Variable aperture conical transducer

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A new long-range focusing transducer is proposed which is constructed by applying the variable aperture technique to a conical radiator. It is shown that, although the technique was originally developed for a concave radiator, it works more effectively in a conical radiator than in a concave one. Through the theoretical and experimental examinations, it is demonstrated that a conical type is superior to a concave one especially in the focusing performance in the near region when it is operated with a limited aperture.

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1. INTRODUCTION

One of the most important requirements for ultrasound transducers used in imaging systems is the high capability in maintaining good lateral resolution over a large depth. Conventional concave transducers or acoustic lenses with a fixed focal-length cannot meet such a condition because lateral resolution of these focusing elements can be improved only within a limited depth of focus. In order to overcome this problem, several methods have been devised so far. One example is dynamic-focusing which is used mainly in medical diagnostic systems. This employs phased transducer-array where electric pulse-signals are applied to the transducer elements through quadratically tapered variable delay lines. Delays applied to the elements are time-controlled depending on the inspection depth so that the array performs diffraction-limited imaging at all depths. The dynamic focusing systems, however, need a complex electronic circuitry for the delay control and signal processing, and therefore require high manufacturing costs.

A rather simple method to extend the effective depth-of-focus has been proposed by Okujima and Ohtsuki,¹⁾ which was named "variable aperture transducer." The method makes use of the phenomenon that, even for a concave transducer with a fixed radius of curvature, the axial position

giving the minimum beamwidth and the maximum acoustic pressure can be shifted towards the transducer by limiting the effective aperture diameter. The aperture of the transducer is divided concentrically into several segments and the diameter of the active area is varied depending on the depth, i.e., a small aperture is applied for imaging in near regions and a full aperture for far regions.

Another approach to obtain an extended focal range is the use of conical focusing elements.²⁻⁸⁾ Since a conical element produces a sound beam that converges to a line focus, it has an advantage over a concave one in having intrinsically a large depth of field. So, a long-range-focusing transducer is expected if we apply the technique of variable aperture to a conical radiator.

In the present paper we propose a new class of focusing elements, namely, a variable aperture conical transducer. We examine the acoustic fields of variable aperture transducers of conical and concave types, and demonstrate that the variable aperture technique works more effectively in a conical radiator than in a concave one.

2. ACOUSTIC FIELDS OF VARIABLE APERTURE TRANSDUCERS OF CONICAL AND CONCAVE TYPES

Figure 1 illustrates the variable aperture transducers of (a) a conical type proposed here and (b)

Fig. 1 Variable aperture transducers of (a) conical type and (b) concave type.

a concave type. Here, a_0 is the maximum radius of the aperture, θ is the cone angle and b_0 is the radius of curvature of the spherical concave. The transducer apertures are divided concentrically into n -segments (shown for $n=3$ in Fig. 1) and the radius a_d of the effective area, within which the transducer elements are activated, is varied discretely depending on the inspection depth.

Even for transducers with a curved radiating surface, the acoustic pressure p produced in a fluid medium can be calculated approximately by using Rayleigh's formula.⁵⁻⁸⁾ The formula is given by the following equation, provided that every part of the activated area S of the transducer surface vibrates in phase with a velocity amplitude v_0 at an angular frequency ω :

$$p = \frac{\rho c v_0}{j\lambda} e^{-j\omega t} \int_S \frac{e^{j(2\pi/\lambda)s}}{s} dS \quad (1)$$

Here, c is the wave velocity, λ is the wavelength in the fluid, ρ is the density of the fluid and s is the distance from a point in the fluid to a surface element dS on the transducer.

2.1 Beamwidth Characteristics of Conical Type

In order to give design criteria, beamwidth characteristics of a variable aperture conical transducer are examined theoretically by calculating field distributions for the case of $a_0/\lambda = 30$.

Figure 2 shows the variations of the normalized minimum -6 dB beamwidth $B_{W \min}/\lambda$ on the cone angle θ for a_d/a_0 of 0.5, 0.7 and 1.0. As the θ reduces, the beamwidth becomes narrow and the difference in beamwidth caused by the difference of the effective aperture size becomes small.

Fig. 2 Variations of minimum -6 dB beamwidth on cone angle θ calculated for a_d/a_0 of 0.5, 0.7 and 1.0.

Fig. 3 Variations of focal ranges on cone angle θ calculated for a_d/a_0 of 0.5, 0.7 and 1.0.

The axial ranges in which the beamwidth B_W falls within $\sqrt{2}$ times the corresponding minimum values are shown in Fig. 3 for the same values of a_d/a_0 as in Fig. 2. Here, the ordinate is the axial distance z normalized to a_0^2/λ and the abscissa is the cone angle θ . It is seen that the three ranges widely cover the inspection depth and that the focal depth of a conical transducer, which is intrinsically large, can further be extended effectively by controlling the aperture size. By using Figs. 2 and 3, proper cone angle of the transducer can be determined for realizing desired beamwidth within a required inspection range.

