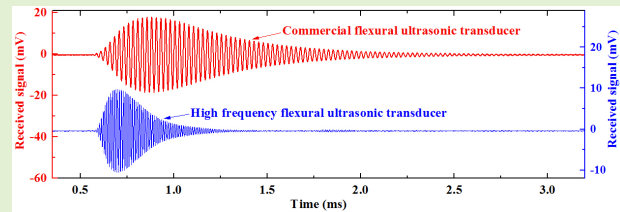


# The High Frequency Flexural Ultrasonic Transducer for Transmitting and Receiving Ultrasound in Air

Lei Kang<sup>1</sup>, Andrew Feeney<sup>1</sup>, and Steve Dixon<sup>1</sup>

**Abstract**—Flexural ultrasonic transducers are robust and low cost sensors that are typically used in industry for distance ranging, proximity sensing and flow measurement. The operating frequencies of currently available commercial flexural ultrasonic transducers are usually below 50 kHz. Higher operating frequencies would be particularly beneficial for measurement accuracy and detection sensitivity. In this paper, design principles of High Frequency Flexural Ultrasonic Transducers (HiFFUTs), guided by the classical plate theory and finite element analysis, are reported. The results show that the diameter of the piezoelectric disc element attached to the flexing plate of the HiFFUT has a significant influence on the transducer's resonant frequency, and that an optimal diameter for a HiFFUT transmitter alone is different from that for a pitch-catch ultrasonic system consisting of both a HiFFUT transmitter and a receiver. By adopting an optimal piezoelectric diameter, the HiFFUT pitch-catch system can produce an ultrasonic signal amplitude greater than that of a non-optimised system by an order of magnitude. The performance of a prototype HiFFUT is characterised through electrical impedance analysis, laser Doppler vibrometry, and pressure-field microphone measurement, before the performance of two new HiFFUTs in a pitch-catch configuration is compared with that of commercial transducers. The prototype HiFFUT can operate efficiently at a frequency of 102.1 kHz as either a transmitter or a receiver, with comparable output amplitude, wider bandwidth, and higher directivity than commercially available transducers of similar construction.

**Index Terms**—Air-coupled ultrasonic transducer, finite element analysis, flexural ultrasonic transducer, ultrasonic measurement.



## I. INTRODUCTION

AIR-COUPLED ultrasonic transducers operating as either transmitters, receivers or transceivers have found many applications in fields such as robotics, automotive, communication, haptics, particle manipulation, flow measurement, and non-destructive testing and evaluation [1]–[12]. The parameters of an ultrasonic measurement system such as transduction efficiency, operating frequency, bandwidth, directivity, operating voltage (or current), and power consumption are all underpinned by the performance of the ultrasonic transducers. For air-coupled ultrasonic transducers that operate via the through thickness or radial resonant mode of a piezoelectric disc, a significant limitation is the mismatch of acoustic

impedance between the transducer and gas, which can be improved to some extent by attaching an acoustic matching layer to the piezoelectric ceramic disc [13]. Micromachining techniques have been introduced to develop MEMS-based array transducers achieving good control of the acoustic radiation patterns [14], [15], with relatively high intensity such as Capacitive Micromachined Ultrasonic Transducers (CMUTs) [15]. Active films exhibiting low acoustic impedance, such as polyvinylidene fluoride (PVDF) piezoelectric film, scandium-doped aluminium nitride (ScAlN) film and electromechanical film (EMFi), have also been adopted for ultrasonic transducers in order to achieve better acoustic coupling between the transducer and air [16], [17]. More recently, wideband electromagnetic dynamic acoustic transducers and piezoelectric composite transducers have been developed which can couple directly to the air without the need for matching layers [18], [19].

Among various air-coupled ultrasonic transducers, the flexural ultrasonic transducer (FUT) is the most prolific transducer, primarily due to its use as car parking sensor. The FUT consists of a piezoelectric ceramic disc bonded to the underside of an elastic plate with epoxy adhesive. The FUT operates by vibrating at one of the resonant modes of the

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plate-piezoelectric disc composite structure, with a relatively high transduction efficiency at low power and low voltage (<10 V) excitation. The simple structure is easy to manufacture, resulting in a low cost, mechanically robust transducer [20]–[29]. One of the principal limitations of the FUT has been the assumption that operating frequency is generally limited to below 50 kHz, with the most common operation frequency for commercially available FUTs being 40 kHz [21]. Higher operating frequencies can be beneficial for an ultrasonic measurement system [8], [20], [21], where a shorter wavelength can provide improvements in measurement accuracy and detection sensitivity. FUTs can be driven by exciting the piezoelectric disc at a resonant frequency using a tone burst signal or a suitable broadband signal that will result in the composite structure of the FUT vibrating at the desired resonant frequency. Measurements can be made in either a pitch-catch type arrangement using two FUTs or in a pulse-echo configuration using a single FUT transceiver. Whilst the response of a FUT depends on how it is driven and its vibration decay characteristics, in general a higher frequency device will produce an ultrasonic wave pulse that is temporally shorter. This is advantageous in the separation of multiple coexisting ultrasonic signals with marginally different times of flight.

