HiFFUT - A New Class of Transducer

Update Report 3

Dr Andrew Feeney and Dr Lei Kang

a.feeney@warwick.ac.uk; l.kang.1@warwick.ac.uk

Research Fellows in the Centre for Industrial Ultrasonics

Department of Physics

University of Warwick

Coventry CV4 7AL, United Kingdom

Website: www2.warwick.ac.uk/fac/sci/physics/research/ultra/research/hiffut

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General Overview

This report is provided as an update of the HiFFUT research project between September 2017 and March 2018. For clarification, the targets defined in Update Report 2 distributed for the September 2017 meeting are shown in the list below.

1. Develop HiFFUT design strategies for projection and detection at high frequencies.
2. Expand what has been provided on-line through guidelines for pressure and temperature considerations, and accounting for compliance in the HiFFUT membrane.
3. Further investigation of laser welding of titanium for transducer cap fabrication.
4. Fabrication of a laser-welded flexural transducer, with measurement of electrical and dynamic properties of the transducer as a function of temperature.
5. Assemble and test the pressure vessel.
6. Influence of bonding pressure level on the performance of flexural transducers.
7. Investigate candidate transducer designs for operation in pressurised environments, up to 200 bar.

In the list, green items are those addressed, orange items are currently under investigation, and red items are those not yet undertaken. For example, item 4 was achieved but with the use of a high-temperature epoxy resin to bond the membrane to the side-wall of the HiFFUT, rather than laser welding, which will be reported later in 2018. Included in this report are results from the measurement of high frequency ultrasound using FUTs in air, measurement of FUT performance at high pressure levels using the custom pressurisation system, and initial experimental results from a HiFFUT designed for high temperature environments.

1. High Frequency Ultrasound Measurement using FUTs

The transmission and detection of high frequency ultrasound waves, above 50 kHz, in air over a distance of 500 mm, has been achieved, up to a frequency of 318 kHz. A brief overview of the experimental process is shown in this section, with a selection of experimental results. This research has been submitted to *IEEE Sensors Journal* for publication.

1.1 Methodology and Experimental Process

Two Multicomp FUTs were set in a transmit-receive configuration, as exhibited in Figure 1.1. The transmitter and receiver FUTs were nominally identical in terms of vibration characteristics and resonance frequency, and the transmitter was given the capacity to be rotated as shown.

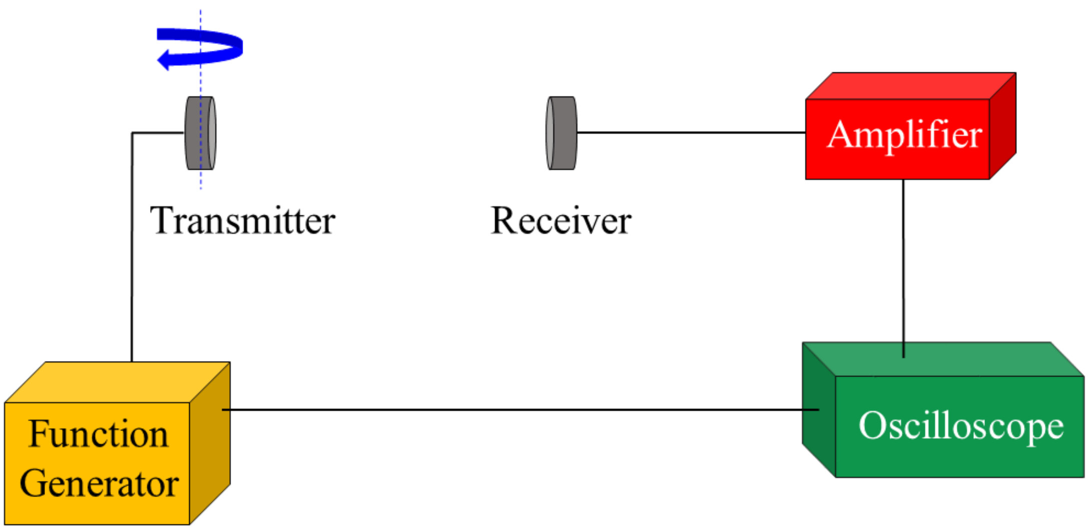


Figure 1.1: Experimental setup for high frequency ultrasound measurement.

The three fundamental axisymmetric modes of vibration were investigated, comprising the (0,0), (1,0), and (2,0) modes, primarily to determine the capability of this setup for the acquisition of high quality ultrasound measurements at high frequencies, upwards of 50 kHz, in air. This has been achieved for a FUT-FUT separation of 500 mm, with the capacity for data capture at much greater distances.

Laser Doppler vibrometry (LDV) was used in this study only for confirmation of the mode shapes, where the resonance frequencies were determined using electrical impedance analysis. LDV measures purely the membrane vibration, and in the near-field, and so is not an accurate representation of the interaction between two ultrasound sensors, or an ultrasound wave in the far-field. An acoustic microphone was not used in this study, since it is not calibrated for use at the frequencies of the (1,0) and (2,0) modes. Using the two FUTs in a transmit-receive configuration, ultrasonic response profiles and amplitude-time spectra were measured for each mode of vibration, demonstrating the suitability of the technique for the propagation and acquisition of ultrasound waves in air up to 318 kHz.

1.2 Experimental Results

The electrical impedance measurements for the transmitter are shown in Figure 1.2, where MI, MII, and MIII represent the vibration modes likely associated with the axisymmetric (0,0), (1,0), and (2,0) modes. These were confirmed through LDV, where the results are shown in Figure 1.3.

The Bessel functions used to build the on-line mode estimator tool were used to predict at approximately which resonance frequencies the vibration modes would appear. The (0,1), (0,2), and (1,1) modes were predicted to be at 84 kHz, 137 kHz, and 239 kHz. Therefore, the estimations for MI, MII, and MIII could be made as shown in Figure 1.2 with some confidence. There will be inevitable slight discrepancies between the estimator results and those from finite element analysis (FEA) or experiment, since the Bessel functions are specifically associated with an edge-clamped disc. The frequencies associated with MI, MII, and MIII shown in Figure 1.2 were found to correlate closely with the frequencies found for the mode shape results in Figure 1.3.

