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Measurement using flexural ultrasonic transducers in high pressure environments

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The flexural ultrasonic transducer comprises a metallic membrane to which an active element such as a piezoelectric ceramic is attached. The normal modes of the membrane are exploited to generate and receive the desired ultrasonic wave. Flexural ultrasonic transducers are popular due to their ability to couple to different media without requiring matching layers. There is growing demand for ultrasound measurement using flexural ultrasonic transducers in high pressure environments, such as in gas metering. However, their sealing increases the risk of transducer deformation as the pressure level is raised, due to pressure imbalance between the internal cavity of the transducer and the external environment. In this study, a novel form of flexural ultrasonic transducer for operation in high pressure environments, those above 100 bar, is shown alongside key measurement strategies. Different methods can be used to enable pressure equalization between the internal cavity and the external environment, one of which is venting and used in this study. Dynamic performance is monitored via pitch-catch ultrasound measurement in air up to 130 bar. The results suggest the suitability of the vented transducer for operation in high pressure environments compared to the classical flexural ultrasonic transducer, constituting a significant development in ultrasonic measurement.

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1. INTRODUCTION

The classical flexural ultrasonic transducer (FUT), the form of which has found popularity in a range of industrial applications such as proximity and flow measurement, is composed of a circumferentially-clamped metallic membrane to which an active element such as a piezoelectric ceramic is bonded through a sufficiently high-strength adhesive such as epoxy resin. The normal axisymmetric vibration modes of the membrane are exploited to generate the desired ultrasonic wave for either the generation or detection of ultrasound, or both using a single device in conjunction with appropriate electronics. These vibration modes are induced through the driving element, which in the case of this research is a piezoelectric ceramic disc. A relatively low voltage can be supplied to this piezoelectric ceramic disc which causes it to vibrate at a relatively high frequency, thereby inducing the vibration modes of the membrane. The vibration characteristics of the transducer are primarily dependent on the physical properties of the membrane. In particular, the modulus of elasticity and the density of the material and the diameter and thickness of the membrane directly influence the resonance frequencies and vibration amplitude. The ability to switch between axisymmetric modes is a key advantage of the transducer, albeit it is generally only designed for efficient operation at one of these vibration modes. A section-view schematic of the classical FUT and two fundamental axisymmetric operating modes which are typically utilized in practical application are illustrated in Fig. 1.

