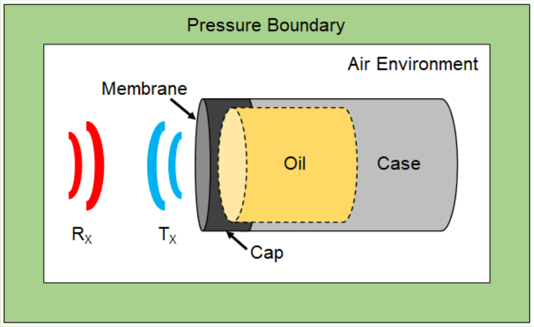
Design and Dynamics of Oil Filled Flexural Ultrasonic Transducers for Elevated Pressures

William E. Somerset, Andrew Feeney, *Member, IEEE*, Lei Kang, Zhichao Li, and Steve Dixon



***Abstract*—The flexural ultrasonic transducer has traditionally been limited to proximity measurement applications, such as car-parking systems and industrial metrology. Principally, their classical form is unsuitable for environments above atmospheric 1 bar pressure, due to an internal air cavity which creates a pressure imbalance across the transducer's vibrating membrane. This imbalance leads to physical deformation and degradation of the transducer's structure, restricting the membrane's capacity to vibrate at resonance to transmit and receive ultrasound. There is a requirement for ultrasonic sensors which can withstand environments of elevated pressure, for example in ultrasonic gas metering. Recent research demonstrated the dynamic performance of flexural ultrasonic transducers with vented structures, allowing the pressure to balance across the transducer membrane. However, a hermetically sealed transducer is a more practical and robust solution, where the internal components of the transducer, such as the piezoelectric ceramic disc, will be protected from harmful environmental fluids. In this research, the design and fabrication of a new form of flexural ultrasonic transducer for environments of elevated pressure is demonstrated, where the internal air cavity is filled with an incompressible fluid in the form of a non-volatile oil. Dynamic performance is measured through acoustic microphone measurements, electrical impedance analysis, and pulse-echo ultrasound measurement. Together with finite element analysis, stable ultrasound measurement is achieved above 200 bar in air, opening the possibility for reliable ultrasound measurement in hostile environments of elevated pressure.**

***Index Terms*—Elevated pressure, flexural ultrasonic transducer, oil filled transducer.**

I. INTRODUCTION

MEASUREMENT of ultrasound and time-of-flight (ToF) at elevated pressure levels is vital for a range of metrology and industrial processing applications [1]–[3]. High pressure applications include ultrasonic gas flow measurement and monitoring flare gas [4]–[6], where current ultrasonic transducers are not suitable and pressures can reach 300 bar [7], [8]. Hence, there is an application driven need for robust, low-cost ultrasonic transducers that can operate at pressures of hundreds of bar.

A. The Classical Sealed Flexural Ultrasonic Transducer

The flexural ultrasonic transducer (FUT) has been extensively investigated in recent years due to its potential for industrial metrology and ToF applications, and is principally used in automotive proximity sensing applications or for metrological functions including flow measurement [3]. A FUT is constructed from a circular metallic membrane, on to which a piezoelectric ceramic disc is bonded with an epoxy resin. The membrane is effectively held under clamped boundary conditions [9]–[11], forming a cap, the rear of which is usually sealed with a silicone rubber. A schematic diagram of the classical FUT design is shown in Fig. 1.

The dynamic performance of the FUT has received significant attention [10]–[15], leading to a greater understanding of how FUT can be optimized for specific applications [15]. The resonance frequency of the FUT for a specific vibrational resonant mode can be mathematically predicted with high accuracy [10]–[15], with its dynamics dominated by the membrane's material and geometrical properties, and

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William E. Somerset and Steve Dixon are with the Department of Physics, University of Warwick, Coventry CV4 7AL, U.K. (e-mail: w.somerset@warwick.ac.uk).

Andrew Feeney was with the Department of Physics, The University of Warwick, Coventry CV4 7AL, U.K. He is now with the James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, U.K. (e-mail: andrew.feeney@glasgow.ac.uk).

Lei Kang was with the Department of Physics, The University of Warwick, Coventry CV4 7AL, U.K. He is now with the School of Energy and Electronic Engineering, University of Portsmouth, Portsmouth PO1 3DJ, U.K. (e-mail: lei.kang@port.ac.uk).

Zhichao Li was with the Department of Physics, The University of Warwick, Coventry CV4 7AL, U.K. He is now with the Harbin Institute of Technology, Harbin 150001, China (e-mail: zhichao.li@hit.edu.cn).

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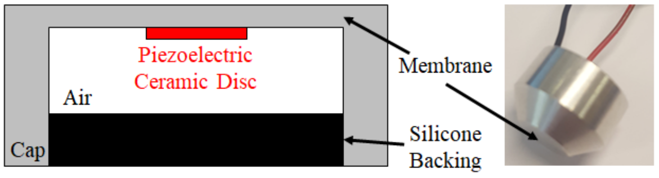


(a) (b)

Fig. 1. The classical sealed FUT, shown (a) schematically, and (b) as an example of a sensor currently available. The flat membrane structure shown by the schematic in (a) is typical of many types of FUT. The image in (b) is provided to show the configuration used as the foundation for the oil filled transducer reported in this study.

