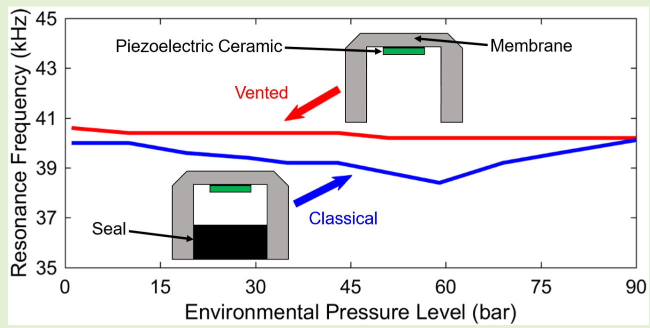
Venting in the Comparative Study of Flexural Ultrasonic Transducers to Improve Resilience at Elevated Environmental Pressure Levels

Andrew Feeney, Lei Kang, William E. Somerset, and Steve Dixon

***Abstract*—The classical form of a flexural ultrasonic transducer is a piezoelectric ceramic disc bonded to a circular metallic membrane. This ceramic induces vibration modes of the membrane for the generation and detection of ultrasound. The transducer has been popular for proximity sensing and metrology, particularly for industrial applications at ambient pressures around 1 bar. The classical flexural ultrasonic transducer is not designed for operation at elevated pressures, such as those associated with natural gas transportation or petrochemical processes. It is reliant on a rear seal which forms an internal air cavity, making the transducer susceptible to deformation through pressure imbalance. The application potential of the classical transducer is therefore severely limited. In this study, a venting strategy which balances the pressure between the internal transducer structure and the external environment is studied through experimental methods including electrical impedance analysis and pitch-catch ultrasound measurement. The vented transducer is compared with a commercial equivalent in air towards 90 bar. Venting is shown to be viable for a new generation of low cost and robust industrial ultrasonic transducers, suitable for operation at high environmental pressure levels.**



***Index Terms*—Flexural ultrasonic transducer, elevated Pressure, air-coupled ultrasound, unimorph.**

I. Introduction

THE measurement of ultrasound is essential for a range of applications in different industries, for example proximity sensing for robotics or automobiles, and flow measurement in the petrochemical, water, and energy industries. Developments in ultrasonic transducer technology are required to meet the demands of industry, and in particular the measurement of ultrasound in hostile environments, such as those of high pressure. A variation of a common transducer type, the flexural ultrasonic transducer, is proposed for such environments.

A. The Classical Flexural Ultrasonic Transducer

The flexural ultrasonic transducer is commonly used for the generation or detection of ultrasound in automotive parking sensor applications, or in metrological systems such as flow measurement [1]–[3]. The classical flexural ultrasonic transducer (CFUT) typically comprises a cap housing, containing a piezoelectric ceramic disc as the driver element bonded with an epoxy resin to the underside of a circular metallic membrane. A relatively low voltage of several volts is sufficient to induce the vibrations of the piezoelectric to generate high amplitude vibration of the membrane [4], which itself is analogous to an edge-clamped plate [4]–[6]. The CFUT is usually sealed at the rear with a material such as silicone. The CFUT components are supported within a housing, and the vibration modes of the transducer are dependent on its material and geometrical characteristics [7], dominated by the mechanical response of the membrane. Common CFUT membrane materials include aluminium, titanium, and stainless steel, selected for their properties such as compliance and robustness for different environments [4], [8]. The vibration modes which are exploited tend to be those which are axisymmetric. These mode shapes have been demonstrated in depth in the literature [4], [8].

A key advantage of using a CFUT for measurement in a gas or liquid, is that it overcomes the acoustic impedance mismatch limitation of alternative forms of ultrasonic transducer, such as those operating via through thickness or radial resonant modes of a piezoelectric ceramic, and which often require quarter wave matching layers for efficient operation. The acoustic impedances of piezoelectrics tend to significantly differ to those of fluids such as air or water [9], [10].

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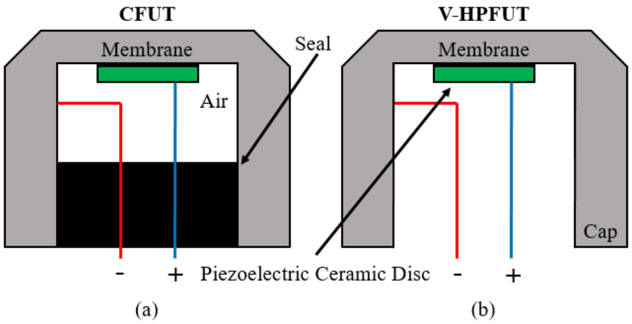

Fig. 1. (a) A general schematic of a typical CFUT, where the seal is commonly silicone; (b) a V-HPFUT, where the pressure between the internal structure and the external environment is balanced through seal omission.

