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Radiation properties of truncated cones to enhance the beam patterns of air-coupled transducers

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Abstract

Radiation properties of cones are used to steer energy from the side lobes toward the center of the beam pattern of an air-coupled source. Two structures of superposed truncated cones are designed and implemented in a finite element package to modify the beam pattern of a piston model simulating an air-coupled transducer. Results show how the energy from the sides of the beam is conveyed toward the center of it thus widening the main lobe angular domain and smoothing the beam curve. This work is intended to support methods for range estimation performed with air-coupled transducers and localization strategies with broadband ultrasonic signals, as well as to investigate mathematical relationships at the base of radiation properties of conical structures.

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Keywords: truncated cones, beam pattern, air-coupled transducer, piston model, lobe, acoustic simulation.

1. Introduction

Air-coupled transducers are widely used to perform target localization and range estimation. In Barshan et al. (1990) the orientation of the transducers is set to align the maximum gain of the beam pattern to the target, while Schillebeeckx et al. (2010) implements a bat-inspired broadband localization strategy. These transducers are directional and their acoustical properties can be modified by mounting appropriate external structures. For example,

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conical structures, horns and flares are used in radio communications, Arumugam et al. (2009) and Cheng et al. (2011), to modify the directional properties of antennas. The purpose of this paper is to enhance the beam pattern of an ultrasonic broadband airborne sound source using the acoustic properties of cones. In particular, two structures of four superposed truncated cones are mounted around the source to enlarge the angular extension of the main lobe in the source beam pattern over a range of frequencies by steering acoustic energy from the side lobes toward the main lobe: this makes the beam pattern monotonic over a wider set of orientations. Air-coupled transducers engaged in localization problems will benefit from having a wider main lobe as a bigger area can be inspected with one emission only, while monotonicity of the beam pattern over a set of orientations will guarantee a unique solution in localizing reflecting targets whose positions are estimated from directional properties of the transducer itself.

2. Structures of superposed cones

Two representative structures are considered to evaluate the influence of different cone geometries. Each structure is comprised of four superposed truncated cones and designed to direct the acoustic energy of side lobes (between 60° and 90° off the beam pattern's main axis) toward the region of the main lobe: 30° off the main axis for structure 1, and 10° off the main axis for structure 2. The flare rate of the cones is linear and is calculated to reflect the incident sound from the vibrating piston source at the desired angular direction ρ according to the formula:

$$\rho = 2\phi - (90^{\circ} - \alpha) \tag{1}$$

In Eqn (1) α is the angle of the sound direction from the source and φ is the angular flare of the cone with respect to the vertical direction, see Fig. 1. MatLab code was implemented to calculate the dimension of each cone depending on the orientation α and the desired direction ρ, and so that in each cone the flare rate φ was calculated with Eqn (1) according to the desired direction ρ for one value of α, and all angles in [α-5°, α+5°].

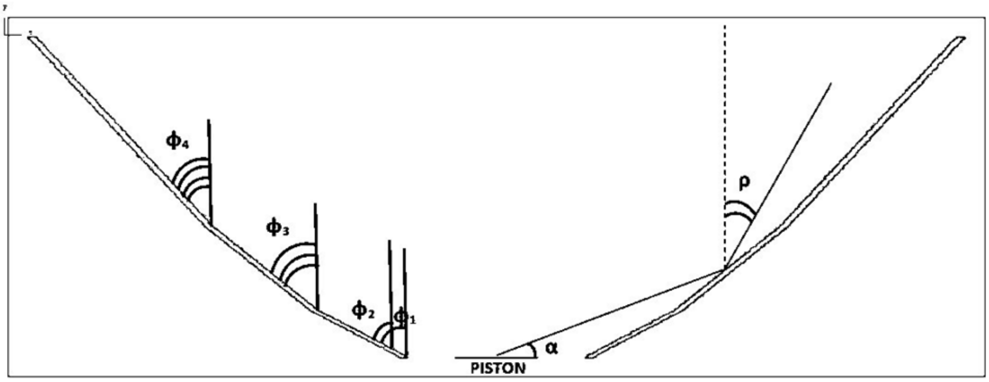

Fig. 1. Cross-section of 4 superposed cones around the circular baffled piston.

