論 文 の 内 容 の 要 旨

論文題目　Investigation on improving performance of parametric array
（パラメトリックアレイの高性能化に関する研究）

氏　　名　　藤澤 慶

1. Introduction

A parametric array is one of the nonlinear transduction mechanisms. It is characterized by low side lobe secondary waves at harmonics and the parametric sound at the sum and difference frequencies of the transmitted primary waves in comparison with a conventional linear array. The parametric sound at the sum and difference frequencies are generated through the nonlinear interaction of primary waves at two different frequencies in a fluid, as reported by Westervelt [1] and the author indicated that the difference frequency generated from the parametric array contributes to a narrow, nearly side lobe free low frequency beam with a small sound attenuation during long distance propagation. Later, Muir [2] showed that the narrower main lobe and lower side lobe of the parametric sound at the sum frequency compared to the transmitted primary waves in a water environment. These acoustic characteristics of parametric sound are useful in measurement and imaging in water environment since it improves size measurement accuracy and acoustic image quality. However, such nonlinear effects are generally small compared to transmitted primary waves. This would result in a low signal-to-noise ratio in measurement and imaging for application that utilizes the nonlinear acoustic effects.

In this paper, the mechanism of parametric sound enhancement in different fluid layers is theoretically derived and numerically and experimentally studied. Furthermore, together with a shadow imaging technique, this concept is applied to the noninvasive detection of underwater structures.

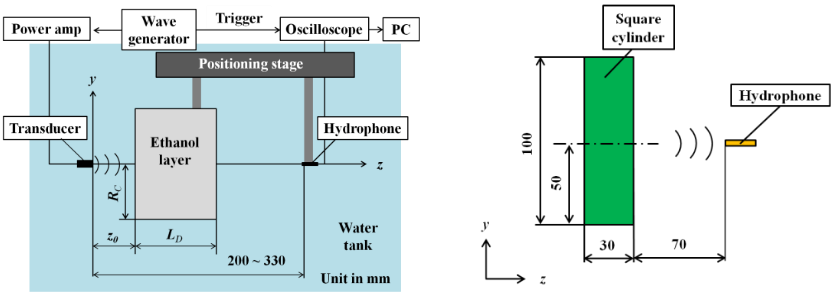
2. Theory

Parametric sound enhancement through different fluid layers is a promising technique for improving performance of parametric array in water environment [3]. In order to understand the nonlinear acoustic effects with the different fluid layer, the ratio of the sound pressure through the different fluid layer to that of water (enhancement ratio) is theoretically derived from the Burgers equation for a large Goldberg's number in sound propagations using quasi-linear approximation as follows:

$$\eta = \frac{T_{DW}\left(T_{WD}\chi_W z_0 + T_{WD}{}^2 \chi_D L_D\right) + \left(T_{WD}T_{DW}\right)^2 \chi_W L_W}{\chi_W z} \qquad \text{Eq. 1}$$

$$L_W = z - z_0 - L_D,\ \ \chi_D = \beta_D / \rho_D {c_D}^3,\ \ \chi_W = \beta_W / \rho_W {c_W}^3 \qquad \text{Eq. 2}$$

where c: sound speed, $_D$: fluid properties of the different fluid, L_D: length of different fluid, T_{WD} and T_{DW} : sound pressure transmittance from water to different fluid and sound pressure transmittance from different fluid to water, $_W$: fluid properties of water, z: propagation distance, z_0: length of the water near the transducer and β (= 1 + B/2A): the coefficient of nonlinearity, ρ: density.



(a) (b)

Figure 1 Parametric sound enhancement through different fluid layers and its application to noninvasive detection of square cylinder. (a) Experimental setup, (b) Square cylinder.

3. Numerical method

A numerical method for nonlinear sound propagation in different fluid layers, called hybrid model is newly developed, especially to consider the reflection at the interface between two fluids. This combines the Fluid dynamic equations (Eq. 3 – Eq. 6) in the vicinity of sound source and the Khokhlov - Zabolotskaya - Kuznetsov equation (Eq. 7) in the far-field [4].

