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Improving the air coupling of bulk piezoelectric transducers with wedges of power-law profiles: A numerical study

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ABSTRACT

An air-coupled ultrasonic transducer is created by bonding a bulk piezoelectric element onto the surface of a thick plate with a wedge of power-law profile. The wedge is used to improve the ultrasonic radiation efficiency. The power-law profile provides a smooth, impedance-matching transition for the mechanical energy to be transferred from the thick plate to the air, through the large-amplitude flexural waves observed in the thinnest region of the wedge. The performance of the proposed transducer is examined numerically and compared to that of a design where the piezoelectric element is isolated and where it is affixed to a thin plate of uniform thickness. The numerical analysis is first focused on the free-field radiation of the transducers. Then, time-reversal experiments are simulated by placing the transducers inside a cavity of arbitrary shape with some perfectly reflecting boundaries. In addition to time-reversal mirrors, the proposed concept could be integrated in the design of phased arrays and parametric arrays.

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1. Introduction

The ability to create a high-amplitude excitation focused in space and time is critical to achieve high-resolution imaging in nondestructive evaluation (NDE) of elastic structures [1,2]. Other applications include medical needs (imaging, hyperthermia, and lithotripsy) [3] and underwater communication [4]. NDE techniques rely increasingly on air-coupled transducers due to the many advantages they offer. As bonding between the transducer and the structure is no longer necessary, rapid imaging of large areas is then becoming possible.

Air-coupled transducers can be separated mainly in two categories: bulk piezoelectric transducers and micro-machined ultrasonic transducers (MUTs). The first category is still used extensively for NDE applications. A bulk piezoelectric transducer performs well when its impedance is of the same order of magnitude as that of the medium it is coupled to. For this reason, they are preferred when bonding with the test specimen is possible and high amplitude excitation is required. For the same reason, coupling with air is problematic because of the impedance mismatch, by several orders of magnitude, between air (~400 Rayl and typical piezoelectric materials (~35 MRayl). This limitation is most commonly addressed by the use of matching layers [5,6] but at the expense of a reduced bandwidth and the subsequent ringing of the device. The second category of air-coupled transducers (MUTs) offers excellent impedance matching with air, a broader bandwidth, and a reduction in size of the apparatus. However, these transducers cannot be fabricated and implemented without micro-fabrication capabilities. Capacitive MUTs have been introduced in the 1990s [7,8]. A single element of these transducers typically consists of an air-filled cavity enclosed on one side by a stretched, flexible, metallic membrane (sensing and emitting element) and on the opposite side by a rigid conducting back plate, which drives the membrane through an applied alternating voltage. More recently, piezoelectric MUTs have been developed by using thin piezoelectric membranes [9–11], thus removing the need for a conducting back plate. An electric field is applied across the thickness of the piezoelectric film, which in turn induces a deformation of the membrane according to its bending modes.

Ultrasonic arrays of transducers have been increasingly preferred over single-element transducers because they offer more flexibility in the type of ultrasonic fields generated, better imaging capabilities, and may be used to focus ultrasonic energy at desired locations. Drinkwater and Wilcox [12] give an extensive review on this topic, focusing on phased arrays, where the transducer materials and array geometries are discussed. The operation of phased arrays is based on the use of appropriate time delays between the signals applied to or received from the individual transducers. Although widely used, phased arrays suffer from a number of limitations. First, computing time delays in a reverberant environment

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is not a trivial task. Second, it is important to reduce or ideally eliminate the cross-talk between the transducers so that they can be controlled independently. Third, the performance of a phased array is limited by the number of transducers.

An alternative strategy consists of using the concept of time reversal (TR) with an array of transducers to create a TR mirror (TRM) [13,14]. Unlike a phased array, this device can focus energy in space and time without *a priori* knowledge of the time delays between the transducer signals. Besides, its performance increases with the amount of scattering in the environment. In fact, the size of the TRM can be reduced to a single element in a reverberant environment of non-regular shape, which is often referred to as a *chaotic cavity* [15–18]. The multiple reflections in the environment act as virtual transducers (additional degrees of freedom) that can be used to improve the quality of the focusing. On the other hand, the non-regular shape of the environment breaks any symmetry that could potentially exist in the problem. Based on this concept, Etaix et al. [19] proposed an air-coupled TRM where a bulk piezoelectric transducer is glued onto a thin plate for 3D imaging applications (e.g. detection of objects) in air. The high modal density of the plate vibration provides the required reverberant environment in 2D. The focusing in 3D is achieved through the fluid–structure interaction. Other than shape and size, the modal density of the plate vibration can also be increased in a limited bandwidth via an array of periodically-spaced resonators (metamaterial-inspired approach) connected to the plate [20]. Le Bas et al. [21] developed an air-coupled TRM for NDE applications where relatively large amplitude of the focused energy is required to excite the non-linear features (e.g. crack, delamination, and other flaws) of the test sample. Their device consists of an acoustic cavity of pyramidal shape enclosed by thin metallic walls onto which bulk piezoelectric transducers are glued. The cavity creates a diffuse wave field inside, through the vibration of the walls, the multiple reflections inside the cavity, and the fluid–structure interaction. The cavity also contains an opening to allow a progressive emission of the scattered waves toward the location where ultrasonic energy should be focused. This work follows directly that from Arnal et al. [22] where a chaotic cavity was developed to focus ultrasonic energy in water. It is worth mentioning that it is easier to achieve higher pressure levels in water than in air because the fluid–structure coupling is more important when the structure is light relative to the surrounding fluid (i.e. better impedance matching).

