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Measurement stability of oil filled flexural ultrasonic transducers across sequential in-situ pressurization cycles

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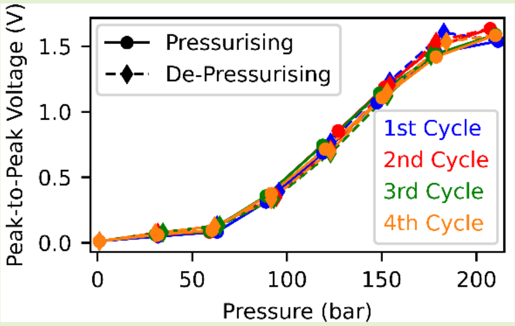
***Abstract*—Recently, flexural ultrasonic transducers for ultrasound measurement towards 200 bar were demonstrated, overcoming the major limitation of commercial variants associated with pressure imbalances due to their rear seals. One solution is through venting approaches, and another is introducing an incompressible fluid to the transducer's interior, thus creating a pressure balance across the vibrating plate. However, this approach has not been validated for repeated pressurization cycles consistent with practical industrial applications. Here, the structural resilience and dynamic responses of oil filled flexural ultrasonic transducers towards 200 bar are investigated through finite element and experimental methods, including electrical impedance and pitch-catch measurements. Sequential pressurization and depressurization cycles are applied, where the relationship between dynamic response and pressure level is monitored, and the transducer is assessed for its potential longevity in performance. The results demonstrate that via an incompressible fluid in the sensor cavity, stable and reliable ultrasound measurements, across frequency, electrical impedance, and amplitude, are possible across multiple pressurization and depressurization cycles towards 200 bar, where associated pulse envelopes can be used to directly correlate with the environmental pressure level.**



***Index Terms*—Ultrasonic transducer; flexural; elevated pressure; dynamic stability; finite element analysis**

I. INTRODUCTION

THERE is a growing requirement by several industry sectors for highly accurate time-of-flight measurements in hostile environments, those of elevated pressure or temperature [1-4]. Progress has been limited by the inability of key ultrasonic devices to withstand such conditions. Traditionally, ultrasonic transducers for industrial metrology and time-of-flight measurement have included contact and immersion transducers [5-6], and there have been significant recent developments in electromagnetic acoustic transducers (EMATs), including for corrosive or high temperature environments [7-9]. Popular forms ultrasonic transducer for metrology and nondestructive testing and evaluation are the piezoelectric micromachined ultrasonic transducer (PMUT), which comprises a piezoelectric ceramic with a matching layer to ensure the minimization of acoustic impedance mismatch [10], and the capacitive micromachined ultrasonic transducer (CMUT), which requires a relatively large DC bias to perform with high sensitivity in the reception of ultrasound [11]. The piezoelectric flexural ultrasonic transducer (FUT), for time-of-flight and industrial measurement, has been used in multifarious distance ranging applications at ambient pressures for decades.

A. Operating Principle of the FUT

The FUT has been prevalent in proximity sensing for many years [12-13], predominantly as part of parking systems in automobiles. It is relatively straightforward, consisting of a piezoelectric ceramic disc bonded to a metallic circular thin plate. The application of a voltage in the 1V - 20V range to the piezoelectric ceramic excites motion in the thin plate following its resonant vibration modes, which can be mathematically predicted using standard plate vibration theory [14]. The structural composition of the traditional FUT has been demonstrated in several prior publications [15-21].

Apart from an important early study [22], the FUT has only

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recently been the subject of detailed scientific investigation, specifically regarding design, optimization, and new fabrication techniques. Traditionally, the principal limitation of the FUT has been its inability to withstand pressure levels significantly above atmospheric 1 bar [23-24]. The study of the FUT is vital for the development of ultrasonic devices resilient to hostile environments, including for the gas metering industry, where the pressure can be hundreds of bar [25-26].

The conventional method of FUT manufacture results in an internal air cavity, the intrinsic pressure of which can change at a different rate to that of the external environment. A pressure imbalance has been known to occur between the internal air cavity of the traditional FUT and the external environment, for pressure levels above atmospheric 1 bar.

B. The OFFUT Concept

The pressure imbalance in the traditional FUT was successfully eliminated in the vented FUT, an adapted form of the FUT where the cavity is vented to the external environment [23-24]. Overcoming the pressure imbalance led to the oil filled FUT (OFFUT), which addressed key design and operation limitations associated with the vented design [27], including likely vent blockage or the exposure of the piezoelectric ceramic disc to harmful particles or fluids. Through filling the FUT cavity with oil, a quasi-incompressible system boundary condition was created, thus enabling operation in elevated pressure environments.

The research conducted thus far has neglected to consider the measurement stability of the OFFUT across successive pressurization cycles, vital for industrial application, both in terms of dynamic performance (including resonance frequency and electrical impedance), and structural integrity of the sensor. Furthermore, a robust finite element simulation has not yet been demonstrated to provide explanations for the observed dynamic characteristics. In this study, the measurement stability of the OFFUT is reported in detail for sequential pressurization cycles, alongside a comprehensive finite element simulation, providing practical insights into how the sensor can be exploited and developed for future industrial applications.