2.2 Field Profiles of Conical and Concave Types

The sound fields radiated from a conical type are

calculated for a_d/a_0 of 0.5, 0.7 and 1.0, and compared with those of a concave type. Here, the cone angle θ is chosen to be 174° and the ratio a_0/b_0 of the concave type is set to 0.078 so that the axial position giving the maximum pressure is coincident with that of the conical one.

Figure 4 shows the variations of (a) the fractional sidelobe level, (b) the normalized -6 dB beamwidth B_w/λ and (c) the normalized pressure amplitude $|p|/\rho cv_0$ on the normalized axial distance $\lambda z/a_0^2$ ($a_0/\lambda=30$). The solid and the dashed curves are for the conical and the concave types, respectively. In both types the positions giving the minimum beamwidth coincide with those giving the maximum

acoustic pressure. These positions can be brought close to the transducers by limiting the size of the effective apertures. In the conical type, sidelobes become minimum at positions where the beamwidths are minimum. In the concave type, however, the sidelobe minima are obtained near the geometric center of the spherical concave $z=b_0$ ($\lambda z/a_0^2=0.43$ for the present case) irrespectively of the aperture size. Therefore, sidelobes of the concave type are higher than those of the conical type for small values of a_d/a_0 . Furthermore, comparing with the concave type, the conical type presents narrower beamwidths at axial positions closer to the transducer. These results indicate that the conical type has advantages over the concave one in the focusing performance in the near region.

3. EXPERIMENTS

Variable aperture transducers of conical and concave types were constructed by gluing circular PVDF sheets of 25 mm diameter and 0.12 mm thickness to backing materials made of bakelite whose front surfaces were formed into a conical or a concave shape. The transducer apertures were divided into three segments. The segmentation was made by dividing the electrode on the back surface of the PVDF sheets with circular gaps having the radius of $0.5a_0$ and $0.7a_0$. The size of the activated area was varied by appropriately selecting the electrodes to which the electric signal was applied. The transducers were driven in water with an RF pulse voltage whose center frequency f_0 was 3.6 MHz ($\lambda=0.42$ mm). A hydrophone of 1.5 mm diameter was used to detect the sound pressure.

Figures 5 and 6 show the distance dependence of (a) the fractional sidelobe level, (b) the -6 dB beamwidth and (c) the pressure amplitude obtained for the conical type ($\theta=174^\circ$) and the concave type ($a_0/b_0=0.078$), respectively. The results are shown for a_d/a_0 of 0.5 (+), 0.7 (Δ) and 1.0 ($\circ$), and compared with the theoretical curves. In Figs. 5(c) and 6(c), the experimental results are plotted such that the peak pressure for $a_d/a_0=1.0$ coincides with the theory. It is seen that the experimental results exhibit almost the same variation as the theoretical curves. In Fig. 6(c), the experimental results do not show such a distinct difference as predicted by the theory with regard to the relative levels of the pressure amplitude for the three values of a_d/a_0 . Although the transducer elements were driven with a

Fig. 4 Focused field characteristics obtained theoretically for conical type (solid lines) and concave type (dashed lines) for $a_d/a_0=0.5, 0.7$ and 1.0 : (a) fractional sidelobe level, (b) -6 dB beamwidth, and (c) on-axis pressure amplitude.

Fig. 5 Variations of (a) sidelobe level, (b) beamwidth and (c) pressure amplitude measured and calculated for conical type with a_d/a_0 of 0.5 (+), 0.7 (Δ) and 1.0 ($\circ$).

Fig. 6 Variations of (a) sidelobe level, (b) beamwidth and (c) pressure amplitude measured and calculated for concave type with a_d/a_0 of 0.5 (+), 0.7 (Δ) and 1.0 ($\circ$).

constant electrical voltage, bonding of the lead wire to the electrodes of the outmost element might be imperfect and this might result in smaller vibration amplitude in the full-aperture operation than in the limited-aperture operations.

The experimentally obtained lateral field distributions and their corresponding theoretical curves are shown in Figs. 7 and 8 for the conical and the concave types, respectively. The field distributions were examined at three axial positions each giving the peak pressure for a_d/a_0 of (a) 0.5, (b) 0.7 and (c) 1.0. Appreciable "shoulders" which will grow up to be the sidelobes are noticed in the field profiles of the concave type. These results show the superiority of the conical type when it is used with a limited aperture for inspection in the near region.

4. CONCLUSION

A variable aperture conical transducer has been proposed and its focusing performance has been examined. It has been demonstrated through theoretical and experimental examinations that a conical type variable aperture transducer is superior to a concave type especially in the focusing performance in the near region. It can be said that the variable aperture technique works more effectively in a conical type than in a concave one for realizing a transducer with a long focal range.

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Fig. 7 Measured and calculated lateral field distributions for conical type at peak-pressure distances for a_d/a_0 of (a) 0.5, (b) 0.7 and (c) 1.0.

Fig. 8 Measured and calculated lateral field distributions for concave type at peak-pressure distances for a_d/a_0 of (a) 0.5, (b) 0.7 and (c) 1.0.

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