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A HIGHLY-DIRECTIONAL ULTRASONIC RANGE SENSOR USING A STEPPED-PLATE TRANSDUCER

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Abstract: A new type of highly-directional ultrasonic range sensor is designed, fabricated, and tested in this paper. To improve directivity, the parametric acoustic array, a nonlinear effect of media between two intensive waves, is applied to an ultrasonic range sensor. Additionally, a new type of the stepped-plate transducer is applied for generating high amplitude waves consisting of two frequencies. The proposed transducer shows a half power beam width(HPBW) of 5° at 40 kHz that is much higher directivity than the general ultrasonic range spatial sensor (typically 20°). Therefore, this research shows the possibility to improve the resolution of the ultrasonic range sensor.

Keywords: Sensors and actuators, Navigation, Sensing, Ultrasonic range sensor, Parametric acoustic array,

1. INTRODUCTION

An ultrasonic range sensor is generally installed in a robot for range detection and obstacle recognition. Many researches of ultrasonic range sensors were conducted from the 1900s and many commercial products have been released (Murata; Polaroid). One of the most important reasons for using several tens of kHz for the range sensor focuses on the directivity of the sensor. The half power beam width (HPBW) of the piston source with a diameter D can be determined by this equation 1 (L. Kinsler, *et al.,* 1982).

$$\theta = Sin^{-1}[1.22 \times c/(f \times D)] \qquad (1)$$

Therefore, the increment of the piston area and the frequency leads to higher directivity. However, the piston area is limited by its incorporation into a robot. Also, a frequency limit exists due to the high absorption characteristic of high frequency. Due to these conditions, directivity is limited in traditional methods. The general ultrasonic range sensor has a HPBW of 20° (Polaroid) or 40° (Murata) at 40 kHz .

A new type of highly-directional ultrasonic range sensor is proposed in this paper. To improve directivity, the parametric acoustic array, a nonlinear effect of the media between two intensive waves is used. As two high frequency (primary) waves of sufficiently high amplitude propagate, the difference frequency (secondary) wave is generated due to the nonlinear effect of the media. Because the media acts like a mutual line source, a directional sound beam can be generated in low frequency region. The secondary wave exhibits cumulative and fewer attenuation characteristics, therefore, only the secondary wave remains in the far-field region making it suitable for long-range detection. Since Westervelt (P.J.Westervelt 1963) first described this phenomenon, numerous studies have been conducted on underwater acoustics for sonar applications.

The transducer design is also important for generating the high-amplitude primary wave. Because the parametric acoustic array requires a highly intensive primary wave, the transducer should have a large radiation area. Generally, there are two approaches for a large radiation area. One is using an array of transducers and the other is using a thick radiation plate. However, the array transducer is expensive to fabricate and the transducer with a thick plate has low power efficiency. To improve on these problems, the stepped-plate, which is less expensive yet has high power efficiency, is applied for the radiation plate. The steps that have a height of half wavelength of sound in air compensate the flexural vibration of the plate. Therefore, a large and thin radiation plate leads to high power efficiency. The base model proposed by Gallego-Juarez (Gallego-Juarez *et al.,* 1978) is suitable for only monofrequency radiation. However, high amplitude radiation with two frequencies is required for difference frequency generation. Therefore, a new type of the stepped-plate that generates a high-amplitude wave with two frequencies is proposed.

In this manner, a new type of highly-directional ultrasonic range sensor is proposed in this paper. The sensor can radiate a high-amplitude ultrasonic beam with two frequencies for difference-frequency generation. The difference frequency wave shows a HPBW of 5° that is primarily directional. However, it has large side lobes in its directional pattern of difference frequency. Considering as the first model, it can be better in the next model. Therefore, this type of transducer shows possibilities for improving the resolution of the ultrasonic range sensor.

2. DESIGN METHOD

2.1 Axiomatic design.

The directional ultrasonic range sensor has the following functional requirements.