The characteristics of FUTs have been investigated in detail, including their dynamic nonlinearity and electromechanical behaviour [22]–[25], and their resonant characteristics when operating in different modes of vibration, through both simulation and experiments [20], [21]. Commercial 40 kHz devices can be used to generate and receive ultrasound at frequencies higher than 300 kHz, once their behavior is understood [21]. As expected, the amplitude of the higher frequency ultrasonic waves generated by the FUT and the amplitude of the received ultrasonic signal are significantly lower than those measured at the nominal operation frequency of 40 kHz [21]. In addition to the transducer's response leading to lower amplitude detection signals and wave generation, the acoustic damping coefficients of air are approximately proportional to the second power of the frequency of the ultrasonic wave [30], making higher frequency operation challenging. One approach that has been used to increase signal amplitude with FUTs at higher frequencies has been to use flexural ultrasonic array transducers [26]–[28]. However, many applications require smaller, individual transducers with good sensitivity, and so a systematic approach is used in the development of a high frequency FUT (HiFFUT).

## II. DESIGN METHODOLOGY

A FUT essentially consists of a piezoelectric ceramic disc adhesively bonded to a cap or an elastic plate, and a pair of conductive wires, as shown in Fig. 1. The front face of the cap can be considered as an edge-clamped-like elastic plate. This plate, which is generally below 1 mm in thickness, vibrates in a flexural motion at its resonant modes upon mechanical excitation. The FUT is capable of operating effectively in gas or liquid. Mechanical excitation is provided by applying a time varying voltage to the piezoelectric disc as shown in Fig. 1, inducing mechanical vibrations of the plate. As a detector the plate vibrates strongly at its resonant frequency,

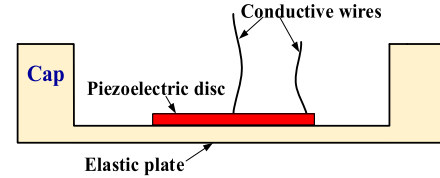


Fig. 1. A typical cross-sectional diagram of a flexural ultrasonic transducer.

bending the piezoelectric disc and inducing a time varying voltage across its electrodes. In practice, the piezoelectric disc and the wires can be protected in a sealed cavity formed by the side wall of the cap and flexible sealant [21], or a rigid backplate [26].

The resonant vibration modes of the elastic plate can be quantitatively estimated utilising classical plate theory [31]. For an edge-clamped circular plate, its time-dependent out-of-plane displacement is governed by a fourth-order partial differential equation [31], as shown by (1).

$$\frac{Eh^3}{12(1-\nu^2)} \times \nabla^4 w + \rho \frac{\partial^2 w}{\partial t^2} = 0 \quad (1)$$

where  $E$  is Young's modulus,  $h$  is the thickness of the plate,  $\nu$  is Poisson's ratio,  $w$  is the out-of-plane displacement,  $\rho$  is the volume density and  $t$  represents time.

Where the origin of a polar coordinate system coincides with the centre of the circular plate, the mode shapes  $W_{m,n}$  of the resonant vibration of the plate can be obtained by solving (1), and are given by (2).

$$W_{m,n}(r, \theta) = \left[ A_n I_n \left( \frac{\lambda_{m,n} r}{a} \right) + B_n J_n \left( \frac{\lambda_{m,n} r}{a} \right) \right] \cos(n\theta) \quad (2)$$

In (2),  $m$  denotes nodal circles (excluding the boundary circle),  $n$  denotes nodal diameters,  $r$  is the radial distance,  $\theta$  is the polar angle of the polar coordinate system,  $A_n$  and  $B_n$  are constants determined by the boundary conditions,  $I_n$  is the Bessel functions of the first kind and  $J_n$  is the modified Bessel functions of the first kind,  $a$  is the plate radius, and  $\lambda_{m,n}$  is the mode constant for the  $(m, n)$  mode. The corresponding modal frequencies  $f_{m,n}$  are given by (3).

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

Through (1) to (3), it is evident that there are infinite resonant modes for a given edge-clamped circular plate, and these equations have been utilised to provide an expedient estimation of the lower modal frequencies and mode shapes of a FUT [20]. The mode shapes of the two fundamental resonant modes, (0,0) and (1,0) modes can be mathematically determined based on (2), and are shown in Fig. 2. These two modes are most commonly exploited by commercial FUTs, due to the axisymmetric features of their mode shapes and radiation patterns and their relatively high vibration amplitudes, but the operating frequencies of the commercial FUTs are generally around 40 kHz [22].

