High Stiffness Resin for Flexural Ultrasonic Transducers

A. Hamilton[1], S. Adams[1], Y. Liu[1], M. Hafezi[1], W. Somerset[2], K. Lam[1], L. Kang[3], S. Dixon[4], S. Cochran[1], A. Feeney[1a]

[1]James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK, [2]School of Biological Sciences, University of Bristol, Bristol, BS8 1TQ, UK, [3]School of Energy and Electronic Engineering, University of Portsmouth, Portsmouth, PO1 3DJ, UK, [4]Department of Physics, University of Warwick, Coventry, CV4 7AL, UK.

Abstract. The flexural ultrasonic transducer is a widely used commercial sensor popular for proximity sensing and in car parking systems. It is traditionally composed of a piezoelectric ceramic bonded to a circular metallic plate, usually aluminium, generally operating in the low ultrasonic frequency range of 30-40 kHz. To expand potential applications and device performance, stereolithography apparatus 3D-printing of transducer plates is investigated through material characterisation and prototype fabrication. Tensile and viscoelastic testing are performed on resin, with electrical impedance measurements obtained from a fabricated prototype device. Together, the results show that high-stiffness resin is a viable material for engineering flexural ultrasonic transducers with operating frequencies into the hundreds of kHz, in this case exceeding 300 kHz. There is hence the potential for a wide range of high frequency industrial measurement applications for this transducer.

Introduction

Flexural ultrasonic transducers (FUTs) are widely utilised across automotive and proximity sensing applications [1,2]. These devices typically consist of a circular metallic plate with a piezoelectric disc adhesively bonded to the underside. Driven by an electrical signal, FUTs can generate ultrasound at a frequency based on the geometric and material properties of the plate, with numerous axisymmetric and asymmetric vibration modes possible. A schematic illustrating the key components of an FUT is shown in Fig. 1.

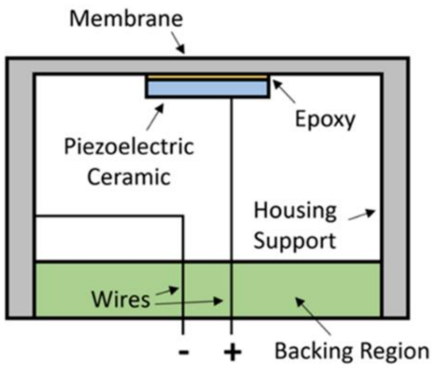

Fig. 1: Schematic of a typical FUT for air-coupled applications at ambient temperatures.

The plates of commercial FUTs are usually composed of thin-walled aluminium or titanium, and the FUTs generally operate between 30 kHz and 40 kHz in a fundamental axisymmetric mode. Limitations of commercial FUTs are their narrow frequency bands (for practical detection sensitivities), and the fact they all conform to the similar circular metallic cap configuration. Hence, this research investigates the potential for FUTs with plates fabricated using stereolithography apparatus (SLA) printing. Here, material properties including the Young's modulus, storage modulus, and loss modulus of the resin have been characterised. This information has been used to benchmark the use of high-stiffness SLA resin (Formlabs Rigid 10K, MA, USA) relative to competing FUT plate materials, showing a potential new avenue of investigation for FUTs.

Methods

A target resonance frequency f of a FUT can be defined using Eq. 1, where ψ denotes the Bessel function associated with the mode shape of interest, a is the radius of the plate, D is the rigidity, ρ is the mass density of the plate, and h is the plate thickness.

$$f = \frac{1}{2\pi}\left(\frac{\psi}{a}\right)^2 \sqrt{\frac{D}{\rho h}} \quad (1)$$

Through Eq. (1), the necessary material properties for a resin can be defined, to configure a potential FUT plate for operation into the kHz. This is novel considering the prevalence of circular metallic plates in commercial devices. Here, the Young's modulus of the resin was determined through tensile testing for a range of trial resins at a displacement at a rate of 2 mm/min. The viscoelastic properties of the resin were determined to gain insight into how the viscoelastic nature of the material would impact the vibrational response, where the storage and loss moduli were calculated based on data from dynamic mechanical analysis (DMA 8000, PerkinElmer Inc., MA, USA). Finally, a prototype FUT was manufactured using the resin to synthesise a suitable cap, before electrical impedance analysis (4294A, Keysight Technologies, CA, USA), was undertaken to measure the electrical impedance as a function of frequency, and to determine prototype resonance.