- **FR1 – high efficiency for ultrasonic radiation**
  - FR11 high acoustic intensity
    - ✓ FR111 high velocity amplitude of radiation plate
    - ✓ FR112 high radiation impedance
  - FR12 low current consumption
- **FR2 – high efficiency for difference frequency generation**
- **FR3 – low manufacturing cost**
- **FR4 – two frequency band**

Figure 1 illustrates the schematic diagram of functional requirements.

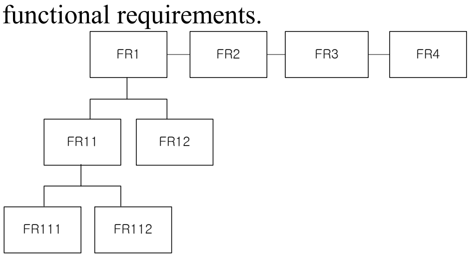

Fig. 1. Schematic diagram of functional requirements

Each functional requirement relates to the following design parameters.

- **DP111 – plate mass, type and size of mechanical amplifier (operating material and operating method)**
- **DP112 – position of steps, radiation area.**
- **DP12 – size of electrodes (operating material)**
- **DP2 –primary and secondary frequency, piston radius**
- **DP3 – material (operating material)**
- **DP4 – natural frequency of each component, material (frequency band of modulating signal)**

2.2 Parametric acoustic array design.

The transducer design procedure can be divided into two steps: design of the parametric acoustic array and design of the stepped-plate. Firstly, the optimal primary frequencies are determined by a simulation of the parametric acoustic array. Then, the transducer is designed to operate for optimal primary frequencies.

The difference frequency is determined to be 40 kHz that has been used generally in ultrasonic range sensor. Under this condition, primary frequencies are determined by parametric acoustic array simulation. The optimal frequencies with respect to sound pressure level and beam width are determined for difference frequency generation (B.K.Novikov *et al.,* 1987). Figure 2 shows the sound pressure level of the difference frequency at a distance of 4 m with respect to the first primary frequency. The peak appeared at the first primary frequency of 78.1 kHz. Therefore, the transducer is designed to operate at the frequencies of 80 kHz and 120 kHz.

Fig. 2. Difference frequency generation with respect to the first primary frequency

2.3 Transducer design.

One of the most important design parameters of a highly directional ultrasonic transducer is the radiation area. The radiation area is related not only to the sound pressure level but also to the directional pattern. However, an increase of the radius of the plate for a large radiation area results in flexural vibration. Figure 3 demonstrates the vibration test of the plane by the scanning vibrometer manufactured by Polytec It shows (a) flexural vibrating mode of plate and (b) discrete phase difference. The directional pattern of the large plate with flexural vibration is shown in Figure 4. A poor directional pattern resulted from the discrete phase difference of the plate.

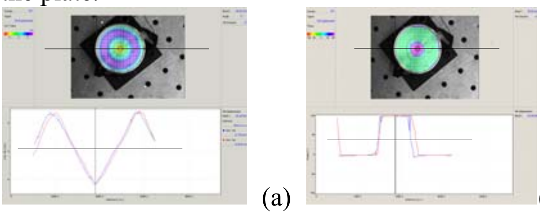
(a) (b)

Fig. 3. (a) Flexural mode of the vibrating plate (a) and (b) discrete phase difference

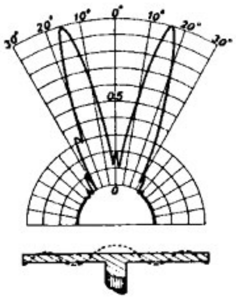

Fig. 4. Directional pattern of flexural vibration (Gallego-Juarez *et al.,* 1978)

Therefore, Gallego-Juarez *et al.* proposed the stepped-plate transducer in order to have a large radiation area. Figure 5 shows the Gallego-Juarez plate and its compensating method. The compensated discrete phase difference was generated by placing a step at the nodal line of the plate. The steps have the height of half wavelength of sound in air. Therefore, the plate vibrates in phase like a uniform piston.

