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NONLINEAR ACOUSTICS

A Self-Silenced Sound Beam[1]

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Abstract—Parametric loudspeakers are transmitting two high power ultrasound frequencies. During propagation through the air, nonlinear interaction creates a narrow sound beam at the difference frequency, similar to a light beam from a torch. In this work is added the physical phenomenon of propagation cancellation, leaving a limited region within which the sound can be heard—a 1 meter long cylinder with diameter 8 cm. It is equivalent to a torch which would only illuminate objects within 1 meter. The concept is demonstrated both in simulation and in experiment.

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1. INTRODUCTION

Creation of an audible sound beam from ultrasound loudspeakers—called parametric loudspeakers—is based on the idea by Westervelt from the 1960s [1] and was first utilized for underwater applications [2]. Also in the 1960s, Zverev patented a similar idea, but the corresponding paper was published in a journal open for general use much later (see historical note [3]). The first to produce the same effect in air were Bennet and Blackstock in the 1970s [4] Today ultrasonic sound systems for the creation of sound in air exist [5–9]. A simile can be made with a light bulb and a torch. A conventional speaker radiates the sound like a light bulb, the regular ultrasonic parametric speaker is radiating low frequency audible sound like a torch.

This Letter presents a new concept, cancelling out the sound produced by a parametric sound source, by transmitting a second parametric signal producing audible sound of equal amplitude and in anti-phase of the first sound. The audible sound from the two frequency pairs will be generated at different distances, giving a region where the sound can be heard without interference in the desired audible volume. In the light analogy this is a torch with light that only illuminates, or is even seen from, within a couple of meters. The control of phase between the frequencies are crucial for the implementation. Influence of phase on the regular parametric array properties has been investigated by Akiyama et al. [10].

[1] The article is published in the original.

2. THEORETICAL BASIS

The analysis is based on a one-dimensional quadratic nonlinear equation with dissipation (the Burgers' equation, see e.g., [2, 11]):

$$\frac{\partial p}{\partial z} - p\frac{\partial p}{\partial \theta} = \Gamma \frac{\partial^2 p}{\partial \theta^2}, \tag{1}$$

where $p = p'/p'_0$, $z = x/(c_0^3 \rho_0/\epsilon\omega_0 p'_0)$, $\theta = \omega_0(t - x/c_0)$, and $\Gamma = b\omega_0/(2\epsilon p'_0)$. The dimensionless parameters above consists of: p' is the pressure disturbance, p'_0 is the source amplitude of the pressure disturbance, x is the distance from source, c_0 is the small signal sound velocity, ρ_0 is the undisturbed density, ϵ is the coefficient of nonlinearity, ω_0 is a characteristic source angular velocity—from now on put to be equal to $2\pi \times 10^3$, t is time, and b is a dissipation parameter.

The difference frequency amplitudes from each of the two ultrasound pairs of 50/52 kHz and 75/77 kHz are shown in the two dotted curves in Fig. 1. The source conditions to Eq. (1) are $p_L(z = 0, \theta) = A_L\sin(50\theta) + A_L\sin(52\theta)$, and $p_H(z = 0, \theta) = A_H\sin(75\theta) + A_H\sin(77\theta)$. Each of these pairs create an audible sound at frequency 52–50 = 77–75 = 2 kHz. The source amplitudes A_L and A_H are determined so that the 2 kHz amplitudes for large distances are equal. But—and this is the key to the concept—within a short range region close to the source they have different amplitudes, as the frequency pair 75/77 in curve (i) creates the 2 kHz difference frequency faster than the 50/52 kHz pair in curve (ii).