C. Novel Contributions to Knowledge

There is industrial need and academic interest in engineering ultrasound transducers for environments of elevated pressure. For example, a recent study has demonstrated the operation of 6 MHz piezoelectric composites bonded to matching layers towards at 1000 bar in silicone oil [28], though this study along with others, do not consider a configuration like the FUT.

In prior research [27], the authors outlined a suitable fabrication process for the OFFUT, giving a general insight into how aspects of transducer performance such as the resonance frequency can be affected. Key dynamic characteristics of the OFFUT when operating at atmospheric 1 bar conditions were also demonstrated, complemented by a selection of A-scans obtained at several environmental pressure levels above atmospheric, using the pitch-catch approach. This showed the quality of ultrasound measurement obtainable using the OFFUT concept in an elevated pressure environment. Importantly, this study showed the sensor performance for one pressurization cycle, demonstrating that dynamic performance was broadly recoverable for exposure to pressure of at least 200 bar.

In this investigation, the dynamic stability of the OFFUT in response to sequential pressurization and depressurization cycles is studied in the range of atmospheric 1 bar, to above 200 bar in air. The structural resilience of the sensor is assessed, along with a variety of dynamic features associated with sensor response, including resonance frequency and modal behaviour. The work provides valuable insights for the practical application of the OFFUT for in-situ ultrasound measurement at elevated pressure levels. As a concise overview, the novel contributions to knowledge are:

1. The demonstration of measurement stability, in terms of dynamic performance and structural integrity, of the OFFUT across sequential pressurization and depressurization cycles between atmospheric 1 bar and 211 ± 1 bar. This has a direct impact on sensor longevity and reliability for ultrasound measurement applications.
2. The demonstration of the OFFUT as a combined proximity transducer and pressure sensor, where the pulse envelopes from A-scans directly correlate with the environmental pressure level. These unique pulse envelopes are also used to provide strong evidence that receiver voltage amplitude alone is not an ideal measure of sensor performance.
3. Evidence of a settling phase in the dynamic response of the OFFUT, vital for practical ultrasound measurement.
4. An explanation for the origins of dual axisymmetric modes observed in the system responses.
5. The demonstration of mode shape measurements for OFFUTs at different operating frequencies.
6. An understanding of how environmental pressure level influences transducer damping.
7. The development of a robust finite element simulation to complement experimental observations.

II. METHODOLOGY

A. OFFUT Design and Construction

The motivation to inject the cavity of a FUT with oil is that by introducing a sufficiently dense fluid into the internal cavity of the FUT, there exists quasi-incompressibility, enabling the FUT to operate at elevated environmental pressure levels. Although no liquid is wholly incompressible, the environmental pressure levels utilized, up to 200 bar, are sufficiently low for a wide range of liquids to prevent excessive deformation of the FUT and maintain good transduction efficiency. Different liquids can be used to ensure incompressibility in the FUT. A generalized schematic of the OFFUT configuration is shown in Fig. 1, which can be compared with those for conventional commercial FUTs [15-21].

In conventional FUTs, the rear of the transducers are usually sealed using a material such as silicone. Rupture of the silicone seal at even modest increases in environmental pressure level has been identified in prior research [24,29], and causes a variety of complications including instability in dynamic performance and exposure of sensitive internal components of the FUT to the external environment. This can be especially problematic if the environmental fluid causes damage the internal components of the FUT. The ingress of a surrounding fluid into the FUT cavity will result in changes to the the intrinsic performance of the sensor and can severely reduce or entirely cease the operational capacity of the FUT, and effectively expose the external fluid to the voltage provided to the FUT.

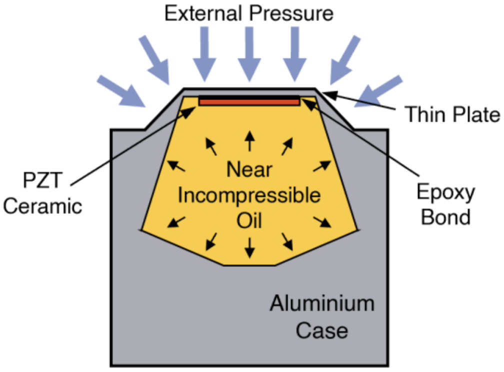

Fig. 1. A generalized schematic of the OFFUT, showing the thin plate on to which a piezoelectric (PZT) ceramic is bonded, and behind which is a cavity filled with near incompressible oil.

The OFFUT instead accommodates a liquid in the former internal air cavity, which is injected at a specific pressure which can be atmospheric 1 bar. A vacuum chamber can be used to ensure any air bubbles are eliminated from the cavity through this process. Once the internal cavity is filled with liquid, the cavity is sealed. As the environmental pressure level external to the sensor is raised above that of the internal cavity, static deformation of the vibrating structure, consisting of the piezoelectric ceramic disk bonded to the thin metallic plate, is reduced by the liquid inside the OFFUT. This allows the OFFUT to be safely exposed to significantly higher levels of pressure when compared to the classical FUT.

There are typical mode shapes associated with the operating modes of the FUT. Some of these are shown in Fig. 2, for both axisymmetric and asymmetric modal responses of the thin plate. In this study, the OFFUT is designed to optimally operate where the plate exhibits the axisymmetric (0,0) mode shape, which is usually verified using a laser Doppler vibrometry (LDV) measurement.

