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Experimental and simulation characterisation of flexural vibration modes in unimorph ultrasound transducers

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ABSTRACT

A unimorph flexural transducer design is proposed and tested with regard to mode shapes and frequencies. The transducers consist of a passive metal cap structure, and a thin piezoelectric disc, rigidly bonded to the inside. Extensive finite element (FE) modelling, and experimental 2D, time-resolved displacement measurements were done to characterise the transducers flexural properties, and to compare them to the analytical solutions of thin vibrating plates. Emphasis was put on characterising the passive layer of the unimorph structure, before bonding the piezoelectric element, to understand how the active element affects the behaviour of the flexing plate. A high power Nd:YAG laser was used to actuate the metal plate (non-contact), and the frequency content of the resulting displacement signal was analysed to identify the flexural modes. The non-axisymmetric modes, which are conventionally disregarded because of their unfavourable acoustic properties, were also taken into account. There was excellent agreement between the experimental results and the FE simulation data. There was good agreement with the analytical edge clamped plate model, but with some notable deviations, which have not previously been identified or commented upon. Specifically, the second axisymmetric mode is split into three separate modes, which is not explained by the traditional theory of vibrating plates.

1. Introduction

The field of air-coupled ultrasonics has received an increased interest over the years, as it has expanded into new areas of application, including wireless communication [1], contactless material characterisation [2], gas flow metering [3,4] and robotics [5]. Each application has its own set of requirements, which has pushed the development of transducer technology. The usual problem with air-coupled transduction is the large acoustic impedance mismatch, between the transducer element, typically lead zirconate titanate (PZT), and the propagation medium, causing an inefficient power output and narrow operating bandwidth.

The classical solution is to gradually decrease the impedance along the path of propagation, by introducing one or more matching layers [6], often with a combined thickness of a quarter wavelength. In order to match the transducer impedance to air, low density, often porous, materials are needed [7] that can have undesirable high attenuation. This as well as the introduction of multiple boundaries that can cause failure by debonding, makes the transducer less robust and unsuitable for some industrial applications. For example, ultrasonic transducers used for flow measurements, often incorporate a metal cap that shields the piezoelectric and matching layer elements, but which inevitably causes signal loss and consequently the requirement of higher excitation voltages in these applications.

More recently, piezocomposites [8,9] and ferroelectrets [10] have successfully been used instead of traditional piezoceramics, because of their lower acoustic impedances. Piezocomposites will in general still require a matching layer to achieve acceptable efficiency, and ferroelectrets have high attenuation and are in themselves not very robust.

Electrostatic transducers, such as capacitative micromachined ultrasonic transducers (CMUTs) [11,12], have been demonstrated to have excellent coupling to air, as well as an enhanced bandwidth. However, the requirements of a large bias voltage, as well as a thin flexible membrane as the radiating front face, can be problematic for some applications, including gas flow measurements, where intrinsic safety is highly critical.

Another solution is to use the flexural modes of a metal plate or membrane to produce ultrasound. Because the plate displaces the air by bending, its mechanical impedance is much lower than the acoustic impedance of the plate material [13]. Transducers built on this principle, known as flexural transducers [14–19], can

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produce large displacements for a relatively low excitation voltage. In such a device configuration, a piezoelectric disc can be bonded directly to the back of the plate, without matching layers, thus minimising the number of surface bonds that can fail over time. Also, by having a metal plate as the radiating front face, the transducer gains an inherent robustness, for which other transducers would suffer a signal loss. These types of ceramic–metal transducers, also known as unimorphs [20], bimorphs [21] or multimorphs depending on the number of active layers, are not only used for ultrasound transduction, but can be found in a variety of actuator applications, e.g. energy harvesting [22], where their vibrational and flexing properties are exploited.

Air-coupled flexural transducers are typically used for low power proximity measurements [23], e.g. in parking sensors, as well as for high power ultrasonics [24,25]. Low frequency, typically 40 kHz or lower, flexural transducers are commercially available. However, many applications require higher frequency signals, and the designs proposed in this paper allowed operating frequencies of ∼90 kHz and ∼150 kHz respectively. Some initial results and analyses by the authors on flexural transducers, upon which this article extends, can be found in the conference proceedings [26,27].

The frequency of the vibrations and hence of the ultrasonic wave, depends on the driving frequency of the electrical signal applied to the piezoelectric element, but large amplitude displacements are achieved by driving the system at its resonance frequencies. The resonance frequencies, i.e. the modal frequencies, of the system depend on the geometry of the passive layer and the piezoelectric disc, and are not significantly affected by the through thickness resonance modes of the piezoelectric element, which due to the small thickness are typically over an order of magnitude greater than the operational frequency of the flexural transducer.