However, the CFUT's vibrating membrane directly couples to the environmental fluid, where the piezoelectric is isolated from the external environment. The CFUT can be straightforward to fabricate, and does not require the relatively high biasing voltage required by a device such as a capacitive micromachined ultrasonic transducer (CMUT) [5], making the CFUT attractive for potential deployment in different types of fluid environment.

B. Transducers for Environments of Elevated Pressure

One major limitation of the CFUT is that it is not designed for operation in environments above around 1 bar. Despite the advantages of using a CFUT for measurement in different fluids, rupture or deformation is possible at elevated pressure levels due to the enclosure formed by the housing and silicone. Therefore, an alternative transducer is required for ultrasonic measurements in applications with elevated pressure levels. There are numerous industrial applications in gas and flow metering which can reach pressures of several hundred bar, including in the petrochemical industry and natural gas transportation, and new devices for these conditions are vital.

Ultrasound velocity measurement in liquids such as octane and pentane has been demonstrated up to around 1000 bar [11], although the piezoelectric transducers used for the investigation were not deployed into these environments. Instead, ultrasound waves were transmitted through a vessel wall. Natural gas flow measurement at around 60 bar has been reported using ultrasonic flow-meters [12], however the transducers were not flexural-type, and the process involved the measurement of relatively large flows, in the order of 10,000 m^3/h.

There have been more recent developments in ultrasonic transducers capable of reliable operation above 1 bar. A modified form of CMUT for flare gas metering has recently been demonstrated which incorporates venting to equalize pressure [13], [14]. However, as described in Section IA, the CFUT operates differently to the CMUT, exhibiting the potential to be significantly more robust than the CMUT with a lower complexity and cost. The modified CMUT for applications of varying pressure is also fabricated differently, through the etching of a silicon wafer and the inclusion of etched holes, resulting in the generation of Helmholtz resonances based on its geometry. The modified CMUTs were characterized through pitch-catch ultrasound measurement, up to a limit of 20 bar in gas. As the pressure was raised towards 20 bar, there were notable observations made, including the presence of a distinct reflection in the measurement signal from the wall of the measurement chamber, and a dominance of the resonant mode at lower pressure levels which diminished as pressure increased, in addition to the frequency and bandwidth of the transducer. The mode representing the Helmholtz resonance was shown to emerge at higher pressure levels, and the mode was observed to maintain its frequency and bandwidth. More recently, venting has been adopted as a strategy for simultaneously widening the bandwidth and ensuring a low minimum detectable pressure in CMUTs, through gaseous squeeze film damping [15].

Venting has also been demonstrated in forms of the piezoelectric micromachined ultrasonic transducer (PMUT) for purposes including the recycling of back-cavity pressure in the transducer [16], [17]. Recently, we investigated the influence of air pressure on the dynamics of different flexural ultrasonic transducers, including a vented form of the CFUT [18]. We demonstrated fundamental ultrasound measurement principles for transducers operating in environments with elevated pressure levels and the reliability potential of the vented configuration. However, little scientific study of the transducer or its physics has been reported, and is the principal subject of this investigation. It is essential that this transducer is understood for widespread industrial implementation.

C. Summary of Research

In this study, the venting strategy is investigated for its effect on how the flexural ultrasonic transducer can be made resilient to elevated pressure levels, above 1 bar. The underlying principle is that if the pressure inside the transducer is balanced with the changing environmental pressure, then the membrane will not deform due to pressure that may restrict its ability to vibrate. Also, the physical integrity of the transducer structure can be ensured. To introduce this pressure balance, the CFUT's internal cavity is exposed to the external environment as a vent. This vented flexural ultrasonic transducer (V-HPFUT) is characterized inside a custom pressure chamber, with key physical parameters investigated. The V-HPFUT represents just one design of flexural ultrasonic transducer for ultrasound measurement at elevated pressures, where alternatives can include a hermetically-sealed form of transducer comprising an incompressible fluid such as oil. This type of transducer will be investigated in future research. In this study, the V-HPFUT is compared with the CFUT where required, and experimental characterization is undertaken at pressure levels towards 90 bar in air through electrical and acoustic measurements. The results are used to develop design and operation principles for flexural ultrasonic transducers in environments of elevated pressure.

II. Methodology

A. Introduction of Venting into the CFUT

This study utilizes a commercial-type aluminium CFUT (Multicomp) which has a nominal operating frequency

Fig. 2. The transducer used in this study.

of 40 ± 1 kHz operating in the fundamental (0,0) mode of vibration [5], with membrane diameter of 10 ± 0.5 mm. It is essential to demonstrate the performance of commercial-type sensors. This CFUT contains a rear seal principally composed of silicone, and possesses an internal air region behind the piezoelectric ceramic. The V-HPFUT comprises the same specification, but instead it is vented through seal removal to allow pressure equalization between the internal air cavity of the transducer and the external environment. The CFUT and V-HPFUT schematics are shown in Fig. 1(a) and Fig. 1(b) respectively.

Two V-HPFUTs are fabricated for this study, where the generator V-HPFUT is designated as V-HPFUT$_G$ and the detector is V-HPFUT$_D$. The transducer is shown in Fig. 2.

