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Airborne broad-beam emitter from a capacitive transducer and a cylindrical structure

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***Abstract*—Beamwidth broadening of an ultrasonic air-coupled transducer is performed by an emitter constituted of an electrostatic transducer and of a cylinder with an opening at the top covering the surface of the transducer. The acoustic emission is thus forced through a hole smaller than the diameter of the transducer's surface. In particular, a cylinder with an upper diameter of 10mm and a height of 5mm ensures the beam pattern of the final emitter is broad across a wide frequency range. Sound attenuation is reduced and lobes in the transducer's beam pattern are cancelled. Beam broadening can improve range estimation techniques and ultrasonic sonar as a wider area can be inspected with one emission with no need for scanning.**

***Index Terms*—Beam pattern, broad beamwidth, ultrasonic emitter, airborne transducer, sonar, ultrasonic ranging.**

I. Introduction

Air-coupled transducers are widely used in ultrasonic ranging and sonar. Ultrasonic ranging is accomplished with probes designed to produce and receive ultrasonic signals to calculate target distance from the measurement of time between emission and reception [1]- [3]. Polaroid transducers are typical for this application [3], [4] and their beam pattern is narrow across frequencies. For this reason, scanning is required to tilt the probe and direct the sound at several locations with enough acoustic energy to get reflected sound back so that ultrasonic ranging can be accomplished. Sonar systems based on air-coupled transducers implementing localization strategies inspired by bat echolocation [5]- [9] use frequency ranges within $[20, 150]$kHz. Also in this case the directional properties of the emitter limit the acoustic field of view of the overall sonar system as only a small area can be ensonified in one emission.

The transducers typically employed for the above applications could benefit from beamwidth broadening. Indeed, instead of scanning, a single emission of the ultrasonic signal would allow the sound to be directed over a wider area in front of the emitter.

Previous techniques to enlarge the beam pattern of probes are: cylindrical PVDF film transducers [10], twisted acoustic lenses [11] and spherical piezoelectric transducers [12]. PVDF film transducers [10] are cylindrical therefore their pressure field is constant for orientations $0°$ to $180°$ along a plane normal to the height of the cylinder. Nevertheless, because of the geometry of the cylinder itself, the spreading of acoustical pressure in the vertical direction is very directional: the beam pattern decreases 40dB within $\pm 30°$ off the main axis. Twisted lenses [11] provide an enlarged beam pattern, though the difference between the maximum and the minimum values of the beam pattern is 20dB to 30dB. Finally, although radial modes of spherical piezoelectric transducers [12] are detailed, the directional properties of these probes are not.

The use of cylindrical structures appropriately designed and placed in front of an airborne transducer's membrane is explored in this paper. The purpose is to provide the assembled emitter with a broad beamwidth both in the horizontal and vertical direction.

II. Cylindrical structures

The emitter proposed in this paper for sonar applications is composed of an air-coupled transducer and a cylindrical structure mounted in front of the transducer's membrane. The purpose of the structure is to reduce the opening of the probe so providing the emitter with a wider beam pattern than that of the transducer over a frequency range typically used for ultrasonic localization.

A. Design and 3D printing

The cross section of the cylindrical template is shown in Fig. 1. This template is defined by its lower diameter D, which matches the diameter of the transducer's membrane, the upper diameter d and its height h. Given that the diameter of the transducer's membrane is 5cm, D was chosen as $D = 56$mm so not to be in contact with the membrane itself.

The structure was designed using FreeCAD, a parametric 3D model software. After being implemented it was saved as an STL file for 3D printing. The STL file was then uploaded onto a MakerBot Replicator 2 printer. The technology used by this printer is Fused Deposition Modeling which works by melting Polylactic acid (PLA) and laying down the molten material in layers. To produce this structure the resolution was changed to 200um per layer, this resolution guaranteeing enough accuracy.

III. Measurements

A. Measurement setting

Measurements were conducted in a soundproof room. An Ultrasound U/S $S55/6$ Loudspeaker [13] was driven with a 5-cycle toneburst at frequencies in the range $[20, 70]$kHz with

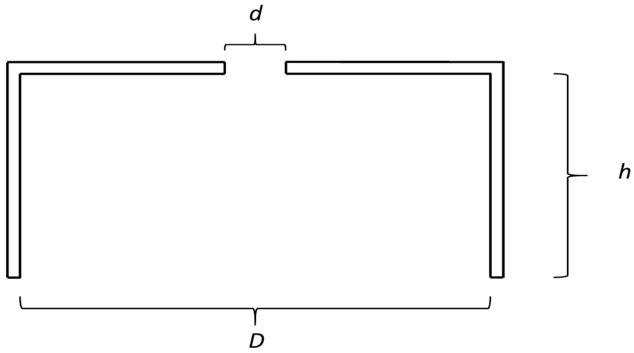

Fig. 1. Cross section of cylindrical structure defined by parameters: diameter *D* of lower opening (same as transducer's diameter), upper opening's diameter d and height h.

Fig. 2. Ultrasound Loudspeaker (left) as the air-coupled transducer used in the measurements. Assembly transducer-cylindrical structure (right) as one of the emitters.