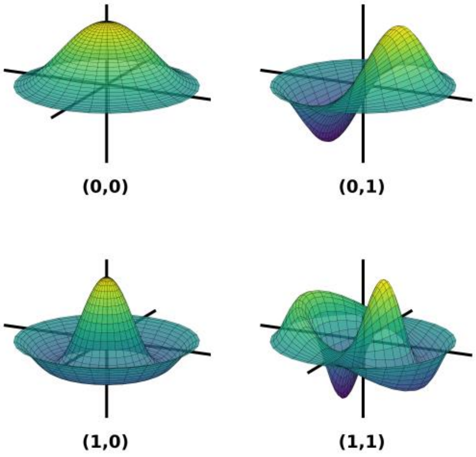

Fig. 2. The commonly exploited axisymmetric (fundamental (0,0) and (1,0)), and asymmetric ((0,1) and (1,1)) mode shapes of the FUT.

In principle, there are two important requirements for the OFFUT with respect to the liquid in the internal cavity; the liquid density needs to be high enough to provide effective resistance to deformation of the thin plate at elevated pressure levels and the liquid needs to be effectively inert when in contact with the internal components of the transducer. In this research, silicone oil is chosen as it is non-volatile and will not confer corrosive or destructive influences on the electrodes, the epoxy resin, or the piezoelectric ceramic disc inside the sensor, being chemically inert [30]. It is also sufficiently dense, in the order of 959 kg/m^3, although it is one of many liquids which could theoretically be injected into the internal cavity.

The OFFUT used for this research is fabricated with an aluminium thin plate with a nominal diameter of 10 mm, consistent with prior research and adhering to the same general fabrication process [27], where the complete schematics and images of the internal components can be viewed in [27]. An aluminium case is attached to the cap rear, through which silicone oil (Polydimethylsiloxane, CAS 63148-62-9) is injected, before being sealed with potting epoxy resin (Electrolube ER1448). An acrylonitrile butadiene styrene (ABS) strain relief backing is also attached to the OFFUT to protect the electrode connections during operation.

It is important to achieve total degassing of the silicone oil prior to the hermetic sealing of the OFFUT to obtain a stable resonance response; accomplished in this work using a vacuum pump. Oil is relatively dense and will contribute a mechanical damping effect on the vibrating plate, and to differing magnitudes if any air bubbles exist inside the cavity resulting from the transducer fabrication process. The density of any air pocket is significantly lower than silicone oil and will shift location in the cavity depending on the orientation of the OFFUT, altering its dynamic performance if not removed.

B. Finite Element Simulation

The first investigative step in the study was to construct a representative finite element model of the OFFUT, beyond what has been demonstrated in prior research. The OFFUT was defined in COMSOL Multiphysics® software, consistent with the physical parameters and geometry shown above and in the preliminary study [27], where the model is illustrated in Fig. 3.

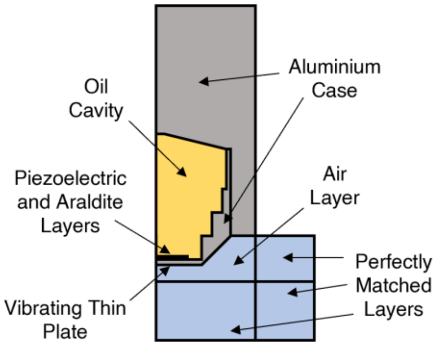

Fig. 3. The finite element model of the OFFUT.

Fig 3. illustrates the 2D model swept around the central axis to create a representative 3D model of the OFFUT to investigate its response in air at pressures of both 1 bar and at 200 bar. This methodology allowed for any contributions from non-axisymmetric modes to be seen. The key purpose of this 3D model is to demonstrate the modal behaviours at elevated pressure levels and in the presence of an incompressible fluid, where this can be applicable to a wide range of (incompressible) liquids. Key dimensions for the modelled device include: the vibrating plate's radius of 5.5 mm (the plate diameter was measured as 11 mm); the araldite epoxy and PZT-5H layers each having a radius of 3.75 mm, and thicknesses of 0.1 mm and 0.25 mm respectively; the device's internal cavity having a maximum depth of 14.84 mm; and an air layer of 2 mm thickness, with ideally (or perfectly) matched layers of 7.15 mm thickness. Both the oil inlet port and the electrode ports are neglected in the model, and the internal cavity is modelled using a sound speed that was measured in the silicone oil to be (1060 ± 3) ms^{-1}. Using this model, the modal responses of the OFFUT for ambient conditions, with the external air layer at 1 bar, and in a hostile environment, with the air layer pressurised to 200 bar, were simulated.

C. Dynamic Characterization

The experimental part of this investigation was conducted in two stages. First, the fundamental dynamic properties of two nominally identical OFFUTs, one designated as a transmitter and the other as a receiver, at ambient room temperature and atmospheric pressure conditions were captured using a combination of electrical impedance analysis (EIA, Agilent 4294A) and laser Doppler vibrometry (LDV, Polytec OFV-5000). The overall objective of this first stage was to assess the similarity in characteristics of the two OFFUTs and investigate their vibrational response at multiple operating frequencies. EIA was first applied to verify the series resonance frequencies of the prominent resonances for each OFFUT, the mode shapes of which were subsequently measured using LDV analysis and can be compared with the associated mode shape for conventional FUTs shown in Fig. 2. This is important for assessing the viability of OFFUT operation at multiple resonant vibration modes, and the usefulness of these modes for ultrasonic measurement in high pressure applications.

