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A HIGHLY DIRECTIONAL AUDIO SYSTEM USING A PARAMETRIC ARRAY IN AIR

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ABSTRACT

A highly directional loudspeaker like a spotlight is actually realized by the self-demodulation of an intense ultrasound beam amplitude-modulated by audio signals. This loudspeaker is based on the generation of a parametric array in the beam space, and is able to transmit an audio sound to a specific area that cannot be detected by people in adjacent locations. To expand practical applications of a parametric loudspeaker more widely, some new technologies such as appropriate signal processing to reduce harmonic distortion and electric power consumption in driving the loudspeaker are reported.
KEYWORDS: Parametric loudspeaker, Audio spotlight, Nonlinear acoustics

INTRODUCTION

In 1983 Yoneyama *et al.* first reported a new type of loudspeaker, that utilizes the self-demodulation effect of an intense ultrasound beam amplitude-modulated by audio signals [1]. A special acoustic property of this loudspeaker is its sharp directivity that can not be realized by any conventional loudspeakers with the same aperture size. They coined a new technical term, *sound spotlight*, for the loudspeaker. Later, other individuals and companies in Japan had tried to develope the loudspeaker, that is called *parametric loudspeaker* in acoustics, to produce on a commercial basis, however, failed due to the primary reason of very low conversion efficiency from electric power to parametric sound power. Even so, the practical development of a parametric loudspeaker has revived recently owing to its attractive and promising feature of sharp directivity all over the world [2, 3, 4]. A technology overview on parametric loudspeakers reported by American Technology Corporation would be helpful for those who are interested in them [5].

In this paper, we would like to present current research and practical development on parametric loudspeakers.

PARAMETRIC ARRAY

When two finite-amplitude sound beams of different but neighboring angular frequencies (ω_1 and ω_2) are propagated in the same direction, a parametric acoustic array is formed in the beams [6]. This is a well-known physical fact. Actually, nonlinear interaction of two primary beams provides a component at the difference frequecy $\omega_1 \sim \omega_2$. Additional components at higher frequencies such as harmonics are generated simultaneously. However, only the difference-frequency component can travel a long distance because sound absorption is generally increased with frequency, and then the components at higher frequencies decay their amplitudes greatly compared with the difference frequency. The most remarkable property of the parametric array is its sharp directivity. Additionally, the side-lobes, that usually exist for a directive sound source, are suppressed considerably.

Parametically generated sound fields can be theoretically predicted by the Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation [7], that combines successfully nonlinearity, dissipation, and diffraction of a directive finite-amplitude sound beam. This model equation is described as:

$$\frac{\partial^2 p}{\partial z \partial t'} = \frac{c_0}{2} {\nabla_\perp}^2 p + \frac{\delta}{2c_0^3} \frac{\partial^3 p}{\partial t'^3} + \frac{\beta}{2\rho_0 {c_0}^3} \frac{\partial^2 p^2}{\partial t'^2}, \tag{1}$$

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. It is not easy to solve analytically the KZK equation even when nonlinearity is weak. Especially, when nonlinearity is moderate or strong, we resorts to numerical computation methods such as a finite difference scheme to obtain the solution.

We now demonstrate the fundamental characteristics of a parametric sound in air. An ultrasound source whose circular aperture is 10 cm in radius radiates bifrequency waves of 38 kHz and 40 kHz with the same pressure amplitudes of $p_0 = 50$ Pa (125 dB *re.* 20 μPa.) at the source face. Figure 1 shows the axial pressure profiles of the primary waves and the parameric tone of the difference frequency 2 kHz. As can be seen, the amplitude of the parametric tone increases with propagation, and attains the maximum at about 1.5 m from the source, and then decreases gradually. For the present source conditions, the ultrasound power radiated from the source is given by the product of the intensity $2 \times p_0^2/2\rho_0 c_0 = 6.1$ W/m^2 and the aperture area of the source 0.031 m^2, and resulting in a value of 0.19 W. Whereas the sound pressure level of the difference frequency sound is

