Design of Ultrasonic Transducer for Secondary Wave Generations with High Directivity

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In this paper, we described a method of designing ultrasonic transducer which simultaneously radiates two finite-amplitude ultrasonic waves to produce the secondary waves with high directivity. For nonlinear effects, it is necessary that the frequencies of two primary waves are coincident with natural frequencies of the ultrasonic transducer. The main problem here is to predict the resonance frequencies of the first mode as well as higher modes. While the first resonance frequency of the transducer can be estimated easily, it is not trivial to do higher ones. When the length of transducer is much greater than its diameter, this problem is reduced to one-dimensional and higher mode frequencies are nothing but multiples of the first mode frequency. However, such a case is seldom encountered. Using the transfer matrix method, we obtained the resonance frequencies of the transducer analytically and compared these with numerical results from the simulation. The theoretical and simulation results are in good agreement with the difference of 3–6kHz.

1. INTRODUCTION

Generally, polaroid-type sensors of Murata and SensComp have a directivity of about 20° at working frequencies, meaning that the beam is about 35 cm wide at a distance of one meter from the sound source.1–3 Such a directivity limits applications in several areas, such as detection and ranging in underwater and air, non-destructive testing of solid materials and medical inspection, etc. One possible way to improve directivity while keeping the frequencies the same is the use of nonlinear effects. The nonlinear effects in the propagation of sound waves have been discussed by many researchers.4–10

When two finite-amplitude primary waves propagate together in fluids, the sum and difference frequency waves as well as higher harmonics are produced as secondary waves, owing to the nonlinear interaction between the primary waves. From the absorptive properties of the medium, which prefer higher frequencies to lower ones, there remains only the difference frequency wave in the far-field.11–14 Darvennes and Hamilton showed that the directivity of the difference frequency wave in the far-field is governed by the product of the primary directivities, which becomes sharper. This observation, commonly known as the product directivity (PD) model has been widely used for many acoustic applications, especially for parametric array loudspeakers.15,16 The parametric loudspeaker was first devised by Yoneyama et al., who showed that an audio signal with a high directivity could be produced from ultrasonic waves due to the nonlinearity of the air.17 Since then, many later works have been done for the digital beam steering for parametric loudspeakers including the digital implementation of a beam steering algorithm, active noise control system, and the introduction of pre-processing methods.18–21

In spite of these successes of the PD model, there are some mismatches between the measured directivities and the theoretical results. Shi and Gan revisited the original theories, proposed three modified models for the directivity of the difference frequency waves, and compared the numerical results with experimental results.22 According to their results, the shorter the distance between the sources of primary waves, the higher the directivity of the difference frequency wave. It is, therefore, obvious that a higher directivity of difference frequency wave can be obtained if two primary waves are radiated by one transducer. For doing so, the resonance frequencies of a transducer have to be separated as far as one of interest and the transducer must be designed so as to satisfy such a condition. It is easy to estimate the first mode frequency, but it is difficult to do higher modes. If a transducer satisfies the condition such that the length should be much greater than the diameter, higher mode frequencies become multiples of the first mode, but in other cases the evaluation is not so simple. In this paper, the resonance frequencies of the transducer are theoretically found using the transfer matrix method, and its validity is confirmed through the comparison with the simulation results using ANSYS 14.5.

2. DESIGN PROCEDURE

The transfer matrix expresses the relationship between the forces and velocities at both end-sides of the medium through which a plane wave propagates. The transfer matrix method has been applied for designing some acoustic structures, especially layered structures and simulating or analysing the propagation of sound waves within such structures.23,24

For the constant cross section, the transfer matrix is given as follows:25

$$
\begin{align*}
\begin{pmatrix}
\dot{\xi}_2 \\
\dot{F}_2
\end{pmatrix} &= \begin{pmatrix}
\cos kl & -\rho cs \sin kl \\
-\rho cs \sin kl & \cos kl
\end{pmatrix}
\begin{pmatrix}
\dot{\xi}_1 \\
\dot{F}_1
\end{pmatrix} \\
\end{align*}
$$

(1)

where $\dot{\xi}_1$ and $F_1$ are the vibration velocity of the medium particle and the force exerted on the incident boundary, respectively, and $\dot{\xi}_2$ and $F_2$ are the counterparts on the opposite one.