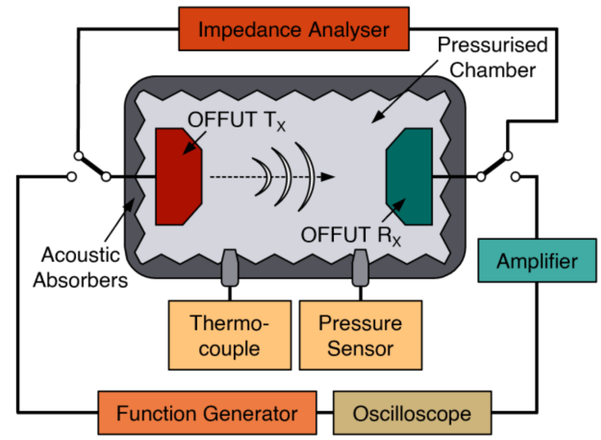

Fig. 4. The pressure vessel, showing the characterization setup.

The second stage of the experimental investigation focused on subjecting both transmitter and receiver OFFUTs to a series of pressurization and depressurization cycles. The transducers are installed in a stainless-steel pressure vessel containing air. A schematic for the pressure vessel used for this purpose is shown in Fig. 4, illustrating how the peripheral experimental characterization instruments were integrated.

The OFFUTs were subjected to environmental air pressure levels beyond 200 bar, where both pressure and temperature were monitored. For both OFFUTs, electrical impedance measurements were recorded at atmospheric pressures, in addition to A-scans for each pressure level increment above atmospheric acquired through pitch-catch ultrasound measurement. Nominally, pressures at 30 bar intervals were generated for four successive cycles of pressurization to the maximum of 210 bar, prior to a depressurization step to atmospheric 1 bar, before pressurization again towards 210 bar for the subsequent cycle. A-scans were performed at these 30 bar intervals in both pressurization and depressurization steps.

III. RESULTS AND DISCUSSION

A. Electromechanical Properties

The series resonance frequencies of the transmitter and receiver OFFUTs were measured prior to and post implementation of a pressurization and depressurization cycle using their electrical impedance as a function of frequency. The results are shown in Fig. 5, for a measurement step of 93.75 Hz.

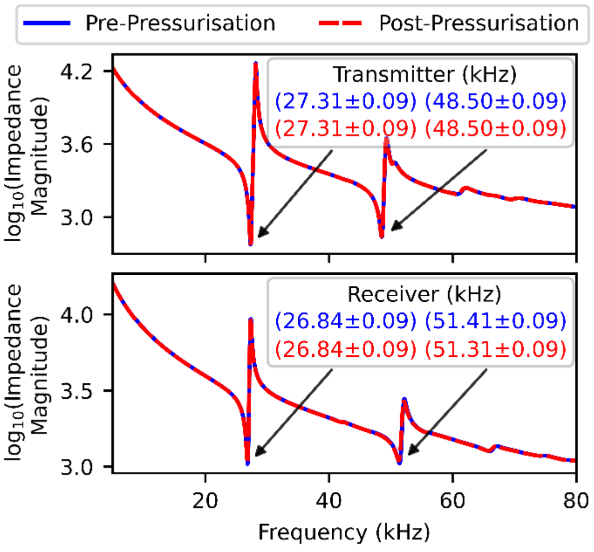

Fig. 5. Electrical impedance spectra for the transmitter and receiver OFFUTs, for pre- and post-pressurization conditions.

There is a close match between the series resonances for both OFFUTs, which is desirable for efficient pitch-catch measurement. The second fundamental modes are indicated in Fig. 5, set as the foundation for the subsequent measurements. Here, there is an approximate 3 kHz difference between transmitter and receiver. Conventional air cavity FUTs exhibit similar levels of variations in resonant frequency, caused by small variations introduced in manufacturing. Importantly, it is notable that for the OFFUTs, there is negligible change to the series resonance of the two modes from the pressurization process towards 200 bar and depressurization to 1 bar.

Using the series resonance measurements from EIA, the mode shapes at resonance for the transmitter OFFUT were measured using LDV. These mode shapes are shown in Fig. 6 measuring the velocity of the vibrating thin plate only.

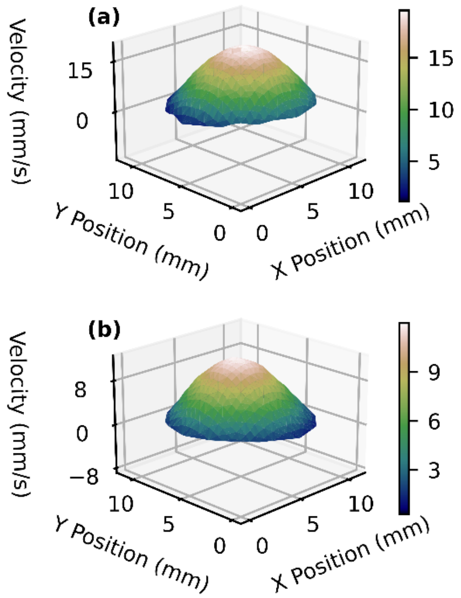

Fig. 6. Mode shapes of the transmitter OFFUT at (a) 27.52 kHz, and (b) 48.75 kHz, showing the existence of a (0,0) mode-like shape at both frequencies.

