Oil Filled Flexural Ultrasonic Transducers for Resilience in Environments of Elevated Pressure

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***Abstract*— In recent years, flexural ultrasonic transducers (FUTs) have gained popularity in a wider scope of applications, due to their robust design and efficient coupling to different fluids. They comprise a metallic membrane with a piezoelectric ceramic bonded to its underside, typically protected with a silicone backing to seal the FUT from its environment. However, the sealed interior of the commercially available and widely used FUT has restricted its application in environments above 1 bar, where pressure imbalances are known to lead to unstable dynamic performance, and deformation of the piezoelectric-membrane structure and the housing of the transducer. The recently reported approach of venting, such as the removal of the hermetic seal, has been shown to boost the resilience of FUTs to environments of elevated pressure, but an alternative approach is needed to prevent exposure of sensitive internal structures within the transducer to an external fluid. In this study, a novel FUT design for ultrasound measurement in elevated pressure environments is proposed, where the vibrating membrane is backed with an incompressible fluid comprising a non-volatile oil. Prototype oil-filled flexural ultrasonic transducers (OFFUTs) are fabricated, and their dynamic performance monitored through acoustic microphone, electrical impedance, and pitch-catch ultrasound measurements. Enhanced resilience of the OFFUT to environmental pressures approaching 200 bar is displayed, expanding the potential applications of this device towards challenging flow and gas monitoring systems.**

Keywords—Air-coupled ultrasound, Elevated pressure, Flexural ultrasonic transducer

I. Introduction

The flexural ultrasonic transducer (FUT) is a class of narrowband ultrasonic transducer that has widespread use in industrial flow metering and proximity sensing settings [1,2], most commonly as parking sensors in the automotive industries. The fundamental design of an FUT is composed of an active element, usually a piezoelectric ceramic disc, bonded to the underside of a thin metallic membrane with an epoxy resin. This structure is held in a metallic housing and is typically modelled as an edge clamped plate [3,4], where the bending modes of the membrane are exploited to efficiently transmit or receive ultrasonic signals in fluid coupled applications without the need for acoustic impedance matching [3,5].

Commercial FUTs are typically made more robust by sealing the rear of the metallic housing with a silicone backing, as illustrated in Fig 1. This backing creates a hermetically sealed internal air cavity within the FUT, causing a pressure differential across the membrane when the transducer is exposed to external pressures above 1 bar.

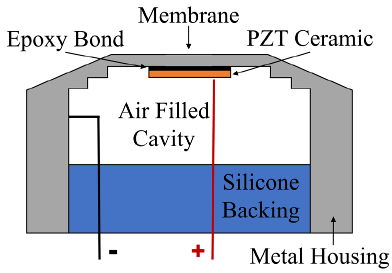

Fig 1. Cross-section schematic of a typical FUT.

Commercial FUTs are constrained to operation around atmospheric pressure levels because of this, to avoid pressure imbalances influencing the dynamics of the membrane and possible deformation of the transducer.

To realise the advantages of FUTs for a broad range of metrology applications, different strategies have been proposed to increase resilience to increasing and fluctuating pressure levels. Recently, the authors have published research into the vented flexural ultrasonic transducer (VFUT) and its dynamic performance towards 100 bar in air [6,7]. It was shown that through removal of the hermetic seal and equalisation of pressure across the membrane of an FUT, reliable ultrasound measurements can be conducted in an air environment at relatively high levels of pressure. However, to prevent exposure of the FUTs sensitive internal structures to an external fluid, an alternative approach is needed to mitigate pressure imbalances across the membrane whilst maintaining the original robust design of the transducer.