B. Development of Support Fixture

Each transducer must be positioned inside the pressure chamber with a suitable fixture, which itself will influence the dynamics of the transducer. This occurs because the clamping condition around the transducer cap can change. Therefore, a support fixture is developed where the resonance performance of each transducer at standard room temperature and pressure conditions is monitored throughout the process by using an impedance gain/phase analyzer (Agilent 4294A) to determine the series resonance frequency. Monitoring resonance performance is essential to ensure that a support fixture is developed which allows reliable measurement.

The flexural ultrasonic transducer is sensitive to even minor variations in clamping or boundary conditions. Even slight stress or deformation to the membrane surface, or a small change in the circumferential force applied to the cap, can cause shifts in resonance in the order of hundreds of Hz. Therefore, it is not appropriate to drive a nominal "40 kHz" transducer at this frequency and assume it will be operating optimally. In the process of developing the support fixture for the transducers, three different stages of fixture development are investigated. These are illustrated in Fig. 3. The first shows a transducer without any support fixture, as shown in Fig. 3(a). The second shows a transducer bonded with a standard cyanoacrylate (Loctite®) into a custom acrylonitrile butadiene styrene (ABS) holder as shown in Fig. 3(b), and the third constitutes the transducer bonded into a holder which is then embedded in an ABS baffle for positioning inside the pressure chamber, as shown in Fig. 3(c). The fabricated transducers are exhibited in Fig. 3(d), with key physical dimensions provided in Table I.

It is important to consider the influence of different support fixture conditions on the resonant performance of the transducers and have consistent conditions, as this can influence measurements in practical ultrasonic metrology applications. The key steps of the process required to produce the fixture configuration as shown in Fig. 3(c) are considered, with measurements obtained for each. Each holder and baffle is relatively lightweight since ABS is used for fabrication. Eight equally-spaced apertures are included in the holder as shown in Fig. 3(b), to reduce the influence of holder flexure on the transducer vibration response. The baffle is fabricated to be rigid and also ensure the transducers are collinear inside the pressure chamber. The general rigidity and relative size of the baffle allows holder vibration to be minimized.

C. Transducer Characterization at Elevated Pressure Levels

Once a suitable support fixture is developed where reliable measurement of resonance performance can be ensured, the transducers are positioned inside the custom pressure chamber for characterization at different environmental pressure levels. Each transducer is positioned using a holder and baffle together, as shown in Fig. 3(c). The transducers are characterized using both electrical impedance analysis, as outlined in Section IIB, and pitch-catch ultrasound measurement.

The vibration responses of the CFUT and V-HPFUT$_G$ using V-HPFUT$_D$ as the detector in a pitch-catch configuration can be measured as shown via the schematic diagram of the custom pressure chamber in Fig. 4. This diagram illustrates that the pressure of the internal environment P_{ENV}, is controlled through a pressurization inlet port to which a standard air pump (Ernest H. Hill Limited) is connected. The input voltage V_{IN} to the generator flexural ultrasonic transducer G and output voltage V_{OUT} to the detector flexural ultrasonic transducer D are both monitored in addition to the temperature of the environmental fluid within the chamber T_{ENV}.

The pressure chamber, shown in Fig. 5, comprises a cylindrical cavity, two panels through which the transducer cabling can be passed, and high pressure insulated wire sealing glands (Thermal Detection) which are fabricated from stainless steel 316L and incorporate Viton sealant to accommodate the cabling and prevent pressure loss as the internal pressure is raised. The sealing gland specification shows effective sealing performance in excess of 200 bar. A ratiometric pressure sensor (MLH Series, Honeywell) is incorporated into the pressure chamber for verification of the internal environmental pressure. This pressure sensor is rated up to approximately 207 bar.

The appropriate drive condition must first be configured. A gated 2-cycle, 40 kHz sine wave with a nominal input voltage V_{IN} of 20 V_{P-P} from a function generator of 50 Ω output impedance is used as the excitation signal for the generator transducer G, since its resonance frequency can marginally differ to that of the detector D. G is connected to an arbitrary function generator (Tektronix AFG3021B) and D is connected to a custom 50 Ω input impedance, variable-gain amplifier and low-pass filter, with a -6 dB bandwidth of 29 kHz

