HiFFUT - A New Class of Transducer

Update Report 4

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Overview

This report outlines research progress from March to September 2018. The targets defined in Update Report 3 are shown in the list below.

1. Further develop electromagnetically-driven HiFFUTs for hostile environments.

2. Complete fabrication and testing of demonstrator piezoelectric HiFFUTs.

3. Design and test HiFFUTs for high pressure environments towards 200 bar.

4. Construct and test a laser-welded HiFFUT.

5. Develop the second phase of HiFFUTs for high temperature applications.

A significant amount of industry research and development has been undertaken, including the successful completion of a project with an industrial partner developing new ultrasound technology. Furthermore, progress has been made in the protection of our new sensor designs, where we have begun the patent filing process for a new type of electromagnetic flexural ultrasonic transducer, and also flexural ultrasonic transducers for operation at the high pressure levels into the hundreds of bar. We are also in the fabrication stages of two further devices which will be of interest to the ultrasound measurement community, which we hope to file in the patent process towards the end of 2018. In this report, the latest developments of the electromagnetic transducers, laser welding for the fabrication of HiFFUTs, and the optimisation and the dynamic nonlinearity of flexural ultrasonic transducers are outlined. Where relevant, more details of the devices shown in this report will be distributed at a later stage, after protection and formal publication are sought.

1. Laser Welding for HiFFUT Fabrication

The fabrication of FUT caps through laser welding is being undertaken in collaboration with the Warwick Manufacturing Group (WMG) at the University of Warwick. Cap membranes and side-walls have been supplied to WMG, where a laser welding process is currently being administered to create a weld around the circumference of the cap membrane, with a heat affected zone (HAZ) as small as possible relative to the size of the cap. It is hoped that this will demonstrate a reliable cap fabrication method without the need for adhesive bonding, allowing the formation of caps with different membrane materials irrespective of the side-wall support material, and critically, a flat membrane surface, which can be difficult to achieve using the milling methods we currently have at our disposal. The difference of transducer performance with those fabricated using adhesive bonding will be investigated, and the effectiveness for welding different materials will also be assessed. It is a valuable collaborative exercise, where WMG are able to obtain useful information regarding the welding of dissimilar materials, and can demonstrate their ability to weld targets of relatively small size. Caps are being fabricated from aluminium, brass, stainless steel, and titanium.

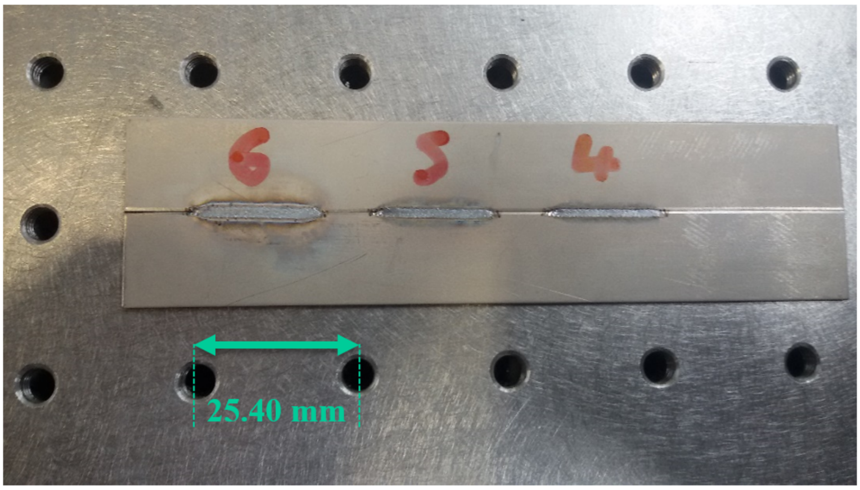
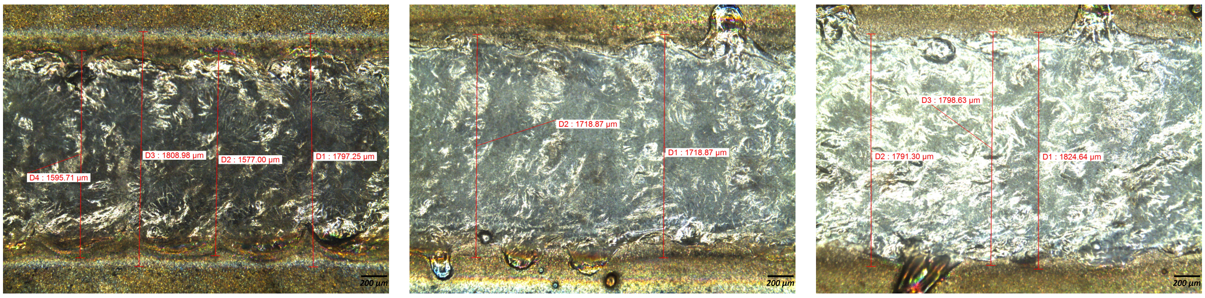


Figure 1.1: Test welds on a sample of titanium sheet.