Although the analytical solutions used to produce the mode shapes shown in Fig. 2 are useful for estimating the resonant characteristics of FUTs, they do not consider

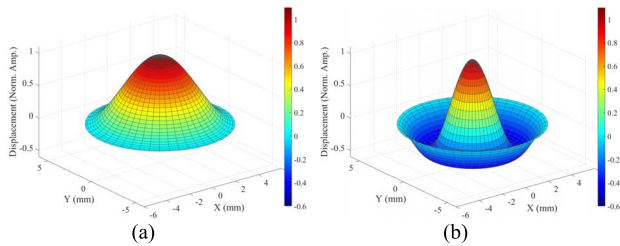


Fig. 2. Mode shapes of the two fundamental axisymmetric resonant vibration modes of an edge-clamped circular plate, showing (a) the (0,0) mode, and (b) the (1,0) mode.

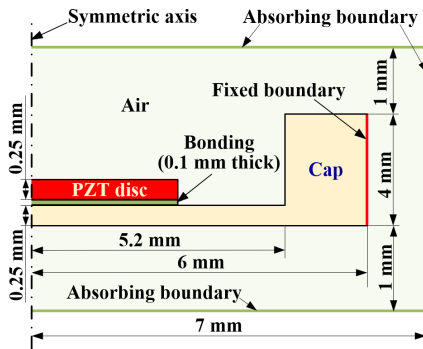


Fig. 3. Schematic of an axisymmetric model of a FUT, where the dimension scales have been adjusted for clarity.

the piezoelectric ceramic disc bonded to the elastic plate. The plate-piezoelectric composite vibrates as a single entity, where the resultant mechanical resonant vibration of the FUT is directly affected by the physical properties and the dimensions of all the components of the composite plate. The analytical solutions described in (2) do not account for this. In order to quantify the influence of the piezoelectric disc and design a HiFFUT with improved transduction efficiency, a three-dimensional axisymmetric finite element (FE) model for a FUT transmitter is developed using PZFlex®FE software, as illustrated in Fig. 3.

The strategy for designing a HiFFUT starts with a transducer diameter that is practical and a plate thickness and diameter that produces a mechanically robust transducer. Titanium was selected as the cap material based on its favourable properties [20], and a cap design was used as the basis of the modelling process. The inner diameter of the cap is 10.4 mm, the outer diameter is 12 mm, the thickness of the elastic plate (titanium plate) is 0.25 mm and the height of the cap is 4 mm. The simple analytical edge clamped plate model for this transducer predicts resonant frequencies of approximately 23.2 kHz for the (0,0) mode and 90.4 kHz for the (1,0) mode. Preliminary experiments and modelling have shown that the addition of the bonded piezoelectric disc tends to shift these frequencies. As a frequency of operation greater than 40 kHz was desired, this work focused on exciting the HiFFUTs operating in the (1,0) mode.

Thin piezoelectric discs (PZT-5H, PI Ceramic) with a thickness of 0.25 mm have been utilised in our previous FUT research [20, 26, 28], and are therefore chosen for this study. PZT discs of different diameters were modelled with a fixed thickness of 0.25 mm, bonded to the inside of the cap with a 0.1 mm thick layer of epoxy adhesive (Araldite 2014-1).

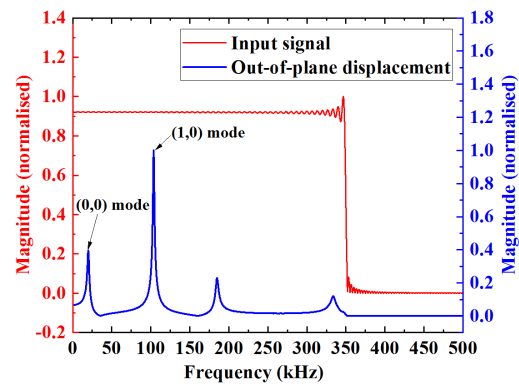


Fig. 4. Frequency response of a FUT with a 5 mm diameter piezoelectric ceramic disc through finite element analysis, showing the frequency spectrum of the transducer driving signal (red), and the resultant frequency spectrum of the out-of-plane displacement of the centre-point of the front face of the FUT (blue).

The PZT disc simultaneously vibrates with the elastic plate operating in its flexural resonant modes, but the rigidity and the mass of the HiFFUT as a whole are not significantly modified by the addition of the bonded PZT disc.

In the model, air is assumed as the propagation medium, and an acoustic absorbing boundary condition is applied to the model, to suppress the influence of echo signals. A realistic fixed boundary condition is also applied to the external wall of the cap. The material parameters used in the finite element model are available as standard through PZFlex®FE software. The frequency response results of a HiFFUT with a PZT-disc diameter of 5 mm are firstly studied as an example, which are shown in Fig. 4, where a sinc function time-domain voltage signal is applied to the PZT element [18]. The frequency spectrum of the driving voltage signal is shown by the red data plot in Fig. 4, indicating that the input energy in frequency domain has a comparatively uniform distribution ranging from 0 to around 300 kHz. This broadband excitation, with uniform energy distribution across the frequency range examined ensures that the resonant modes are consistently excited. The resultant spectrum of the out-of-plane displacement of the centre-point of the front face of the FUT is also shown in Fig. 4 (blue line), demonstrating that the resonant frequencies of the (0,0) and (1,0) modes are 19.6 kHz, and 102.9 kHz respectively.