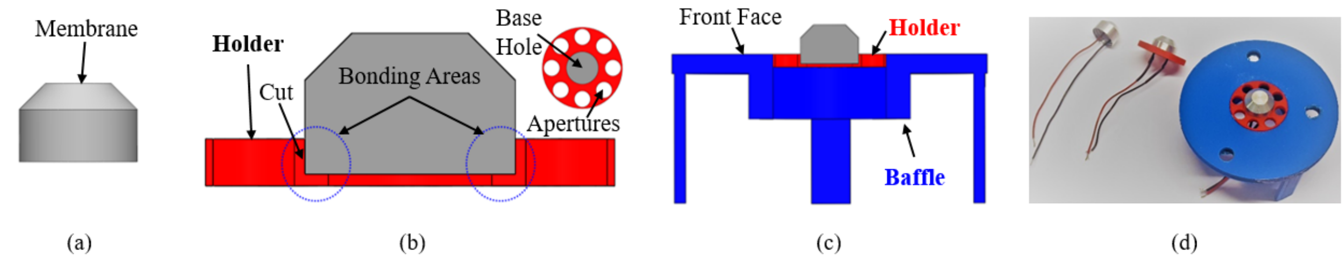

Fig. 3. The development of a suitable support fixture, showing a transducer (a) without holder or baffle, (b) bonded into a holder, (c) bonded to a holder which is then embedded in a baffle, and (d) the fabricated transducers. Note that sub-figure (c) also comprises acoustically-absorbent material in practice, thereby exposing only the transducer membrane. This material is excluded from this figure for clarity.

TABLE I
KEY PHYSICAL DIMENSIONS FOR SUPPORT FIXTURE DEVELOPMENT

Component	Dimension	Magnitude (mm)
Flexural Ultrasonic Transducer Cap	Membrane Diameter	10 ± 0.5
	Total Height	12 ± 0.1
	Total Cap Diameter	18 ± 0.1
Holder	Aperture Diameter	7 ± 0.5
	Base Hole Diameter	14 ± 0.5
	Cut Depth	3 ± 0.5
	Holder Thickness	4 ± 0.5
	Outer Diameter	35 ± 0.5
Baffle	Outer Diameter	97.5 ± 0.5
	Front Face Thickness	6 ± 0.5

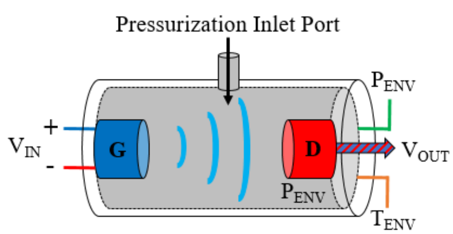

Fig. 4. The experimental setup showing ultrasound propagation.

to 1.68 MHz. P_{ENV} is raised through the pressurization port towards 90 bar, as shown in Fig. 5 using the air pump. The temperature of the fluid within the chamber T_{ENV} is also monitored with a thermocouple at all times. The pressurization system can be assumed to cause adiabatic compression of the fluid, but the chamber is composed of stainless steel, and so a proportion of the heat generated through pressurization will be conducted through the chamber itself. In general, ultrasonic waves are received by D and converted to a voltage output signal V_{OUT}.

III. EXPERIMENTAL RESULTS

The variations in the electrical impedance spectra of the transducers caused by different support fixtures are displayed in Fig. 6. Each transducer exhibits a fundamental resonance frequency around the nominal frequency specified in Section IIA. The resonance frequency of a flexural ultrasonic transducer is largely dependent on the dimensions and material type of the membrane [8], and even sub-millimeter disparities in the geometrical dimensions between similar transducers can

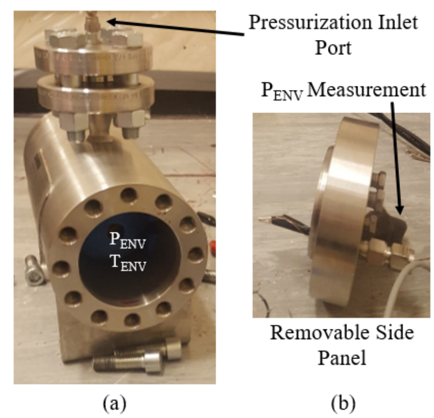

Fig. 5. (a) The stainless steel pressure chamber, with a wall thickness of 27 mm, showing the location pressurization inlet port; (b) the removable side-panel with an embedded pressure sensor for monitoring of P_{ENV}.

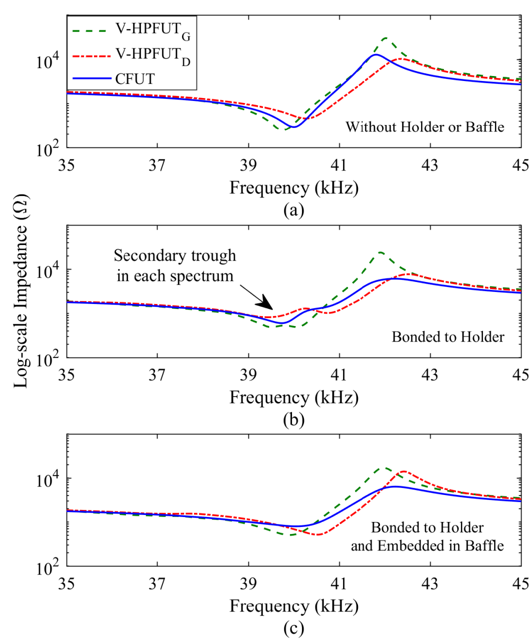

Fig. 6. Electrical impedance spectra at 1 bar in air for the CFUT, V-HPFUT$_G$, and V-HPFUT$_D$ (a) without holder or baffle, (b) bonded into a holder, and (c) embedded in a holder-baffle fixture (this was used for subsequent experiments).

cause resonance frequency differences into the hundreds of Hz. This is an important consideration for efficient practical operation and measurement accuracy of transit time from the phase of a detected electrical signal. A secondary trough is evident in each spectrum for the transducers supported with a holder only, shown by Fig. 6(b), which correlates to a vibration mode of the coupled transducer-holder system. The key problem with a secondary trough is that there is a risk of modal coupling in operation, which could restrict accurate ultrasonic transit time measurement. Through attachment of the baffle for insertion into the pressure chamber, this secondary trough is observed to be largely eliminated, as shown by Fig. 6(c). Therefore, this support fixture configuration is adopted for reliability.