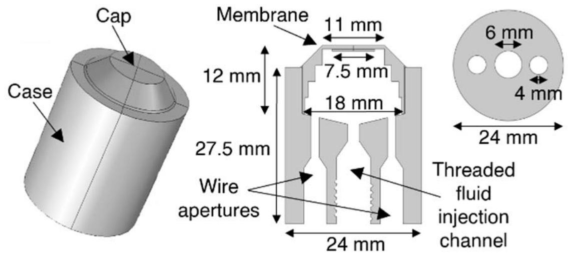


Fig. 2. Structural components of the OFFUT, showing an external view (left), a cross-sectional view (centre), and a bottom-up view (right).

only slightly perturbed by bonding a thin piezoelectric disc to the membrane [16]. Most practical applications tend to use axisymmetric vibrational modes of the membrane, where the directivity and intensity of the generated ultrasonic wave is dependent on the particular mode used. These mode shapes have been reported in the literature [10]–[15]. The FUT can be driven with just a few volts and with a short-cycle excitation burst, whilst generating a comparatively high amplitude pressure wave [12], [13], making it an efficient and attractive ultrasonic transducer design for a variety of industrial applications.

The presence of the internal air cavity that is prevalent in commercial FUTs (as illustrated in Fig. 1), limits its applicability to elevated pressure levels. If the external pressure is raised above 1 atmosphere, the pressure differential generated with the internal cavity affects the dynamic response of the FUT and its structural integrity [17]. For reliable high-pressure operation, the highly deformable and easily damaged silicone sealant at the rear of the FUT needs replacing with a robust and rigid plate, maintaining its hermetic seal. In doing so, any air-filled void inside the FUT can lead to deformation of the FUT's membrane and body as the external pressure increases. The dynamic performance of a vented flexural ultrasonic transducer (VFUT) has been evaluated in air up to pressures of 100 bar [17], [18]. The VFUT has no rear seal, facilitating direct pressure balancing across the membrane of a FUT and efficient operation at elevated external pressures. However, the lack of a hermetic seal limits its field of applications.

B. Pressure Balancing a FUT Membrane

An alternative cap design to the VFUT that is hermetically sealed is required for ultrasonic measurements in high pressure fluid environments. A recent concept has been introduced, the oil filled FUT (OFFUT) [19], where the internal air cavity of a FUT is filled with oil that is effectively incompressible. As external pressure is increased, the pressure difference across the membrane is minimized as the membrane undergoes small deformations that compress the liquid in the FUT to a pressure level close to the external pressure. The OFFUT can efficiently generate and detect ultrasound with this small level of deformation its structure. For the first time, we report the dynamic characterisation and finite element modelling of the OFFUT in order to understand its physical characteristics.

Ultrasonic transducers have been used for measuring velocities in liquids at pressures up to 1000 bar [20], but these transducers were not directly subjected to these elevated pressure levels. There are other designs of ultrasonic transducer that are capable of operating at elevated pressures including capacitive micromachined ultrasonic transducers (CMUTs) with vented cavities used up to 20 bar [4], [5], [21], and piezoelectric transducers with solid internal components and that can be used to over 100 bar [22]. FUTs are robust and low-cost sensors that are suitable for a range of environments and measurement applications, where the entire external case and membrane can be constructed from titanium if required. The OFFUT is one of a small number of ultrasonic transducer designs suitable for operation at high pressures in fluids.

C. Summary of Novel Research Contributions

In this study, the fabrication process of two silicone oil filled OFFUTs is described, constructing the OFFUT by adapting a common commercial FUT design. Finite element analysis of the OFFUT is used to investigate the limitations of the design approach, highlighting important considerations for the fabrication of the devices which can be used to optimise the transducer design process. Dynamic characterisation of the OFFUT pair is performed at atmospheric conditions, important for establishing operational parameters. Details of the pitch-catch method used for generating A-scans at elevated pressures above 200 bar are given, examining the OFFUT's dynamic performance through pitch-catch ultrasound measurement.

II. METHODOLOGY

A. Transducer Fabrication

The OFFUT design used in this study is a standard FUT cap supported in a thicker, hermetically sealed case. Any suitable cap design can be used in an OFFUT, providing the physical characteristics of the membrane are known. To demonstrate the fabrication of an OFFUT using comparable membrane characteristics to those currently available, the membrane of an aluminium, commercial-type FUT is selected (Multicomp). This FUT has been studied previously [11], [13], [17]: the fundamental axisymmetric (0,0) vibration mode of the FUT is nominally 40 ± 1 kHz. Schematic diagrams of the OFFUT are shown in Fig. 2, which will be referred to in later discussions of the fabrication process.

The outer case supports the cap in place and allows complete sealing of the internal cavity from the external environment. The case contains a channel, through which the silicone oil is injected into the internal cavity of the OFFUT. Apertures

1. Cap Selection
2. Remove silicone
3. Aperture potting
4. Cap bonding
5. Oil submersion and de-gassing
6. Rear sealing
7. Fabricated transducer

Fig. 3. A simplified fabrication process for an OFFUT. Note that Step 5 shows the vacuum chamber with the sealing lid removed for clarity. The fabricated transducer shown in Step 7 is complete with acrylonitrile butadiene styrene (ABS) plastic strain relief.

are machined into the case for wires that are connected to the piezoelectric disc. This is not presented as an optimal OFFUT design, but is a demonstration of the approach and potential performance of this type of ultrasonic transducer. Design features of the OFFUT can be adjusted for different application environments. The fabrication of this OFFUT is described in detail, with reference to Fig. 3.