Firstly, it should be clarified that the resonance frequencies identified from the EIA process in Fig. 5 differ to those in Fig. 6, because the driving conditions required for each process are different, and so the resonance frequencies exhibit differences. For example, the driving voltage used for LDV is lower than that for EIA, and therefore given the relationship between driving voltage and resonance [16-17], there can be inevitable discrepancies in the responses. This has been reported in several previous studies [12,18, 27]. The key point here from this data is that this LDV result is both unexpected and significant. Typically, a FUT exhibits axisymmetric and asymmetric modes of vibration, consistent with the schematics shown in Fig. 2. With the OFFUT, LDV has been used to clearly demonstrate a response for two modes of vibration, that appear to be axisymmetric, with a similar shape to the (0,0) mode seen in FUTs. This means that in theory, one or another mode of vibration could be selected for measurement. The presence of the silicone oil in the cavity is likely the primary cause of this characteristic response, which has been verified through finite element analysis as shown in Fig. 7.

It should be first noted that since there are significant differences in peak magnitudes from these results, the colour bars are retained as uniform to ensure clarity in the data presentation. It is evident that the presence of the silicone oil in the cavity, increasing the acoustic coupling between it and the vibrating plate, allows for the formation of the secondary (0,0)-like resonance from interactions in the cavity geometry that would typically not be observed in the case of the traditional air-backed FUT. The slight asymmetry in the secondary (0,0)-like mode in Fig. 6(b) is not present in the Fig. 7 numerical comparison, indicating that the observed slight asymmetry is likely due to small imperfections in fabrication. The discrepancy between the physical device dynamics and the FEA results is likely due to the numerical model not accounting for asymmetrical placements of electrode/solder points and the oil injection/electrode inlets present in the OFFUT. These features break the transducer's cylindrical symmetry and may affect the devices dynamic outputs.

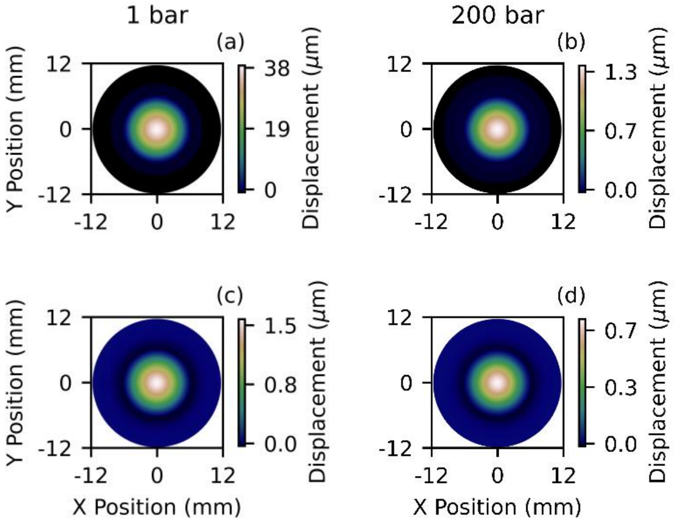

Fig. 7. A top-down view of the OFFUT simulated using finite element software, where the out-of-plane displacement is plotted to show the transducer's modal response. Here, (a) and (b) demonstrate the modal response of the primary (0,0)-like resonance, at 25.95 kHz and 24.75 kHz respectively, and (c) and (d) show the secondary at 48.55 kHz and 47.90 kHz respectively.

Both the experimental mode shape measurements in Fig. 6 and the FEA results in Fig. 7 highlight the novelty of the OFFUT, displaying dual axisymmetric (0,0)-like modal behaviour. Though the first mode is assumed to follow the edge clamped plate mathematical approximation, an increase in baffle displacement is observed for the secondary mode in Fig. 7 such that the edge clamped approximation may no longer be valid. The existence of two (0,0)-like modes in the OFFUT's dynamic profile may be possible if the secondary resonance is described using an elastically supported thin plate analogue. Fig. 7 also highlights that the dual axisymmetric (0,0) mode response is likely still present in environments of elevated pressure and demonstrates that the OFFUT has at least two stable axisymmetric resonances which can be exploited.

B. Pressurization Cycles

The pressurization and depressurization cycles were then implemented on both the transmitter and receiver OFFUTs simultaneously, where electrical impedance spectra and A-scans were all recorded. The A-scans are shown in Fig. 8, for an excitation voltage of 20 $V_{P\text{-}P}$ using a burst sine with 5 cycles in each case, with the transducers facing one another. The