Flexural transducers share many traits with the more recently developed piezoelectric micromachined ultrasonic transducers (pMUTs) [28], which combine the enhanced fluid coupling of flextensional vibrations of a plate with micro electromechanical systems (MEMS) technology. In essence, a pMUT is an array of miniaturised flexural transducers operating in the fundamental bending mode. pMUTs have enhanced bandwidth and good fluid coupling, but lack the intrinsic robustness of the macro flexural transducer. Also, because of the microscopic nature of pMUTs, the manufacturing process is more complicated and expensive. The analysis of macroscopic flexural transducers in this paper is similar to that of contemporary pMUT research. An excellent article with experimental validation of theoretical calculations on the flexural properties of the single pMUT element is found in [29].

1.1. Theory of vibrations in plates

The equation describing the time dependent, normal displacement of a thin plate is a fourth order partial differential equation [30]:

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

where w is the normal displacement of the plate, ρ is the volume density and D is the rigidity, which is given by

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

where E is Young's modulus, h is the plate thickness and ν is Poisson's ratio. Solving (1) to find mode shapes $W_{m,n}$ gives

$$W_{m,n}(r,\theta) = \left(A_n I_n\left(\frac{\lambda_{m,n}}{a}r\right) + B_n J_n\left(\frac{\lambda_{m,n}}{a}r\right)\right)\cos(n\theta), \tag{3}$$

where A_n and B_n are constants determined by the boundary conditions, a is the plate radius, $\lambda_{m,n}$ is the mode constant for the (m,n) mode, which has m radial nodes (excluding the outer edge) and n nodal diameters. The frequency of a mode is given by

$$f_{m,n} = \frac{1}{2\pi}\left(\frac{\lambda_{m,n}}{a}\right)^2\sqrt{\frac{D}{\rho}}. \tag{4}$$

Fig. 1 illustrates the mode numbering convention used, which is also used in [30]. Some numerically calculated values of λ are given in Table 1.

2. Methods

The transducer design introduced in this paper is schematically shown with labeled dimensions in Fig. 2. Two types of transducers were made, one from aluminium and one from titanium. The dimensions of the transducers were chosen such that the vibrating front face of the passive layer is significantly thinner than the sides of the cap, in order to simulate clamped boundary conditions. Also, for the Al transducer the thickness and radius of the cap were chosen such that the (1,0) mode should be above 100 kHz. The values of the dimensions for each type of transducer is given in Table 2. Aluminium was chosen because it is easy to process, and titanium because of its robustness, durability and strength to weight ratio for industrial applications. For similar reason stainless steel was also initially tested, but its material properties, e.g. high rigidity, makes it less efficient for flexural transduction, and consequently not considered within this paper.

Finite element (FE) methods [31], using software package PZFlex (Weidlinger Associates Inc., USA), were used to simulate axisymmetric flexural transducers. The FE model was used to identify the modal frequencies of the transducer as well as for

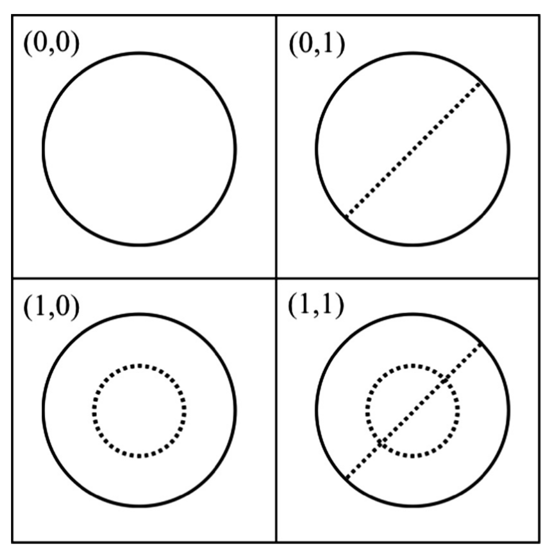

Fig. 1. Nodal lines of the four first modes of an edge clamped plate.

Table 1
Numerically calculated values of the mode constant $\lambda_{m,n}$ of a clamped plate, from (3), for $m = 0,1,2$ and $n = 0,1,2,3$.

m	n 0	1	2	3
0	3.19625	4.61085	5.90565	7.14355
1	6.30645	7.79925	9.19685	10.5366
2	9.43945	10.958	12.4022	13.795