First, the seal of the aluminium FUT is removed with the aid of a specialized solvent (Dynasolve 230, Dynaloy). This step reduces the chance of damaging the internal components when compared to directly mechanically removing the silicone rubber seal. After removing the silicone, copper-enamel electrode wires are attached to the cap and are then fed through the apertures in the outer case. The wire apertures are then sealed with a low viscosity potting epoxy resin (Electrolube ER1448), as shown in Step 3 in Fig. 3, where the low viscosity ensures that the epoxy resin seals the apertures for the wires. It is important to minimize the presence of trapped air bubbles within the OFFUT structure, as trapped bubbles would be highly compressible, leading to significant deformation of the membrane at elevated pressure levels, affecting transducer efficiency and dynamic characteristics such as resonance frequency. Once a robust seal is created, the cap is positioned inside the case as shown in Step 4 in Fig. 3, where it is bonded in place using an epoxy resin (Araldite 2014-1).

Once the epoxy adhesive bonding the cap to the case sets, the OFFUT is then submerged in silicone oil, as illustrated in Step 5 of Fig. 3, filling the central cavity through the fluid injection channel. A vacuum chamber is also used at this stage of the fabrication process, minimizing the chances of air bubbles being trapped inside the cavity. The sealing element used in Step 6 of Fig. 3, is also de-gassed in the oil bath.

The selection of a suitable injection fluid is not just dependent on incompressibility, but also how compatible the fluid is with the sensitive internal materials and components. The fluid should not change the electrical or mechanical properties of the piezoelectric ceramic disc, the wire electrodes, the epoxy resins, and the wires themselves, but will influence the vibration response of the electromechanically coupled system of the piezoelectric and the membrane. For the purposes of this study, a synthetic silicone oil (PDMS, 50 cPs viscosity) was selected as the incompressible injection fluid. Prior to injection into the OFFUT, a specimen of piezoelectric ceramic material bonded with epoxy resin (EPO-TEK® 353ND) to an aluminium membrane was submerged for 24 hours in the silicone oil, with no degradation or other effect observed.

Once the injection of oil is complete, the channel is sealed at the rear of the case, using a bolt with potting epoxy resin (Electrolube ER1448) to create a hermetically sealed structure, as shown in Step 6 of Fig. 3. The wires are covered by protective 3D printed ABS enclosures that are bonded to the rear of the OFFUT, as shown in Step 7 of Fig. 3. This constitutes the key steps of the OFFUT fabrication process. Two OFFUTs are fabricated following the method outlined and are used in a pitch-catch configuration for this experiment.

B. The Dynamic Characterisation Process

The OFFUT characteristics are first studied at 1 bar, where more characterisation experiments can be easily performed that will help inform the understanding of behaviour at elevated pressures. The orientation dependent response of the OFFUTs is investigated, as the inclusion of any air bubbles in the fabrication step would be expected to have notable influence.

The dynamic characterisation at atmospheric pressure levels consists of electrical impedance analysis, using an impedance gain/phase analyser (Agilent 4294A) and acoustic microphone measurements (GRAS 46DP-1). Electrical impedance measurements are used to monitor changes in resonance frequency, identified at the location of minimum electrical impedance around resonance for reference. Prior to pressurisation, acoustic microphone measurements are made of the pressure waves generated by the OFFUTs positioned inside the pressure chamber. A schematic of this chamber is shown in Fig. 4. The acoustic microphone is not suited to measurement at elevated pressure levels, but the mitigation of disruptive interference inside the pressure chamber must be ensured [19]. An acoustic microphone, and the lining of reflective walls within the pressure vessel with acoustically absorbent material, is key to achieving this objective.

The dynamic performance of the OFFUT pair is then investigated in a pitch-catch configuration within the pressure chamber, shown in Fig.4. Baffles are 3D printed from ABS for the OFFUTs, so that they can be securely positioned inside the pressure chamber. Prior research has shown that small variations in the dimensions and clamping of flexural transducers can influence the position of their series resonance [19], but here the OFFUT pair are fabricated using identical methods and hence should possess similar resonance frequencies, making them suitable for this measurement. The response of the OFFUT pair at elevated pressure levels is investigated, with both transducers within the stainless steel pressure chamber of internal volume 2.2 L.

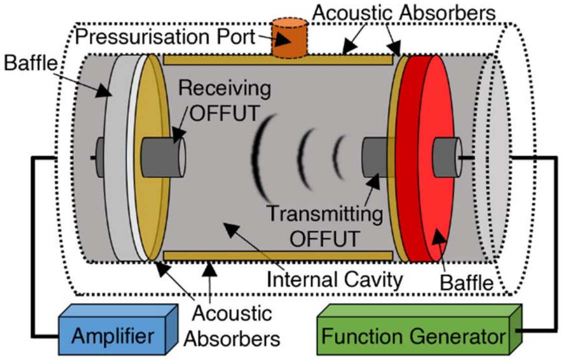


Fig. 4. The pitch-catch ultrasound measurement method, showing the OFFUTs in ABS baffles within the pressure chamber. Acoustic absorbing material lines the internal cavity and baffles.

