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Glass-windowed ultrasound transducers

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ABSTRACT

In research and industrial processes, it is increasingly common practice to combine multiple measurement modalities. Nevertheless, experimental tools that allow the co-linear combination of optical and ultrasonic transmission have rarely been reported. The aim of this study was to develop and characterise a water-matched ultrasound transducer architecture using standard components, with a central optical window larger than 10 mm in diameter allowing for optical transmission. The window can be used to place illumination or imaging apparatus such as light guides, miniature cameras, or microscope objectives, simplifying experimental setups.

Four design variations of a basic architecture were fabricated and characterised with the objective to assess whether the variations influence the acoustic output. The basic architecture consisted of a piezoelectric ring and a glass disc, with an aluminium casing. The designs differed in piezoelectric element dimensions: inner diameter, ID = 10 mm, outer diameter, OD = 25 mm, thickness, TH = 4 mm or ID = 20 mm, OD = 40 mm, TH = 5 mm; glass disc dimensions OD = 20–50 mm, TH = 2–4 mm; and details of assembly.

The transducers' frequency responses were characterised using electrical impedance spectroscopy and pulse-echo measurements, the acoustic propagation pattern using acoustic pressure field scans, the acoustic power output using radiation force balance measurements, and the acoustic pressure using a needle hydrophone. Depending on the design and piezoelectric element dimensions, the resonance frequency was in the range 350–630 kHz, the −6 dB bandwidth was in the range 87–97%, acoustic output power exceeded 1 W, and acoustic pressure exceeded 1 MPa peak-to-peak.

3D stress simulations were performed to predict the isostatic pressure required to induce material failure and 4D acoustic simulations. The pressure simulations indicated that specific design variations could sustain isostatic pressures up to 4.8 MPa.The acoustic simulations were able to predict the behaviour of the fabricated devices. A total of 480 simulations, varying material dimensions (piezoelectric ring ID, glass disc diameter, glass thickness) and drive frequency indicated that the emitted acoustic profile varies nonlinearly with these parameters.

1. Introduction

In research and industrial processes, it is increasingly common to combine multiple measurement modalities. Nevertheless, experimental tools that allow the co-linear combination of optical and ultrasonic transmission are rare [1]. Hence, the aim of this study was to develop and characterise a water-matched ultrasound transducer architecture, with a central optical window larger than 10 mm in diameter, which allows optical transmission.

Such a device could be used in research applications such as chemical dissolution, where the window would allow collinear optical spectroscopy [2], and flow metering [3,4], where the optical window would allow illumination or imaging of flow and contamination using digital cameras. Adding ultrasound transmission elements to the optical examination port in a pipeline could prevent fouling by inducing inertial or stable cavitation [5], and allow Doppler based velocity measurements [6]. Adding an optical window in a single element ultrasound transducer creates a means to simplify experimental configurations by illuminating, imaging, or measuring through the ultrasound transducer.

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To achieve simultaneous optical imaging and ultrasonic sonication or detection, several experimental configurations have previously been designed, such as applying ultrasound at obtuse angles and adding wave-guides to align optical and acoustic fields when visualising ultrasonic effects using microscopes [7–11]. However, these configurations require time-consuming alignment techniques and changes in drive frequency or number of pulses requires re-alignment with the optical field. A transducer design allowing trans- and co-linear optical visualisation in the acoustic propagation direction would reduce complexity and provide possibilities for new experimental configuration for research and industrial applications.

Previously, only one type of optically transparent ultrasound transducer has been reported, to our knowledge. This design is based on lithium niobate (LNO) crystals coated with transparent indium tin oxide (ITO) electrodes with resonance frequencies of 6.3 and 7.1 MHz [1]. The device has no case or backing and is intended for use in particle manipulation in microfluidic devices, producing output pressures of up to 0.5 MPa. The ∼600 nm thick ITO electrodes affected the optical transmittance resulting in non-linear wavelength-dependent transmission. The electrodes are also susceptible to chemical and contact damage, and do not work under isostatic pressures surpassing 110 MPa [12]. Furthermore, ITO deposition is more complicated and costly than more common electrode coatings such as conductive silver paint or vacuum-deposited gold.

Here, an ultrasound transducer architecture is presented, and four design variations based on it, with a circular optical window with diameter 10 or 20 mm, where the piezoelectric element is encased within the device. The fabrication procedure is described for all the designs. Their frequency responses were characterised using electrical impedance spectroscopy and pulse-echo measurements, the acoustic propagation pattern using acoustic pressure field scans, the acoustic power output using radiation force balance measurements, and the acoustic pressure output using a needle hydrophone. 3D stress simulations were also performed to predict the isostatic pressure required to induce material failure and 4D acoustic simulations to assess the possibility to simulate and hence optimise the transducer response.