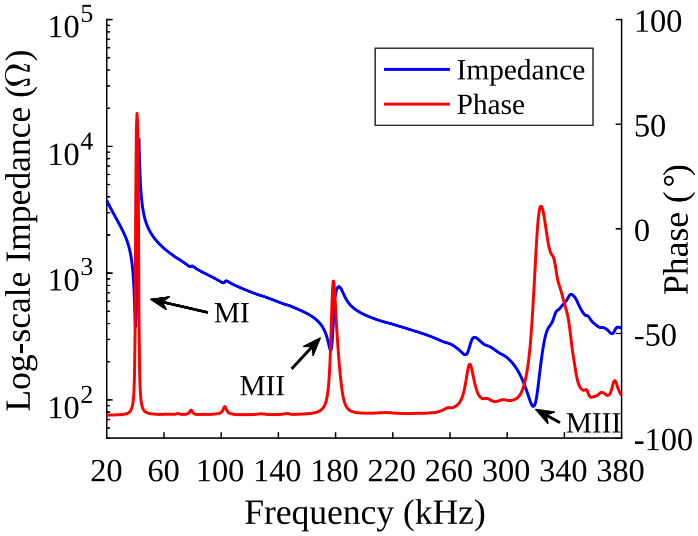


Figure 1.2: Impedance and phase spectra as functions of frequency, for the FUTs used in the measurement of ultrasound at high frequency.

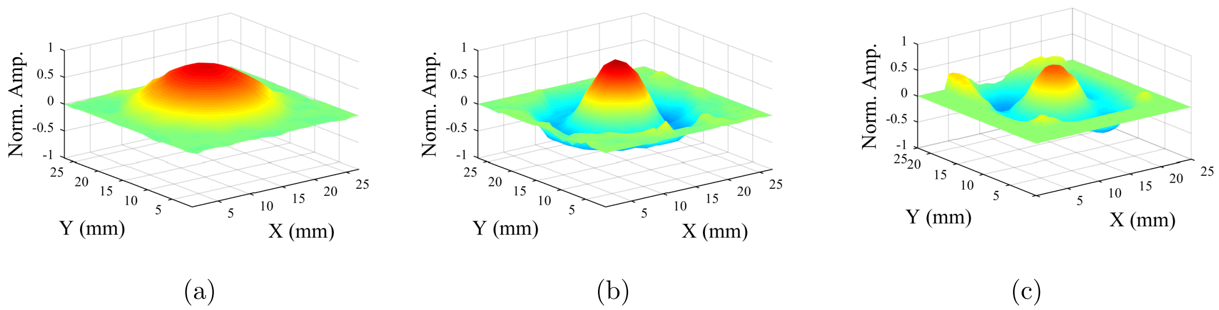


Figure 1.3: The mode shapes of the FUT used for high frequency ultrasound measurement, showing (a) the (0,0) mode at 40.5 kHz, (b) the (1,0) mode at 177.4 kHz, and (c) the (2,0) mode at 318.7 kHz.

The ultrasonic response profiles of the (0,0) and (1,0) modes are shown in Figure 1.4. There was insufficient signal resolution to accurately capture the ultrasonic response profile for the (2,0) mode, and so only the (0,0) and (1,0) mode data are presented.

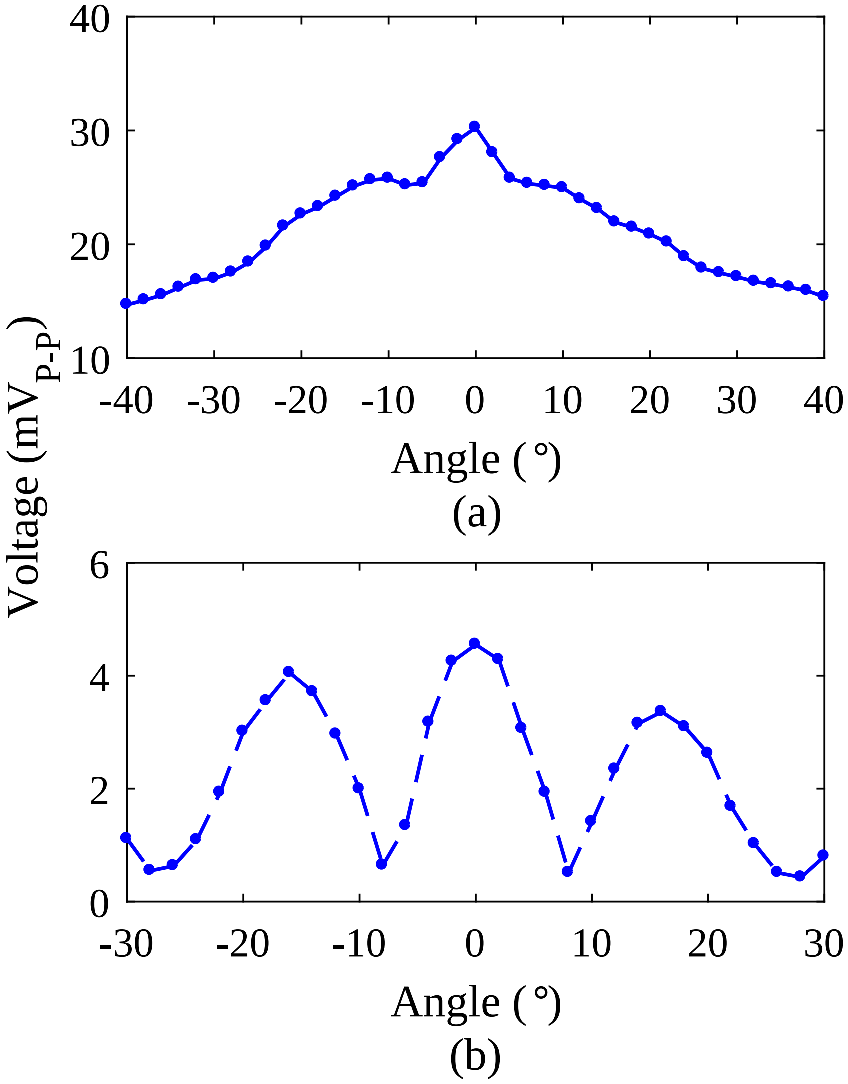


Figure 1.4: Ultrasonic response profiles measured using two FUTs in a transmit-receive configuration, showing (a) the (0,0) mode at 39.9 kHz, and (b) the (1,0) mode at 176.2 kHz.