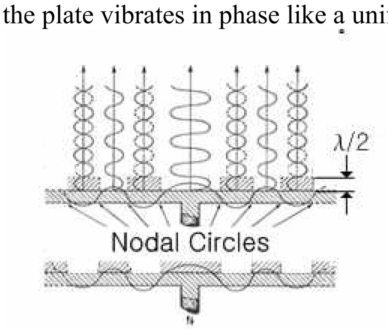

Fig. 5. The stepped-plate and its compensating method (Gallego-Juarez *et al.,* 1978)

The original model of Gallego-Juarez *et al.,* (1978) is suitable for monofrequency radiation only. In order to generate the difference frequency efficiently, a sufficiently high amplitude wave with two frequency components is required. Therefore, in this research, the stepped-plate is upgraded to compensate the flexural vibration for two frequency components.

Figure 6 illustrates the compensating method of the new stepped-plate transducer. The principle that the wavelength at 80 kHz is $3/2$ times longer than the wavelength at 120 kHz is applied. Let λ be the wavelength of the 120 kHz ultrasonic wave. Subsequently, the steps should have the height of $\lambda/2, 3\lambda/2, 5\lambda/2...$ to phase compensation of the 120 kHz vibration. For an 80 kHz ultrasonic wave, the wavelength is $3\lambda/2$. The step height required to compensate an 80 kHz wave is $3\lambda/4$. Therefore, after compensation of the 80 kHz wave with the steps of $3\lambda/4$ height, the compensation of the 120 kHz wave with the steps of $3\lambda/2$ height can be conducted less influence to the 80 kHz wave. Figure 7 shows the mode shape of the stepped-plate simulated by FEM tools. The step position is determined at the nodal point of mode shaped.

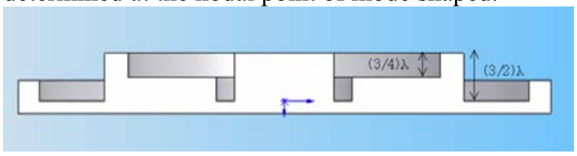

Fig. 6. Compensating method for two frequencies

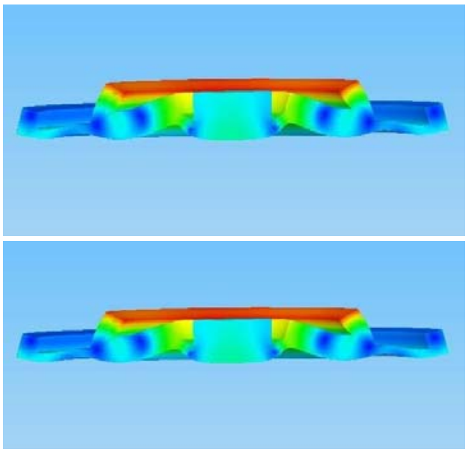
(a)
(b)

Fig. 7. Mode shape of the plate of (a) 80 kHz and (b) 120 kHz

The directional pattern is predicted by the Rayleigh integral. In the Rayleigh integral, an infinitesimal area of the plate is assumed to be a spherical source. Subsequently, the directional pattern can be obtained by integration over all infinitesimal elements. The sound pressure level can be determined by the following equation. (Kinsler, *et al.,* 1982)

$$p = \frac{j\rho_0 c}{2}\frac{1}{\lambda}\int_0^a\int_0^{2\pi}\frac{e^{j(\omega t-kr')}}{r'}U(\sigma,\phi)d\phi d\sigma \quad (3)$$

