Applied Acoustics 71 (2010) 793–800

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Near-field characteristics of the parametric loudspeaker using ultrasonic transducers

Hyeong Sick Ju [a], Yang-Hann Kim [b,*]

[a] Graduate Program in Acoustics, The Pennsylvania State University, 201 Applied Science Building, University Park, PA 16802, USA
[b] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 27 June 2009
Received in revised form 16 November 2009
Accepted 13 April 2010
Available online 18 June 2010

Keywords:
Parametric loudspeaker
Near-field
Directivity
Attenuation
Spurious signal

ABSTRACT

A parametric speaker is a device for generating and focusing highly directional sound beams. It is essentially a by-product that comes with the nonlinearity of ultrasound. It is noteworthy that this directional beam was controlled and utilized mostly for far-field applications in the past. We empirically study the directivity and attenuation characteristics of the parametric loudspeaker in the near-field where we desire to use it. Physical parameters for experiments are imported from a theoretical model based on the far-field approximation. The findings are that increases in aperture size and modulation frequency cause higher directivity, but have more than twice the beamwidth of the far-field approximation. The attenuation also does not obey the inverse-square law which describes far-field spreading from acoustic sources. The results conclusively explain a series of formation and attenuation of the virtual sound sources and define limitations of use in the near-field.

1. Introduction

In recent years a new type of loudspeaker called the parametric loudspeaker has been developed to generate highly directional sound, and is now commercially available. Sound focusing by the parametric loudspeaker is utilized to deliver audible information to people in a particular region without disturbing others. The beam-like spreading of the focused sound can also be used for long distance communication and for generation of virtual sound on a wall by reflection.

The parametric loudspeaker is based on parametric array theory, which has been utilized in underwater sonar for a few decades. The parametric array devised by Westervelt [1] consisted of multiple ultrasonic transducers and generated finite-amplitude ultrasonic carrier waves with two closely spaced frequencies. Nonlinear interaction of the two-tone waves produced a highly directional acoustic wave with a relatively low-frequency, which corresponded to the difference between the carrier frequencies. Amplitude modulation of the ultrasonic carrier waves introduced by Berktay [2] could substitute a frequency spectrum for the tonal difference-frequency. Since Bennett and Blackstock [3] successfully carried out the experiment of the parametric array in air, it has been utilized in audio applications by Yoneyama et al. [4]. Serving as a parametric loudspeaker, the audible sound beam could be generated by self-demodulation of the carrier ultrasound and by high directivity inherited from the parametric array. Various physical aspects of the parametric loudspeaker have been investigated as its applications increase. Kamakura et al. [5] introduced the rectangular aperture to the parametric loudspeaker, and Pompei [6] utilized the pre-processing scheme to reduce unwanted harmonic distortions. Karnapi et al. [7] enhanced low-frequency perception, and Kim and Sparrow [8] attempted the numerical analysis of the nonlinear sound generation. More recently, hardware design and fabrication were investigated by Roh and Moon [9], and a beamforming algorithm was developed by Yang et al. [10]. These studies achieved notable improvement in signal processing and far-field analysis and offer a few theoretical solutions. However, the spatial distribution of the audible sound beam has rarely been explored in the near-field.

It is important to investigate the practical near-field characteristics of the audible sound beam because listeners are commonly placed in that region due to the limited installation space of the parametric loudspeaker. In this region, the ultrasonic carrier coexists with the generated audible sound and influences performance measurement. The influence of individual transducer units in the parametric loudspeaker may also not be ignored. For effective use under these conditions, it is necessary to directly measure and evaluate the directivity and attenuation of the parametric loudspeaker. These are meaningful because the directivity limits the focused region, and the attenuation determines the optimal

* Corresponding author. Tel.: +82 42 350 3025; fax: +82 42 350 8220.
E-mail addresses: huj110@psu.edu (H.S. Ju), yanghannkim@kaist.ac.kr (Y.-H. Kim).

0003-682X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apacoust.2010.04.004

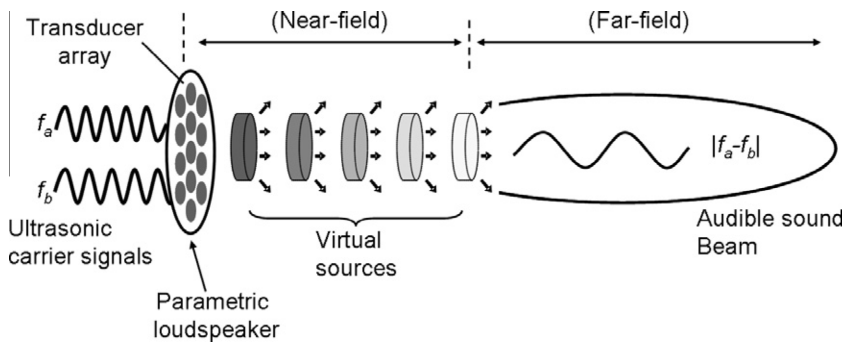

Fig. 1. Schematic illustration of sound beam generation in the parametric loudspeaker. The shading of the virtual sources represents their decay with distance from the array.

distance for listeners. In this study, the directivity and attenuation characteristics are empirically studied by controlling relevant physical variables.