The mode frequencies closely correlate with those of the electrical impedance and LDV techniques, and any minor differences are attributable to differences in clamping condition. The ultrasonic response profiles shown in Figure 1.4 are a consequence of the interaction between the transmitted ultrasound wave and the vibration response of the receiver, and therefore do not precisely match the mode shapes measured using LDV.

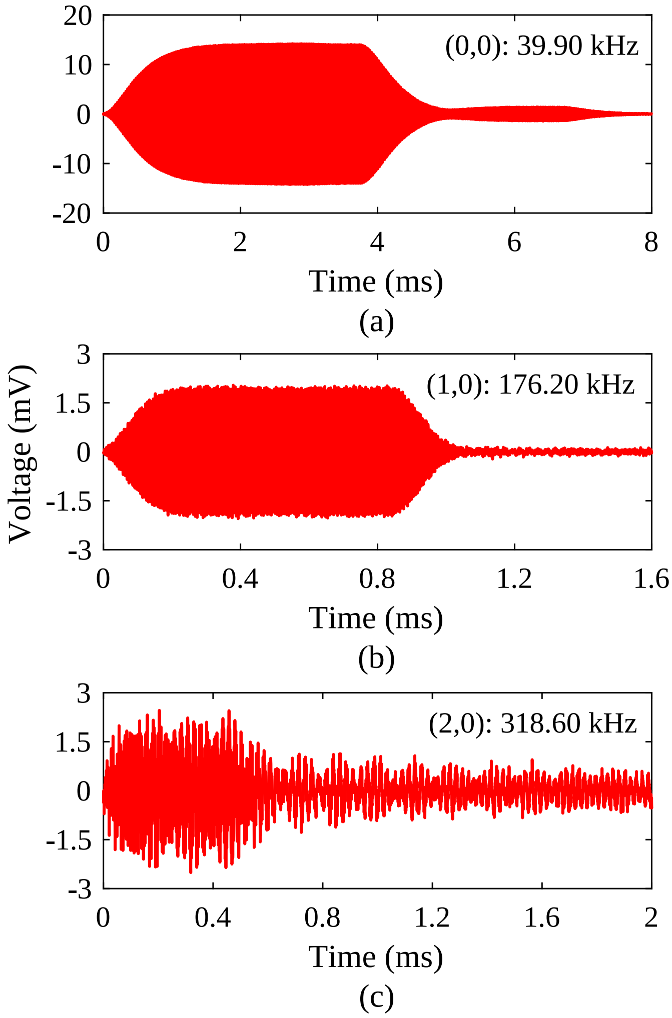


Figure 1.5: Amplitude-time spectra of the FUT for the (a) (0,0), (b) (1,0), and (c) (2,0) vibration modes, measured with 500 mm of separation between the transmitter and receiver FUTs.

The signal gains required to measure the (0,0) and (1,0) modes were approximately 14 and 21 respectively. The amplitude-time responses for the transmitter measured by the receiver are shown in Figure 1.5, where the gain required to capture the (2,0) mode was in the region of 88. The associated FFT results are exhibited in Figure 1.6. Close correlation with the mode frequencies with the other experimental techniques has again been observed.

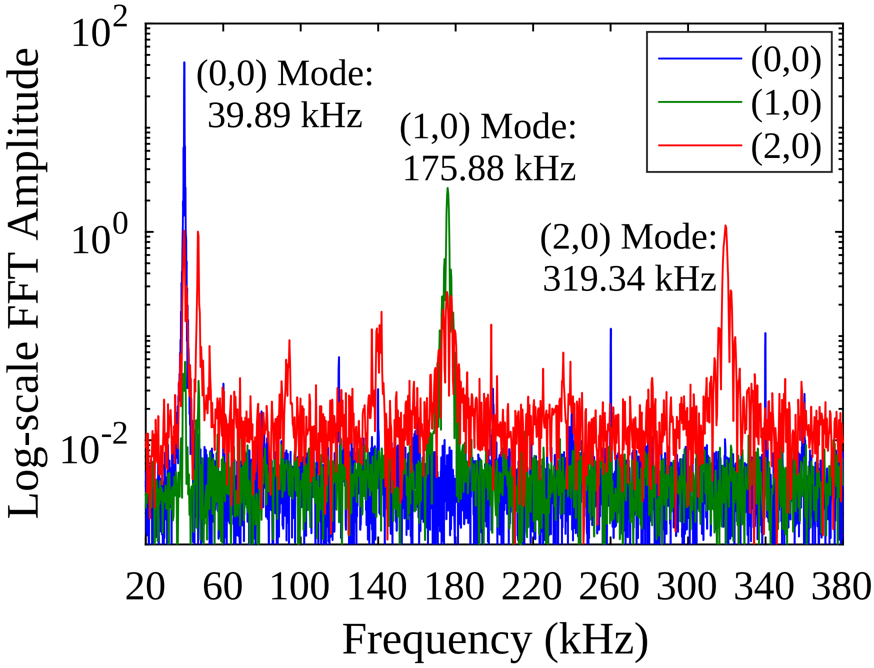


Figure 1.6: FFT results of the amplitude-time spectra of the FUT for the three fundamental axisymmetric vibration modes.

This study has demonstrated the transmission and acquisition of high frequency ultrasound waves in air up to 318 kHz, at higher order modes of vibration. The outcomes of this investigation will be used to further develop HiFFUT technology.