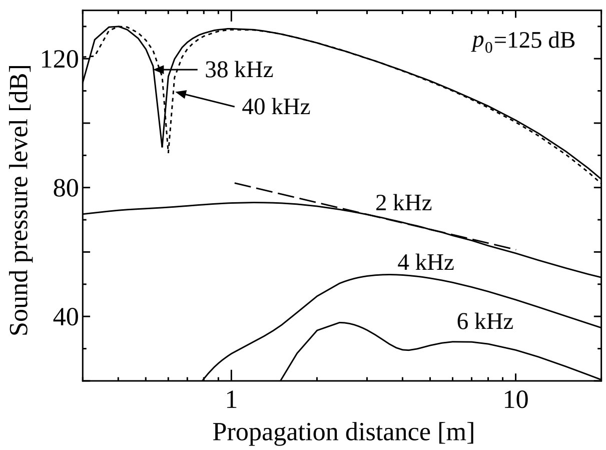

Figure 1. Axial sound pressure curves for the primary and secondary waves(theory). The two primary waves of 38 kHz and 40 kHz from a sound source of 10 cm in radius produce a 2-kHz differece frequency tone in the air. The initial source pressures of the primaries are the same to be 125 dB. The dash line denotes an extrapolated -6 dB/dd line.

estimated to be 81 dB at 1 m from the curve in the farfield, as the dotted line indicates. Thus obtained speculation provides that if an ultrasound source convertes electric power into sound power in high efficiency parametric sounds should be produced at relatively high level with less electric power. We also note in Fig. 1 that unnecessary or unwanted harmonic tones such as a 4-kHz component are prominently generated in the farfield. In designing parametric loudspeakers, it is of great importance to reduce such harmonic distortion and cross-modulation distortion as much as possible.

Figure 2 shows the comparison of pressure distributions produced by a parametric array

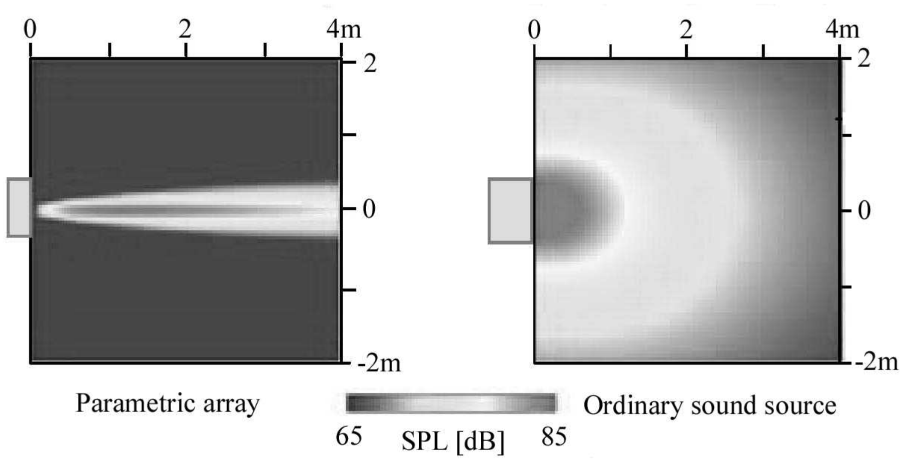

Figure 2. Sound pressure distributions of a parametric array (left) and an ordinary sound source (right). Both the source have the same radius 10 cm, radiating sounds at a frequency of 1 kHz.

and an ordinary piston source under the conditions that the source radii are both 10 cm and frequencies are 1 kHz. Evidently, the directivity of the parametic array is dramatically sharper than that of the ordinary source.

REALIZATION OF PARAMETRIC LOUDSPEAKERS

When utilizing a parametric array as a loudspeaker, the primary wave that is usually chosen in the frequency range above 20 kHz, typically at around 40 kHz, is amplitude-modulated by audio signals. Thus amplitude-modulated ultrasound wave has the carrier, upper and lower side-band components, and results in reproduction of the audible sound in air due to the nonlinear interaction of the carrier and each side-band in the ultrasound beams. Needless to say, the directivity of the produced audible sound is very sharp owing to the characteristic of a parametic array.