The diameter of the piezoelectric ceramic disc shown in Fig. 3 was adjusted as part of a further finite element analysis (FEA) step. The resonant frequencies associated with the (0,0) and (1,0) modes were determined based on the adjusted diameter value, and the results are shown in Fig. 5. The diameter of the PZT disc has a significant, non-monotonic influence on the behaviour of the (0,0) and particularly the (1,0) modes of the FUT. It should be noted that the maximum modelled diameter of the PZT disc is set to just smaller than the inner diameter of the cap. The highest resonant frequency calculated for the (0,0) mode is 26.3 kHz at a PZT diameter of 10.2 mm. The (1,0) mode has higher resonant frequencies of 102.9 kHz and 103.8 kHz for PZT disc diameters of 5.0 mm and 10.2 mm respectively. The next stage is to examine the relative vibration amplitude of the (1,0) modes, as we require efficient transduction at high frequency.

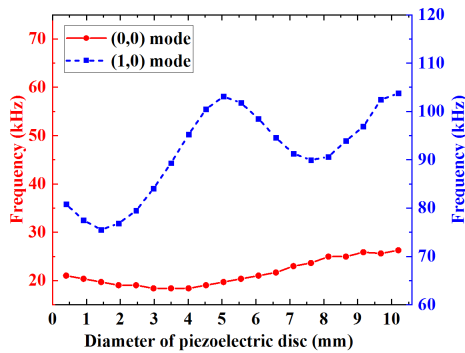


Fig. 5. Modal frequency as a function of piezoelectric ceramic disc diameter for the (0,0) mode (red) and the (1,0) mode (blue), determined through FEA.

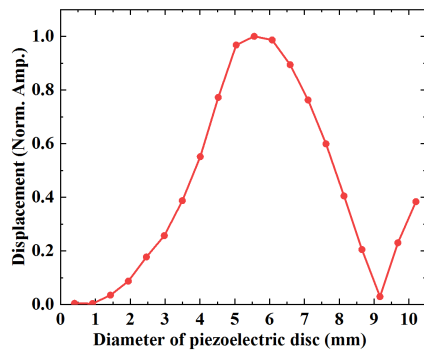


Fig. 6. Amplitude of displacement in the (1,0) mode calculated at the centre of the plate as a function of piezoelectric ceramic disc diameter, determined through FEA.

FEA was used to determine the influence of the piezoelectric disc diameter on the amplitude of displacement at the centre of the transducer, whilst operating in the (1,0) mode. The results of normalised amplitude are shown in Fig. 6, varying significantly and non-monotonically with the diameter of the PZT disc, having a maximum value for a disc diameter of 5.6 mm, and a local minimum for a disc diameter of 9.2 mm. This shows that when considering the efficiency of a HiFFUT generator alone (where reception performance is not yet considered), a PZT disc diameter of approximately 5.6 mm can be considered to be an optimised design as the frequency of operation is in excess of 100 kHz, with large transducer front face displacement. Whilst it depends on the requirements of the application, by taking account of the results in Figs. 5 and 6, one can consider a desirable PZT disc diameter to be in the range of 4 mm to 7 mm, as this yields an operation frequency exceeding 90 kHz across that range.

The HiFFUTs behaving as an ultrasonic receiver or transmitter for many practical applications must also be considered. A HiFFUT can operate as a single transducer in a pulse-echo configuration, or a pair of HiFFUTs can be used in a pitch-catch configuration either directly or from a reflector. In considering such a system, a holistic view is required where an FEA model for a pair of HiFFUTs operating in a pitch-catch configuration can be constructed, as illustrated in Fig. 7. The exact behaviour may vary for different transducer separations, as the acoustic field profile from the (1,0) mode particularly is complex, but here a generic approach for designing the transducer is described, where a realistic separation of 100 mm has

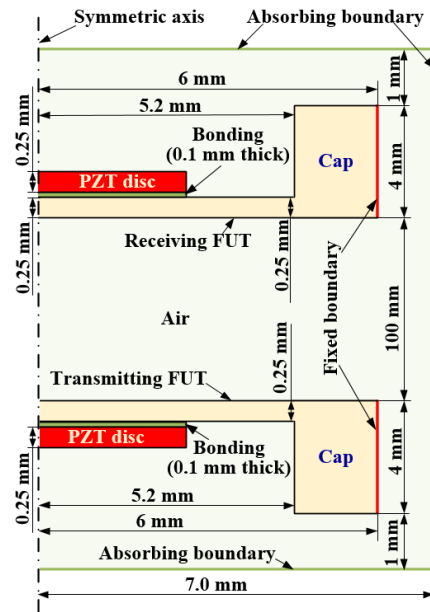


Fig. 7. Schematic of a three-dimensional axisymmetric model of a pitch-catch configuration consisting of a transmitting HiFFUT and a receiving HiFFUT, where the dimension scales have been adjusted for clarity.

