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Flexural Ultrasonic Transducers with Nonmetallic Membranes

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***Abstract*— The flexural ultrasonic transducer is a sensor primarily composed of a circular metallic membrane, to which a piezoelectric ceramic disc is bonded. The vibrations generated from the piezoelectric ceramic stimulate plate modes in the membrane, thereby generating ultrasound waves. FUTs are typically utilized for industrial and proximity measurement, but there has been growing research activity in recent years focusing on alternative applications, such as those requiring elevated pressure and temperature. The membrane of the FUT remains limited to circular metallic configurations, but there are opportunities for more complex and targeted ultrasound responses if the physical properties and shape of the membrane can be manipulated. These can include focused ultrasound beams, enhanced bandwidth, and the generation of higher order modes at desirable frequencies for measurement. The aim of this study is to investigate the viability of using nonmetallic materials such as acrylics, including through 3D printing, to tailor membrane design, and thus FUT dynamics.**

Keywords* — *FUT, circular metallic membrane, plate modes nonmetallic materials, acrylics, dynamics

I. INTRODUCTION

The field of ultrasonics is an important area regarding engineering applications to the real world, encompassing proximity sensing in robotics, industrial metrology, and automotive car parking sensors [1], [2]. Industrial measurement applications incorporating ultrasound measurement techniques have been widely researched for years and have led to the development of several classes of transducers for industrial use. One was the design of micromachined transducers, including the piezoelectric micromachined ultrasonic transducer (PMUT) and the capacitive micromachined ultrasonic transducer (CMUT), capable of producing a wide frequency bandwidth at higher frequencies [3], [4] with reliable air coupled performance.

More recently, the flexural ultrasonic transducer (FUT) has emerged as a novel approach to air-coupled sensing [2], [3], removing the need for matching layers normally required for a PMUT, or high biasing voltages needed to drive a CMUT. The traditional FUT is composed of a circular metallic membrane with a piezoelectric ceramic disc bonded underneath, and is predominantly used for proximity sensing and in flow measurement [1] – [3]. The vibrations generated from the piezoelectric ceramic in response to low voltage inputs stimulate plate modes in the membrane, thereby generating ultrasound waves. Key features of the FUT are presented in Fig. 1.

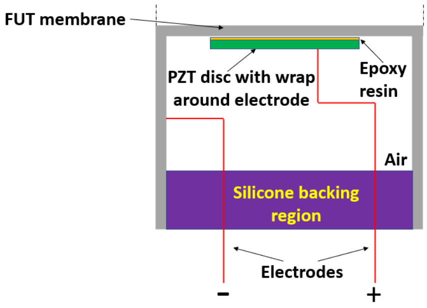


Fig. 1. Typical schematic of a conventional FUT.

There has been significant research into the dynamics of the traditional FUT [2], [5] but in terms of commercially available transducers, the scope of the technology is effectively limited by the reliance on circular metallic membranes, which restricts the attainable dynamic properties of these sensors. This has prompted new research into methods of enhancing dynamic characteristics of FUTs via geometrical or material means to tailor device dynamics. The membrane of the FUT remains limited to circular metallic configurations, but there are opportunities for more complex and targeted ultrasound responses if the physical properties and shape of the membrane can be manipulated. These can include focused ultrasound beams, enhanced bandwidth, and the generation of higher order modes at desirable frequencies for measurement.

In general, the FUT requires relatively low voltages to operate, and from the commercial perspective are typically composed of aluminium, with a fundamental resonance frequency in the (0,0) axisymmetric mode of vibration around 40 kHz [3]. Currently, there has been little progress into varying membrane shapes or integrating alternative nonmetallic membrane materials into the FUT to enhance key dynamic properties including bandwidth. In this research, an acrylic polymethyl methyl acrylate (PMMA) membrane was used with a 3D printed ABS (acrylonitrile butadiene styrene) housing to realise a FUT concept with broader bandwidth than potential metallic-based equivalents. The potential of this research is the rapid prototyping of FUTs with enhanced dynamics compared to commercial equivalents, able to be incorporated into a wide range of industrial measurement applications.