2. Measurement of Ultrasound at High Pressure

Initial experiments into the performance of FUTs at high pressure levels have been conducted, through the modification of commercial FUTs. The pressure vessel was integrated with the sealing glands and a commercial air pump (Hill Air Pump, Ernest H. Hill Ltd) for pressurisation up to 200 bar, with a pressure sensor (Honeywell) used for verification of the pressure within the vessel. For the pressurisation of liquid within the vessel chamber, it is proposed that a small volume of air is pressurised within the chamber, instead of the original proposal to apply the pressure to a compliant membrane. The inclusion of a compliant membrane was not possible with the vessel design. The complete pressurisation system is shown in Figure 2.1.

Sample measurement data was collected, with contribution from two *M.Phys.* dissertation students. The voltage output as a function of pressure within the chamber was collected for FUTs in three different configurations. The first is an unmodified Multicomp FUT, with a centre resonance frequency of 40 kHz in the (0,0) mode of vibration. The second FUT is a completely sealed version of this device, and the third is modified for high pressure environments. The results are shown in Figure 2.2.

It is evident that the FUT which is sealed fails at a relatively low pressure. This is based on the pressure causing an irreversible deformation of the transducer cap membrane. The unmodified FUT likely contains leakage points which allows a degree of pressure equalisation, but with relatively low output at higher pressure levels. This is also problematic, because in the application of this device in a corrosive fluid or hostile environment, leakage points must be eliminated to prevent further damage to the FUT. The modified device has exhibited high output at higher pressure levels, albeit with drops, the causes for which must be investigated.

Figure 2.1: The pressurisation system, comprising the pressure vessel manufactured by Gilwood (Fabricators) Company Ltd. connected to the Hill Air Pump.

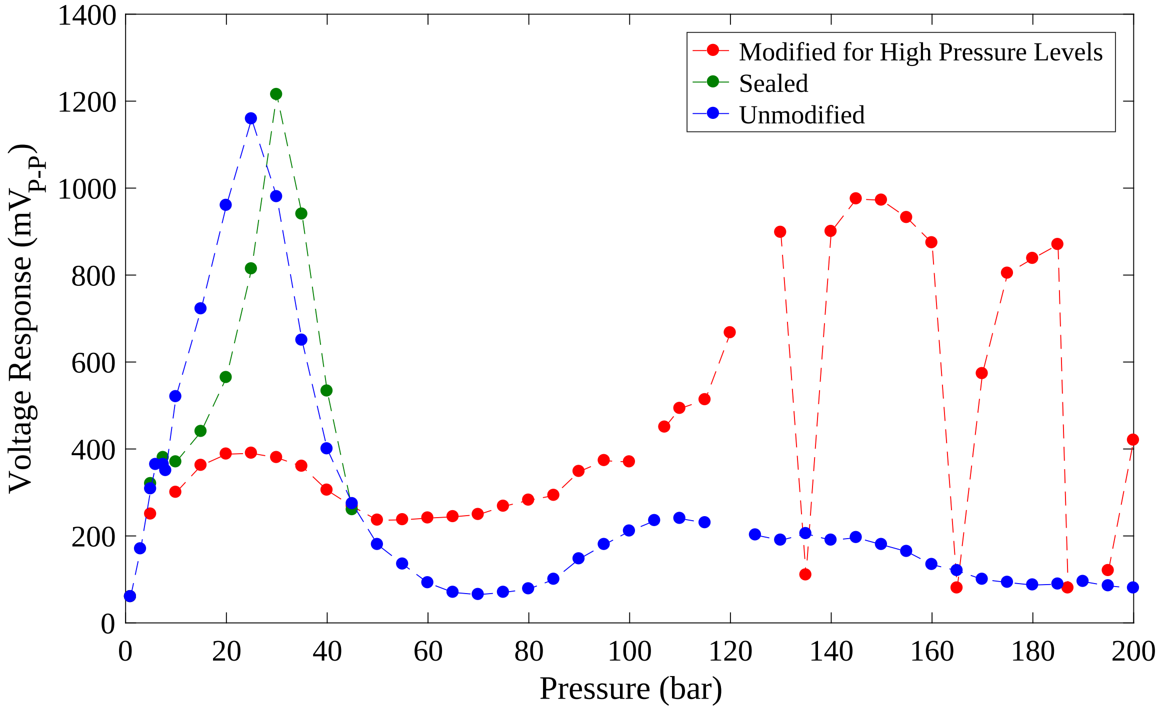
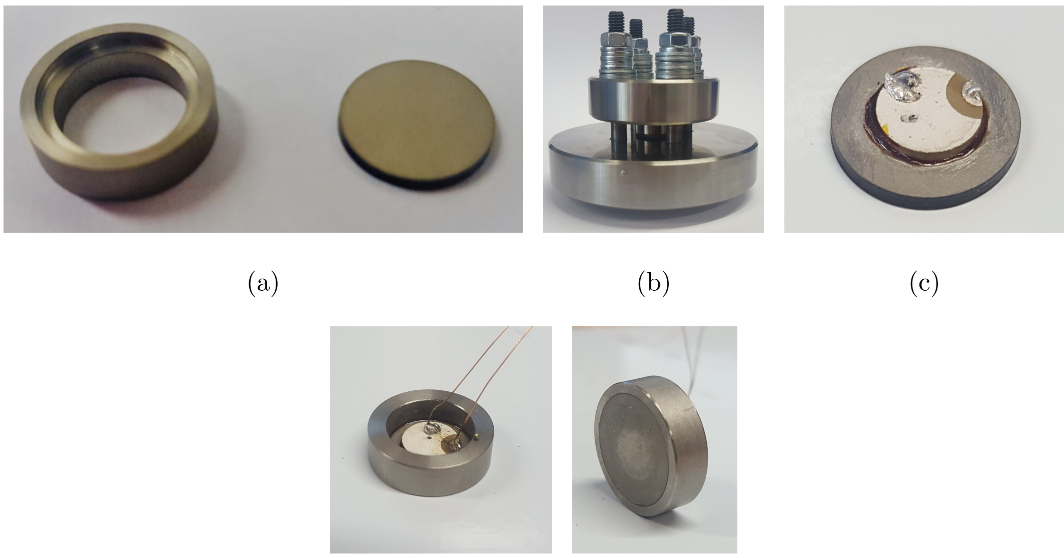


Figure 2.2: The voltage-pressure response for FUTs in different configurations, comprising unmodified, sealed, and modified. These are initial results which will require further investigation.