It is theoretically conveninent to employ the Merklinger's solution that predicts the dynamical response of a parametric array in its de-modulation process of a nonlinear medium [8]. The solution of the parametric sound $p_s(t')$ is given in the farfield by

$$p_s(t') = \frac{Sp_0}{4\omega\pi c_0 z}\frac{\partial^2}{\partial t'^2}\left[f(t')\tan^{-1}\left\{\frac{\beta\omega p_0 f(t')}{4\alpha\rho_0 c_0^3}\right\}\right], \quad (2)$$

where S is the aperture area of an ultrasound emitter or source, ω is the carrier angular frequency, p_0 is the carrier ultrasound amplitude, α is the absorption coefficient of the carrier, and $f(t')$ is the envelope function of the amplitude-modulated signal. In eq. (2), the soultion is approximated subject to $p_0 \ll 4\alpha\rho_0 c_0^3/\beta\omega$ as

$$p_s(t') \propto \frac{p_0^2}{z}\frac{\partial^2}{\partial t'^2}f^2(t'). \quad (3)$$

In contrast, when the condition $p_0 \gg 4\alpha\rho_0 c_0^3/\beta\omega$ is satisfied, the solution becomes

$$p_s(t') \propto \frac{p_0}{z}\frac{\partial^2}{\partial t'^2}\left|f(t')\right|. \quad (4)$$

A parametric loudspeker has been technically developed and advanced for practical use so far. However, several problems remain still unclear, and improvements are needed for further development of the loudspeaker. We now focus on the following challenges.

Promising modulation for the primary wave

Originally, an amplitude modulation (AM) technique was proposed as the primary wave excitation [1]:

$$f(t) = 1 + ms(t), \quad (5)$$

where $s(t)$ is an audio signal and m is the modulation degree. Substituting of eq. (5) into eq. (3) yields

$$p_s(t') = \text{const} \times \frac{\partial^2}{\partial t'^2}\{2ms(t') + m^2 s^2(t')\}. \quad (6)$$

As is descibed above, harmonic distortion appears as $m^2 s^2(t')$. To reduce such distortion the authors have proposed the following amplitude modulation with square-rooting [9]:

$$f(t) = \sqrt{1 + ms(t)}. \tag{7}$$

Using thus square-rooted envelope, parametric sounds without distortion can be obtained theoretically. In general, the bandwidth of the primary signal widens because of the nonlinear transformation. Hence, to realize the square-rooted modulation, the emitter requires a wide-band frequency response characteristic. Otherwise parametric sounds would be rather distorted.

Although any modulation methods so far are straightforward or simple, the carrier ultrasound of finite amplitude is always radiated even if the audio signal is very small or turned off. Consequently, attention has to be paid to the problems of electric power loss as well as physiological effects on human beings. To conquar such problems a new type of modulation has been presented by the authors to reduce the average radiant power of ultrasound as effectively as possible [10]. Incidentally, audio signals such as speech vary dynamically their amplitudes in time. Let the envelope of the signal be $e(t)$. The new type modulation takes the form:

$$f(t) = \sqrt{e(t) + ms(t)}. \tag{8}$$

The demodulated sound consists of two signals; one is the original signal $s(t)$ and the other the envelope signal $e(t)$. The sound $e(t)$ is practically unaudible because of its only low frequency components. No sooner is $s(t)$ present than the carrier is radiated; the audio signal controls directly the ultrasound radiant power. Electric average power consumption was measured by working a parametric loudspeaker that consists of about 2000 small PZT monomorph transducers of resonace frequency 28 kHz. A news programme spoken by a male announcer was used for the speech transmission test. Without degradation of tone quality the power used by the dynamic modulation method based on eq. (8) has been reduced to about one-third of that used by the conventional AM method. Nowadays, some promising modulation methods such as a single side-band (SSB) modulation attract much attention for producing parametric sounds with minimizing distortion [5, 11, 12]. All the modulators tend towards digitalization to provide good quality for tuning up them.