II. METHODOLOGY

First, finite element analysis (FEA) was used to generate two FUT concepts, one based on PMMA and the other on aluminium, to allow for some comparison between transducers of equivalent size. FEA was used to estimate the resonance frequency of the (0,0) mode in each case, and provide an indicator of bandwidth and directivity. For this, OnScale Solve was adopted for generating a 2D axisymmetric representative model of the outlined devices, where the material properties of the FUTs are shown in Table I.

Table I. FUT membrane properties.

Properties	Membrane Material	
	Acrylic PMMA	*Aluminium*
Diameter (mm)	15	15
Thickness (mm)	3.1	3.1
Density (kg.m^{-3})	1190	2700
Young's Modulus (GPa)	2.9	69
Poisson's Ratio	0.37	0.33
Mode of Vibration	(0,0)	(0,0)
Predicted (0,0) Modal Frequency (kHz)	43.467	138.530

PMMA was used for FUT design with a Young's modulus of 2.9 GPa [6], chosen for tailoring the FUT to a suitable frequency in the low ultrasonic frequency range. Leissa's plate theory [7] was used as a preliminary measure to identify a suitable membrane thickness and diameter for the transducer. The transverse displacement (w) of the cap membrane can be determined through the differential equation (1), in terms of rigidity (D), radius (x), membrane thickness (h), and cap with material density (ρ).

$$D\nabla^4 w(\vec{x},t) + \rho\frac{\partial^2 w(\vec{x},t)}{\partial t^2} = 0 \tag{1}$$

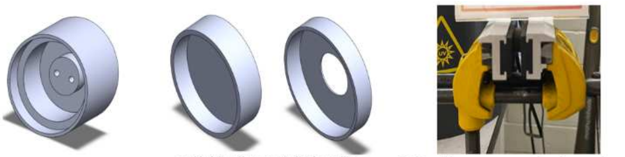
In addition to this, the rigidity of the membrane can be calculated by (2), where E is the Young's Modulus and υ is the Poisson's ratio.

$$D = \frac{Eh^3}{12(1-\upsilon^2)} \tag{2}$$

Finally, to predict the resonance frequencies of the membrane, (3) can be used in which λ represents a Bessel function constant relating to the mode shape of the device and a is the cap radius for the condition x=a.

$$f_{m,n} = \frac{\lambda_{m,n}^2}{2\pi a^2}\sqrt{\frac{Eh^3}{12(1-\upsilon^2)\rho}} \tag{3}$$

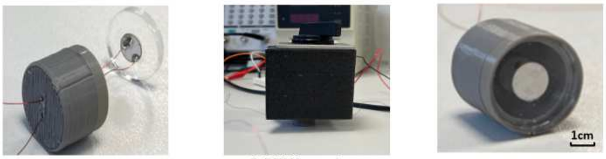
The relationships (1)-(3) allow the modal frequencies of an edge-clamped plate to be predicted, which is postulated to be equivalent to the membrane of a FUT, since the piezoelectric ceramic disc in a FUT together forms a compound structure with the membrane [5]. The predicted frequencies using this approach for the two FUT concepts are included in Table I, and it should be noted that these are estimates for an edge-clamped plate and only used as a guideline for FUT design. The next step was the fabrication of a PMMA-based FUT, by following the process illustrated in Fig. 2.



1. FUT housing created

2. Holder for centrally bonding piezoceramic to membrane

3. Bonding process using foam clamps



4. Wires soldered to PZT-5H piezoceramic

5. PMMA membrane bonded to housing

6. PMMA FUT

Fig. 2. PMMA FUT fabrication process.