The first structure is designed to direct the sound at ρ=30°; from (1), φ_1=60° for α=0°, φ_2=55° for α=10°, φ_3=50° for α=20°, and φ_4=45° for α=30°. The second structure is intended to direct the sound at ρ=10°; from the scheme of Fig. 1 and (1), φ_1=50° for α=0°, φ_2=45° for α=10°, φ_3=40° for α=20°, and φ_4=35° for α=30°.

3. Beam pattern modifications

3.1. Beam pattern profiles

A circular baffled piston model was used to simulate the acoustic behavior of an air-coupled transducer. Its radiation, Kinsler et al. (2000), can be modelled as:

$$D(\theta, f) = \frac{2J_1(ka\sin\theta)}{ka\sin\theta}, \tag{2}$$

where θ is the direction angle of sound off the main axis, f is the frequency, $k=2\pi/\lambda$ is the wave number, a is the piston radius and J_1 is a first kind-first order Bessel function. The beam pattern in Eqn (2) was simulated in PZFlex (PZFlex Weidlinger Associates Inc. 399 West El Camino Real Mountain View CA 94040-2607), a Finite element package. Structures 1 and 2 as in Fig. 1 were also implemented in the Finite element model and the beam pattern of the piston altered by these structures was calculated. Cross sections of their beams in the angle domain [0°, 90°] are shown in Fig. 2 for frequencies in the range [35, 65]kHz, and in Fig. 3 for frequencies in the range [40, 50]kHz, the latter having a side lobe in the range [50°, 90°] that was steered toward the center of the angular range by both structures. In Fig. 2 and 3 the beam pattern associated with the piston model is depicted with the continuous line, the one for structure 1 is the dotted line while that associated with structure 2 is the dashed line.

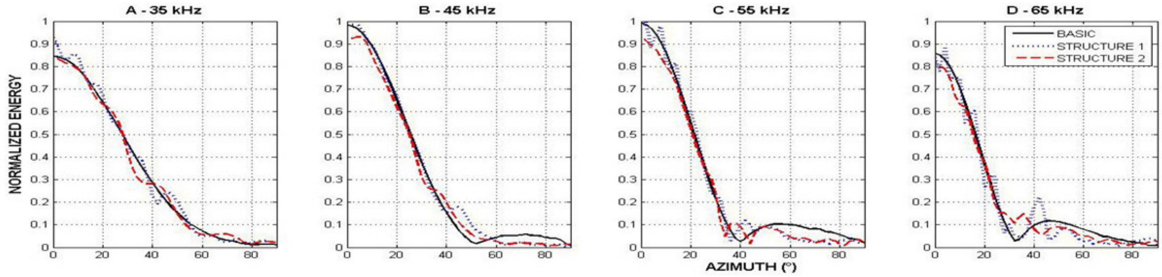

Fig. 2. Beam patterns associated with piston (continue line), piston with first superposed cone structure (dotted line), piston with second superposed structure (dashed line) at frequencies (A) 35kHz, (B) 45kHz, (C) 55kHz, and (D) 65kHz.

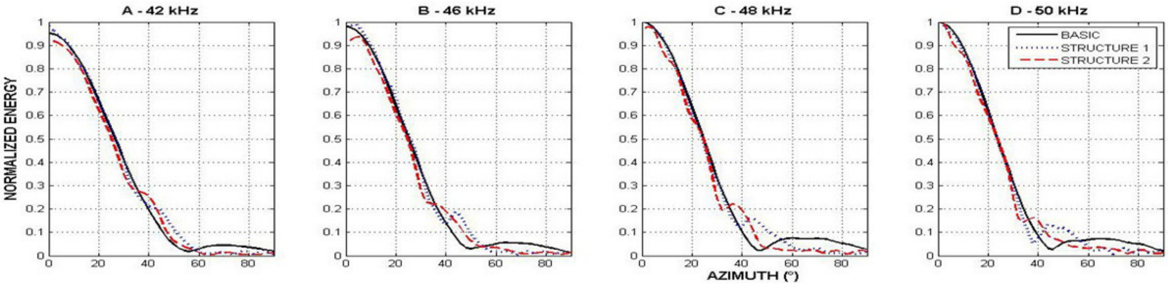

Fig. 3. Beam patterns associated with piston (continue line), piston with first superposed cone structure (dotted line), piston with second superposed structure (dashed line) at frequencies (A) 42kHz, (B) 46kHz, (C) 48kHz, and (D) 50kHz.