Prior to laser welding, the process parameters for welding are configured, requiring a control algorithm for the laser welder, ensuring only the interface between the membrane and side-wall surfaces are targeted. Then, an acceptable HAZ must be determined, depending on the penetration depth necessary, and its permissible width. A test specimen of titanium is shown in Figure 1.1, where three different weld conditions have been administered. As shown, the HAZ can vary noticeably in width, but also in terms of penetration depth. For a FUT cap, the penetration depth is sub-millimetre, and so a relatively thick HAZ is likely not necessary, that which is identified by the number 6 in Figure 1.1. Furthermore, the HAZ can be convex-shaped in profile after welding, but any excess material can be carefully removed post-fabrication. Microscope images of the welds shown in Figure 1.1 are provided in Figure 1.2, where the HAZ regions are all below 1.85 mm in width, and relatively uniform in composition along the weld path.



(a) (b) (c)

Figure 1.2: Microscope images from the laser welding of grade 2 titanium, showing three different process parameter conditions which result in (a) thin (marked as 4), (b) medium (marked as 5), and (c) thick (marked as 6) weld HAZ profiles.

It is hoped that microscope images such as those shown in Figure 1.2 will be produced for different combinations of substrate materials. The analysis of vibration performance of sensors fabricated using laser welding and adhesive bonding will be compared, including for different excitation voltage levels, and transducer efficiency.

2. Dynamic Nonlinearity in Piezoelectric Flexural Ultrasonic Transducers

The extension of the research into dynamic nonlinearity, which can be observed through even relatively minor differences in excitation voltage, has been undertaken. This section describes the experimental process, with a selection of results included. It has previously been demonstrated that as the excitation voltage of a piezoelectric flexural ultrasonic transducer is increased, a reduction in its resonance frequency takes place, termed a softening nonlinearity. This was shown for commercial-type, aluminium sensors.

2.1 Experimental Details

Two types of commercial transducer have been studied, comprising small and large commercial flexural transducers (S/LCF), both composed of aluminium. Three custom-made transducers have also been analysed, two made using a titanium membrane, and the other made from brass. The transducers are all shown in Figure 2.1. The objective of this research is to investigate nonlinearity in piezoelectric flexural ultrasonic transducers, and identify some possible sources. The resonance frequency of each transducer is determined, before each is driven around this frequency at increasing excitation voltage levels. A LabVIEW program has been developed which allows control of the function generator, through a power amplifier, and extracts the peak-to-peak voltage of the response directly from the oscilloscope for each drive frequency. The incremental step of the drive frequency can be configured in the LabVIEW environment, and the process is fully automated for each excitation voltage level. The transducers are excited with a continuous sine wave from 20 V_{P-P} to 40 V_{P-P}, in steps of 50 Hz, and over a minimum frequency span of 2 kHz around resonance.

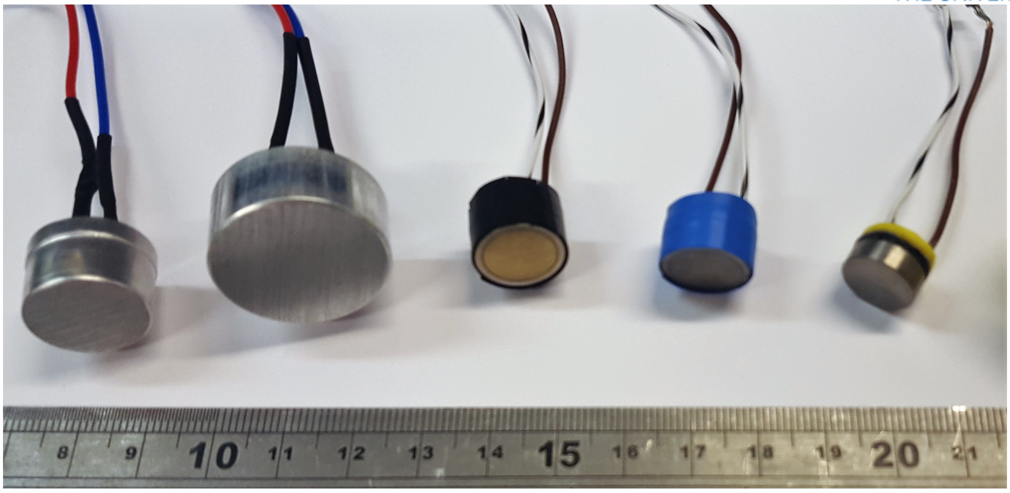


Figure 2.1: The complete set of flexural ultrasonic transducers for study, from left to right: the SCF, LCF, brass FUT, titanium FUT 1, and titanium FUT 2.