The PMMA FUT was fabricated using the following process. First, the geometric and material specifications used to generate the FEA simulations were used to print a FUT housing, using ABS (Replicator+ Desktop 3D Printer, MakerBot), as shown by Step 1 in Fig. 2. The FUT membrane was cut from PMMA sheet to the appropriate size as indicated in Table I, and a suitable epoxy resin (Ablestik 45, Henkel Loctite) was procured to bond the components together. A piezoelectric ceramic disc with a silver wrapped electrode was selected for the FUT, being a soft PZT-5H type consistent with most FUT designs (PIC255, PI Ceramic GmbH). Soft ceramics are particularly well suited for sensing applications.

A holder for centrally aligning the piezoelectric ceramic disc to the PMMA membrane was designed using computer aided design software (SolidWorks), as shown by Step 2, before the PMMA membrane and piezoelectric ceramic disc were bonded together using the epoxy resin in a clamp fixture for 24 hours, depicted in Step 3. Once this step was completed, wires were soldered to the electrodes of the piezoelectric ceramic, before the PMMA membrane with piezoelectric ceramic attached was bonded to the ABS housing, as illustrated through Steps 4 and 5 respectively. This constitutes the fabrication process for the PMMA FUT, where the completed transducer is shown in Step 6.

FUTs are designed to operate at a particular mode of vibration, which in this case was the axisymmetric (0,0) mode. To capture and measure the resonance frequency and mode shape of interest, a combination of electrical Impedance Analysis (EIA, Agilent 4294A Precision Impedance Analyzer, Keysight Technologies, CA, USA) and laser Doppler vibrometry (LDV, MSA-100-3D, Polytec GmbH, Waldbronn, Germany) was employed. Here, the series resonance frequency was measured using EIA, before the mode shape was determined using LDV. A scan range of 0 – 62.5 kHz was used to capture the mode shape data, with a 5 V sinusoidal burst signal and 401 points. The final characterisation step was to use an acoustic microphone (GRAS 46DP-1 1/8" LEMO Pressure Standard Microphone Set, GRAS Sound and Vibration, Holte, Denmark) to capture amplitude-time spectra and radiation pattern responses. The experimental acoustic microphone setup is shown in Fig. 3.

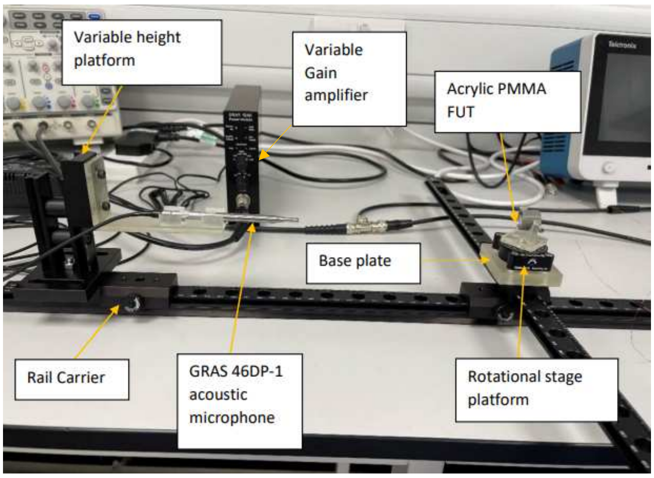


Fig. 3. GRAS 46DP-1 acoustic microphone experimental apparatus used to obtain radiation pattern, voltage-time spectra and acoustic bandwidth for the PMMA FUT.

It should be noted that only the PMMA FUT was constructed, from the information shown in Table I. This is because an aluminium FUT with a 3.1 mm thick membrane would be impractical for generating sufficiently high vibration amplitudes, and thus shows the versatility of using nonmetallic membrane materials of lower density.

III. RESULTS AND DISCUSSION

Here, the EIA results are presented first to allow a comparison of the mode shape extracted using LDV with that predicted using FEA. The electrical impedance as a function of frequency is shown in Fig. 4, alongside the phase relationship with frequency.

