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Ultrasonic radiation from wedges of cubic profile: Experimental results

Brian E. Anderson [a,*], Marcel C. Remillieux [a], Pierre-Yves Le Bas [a], T.J. Ulrich [a], Lukasz Pieczonka [b]

[a] *Geophysics Group (EES-17), MS D446, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

[b] *Department of Robotics and Mechatronics, AGH University of Science and Technology, Al. A. Mickiewicza 30, 30-059 Krakow, Poland*

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A B S T R A C T

This paper presents experimental results demonstrating the increase in ultrasonic radiation obtained from a wedge of cubic profile relative to a plate of uniform thickness. The wedge of cubic profile provides high efficiency sound radiation matching layer from a mounted piezoelectric transducer into the surrounding air. Previous research on structures with indentations of power-law profile has focused on vibration mitigation using the so called "acoustic black-hole" effect, whereas here such structures are used to enhance ultrasonic radiation. The work provides experimental verification of the numerical results of Remillieux et al. (2014).

1. Introduction

Efficient radiation of ultrasonic sound, for the purpose of non-contact nondestructive evaluation and testing applications, presents unique challenges [1]. Piezoelectric transducers, which can be easily designed to have resonance frequencies in the ultrasonic frequency range (>20 kHz), suffer from a large impedance contrast on the order of 10^5 for radiation into air. Nonetheless, piezoelectric transducers are relatively inexpensive and have the capacity to generate a large amount of energy. Coupling the vibration energy produced by a piezoelectric transducer into acoustic radiation into air can be made more efficient with the use of matching layers [1]. Here we present results from an unconventional matching layer.

The "acoustic black-hole" effect obtained from structures with indentations of power law profiles has been used for vibration mitigation, with expected applications in the aerospace and automotive industries [2,3]. This effect was first evidenced by Mironov [4] and Krylov [5], who showed theoretically that a flexural wave slows down and eventually stops when traveling down a wedge with a thickness decreasing smoothly to zero according to a power law. As a result, the flexural wave is not reflected from the wedge tip and the elastic energy becomes trapped in the thinnest portion of the wedge. In practice, however, manufacturing a perfect wedge with a tip of zero thickness is not feasible, which is detrimental to the absorptive properties of the wedge. In addition, the length of the wedge should be comparable to or larger than the acoustic wavelength targeted, which restricts its use above 2 kHz in industrial applications [3].

Rather than using plates of power-law profile for vibration mitigation, Remillieux et al. recently proposed the idea of using these structures as a matching layer for coupling more efficiently the energy emitted by a piezoelectric transducer into air [6]. They used 2D numerical simulations to compare the radiation from wedges of quadratic, cubic, and quartic profiles. They found that the cubic and quartic profiles provided more efficient sound radiation than a quadratic profile, but that the quartic profile wedge did not provide a significant increase in efficiency over the cubic profile to warrant machining the more difficult quartic profile. The cubic profile increased the sound radiation by a factor of 5.5 (14.8 dB) over the sound radiated by the piezoelectric transducer alone. It is noted that this comparison was made at the respective peak resonance frequencies for each configuration, but the cubic profile introduced several strong resonances, whereas the bare piezoelectric radiation only possessed one resonance frequency.

The purpose of this paper is to provide the first experimental verification of the idea of using wedges of power-law profiles to enhance ultrasonic radiation of piezoelectric transducers into air. Wedges of linear, quadratic, and cubic profiles were manufactured and piezoelectric transducers were mounted to them. Experimental measurements of their sound radiation are compared to radiation from a piezoelectric transducer mounted to a thin plate and to a transducer mounted to a thick plate. Each of the wedge assemblies provide more efficient ultrasonic radiation compared to the thin and thick plates. Further, the experiments show that the wedge of cubic profile provided more efficient radiation than those of linear and quadratic profiles as was also

* Corresponding author.
E-mail address: bea@lanl.gov (B.E. Anderson).

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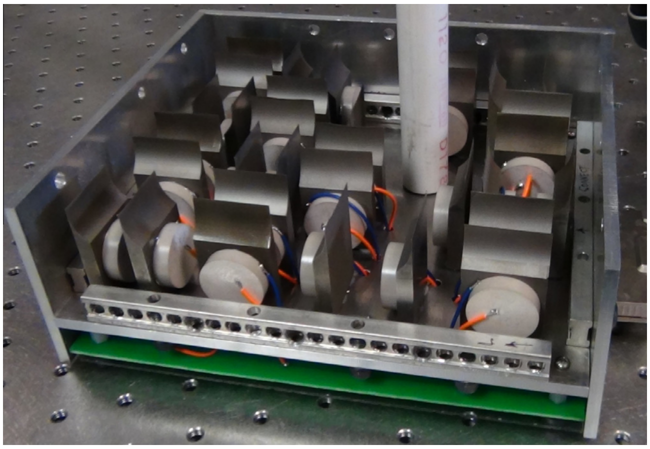

Fig. 1. Photograph of the bottom half of a Time Reversal Acoustic Non-Contact Excitation (TRANCE) device with 32 cubic wedge transducers mounted inside. The 2.54 cm × 2.54 cm screw hole pattern in the optical table in the background provides a scale reference.

