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Citation: Proc. Mtgs. Acoust. **32**, 045003 (2017); doi: 10.1121/2.0000685
View online: https://doi.org/10.1121/2.0000685
View Table of Contents: http://asa.scitation.org/toc/pma/32/1
Published by the Acoustical Society of America

Proceedings of Meetings on Acoustics

Volume 32 http://acousticalsociety.org/

2017 ICU Honolulu

Sixth International Congress on Ultrasonics

Honolulu, Hawaii, USA
18-20 December 2017

Physical Acoustics: Paper ICU2017 - 20

HiFFUTs for high temperature ultrasound

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Flexural ultrasonic transducers have been widely used as proximity sensors and as part of industrial metrology systems. However, there is demand from industry for these transducers to have the capability to operate in both liquid and gas, at temperatures of 100-200°C and higher, significantly greater than those tolerated by current flexural transducers. Furthermore, flexural transducers tend to be designed for operation up to around 50 kHz, and the ability to operate at higher frequencies will open up new application and research areas. A limitation of current flexural transducers is the electromechanical driving element, usually a lead zirconate titanate piezoelectric ceramic, which experiences significantly reduced performance as temperature is increased. This investigation proposes a new type of flexural transducer, the HiFFUT, a high frequency flexural ultrasonic transducer, comprising a bismuth titanate ceramic for operation at high temperatures, that could be replaced by another suitable high Curie temperature piezoelectric material if required, bonded to the membrane with a high temperature adhesive. The dynamic characteristics of the HiFFUT are studied as a function of temperature, providing insights into its usefulness for industrial applications.

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https://doi.org/10.1121/2.0000685

1. INTRODUCTION

The flexural ultrasonic transducer (FUT) is an ultrasound sensor principally utilised for industrial metrology, flow measurement, and proximity sensing applications. The fundamental operating principle of a FUT is through the bending of a compliant metallic membrane. The vibrating membrane of the FUT is the radiating face of a metal cap, in which a driver element is supported. This membrane is can be considered as a circular plate, constrained around its circumference, where the dynamic modes of this circular plate correlate with the modes of vibration of a FUT. The metal cap is usually fabricated from materials such as aluminium or titanium[1], based on the physical properties of these metals, which exhibit the suitable compliance, density, and robustness for industrial applications. The high frequency flexural ultrasonic transducer (HiFFUT) is an evolution of the conventional FUT, specifically developed for multi-mode operation at high frequencies, and in hostile environmental conditions. This study demonstrates fundamental developments of HiFFUTs, outlining a novel fabrication method, design for operation at high frequencies, and a demonstration of operation at temperatures exceeding those at which the conventional FUT can withstand. The composition of the HiFFUTs studied in this investigation is shown in Figure 1.

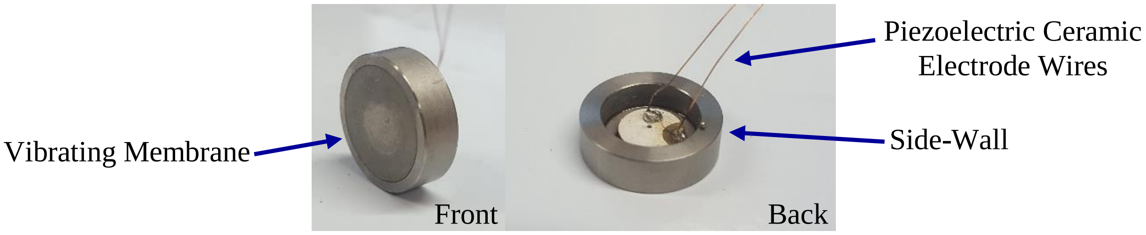


Figure 1: The high frequency flexural ultrasonic transducer fabricated for this study.

The activation of the driver element inside the metal cap generates the high frequency vibrations required to cause a bending of the metallic membrane, thereby producing the ultrasound signal. Traditionally, FUTs have been driven in two ways. The first is electromagnetically, through the inclusion of a wire coil inside the metal cap[2], and the second is by using a piezoelectric ceramic disc[1]. This research focuses on HiFFUTs fabricated using piezoelectric ceramics. Piezoelectric FUTs produce an ultrasound signal in response to a voltage across the piezoelectric ceramic disc. This ceramic must be positioned precisely in the centre of the underside of the membrane, to generate the required vibration modes. FUTs are generally operated in their axisymmetric modes, examples of which are shown in Figure 2, referred to as the (0,0) and (1,0) modes. The nomenclature (x,y) refers to the nodal radius and diameter respectively, consistent with the literature[1]. The modes were simulated using PZFlex® finite element analysis software.