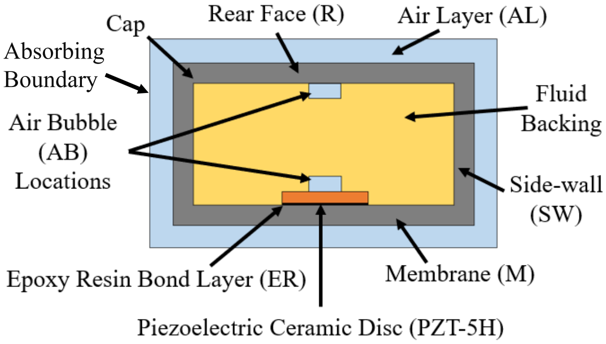


Fig. 5. The finite element model of an OFFUT.

The pressure level is controlled through an air compressor (300 bar PCP compressor, IYS), measured by a ratiometric pressure sensor (MLH Series, Honeywell) within the chamber. Two sets of measurements are captured at each pressure change, the first being the electrical impedance of the OFFUT measured by the impedance analyser, and the second being the received ultrasonic signal for the pitch-catch measurement. Ultrasonic waves are generated by the transmitter OFFUT, driven by a function generator (Tektronix AFG3021B) with a 5 cycle, 10 Volt peak-to-peak voltage at a frequency halfway between the measured series resonances of the two OFFUTs (which differ slightly). The receiver OFFUT voltage output is amplified using a variable gain preamplifier and is acquired on a digital oscilloscope. Data is acquired over the 1 to above 200 bar pressure range.

III. FINITE ELEMENT ANALYSIS

The pressure-balancing of a FUT membrane is investigated using finite element analysis software (PZFlex®, Weidlinger Associates). The finite element model is based on the classical FUT design, but is modified to accommodate different fluids in the internal cavity. The schematic of the finite element model is shown in Fig. 5, with key parameters labelled.

Four different FUT conditions are investigated. The first is with air in the cavity, designated as the "air fill". The second is with an oil fill, using the in-built properties of castor oil which are relatively close to silicone oil. The third and fourth conditions are with an oil fill, but with an air bubble inside the cavity, at the front, behind the piezoelectric ceramic disc, and at the rear, respectively. Specific structural dimensions and material properties are shown in Table I and Table II.

TABLE I

MAJOR STRUCTURAL DIMENSIONS OF THE FINITE ELEMENT MODEL IN mm

Property	$Ø_{CAP}$	h_{CAP}	t_{SW}	$t_{M,R}$	t_{ER}, $Ø_{ER}$
Magn.	9.00	0.40	0.50	0.40	0.10, 3.00
Property	$Ø_{PZT}$	t_{PZT}	t_{AL}	$Ø_{AB}$	t_{AB}
Magn.	3.00	0.25	1.00	1.50	0.20

[a] Ø: diameter; h: height; t: thickness

TABLE II

KEY MATERIAL PROPERTIES OF THE FINITE ELEMENT MODEL

Property	Air (R.T.)	Aluminium	Araldite	Castor Oil
Density (kg/m^3)	1.24	2690	1146	969
Long. Vel. (m/s)	343	6306	2658	1477
Shear Vel. (m/s)	-	3114	1237	-
Rel. Perm.	1.00	3.10	3.50	0.00
Bulk Damp.	-	-	4.00	-
Shear Damp.	-	-	12.59	-

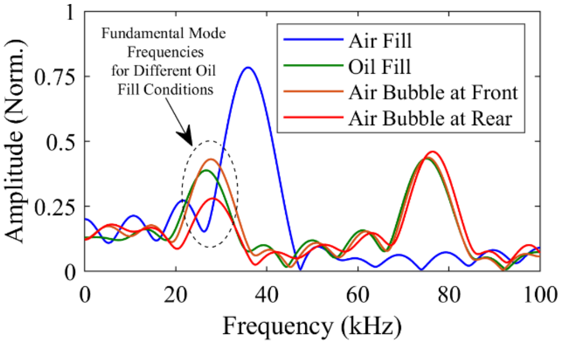


Fig. 6. The FFTs obtained through finite element analysis for different FUT conditions. The results show that, for this transducer simulation, filling the cavity with castor oil reduces the resonance frequency by 7 kHz and reduces the amplitude by 50%, compared to a transducer filled with air. The location of any air bubbles also has a significant effect on both resonance frequency and amplitude. Note – the "front" is when the bubble is behind the piezoelectric ceramic disc as shown in Fig. 5.

The normalised amplitude finite element analysis results are shown in Fig. 6. The resonance frequency of the fundamental mode was determined to be 38.02 kHz for an air fill, 31.23 kHz for an oil fill, 29.87 kHz for an oil fill with an air bubble behind the piezoelectric ceramic (at the front), and 32.59 kHz for an oil fill with an air bubble behind the rear wall. If the vibration amplitudes in Fig. 6 are normalised to the air fill condition, the normalised amplitude for the oil fill with no bubbles is 0.49, for the air bubble behind the rear wall is 0.41, and for the air bubble behind the piezoelectric ceramic disc is 0.78.