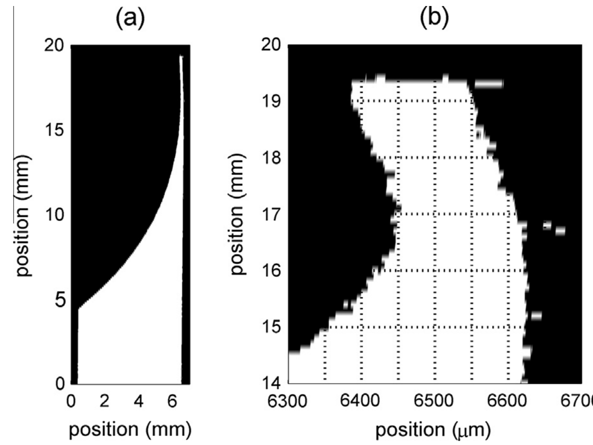

Fig. 2. Cubic wedge side profiles obtained from a white light profilometer. (a) Zoomed out with x and y axes to scale. (b) Zoomed in image, with the x scale enlarged.

demonstrated in the work of Remillieux et al. [6], despite the fact that the model was restricted to two dimensions, whereas the wedges used here have a finite width in the third dimension, giving rise to the possibility of structural modes in this third dimension.

The goal of this work is to develop a highly efficient radiator of sound spanning the frequency range of 20–100 kHz. One of the intended applications for these radiators is to use them as the primary sources in a Time Reversal Acoustic Non-Contact Excitation (TRANCE) source [7]. TRANCE relies on the focusing properties of the time reversal process [8,9] and is used to excite structures without contact for nondestructive evaluation purposes. In terms of excitation amplitude, a preliminary and unoptimized design of TRANCE has been shown to be more efficient by nearly an order of magnitude than traditional sources, such as a focused ultrasound transducer. Fig. 1 displays a photo of the non-contact sources under investigation in this paper, mounted in a TRANCE device. The top half of the TRANCE device is missing from the photo. Typically the sources are mounted in a nearly enclosed cavity to generate reverberation and thus the directional or omni-directional nature of the radiator is not necessarily important, but rather the cumulative radiated sound energy from each primary source.

2. Experiment

As described in the previous section, the acoustic black-hole theory suggests that it is ideal to have the wedge tip approach a zero thickness. It was found that an Electro Discharge Machine (EDM) was able to create thinner wedge tips than a Computer Numerical Control (CNC) machining process. A Mitsubishi FA-10 and 0.254 mm (0.010 in.) diameter Van-TG brass, plus premium wire was used with 5 skim passes on each 304L stainless steel (density = 8030 kg/m^3, Young's modulus = 193 GPa, and Poisson's ratio = 0.24) wedge. The resulting manufactured parts have dimensions of 45 mm × 30 mm along the bottom surface, including a 30 × 30 mm^2 portion with a constant thickness of 6 mm and a 15 × 30 mm^2 portion following a power-law profile from an original thickness of 6 mm down to an initial design tip thickness of 75 μm according to Ref. [6]. Using a Nanovea ST400 white light profilometer to measure the surface profile, it was found that the cubic profile tip could be tapered down to a thickness of 156 μm. Attempts to machine the tip thickness to smaller thicknesses failed, resulting in removing material from the wedge taper length and/or significant warping of the shape of the tip. Fig. 2 displays the measured side profile, obtained by the profilometer, of the cubic wedge. While not specifically measured, it is assumed by visual inspection that the quadratic and linear wedges were machined down to approximately the same thickness. The thickness of 6 mm was selected to provide a good initial impedance match for the piezoelectric transducer. The thin plate measured 45 mm × 30 mm × 0.45 mm, with the thickness selected according to the results shown in Fig. 7 of Remillieux et al. [6]. The thick plate measured 45 mm × 30 mm × 6.0 mm. The piezoelectric transducers used were made by APC International of type 850 and dimensions of 25.4 mm diameter by 6.3 mm thick. Devcon® 5 Minute epoxy was used to bond the transducers to the wedges or plate. Fig. 3(a) displays a photograph of the transducer assemblies studied.

The transducer wedge/plate under test was mounted to the end of 74 cm length rod that was connected to a Newport SR50CC rotation stage. Fig. 3(b) displays a schematic of the setup. A 12-bit Gage CompuGen 8150 card was used to output a 1 Vpp chirp signal spanning 20–100 kHz of 58 ms duration. A Tabor 9400 power amplifier was used to amplify the chirp signal with a 50 times gain. A GRAS 40BE 6.3 mm (0.25 in.) diameter microphone, with a 4.31 mV/Pa sensitivity, was placed 31 cm from the transducer assembly, perpendicular to the axis of rotation. The axis of rotation is about the axis of the rod as indicated in Fig. 3(b). A PCB 482C signal conditioner was used in conjunction with the microphone. A 14-bit Gage CompuScope 14200 card with a 10 MHz sampling frequency was used to record the microphone signals for 65.5 ms. Measurements were made by rotating the transducer assembly at 5° increments from 0° to 360° around the axis of the supporting rod, using 244 averages at each position. A signal to noise ratio of at least 40 dB was obtained over the entire range of frequencies.

The recorded responses were then cross correlated with the chirp signal and the correlation result was time gated to include only the direct arrival of sound (and ignore any reflected energy). A fast Fourier transform is applied to the direct sound signal to obtain a spectrum for the sound radiated from the transducer assembly at each rotation position. Fig. 4 displays surface profile plots of the spectra recorded at each rotation angle for the thin plate transducer, the linear wedge, the quadratic wedge, and the cubic wedge transducer. Results for the thick plate are not displayed here as the thin plate easily outperformed the thick plate, as expected from Ref. [6]. An angular averaging was done for each set of spectra to obtain an average sound pressure level spectrum. Additionally, a frequency averaging was done at each angle to determine an average sound pressure level directivity.