3. Prototype HiFFUTs for High Temperatures

Two prototype high temperature HiFFUTs were constructed, which were designed using PZFlex FEA to operate above 50 kHz in the (0,0) mode of vibration and at high temperatures, upwards of 100℃. For this purpose, bismuth titanate in the form of PZ46 (Meggitt), with a Curie temperature of 650 ℃, was selected as the driver element for the HiFFUT. The cap material was defined as titanium, and the cap itself was fabricated in two parts to ensure the bonding of the piezoelectric ceramic at the centre of the cap membrane. The HiFFUTs were then assembled using a custom-designed pressure rig. The assembly process is shown in Figure 3.1.



(a) (b) (c)

(d) (e)

Figure 3.1: The assembly process for the high temperature HiFFUT, showing (a) the components of the HiFFUT cap, (b) the assembly rig, (c) the bismuth titanate ceramic bonded to the cap membrane, and (d) and (e) the assembled device.

The membrane diameter of each was 11.46 mm with a thickness of 1 mm, and bonded to a cap with a recess of 1.12 mm around the circumference. A thin layer of high temperature epoxy resin (EPO-TEK® 353ND) was applied to each device, in both the recess of the side-wall and between the ceramic and the cap membrane.

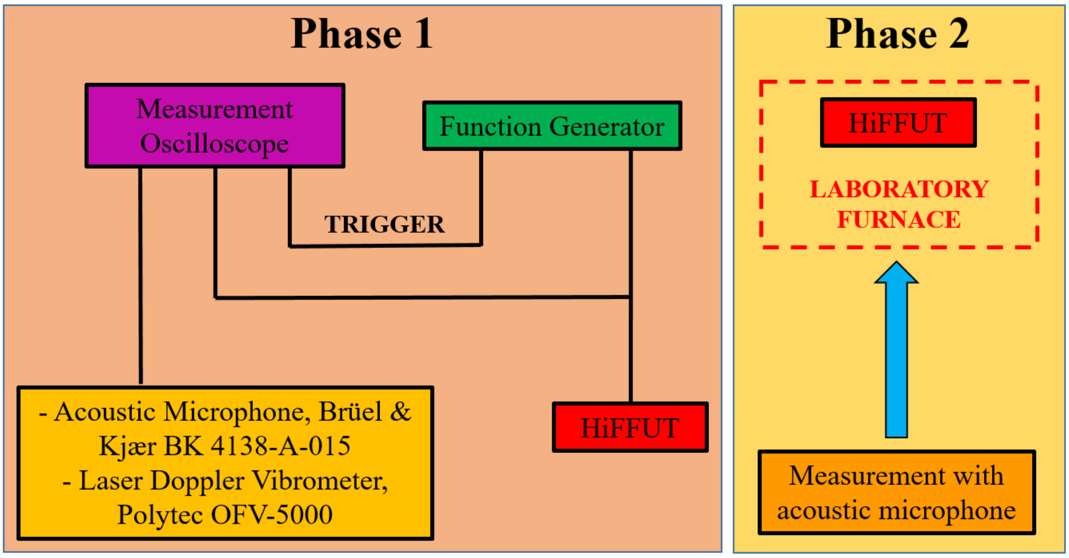


Figure 3.2: Measurement setup used to test the high temperature HiFFUT.

The experimental process shown in Figure 3.2 was implemented. First, LDV was conducted at room temperature to verify the (0,0) mode shape, the result of which is shown in Figure 3.3 for high temperature HiFFUT 1. Then, an acoustic microphone was used to measure the amplitude-time response at a distance of 65 mm for the (0,0) mode of vibration at room temperature, and then 300 mm during thermal characterisation, for both high temperature HiFFUTs 1 and 2. The devices were situated inside a laboratory furnace (Pyrotherm), where the microphone was protected from the high temperatures.

It should be noted that the cost of using a piezoelectric ceramic fabricated for high temperatures, such as bismuth titanate, is that its output is much lower than that of a lead-based piezoelectric ceramic such as PZT-5H, for a given input voltage. The piezoelectric properties are much lower, such as the d_{33} property, and so even though the Curie and operating tem-

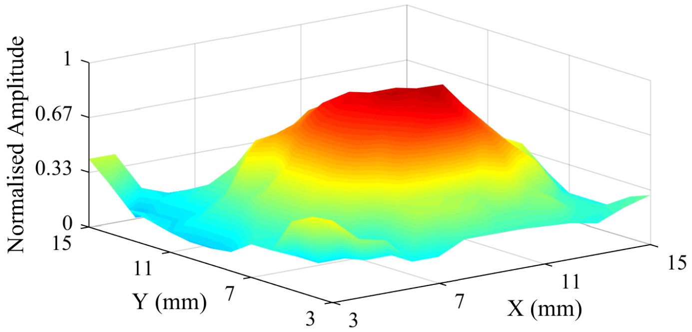
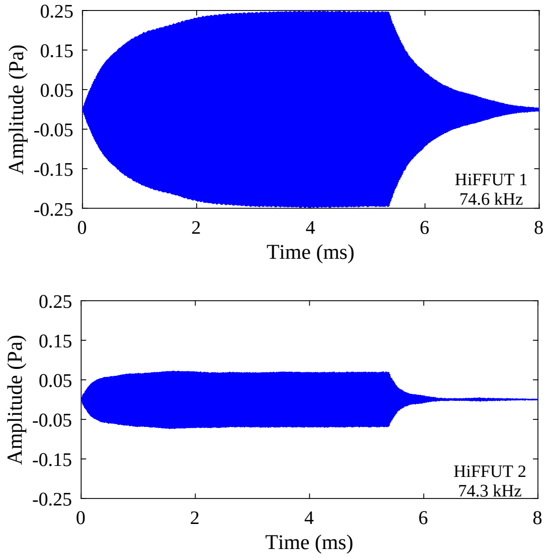