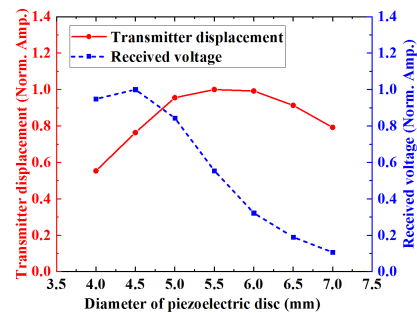


Fig. 8. Comparison between the amplitude of displacement at the centre of the front face of the transmitting HiFFUT (red) and the voltage signal amplitude of the receiving HiFFUT (blue), as a function of the piezoelectric ceramic disc diameter.

been defined for computational expediency. The dimensions and the boundary conditions of both transmitting and receiving HiFFUTs in Fig. 7 are the same as those shown in Fig. 3.

The PZT disc diameter is the same in each HiFFUT, but each disc diameter is simultaneously varied over a 4 mm – 7 mm range. Having the same PZT disc diameter in each transducer (and hence identical transducers) ensures that the resonant frequency of each should be identical in the model, and would be favourable in a real device. The received voltage signal output from the PZT element of the receiving HiFFUT is calculated, where the transmitting HiFFUT is excited with a 5-cycle tone burst voltage signal with an amplitude of 20 V, tuned to the resonant (1,0) mode frequency of transmitting HiFFUT using the data from Fig. 4. The results are shown in Fig. 8, where a large variation in the received voltage signal amplitude (blue line) can be found as the PZT disc diameter increases from 4 mm to 7 mm. The amplitude of the displacement (red line) at the centre of the generating HiFFUT is shown for comparison, demonstrating that the maximum signal output on the detecting HiFFUT does not correspond to the maximum displacement amplitude of

the generating HiFFUT. The acoustic wave pressure field (and hence transducer separation) and response of the detecting transducer give rise to the results shown in Fig. 8.

The blue curve of Fig. 8 demonstrates that the received signal amplitude for a PZT disc diameter of 7 mm is approximately 10.7% of that for a diameter of 4.5 mm, showing that relatively small variations in PZT disc diameter produce a significant difference in received voltage. In the configuration examined, if a PZT disc diameter of 5.5 mm had been used, generating the largest vibration amplitude on the generation transducer (as shown by the red curve of Fig. 8), the detected signal amplitude would be 44.5% lower than that obtained using 4.5 mm diameter discs (as shown by the blue curve of Fig. 8). The results in Fig. 8 also indicate that varying the PZT disc diameter also has a significant influence on a FUT as a receiver.

The use of two FUTs in a pitch-catch measurement is utilised for applications such as ultrasonic flow measurement and ultrasonic communication [5]–[7]. These results are also applicable to when a single FUT or HiFFUT transceiver operates in a pulse-echo configuration. Where a pitch-catch method is used and one FUT acts as a dedicated ultrasonic transmitter and second as a dedicated receiver, as in some NDT applications using alternative transducer designs [8], it is conceivable that the optimal design for each might be different. In this work we describe an approach for HiFFUT design, and illustrate associated performance results, given certain starting constraints on transducer cap size and PZT thickness, ensuring that realistic parameters are considered when investigating the multivariable parameter space. A transducer design approach beginning with a specific geometry of PZT disc is an alternative but equally valid method, using the procedures described in this research. Multi-parameter transducer optimisation processes could be achieved through a holistic and systematic approach, for example through a combination of FEA with the orthogonal test method [32], but this is beyond the scope of this paper.

The main purpose of this research is to demonstrate that a HiFFUT can be designed to operate as an efficient air-coupled ultrasonic transceiver at a frequency significantly higher than 40 kHz. FEA results shown in Figs. 5 and 8 have demonstrated that a HiFFUT with a ceramic disc diameter of 5 mm has a comparatively high transduction efficiency, operating as a transceiver at over 100 kHz (Fig. 5), with a detected signal amplitude only 15.6% lower than the predicted maximum (Fig. 8). The cross-sectional view of a HiFFUT with a 5 mm diameter piezoelectric ceramic disc is shown in Fig. 9, which consists of a titanium cap, a piezoelectric ceramic disc, a backing layer and a pair of conductive wires. The conductive wires are soldered to the electrodes of the ceramic disc. The physical properties and dimensions of the titanium cap of the HiFFUT are critical to the performance of the transducer. The cap is thus fabricated using a computer numerical control machine (XYZ 500 LR, XYZ Machine Tools) with an accuracy of  $\pm 5 \mu\text{m}$ . The plastic backing layer is attached to the rear of the cap to form an enclosed cavity together with the side wall of the cap, to protect the internal transducer components. As the backing layer does not directly contact the elastic plate