U : Source distribution

r': Distance from piston

a : Piston radius

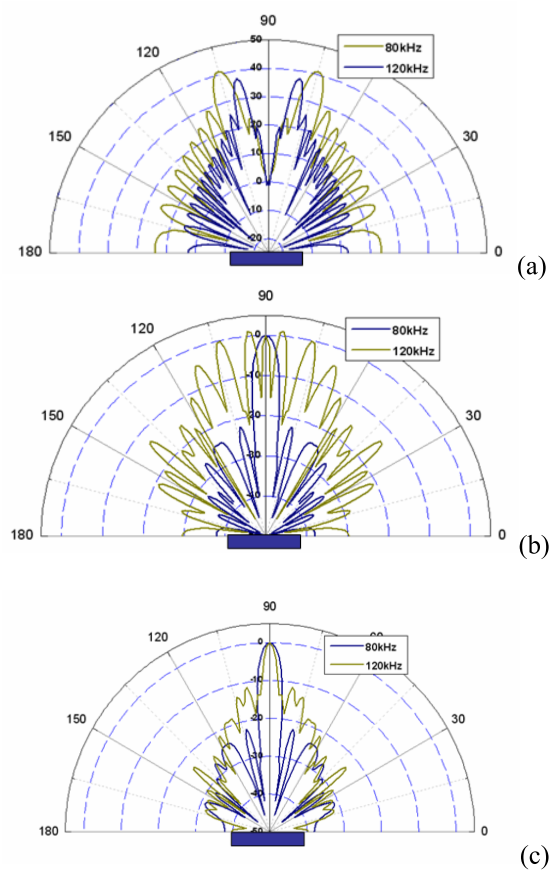

Fig. 8. Directional pattern of (a) the uniform plate, (b) the Gallego-Juarez stepped-plate, and (c) the new type of stepped-plate

Figure 8 shows the directional pattern of uniform plate, Gallego-Juarez stepped plate and the new type of the stepped plate. The uniform plate shows poor directional patterns for both frequencies due to the flexural vibration of the piston. The Gallego-Juarez stepped-plate demonstrated a good directional pattern at 80 kHz, but a poor directional pattern at 120 kHz. The new model proposed in this research showed good directional patterns at both 80 kHz and 120 kHz. Therefore, good directional patterns for both frequencies can lead to efficient difference frequency generation (Novikov *et al.,* 1987).

The resonance frequency and the position of the nodal line are determined by classical plate theory (Airey, 1910). The steps are positioned at the nodal line of the plate. Using FEM tools, the resonance frequency is tuned because steps are added to the plane of the plate. The selection of the transducer material is also an important problem. The maximum acoustic power generated by the transducer is related to the material of which the transducer is composed. Materials having high wave-propagation speeds can have sufficient stiffness in a relatively thin plate (Gallego-Juarez *et al.,* 1978). Therefore, an aluminum alloy is used for the ultrasonic range sensor. A type of mechanical amplifier is determined to the stepped horn that has the largest magnification factor (Eisner and Seager, 1965). The radius of the plate is 5 cm, and the length of the horn is 5 cm.

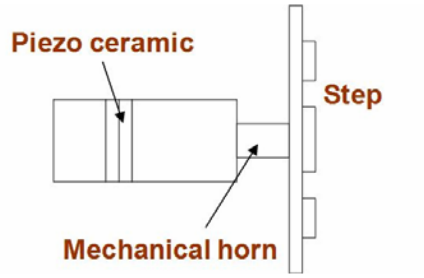

Fig. 9. Schematic design of the transducer

3. EXPERIMENT

Experiments were conducted to determine the radiation characteristics of the transducer. The transducer has resonance frequencies at 74.8 kHz and 115 kHz. The small difference in the design frequency is due to the error in material properties and fabrication. The difference frequency is generated at 40 kHz. Figure 10 shows the designed transducer.