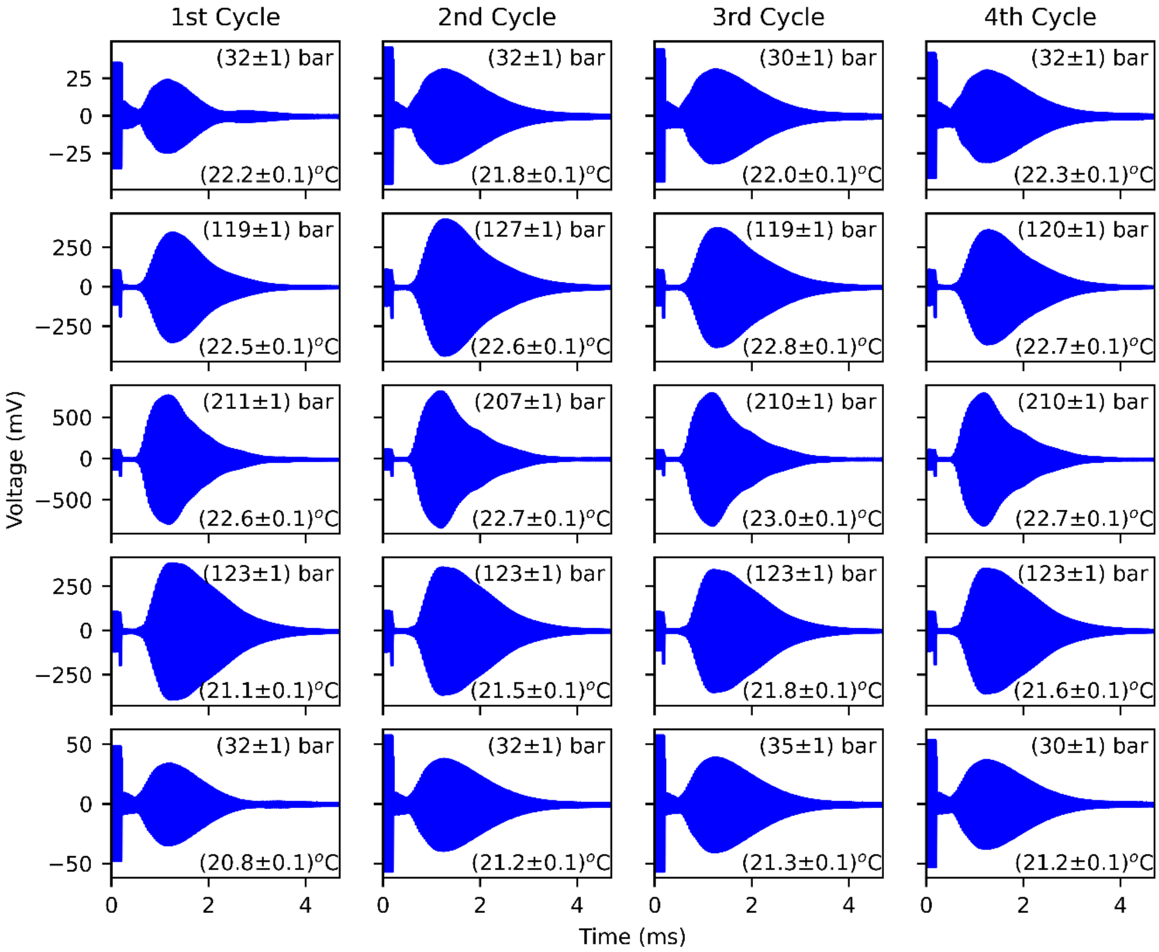

Fig. 8. A-scans measured using the receiver for different pressure levels, using ultrasound generated from the transmitter.

excitation frequency was maintained at a constant value over each individual pressurization and depressurization cycle, with a value determined by midpoint between the series resonances of the transmitting and receiving OFFUTs measured at atmospheric 1 bar before each cycle. This excitation condition was selected with the aim of maximizing the amplitude acquired in each measurement, where series resonance was determined via a frequency sweep. A characteristic of the voltage output of a FUT-based transmitter and receiver system is that it comprises a convolution of responses between the two transducers in the system, based on the piezoelectric and inverse piezoelectric effects. This affects the frequency of optimal ultrasound wave propagation amplitude, as demonstrated by these results, and this has also been noted in prior research [31]. A-scans at select air environment pressures are shown for measurements over multiple pressurization and depressurization cycles.

It is notable from the data that there is a high degree of consistency in the pulse shape of the envelope across multiple cycles of pressurization and depressurization. The envelope shape itself changes depending on the pressure level, but importantly it is highly repeatable over successive cycles. This suggests that pulse shape may be used as a reliable indicator of environmental pressure level. This also means that whilst peak-to-peak voltage level is a valid measure of transducer performance at elevated pressure levels, accounting for the shape of the pulse envelope allows for a more detailed quantification of pressure level. It should be noted that the only exception to this is the very first cycle, which it has been found constitutes a settling cycle. In a physical sense, the OFFUT requires a settling pressurization cycle for the structure to equilibrate with the changing pressure of the environment. After this cycle, the responses are all repeatable across successive pressurization and depressurization cycles. This is a novel observation because reports thus far have been limited to single cycle responses. After this, the electrical impedance measurements were collated for both OFFUTs after each pressurization and depressurization cycle at the mode of interest, around 27 kHz, and these results are shown in Fig. 9, for a measurement step of 6.25 Hz.

The difference between the impedance-frequency response for the first settling cycle and the subsequent cycles is evident for both OFFUTs. There is also a relatively close correlation between them, in the order of just 0.1-0.2 kHz maximum difference between the series resonance frequency for the transmitter to the receiver over all pressurization cycles. Notably, the maximum variation in local impedance minima for the transmitter and receiver after the initial settling cycle is (0.031±0.009) kHz. Also, this difference can change in magnitude depending on the vibration mode, but the critical point for application is that in subsequent cycles there is only very minor change in performance. This is observable in both impedance magnitude and resonance frequency, thus promising for practical implementation of this transducer configuration. Furthermore, the electrical performance correlates closely with the A-scans in terms of consistency in performance across multiple pressurization and depressurization cycles.