The results show that denser fluids inside the cavity reduce both the resonance frequency and the vibration amplitude of the FUT, and that the location of the air bubble makes a significant difference to the dynamic response. For example,

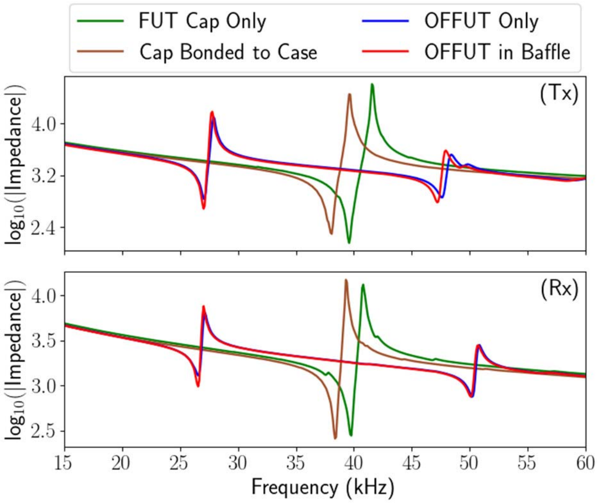


Fig. 7. Electrical impedance spectra different stages of the OFFUT fabrication process for the designated transmitter and receiver OFFUTs (Tx and Rx respectively). Refer to Fig. 3 for each fabrication stage. Note that where possible, these measurements were made with the OFFUT membrane oriented horizontally.

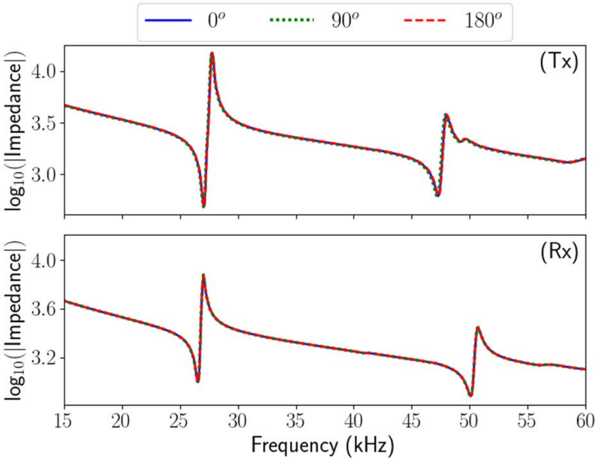


Fig. 8. Electrical impedance spectra for the OFFUTs positioned in three principal directions, for the designated transmitter OFFUT (Tx) and receiver OFFUT (Rx). Note that OFFUTs are held in their ABS baffles for this experiment.

the membrane is more compliant if the air bubble is behind the piezoelectric ceramic, reducing the influence of the oil on the response of the FUT. These are key considerations necessary for the experimental investigation.

IV. EXPERIMENTAL RESULTS

A. Dynamic Characteristics at Atmospheric Pressure

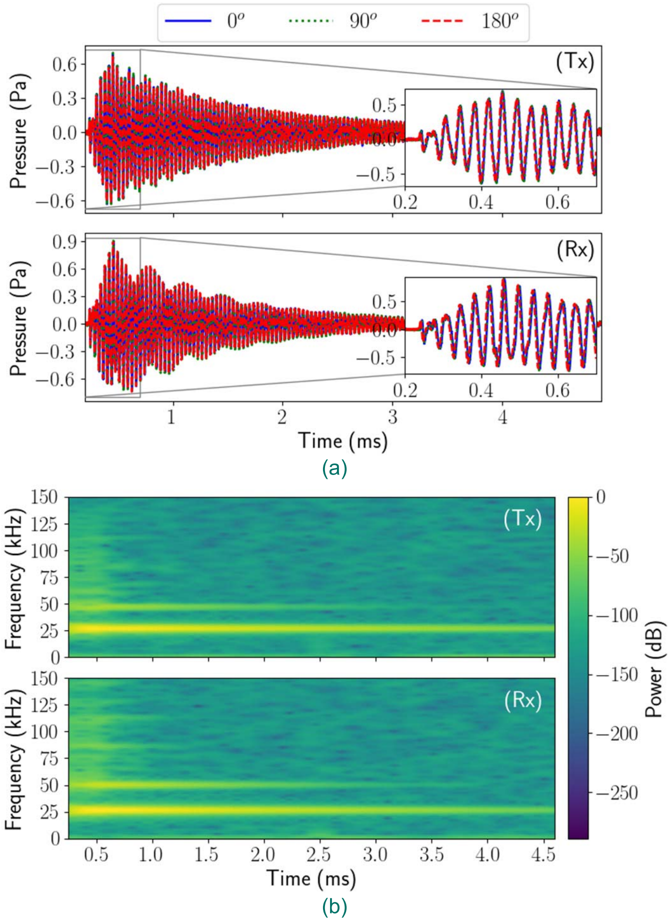
The electrical impedance of each OFFUT was monitored at several stages throughout the fabrication process outlined in Fig. 3, isolating the effects of changing the shape of the case for the traditional FUT (Steps 1-4), and after injecting the oil (Steps 5-7). These impedance spectra are displayed in Fig. 7 for the transmitter OFFUT (Tx) and the receiver OFFUT (Rx) in the pitch-catch configuration. These spectra are associated with the OFFUT in different stages in the fabrication process, comprising the adapted commercial FUT cap only; with the silicone backing removed, but with piezoelectric ceramic disc attached; the cap bonded to the fabricated case; the OFFUT without any peripheral baffle support structure; and the fully assembled OFFUT embedded in the ABS baffle.

