AN APPLICATION OF NONLINEAR INTERACTION OF SOUND WAVES TO THE LOUDSPEAKER
------ FUNDAMENTAL AND IMPROVEMENT ------

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Introduction

The phenomenon that is known as nonlinear interaction of sound waves, has already been applied into sonar in the field of underwater acoustics[1].

On the other hand, the authors have investigated it for the application to loudspeaker[2]. This is the first time for this phenomenon to be used practically in the air. This type of loudspeaker consists of ultrasonic transducer array which can radiate a finite amplitude ultrasound beam, amplitude modulated by audio signal, into the air. This AM ultrasound wave is self-demodulated in the air by the nonlinearity of the air. This type of loudspeaker is quite different from ordinary loudspeaker which radiate sound from a vibrating diaphragm, and shows very sharp directivity pattern.

Acoustic reproduction theory by nonlinear interaction of finite amplitude ultrasonic in air

When a finite ampltude sound wave having composite spectra (primary wave) is radiated into the air, new sound waves (secondary waves) having new spectrum construction may be produced as the result. This phenomenon is well known as the nonlinear interaction of sound waves[1].

The sound pressure p_s of secondary wave produced by this phenemenon, was first derived by Westervelt as the solution of the following equation[3].

$$\begin{cases} \nabla^2 p_s - \dfrac{1}{c_0^2}\dfrac{\partial^2 p_s}{\partial t^2} = -\rho_0 \dfrac{\partial q}{\partial t} & (1) \\ q = \dfrac{\beta}{\rho_0^2 c_0^4}\dfrac{\partial}{\partial t} p_1^2 & (2) \end{cases}$$

where, c_0: small signal sound velocity, ρ_0:density of fluid

β:nonlinear parameter of fluid and p_1:primary wave sound pressure.

Now, a finite amplitude AM ultrasonic plane wave shown in eq.(3) is considered as the primary wave.

$$p_1 = p_0\{1 + m \cdot g(t - \frac{x}{c_0})\} e^{-\alpha x} \cdot \sin \omega_0 (t - \frac{x}{c_0}) \qquad (3)$$

Where, p_0:initial sound pressure of carrier sound
m:a parameter indicating modulation index
α :absorption coefficient of carrier sound
$g(t)$:modulation signal (audio signal).

In this case, the carrier component and the side band component interact nonlinearly each other, and as the result,the AM ultrasound is self-demodulated in the air.

If a carrier plane wave with radius a is assumed to be radiated from the transducer array, the sound pressure of the secondary wave at the point r distant from the array on the axis, can be calculated approximately. In the case of sinusoidal modulation, we get,

$$\begin{cases} p_s = -\dfrac{\beta p_0^2 a^2 m \omega^2}{8 \rho_0 c_0^4 \alpha r} \cdot \sin \omega (t - \dfrac{r}{c_0}) & (4) \\ p_d = \dfrac{\beta p_0^2 a^2 m^2 \omega^2}{8 \rho_0 c_0^4 \alpha r} \cdot \cos 2\omega (t - \dfrac{r}{c_0}) & (5) \end{cases}$$

In above equation, p_s and p_d show the signal sound pressure and 2nd harmonic distortion sound pressure,respectively.

Accordingly,it is possible to construct a new type of loudspeaker if the modulation signal is selected as the programed audio signal. Figure 1 shows the signal sound pressure based on the calculation of eq(4).

By eq.(4) and(5), it is clear that the signal sound pressure is proportional to m and the second harmonic distortion sound pressure is proportional to m^2. Therefore a good distortion ratio requires a very small m to prevent cross-interaction between the lower and the upper side band waves. The second harmonic distortion ratio ε can be expressed as

$$\varepsilon = \frac{|p_d|}{|p_s|} \times 100\ \% = m \times 100\ \% \qquad (6)$$

Experiments

The loudspeaker was developed by using 547 pieces of PZT bimorph transducers. The fundamental resonant frequency of a transducer is about 40kHz and the sound pressure level is 100 dB at the point 1m from it on axis.

A front view of the loudspeaker appears in Fig.2. The sound pressure frequency response characteristics of the primary wave and the directivity pattern at 40kHz of

the loudspeaker are shown in Fig.3 and 4, respectively.