Results and Discussion

An approximate Young's modulus value of 7.2 GPa was obtained via tensile testing, where the relevant stress-strain data is shown in Fig. 2(a). This value was used to determine the plate rigidity and substituted into the analytical equation shown by Eq. (1). Using a value of 7.2 GPa, a plate thickness of 5 mm, and plate diameter of 15 mm, fundamental modes of vibration greater than 300 kHz are achievable, significantly beyond that of any commercially available device.

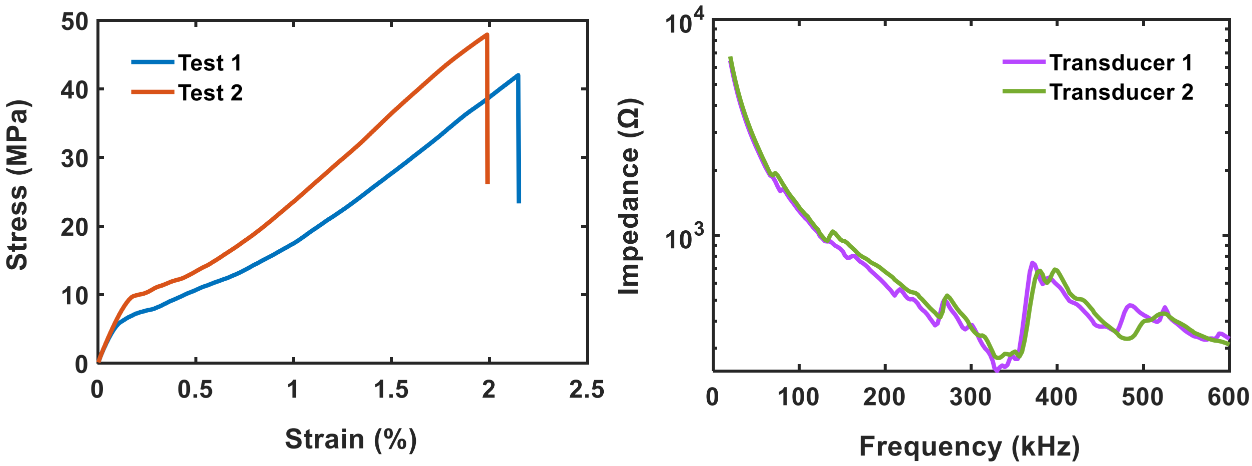

Fig. 2: (a) Measurements on the SLA resin, showing the stress-strain responses for two dog-bone specimens (Test 1 and Test 2) resulting in an average Young's modulus value of 7.2 GPa, and (b) impedance spectra for two fabricated FUTs (Transducer 1 and Transducer 2)

The viscoelastic properties of the resin were quantified via DMA to assess the resistance of the material undergoing stress inducement which occurs in a FUT via the piezoelectric disc during excitation. Preliminary results indicate that the tan(δ) value (the ratio of loss modulus to storage modulus) is approximately 0.09 at 25˚C and notably increases to 0.2 at 75˚C, illustrating a propensity for material softening as the glass transition temperature is approached, and a proportional loss in vibrational energy transmission. Therefore, although the vibration amplitude of a FUT with a resin plate may be lower per unit volt of excitation than one with a metallic plate, there is the potential for practical ultrasound generation and detection to be made. To illustrate this, electrical impedance spectra results, as shown in Fig. 2(b), verify a resonant mode at approximately 343 kHz, around the series resonance, in good agreement with analytical model predictions. This indicates the viability of a new generation of non-metallic FUTs for high frequency measurement. In general, the ability to exploit SLA resins for the manufacture of FUTs opens possibilities for many novel configurations of device with tailored resonance responses for a wide range of industrial applications.

Conclusion

The viability of utilising 3D-printed resins for the fabrication of flexural ultrasonic transducers has been assessed through material characterisation techniques including tensile testing and dynamic mechanical analysis. Through electrical impedance measurements on a fabricated prototype, this research has verified the feasibility of high stiffness SLA-based resins for high frequency-sensing applications. The outcomes provide a platform for further exploration into different transducer plate designs and alternative materials.

References

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