The first important observation from the results shown in Fig. 7 is the influence of the seal in the vibration response of a FUT. The spectrum shown for Rx FUT cap only indicates the presence of multiple modes of vibration around resonance, but these have been demonstrated to be attributable to vibration of the side wall of the FUT in prior research [17], [18]. The silicone seal of a FUT ensures a single-frequency response around resonance by providing damping of unwanted modes, in addition to mechanical sealing. Bonding the FUT to the thick outer case suppresses vibrations in the FUT side walls, producing a single-frequency response around the axisymmetric resonance frequency. The greater effective mass loading of the degassed oil on the membrane of the OFFUT can be observed through the reduction in series resonance frequency for both the Tx and Rx OFFUTs. A secondary prominent resonance mode at around 50 kHz is also displayed in the electrical impedance spectra of the OFFUTs which may affect the dynamics of the transducer's vibration response. However, in this study OFFUTs are operated around their primary series resonance so investigation into this secondary resonance will be addressed in subsequent research. Finally, it is evident that the attachment of the baffle does not appear to significantly influence the dynamic response of either OFFUT, where the data plots effectively overlap. This implies that the baffle design is highly suited to the OFFUT, providing appropriate support, but imparting little influence on the dynamic response of the transducer.

A critical observation from the results of finite element analysis is that the presence and position of air bubbles within the OFFUT may affect the dynamic performance of the transducer, with the position of any air bubbles partly determined by the transducer's orientation. Since air bubbles will be less dense than the oil inside the OFFUT's cavity, they will rise towards the underside of the membrane by the piezoelectric ceramic disc if oriented vertically upwards, reducing the effective mass applied acting on the membrane compared to the OFFUT oriented vertically downwards. In this instance, we expect its series resonance to increase, shifting closer to 40kHz as would be the case if the cavity was filled with air. Reducing the presence of any air bubbles will help to ensure the physical structural integrity of the OFFUT, and limit undesirable changes to the dynamic response of the membrane.

To investigate this in more detail, electrical impedance analysis and acoustic microphone measurements were conducted on both OFFUTs positioned in three principal orientations, comprising 0°, 90°, and 180°, correlating with vertical upwards, horizontal, and vertical downwards directions, respectively. Results are shown in Fig. 8 and Fig. 9.

The results shown in Fig. 8. indicate that the orientation of the OFFUT pair does not have a significant effect on the resonance frequency of either transducer, with the measured electrical impedance spectra largely overlapping for both Tx



(a)

(b)

Fig. 9. (a) A-scans captured at 1 bar in the pressure chamber for Tx and Rx in three orientations, and (b) spectrograms examining the A-scans captured at 90° for Tx and Rx.

and Rx, indicating that orientation has little effect on the transducer's dynamic performance. This would imply that the effective mass loading on the membrane of the transducers can be regarded as constant, indicating the OFFUTs have oil filled cavities that do not appear to contain air bubbles, and were successfully de-gassed using the vacuum chamber prior to the rear sealing of the transducers.

Fig. 9. (a) illustrates the vibration response measured by an acoustic microphone, for an OFFUTs driven by a short-cycle burst of 5 cycles at an amplitude of 10 $V_{\text{p-p}}$, to characterize the dynamic response of the OFFUT at elevated pressure levels, shown in Section IV.B. The OFFUTs are driven at their (0,0) mode resonance frequency, as measured in Fig. 8. As a preliminary characterisation step to ensure interference inside the pressure chamber is reduced as much as possible, each OFFUT is positioned inside the pressure chamber as shown in Fig. 4, in separate experiments, after which the acoustic microphone is used to measure the ultrasonic pressure wave characteristics. The results in Fig. 9(a), taken at 1 bar show that the acoustically absorbent material on the inner wall of the pressure chamber suppresses interference signals from spurious reflections off the walls. This provides a reliable measurement environment for the investigation of the OFFUT's dynamic response at higher pressures. The reliability of this approach has been demonstrated in prior research [17], [18], [19].

This experiment is repeated for the three principal directions as performed in Fig. 8, and show consistency between each A-scan. This again indicates that the vibrational responses of the OFFUTs are independent of orientation at atmospheric pressures, and therefore have negligible air bubble entrapment in the oil filled cavity. However, multiple signal frequencies can be observed in the A-scans of the OFFUTs, even after the short-cycle input, as observed in prior research [19]. This contrasts with the narrowband ringing in the original commercial FUT, which for this design is dominated by the (0,0) mode resonance only [11], [13], [17]. The results in Fig. 9(b) show the power spectrograms of the A-scans measured at 90° for the Tx and Rx OFFUTs, which highlight the two prominent frequencies present in the ringing of each transducer, aligning with the two prominent resonances in their electrical impedance spectra in Fig. 8. It is evident that the dynamic response of the OFFUTs is influenced by this secondary resonance, even when operated at their primary resonant frequency. This warrants further investigation into the nature of the secondary resonant mode in future research.