Figures 5 and 6 show the frequency characteristics and the directivity pattern of the secondary wave, respectively. In this case, the input voltage to the loudspeaker was 10V r=4m and m=0.5. It is clear from Fig.6 that the secondary wave (signal wave) has very sharp directivity. The signal and 2nd harmonic distortion compornents of the secondary wave were analyzed by spectrum analizor to check the distortion ratio. These results are shown in Fig.7 about three different m.

Discussion and Improvement

The most important feature of this type of loudspeaker is extreme sharpness of the directivity. No ordinary type of loudspeaker has ever had such a sharp directivity. However, to put to practical use there are many problems as follows,
(1)electrical power efficiency, (2)sound pressure increse (3)distortion ratio improvement (4)flattening of frequency characteristics (5)primary wave interception.

One of the effective methods for decreasing 2nd harmonic distortion is to use single side band (SSB) modulation. As interaction between lower and upper side band is avoidable by using SSB, it is possible to perform low distortion reproduction. When SSB modulation is used, a deep modulation (large m) can be available without increasing harmonic distortions. This is excellent feature of SSB modulation. A experimental result is shown in Fig.8. The figure shows that the 2nd harmonic distortion sound pressure yielded by SSB modulation is about 10dB lower than that yielded by normal AM modulation under the same conditions.

References

1)R.T.Beyer:"Nonlinear Acoustics",Naval Ships System Command (1974)
2)M.Yoneyama et.al.: J.Acoust.Soc.Am. (will be published)
3)P.J.Westervelt: J.Acoust.Soc.Am. 35,4,(1963) p535

Figures

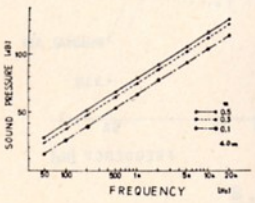


Fig.1

Fig.2

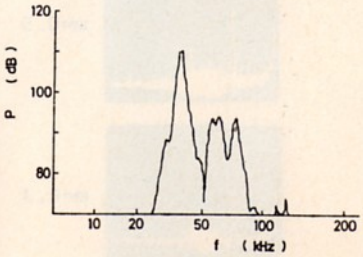


Fig.3

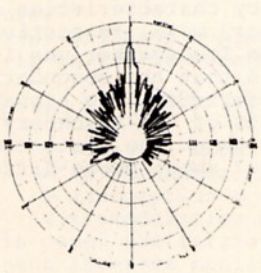


Fig.4

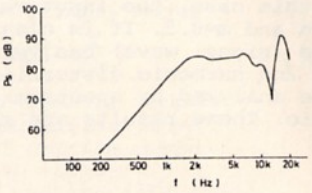
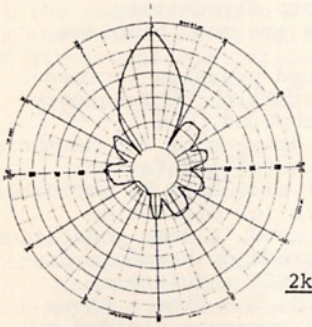
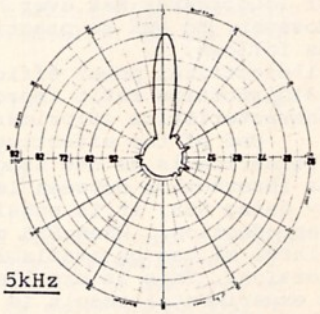


Fig.5



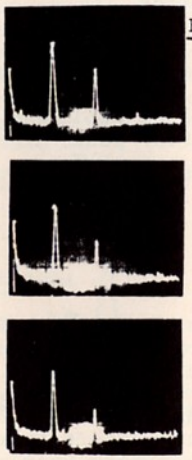
2kHz

Fig.6



5kHz

Fig.7



m=1.0

m=0.5

m=0.3

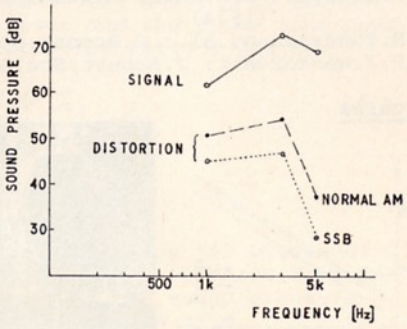


Fig.8