In this research, the design, fabrication, and characterisation of novel FUTs for ultrasonic measurement in pressurised air environments approaching 200 bar is demonstrated. An incompressible fluid is hermetically sealed within the interior cavity of the transducers to counteract pressure imbalances with the environment and help mitigate structural failures. The fabrication process is outlined, including the challenges associated with ensuring stability of measurement, and is supported by finite element modelling (COMSOL Multiphysics®). A non-volatile silicone oil is chosen as the incompressible fluid for the fabrication of two oil-filled FUTs (OFFUTs), to demonstrate the capability of performing high quality pitch-catch ultrasound measurements at elevated environmental pressures. A-scans from acoustic microphone measurement, and electrical impedance analysis at atmospheric 1 bar, are also obtained to monitor key experimental parameters.

II. Methodology

A. OFFUT Fabrication

The basic design of an OFFUT is comparable to the FUT, with a piezoelectric ceramic driven metallic membrane hermetically sealed into a housing structure. In this study, OFFUTs are created using the membrane, piezoelectric element, and housing of a commercial FUT (Multicomp MCUSR18A40B12RS) with a nominal 40 kHz resonance frequency. The rear silicone seal of the FUT is removed, before permanently embedding the structure into custom aluminium casing, comprising sidewalls, a central cavity for oil and channels for its injection into the structure. A schematic of this is illustrated in Fig 2.

A synthetic silicone oil (PDMS, 50 cPs viscosity) is chosen to be injected into the central cavity over any liquid fats such as vegetable oil, to improve the longevity of the device, as possible bio-organic processes or shorter shelf-life of the liquid can be avoided. Air bubbles within the oil filled cavity may also cause inconsistencies in the dynamic performance of the transducer at elevated pressure, changing the compliance of the vibrating membrane if a bubble forms against it. A vacuum chamber is utilised after the oil injection process to ensure there are no significant air bubbles in the cavity before hermetically sealing the transducer with a bolt.

B. Finite Element Analysis

COMSOL Multiphysics® models of the hermetically sealed FUT and OFFUT are used to investigate the efficacy of an incompressible oil backing at counteracting pressure imbalances across the vibrating membrane. The electrical impedance of the piezoelectric element in the finite element model is monitored at varying levels of external air pressure for air-filled and oil-filled variants. The model variants differ only in the fluids in their internal cavity, where the properties of vegetable oil are used to simulate an incompressible fluid backing to the vibrating membrane in the OFFUT case.

The characteristic resonance and anti-resonance profiles of the electrical impedance spectra of an FUT [8,9] can be seen in Fig 3. for both the air-filled and oil-filled cases at atmospheric 1 bar at around 40 kHz. However, only the oil filled transducer maintains this characteristic behaviour in the high-pressure air environments, giving a strong indication that OFFUTs will display enhanced resilience to elevated pressure compared to commercial FUTs. The shift in the series resonance of the oil-filled transducer, measured at the local minima of the impedance profile in Fig 3., may also indicate that the resonance frequency of the fundamental mode of OFFUT will decrease in environments of elevated pressure.

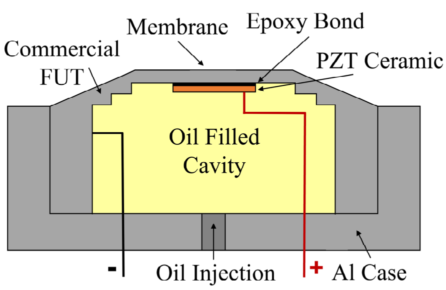

Fig 2. Cross-section schematic of the OFFUT.

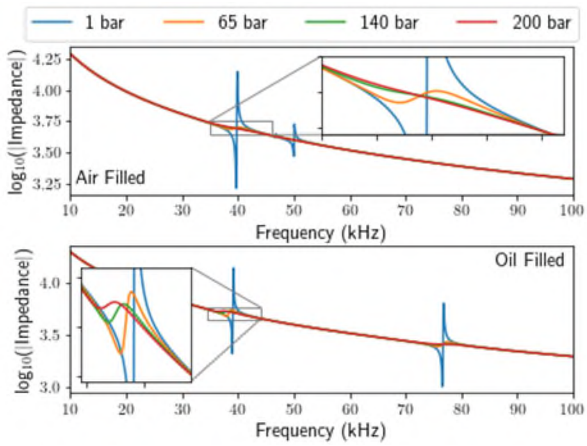

Fig 3. The electrical impedance obtained through finite element analysis of hermetically sealed air-filled FUT style (top), and oil-filled OFFUT style (bottom) transducers. Transducers are subject to an external environment of air at various pressures. The oil-filled transducer variant displays a resonance around 40 kHz, even at elevated pressures.