3.2. Evaluation and discussion

For each angle of the beam patterns in Fig. 2 and 3, the difference of the normalized energy was calculated between the basic beam pattern and the one associated with structure 1 and structure 2. The difference was then summed over the two sets of angles [60°, 90°] and [35°, 60°] as these ranges correspond to the orientations the structures steer the energy from and to, respectively. Table 1 shows these values over the angular ranges, which were adjusted depending on the beam shape at the different frequencies.

Table 1. Difference of normalized energy values.

Sum of energy values difference	E(Struct.#1) – E(Piston)	E(Struct.#2) – E(Piston)
42kHz in [40°,60°]	0.4	0.3
42kHz in [60°,90°]	-0.35	-0.4
46kHz in [40°,56°]	0.45	0.3
46kHz in [56°,90°]	-0.45	-0.5
48kHz in [38°,52°]	0.55	0.6
48kHz in [52°,90°]	-0.65	-0.9
50kHz in [38°,55°]	0.35	0.45
50kHz in [55°, 90°]	-0.5	-0.7

In Table 1, structure 2 subtracts most of the energy at frequencies 48kHz and 50kHz and, in particular, it is more efficient than structure 1 in the range [40, 50]kHz where the basic beam shows a side lobe at orientations [50°, 90°]: the energy of this side lobe is steered by the two structures toward another direction close to the main axis. Indeed, it can be noted in Fig. 2 that at frequencies 45, 55 and 65kHz the notches in the basic beam are cancelled as well as those at frequencies 46, 48 and 50kHz in Fig. 3. In Fig. 3 at 48kHz and 50kHz the beam associated with structure 1 presents a significant change in the gradient as a function of the angle whereas it can be noted in Fig. 2 and 3 that the beam pattern associated with structure 2 is monotonic at more frequencies in [40, 50]kHz over the angular domain.

4. Conclusions and future work

Broadband air-coupled transducers engaged in range measurements using broadband signals will benefit from the possibility of inspecting a wider area with one signal emission, and in having a monotonic beam pattern over a set of orientations when determining the location of a target. Two structures of four superposed cones are presented and their effect on the beam pattern of a transducer modelled as a circular piston is simulated and evaluated. Results using a finite element method show that notches are cancelled in the beam pattern of the piston along with a wider angular extension of the main lobe when structure 2, associated with a linear flare rate to steer the side lobe energy at 10° off the main axis, is applied to the piston model.

Structures with more cones for finer angle resolution will be designed, thus leading to parabolic and exponential flare cones. Measurements in a laboratory environment will follow to experimentally validate these models.

5. Acknowledgements

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References

Barshan, B., Kuc, R., Sonar system for obstacle localization with insights from the echolocating bat. The Journal of the Acoustical Society of America, 88, S5-S5 (1990).

Schillebeeckx, F., De Mey, F., Vanderelst, D., Peremans, H. (2010). Biomimetic sonar: Binaural 3D localization using artificial bat pinnae. The International Journal of Robotics Research, 0278364910380474.

Arumugam, D. D., Engels, D. W., Mickle, M. H. (2009). The use of flare structures in increasing the performance of passive UHF RFID tags within metal pipes. In Radio and Wireless Symposium, 2009. RWS'09. IEEE, pp. 453-456.

Cheng, Y. J., Hong, W., Wu, K., Fan, Y. (2011). Millimeter-wave substrate integrated waveguide long slot leaky-wave antennas and two-dimensional multibeam applications. Antennas and Propagation, IEEE Transactions on, 59(1), pp. 40-47.

Kinsler, L., Frey, A., Coppens, A., Fundamentals of Acoustics. Publisher: John Wiley & Sons; 4^{th} Edition, 2000, pp. 179-181.