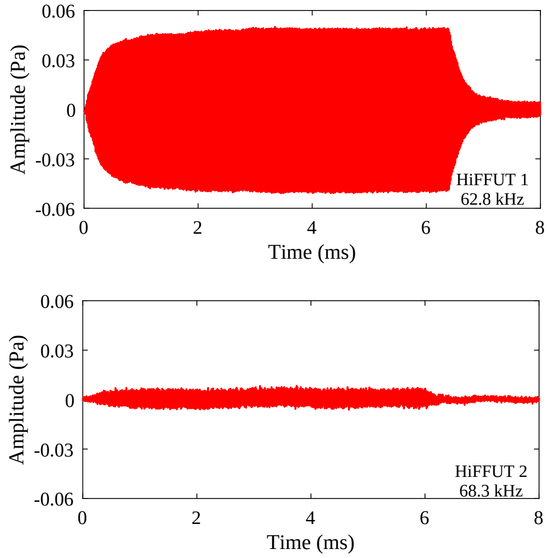
Figure 3.3: The (0,0) mode of the high temperature HiFFUT at 74.5 kHz, measured using LDV at room temperature.

peratures are generally higher, the output amplitudes achievable for a specific input are lower. To obtain the amplitude-time spectra for each device, measurements were first made in air prior to thermal characterisation, before data was recorded inside the laboratory furnace up to 150℃ in 50℃ increments. The devices were maintained at each temperature level for at least 15 minutes to ensure thermal equilibriation. In each case, a burst sinusoidal drive signal of 20 V_{P-P} and 400 cycles was administered. The amplitude-time spectra before and after thermal characterisation are shown in Figure 3.4, and the relationship between resonance frequency and temperature is exhibited in Figure 3.5 for high temperature HiFFUT 2.

There is a reduction of amplitude and frequency for both devices. The amplitude reduction is expected since the measurement distance had to be changed. However the ratios between the amplitudes of both devices at steady-state are consistent, providing an indication of device robustness at high temperature levels, particularly in relation to the PZ46 piezoelectric ceramic. Thermal expansion of the metal cap components is likely a major cause of the resonance frequency reduction. Also, the glass transition temperature of the epoxy resin was passed, influencing the coupling strength of the bond between the membrane and the side-wall. To address this, laser welding of the cap will be reported in the next update. However, the functionality of both high temperature HiFFUTs remains after operation at 150℃. With adapted high temperature HiFFUT design and experimental processes, there is potential for HiFFUTs suitable for application at a range of operational frequencies at temperatures towards 500℃.



(a)



(b)

Figure 3.4: The amplitude-time spectra for the high temperature HiFFUTs, showing (a) prior to and (b) post 150℃ thermal characterisation.

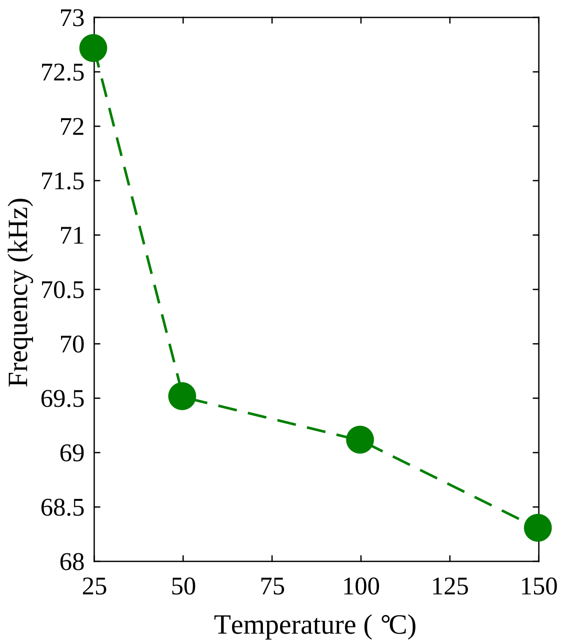
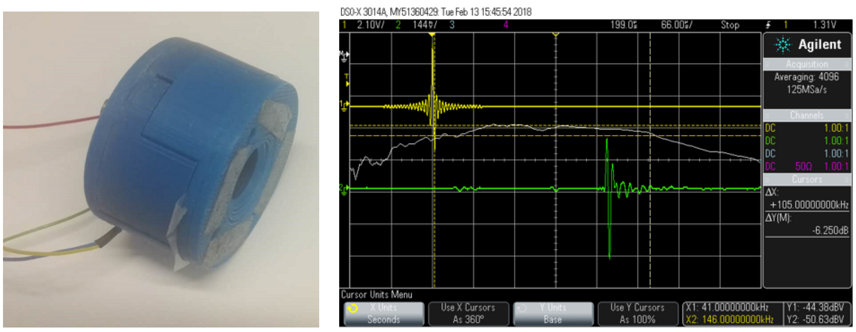


Figure 3.5: Frequency-temperature relationship for high temperature HiFFUT 2.

4. Electromagnetically-driven HiFFUTs

Metallic membranes can be driven through electromagnetism, rather than by using a piezoelectric ceramic. This method utilises the Lorentz force, magnetostriction force and/or magnetization force. Advantages of electromagnetically-driven ultrasonic transducers include no requirement of bonding, no soldering points on the metallic membrane, and greater control of the operating mode, with a wider band frequency response.

A novel wideband electromagnetically-driven ultrasonic transducer for fluid-coupled applications has been designed and fabricated, shown in Figure 4.1, showing the device with a sample vibration response spectrum. A patent application will be filed for this device.