C. Measurement at Elevated Pressure

Two fabricated OFFUTs are used to perform pitch-catch measurements in air at elevated pressures. Transducers are fully enclosed inside a custom stainless steel pressure chamber, as illustrated in Fig 4., with internal pressures controlled using a ratiometric pressure sensor (MLH Series, Honeywell) and an air compressor (300 bar PCP compressor, IYS). The temperature of the pressurised environment is also monitored using a thermocouple. Prior research has established the sensitivity of FUTs to variations in boundary loads [7,8], and therefore consistent clamping conditions and alignment of the transducers are obtained here through printed ABS baffles which support the transducers within the chamber. Electrical impedance measurements of the two OFFUTs are taken while in the chamber both before and after pressurisation (Agilent 4294A), with series resonances of the two transducers found to be 27.03±0.09 kHz and 26.56±0.09 kHz pre-pressurisation.

Acoustic absorbing foam is utilised in the cylindrical pressure chamber to reduce the influence of reflections on signal measurement. Calibrated microphone measurements (GRAS 46DP-1) are made to examine the propagation of

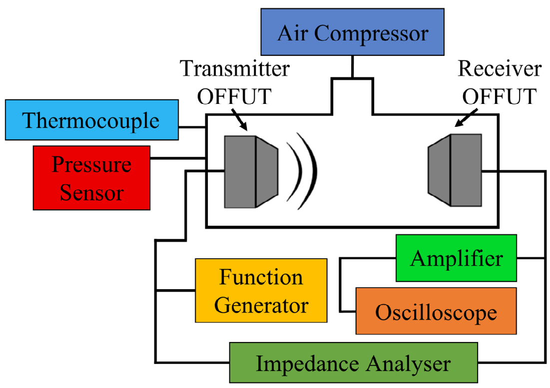

Fig 4. A schematic of the experimental setup for performing pitch catch ultrasound at elevated pressures in a steel pressurisation chamber.

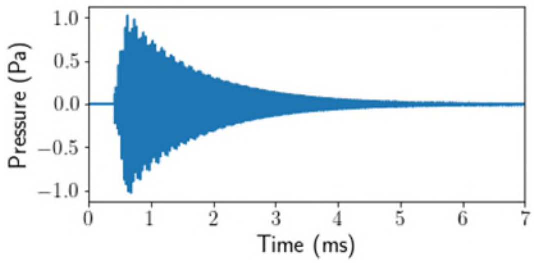

Fig 5. The ultrasonic pressure output of the OFFUT designated as the transmitter whilst in the pressurisation chamber. The A-scan shows no interference from reflected signals.

ultrasound within the chamber and shown in Fig 5. Here, the OFFUT designated as the transmitter in the pitch-catch system is driven with 5 cycle, 10 V_{P-P}, sinusoidal voltage signal (Tektronix AFG3021B) at its resonant frequency, with measurements recoded on an oscilloscope (Agilent DSOX3014A). No reflections are observed in the ultrasonic signal, but a frequency component away from the targeted resonance frequency can be observed in the vibrational response of the OFFUT. This could be due to various effects and will be investigated in future work but has no significant impact on the general performance as discussed here.