2.2 Experimental Results

The mode shapes of each transducer are shown in Figure 2.2, where the amplitude in each case has been normalised. Titanium FUT 2 was also operated in two different vibration modes, with reference to the mode shapes shown in Figure 2.3, to identify differences in dynamic nonlinearity, although the results of just the (1,0) mode are presented here. These mode shapes were captured using scanning laser Doppler vibrometry.

The peak-to-peak output voltage of each transducer was then measured. The laser beam was focused at the centre, and perpendicular to, the transducer membrane in each case. The voltage magnitudes were converted to velocity in post-processing. The vibration velocities of the devices as functions of drive frequency, for different levels of excitation voltage, are shown in Figure 2.4. The dissimilar ordinate scales, and also the trend-lines, in some cases should both be noted, shown in this way for clarity. For continuous wave input, 40 V_{P-P} is the stated operational limit for the SCF, and around 55 V_{P-P} for the LCF. As the excitation voltage is raised from 20 V_{P-P} to 40 V_{P-P}, a reduction in the resonance frequency of these transducers in

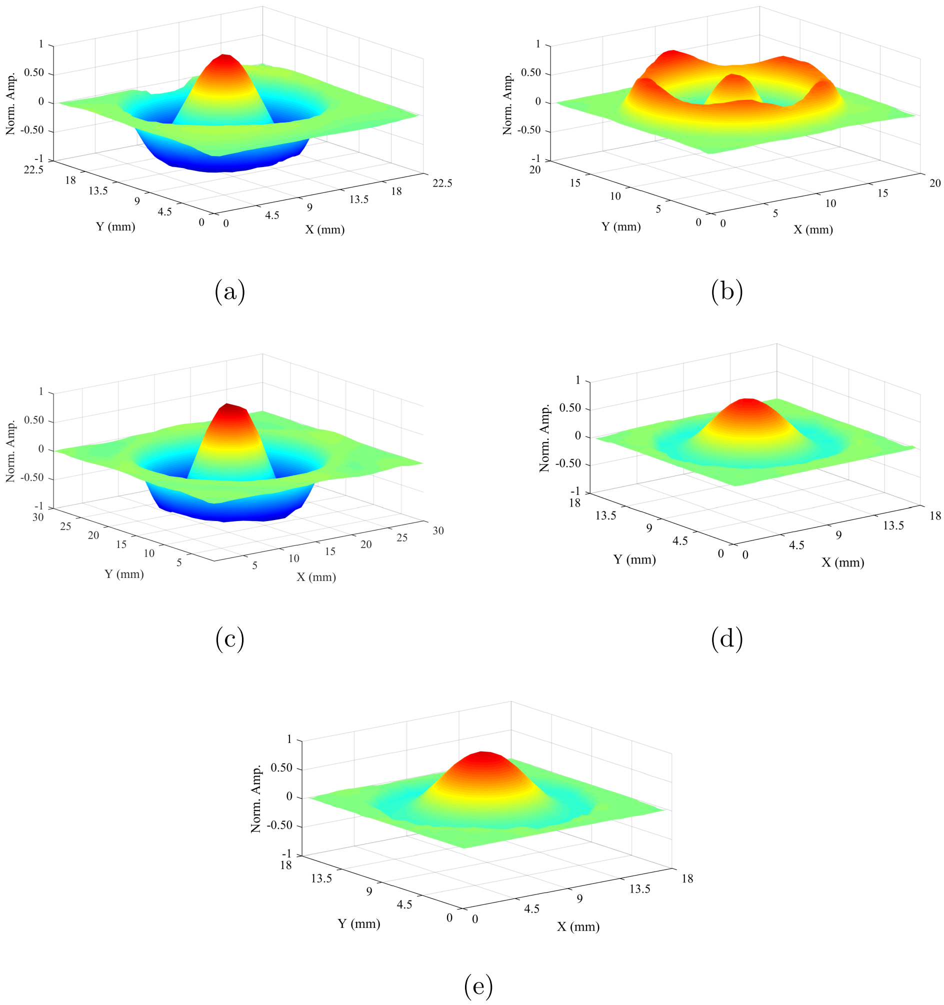
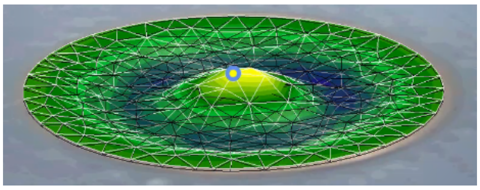
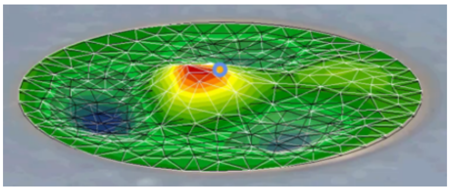