(a) (b)

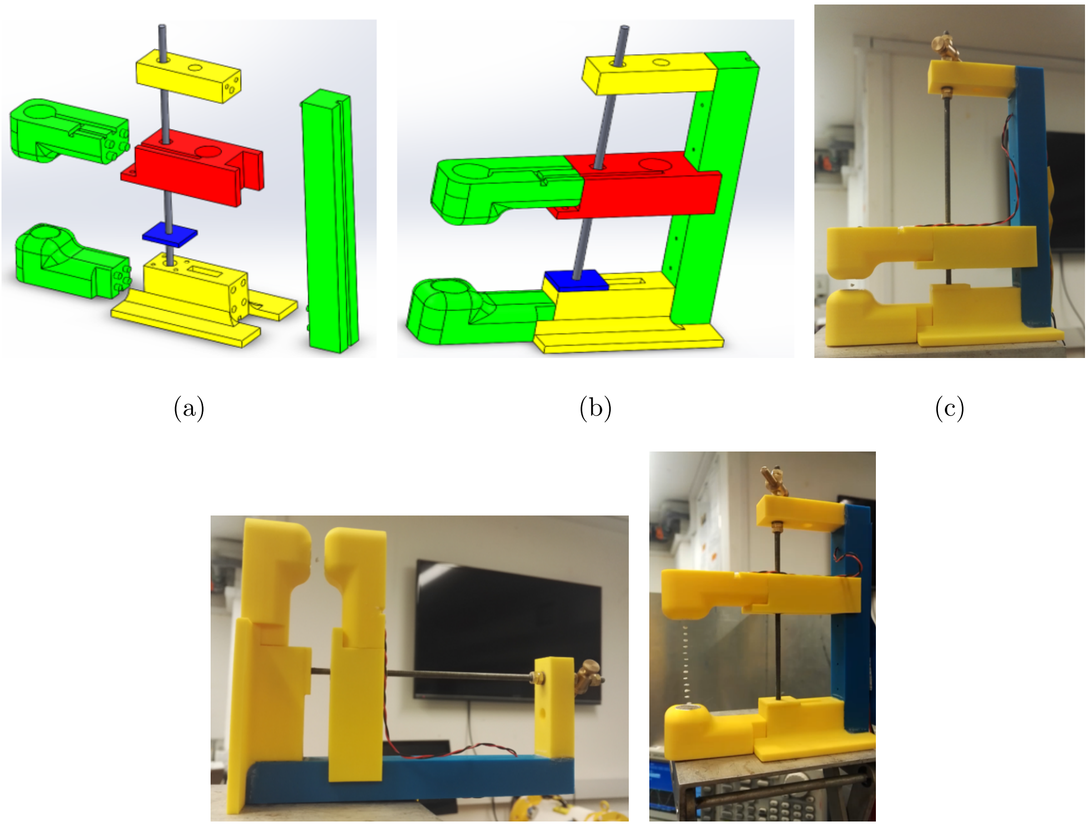
Figure 4.1: An electromagnetically-driven HiFFUT, showing (a) the device structure, and (b) its vibration response.

Key features of this device which have been observed through experiment include:

- High sensitivity (approximately 80 dB SPL at 100 mm with 7 V_{P-P} input)
- Wide bandwidth (-6 dB bandwidth: 40 kHz to 140 kHz)
- Flat response (no obvious centre frequency), with high directivity (less than 10° half-beam angle)

5. Acoustic Levitation

A 3D-printed mechanical structure has been designed to hold two 40 kHz flexural ultrasonic transducers facing each other, where the distance between the transducers can be adjusted. The structure is shown in Figure 5.1, including in operation.



(a) (b) (c)

(d) (e)

Figure 5.1: Acoustic levitation with FUTs, showing ((a); (b)) the levitator device construction, and ((c); (d);(e)) the levitation of polystyrene, as single particles but also in a line of multiple particles, with the capability of being oriented at different angles.

A standing wave with a wavelength of 8.6 mm is formed in the air by the constructive interference between the two ultrasonic transducers. Small particles like polystyrene balls and droplets can be trapped in the antinodes of pressure of the standing wave, which is shown in Figure 5.1. The pressure at the antinodes is sufficiently strong, with an input voltage 20 V_{P-P}), to overcome gravity, where the particles are hence levitated. This effect also functions horizontally, where the orientation of the levitator device can be varied, whilst at the same time maintaining levitation. Furthermore, multiple particles can be levitated simultaneously, under an operating voltage of 80 V_{P-P}. This levitation system could potentially be employed for contactless manipulation of particles in both industrial and medical applications.

6. Publications and Presentations

The publications disseminated and details of the public and professional outreach undertaken in this reporting period, since September 2017, are outlined in the following lists. One point to be acknowledged from this information, is that in response to our research presentations delivered to the 2017 International Congress on Ultrasonics, we have received a number of notes of interest from organisations based in the USA, China, and Japan, which will help in the impact and promotion of the research outcomes.

REFEREED JOURNAL & CONFERENCE PUBLICATIONS

1. A. Feeney, L. Kang, and S. Dixon, "High frequency measurement of ultrasound using flexural ultrasonic transducers," *IEEE Sensors Journal*, Accepted subject to approval of revision, 2018.

2. A. Feeney, L. Kang, and S. Dixon, "HiFFUTs for high-temperature ultrasound," *Proceedings of Meetings on Acoustics*, vol. 32, 2018.

3. A. Feeney, L. Kang, G. Rowlands, and S. Dixon, "Dynamic characteristics of flexural ultrasonic transducers," *Proceedings of Meetings on Acoustics*, vol. 32, 2018.

4. L. Kang, A. Feeney, and S. Dixon, "Flow measurement based on two-dimensional flexural ultrasonic phased arrays," *Proceedings of Meetings on Acoustics*, vol. 32, 2018.

5. A. Feeney, L. Kang, and S. Dixon, "Nonlinearity in the dynamic response of flexural ultrasonic transducers," *IEEE Sensors Letters*, vol. 2, no. 1, pp. 1-4, 2018.

6. A. Feeney, L. Kang, G. Rowlands, and S. Dixon, "The dynamic performance of flexural ultrasonic transducers," *Sensors*, vol. 18, no. 1, 270, pp. 1-14, 2018.

CONFERENCE & SYMPOSIUM PRESENTATIONS

1. **A. Feeney**, L. Kang, and S. Dixon, "HiFFUTs for high-temperature ultrasound," *The 2017 International Congress on Ultrasonics*, Honolulu, Hawaii, USA, December 2017.