The pressure chamber used in this study is effectively a thick-walled metallic pipe. The internal cavity is fully enclosed by metallic surfaces during operation, where the removable panels are fixed in place. The ultrasonic waves generated from G are directed towards D, but have few paths inside to which the energy can dissipate without interfering with the measurement of the ultrasonic signals on V-HPFUT$_D$. Therefore, even by using acoustically-absorbent materials of different acoustic properties, there may be a practical limit to the removal or mitigation of sound wave reflections within the pressure chamber, especially a chamber of the size used in this study.

Each transducer was embedded in a holder-baffle fixture, as shown in Fig. 3(c), and operated around resonance. The holder-baffle fixture is surrounded by acoustically-absorbent material, from which a wall is created along the length of the pressure chamber cavity, which comprises an irregular geometry to scatter sound waves which are not directed perpendicular to the membrane of D. The voltage-time responses of the CFUT and V-HPFUT$_G$ measured at 1 bar and room temperature using V-HPFUT$_D$ as D are shown in Fig. 7(a) with associated fast Fourier transforms (FFTs) displayed in Fig. 7(b).

The transducers exhibit marginally different resonance frequencies consistent with the results shown in Fig. 6(c), but show similarity in voltage amplitude and little significant sound wave interference at 1 bar. The effect of seal absence in V-HPFUT$_G$ is prominent through the extended resonant decay compared to that of the CFUT. This is key since the seal generates a damping effect in the transducer's dynamic response in addition to mechanical sealing. There is sufficiently low interference at 1 bar and room temperature, where secondary sound wave influences in the vibration responses are not detected. The FFTs provide a measure of consistency in the dynamic performance of the two G devices, aligning with the outcomes of the electrical impedance analysis shown in Fig. 6. A 20-60 kHz brick-wall band-pass filter was applied to the voltage responses in post-processing to eliminate noise, where the FFTs were computed using measured acoustic data.

The series resonance frequency, or frequency of minimum impedance, of each transducer is then monitored as a function of the environmental pressure level, P_{ENV}, extended from prior research [18]. The results are shown in Fig. 8.

The resonance frequencies of both V-HPFUTs remain generally stable from ambience towards 90 bar, each experiencing only a minor reduction in resonance frequency in the order of 0.5-1%. However, the resonance frequency of the CFUT is measured to reduce by approximately 4% from 1 bar to 60 bar.

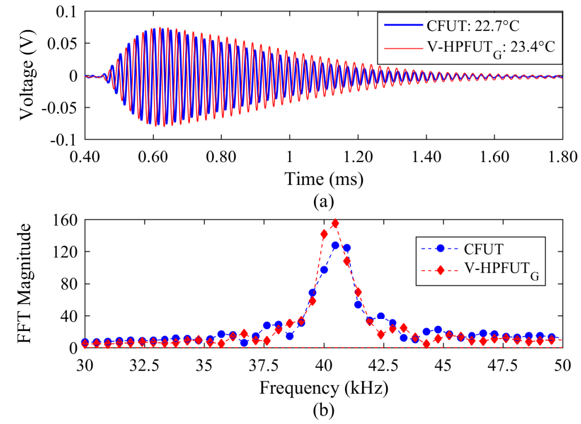

Fig. 7. (a) Pitch-catch ultrasound signals detected at 1 bar with a 20-60 kHz band-pass filter applied in signal processing; (b) FFTs of each response.

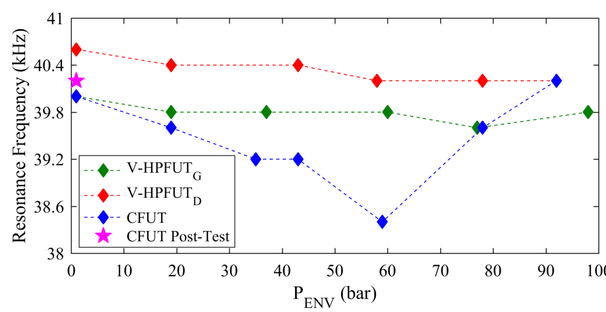

Fig. 8. Series resonance frequency as a function of P_{ENV}. There is an uncertainty of ± 0.5 bar associated with the pressure measurements.