Figure 2.2: Experimental mode shapes from laser Doppler vibrometry, showing (a) the SCF in the (1,0) mode at 38 kHz, (b) the SCF in a higher-order five-fold symmetry (FFS) mode at 71 kHz, (c) the LCF in the (1,0) mode at 39 kHz, (d) the brass FUT in the (0,0) mode at 53 kHz, and (e) titanium FUT 1 in the (0,0) mode at 64 kHz.



(a)



(b)

Figure 2.3: Experimental mode shapes of titanium FUT 2 from scanning laser Doppler vibrometry for a 3 V chirp input, showing (a) the (1,0) mode at 58 kHz, and (b) a higher-order mode at 94 kHz.

their (1,0) modes occurs. If the results of the SCF operating in the (1,0) and the FFS modes are compared, where the only difference is the mode of vibration which is excited, the reduction in resonance is approximately 200 Hz for the (1,0) mode and negligible for the FFS mode, around zero. The difference between the SCF and the LCF is principally in size, being composed of the same material and operating in the same mode of vibration. The reduction in resonance for the LCF is also around 200 Hz. These results suggest that the reduction of frequency is mode-dependent, but appears to be principally influenced by vibration amplitude, and if the device is operated in its optimised mode of vibration.

The resonance frequency of the brass FUT reduces by approximately 300 Hz, broadly consistent with aluminium, but the resonance frequency of titanium FUT 1 drops by around 1300 Hz. This suggests the type of membrane material is a significant influence on dynamic nonlinearity. Over a relatively modest excitation level range, and within the operational limits of flexural ultrasonic transducers, a shift in resonance of over 1 kHz has been measured for both titanium transducers, with implications for the operation of these devices in practical applications.