III. Results

The fabricated OFFUTs are used to perform pitch-catch ultrasound measurements in elevated pressure environments approaching 200 bar, with the output voltage response of the receiving OFFUT monitored. The systems response to excitation with a 10V_{P-P}, 5 cycle gated sinusoidal driving voltage is shown in Fig 6. at three pressure levels. In each case a driving frequency of 27.030±0.001 kHz is used, the resonant frequency of the transmitter prior to pressurisation. Enhanced performance of the OFFUT pair is observed at elevated pressure, where increasing peak voltage magnitude suggests the OFFUT displays greater sensitivity in high pressure environments. Vibration of the OFFUT's front

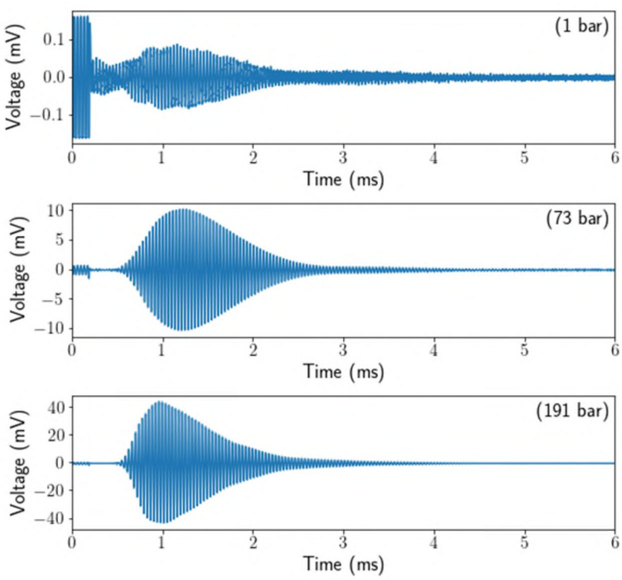

Fig 6. Voltage response of the receiver OFFUT in the pitch-catch system at different environmental air pressure levels.

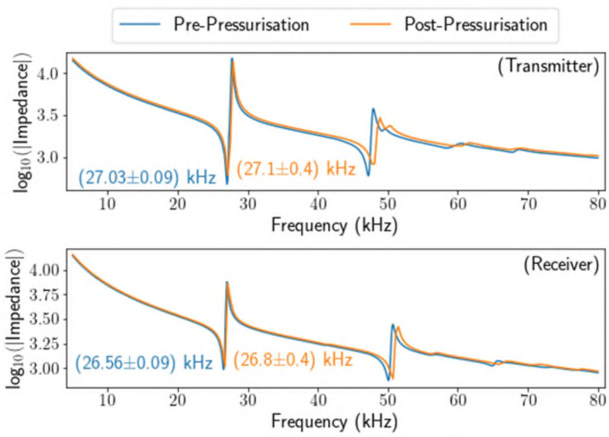

Fig 7. Electrical impedance spectra of the transmitting (top) and receiving (bottom) OFFUT measured at ambient RTP. Measurements are taken both prior to (blue) and post (orange) pressurisation to environments approaching 200 bar. Local minima of the impedance spectra are denoted.

membrane appears not to be restricted by the incompressible fluid at high pressure levels.

As is seen in the ultrasonic emissions from the transmitting OFFUT in Fig 5., Fig 6. also displays a beating effect in the response of the receiver OFFUT at ambient pressures. Multiple frequencies are not expected in the vibration response of a conventional FUT when driven at its resonant frequency, so further study is required to understand the origin of this effect and will be examined in future research. The beating property in the receiver OFFUTs response shown in Fig 6. becomes less prominent at higher pressures, showing the suitability of this transducer for measurement in environments of elevated pressure.