Furthermore, this change in resonance frequency is characterized by a steady reduction, culminating in a drop in resonance of over 1.5 kHz by the point that P_{ENV} is 60 bar. This decrease in resonance frequency is significant, and could be problematic for ultrasound measurement systems requiring robustness and accuracy. In addition, the resonance frequencies of both V-HPFUTs were observed to return to their original magnitudes post-test, measured at an ambient pressure of 1 bar. However, the CFUT returned to 40.20 kHz as indicated by the star in Fig. 8, a shift of 200 Hz from the original value. This suggests that the pressurization towards 90 bar and subsequent depressurization has caused irreversible changes to the CFUT.

For most ultrasonic measurements, the transducers' resonance frequencies should be suitably matched and ideally experience minimal variation in response to changes in environmental conditions. Shifts in resonance frequency have been known to arise due to nonlinear dynamic phenomena [8], [19]–[23], but there are other explanations for the distinctive reduction in the CFUT's resonance frequency in these experiments. As P_{ENV} is increased, there will be a direct influence on the boundary condition of each transducer. Even minor changes to boundary conditions can cause discernible changes in dynamic performance, as demonstrated in prior research [8]. This contributes in part to the change in resonance frequency as pressure increases. However, there is a significantly larger shift of resonance frequency for the CFUT compared to either

V-HPFUT which cannot be accounted for by the change in boundary condition alone. The air trapped in the internal structure of the CFUT is at a different pressure to P_{ENV} during pressurization. This can cause membrane deformation of the CFUT, which will influence the CFUT's dynamic performance. The trapped air is at a significantly lower pressure than P_{ENV}, and so as P_{ENV} increases, the force causing deformation of the CFUT membrane will increase, also causing an associated stress on the piezoelectric ceramic. The air pressure either side of the membrane is equal for the V-HPFUT, therefore an associated variation in resonance frequency is not observed. For the CFUT, there is an increase in effective mass loading on the membrane up to 60 bar which results in a drop in resonance frequency, according to the analog model presented in prior research [9]. However, the general compliance of the membrane will decrease as pressure rises, causing an increase in resonance frequency. Therefore, a complex relationship between these factors on the dynamic performance exists. In general, there is balanced pressure on either side of the V-HPFUT membrane, and thus a lower prospect of membrane deformation. This is an advantage that eliminates the significant shifts in resonance frequency observed for the CFUT.

The rise of resonance frequency for the CFUT from 60 bar towards 90 bar can be attributed to the formation of an air leak in the transducer, which can be considered as a vent, and most likely originates via the silicone-type seal. Prior to 60 bar, the pressure level of the internal cavity of the CFUT differs significantly to P_{ENV}, until the structural stability of the CFUT seal at 60 bar reduces such that a leak forms. The cause of the leak formation at this pressure level is likely the physical deformation of the relatively soft silicone, particularly at the bonded interface with the aluminium cap. Silicone deformation was observed immediately after depressurization. It is also likely that the bonding layer between the silicone and the cap is susceptible to degradation. After this leak formation, the pressure difference between that of the internal cavity of the transducer and the environment begins to balance, although full equalization of pressure may be prevented if the leak reseals below a particular pressure difference. This can occur since the silicone is a relatively soft and flexible material. The time taken to achieve balanced pressure will depend on the physical size of the leak source in the transducer, but rapid and substantial pressure changes could in theory cause physical or irreversible deformation of the transducer cap or seal. In general, this leak formation can be a severe limitation in practical applications, as it renders the CFUT unreliable, where the dynamic performance cannot be accurately predicted. It should be noted that although the exposure to voltage connections would be undesirable in a practical application, the V-HPFUT design presented in this research also permits this. However, the objective here is to demonstrate a form of flexural ultrasonic transducer with balanced pressure on the membrane. A vented transducer would be susceptible to obstruction of the vents, depending on their geometry. More robust designs will be considered in future, including a sealed transducer with an internal cavity filled with an incompressible fluid such as an oil.

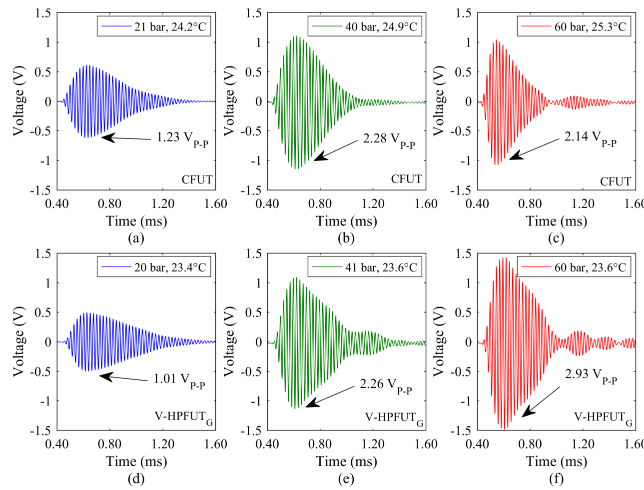

Fig. 9. Voltage responses and T_{ENV} for three magnitudes of P_{ENV} (± 0.5 bar) for (a), (b), (c) the CFUT, and (d), (e),(f) V-HPFUT$_{\mathrm{G}}$ as G, with V-HPFUT$_{\mathrm{D}}$ as D in each case, and a 20-60 kHz band-pass filter applied in signal processing. The peak-to-peak voltages are also shown for each first response peak.