Let the two frequency pairs be transmitted simultaneously. The loudspeaker source condition is $p(z = 0, \tau = t) = A_L\sin(50\theta) + A_L\sin(52\theta) + A_H\sin(75\theta) +$

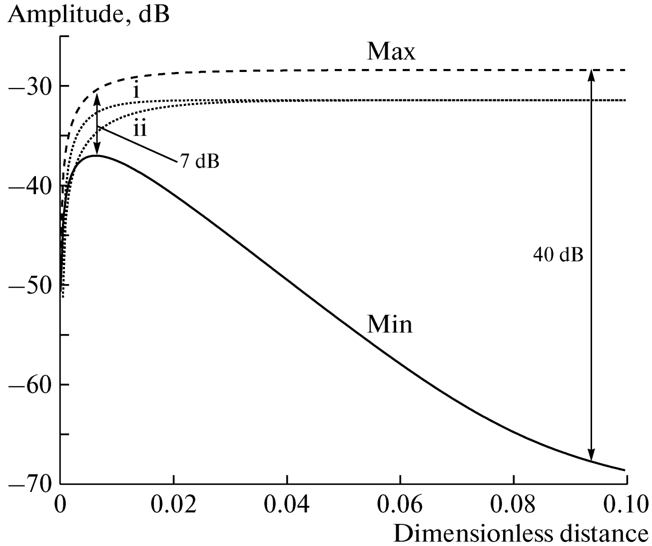

Fig. 1. Simulations of the amplitude of the 2 kHz difference frequency for different source conditions with $\Gamma = 0.08$. The dotted line (i) is from $1.5051\sin(75\theta) + 1.5051\sin(77\theta)$. The dotted line (ii) is from $\sin(50\theta) + \sin(52\theta)$. The Max-curve (dashed) is from $\sin(50\theta) + \sin(52\theta) + 1.5051\sin(75\theta) + 1.5051\sin(77\theta + \phi)$, with $\phi = 0$, and the Min-curve (solid) is with $\phi = \pi$.

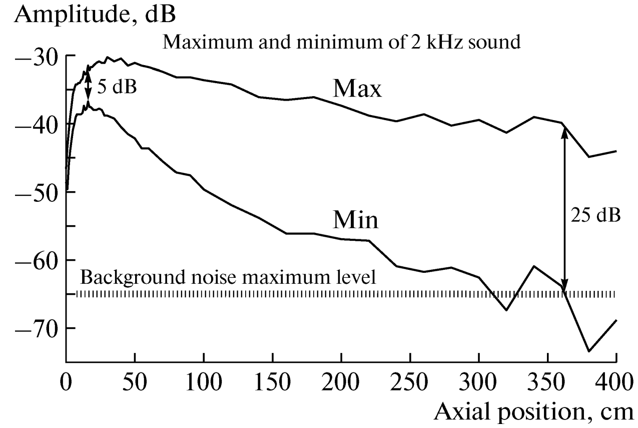

Fig. 2. The measurement of the on-axis amplitude of the audible 2 kHz frequency, expressed in SPL re 20 μPa.

$A_H\sin(77\theta + \phi)$. For the length-limitation of the beam, A_H and A_L must be chosen so that the difference frequency amplitude is cancelled at large distances. The simulation parameters were determined to be $A_L = 1$ and $A_H = 1.5051$. In addition, the phase ϕ must be π so that the 2 kHz contributions from the pairs are in antiphase and cancel each other. When the phase ϕ is zero, the difference frequency wave from the pairs are in phase, and their amplitudes are added instead of subtracted.

The Min-curve in Fig. 1 is the simulation of the length-limited sound beam for the one-dimensional wave propagation. Its cancellation takes place in a very nice way—there are no recurring oscillations. The Max-curve is the simulation of the regular parametric addition of the 2 kHz from the two frequency pairs.

The only parameter change between the Max- and Min-curves is the phase change from $\phi = 0$ to $\phi = \pi$. The Max-curve amplitude is 40 dB larger than the Min amplitude at the end of the interval, and the amplitude factor at maximum of the Min-curve is about 10 dB.