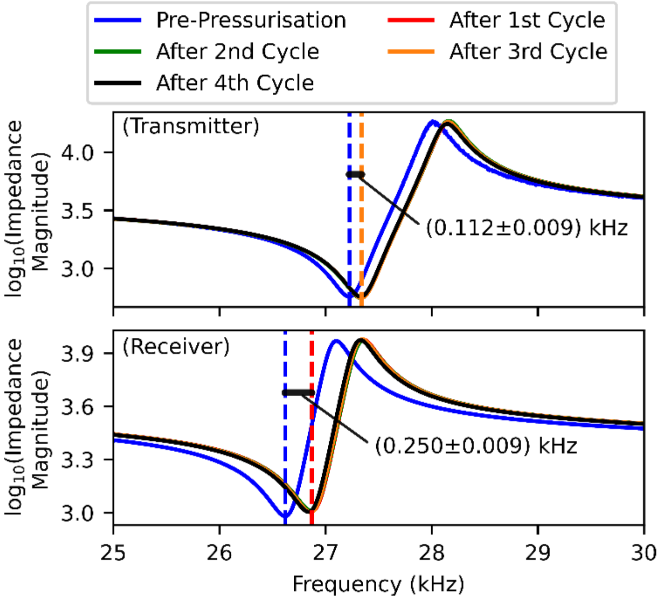

Fig. 9. Electrical impedance spectra for the OFFUTs after each pressurization and depressurization cycle, measured at 1 bar.

Cognizant of the unique shapes of the pulse envelopes for different environmental pressure levels, the peak-to-peak voltage magnitudes for successive cycles were then investigated, the results for which are shown in Fig. 10.

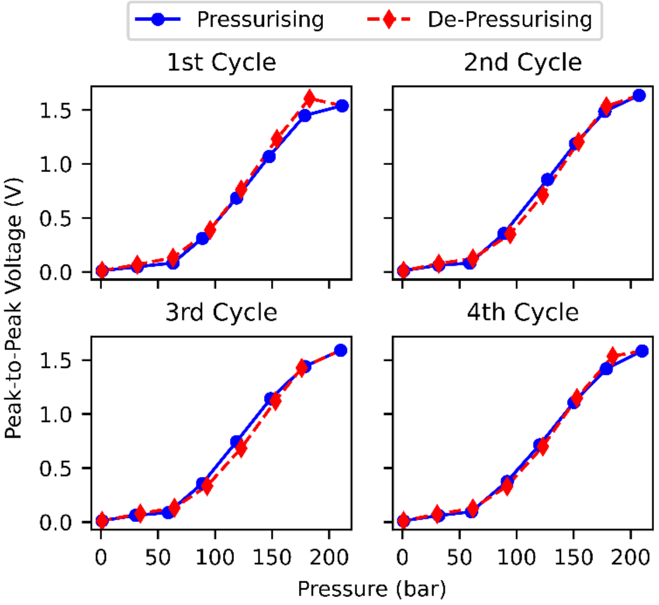

Fig. 10. Peak-to-peak voltage as a function of environmental pressure level across successive pressurization and depressurization cycles for the transmitter OFFUT propagating ultrasound to the receiver OFFUT.

As has been argued in prior research [27], peak-to-peak voltage measurements may not be an entirely accurate method for determining the effect of environmental pressure on the OFFUT's pitch-catch performance. The previously observed change in fundamental resonance frequency of the OFFUTs with pressure, in addition to the enhancement of higher order and more complex modal behaviour, mean that OFFUTs are not consistently driven at resonance over the entire pressurization and depressurization cycle. Hence, peak-to-peak voltage may not be an appropriate method to describe measurement performance over an individual cycle. However, this method does highlight the high level of consistency between both pressurization and depressurization steps in successive cycles, where there is little hysteresis and a general trend of repeatability in each case. Minor hysteretic effects are possibly attributed to the approximately 2°C variation in temperature over measurement cycles. The A-scan measurements in Fig. 8 demonstrated that unique pulse shapes can be a reliable indicator of environmental pressure level, but the voltage measurements shown in Fig. 10 indicate another dimension to the measurement capability of this system. Here, it is evident that voltage amplitude can also be used as an indicator of pressure level with reasonable accuracy, irrespective of whether a pressurization step or a depressurization step is employed, and accounting for the emergence of complex modal responses.

The final step of this study was the investigation of the effects of external pressure on the resonant behaviour of OFFUTs. Characteristic parameters of the transmitting OFFUT's resonant behaviour can be investigated by modelling its impulse response using a damped harmonic oscillator mechanical analogue. Here, the electromechanically coupled ringing caused by the cessation of the pulsed drive input is modelled in Fig. 11, using (1), for the damping coefficient a and resonant frequency f_0, where A is amplitude and ϕ is phase.