The final characterization step is through pitch-catch ultrasound measurement. The results for V-HPFUT$_{\mathrm{G}}$ as G are displayed in Fig. 9 compared alongside the results for the CFUT as G, with V-HPFUT$_{\mathrm{D}}$ as D in each case.

Similar to the response at 1 bar shown in Fig. 7, the voltage-time responses around 20 bar do not exhibit distinct evidence of sound wave interference, giving further evidence of a reliable experimental setup. In general, the peak-to-peak voltage of the first detected response peak can be determined as a quantitative comparison for analysis, as indicated by the arrows in Fig. 9. For analysis, there are two factors to consider. The first assumes the operational capability and reliability of D at each pressure level. The second is the influence of interference, constructive or destructive, and as evidenced by Fig. 9, this can be difficult to determine. There exist artefacts in the voltage-time responses above 20 bar, which are the response peaks appearing after the first response peak in the time domain, and can appear due to sound wave interference. There are also vibration influences from the side-walls of the cap to consider, where the V-HPFUT possesses a side-wall of higher compliance than that of the CFUT, and so the vibrations associated with the side-wall will be more prominent in the vibration response compared to the CFUT. It can be difficult to explicitly determine changes in measured voltage amplitude which are not influenced by sound wave interference. However, in this study the peak-to-peak voltage of the first detected response peak is used for analysis.

As P_{ENV} is raised towards 40 bar, there is a minor increase in T_{ENV} which is expected, but distinct evidence of sound wave interference emerges for V-HPFUT$_{\mathrm{G}}$. This interference is not detected for the CFUT and should not be confused with beating, which can occur due to the difference between the drive signal and the resonance frequency of the transducer. The second peak which is emergent in the response measured at 41 bar for V-HPFUT$_{\mathrm{G}}$ can be assumed to originate from sound wave interference, in part based on the proximity of

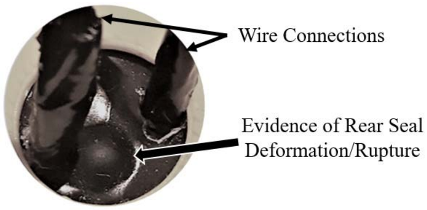

Fig. 10. CFUT rear seal deformation/rupture, identified post-test. This can be compared with the condition of the rear seal shown in Fig. 2.

the transducer to the internal cavity wall of the pressure chamber. As P_{ENV} is further raised to 60 bar, evidence of interference in the vibration response emerges for both the CFUT and V-HPFUT$_{G}$. The measured voltage amplitude is also shown to increase with P_{ENV} for the V-HPFUT$_{G}$ in pitch-catch configuration with V-HPFUT$_{D}$, but not the CFUT in pitch-catch with V-HPFUT$_{D}$. This behavior can be caused by different factors. Firstly, there is not a pressure imbalance on the V-HPFUT's membrane, unlike for the CFUT. The rising pressure on the CFUT increases the load on the CFUT membrane, causing the measured voltage amplitude associated with the CFUT in pitch-catch to reduce. Furthermore, despite the presence of the air leak, it is not likely that the pressure inside the CFUT will instantaneously balance with P_{ENV}, thereby creating residual pressure imbalance. Physical evidence of the damage to the CFUT, showing the deformation, or rupture, of the rear seal of the CFUT in its post-test condition, was observed and is provided in Fig. 10.

Another factor contributing to the phenomena shown in Fig. 9 is that the attenuation coefficient of the air inside the pressure chamber will change as a function of both P_{ENV} and T_{ENV}, thereby in principle causing measured voltage amplitudes to rise. The temperature changes as shown in Fig. 9 are minor from 20 bar through to 60 bar. However, given the volume inside the pressure chamber is approximately 2200 cm^3, small temperature changes are expected. Since P_{ENV} also changes, there will be a direct influence on the nature of sound wave propagation between G and D, irrespective of the transducer under study. The suitability of the flexural ultrasonic transducer for coupling to a wide range of environmental media has been reported [9], [10], but the acoustic impedance of the fluid in which the ultrasonic waves propagate must be considered. From the ideal gas law, the speed of sound of dry air should not change significantly with increased pressure, but will change with increased temperature [24]. As the density of the gas increases with pressure, one would therefore expect the acoustic impedance of the gas to increase mainly due to the change in pressure for relatively small changes in temperature. The vented form of flexural ultrasonic transducer has some advantages for ultrasound measurement in a hostile high pressure environment when compared to PMUT or CMUT type devices, where the V-HPFUT is a robust and sensitive device that can be operated with a relatively low voltage input, and is simple to construct from low cost materials and requires only very basic, low cost electronic drivers and amplifiers. The vented flexural ultrasonic transducer would therefore be an attractive candidate in a wide range of water and gas metering systems for which there is currently no reliable option.