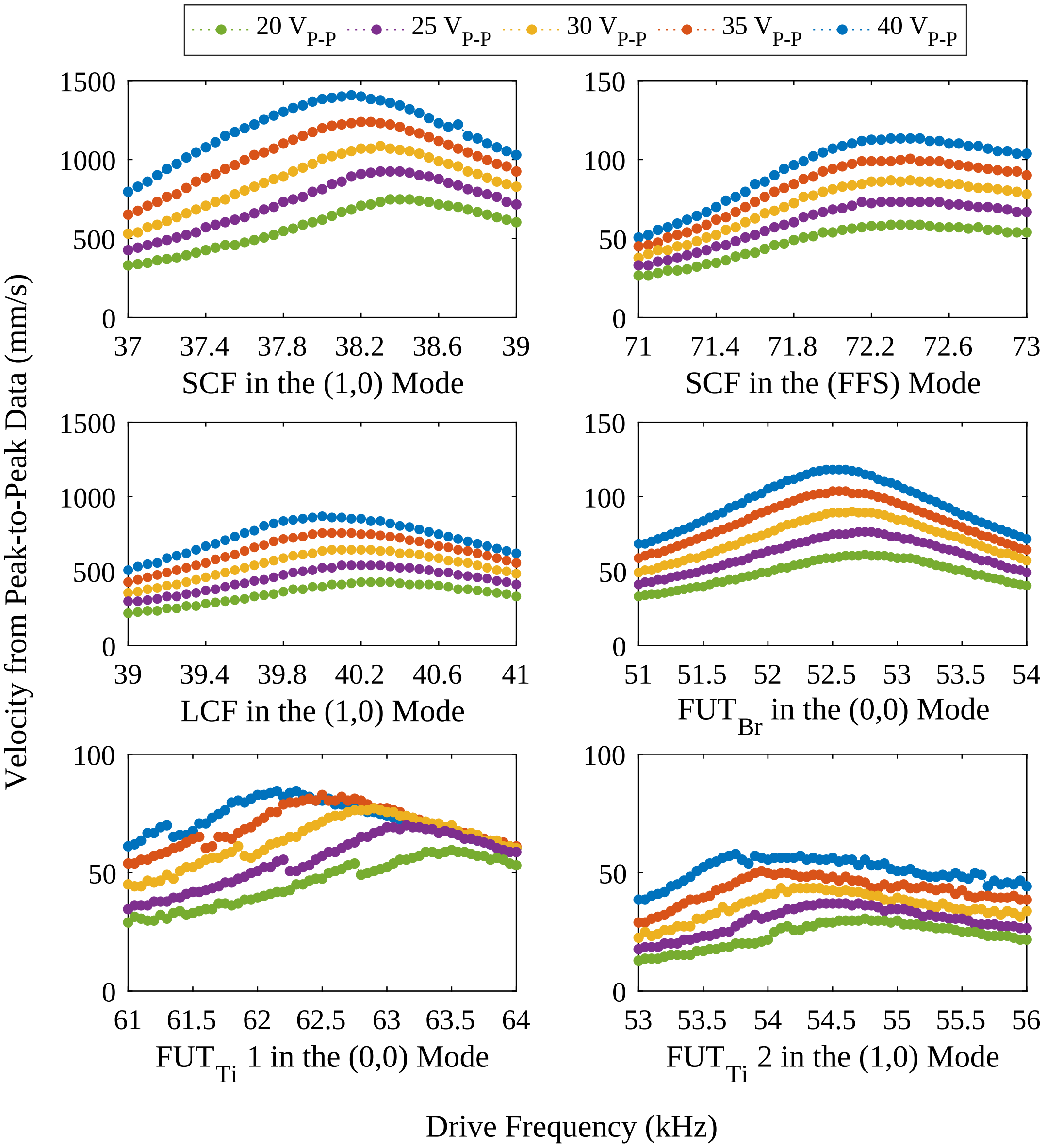


Figure 2.4: Vibration velocity of each transducer as a function of drive frequency, clearly demonstrating softening nonlinearity in each case. The results are calculated from peak-to-peak voltage data, and note the different ordinate axis scales, set for clarity.

3. Optimised HiFFUT

The operating frequency of comnmercial FUTs tends to be 50 kHz or lower, and 150 kHz and higher for air-coupled ultrasonic transducers with matching layers. Higher operating frequencies are desirable, because they allow greater resolution for time-of-flight measurement, and also improved sensitivity for non-destructive testing processes. This section details the characteristics of a new, optimised high-frequency FUT for operation at 100 kHz. The finite element configuration, using PZFlex®, is shown in Figure 3.1, showing two HiFFUTs operating in a pitch-catch arrangement.

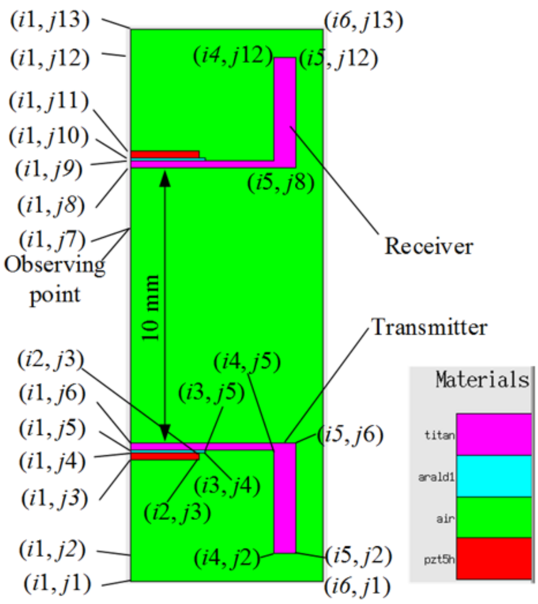


Figure 3.1: Finite element model of the optimised FUT, showing two transducers in a pitch-catch configuration.

Two FUTs were fabricated, each operating in the (1,0) mode of vibration. The performance of these transducers in a pitch-catch configuration were compared with that of two commercial, 40 kHz, FUTs operating in their (0,0) mode. The results are shown in Figures 3.2 and 3.3, showing a comparable received signal between the commercial and optimised FUTs.

Figure 3.2: Pitch-catch results for two 40 kHz commercial FUTs in the (0,0) mode.