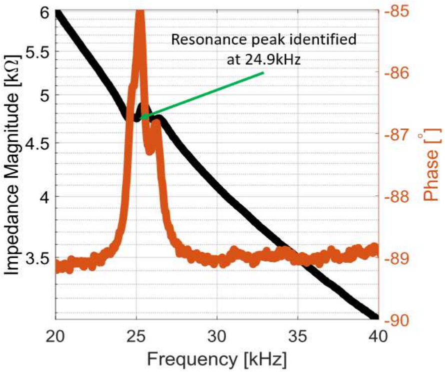


Fig. 4. Electrical impedance analysis where the series resonance frequency for the PMMA FUT is determined to be at 24.9 kHz.

The series resonance frequency was identified at 24.9 kHz. This value is lower than the predicted 43.5 kHz using an edge clamped plate approximation as shown in Table I. However, this suggests that the material properties (particularly the Young's modulus and Poisson's ratio) used to estimate the resonance frequency for the (0,0) mode are not quite accurate. It is also true that the edge clamped plate, whilst a useful indicator of FUT dynamics, is not a comprehensive finite element mathematical model, and its application requires careful consideration.

Next, LDV was undertaken around the resonance frequency identified using EIA, to identify the mode shape. In Fig. 5(a), a mathematically generated representation of the (0,0) mode shape is depicted, using arbitrary parameters. This is the physical deformation of the FUT membrane at resonance. Using FEA, the PMMA FUT was simulated by driving with a wideband signal at 200 kHz with 4 cycles, thereby generating the first modal frequency. This was found to be 25.9 kHz, which closely correlates with the EIA result. The (0,0) mode shape was then identified by simulating the PMMA FUT model to operate at 25 kHz at 300 cycles, thereby generating a (0,0) mode shape consistent with the mathematical representation shown in Fig. 5(a). This result is shown in Fig. 5(b). Finally, the experimentally measured (0,0) mode shape, obtained using LDV, is shown in Fig. 5(c).

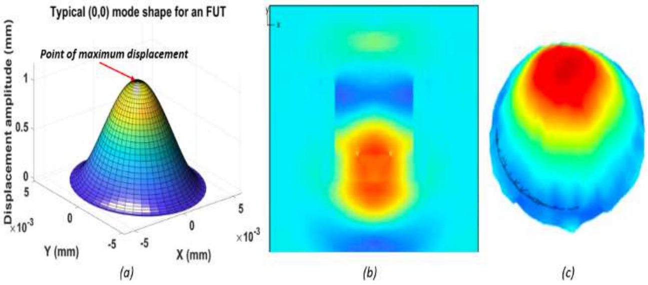


Fig. 5. (a) A typical (0,0) mode shape using Leissa's plate theory; (b) the (0,0) mode at 25.9 kHz from FEA; and (c) the (0,0) mode at 25.9 kHz using LDV.

There is high confidence in the design process of a FUT fabricated using a nonmetallic material for the membrane. There is close correlation between experimental and numerical methods (EIA and LDV with FEA), and both the limitations and the benefits of the Leissa approach are understood. The final step in the experimental process was to generate amplitude responses using the PMMA FUT for measurement with the acoustic microphone. The parameters used to perform the microphone experiments are shown in Table II.

Table II. Parameters used for microphone measurements.

Signal Properties	**Experiment**	
	Resonance measurement	***Radiation pattern measurement***
Drive Frequency (kHz)	24.9	24.9
Voltage Amplitude (V)	10	10
Cycles	50	50
Trigger Interval (ms)	1	1
Trigger Delay (ms)	10	10
Amplifier Gain (dB)	40	50
Averaging	16	16

The voltage time response of the FUT driven using the resonance measurement parameters detailed in Table II are shown in Fig. 6(a), and the radiation pattern of the FUT measured by driving the FUT at 24.9 kHz around a 180° angle is shown in Fig. 6(b).