2. **A. Feeney**, L. Kang, G. Rowlands, and S. Dixon, "Dynamic characteristics of flexural ultrasonic transducers," *The 2017 International Congress on Ultrasonics*, Honolulu, Hawaii, USA, December 2017.

3. L. Kang, **A. Feeney**, and S. Dixon, "Flow measurement based on two-dimensional flexural ultrasonic phased arrays," *The 2017 International Congress on Ultrasonics*, Honolulu, Hawaii, USA, December 2017.

PUBLIC OUTREACH

1. A. Feeney and L. Kang, demonstrators of ultrasonics and HiFFUT research to the public, *XMaS Science Gala*, University of Warwick, January 2018.

7. Summary and Next Steps

Initial investigations in the design, fabrication and characterisation of high temperature HiFFUTs have been conducted. The pressure vessel has been assembled and interfaced with a suitable air pump, and used to perform experiments on commercial FUTs, including those modified for use in pressurised environments. The updated Gantt chart for this project is shown in Figure 7.1, and a list of objectives for the coming months towards the next meeting are outlined in the following list.

1. Complete fabrication and testing of demonstrator piezoelectric HiFFUTs.
2. Develop the second phase of HiFFUTs for high temperature applications.
3. Construct and test a laser-welded HiFFUT.
4. Design and test HiFFUTs for high pressure environments towards 200 bar.
5. Further develop electromagnetically-driven HiFFUTs for hostile environments.

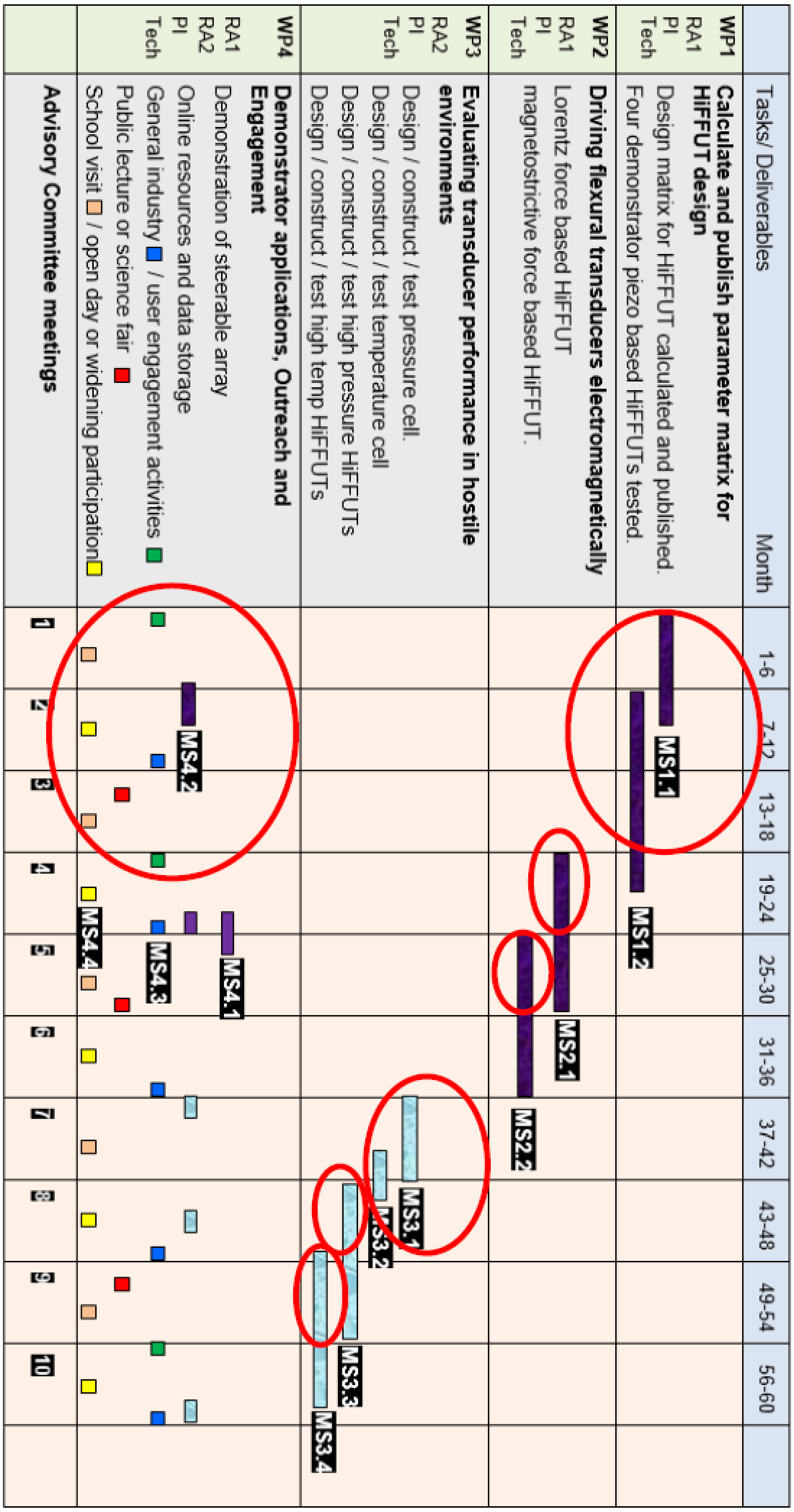


Figure 7.1: Gantt chart, indicating the areas in which the current research has addressed.

8. Acknowledgements

- Engineering and Physical Sciences Research Council (EPSRC) Grant No. EP/N025393/1.
- Dr Susan Burrows, University of Warwick, for advice on adhesives and ceramics.
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- Mareike Herrmann, University of Warwick, for assistance with laser cutting.
- Dr Mark Potter, University of Warwick, for assistance with temperature testing.
- Prof George Rowlands, University of Warwick, for assistance with analytical modelling.

EPSRC
Engineering and Physical Sciences Research Council

Link to grant information (Grants on the Web, EPSRC)

gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/N025393/1