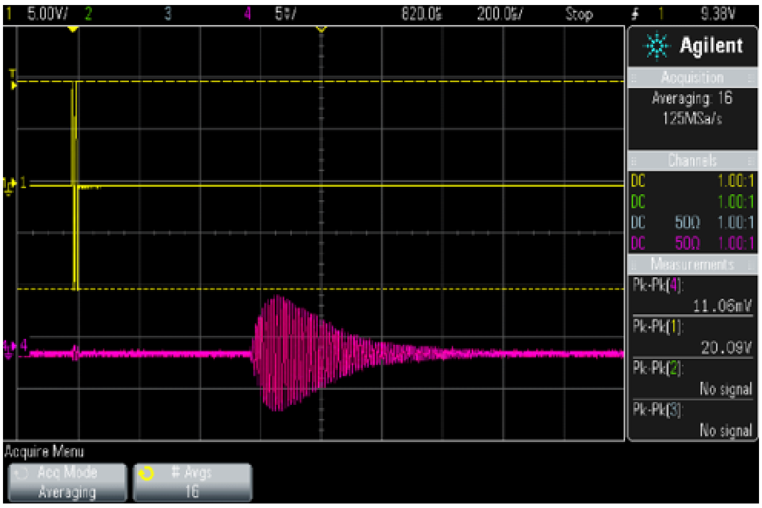


Figure 3.3: Pitch-catch results for two 100 kHz custom-made, optimised, FUTs in the (1,0) mode.

4. Wideband Electromagnetic Acoustic Transducer

FUTs and piezoelectric-based devices such as pMUTs are narrowband. This section outlines the design and characterisation of the wideband electromagnetic acoustic transducer (WEMDAT), developed with improved bandwidth for increasing the time resolution for time-of-flight measurements, and for matching to different devices. The research shown in this section relates to a filed patent design, and contains key features such as an adjustable distance between the solenoid and the vibrating membrane, wideband, efficient, and a high level of directivity. Characterisation results of the WEMDAT using a B & K acoustic microphone are shown in Figures 4.1 and 4.2. A sharp pulse in the time domain indicates a promising and reliable method of time-of-flight measurement.

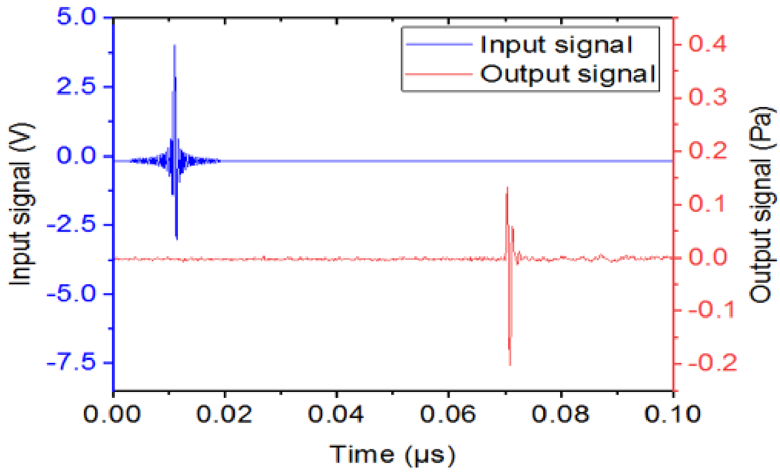


Figure 4.1: Sound pressure measurement of the WEMDAT, driven directly by a function generator, and measured by an acoustic microphone at 200 mm.

Two WEMDATs were then assessed in pitch-catch configuration, and the results are shown in Figure 4.3, where a drive signal of 75 kHz was used for a 3-cycle tone burst, at a distance of 200 mm. The results show that the WEMDAT is a promising candidate for efficient, wideband measurement. Further investigations will address optimisation, including adaption of the design for different frequency ranges and temperatures.

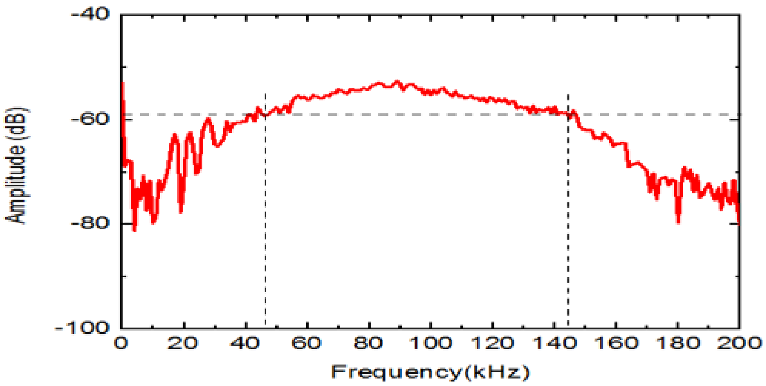


Figure 4.2: The frequency spectrum of the sound pressure measurement.

