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Passive focusing techniques for piezoelectric air-coupled ultrasonic transducers

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ABSTRACT

This paper proposes a novel passive focusing system for Air-Coupled Ultrasonic (ACU) piezoelectric transducers which is inspired by the Newtonian–Cassegrain (NC) telescope concept. It consist of a primary spherical mirror with an output hole and a flat secondary mirror, normal to the propagation axis, that is the transducer surface itself. The device is modeled and acoustic field is calculated showing a collimated beam with a symmetrical focus. A prototype according to this design is built and tested with an ACU piezoelectric transducer with center frequency at 400 kHz, high-sensitivity, wideband and 25 mm diameter flat aperture. The acoustic field is measured and compared with calculations. The presented prototype exhibit a 1.5 mm focus width and a collimated beam up to 15 mm off the output hole. In addition, the performance of this novel design is compared, both theoretically and experimentally, with two techniques used before for electrostatic transducers: the Fresnel Zone Plate – FZP and the off-axis parabolic or spherical mirror.

The proposed NC arrangement has a coaxial design, which eases the transducers positioning and use in many applications, and is less bulky than off-axis mirrors. Unlike in off-axis mirrors, it is now possible to use a spherical primary mirror with minimum aberrations. FZP provides a more compact solution and is easy to build, but presents some background noise due to interference of waves diffracted at out of focus regions. By contrast, off-axis parabolic mirrors provide a well defined focus and are free from background noise, although they are bulky and more difficult to build. Spherical mirrors are more easily built, but this yields a non symmetric beam and a poorly defined focus.

1. Introduction

Air-coupled ultrasound (ACU) sensing offers advantages over conventional fluid coupling techniques where the use of coupling fluids is not possible either for practical reasons or for the undesired effect they may have on the material under study. Applications appear in the fields of Non Destructive Testing (NDT) [1–9] materials characterization [10–14], wireless power and information transmission [15], sensing and analysis of cultural heritage [16,17], water control in agriculture [18,19], 3D surface profiling [20,21], quality control in the food industry [22,23] and computer gesture-based control [24,25].

Main drawbacks are the strong velocity and impedance mismatch between air and solids, which yields a very large reflection coefficient and a strong refraction at any air/solid interface and the high attenuation in the air. This imposes severe restrictions in the system dynamic range and in the alignment of sound beam axes and material surface, making difficult the inspection of non-flat components, rough surfaces and the use of focused beams.

Improvements in the design of ACU transducers [2,26–33], high energy excitations, low noise amplification and digital signal processing [34–38], have enabled the applications previously mentioned. To further reduce losses and keep a reasonable signal to noise ratio (SNR), working frequency is usually kept below 1 MHz. Disk-shaped piezocomposites for these relatively low frequencies have a typical diameter from 15 to 25 mm, which produce a sound beam with poor lateral resolution. There are a number of focusing solutions available to mitigate this problem.

Phased array techniques can be used to this purpose [39]. Direct generation of collimated ultrasound beams has been achieved with annular array transducers with radii set to produce non-diffracting Bessel beams [40,41]. Bessel-type transducers with selective ring poling have been also proposed [42]. A simpler collimated beam design has been achieved by shaping two electrodes in one face of a homogeneous poled ceramic to generate plane or edge waves by switching the excitation [43].

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These "active" techniques require phasing multiple excitations and specifically designed multi-element transducers to get a single beam. By contrast, the same functions have been traditionally achieved with simpler "passive" means: refractive (lenses), apodization (horns), reflexive (mirrors) or interference devices (zone plates), schematically summarized in Fig. 1. In spite of their limitations, these low-cost approaches can be very effective for real-life ACU applications. For capacitive or electrostatic transducers, solutions based on the use of a spherical back plate and adapted Mylar foils [44] or shaped reflective optics solutions (parabolic mirror) [45] have been described.

Refractive lenses are commonly used to focus immersion transducers (Fig. 1a). The most common are spherically focused, although collimator lenses with logarithmic shape to get a large focal depth have been also proposed [46]. In the past, sound focusing in air was carried out by confining CO_2 in a thin wall container with a convex lens shape [47]. However, implementation of this solution results cumbersome.

Apodization allows narrowing the ultrasound beam by attaching masks, horns or cones (Fig. 1b), while this eases transducers alignment and reduces reverberations [48], this is achieved at the expense of significant signal amplitude and SNR losses [49].

Among the reflective techniques, parabolic mirrors have been used to focus ultrasonic beams of capacitive transducers, Fig. 1c [45,50,51]. However, they tend to be bulky, require careful mirror grinding and are rather difficult to align due to the lack of an evident propagation axis.