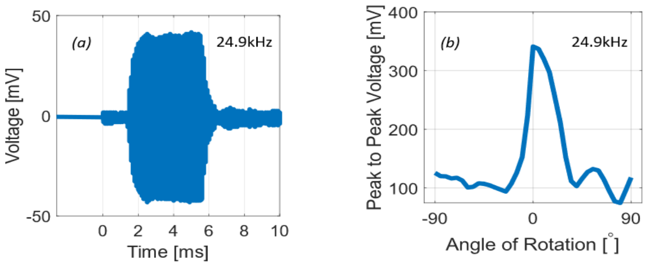


Fig. 6. (a) Voltage-time spectrum; and (b) the radiation pattern obtained over 180° for the PMMA FUT.

First, the purpose of driving the FUT to generate a voltage-time response as shown in Fig. 6(a) is to identify a signal with characteristics suitable for practical industrial ultrasound measurement. It also demonstrates that the FUT is being operated close to resonance, as there is little overshoot at steady state [5]. The radiation pattern shown in Fig. 6(b) has a sharp directional response, with little evidence of significant side-lobes. This presents interesting opportunities for future FUT concepts using nonmetallic membranes, and merits further investigation. In comparison, other studies focusing on metallic membranes report relatively wide radiation patterns [3].

In the final step, the bandwidth of the PMMA FUT was determined using the 3-dB approach. For this part of the study, FEA was used to simulate the aluminium FUT with a 3.1 mm thick membrane as comparison, using the dimensions shown in Table I. The bandwidth calculations are shown in Fig. 7, where the experimentally obtained bandwidth for the PMMA FUT is also provided.

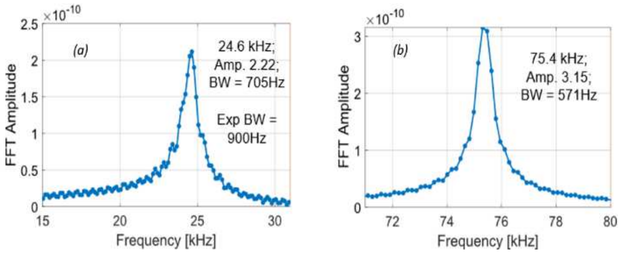


Fig. 7. Acoustic bandwidth data for (a) the PMMA FUT through FEA and by experiment; and (b) the aluminium FUT through FEA.

The acoustic bandwidth of the PMMA FUT was calculated to be 900 Hz using the acoustic microphone. This compared well with the simulated acoustic bandwidth of 705 Hz. By comparison, the acoustic bandwidth of the equivalent aluminium based FUT was calculated to be 571 Hz, but for a (0,0) modal frequency significantly higher, around 75 kHz.

The major implication of the acoustic bandwidth results is that a significantly wider bandwidth appears to be achievable using a nonmetallic membrane compared for a FUT of equivalent size used in air coupled applications. From the FEA results only, the PMMA FUT was calculated to have a bandwidth of 2.87% of the resonance frequency, whereas the aluminium FUT was calculated to have a bandwidth of 0.76% of the resonance frequency. It is evident that the PMMA FUT has a higher bandwidth than the metallic based equivalent.

It is notable that FUTs with membranes are typically no thicker than 0.5 mm, but the evidence here is that FUTs fabricated with nonmetallic membranes that are 6 times thicker can show practical dynamic characteristics for industrial measurement. This limit may be higher using other materials. Furthermore, nonmetallic membranes appear to offer advantages of wide bandwidth, the potential for directional responses, all combined with rapid and cost-effective manufacture. There is hence promising possibility of further optimising the bandwidth of the PMMA FUT, as the membrane thickness used here was 3.1 mm.

IV. CONCLUSION

This study has demonstrated a FUT fabricated using a nonmetallic PMMA membrane, demonstrating enhanced bandwidth, directional ultrasound wave propagation, and practical dynamic characteristics, in comparison to a metallic aluminium FUT of equivalent dimensions. Further work includes investigating nonmetallic membrane designs, to determine if bandwidth can be greatly increased compared to devices used currently in industry. Fundamentally, new avenues are open for fabricating complex membrane configurations to suit a wide range of industrial measurement applications.

ACKNOWLEDGEMENT

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