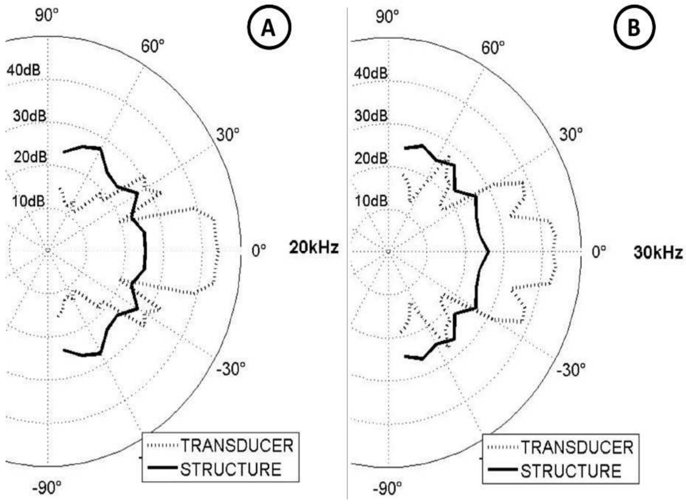

Fig. 3. Measured beam patterns. (A) at 20kHz associated with the transducer (dotted line), and emitter composed of transducer and structure (continuous line). (B) at 30kHz associated with the transducer (dotted line) and emitter (continuous line).

a frequency step of 10kHz and the sound from the transducer was recorded through a B&K 4138 microphone. Microphone positions were on a semi-circumference facing the loudspeaker and centered at the transducer location at a 20cm distance from it, so to definitely be in the far-field region for frequencies $[20, 70]$kHz. These locations on the circumference arc were spaced 10° and spanned the range $[-80^\circ, 80^\circ]$. For each frequency and position, the recorded signal was averaged 128 times. Fig. 2 shows the transducer [13] on the left while on the right the transducer has the cylindrical structure mounted in front of its membrane. Sticky tack was used along the lower edges of the structure to fix it to the transducer and to prevent sound leakage; after measurements at all frequencies and microphone positions were taken, the structure could be easily removed.

B. Results

The acoustic properties of the air-coupled transducer joined with the structure were characterised, and not the radiation properties of the cylindrical structures independently on the transducer they filtered the signal from. Hence, the signals from the transducer-structure mounting were not normalised with respect to acoustic emission from the transducer alone, which is typically the case when there is need to get rid of non-linearity effects due to the source when the final purpose is to investigate radiation properties of the structure only [14].

The results are the values of the beam pattern (only magnitude data) associated with the emitter over an arc of circumference at angles $[-80^\circ, 80^\circ]$, 0° being the direction normal to the surface of the emitter. In this section, the beam patterns of the U/S loudspeaker [13] alone and of the loudspeaker joined with the structure are depicted in the same figure. The emitter's and transducer's beam patterns are symmetric both in azimuth and elevation.

Fig. 3 shows the beam pattern associated with the bare transducer (dotted line) and with the emitter (continuous line) at 20kHz and 30kHz. At 20kHz, as depicted in Fig. 3 A, the transducer's beam pattern is very directional, presents a notch around 20° and -20° and the differs about 25dB between its maximum and minimum values. Mounting the cylindrical structure in front of it makes the acoustic energy at 20kHz spread over all directions and reduces the difference between maximum and minimum values 5dB only. Similar results are obtained at 30kHz, as shown in Fig. 3 B.

In Fig. 4 the beam pattern associated with the emitter is broader than that associated with the transducer only. Across orientations, the beam values differ 12dB at most at 40kHz, see Fig. 3 A, while at 50kHz, Fig. 3 B, the beam pattern is regular as it is smooth and shows no notches. At 50kHz the difference between the minimum and the maximum value in the beam pattern is 9dB. The minimum values are at $\pm 80^\circ$ only.

At 60kHz the beam pattern associated with the emitter is the most regular, see Fig. 5 A. The minimum values, occurring around $\pm 60^\circ$, and the maximum, at 0° differ 2dB only. The design of the cylindrical structure with $d = 10$mm and $h = 5$mm is therefore particularly efficient at 60kHz.

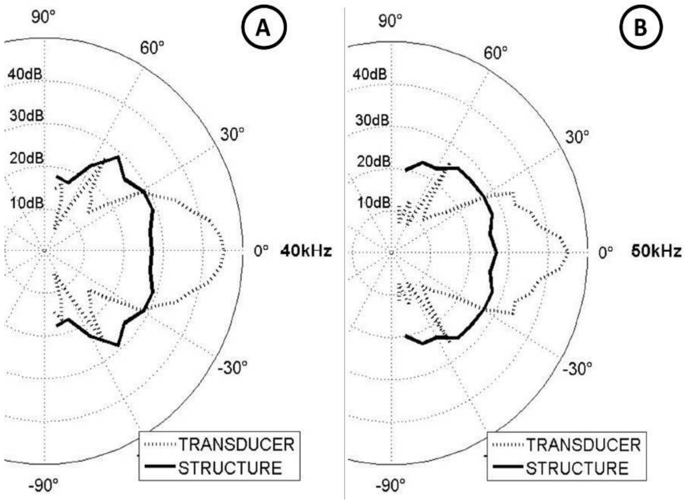

Fig. 4. Measured beam patterns. (A) at 40kHz associated with the transducer (dotted line), and emitter composed of transducer and structure (continuous line). (B) at 50kHz associated with the transducer (dotted line) and emitter (continuous line).