In the recent work on air-coupled TRMs, little attention has been devoted to improving the impedance matching for the coupling of the piezoelectric transducers to the air. Optimizing the acoustic output of the transducers is critical to achieve a sufficient signal-to-noise ratio and to develop a useful tool for imaging or non-contact NDE applications. In this paper, the possibility of using bulk piezoelectric ceramics as efficient air-coupled transducers is examined numerically using finite-element (FE) analysis. The concept of wedges of power-law profiles and their properties on the propagation of flexural waves are exploited for this application. This concept has been used to mitigate plate vibration for automotive and aerospace applications at low frequencies (e.g. <10 kHz) [23,24] but, to the authors' knowledge, not yet to enhance the sound radiation from piezoelectric transducers or for the design of air-coupled ultrasonic arrays. This work intends to bridge the gap between the practicality of using bulk piezoelectric ceramics and the sound-radiation efficiency of MUTs.

This paper is organized as follows. Section 2 introduces the theory behind the propagation of elastic waves in a wedge of power-law profile. This section also describes the main physical mechanisms involved in the problem, including wave propagation in elastic solids, piezoelectric effect, propagation of sound in the surrounding fluid, and fluid–structure interaction. Section 3 describes the numerical model settings and analyzes the free-field ultrasonic radiation of various ultrasonic transducers. Specific attention is given to the acoustic radiation from wedges of power-law profiles. In Section 4, the performance of the proposed design is discussed in the context of a numerical TR experiment. Section 5 concludes.

2. Problem description and resolution

The problem considered in this paper is the vibration of and sound radiation from a bulk piezoelectric element and the plate it is affixed to, as depicted in Fig. 1. Away from the interface between the plate and the piezoelectric element, the thickness of the plate is not necessarily uniform but may decrease smoothly from h_0 to h_1 over the distance x_0 as,

$$h(x) = \frac{(h_0 - h_1)(x_0 - x)^m}{x_0^m} + h_1, \quad \forall x \in [0, x_0] \tag{1}$$

where m is a positive real number.

2.1. Flexural waves in a wedge of power-law profile

Starting from thin-plate theory, it is possible to demonstrate that flexural waves propagating along a wedge of a power-law profile, such as that depicted in Fig. 1, will exhibit low propagation velocities with the elastic energy eventually concentrating near the wedge tip [25,26].

The differential equation governing the motion of a thin plate in vacuum with a variable thickness in the x-direction may be expressed as [27],

$$D(x)\nabla^4 w + 2\frac{dD(x)}{dx}\frac{\partial}{\partial x}\nabla^2 w + \frac{d^2D(x)}{dx^2}\left(\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2}\right) + \rho h(x)\frac{\partial^2 w}{\partial t^2} = 0 \tag{2}$$

where $w(x,y)$ is the normal displacement of the mid-plane of the thin plate, $h(x)$ is the local thickness of the plate, ρ is the mass per unit volume, $D(x)$ is the local flexural rigidity defined as $D(x) = Eh(x)^3/(12(1-\nu^2))$, E is the Young's modulus, and ν is the Poisson ratio. Using geometrical acoustics, the local wavenumber of a plane flexural wave in a wedge with profile $h(x)$ may be expressed as,

$$k(x) = 12^{1/4} k_p^{1/2} h(x)^{-1/2} \tag{3}$$

where $k_p = \omega/c_p$ is the wavenumber of a symmetrical plate wave, ω is its angular frequency, and $c_p = 2c_s\sqrt{1-(c_s/c_l)^2}$ is its phase

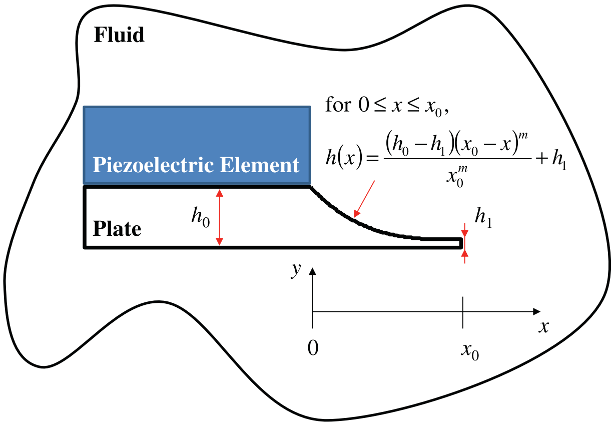

Fig. 1. Schematic representation of the system to be modeled.