3. EXPERIMENTAL DEMONSTRATION

The experimental demonstration was carried out by measuring the wave amplitudes at discrete positions axially and radially. The transducer elements were four ultrasonic transmitters AT-50 (diameter 57 mm) and four AT-75 (diameter 25 mm) from AirMar, with the four 75 kHz frequency ones geometrically centered. Each of the elements in the transducer was fed an electrical signal from a VAC-200 Baltic Engineering amplifier channel. The four frequencies were generated separately by an Agilent 32250 signal generator (one frequency), an Agilent 32220 (one frequency) and an Agilent 8900 (two frequencies). The audible signal was measured with a condenser microphone, and the received signals were processed in a LeCroy LT262 digital oscilloscope.

The procedure was the same as in the simulation. The amplitudes from the two pairs were first measured separately and their audible 2 kHz amplitudes were set to be the same at 4 meters from the source. The sound pressure levels (re 20 μPa at 1 meter) of the ultrasonic primary waves were in this way determined to 115.5 dB for the 77 kHz, 112.8 dB for the 75 kHz, 111.1 dB for the 52 kHz, and 114.6 dB for the 50 kHz. Then the two frequency pairs were transmitted simultaneously. When the phase between the signals resulted in the maximum there was a regular parametric audible sound with its long narrow sound beam, see the Max-curve in Fig. 2. When the phase between the signals resulted in a minimum the length-limited sound with a short reach was achieved, see the Min-curve in Fig. 2.

The cancellation of the sound in the propagation direction was experimentally verified. The sound diminished fast. It could be heard only within a short region from the loudspeaker. At the maximum of the Min-beam at 20 cm from the source, the regular Max-beam sound pressure is only a factor 1.8 larger (5 dB). After 3 meters of propagation, the Max-beam had 23 times larger amplitude (27 dB).

The beam width of the length-limited beam was very narrow, see Fig. 3. The half-amplitude beam width was approximately constant at 4 cm in diameter. There was a complete cancellation of sound radially, as well as axially. The Max-beam's half-amplitude width was wider—after a propagation length of 100 cm it was 18 cm in diameter—and broadening with distance.

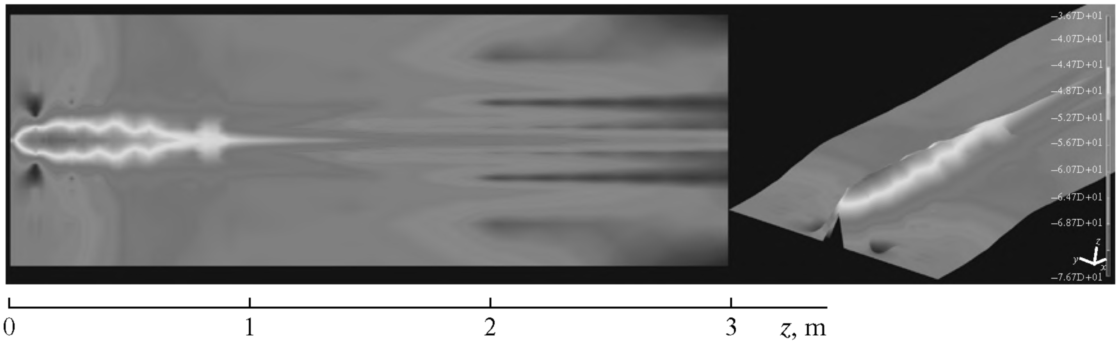

Fig. 3. (Color online) A view of the measured amplitude of the audible 2 kHz beam's radial and axial distribution for the length-limited sound beam.

4. DISCUSSION

This type of cancellation of a signal in the propagating direction has to our knowledge not been made for any types of waves before. It is a definite nonlinearly caused effect, which can not appear in a linear medium. The possibility in creating these types of phenomena therefore requires the existence of a medium nonlinearity.

Most people have an everyday relation with sound and loudspeakers. When told about the length-limited sound beam, they naturally think about listening to music without disturbing their neighbors, outdoor concerts heard only by the audience, or on sound only in front of a computer. But, listening to the length-limited sound is not recommended because the audible sound is still within the region of a high level ultrasound field. Many also relate to the Star Wars light sabres when the light analogy is brought up. This is possible to create in conditions of nonlinear electromagnetic wave propagation, but perhaps not in the air under regular circumstances because of its small nonlinear parameter.

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