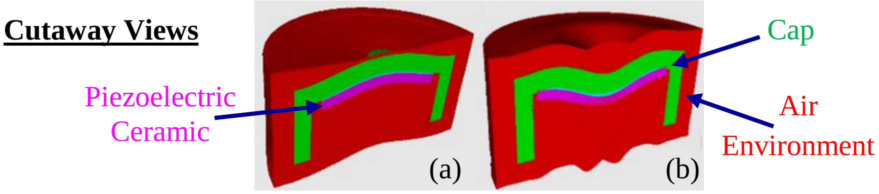


Figure 2: Simulated mode shapes of a HiFFUT, for (a) the (0,0) mode, and (b) the (1,0) mode.

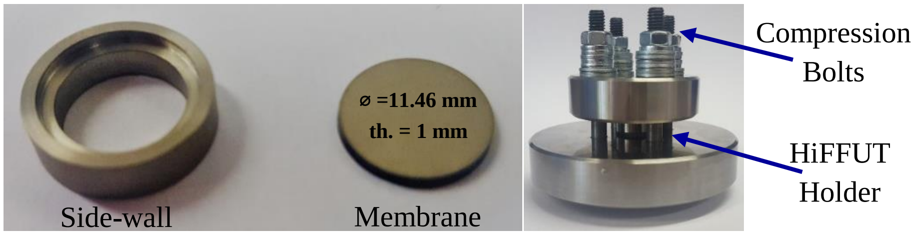
At present, conventional FUTs are designed to operate in ultrasound applications at ambient environmental conditions, up to approximately 50 kHz. Strategies to raise the fundamental resonance frequencies of the axisymmetric modes, and to increase the resilience of the devices to high temperatures, are both investigated in this study. The long-term objective of this research is to develop an array of HiFFUTs and design solutions to address current limitations of FUTs. This investigation provides insights into the foundation of HiFFUT development, and in particular addresses the limitation of conventional FUTs to operate at high temperature levels.

2. EXPERIMENTAL PROCEDURE

A. HIFFUT FABRICATION PROCESS

Two high temperature HiFFUTs are designed, fabricated and tested in this study. The HiFFUTs were fabricated from titanium, designed with the resonance frequency of the (0,0) mode around 75 kHz, satisfying the high frequency ultrasound condition. In a flexural ultrasonic transducer, the piezoelectric ceramic ideally needs to be positioned central on the underside of the cap membrane, in order to generate the axisymmetric modes. One restriction of fabricating a transducer cap as a single component is the difficulty in positioning this ceramic. This is complicated by the fact that the HiFFUTs analysed in this study necessitate the use of high temperature epoxy resin (EPO-TEK® 353ND), which can withstand a temperature of 250°C continuously, or 350°C intermittently. This epoxy resin cures at 150°C for one hour to ensure a high quality bond. Therefore, not only does the ceramic need to be positioned precisely central on the cap membrane, but the compression rig must be able to survive the epoxy resin curing temperature.

To address these challenges, the HiFFUTs were designed as two parts, where the side-wall and membrane were two individual components, shown in Figure 3(a). The advantage of producing the cap in two parts is that it allows the ceramic to be easily bonded to the membrane at the centre, prior to attachment to the side-wall. The side-wall geometry creates problems in centering the ceramic, and so this method is presented as a solution. The compression rig was designed for this study, and is shown in Figure 3(b).



(a) (b)

Figure 3: The fabrication of a HiFFUT, showing (a) the side-wall and membrane, and (b) the compression rig used to bond the transducer components together.

Current FUTs incorporate lead zirconate titanate (such as PZT-5H), which is unsuitable at high temperatures, for example those exceeding around 80°C. To address this, both HiFFUTs were constructed using PZ46 (Meggitt), which is a form of bismuth titanate piezoelectric ceramic. PZ46 ceramic possesses a Curie temperature of 650°C, whereas the Curie temperature of PZT-5H, commonly used in FUTs, is around 190°C[3]. Temperature affects the electromechanical properties of piezoelectric ceramics[3], and the maximum operational temperatures are lower than the Curie temperatures, in the order of 500-550°C for PZ46 (Ferroperm), and approximately 95°C for PZT-5H (Morgan Advanced Materials). However, there is a compromise, since lead zirconate titanate ceramics tend to possess piezoelectric properties of higher magnitude than bismuth titanate, where they can achieve greater output amplitude for a given input. Small amounts of epoxy resin were deposited on the bonding areas of the HiFFUTs, before a torque wrench was used to control the applied torque on the bolts in the compression rig. Once the curing time had elapsed, the HiFFUTs could be extracted from the rig, after which electrode connections were attached.

