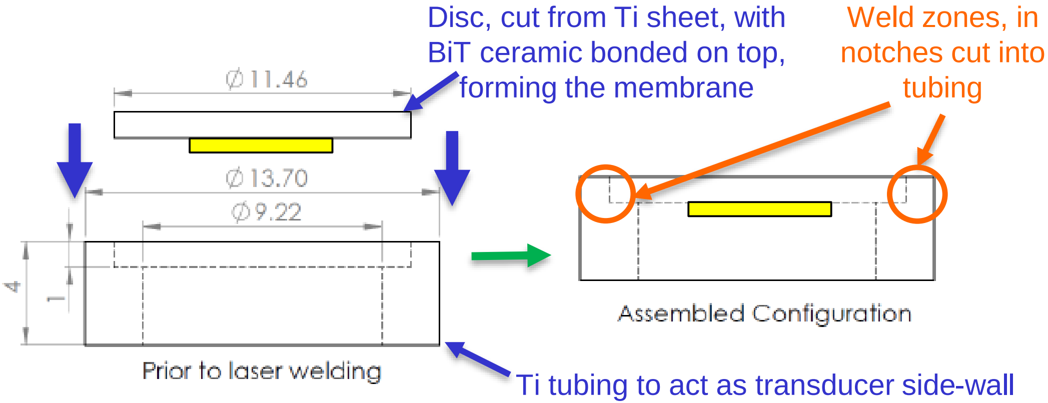


The (0,0) mode in blue, (1,0) mode in green, and the (2,0) mode in red, with minimised electrical noise

- Efforts were made to reduce electrical noise in the setup.
- The experiment was repeated with the same transmitter and receiver FUTs, separated by 500 mm.
- The drive frequency is shown in each plot sub-figure.
- The left-hand side plots are those obtained using frequencies measured using electrical impedance analysis.
- Those on the right are from the estimations using the on-line tool.
- The bottom plot shows the result measured by minimising the over-shoot of vibration amplitude in the build-up to steady-state.
- Using this resonance frequency, a cap thickness of 0.39885 mm is calculated. The cap diameter magnitude used in the on-line tool was maintained as 10 mm.
- There is hence a high sensitivity of resonance frequency to the cap dimensions and material.
- Both impedance analysis and the on-line tool have been utilised with differing degrees of accuracy, to measure the vibration responses of the axisymmetric modes.
- FUTs have the clear potential to detect high frequency vibrations, significantly higher than 50 kHz.

A HiFFUT for High Temperatures

- Laser welding chosen as a new approach to the fabrication of flexural transducers, and hence HiFFUTs.
- Efficiency, repeatability and precision of transducer manufacture.
- Titanium (Grade 2 ASTM) chosen as the base material, to produce a cap of 13.70mm total diameter, side-wall support length of 4.00mm with wall-thickness of 2.24mm, and membrane thickness of 1.00mm.
- Bismuth titanate (BiT) ceramic, 0.89mm thick, 6.35mm in diameter.
- The materials for the first HiFFUT for high temperature environments have been acquired, with fabrication to commence.



Cap components fabricated from laser welding

Pressure Vessel

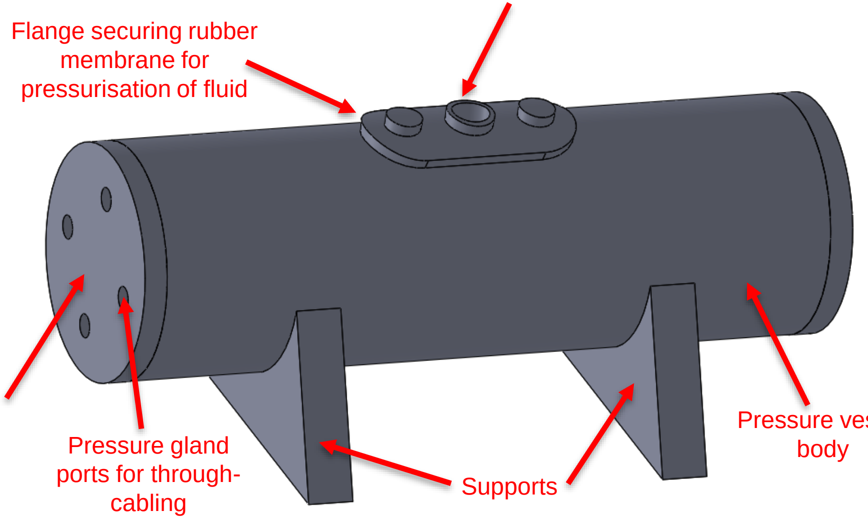
- Currently under manufacture by Gilwood (Fabricators) Ltd.
- Stainless steel.
- PD550:2015 Cat. 1, CE Mark, and certified to the PED 2014/68/EU, Cat. II Per Chart 2. Inspection Module A2.
- Design pressure: 286 barg (28.6 Mpag).
- Hydraulic test pressure: 200 barg (20 Mpag).
- Gland specification: Seals multiple wires, supplied by Thermal Detection Limited.

High Pressure Insulated Wire Sealing Gland (HPPL)

- Seals up to 2070bar (at 20°C)
- Grade 316L stainless steel

MK4 Hill Air Pump

- 1/8” BSP Connection
- Rated up to 4000psi (276bar)



Outside diameter [mm]	Wall thickness [mm]	Volume (l)	Weight [kg]
180	27	2.2	45

Next Steps

- Further investigation of laser welding of titanium for HiFFUT cap fabrication.
- Fabrication of a laser-welded flexural transducer using the titanium caps, with BiT piezoceramic driver, followed by a characterisation process comprising measurement of electrical and dynamic properties of the transducer as a function of temperature where possible.
- Assemble and test the pressure vessel, upon delivery.
- Report on the influence of bonding pressure level on the performance of flexural transducers.
- Begin candidate transducer designs for operation in pressurised environments, around 200 bar.
- Agree on the date of the next meeting.

Project Gantt Chart