An additional contributing factor to the complexity of the dynamic response of the OFFUTs may be the outer aluminium casing shown in Fig. 2. The rear metallic boundary enclosing the oil-filled central cavity may act as an efficient reflector of ultrasound, with any reflected signals influencing the dynamic response of the transducer's vibrating front membrane. Further research involving finite element modelling, or through a modification of the OFFUT design to include acoustically absorbing or scattering material on the underside of the oil-filled cavity, should be undertaken to investigate this.

B. Dynamic Performance at Elevated Pressure Levels

With the measurement environment established as shown in Section IV.A., both OFFUTs were contained inside the pressure chamber together as illustrated in Fig. 4, and the pressure level inside the pressure chamber increased to just above 200 bar. Pressure levels were cycled from 1 bar to above 200 bar and back three times, before a final pressurisation cycle where measurements are taken. During this final cycle, electrical impedance spectra for both OFFUTs and pitch-catch ultrasound measurements were recorded. In each case, an excitation voltage of 10 $V_{\text{p-p}}$ was used to drive a gated 5-cycle burst sinusoid from the function generator at (27.097±0.004) kHz, a frequency half-way between the measured series resonances of both OFFUTs at 1 bar. Characteristic results of the electrical impedance analysis are shown in Fig. 10 at three pressure levels above 1 bar, with an overview of the performance of the OFFUTs with varying pressure in Fig. 12.

Similarly, A-scans from pitch-catch ultrasound measurements that are indicative of the performance of the OFFUT pair are shown in Fig. 11, with results collated in Fig. 12. In general, the results in Fig. 10 and Fig. 11 demonstrate the suitability of the OFFUT for measurements in elevated pressure environments, where increased sensitivity is observed in pitch-catch measurements. With regards to the electrical

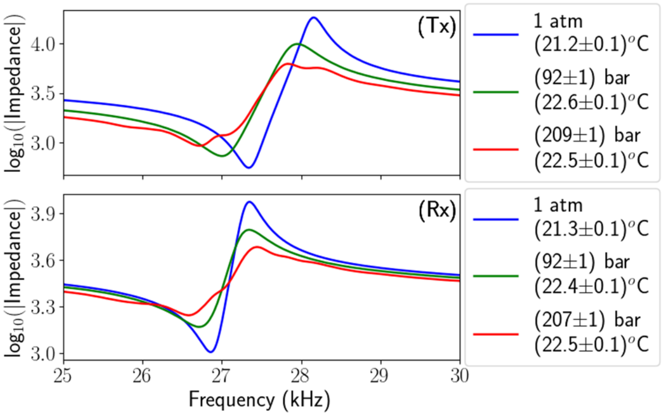


Fig. 10. Electrical impedance spectra for three pressure levels from atmospheric to above 200 bar for the transmitting (Tx) and receiving (Rx) OFFUTs, presented with the air temperature inside the chamber.

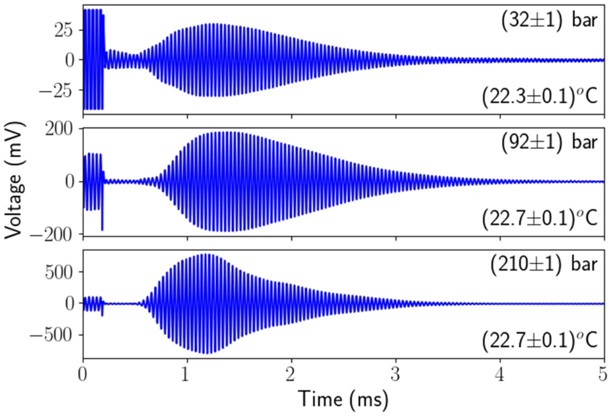


Fig. 11. A-scans obtained for pitch-catch measurement with OFFUT transducers at three pressure levels above atmospheric, with the internal temperature of the pressure vessel denoted.

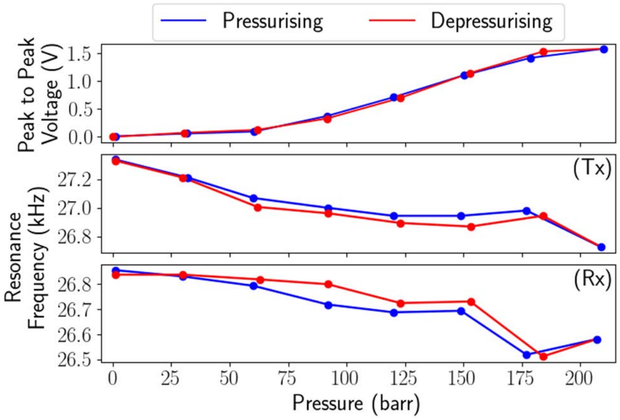


Fig. 12. Peak-to-peak voltage of the receiving OFFUT in pitch-catch ultrasound measurements at elevated pressures (top). The resonance frequency of the transmitting (Tx) and receiving (Rx) OFFUTs, defined here as the local minima in electrical impedance between (25-30) kHz, is also measured.

impedance spectra above 200 bar, it is evident that a physical threshold is approached, after which further pressure increases start to influence electromechanical response more strongly. There are several possible strategies for further optimising the transducer configuration, one of which would involve additional vacuum chamber steps in the fabrication process, but irrespective of this, the capacity of the OFFUT to operate in excess of 200 bar and yield practical measurements has been demonstrated. It should be noted that the electromechanical responses of the transducers exhibit minor differences, as shown in Fig. 10, thus the change in response due to external pressure can be different from one transducer to another.