2. Theoretical background

Generation of a low-frequency sound beam in the parametric array is explained by the nonlinear interaction of acoustic waves and the arrangement of virtual acoustic sources. As shown in Fig. 1, the parametric array usually employs multiple ultrasonic transducers which are regularly arranged on a source plane. Two groups of the transducers are excited with slightly different frequencies, whose difference corresponds to an audio frequency. Equivalently, all the transducers can be excited by a single carrier signal, whose amplitude is modulated by the audio signal. In both cases, the parametric array generates finite-amplitude acoustic waves which propagate as a collimated acoustic beam. These waves interact nonlinearly in the medium and produce an audible sound as a by-product, which forms virtual acoustic sources in space. As these virtual sources line up along the propagation path as a virtual end-fired array, they provide high directivity. The ultrasonic carrier decays after propagating a sufficiently long distance, and only the audible sound survives and serves as a highly directional acoustic beam in the far-field.The nonlinear interaction in 1-D space can be simply demonstrated by the computational analysis of the distortion of a tonal wave [7]. As a finite-amplitude wave with frequency f_0 propagates, its waveform changes into a sawtooth shape because phase velocities in the waveform vary with position; higher amplitude pressures propagate faster than lower amplitude pressures. The Fast Fourier Transform (FFT) of the waveform would show odd and even harmonics generation from the distortion. Similarly, when two-tone waves with frequencies f_a and f_b interact, the nonlinear distortion produces sum-frequency $f_a + f_b$ and difference-frequency $|f_a - f_b|$ components. As

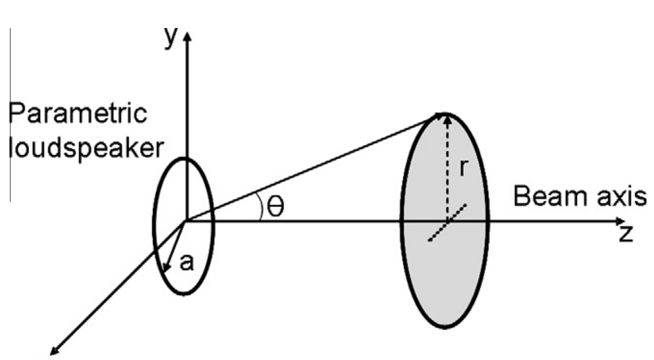

Fig. 2. Coordinate system of the sound beam. The z-axis represents the beam axis along which the sound beam propagates.

the wave propagates a long distance, the two high-frequency (f_a and f_b) and the sum-frequency ($f_a + f_b$) waves decay by absorption in air, whereas the difference-frequency wave ($|f_a - f_b|$) survives. When an ultrasonic carrier is modulated, the audible sound is generated by the self-demodulation in a similar manner.

In the 3-D case, the Khokhlov–Zabolotskaya–Kuznetsov (KZK) equation [11] describes the behavior of the sound beam, which is given by

$$\frac{\partial^2 p}{\partial z \partial \tau} - \frac{c_0}{2}\nabla_\perp^2 p - \frac{\delta}{2c_0^3}\frac{\partial^3 p}{\partial \tau^3} = \frac{\beta}{2\rho_0 c_0^3}\frac{\partial^2 p^2}{\partial \tau^2} \tag{1}$$

where p is the sound pressure, $\tau = t - z/c_0$ the retarded time, c_0 the sound speed, ρ_0 the density, δ the diffusivity for the thermo-viscous absorption, and β the nonlinearity coefficient of the medium. In the coordinates shown in Fig. 2, the Laplacian $\nabla_\perp^2 = \partial^2/\partial r^2 + r^{-1}(\partial/\partial r)$ is applied to the observer plane perpendicular to the beam axis, and the source size is defined as a. The left-hand side of the equation describes the 3-D propagation of the sound beam: $\frac{c_0}{2}\nabla_\perp^2 p$ describes diffraction related to the directivity, and $\frac{\delta}{2c_0^3}\frac{\partial^3 p}{\partial \tau^3}$ describes the attenuation. The right-hand side of the equation is related to generation of the virtual sources by the nonlinear interaction.

A closed-form solution of the KZK equation (1) is not known. However, its far-field solution is available through a quasi-linear approximation which employs finite-amplitude and weak nonlinearity [12]. This solution is written as

$$q_-(r,z) = -\frac{jp_{0a}p_{0b}\beta k_-^2}{4\rho_0 c_0^2 \alpha_T}\frac{e^{-\alpha_- z}}{z} D_W(\theta) D_A(\theta) \exp\left(-\frac{jk_- \tan^2\theta}{2} z\right) \tag{2}$$

$$D_A(\theta) = \frac{2J_1(k_- a \tan\theta)}{k_- a \tan\theta} \tag{3}$$

$$D_W(\theta) = \frac{1}{1 + j(k_-/2\alpha_T)\tan^2\theta} \tag{4}$$

where p_0 is the sound pressure amplitude of the ultrasonic carrier, k is the wave number, and $\alpha_T = \alpha_a + \alpha_b - \alpha_-$ represents the total absorption coefficient consisting of individual classical absorption coefficients. The subscripts a, b, and minus ($-$) indicate the first and second ultrasonic carriers and the difference-frequency wave, respectively.

A few aspects of this solution are notable. The far-field solution is the product of two theoretical directivities: the aperture factor and the Westervelt directivity. The aperture factor $D_A(\theta)$ accounts for a directivity pattern similar to that of a piston source in the far-field, whereas the Westervelt directivity $D_W(\theta)$ accounts for the highly directional characteristic of the parametric array. Fig. 3a shows $D_A(\theta)$, $D_W(\theta)$, and their product. The conditions used to generate these were a 40 kHz carrier frequency, a 1 kHz modulating frequency and a 0.146 m source size. The comparison of these directivities indicates that both $D_A(\theta)$ and $D_W(\theta)$ may contrib-