B. MEASUREMENT OF HIFFUT PERFORMANCE

The dynamic performance of the HiFFUTs was first studied using laser Doppler vibrometry (LDV) to verify the (0,0) mode shape, and an acoustic microphone to measure the amplitude-time spectrum at that mode. Each HiFFUT was then heated to 150°C in a laboratory furnace (Pyrotherm) in increments of 50°C, held at each temperature for 15 minutes, with its response monitored using an acoustic microphone. The complete experimental process is outlined in Figure 4, adapted from prior investigation[4].

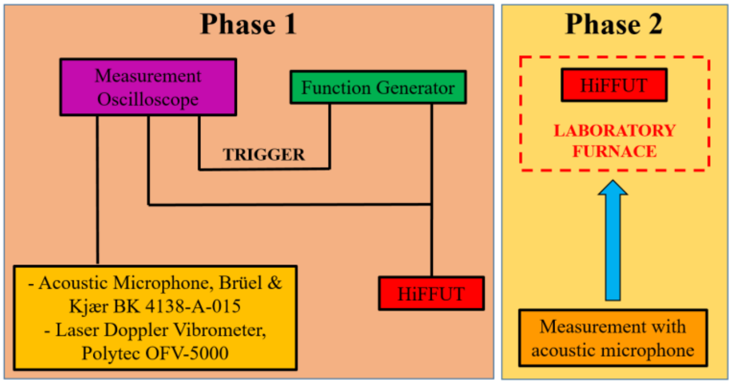
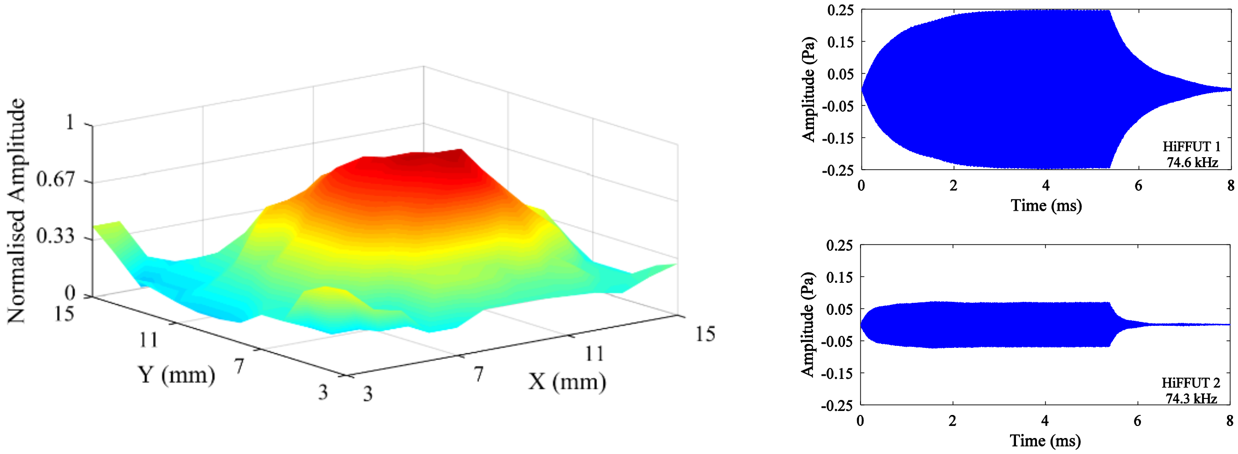


Figure 4: Experimental process for characterisation of HiFFUTs.

3. EXPERIMENTAL RESULTS

The (0,0) mode of HiFFUT 1 is shown in Figure 5(a) as an example, with a resonance frequency of 74.5 kHz. The amplitude-time spectra for both HiFFUTs measured using the acoustic microphone prior to any temperature measurement are shown in Figure 5(b), for a burst sine excitation with nominal drive voltage of 20 V_{P-P}, with 400 cycles. The HiFFUTs were positioned 65 mm from the microphone sensor.

