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Parametric sound fields by phase-cancellation excitation of primary waves

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Abstract. By radiating bifrequency primary waves from two ultrasonic emitters with changing the phases of the primary waves, we can obtain the sound fields that are different from the usual in-phase excitation. Especially, for the excitation of out-phase by 180 degrees the difference frequency wave has the directivity of almost uniformity near the acoustic axis. Additionally, the sound pressure levels of the harmonic components of the difference frequency and the primary waves as well are suppressed by 10 dB and more.

Keywords: parametric sound, in-phase, out-of-phase
PACS: 43.25Lj

INTRODUCTION

When two finite-amplitude sound beams of different but neighboring frequencies are propagated in the same direction, the parametric acoustic array is formed in the beams. Actually, nonlinear interaction of two primary waves provides a spectral component at the difference frequency. Additional components at higher frequencies such as the harmonics and the sum frequency are also generated. However, only the difference-frequency component can travel a long distance because sound absorption is generally increased with frequency, and then the waves at higher frequencies decay their amplitudes greatly compared with the difference frequency. The most remarkable property of the parametric array is its sharp directivity even for the low frequency. Additionally, sidelobes that usually exist in a directive sound are suppressed successfully.

The aim of the present report is to control parametric sound fields by changing only the phases of the primary waves[1]. An ultrasound source with a simple configuration is considered as a theoretical model. Two strip ultrasound emitters with the same width are placed in air by side by side and are operated by two types of the excitation of primary waves: usual in-phase driving and out-of-phase driving. The widths of the emitters are assumed to be 10 cm. As field examples, numerical computation is executed using the Khokhlov - Zabolotskaya - Kuznetsov (KZK) equation [2] for the source driven simultaneously at 26 kHz and 28 kHz. The fields of the difference frequency wave of 2 kHz and its second harmonic as well as the primary waves are all evaluated by some numerical examples. In the following, experiment is carried out in air to verify the theoretically obtained results using an ultrasound source that has two rectangular

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aperture emitters of 12 cm times 24 cm and is driven at two frequencies 26 and 28 kHz.

THEORETICAL PREDICTION

Our theory starts with a sound source whose model is simple: i.e., two strip ultrasound emitters with the same width a that are placed by side by side are radiating individually two ultrasound beams of different but neighboring frequencies f_1 and f_2 $(f_1 < f_2)$:

$$\left.\begin{aligned} p_1 = P_1 \sin(\omega_1 t + \theta) \\ p_2 = P_2 \sin(\omega_2 t + \theta) \end{aligned}\right\} \quad \text{(on the source)}, \tag{1}$$

where $\omega_1 = 2\pi f_1$ and $\omega_2 = 2\pi f_2$ are the primary angular frequencies, and θ is the initial phase. Furthermore, p_1 and p_2 are the sound pressures of the primary waves on the source, P_1 and P_2 being their amplitudes.

Parametrically generated sound field can be theoretically predicted by the KZK equation, which combines nonlinearity, dissipation, and diffraction of a directive finite-amplitude sound beam up to their second order smallness. This model equation is described as:

$$\frac{\partial^2 p}{\partial z \partial t'} = \frac{c_0}{2} \nabla_\perp{}^2 p + \frac{\delta}{2c_0^3} \frac{\partial^3 p}{\partial t'^3} + \frac{\beta}{2\rho_0 c_0{}^3} \frac{\partial^2 p^2}{\partial t'^2}, \tag{2}$$

where p is the sound pressure, c_0 is the sound speed, ρ_0 is the medium density, δ is the sound diffusivity that is related to sound absorption, and β is the nonlinearity coefficient. Moreover, $\nabla_\perp{}^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is a Laplacian that operates in the $x-y$ plane perpendicular to the axis of the beam (z axis), and $t' = t - z/c_0$ is the retarded time. For the present source model, $\nabla_\perp{}^2$ is replaceable with $\partial^2/\partial x^2$ because the field should be formed in the two-dimensional propagation system.

Let the initial phase θ be different for the two emitters. To be more precise, θ always remains to be zero for one strip emitter, while the other emitter can have a phase shift of θ. Two extreme situations are addressed here for the phase: i.e., $\theta = 0$ and π. The former is the 'in-phase' excitation of the primary waves and is usually used for the formation of a parametric array. The latter is the 'out-of-phase' excitation we are especially concerned with. Taking into account of the thus stipulated initial conditions, we solve numerically the KZK equation by employing a finite difference method.

For numerical demonstration, we assign the source parameters as: $f_1 = 26$ kHz, $f_2 = 28$ kHz, $a = 10$ cm, $P_1 = P_2 = 125$ dB, room temperature$= 20°$ C, and relative humidity$= 50$ %. The room temperature and relative humidity determine the sound absorption coefficient of the air, that is readily predicted as a function of frequency using a relatively simple formula.