2. Materials and methods

The design criterion of the device was to allow the insertion of optical devices such as microscope objectives with long working distances (>10 mm), small-aperture cameras such as endoscopic cameras, and fibre or liquid light guides into the transducer to image or illuminate the test medium through the optical window. Based on in-house hardware and experimental configurations, the minimum required window size was determined to be more than 10 mm in diameter and the maximum device diameter to be approximately 70 mm. The acoustic requirements were for the point of highest acoustic pressure to be located collinearly with the centre of the optical window between 0 and 40 mm from the surface of the device; for a bandwidth of >60% to allow a single device to operate at multiple frequencies; and for acoustic pressure output to exceed 1 MPa. The device was also required to sustain as high an isostatic pressure as possible for operation in oil and gas pipes. Furthermore, it should consist of commercially available "off-the-shelf" components that would not require specialised modification, allowing any research or industry laboratory to manufacture such a device.

2.1. Design

An architecture consisting of as few components as possible, with adhesive joining, was chosen to reduce complexity and manufacturing costs. It was based on conventional single-element ultrasound transducer architecture [13,14]. The changes made were to use a piezoelectric ring to replace the piezoelectric disc and to add a glass disc. This architecture was chosen as it involves only geometric shapes *i.e.*, discs, rings, and cylinders, that can be purchased commercially and aligned easily during assembly without specialised hardware.

Four designs were evaluated to determine the effect of geometry differences on the acoustic output and mechanical strength. Graphical renderings and cross-sections of the designs can be seen in Fig. 1A. Fig. 1B shows the parameters that can be varied using this construction whilst Table 1 provides the dimensions used in the prototype transducers. The outer diameters (ODs) and inner diameters (IDs) of the piezoelectric discs were, respectively, 40 mm and 20 mm for two of the designs, and 25 mm and 10 mm for the other two designs. Including the adhesive and case, this resulted in assembled device outer diameters of, respectively, 50 mm and 38 mm.

For this architecture the chosen piezoelectric material was PZ54 (Meggit Sensing Systems: Ferroperm Piezoceramics, Kvistgaard, Denmark) due to its low cost, €11–14 per ring and commercial availability; high mechanical quality factor, $Q_m > 1500$; relatively

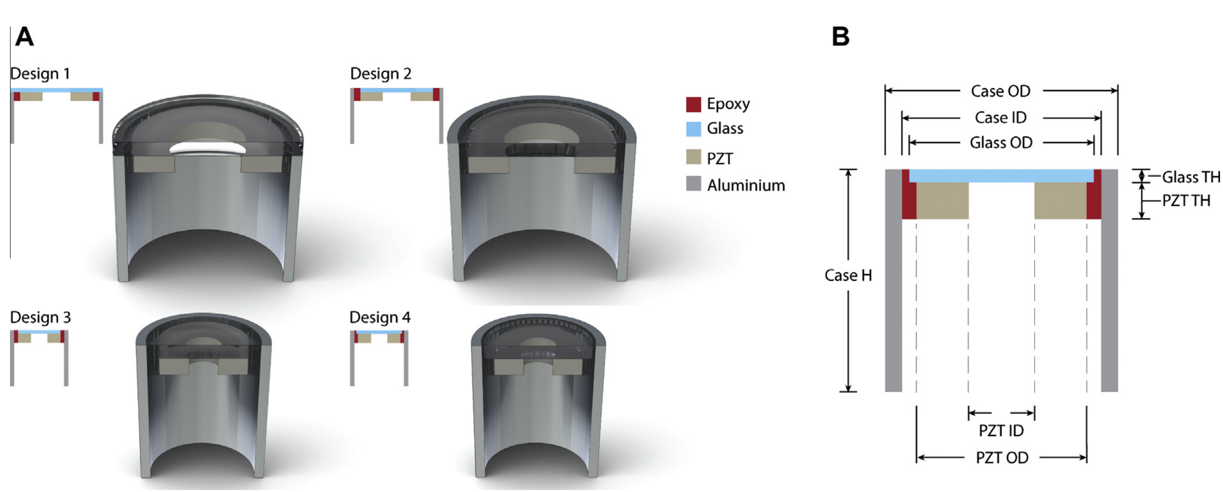

Fig. 1. (A) Graphical representation of designs evaluated with cross-section illustrations depicting component location and geometry. (B) Schematic depicting labels for transducer geometry.