Fresnel Zone Plates (FZP) (Fig. 1d), consist of alternating transmitting and opaque rings and have been tried before for air-coupled capacitive transducers [52–56]. Diffraction at the transmitting rings produce constructive interferences at the focus by proper selection of their radii at the operating frequency. FZP are thin and flat, which represent a compact focusing element. However, only a fraction of the sound beam intensity reaches the focus due to the masking effect of the opaque rings.

Comprehensive theoretical background and experimental data are available, but a comparative analysis for ACU beamforming is missed in the literature. Such study would be useful to choose among the different passive focusing alternatives that best fit a specific application.

In this work three passive focusing techniques for ACU transducers are analyzed: the well known FZP and off-axis focused mirror are compared with a new arrangement proposed here, which derives from the Newtonian-Cassegrain telescope concept. These configurations are tried together with piezoelectric, instead of capacitive transducers, as it was done in previous works, showing the compatibility of the different focusing configurations with the multilayered configuration of air-coupled piezoelectric transducers required to optimize bandwidth and sensitivity.

2. Background on passive focusing techniques

The typical diameter of air-coupled piezoelectric transducers based on 1–3 connectivity piezocomposites is about 15–25 mm for frequencies below 400 kHz. For many applications, some means must be used to reduce the beam width and increase lateral resolution. The most frequently used technique is carving a spherical surface in the ceramic element and in the matching layers. This method provides a fixed focus and different transducers are required to get different focusing distances. Furthermore, accurate fabrication of the stack of matching layers required for ACU transducers may become unpractical.

For a concave transducer with an aperture $D = 2R$, the Full Width at Half Maximum of the field (FWHM) at focal distance F within the near field region ($F < D^2/4\lambda$) is given by [57]:

$$\mathrm{FWHM} = 1.4\frac{\lambda F}{2R}, \tag{1}$$

which determines the half-width lateral resolution. For some ACU applications, part of the focused beam arrives to the target exceeding the critical angle for which full reflection is produced and either Lamb or surface waves may be generated, thus reducing its efficiency. Large focal distances should be used to minimize this effect.

On the other hand, external focusing devices could be attached to a general-purpose flat transducer to change the beam shape and the focal distance. This would involve the use of concave matching layers but this has the undesired effect of breaking the resonant condition which is critical for the optimum design of the ACU transducer. Given these problems, diffractive and reflective techniques have been used instead: the Fresnel Zone Plate (FZP) and the off-axis parabolic mirrors. We briefly describe their working principles and some of their properties by continuous wave simulations using the Monochromatic Transfer Matrix method [58].

2.1. Fresnel Zone Plates (FZP)

A FZP is a diffractive device composed of a series of alternate transmitting and blocking rings, with radii set at:

$$r_n = \sqrt{\lambda F n + \frac{\lambda^2 n^2}{4}} \quad n = 1, 2, 3, \ldots \tag{2}$$

where F is focal distance and λ is wavelength. Starting from the center, the circle with radius r_1 is transparent; the first blocking ring is from r_1 to r_2 and so on. It can be verified that the distances from consecutive r_n to the focus differ by half wavelength. This way, alternating transparent with opaque rings leave signals producing constructive interferences at the focus. The focus position F should be set within the near field limit.

Although designed for a specific focal distance and wavelength, it has been shown that a single FZP is able of focusing in air over a rather large frequency range [54]. This way, a FZP with wideband transducers will provide an increased depth of field.

Simulated field distributions of a FZP designed for $f = 400$ kHz, $R = 12.5$ mm and $F = 35$ mm are shown in Fig. 2a. It can be compared with the field created by an ideal spherically focused transducer of the same diameter at the same depth (Fig. 2b). Bottom panels of Fig. 2a and 2b shows the lateral profile at the focal plane for FZP and spherically focused transducer, respectively. In both cases, maximum field amplitude is found at 35.3 mm, with an estimated FWHM of 1.3 mm and a depth of field of 11.5 mm at −3 dB.

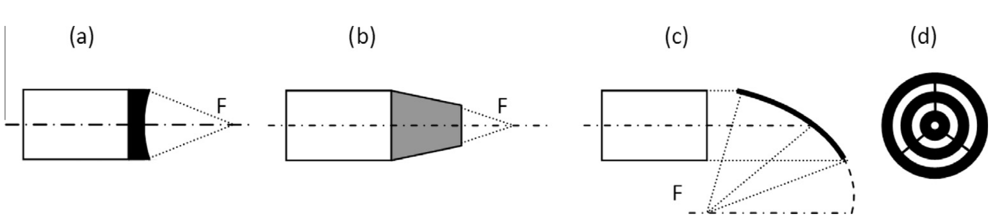

Fig. 1. Passive focusing: (a) Lens for immersion transducer; (b) Apodization cone; (c) Off-axis parabolic mirror and (d) Fresnel zone plate.