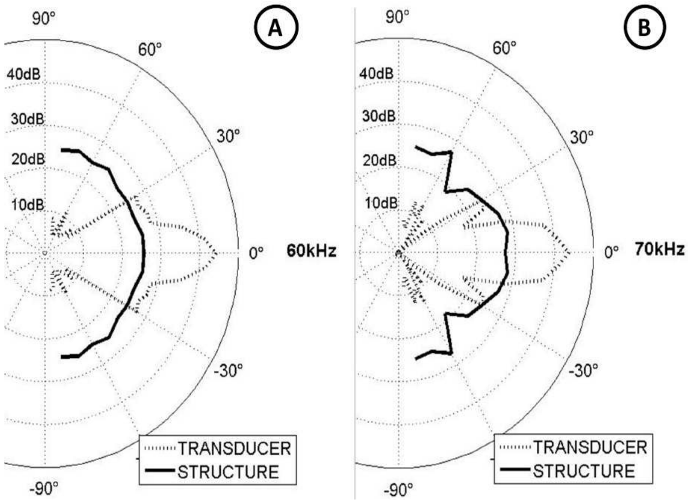

Fig. 5. Measured beam patterns. (A) at 60kHz associated with the transducer (dotted line), and emitter composed of transducer and structure (continuous line). (B) at 70kHz associated with the transducer (dotted line) and emitter (continuous line).

IV. Discussion

The results in section III show beam patterns in dB across the frequency range $[20, 70]$kHz for the emitter implemented using a cylindrical structure with upper diameter $d = 10mm$ and a height $h = 5mm$. The effect of the structure on the emitter beam pattern is to distribute the acoustic energy over a wider set of orientations rather than being concentrated within a narrow angular domain, as in the case of the transducer alone.

The beam pattern is characterised by a single, wide main lobe across frequencies $[20, 60]$kHz. This is evident at 20kHz and 30kHz (Fig.s 3 A, 3 B) while at 40kHz the beam pattern values drop about 10dB for orientations greater than $50°$ and smaller than $-50°$, Fig. 4 A. The beam profile is regular at frequencies 50kHz and 60kHz, and with values around 25dB. Indeed, at these frequencies, the cylindrical structure makes it possible to cancel notches from the beam pattern associated with the transducer, and to quite uniformly spread the acoustic energy over orientations $[-80°, 80°]$ for frequencies $[20, 60]$kHz.

The notch at 70kHz, Fig. 3 B, indicates that the choice of height h and diameter d are efficient in spreading the acoustic energy for frequencies in the range $[20, 60]$kHz.

In general, the structure designed and printed is efficient at uniformly spreading acoustic energy up to 60kHz. This emitter represents a valuable solution for range estimation as well as for sonar system applications such as [9] where the emitter is supposed to be as omnidirectional as possible while spatial filtering is provided by bat-inspired receivers [14]. Practical tests will be conducted and reported in the future.

With respect to the bare transducer only, the structure mounted in front of the transducer reduces the acoustic energy along the $0°$ orientation, see the dotted line in Fig.s 3-5, and spreads it along all the orientations, even at $\pm 80°$.

V. Conclusions

This paper presents the acoustic characterisation of an ultrasonic emitter created from a cylindrical structure mounted on an air-coupled transducer. This emitter has a broad beamwidth over orientations $[-80°, 80°]$ and across frequencies $[20, 70]$kHz. The benefit of using the cylindrical structure is found in the notch cancellation of the beam pattern from the transducer as well as in the absence of secondary lobes.

The purpose of this work is twofold. First, to provide a directional air-coupled transducer with a broad beamwidth: this emitter can be then used in either a sonar system or in an ultrasonic ranging module. Second, it is a proof of concept that cylindrical structures can broaden the beam pattern of an air-coupled transducer. The amount of broadening over a range of frequencies can be set according to parameters such as height h and diameter d. The idea exploited in this paper can of course be extended to transducers other than the Advice loudspeaker such as the Polaroid transducer. In addition, it is easy to conceive that different height h and diameter d values would make it possible to provide the emitter with a broad beamwidth in another frequency range. Hence, it could be possible to “tune” the cylindrical structure and therefore the final emitter to a desired frequency range. Indeed, as shown in Fig. 5 B, significant notches appear at orientations $50°$ and $-50°$ for frequency 70kHz. different values of d and h should remove the notches in the associated beam pattern in a different frequency range.

The process of conveying acoustic energy toward the sides and with no significant notches would enhance the performance of ultrasonic range estimators and ultrasonic sonars. Indeed, using such an emitter makes it possible to ensonify targets that are located quite far off the main axis, and with enough acoustic energy to detect them. In addition, a wide area could be inspected in one emission only.

Acknowledgments

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