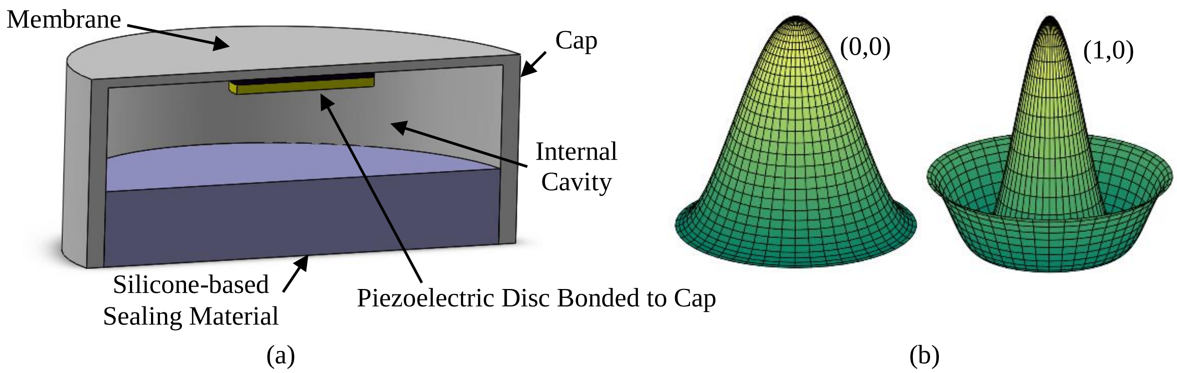


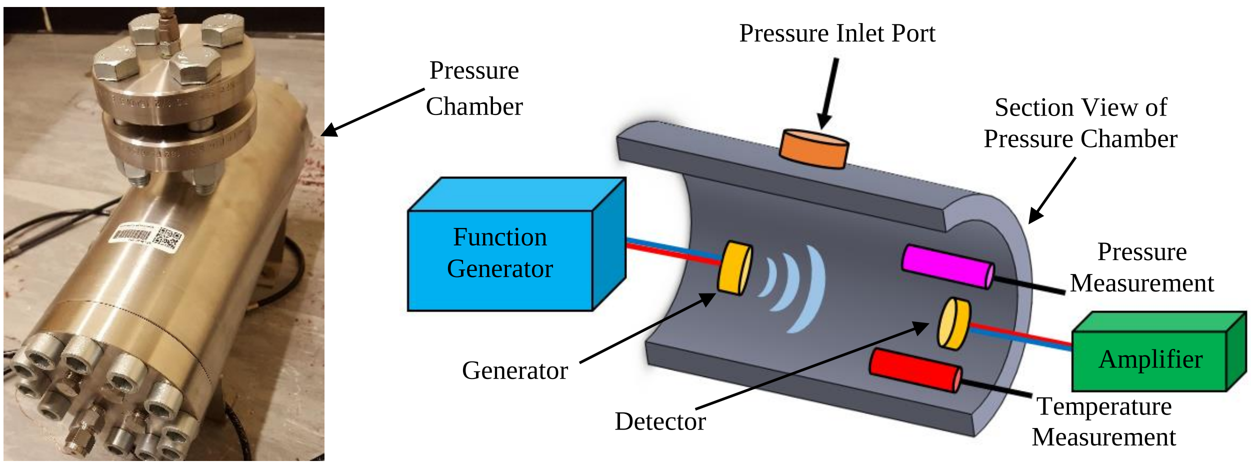
Figure 1. (a) Section-view schematic of the classical FUT and (b) its two commonly exploited fundamental operating modes, the (0,0) and (1,0) modes, mathematically simulated.

The FUT has traditionally been popular due to its relatively straightforward composition and ability to couple to different media without the need for matching layers[1], which is a limitation of a selection of other piezoelectric ultrasonic transducer configurations including types of piezoelectric micromachined ultrasonic transducer (PMUT). Although the FUT is commonly employed in industry, its wider application is limited by its unsuitability for operation in hostile environments, notably those characterized by high pressure levels. This is largely due to the sealing which is common in classical FUTs that creates a pressure imbalance between the internal cavity structure of the transducer and the external environment as the environmental pressure level is raised. The transducer structure is therefore susceptible to deformation at high pressure levels, such as those in gas and flow metering which can exceed 100 bar. This sealing is commonly fabricated using a silicone-type material. In order to widen the application potential of the FUT, it is essential to develop strategies for the design and operation of FUTs in high pressure environments, for accurate and reliable ultrasonic measurement in a diverse range of environmental conditions.

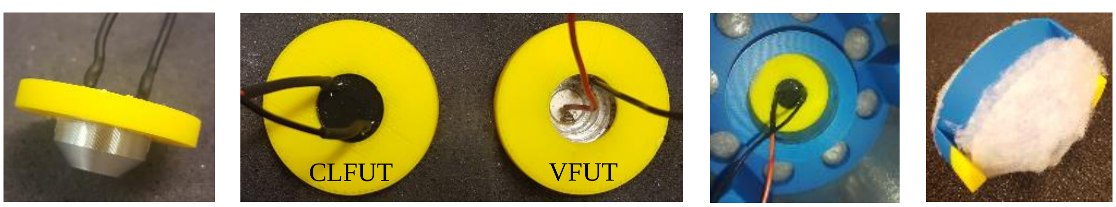
2. METHODOLOGY

Different strategies can be employed in the design and fabrication of FUTs for high pressure environments, such as modification to the geometry of the transducer, for example via a vent, to enable pressure equalization between the internal cavity of the FUT and the external environment. Another strategy can be the injection of an incompressible fluid such as oil into the internal cavity structure (patent applied for). In this study, a vented configuration of FUT is reported. Measurement is conducted through a pitch-catch setup, where the vented FUT (VFUT) is set as the detector of ultrasonic waves and a classical, aluminium-capped FUT (CLFUT, Multicomp) is configured as the generator, transmitting ultrasonic waves towards the detector VFUT. The membrane diameter for both the CLFUT and the VFUT is 10.0 ± 0.1 mm. Using fundamental analytical expressions[2], the resonance frequency is around 40 kHz in the (0,0) mode. Electrical impedance analysis (Agilent 4294A) and laser Doppler vibrometry (LDV, Polytec OFV-5000) are used for experimental verification, where electrical impedance analysis indicates resonance frequency via the frequency associated with a minimum in the measured electrical impedance around resonance, and LDV maps the vibration amplitude profile of the membrane to show the mode shape.

A custom pressure chamber is used as the measurement environment. The chamber is fabricated from stainless steel and constitutes a completely enclosed environment, making the accurate measurement of ultrasonic waves complicated unless certain measures are taken. This is because ultrasonic waves in such an environment will reflect from different surfaces and interfere with one another, and will hence make it difficult to determine dynamic performance with reliability. Suitable reflectors or acoustic absorbers must be used to reduce the influence of reflections on the signal measurement which can cause either constructive or destructive interference that severely affects measurement accuracy. Different absorber materials and acoustic baffles are tested as part of this study, and transducer performance under increasing environmental pressures from ambience towards 130 bar is investigated, where the CLFUT and VFUT are subjected to increasing pressure loading. The VFUT detects the ultrasonic waves from the CLFUT which are converted into voltages. The experimental setup is shown in Fig. 2 but for clarity without the reflecting and absorbing materials inside the chamber.