Electrical impedance spectra of both the transmitter and receiver OFFUTs are recorded at ambient pressure after the transducers are subject to the high-pressure environment. These measurements are displayed in Fig 7., alongside the impedance spectra recorded prior to pressurisation. Slight differences can be seen in the response around the fundamental axisymmetric resonance mode that OFFUTs are usually operated at, with the variation in resonance frequency extracted from the local minima of the electrical impedance. The receiver OFFUT displays the largest change of 0.2±0.4 kHz, a variation which is within tolerances defined for the value of resonance frequency in commercially available FUTs. Greater variation is displayed in the impedance characteristics of the secondary resonant mode displayed in Fig 7., around 47 kHz and 50 kHz for the two OFFUTs. The nature of this resonance will be examined in detail in future research.

Visual inspection of the OFFUTs after pressurisation reveals no noticeable deformation of the structure, showing the physical resilience of this configuration of transducer to elevated pressure levels approaching 200 bar.

IV. Conclusion

This research presents a novel flexural ultrasonic transducer concept for operation in environments of elevated pressure level. Prototype OFFUTs are developed through the injection of an incompressible oil behind the vibrating membrane of an adapted FUT, counteracting the pressure differential it experiences at high pressures. Efficient performance of the OFFUT has been demonstrated up to pressure levels approaching 200 bar, achieved using relatively low amplitude excitation voltages of 10 V_{P-P} with an SNR of up to 36.1±0.2 dB for a single shot, with an amplifier gain of 40 dB. The transducers not only survived high pressure cycling but were seen to operate more efficiently as the pressure increased. Both transducers used in these experiments exhibited some additional interesting behaviour in which small oscillations could be seen superposed on the main resonant frequency signal (as seen in Fig 5. and in Fig 6. at 1 bar). Interestingly this small oscillation appears to be suppressed as the pressure is increased. These measurements demonstrate the potential for using flexural transducers of this design at high pressures, which is extremely attractive as the design of the sensor facilitates the enclosing of the entire transducer in a hermetically sealed metal wall housing.

Acknowledgment

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warwick.ac.uk/fac/sci/physics/research/ultra/research/hiffut/

References

[1] D. E. Chimenti, “Review of air-coupled ultrasonic materials characterization,” Ultrasonics, vol. 54, no. 7, pp. 1804-1816, 2014.

[2] Y. Dobrev, S. Flores, and M. Vossiek, “Multi-modal sensor fusion for indoor mobile robot pose estimation,” Proc. IEEE/ION Position, Location Navigat. Symp. (PLANS), pp. 553-556, Apr. 2016.

[3] A. Feeney, L. Kang, and S. Dixon, "High frequency measurement of ultrasound using flexural ultrasonic transducers," IEEE Sens. J., vol. 18, no. 13, pp. 5238 - 5244, 2018.

[4] A. W. Leissa, Vibration of Plates, Washington, DC, USA: Government Press, 1969.

[5] S. Dixon, L. Kang, M. Ginestier, C. Wells, G. Rowlands, and A. Feeney, “The electro-mechanical behaviour of flexural ultrasonic transducers," Appl. Phys. Lett., vol. 110, no. 22, p. 223502, 2017.

[6] A. Feeney, L. Kang, W.E Somerset, and S. Dixon, “The influence of air pressure on the dynamics of flexural ultrasonic transducers,” Sensors, vol. 19, no. 21, p. 4710, 2019.

[7] A. Feeney, L. Kang, W.E. Somerset, and S. Dixon, "Venting in the comparative study of flexural ultrasonic transducers to improve resilience at elevated environmental pressure levels," IEEE Sens. J., vol. 20, no. 11, pp. 5776-5784, 2020.

[8] A. Feeney, L. Kang, and S.M. Dixon, “High frequency measurement of ultrasound using flexural ultrasonic transducers,” IEEE Sens. J., vol. 18, no. 13, pp. 5238 -5244, 2018.

[9] H. Yihua and H. Wenjin, "Research on the displacement function and equivalent circuit of circular flexural vibration mode piezoelectric ceramic composite transducers," IEEE Trans. Ultrason. Ferr. Freq. Cont., vol. 60, no. 1, pp. 218-234, 2013.