Results for the electrical impedance analysis and pitch-catch ultrasound measurements of the OFFUT pair are shown in Fig. 12, with the pressure raised from 1 bar to above 200 bar and back to 1 bar. There are inherent limitations associated with drawing specific conclusions about the performance of the OFFUT from this figure. For example, it is evident from this research that peak-to-peak voltage may not be an accurate way to monitor measurement sensitivity of the OFFUT, because the envelope of the received signal is not consistent with changing pressure, as observed in Fig. 11. Similarly, the definition of resonance frequency as the local impedance minima may not be accurate in instances of high pressure, where multiple resonances can be observed as seen in Fig. 10. However, these results are useful for highlighting the stability of OFFUT performance and the suitability of the OFFUT for measurements at elevated pressures, showing generally consistent behaviour in measurement sensitivity and position of OFFUT resonance frequency through pressurisation and de- pressurisation of its surrounding air environment. Furthermore, a maximum deviation in resonant frequency for either OFFUT of (0.613±0.008) kHz again highlights the suitability of the OFFUT as a narrowband transducer for ultrasound measurement approaching and above 200 bar, where close matching of transmitter and receiver resonance frequencies is crucial. The results shown in Fig. 12 also add to the findings of prior research [19], where the resilience of OFFUTs to high pressure environments is demonstrated through the peak-to-peak voltage and resonance frequencies of the transducers returning close to their pre-pressurisation values after completion of the pressurisation cycle.

There are also limitations in using a pitch-catch ultrasound measurement to quantify the effects of exposing OFFUTs to environments of elevated pressure. This technique highlights the influence of pressurisation on the system of two transducers, but fails to indicate where pressurisation may affect the dynamics of OFFUTs in transmit mode differently to that of OFFUTs in receive mode. The influence of the pressurised environment on the propagating ultrasonic signal is also unaccounted for and is a topic for further research.

V. CONCLUSION

This research has investigated the concept of using a liquid filled flexural ultrasonic transducer or OFFUT, for operation in high pressure environments. The OFFUT is an adapted form of flexural ultrasonic transducer that is filled with oil as an effectively incompressible fluid, ensuring a pressure balance across the membrane of the OFFUT without significant deformation. Details of the fabrication process for the OFFUT have been provided, highlighting limiting factors of the transducer and design considerations. The influence of the fabrication process on the dynamic properties of the OFFUT have been demonstrated. The OFFUT performance has been investigated in depth, both at atmospheric and elevated pressure levels, indicating where further study is warranted. This study has shown the OFFUT to be a promising candidate for a wide range of industrial measurement applications at elevated pressure levels that are significantly above atmospheric pressure.

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William E. Somerset received the M.Phys. degree in physics from the University of Warwick in 2018, where he is currently pursuing the Ph.D. degree with the Centre for Industrial Ultrasonics (CIU), Department of Physics. His research focuses on new industrial ultrasound systems.

Andrew Feeney (Member, IEEE) received the Ph.D. degree in mechanical engineering from the University of Glasgow in 2014. He was appointed as a Research Associate to investigate ultrasonic technology for sub-sea applications with the University of Glasgow until 2016. Then, he was appointed as a Research Fellow with the Centre for Industrial Ultrasonics (CIU), Department of Physics, University of Warwick, until 2020. He is currently a Lecturer/an Assistant Professor with the James Watt School of Engineering, University of Glasgow. His research interests include multifunctional and smart materials and ultrasonic devices for industrial and medical applications.

Lei Kang received the M.Eng. and Ph.D. degrees in power electronics and drives from the Harbin Institute of Technology in 2006 and 2010, respectively. Since 2011, he has been a Lecturer/an Associate Professor with the School of Electrical Engineering and Automation, Harbin Institute of Technology. He was appointed as a Marie Curie Research Fellow with the Centre for Industrial Ultrasonics (CIU), Department of Physics, University of Warwick, in 2016. He is currently a Senior Lecturer with the School of Energy and Electronic Engineering, University of Portsmouth. His research focuses on the development of application specific ultrasonic transducers and engineering applications of ultrasonic technology, including flow measurement and non-destructive testing and evaluation.

Zhichao Li received the B.S., M.S., and Ph.D. degrees from the Harbin Institute of Technology, China, in 2008, 2010, and 2014, respectively. His research interests include ultrasonics and electromagnetic NDT. He worked on this paper, when he was a Research Fellow with the Ultrasonics Group, University of Warwick, and has now returned to the Harbin Institute of Technology.

Steve Dixon is a Professor of Physics and the Director of the Centre for Industrial Ultrasonics (CIU), University of Warwick. He currently holds an EPSRC Research Fellowship and a Royal Society Industry Fellowship. He has published over 120 peer-reviewed journal articles and is a member of the EPSRC funded U.K. Research Centre for NDE. He has worked in the area of ultrasonics for over 25 years.