Ultrasound emitters

To achive required sound levels at a carrier frequency of 40 kHz or so, it is usual to employ an array of piezoelectric ceramic transducers driven at resonance. Piezofilms such as polyvinylidene fluoride (PVDF) offer promising prospects as a broad-band emitter. From robust and reliable points of view, however, the piezoelectric ceramic transducers have an advantage over the piezofilms. At any rate, a large group of such transducers are needed that are precisely machted in amplitude near resonance, and phase as well.

Here we present some electroacoustic properties of the ultrasound emitter in use. The emitter has a rectangular aperture of 12.5 cm $\times$ 25 cm in size, consisting of 286 small monomorph ceramic transducers of 10 mm in diameter. The resonance frequency is about 40 kHz. (Nippon Ceramic Co., Ltd, Type AT/R40-10) The terminals of all the transducers are connected in parallel. Figure 3 shows the beam patterns of the 39.3 kHz carrier at 3 m from the emitter. Black circles are the measured SPLs and solid curve the theoretical prediction. They are in relatively good agreement. From these data, we obtained acoustic radiant power 0.039 W by integrating acoustic intensity $p^2/\rho_0 c_0^2$ over the receiving surface. Whereas, electric power consumed in working the emitter was measured to be 0.17 W. Flat emitter systems are usually too low in efficiency to generate enough intense ultrasounds for parametric loudspeakers. As for the piezoelectric emitter used here, the electroacoustic conversion efficiency at resonance becomes $0.039/0.17 \simeq 0.23$ (23 %), higher than expected.

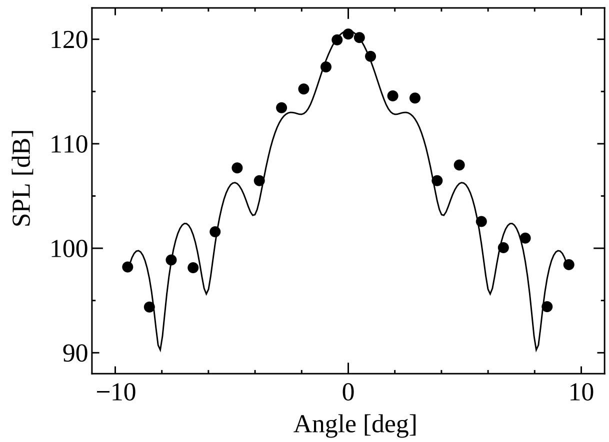

Figure 3. Beam patterns at 3 m from the emitter. The driving frequency is 39.3 kHz. Black circles are the measured data, and the solid line the theoretical prediction. The driving voltage is 2 V_{p-p}.

Figure 4 shows the electric admittance of the emitter measured by a network analyser. The admittance curve draws a round circle as an ultrasound transducer indicates generally. In the figure, circles in black are the data measured by connecting a coil of 24 μH with the output terminals of the emitter. As can be seen, insertion of the coil moves the admittance curve to around the real axis in the plane of complex numbers. It should be expected from this result that reactive power reduction is feasible by the connection of an appropriate coil.

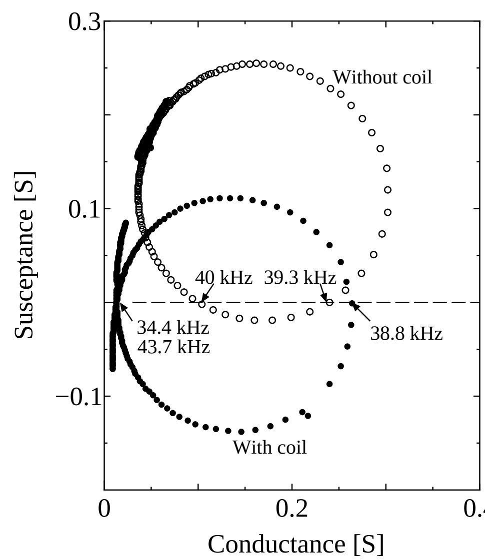

Figure 4. Measured admittance curves in the plane of complex numbers for the emitter when a coil of 24 μH *is connected with the emitter terminals or not.*