IV. Discussion

This research has demonstrated operation of the relatively simple design of a piezoelectrically-driven flexural transducer at pressures above a few bar. A pressure balancing strategy and results have been demonstrated for a novel type of flexural transducer, the V-HPFUT, for operation in environments of elevated pressure. The V-HPFUT contains a vented cap to enable reliable ultrasound measurement in such environments. The development of a suitable support fixture was demonstrated, and important measurement considerations were outlined. This design of relatively low cost and robust transducer is probably the most common type of ultrasonic transducer in use, and its design and operation is distinctly different to that of CMUT or PMUT designs of ultrasonic sensors. Electrical impedance and pitch-catch ultrasound measurements have been used to demonstrate the performance of the V-HPFUT compared to the classical form of the flexural ultrasonic transducer, the CFUT. The importance of transducer characterization has been shown, and the dynamic performance of the V-HPFUT has been demonstrated to exhibit greater dynamic stability compared to the CFUT from 1 bar towards 90 bar, notably with respect to resonance frequency. The pressure balance around the transducer membrane and the properties of the air inside the pressure chamber both determine the dynamic performance of a flexural ultrasonic transducer in an environment of elevated pressure. The formation of an air leak in the CFUT through seal failure creates dynamic instability. A pressure imbalance on the CFUT membrane remains despite the presence of the air leak, since the pressure does not instantaneously balance. The influence of pressure on the membrane hence remains significant, inhibiting flexing operation and reducing the amplitude response.

In this study, artefacts in the vibration responses are detectable at higher levels of pressure above 20 bar, attributable to sound wave interference, emphasizing the necessity of a consistent and stable measurement environment for the transducers. With specific reference to sound wave interference and how ultrasound measurement between two transducers inside metallic pressure chambers can be made more reliable, it may not be possible to fully eliminate this interference in these types of size-limited chambers. Vessels of the size and specification shown in this study exist in commercial and industrial environments and applications. Reflections of ultrasound waves from the internal walls of pressure measurement chambers have been recorded in other studies, such as that by Apte et al. in 2013 [13]. Three artefacts were observed in the study by Apte et al. in their research on a modified CMUT for operation in environments of varying pressure level. The first was attributed to the RF feedthrough, the second was the response of the transmitted 3-cycle burst signal, and the third was observed to be a consequence of signal reflection from the chamber wall. Strategies must therefore be developed to account for interference, for example through the use of multiple frequency sources or signal processing.

It is also essential to understand the performance of each transducer prior to installation in a setup such as that shown in Fig. 4 and Fig. 5, further demonstrating why electrical characteristics are vital to obtain prior to pressurization measurement. It may be possible to develop a tracking system for a threshold vibration amplitude using a given resonance frequency. This would be useful for exploiting the V-HPFUT's resonance stability and to eliminate concerns of modulations in the voltage-time responses arising from sound wave interference. This is one example of why a V-HPFUT may be more desirable for the measurement of ultrasound in environments with elevated pressures rather than the CFUT. However, despite the fact that V-HPFUT$_G$ indicates a higher voltage amplitude at 60 bar compared to that at 41 bar, there may also be constructive rather than destructive interference of sound waves. The complete system must be considered, centred on the interaction between the ultrasonic transducers. A key future objective is to develop transducers which can be calibrated according to P_{ENV}. The measurement environment must be understood to achieve this, including the physical properties of the fluid and the influence on the propagation characteristics of the ultrasonic waves. Although the V-HPFUT exhibits a capacity for greater resonance stability with pressure, further research is required to understand the critical physical and experimental principles to consider for ultrasound measurement at elevated pressure levels, the influence of constructive and destructive interference at high pressure levels, how this interference can be further mitigated, and how variations in acoustic impedance quantitatively affect the propagation of ultrasound waves between G and D.

Future research will focus on alternative designs of flexural ultrasonic transducer for elevated pressure levels, including those more suited to industrial application, such as hermetically-sealed transducers comprising an incompressible fluid such as oil, or with regions of higher compliance which deform instead of the membrane. This research will lead to advanced measurement strategies for environments with elevated pressures, and also the development of alternate forms of high pressure flexural ultrasonic transducer to suit a wide range of industrial gas and flow metering applications, essential for the next generation of ultrasonic measurement technology.

V. Conclusion

Operation of piezoelectric flexural transducers at high pressures of up to 100 bar has been achieved. Venting a flexural transducer provides more reliable and consistent behavior at elevated pressure levels. The V-HPFUT exhibits a higher level of dynamic stability as environmental pressure is increased, and although there exists sound wave interference in the test chamber, the V-HPFUT is resilient to increasing environmental pressure, since it allows a pressure balance around the vibrating membrane of the transducer between the internal cavity and the external environment. The V-HPFUT will be the foundation for robust and advanced ultrasonic measurement technology for industry, particularly for gas and flow metering where pressures can be several hundred bar.

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