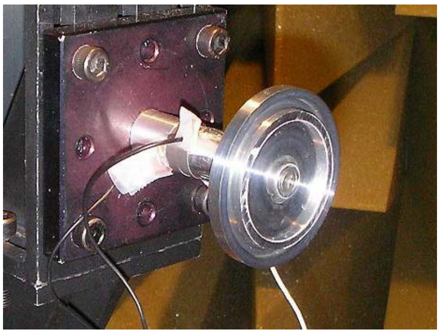

Fig. 10. The designed transducer

In Figure 11, the experimental set-up illustrates the characteristics of the ultrasonic range sensor. The input signal from two function generators is amplified by the power amplifier. Then, the amplified signal is applied to the transducer to generate the primary wave. The difference frequency wave generated by the parametric acoustic array is measured by the microphone. The signal from the microphone passes a conditioning amp and is visualized at the FFT or oscilloscope. All electronic components in this system can be integrated in a small modular circuit for commercial use. Every experiment is conducted in an anechoic room.

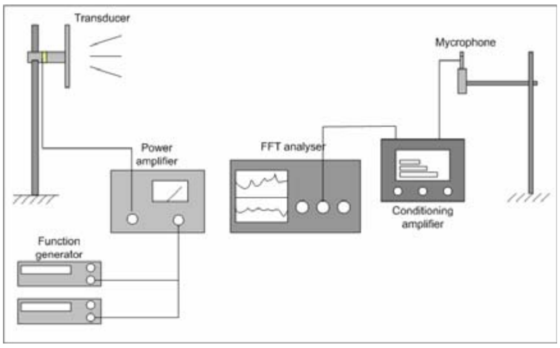

Fig. 11. The experimental set-up

The directivities for both primary and secondary waves are measured at a distance of 1m. The measurements are conducted by moving a microphone from 0° to 90° relative to the acoustic axis. A voltage of 90 Vpk is applied to the transducer through the power amplifier.

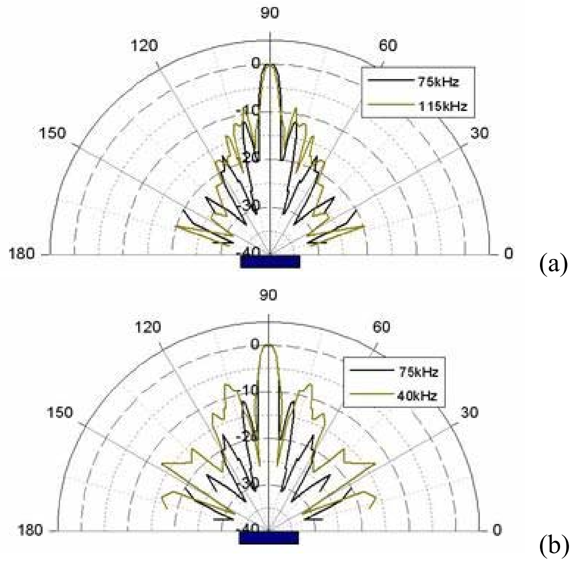

Fig. 12. Directional pattern of (a) the primary wave and (b) the secondary wave

Figure 12 shows the directional patterns for the primary wave and the secondary wave. They show similar directional patterns to those of the Rayleigh integral in figure 8. The directional patterns for 80 kHz and 120 kHz have a HPBW of 5°. Therefore, the performance of the new stepped-plate simulated by Rayleigh integral is confirmed. The secondary wave generated by the parametric acoustic array shows similar directivity to the primary wave. The secondary wave also has a HPBW of 5°. This is much higher directivity than the stepped-plate transducer for 40 kHz that has a HPBW of 12°

However, the directional pattern of the difference frequency shows large side lobes. The level difference between the major lobe and the side lobes is only 10 dB. Therefore, detecting an obstacle with high resolution can be problematic. Theoretically, the difference frequency generated by the parametric acoustic array should not have a discernable side lobe; this will be discussed in section 4.

The sound pressure level of the difference frequency is measured along the acoustic axis by moving the microphone from 5 cm to 1 m. Figure 13 shows the sound pressure level of the primary and secondary waves along the acoustic axis. The maximum sound pressure level is measured 120 dB for the primary wave, and 80dB for the secondary wave. Considering this approach as an initial model, subsequent models can be improved by the optimal design method. From the graph (Figure 13), the attenuation effect of the secondary wave is observed to be less than that of the primary wave. Therefore, in the region greater than 5 m, the difference frequency component will be more intense than the primary wave. Irregular patterns of the secondary wave below 60 cm result from the near-field effect of the piston.