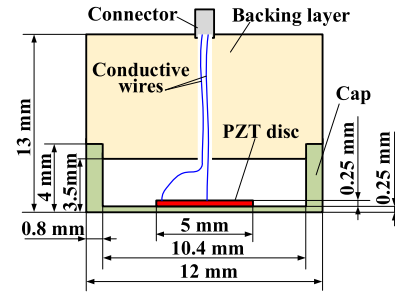


Fig. 9. Cross-sectional view of a HiFFUT.

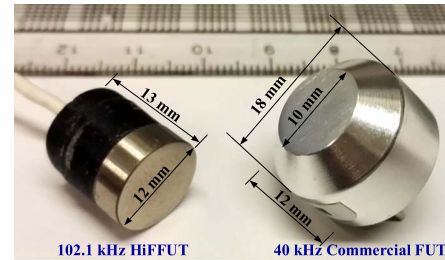


Fig. 10. The HiFFUT prototype and the 40 kHz commercial FUT.

of the cap which dominates the vibrational behaviour of the transducer [20], the resonant frequencies of the transducer are not significantly influenced. The backing layer is made of acrylonitrile butadiene styrene (ABS) thermoplastic polymer, and is fabricated using 3D printing technology which is an efficient solution for constructing peripheral components of the transducer, so that prototype HiFFUTs can be efficiently manufactured.

### III. DYNAMIC PERFORMANCE CHARACTERISATION

Two 40 kHz commercial FUTs (MCUSD18A40B12RS, Multicomp) are selected to provide a baseline comparison to the prototype HiFFUTs. The dynamic performance of these 40 kHz FUTs has been thoroughly investigated [21] and thus is not repeated here. Dynamic performance measurements are conducted in a pitch-catch ultrasound measurement for each transducer pair. For clarity, a 40 kHz commercial FUT is shown alongside a HiFFUT prototype in Fig. 10, where the HiFFUT is 12 mm in diameter and 13 mm in height, whilst the 40 kHz commercial FUT consists of a different shape, with an outer diameter of 18 mm, a height of 12 mm and a plate diameter of 10 mm.

The electrical characteristics of the HiFFUT are determined using an impedance analyser (Agilent 4294A), where the impedance and the phase of the FUTs from 10 kHz to 200 kHz are measured. Fig. 11 shows the presence of the two fundamental resonant frequencies of the HiFFUT at 20.6 kHz and 102.1 kHz, identified through the locations of minimum electrical impedance [21]. The impedances are 6.3 k $\Omega$  and 0.8 k $\Omega$  respectively, and the phases are  $-54.5^\circ$  and  $-28.5^\circ$  for the lower and higher frequency modes respectively. The measured resonant frequencies closely correlate with those calculated through FEA, at 19.6 kHz and 102.9 kHz, providing a high degree of confidence in the FEA.

The mode shapes associated with these resonant modes are then measured on the front face of the HiFFUT using a Laser

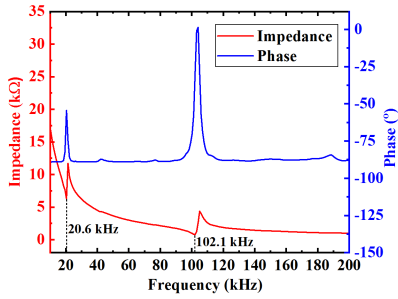


Fig. 11. Electrical characteristics of the HiFFUT in the frequency range of 10 kHz to 200 kHz, where two resonant frequencies at 20.6 kHz and 102.1 kHz are identified.

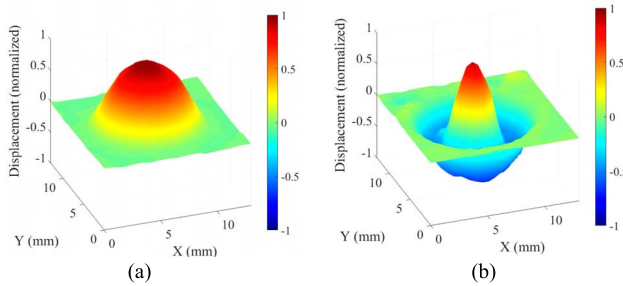


Fig. 12. Mode shapes associated with the mechanical vibration motion of the HiFFUT at (a) 20.6 kHz and (b) 102.1 kHz, demonstrating that 20.6 kHz correlates with the (0,0) mode and 102.1 kHz represents the (1,0) mode.