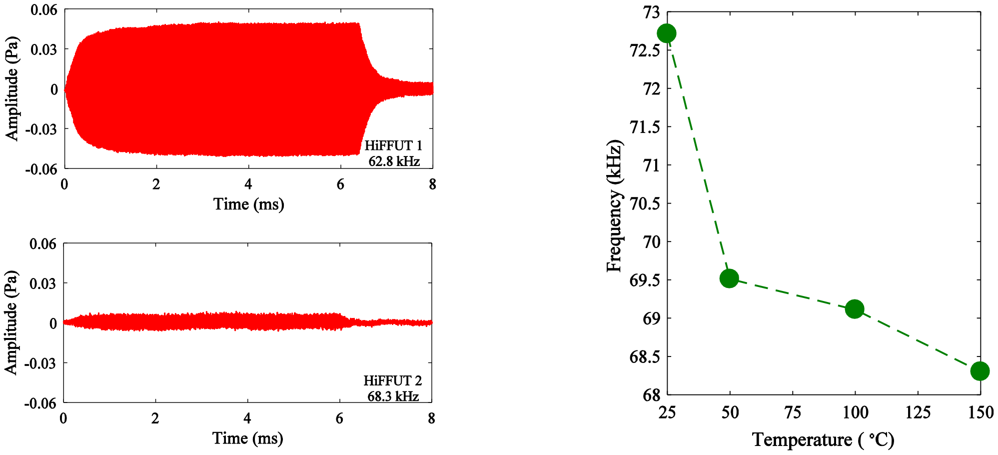


(a) (b)

Figure 5: Resonance frequency measurement, showing (a) the (0,0) mode of HiFFUT 1 at 74.5 kHz from LDV, and (b) the amplitude-time spectrum for each HiFFUT from the acoustic microphone.

The resonance frequencies of the HiFFUTs differ due to minor discrepancies in fabrication, such as the bonding pressure applied to the BiT ceramic. There is also around 100 Hz difference between the LDV and microphone resonance frequencies for HiFFUT 1, arising from the difference in clamping conditions required for the two tests. Low vibration output of the HiFFUTs in air was measured, approximately 0.5 Pa for HiFFUT 1 and 0.15 Pa for HiFFUT 2, at a distance of 65 mm from the microphone sensor for the nominal drive voltage of 20 V_{P-P}. Efficiency must be improved in future HiFFUT designs, and research is currently undergoing on achieving this in other devices based on the flexural ultrasonic transducer[5].

The dynamic response of each HiFFUT as a function of temperature was measured. An amplitude-time spectrum was recorded at ambient room temperature, 50°C, 100°C, and 150°C. The response of each HiFFUT after 150°C was reached is shown in Figure 6(a), with the performance of HiFFUT 2 as a function of temperature measured at a distance of 300 mm displayed in Figure 6(b). The fast Fourier transform (FFT) was applied to the amplitude-time spectra to produce the results in Figure 6(b).



(a) (b)

Figure 6: (a) The amplitude-time spectra for each HiFFUT measured post-thermal testing, and (b) dynamic performance as a function of temperature for HIFFUT 2, computed using the FFT.

As each HiFFUT is heated, it undergoes thermal expansion of its different components, thus affecting the centre frequency and its dynamics. Despite the HiFFUTs remaining functional at high temperature, as shown in Figure 6, the performance of each is limited through thermally-induced frequency drift. The frequency of HiFFUT 1 dropped from 74.6 kHz to around 62.8 kHz, and from 74.3 kHz to approximately 68.3 kHz for HiFFUT 2. The influence of temperature on the HiFFUT components requires further study.

4. CONCLUSION

The design, fabrication, and characterisation of two HiFFUTs for high temperature applications has been demonstrated. The HiFFUTs generate ultrasound at the desired frequency level, over a relatively wide temperature range, feasible for industrial applications. However, the HiFFUTs exhibit decreases in centre frequency with temperature and relatively low efficiency, and so design improvements are required.

ACKNOWLEDGMENTS

This research is funded by EPSRC grant EP/N025393/1. The authors would like to acknowledge Jonathan Harrington, Mareike Herrmann, and Dr Mark Potter of the University of Warwick.

REFERENCES

[1] T.J.R. Eriksson, S.N. Ramadas, and S.M. Dixon, “Experimental and simulation characterisation of flexural vibration modes in unimorph ultrasound transducers,” Ultrasonics, vol. 65 (2016): 242-248.

[2] T.J. Eriksson, M. Laws, S.M. Dixon, and S.N. Ramadas, “Air-coupled flexural electrodynamic acoustic transducers,” In Ultrasonics Symposium (IUS), IEEE International (2014): 1021-1024.

[3] A. Sharma, R. Kumar, R. Vaish, and V.S. Chauhan, “Experimental and numerical investigation of active vibration control over wide range of operating temperature,” Journal of Intelligent Material Systems and Structures, vol. 27, no. 13 (2016):1846-60.

[4] S. Dixon, L. Kang, M. Ginestier, C. Wells, G. Rowlands, and A. Feeney, “The electro-mechanical behaviour of flexural ultrasonic transducers,” Applied Physics Letters, vol. 110, no. 22 (2017): 223502.

[5] L. Kang, A. Feeney, R. Su, D. Lines, A. Jäger, H. Wang, Y. Arnaudov, S.N. Ramadas, M. Kupnik and S.M. Dixon, “Two-dimensional flexural ultrasonic phased array for flow measurement,” In Ultrasonics Symposium (IUS), IEEE International (2017): 1-4.