(a)



FUT Side View | Rear of Transducers In Holders | Rear of Flat Baffle | Conical Baffle

(b)

Figure 2. The measurement setup for investigation into FUT performance in high pressure environments, showing (a) the pressure chamber and the interface with the measurement setup, and (b) the configurations of the CLFUT and VFUT devices for testing in the pressure measurement setup, including different acoustic baffle designs.

A 2-cycle, 40 kHz burst sinusoidal signal is applied to the CLFUT at a nominal voltage of 20 V_{P-P}. The CLFUT emits periodic bursts of ultrasonic waves towards the VFUT whilst the environmental pressure inside the pressure chamber is incrementally increased. Output voltage measurements are obtained in air from ambience towards 130 bar, monitored with a ratiometric pressure sensor (Honeywell), in addition to temperature measurements from a thermocouple. Valuable information relating to ultrasound measurement in a pressurized chamber and the performance of different FUTs at high pressures can therefore be obtained.

3. RESULTS

The electrical impedance measurements and associated resonance frequencies are shown in Fig. 3(a) and were recorded, where indicated, with each transducer in a yellow acrylonitrile butadiene styrene (ABS) holder as shown in Fig. 2(b). The CLFUT and VFUT are both attached to this type of holder for insertion into the pressure chamber. These measurements were obtained in ambient room pressure and temperature conditions, and hence are used to define the configuration of the LDV mode shape measurement setup. Mode shapes measured using LDV are shown in Fig. 3(b) for a CLFUT and a VFUT.

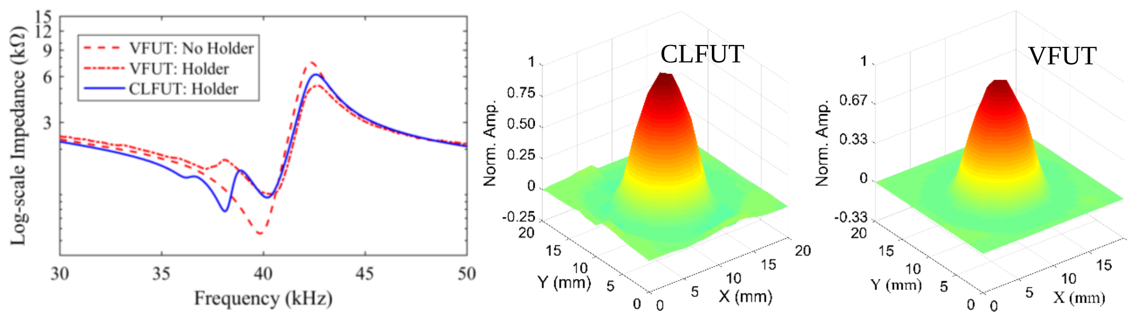


Figure 3. Dynamic characterization at room temperature and pressure, showing (a) impedance-frequency spectra, and (b) the normalized (0,0) operating modes of the CLFUT and a VFUT from LDV.

Clear differences exist in the electrical impedance spectra, shown in Fig. 3(a). Resonance frequency can be extracted through the location of minimum electrical impedance around resonance, but the inclusion of the holders has introduced changes in the electrical impedance spectra as shown in Fig. 3(a). The identification of resonance is therefore not trivial. Regardless, there can be differences in the dynamic characteristics between nominally identical FUTs[3], and the resonance frequencies for the transducers are in relatively close proximity. A wideband signal such as that used in this study is useful for pitch-catch ultrasound measurement between two transducers with slightly unequal dynamic properties. The (0,0) mode shapes of both the CLFUT and VFUT designs are clear through the amplitude maps displayed in Fig. 3(b), and exhibit a strong similarity with one another, showing the capacity of each transducer design to generate the desired (0,0) mode shape.