Doppler Vibrometer (LDV, Polytec OFV-5000). To acquire these measurements, the HiFFUT is driven by a continuous sine wave generated by an arbitrary function generator (Tektronix AFG3102C), and the displacement of the front face of the HiFFUT is incrementally scanned point-by-point by the LDV, with a step-size of 0.25 mm. The displacement amplitudes extracted from a grid of  $54 \times 54$  points on the front-face plane of the HiFFUT are measured and synchronously recorded by a digital storage oscilloscope (Agilent Technologies DSO-X 3014A) [20]–[22]. The displacement amplitudes are then combined to generate the mode shape of the HiFFUT for each resonant frequency, as shown in Fig. 12, proving that the mechanical vibration motion at resonant frequencies of 20.6 kHz and 102.1 kHz are consistent with the (0,0) and (1,0) modes respectively, as shown in Fig. 2.

The results of Figs. 11 and 12 confirm the resonant characteristics of the HiFFUT are consistent with predicted behaviour. The acoustic pressure and bandwidth of the ultrasonic wave produced by the prototype HiFFUT and the commercial 40 kHz FUT are both measured using a pressure-field microphone (Type 4138-A-015 with Type 2670 preamplifier, Brüel & Kjær Sound & Vibration) and a conditioning amplifier (NEXUS WH-3219).

Each transducer is driven by a 5 V continuous sine wave, and the distance between the transmitting transducer and the pressure-field microphone is set to 200 mm, in line with the centre of each transducer. The acoustic pressure generated by the 40 kHz commercial FUT operating in a (0,0) mode is 4.9 Pa whilst that generated by the 102.1 kHz HiFFUT operating in a (1,0) mode is 8.4 Pa. The bandwidths of the FUT and HiFFUT are measured by sweeping the frequency of the

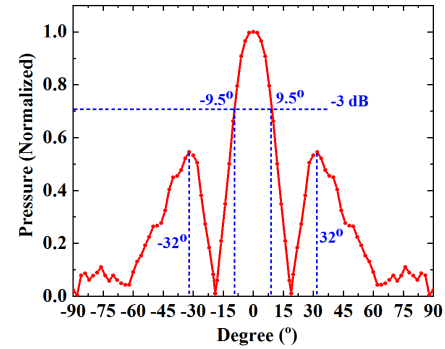


Fig. 13. Radiation pattern of the HiFFUTs operating as a transmitter at 102.1 kHz.

5 V continuous sine wave, showing that the  $-3$  dB bandwidths are approximately 3.0 kHz ( $\sim 2.9\%$ ) and 0.9 kHz ( $\sim 2.3\%$ ) for the HiFFUT prototype and commercial FUT respectively.

The HiFFUT operates at a significantly higher resonant frequency with a higher acoustic pressure output when compared to the 40 kHz FUT, and with a marginally larger but comparable bandwidth. Both transducers have a front face of comparable size, although the HiFFUT is a slightly smaller device overall. However, the radiation patterns of the (0,0) and (1,0) modes are very different. The acoustic pressure field generated by the HiFFUT at 102.1 kHz is measured in  $2^\circ$  increments, using the pressure-field microphone at a distance of 200 mm from the transducer front face. The acoustic radiation pattern is shown in Fig. 13, where the main lobe has a  $-3$  dB beam angle of  $19^\circ$ . In addition to the main lobe, secondary lobes are also observed at  $\pm 32^\circ$ , whose peak amplitudes are approximately 55% of that of the centre of the main lobe. These parameters are entirely suitable for reliable ultrasound measurement in a range of applications, in which some common, slightly larger, commercial FUTs also operate in the (1,0) mode with a similar radiation pattern to that shown in Fig. 13, but only at 40 kHz [22].

The voltage signal amplitude output from the prototype HiFFUTs and 40 kHz FUTs are then compared in a pitch-catch ultrasound measurement configuration. The distance between the transmitting and the receiving transducers in each case is 200 mm, consistent with the pressure-field microphone experiments. Each transmitting transducer is driven directly by the function generator, and the driving voltage signal consists of a 5-cycle tone burst signal with an amplitude of 5 V at the respective centre frequencies for each transducer pair. The received signals are amplified with a fixed gain of 30 by a low-noise wideband amplifier (SAA1000, Sonemat) and the amplified ultrasonic signals are digitized and recorded by the oscilloscope after taking 8192 times of average. The driving voltage signal and the amplified voltage signals from the HiFFUT and the 40 kHz FUT obtained in a pitch-catch configuration are shown in Fig. 14.