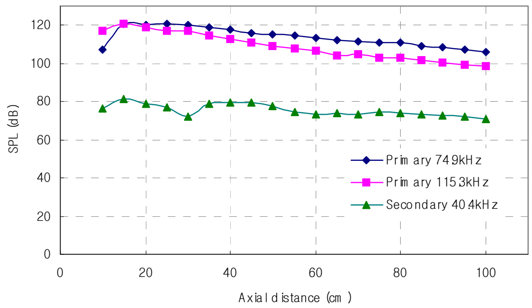

Figure. 13. Sound pressure level along the acoustic axis

4. DISCUSSION

The effects of the proposed stepped-plate transducer are confirmed experimentally. A highly directional beam is generated at 80 kHz and 120 kHz. Additionally, the secondary wave exhibited a HPBW of 5° that is highly directional compared to general ultrasonic range sensors. Therefore, this new type of the transducer is quietly suitable as an ultrasonic range sensor.

However, the new type of the stepped-plate transducer shows relatively large side lobes. Theoretically, the secondary wave should not have side lobes because it has a line source by a nonlinear effect (B.K.Novikov *et al.,* 1987). Even at 30° from the acoustic axis, some side lobes exist that are not negligible.

A nonlinear effect of the transducer is suspected to be the cause of this problem. This transducer consumes high voltage and generates high displacement to produce a high sound pressure level. Therefore, the vibration of the difference frequency component is generated from the nonlinear effect of the transducer. The difference frequency wave radiates directly from the plate. The nonlinear vibration of the plate was confirmed using a laser vibrometer. Figure 14 shows the results. As the input voltage increases, the nonlinear effect becomes more significant.

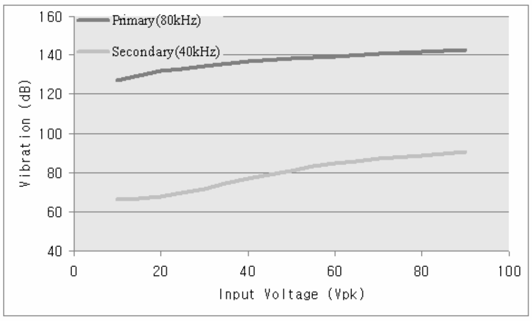

Fig. 14. Nonlinear vibration of the plate

This phenomenon is a near-field effect that usually occurs in the general parametric array apparatus. Therefore, the side lobes resulting from direct generation become less in the far-field region. However, for improved performance, reducing nonlinear effect is required.

A nonlinear effect is difficult to estimate by an analytic method or a FEM simulation. Therefore, an experimental approach and intuitive design is considered. To reduce the nonlinear vibration of the plate, the transducer must be designed to have less stress. In the model examined in this research, all components of the transducer (plate, the mechanical amplifier and the PZT) are assembled by bolting. The nonlinear vibration is generated by the stress applied to the screw. Therefore, in subsequent models, the transducer should be fabricated as a single unit without the need to bolt components together. The mechanical amplifier will be also changed to a linear horn to reduce the stress.

In the future, research to obtain higher sound pressure levels will also be conducted. The design of a mechanical amplifier including piezoelectric characteristics will be considered to estimate more correct resonance frequency. Then, considering the resonance with the plate, a transducer with greater power-efficiency can be designed.

5. CONCLUSION

A new type of highly-directional ultrasonic range sensor is designed, fabricated, and tested in this paper. The new type of the stepped-plate transducer is applied to generate an ultrasonic wave with two-frequency components. Using the parametric acoustic array with this transducer, a highly directional ultrasonic beam having a HPBW of 5° is generated. This type of transducer shows the possibility to improve the resolution of the ultrasonic range sensor.

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