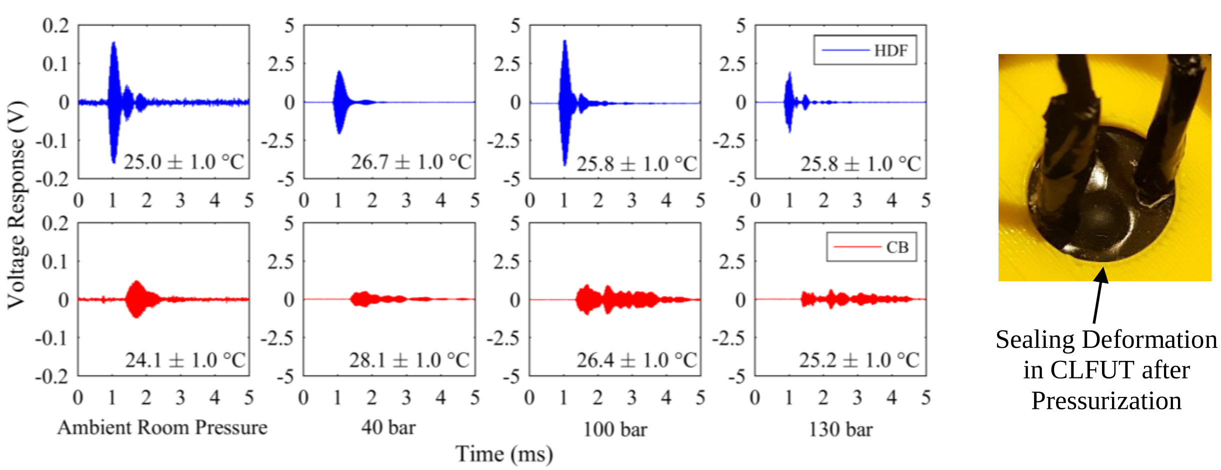


Figure 4. Voltage response as a function of time at different environmental pressure levels in air for the CLFUT-VFUT pitch-catch configuration for two reflector strategies, HDF and CB, with temperature data.

Pitch-catch ultrasound measurement in the form of voltage response as a function of environmental pressure level was then undertaken by first considering the influence of the reflecting and absorbing media inside the chamber. Reflections are significant within the chamber and can be mitigated with different absorbing materials. However, the acoustic properties of these materials may change with pressure and temperature. Reflections can be produced from the inside faces of the removable panels through which all cabling is passed via sealing glands, the chamber inner wall, and the acoustic baffles and holders which support the transducers in place. The holder and acoustic baffle configuration for each transducer is fabricated from ABS, with an example shown in Fig. 2(b). Voltage-time spectra at different environmental pressure levels are shown in Fig. 4 for two reflector configurations, a high density foam (HDF) fixed along the chamber inner wall in front of a flat acoustic baffle as shown in Fig. 2(b), and a conical baffle (CB) encasing each transducer with a foam of lower density, also displayed in Fig. 2(b), situated in front of another flat acoustic baffle. The signals are detected at different times for HDF and CB due to differences in measurement distance.

The results indicate that the HDF strategy mitigates reflections more effectively than CB, but there are still reflections at high pressure levels causing interference which can be reduced. It is likely that these reflections are a consequence of changes in the acoustic properties of the air, and also because neither HDF nor CB creates a completely anechoic measurement environment as shown in this study. Although it is clear that further research into the performance of different reflectors or absorbing materials is essential, there is a notable improvement in the general quality of the measurement signal using the HDF strategy.

The deformation in the sealing of the CLFUT is evident as shown in Fig. 4, whereas no significant deformation is observable in the VFUT. The peak voltage magnitudes measured using the HDF strategy increase towards 100 bar and then decrease as shown by the measurement data at an environmental pressure level around 130 bar. One reason for this could be that as the CLFUT experiences deformation, its rigidity and boundary condition are directly affected, influencing its dynamic response. This phenomenon is difficult to predict and therefore shows the unsuitability of the CLFUT for practical industrial application at high pressure levels. The results suggest a higher tolerance of the VFUT to increasing environmental pressure levels compared to the CLFUT. However, a more robust test configuration is vital, and there are complications arising from the vented design. For example, the temporally longer decay under burst excitation conditions causes a ringing of the transducer membrane. An adapted backing layer would be a viable solution to prevent the influence of this ringing on the accurate measurement of ultrasound inside the pressure chamber. The nature of transducer dynamics at relatively high pressure levels also remains relatively unexplored, and the development of alternative FUT configurations is required for application in a range of environmental conditions. This research constitutes a fundamental and important development in ultrasound measurement.

4. CONCLUSION

A novel strategy for ultrasound measurement at high pressure levels using the FUT has been presented. The FUT can already be operated effectively in different fluids, including liquid and gas, since it can couple efficiently to different media. In this research, the performance of a classical FUT was used in pitch-catch with one modified for operation in high pressure environments, the vented FUT, using air as the environmental medium. The results show the susceptibility of the classical FUT to deformation at high pressure levels for which the vented transducer is designed. The vented design allows the equalization of pressure on either side of the membrane, thereby improving robustness at higher pressure levels. The results also show the effectiveness of high density foam in mitigating interference in the test environment. Further research will focus on improving transducer robustness and measurement techniques, and alternative designs of transducer for operation in high pressure environments.

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

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