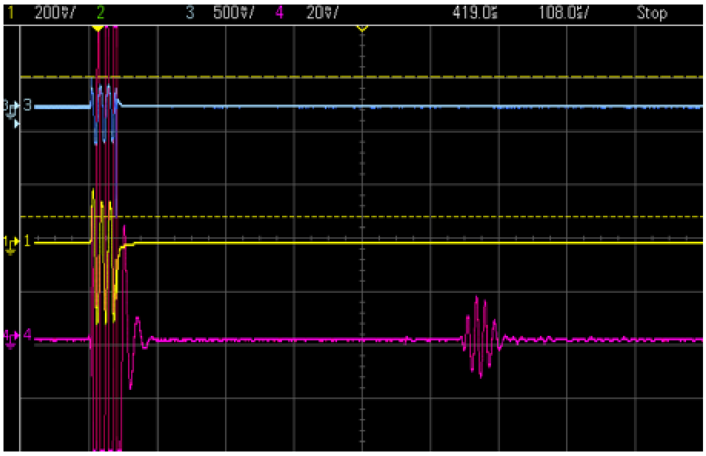
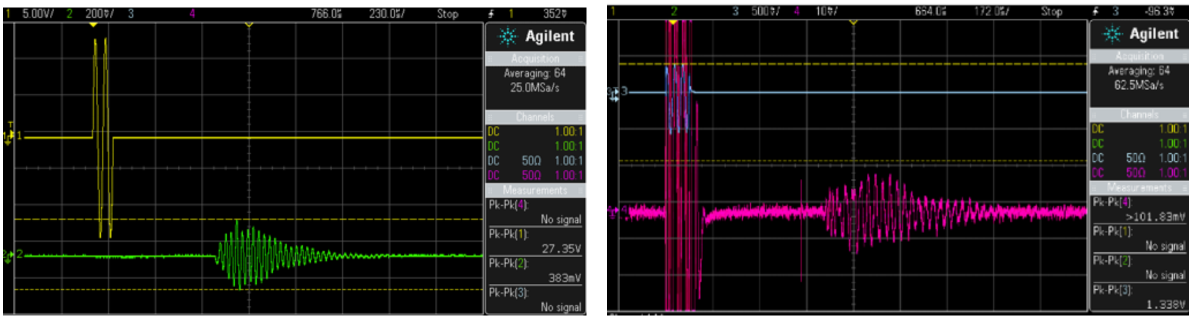


Figure 4.3: Resonance frequency as a function of excitation voltage for the transducers.

5. Coil-Only Flexural Ultrasonic Transducer

The WEMDAT device shown in the previous section requires the use of strong magnets and can incur high cost for production. By exploiting the Lorentz force and the membrane resonance, a coil was integrated into the FUT design to form a narrow bandwidth FUT with an operating frequency around 40 kHz. The FUT was characterised using an acoustic microphone at a distance of 200 mm, and in pitch-catch by using the WEMDAT as a receiver. The results are shown in Figure 5.1, showing this FUT as a promising candidate for robust and inexpensive air-coupled measurement.



(a) (b)

Figure 5.1: Characterisation of the coil-only FUT, showing (a) sound pressure of the coil-only FUT using an acoustic microphone at 200 mm, and (b) pitch-catch measurement using the coil-only FUT as a transmitter and the WEMDAT as the receiver.

6. Publications and Presentations

The publications disseminated and details of the public and professional outreach undertaken in the past 12 months are outlined in the following lists.

REFEREED JOURNAL & CONFERENCE PUBLICATIONS

1. A. Feeney, L. Kang, and S. Dixon, "High frequency measurement of ultrasound using flexural ultrasonic transducers," *IEEE Sensors Journal*, vol. 18, no. 13, pp. 5238-5244, 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, "Analysis of flexural ultrasonic transducers for high frequency applications," *The 47th Ultrasonics Industry Association Symposium*, Atlanta, USA, April 2018.

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

3. **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.

4. 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

Significant progress has been made in protecting the intellectual property of key developments of this project, comprising the electromagnetic and high pressure designs of flexural ultrasonic transducer. It is hoped the specifics of these research areas will be reported in early 2019.

We have also undertaken a substantial amount of industry research in this period, implementing a number of the project outcomes in practical applications. In addition to this industry engagement, we have conducted fundamental research into the optimisation of the flexural ultrasonic transducer, developing electromagnetic transducers, laser welding for the fabrication of these devices, and the origins of dynamic nonlinearity in flexural ultrasonic transducers. The latest version of the Gantt chart for this project is shown in Figure 7.1, and an updated set of objectives for this project are shown in the following list, to be undertaken towards 2019.

1. Complete the fabrication and subsequently characterise the laser welded transducers.
2. High pressure HiFFUTs have been designed for pressures upwards of 200 bar. Testing of these transducers will be completed in the final part of 2018.
3. Optimisation of the transducer fabrication process and of HiFFUT performance.
4. Characterisation of custom transducers at high temperatures.
5. Continue patenting of new devices, and publishing of new results.