On-axis propagation curves of the difference frequency wave of 2 kHz and its second harmonic of 4 kHz are shown in the left side of Fig. 1 with the curve of the primary wave of 28 kHz. As expected, the pressure levels of the primary waves are noticeably different, being quite dependent on the phase: due to phase cancellation the levels for the out-of-phase excitation are too low to be shown in the figure. In contrast, the pressure levels of the difference frequency wave of 2 kHz are almost independent of the initial phases in the nearfield. Actually, the pressure levels are decreased for the

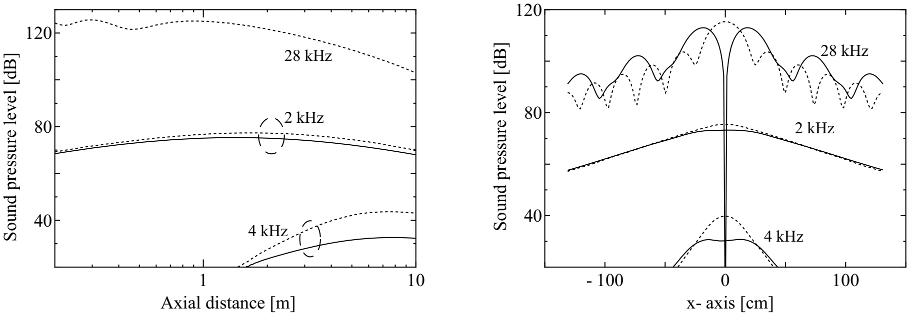

FIGURE 1. Propagation curves on the beam axis (left) and beam patterns at 4 m (right) for an ultrasound source consisting of two strip emitters with 10 cm width. The primary frequencies are 26 kHz and 28 kHz. The sound pressures on the source are 125 dB for both the primary waves. Solid and dotted curves denote the numerically obtained data for the out-of-phase and in-phase excitations, respectively.

out-of-phase excitation. However, the pressure reduction is not great so much, being only a few decibels. Additional interests are observed in the higher harmonics. The second harmonic waves of 4 kHz are expected to reduce their amplitudes by 10 and more decibels in the farfield.

Beam patterns of various frequency components at 4 m from the source are also shown in the right side of Fig. 1. Obviously, the pressure levels of the primary waves are considerably reduced near the beam axis. Instead, the sidelobe levels increase overall by several decibels. For the difference frequency, the waves have no sidelobes within the calculated range of ±120 cm, that is a prominent feature of the parametric array. The pressures around the axis for the out-of-phase excitation are decreased, being only few decibels lower than those for the in-phase excitation. At 50 cm away from the axis, however, there are no differences of the pressures between both the excitations. A similar tendency is observed in the data of the second harmonics.

EXPERIMENTS AND DISCUSSION

Experiment was carried out in air using an ultrasound source that consists of two rectangular aperture emitters of 12 cm × 24 cm. Each emitter consists of 264 small piezoelectric ceramic sensors of 10 mm in diameter. Each sensor has a resonant frequency of 27.5 kHz and an about ±2.5 kHz bandwidth with 10-dB degradation of the sensitivity. The input terminals of all sensors in each emitter are connected in parallel. Two sinusoidal signals of 26 kHz and 28 kHz are electrically mixed and are gated to generate tone-burst waves. The signal is then separated into two signals. For the in-phase excitation, both the signals are directly power-amplified, being fed to the emitters. When executing the out-of-phase excitation, we pass the one signal through an inverter to change the phase by just 180°.

Measured beam patterns are shown in Fig. 2 with the numerical results obtained using the KZK equation[3]. By the best fit of the experiment and theory in the farfield, the

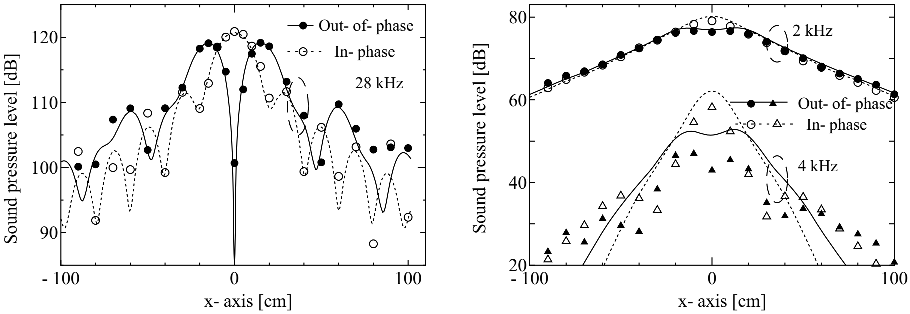

FIGURE 2. Beam patterns at 4 m from the source for the primary waves of 28 kHz (left). The patterns for the difference wave of 2 kHz and its second harmonic of 4 kHz are also shown (right). Symbols are all measured data, and solid and dotted lines are the theoretical predictions.

pressure levels of 26 kHz and 28 kHz waves on both the emitters are predicted to be 127.4 dB and 125.8 dB, respectively. Evidently, the pressure amplitudes of the 28 kHz wave are much reduced near the beam axis for the out-of-phase excitation. It has been confirmed that the beam pattern of the 26 kHz wave has a deep dip on the axis in the same fashion. Interestingly, the difference frequency waves of 2 kHz take almost the same levels within the measurement range of ± 90 cm for both the excitations except for some differences near the axis. The second harmonic waves of 4 kHz have lower pressure levels by about 10 dB and more, especially near the axis. It has been observed that the third harmonic waves of 6 kHz, although the data are missing here, exhibit the same tendencies for the pressure levels. Careful comparison is underway between the measured data and theoretical predictions for all spectral components.

CONCLUSIONS

We have presented numerical and experimental results on parametric array formation for the in-phase and out-of phase excitations of the primary waves. It has been revealed that the sound pressure levels of the primary waves and the harmonics of the difference frequency wave are considerably reduced without deteriorating the acoustic properties of the parametric array by changing only the phases of the primary waves by 180°.

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