$$Ae^{-at}\sin\left(2\pi f_0 t+\phi\right) \tag{1}$$

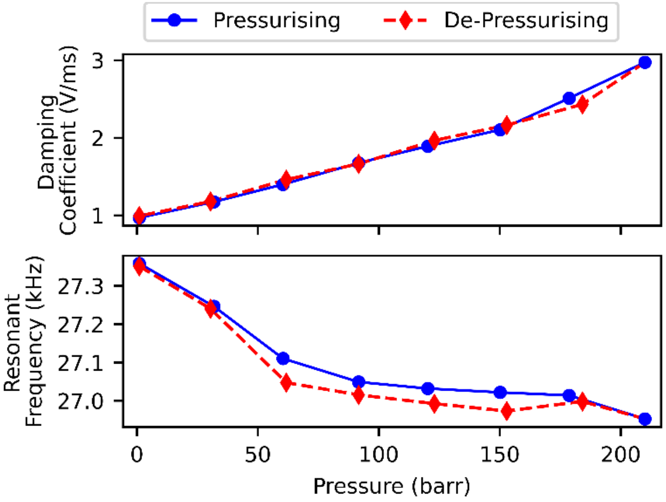

Fig. 11. Damping and fundamental resonance frequency of the transmitting OFFUT as a function of external pressure level.

The mechanical analogue model inherently assumes a single narrowband resonance in the OFFUT's impulse response and gives a reasonable approximation for the dominant fundamental (0,0) mode behaviour over a pressurization and depressurization cycle, independent of the input driving frequency. However, previous research has shown that the contribution of higher order modes to the OFFUT's harmonic response, and the complexity of its operating modes, increases at higher environmental pressures [27], meaning there are limitations in the accuracy of the single resonance fit at higher pressure levels. The results in Fig. 11 show the damping of the transmitting OFFUT's fundamental operating mode increasing almost linearly with the pressurization of the external environment. This implies that the OFFUT becomes more broadband at higher pressures and may increase its time resolution when performing pitch-catch ultrasound measurements. The shift in fundamental resonance frequency of the transmitter over a pressurization and depressurization cycle corroborates the EIA measured behaviour presented in prior publications [27] with a higher degree of measurement certainty, namely the slight decrease in the OFFUT's operating frequency with increased pressure. Furthermore, like some micromachined resonant pressure sensors [32], the results in Fig. 11 also introduce the possibility of using the change in the OFFUT's resonant frequency as an indicator or environmental pressure. Alongside pulse shape, this opens the possibility of simultaneous time-of-flight and pressure measurements using only an OFFUT system.

C. Summary of Findings

The results in this paper have shown for the first time the stability in the dynamic response of OFFUTs across successive pressurization and depressurization cycles from atmospheric 1 bar to those exceeding 200 bar. In addition to there being no observable physical deformation of the sensors, the potential of the OFFUT as a feasible configuration for industrial measurement applications in hostile environments of elevated pressure levels has been demonstrated.

This study has also shown the unique shapes of pulse envelope obtainable from relatively routine A-scan measurements, thus providing a new method of identifying environmental pressure level from the ultrasound signal inside a sealed vessel. The repeatability of this has been demonstrated for the first time, and there is real potential for its implementation in a variety of gas and liquid sensing and monitoring applications.

The settling phase of the OFFUT, or for a transducer incorporating a near-incompressible fluid as the primary mechanism for balancing the pressure external to the device, has been shown to exist in the first stage of pressurization, but then does not influence successive pressurization and depressurization cycles. This has been attributed to the physical equilibration of the transducer configuration to the designated range of environmental pressure levels.

The modal responses of the OFFUTs have also been studied in detail for the first time, with responses complemented by finite element analysis where relevant. Both the mode shape measurements and the comprehensive finite element simulations are novel contributions, which show the versatility of the sensor configuration for operation at different resonant conditions. An axisymmetric, (0,0) mode-like response has been detected in the OFFUT at two different frequencies, as shown through laser Doppler vibrometry and FEA. This is attributable to the influence of the silicone oil on the vibration response of the transducer plate.

Finally, the measurement and analysis of the transmitting OFFUT's resonant behaviour has shown for the first time that increased environmental pressure has an increased damping effect on the narrowband ringing of the device, slightly decreasing the OFFUT's fundamental resonance frequency.

In general, this study has taken the concept of the OFFUT a significant step forward by demonstrating several of its unique characteristic responses that showcase its potential for practical application, in a variety of gas and liquid sensing applications into the hundreds of bar of pressure. It is anticipated that future research will focus on the optimization of the sensor design, the trial of alternative plate configurations, and the investigation of performance in a range of hostile environments beyond those of elevated pressure.

IV. CONCLUSION

This research has demonstrated the measurement stability of the OFFUT, considering resonance frequency, electrical impedance, and vibration amplitude in particular, and its strong potential as a reliable industrial measurement sensor for in-situ proximity and pressure sensing in fluids towards the hundreds of bar pressure. In this study, stability in the dynamic performance of two OFFUTs was demonstrated across a series of pressurization and depressurization cycles, from atmospheric 1 bar beyond 200 bar. It has been observed that stable dynamic properties are achievable over at least four successive cycles of operation. Furthermore, received ultrasonic signal shapes unique to environmental pressure level have been measured, thereby showing the potential of the OFFUT as a dual proximity and pressure sensing device. This also means that parameters such as the damping ratio that quantify the shape of the waveform could be utilised to establish a direct relationship between waveform shape and actual pressure levels. This research has been supported by a comprehensive finite element simulation to investigate the modal response of the OFFUT in atmospheric and elevated pressure environments. It is anticipated that with the development of a suitable calibration routine, these results will enable the development of a range of sensors suitable for practical commercial applications.

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