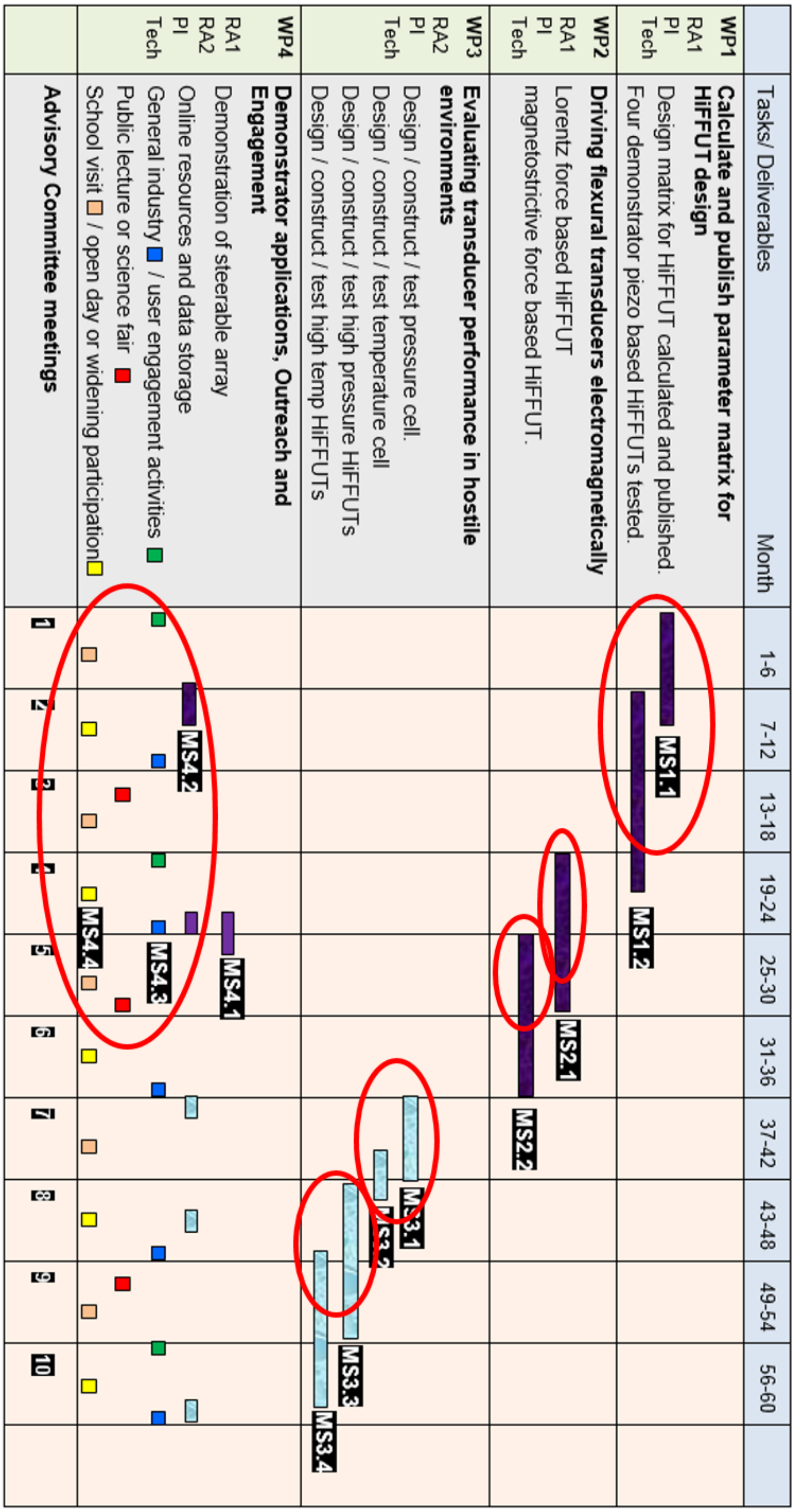


Figure 7.1: Gantt chart, indicating the areas in which the current research has addressed.

8. Acknowledgements

- Engineering and Physical Sciences Research Council (EPSRC) Grant No. EP/N025393/1.
- Professor Darek Ceglarek, Warwick Manufacturing Group, University of Warwick, for access to laser welding.
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- Jonathan Harrington, University of Warwick, for technical support.
- Mareike Herrmann, University of Warwick, for assistance with laser cutting.
- Prof George Rowlands, University of Warwick, for assistance with analytical modelling.
- *Polytec GmbH*, for assistance with scanning laser Doppler vibrometry.

EPSRC

Engineering and Physical Sciences
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Link to grant information (Grants on the Web, EPSRC)

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