Connecting a resistance of 2.36 Ω and an analog power amplifier to the emitter in series, and measuring voltages arcoss the resistance, emitter, and power amplifier, we determened the effective and reactive power consumed in the emitter as a function of the driving frequency. Figure 5 exhibits the power decrease, espectially reactive power reduction, in the wide frequency range except for the resonance by connecting the coil.

It is necessary to confirm experimentally whether the power can be actually reduced in working the parametric loudspeaker. Table 1 shows the averaged power consumption and reduction for two kinds of audio signals; one is the signal of a famale narration for 91 s in duration, and the other is the signal of a music box for 130 s in duration. Electric power loss in the power amplifier was measured using a watt-hour meter under the condition that an applied voltage to the emitter is 20 V_{pp}. Since the time with no or small signal is longer for narration than for music, the narration loss is overall low. Apparently, independent of types of audio signals, the power is reduced by one third by connecting the coil to the emitter.

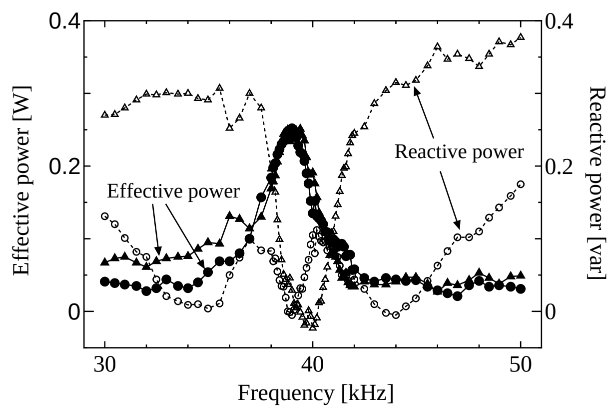

Figure 5. Effective and reactive power curves as a function of frequency when the coil is connected with the emitter(circles) or not (triangles). The closed and open symboles are the data of the effective power and of the reactive power, respectively.

Finally we should stress that driving the parametric loudspeaker by a digital power amplifier in place of an analog power amplifier further dramatic reduction of power consumption is achieved to about a quarter.

Up to now we have focused on the appropriate modulation methods for the ultrasound carier wave, and the emitter with high electroacoustic conversion efficiency. Another important problem we should discuss here is studies on intense airborne ultrasound exposure to human beings. Maximum permissible levels, recommended by research groups or indi-

Table 1. Power consumption and reduction for two kinds of audio signals, female narration and music (music box). All numerical values are average power in W and the values in parentheses are the power which excludes standby power requirement 27 W of a power amplifier. The input voltage applied to the emitter is 20 V_{p-p}.

	Without coil	With coil	Power reduction [%]
Narration	118 (91)	86 (59)	27 (35)
Music	178 (151)	122 (95)	31 (37)

viduals, were levels from 110 to 115 dB above 20 kHz for 8 hour exposure, that would not result in hearing loss in the audible frequencies [13]. Hence, a limit of 115 dB might be a guideline for safe usage of parametric loudspeakers.

CONCLUSIONS

A parametric acoustic array is virtually formed when the intensity of an ultrasound wave is propagated in a nonlinear medium. The results of parametric array effects on modulated, high-intensity, ultrasound waves is the generation and propagation of audio frequency waves that are generated in a manner similar to the nonlinear transform of amplitude demodulation process. The most specific property of the parametric array is its sharp directivity and is successfully utilized for a parametric loudspeaker. To develope the loudspeaker for practical use, several problems remain still undetermined. Especially, intense airborne ultrasound exposure to human beings is an important problem we should extensively research for safe usage of parametric loudspeakers.

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