The results demonstrate that the operating frequency of the HiFFUTs in a pitch-catch configuration is higher than that of the commercial FUTs by a factor of approximately 2.6. Taking a threshold amplitude of 10% of the peak magnitude of the ultrasonic signal (indicated by  $U_{m1}$  for the commercial FUTs and  $U_{m2}$  for the HiFFUTs), the duration of the ultrasonic

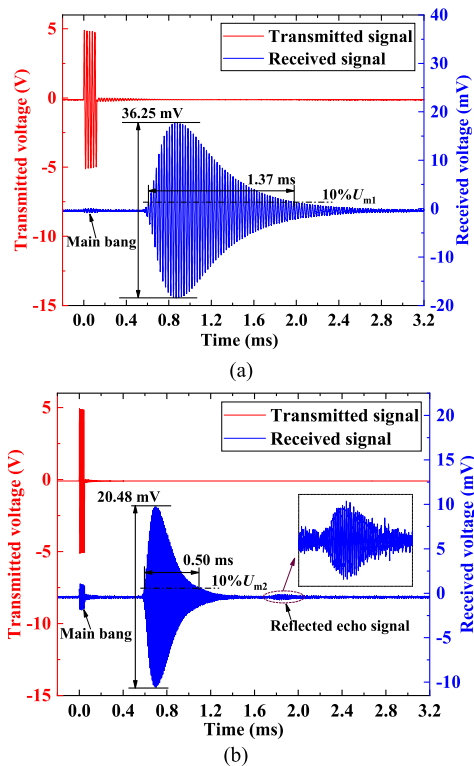


Fig. 14. Comparison of received ultrasonic signals, between (a) a pair of 40 kHz commercial FUTs, and, (b) a pair of 102.1 kHz HiFFUTs, measured in a pitch-catch configuration with a propagation distance of 200 mm.

signal associated with the HiFFUTs is 0.50 ms, and that of the 40 kHz FUTs is 1.37 ms. A temporally-shorter ultrasonic signal is beneficial in ultrasonic measurement, because it generally improves resolution when multiple signals may be present. An example of this is shown by the inset in Fig. 14(b), where a signal echo measured at a time of approximately 1.75 ms is clearly observable. This echo originates from an ultrasonic wave reflection between the transmitting and receiving transducers, but it is indistinguishable in Fig. 14(a), due to the temporally longer pulse. The peak-to-peak amplitude of the received signal for the 102.1 kHz HiFFUT and 40 kHz FUT are approximately 20 mV and 36 mV respectively, but both transducers are relatively very efficient devices for ultrasonic measurements in air.

The design principles for the HiFFUT and a systematic approach, combining the advantages of the computation efficiency of the classical plate theory and the computation accuracy of the FE method, have been described in this paper. Using the classical plate theory, a specific titanium cap, which can potentially operate at a frequency much higher than 40 kHz, is firstly chosen as a candidate cap for the HiFFUT. Using this cap as the starting point of the design, the influence of the diameter of the piezoelectric disc on the transmitting and the receiving processes of the HiFFUT is further examined through finite element analysis, from which a ceramic disc appropriate for the cap is finally determined. Experiments demonstrate that the developed HiFFUTs are able to generate and receive an ultrasonic wave at 102.1 kHz with a similar amplitude and SNR to the commercially available 40 kHz FUTs, despite the higher ultrasonic attenuation in air

at 102.1 kHz compared to 40 kHz. In practical applications, amplification and filtering circuits can be integrated into an ultrasonic measurement system based on HiFFUTs through recent key developments in sensor technology [33], showing the potential for a high level of HiFFUT performance in ultrasonic measurement applications involving longer ranges, for instance, exceeding 500 mm. The HiFFUT operates at a relatively low voltage and low power, with a simple, low cost and robust structure, desirable in a wide range of industrial applications including distance ranging and flow measurement.

#### IV. CONCLUSIONS

The operating frequency of commercial flexural ultrasonic transducers which are currently available is typically below 50 kHz, which is limiting their performance and wider exploitation in measurement applications. A titanium-capped high frequency flexural ultrasonic transducer (HiFFUT) is demonstrated, using the classical plate theory and FEA to guide the design of the transducer fabrication, and its performance has been characterized with comparison to a commercial 40 kHz FUT. Whilst the HiFFUT's resonant frequency is dominated by the resonant vibration modes of its titanium elastic plate, the piezoelectric disc attached to the plate also has a significant and non-monotonic influence on resonant frequency, particularly for the (1,0) mode of vibration. The diameter of piezoelectric disc required to generate the largest amplitude of pressure from a HiFFUT transmitter differs to that necessary for a HiFFUT transceiver to obtain the largest signal amplitude in a pitch catch system. The design parameters utilised in this study show that an optimal ceramic diameter can produce an ultrasonic signal amplitude greater by a factor of around 10 compared to that of a non-optimised design. Using the design principles described, two HiFFUT prototypes were developed with an operating frequency of 102.1 kHz, producing received signal amplitude and SNR comparable to commercial 40 kHz FUTs. The HiFFUTs also have good directivity through a -3dB beam angle of 19°, and a bandwidth wider by a factor of 3.3 when compared to the commercial FUTs, demonstrating that the HiFFUT is a high performance, robust option for industrial ultrasonic applications.

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