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{u} = 0 \qquad \text{Eq. 3,} \qquad \rho\frac{D\mathbf{u}}{Dt} + \nabla\cdot\left(P\,\mathbf{I} - \boldsymbol{\tau}\right) = 0 \qquad \text{Eq. 4,}$$

$$\rho T\frac{DS}{Dt} = \kappa\nabla^2 T + \boldsymbol{\tau} : \nabla\mathbf{u} \qquad \text{Eq. 5,} \qquad P^* = c^2\rho^* + \frac{c^2 B}{2\rho_0 A}\rho^{*2} + \left(\frac{\partial P}{\partial s}\right)_{\rho,0} S^* \qquad \text{Eq. 6,}$$

$$\frac{\partial^2 p^*}{\partial\tau^*\partial\sigma} - \alpha R_d\frac{\partial^2 p^*}{\partial\tau^{*2}} - \frac{1}{2\sigma_D}\frac{\partial^2 p^{*2}}{\partial\tau^{*2}} - \frac{1}{4}\nabla_\perp^2 p^* = 0 \qquad \text{Eq.7}$$

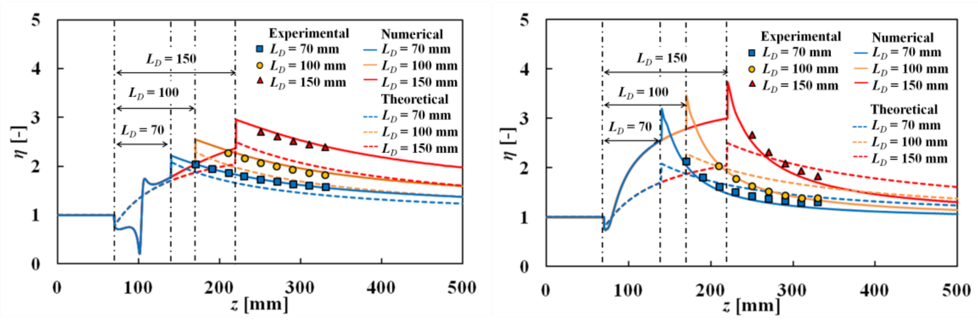
where p^*: normalized sound pressure, t: time, z and r: the axial and radial distance, B/A: parameter of nonlinearity, P^*: sound pressure, S: entropy, T: temperature, κ: thermal conductivity, R_d: Rayleigh distance, α: the absorption coefficient, σ and ξ: the dimensionless axial distance and radial distance, σ_D: normalized shock wave formation distance, τ^*: normalized retarded time, $\mathbf{u}$: velocity vector, and $\boldsymbol{\tau}$: stress tensor.

4. Experiments

To verify the theoretical and numerical results, experiments were carried out by hydrophone measurement in a water tank as shown in Fig 1 (a). The ethanol layer was set at a distance z_0 = 70 mm away from the transducer in the water tank and acoustic waves are measured by traversing receiver hydrophone by a positioning stage and the obtained signals were observed by a digital storage oscilloscope. The ethanol layer was composed of cylinder, which was separated from water using a thin rubber film of thickness 0.1 mm to prevent the mixing of ethanol and water. A circular type transducer of a = 14 mm in radius with a flat surface was used as a sound source.

5. Results and discussions

Two different frequencies of primary waves are set to f_1 = 1.1 MHz and f_2 = 1.2 MHz as sound source of 14 mm in radius to generate the sum frequency at f_S = 2.3 MHz and difference frequency at f_D = 100 kHz. Figures 2 (a) and (b) show the enhancement ratio at the sum and difference frequencies for the three different fluid layer lengths. The results show that η gradually increases in the different fluid layer due to the larger nonlinearity of ethanol. Then, η increases rapidly at the different fluid/water interface, due to the larger acoustic impedance of water compared to ethanol. Both numerical and theoretical results show the similar tendency of increasing η with increasing z in the different fluid layer and decreasing η with increasing z in the far field. The maximum enhancement ratio was 3.7 for the difference frequency at an ethanol length of 150 mm which is larger than 2.7 for the sum frequency. This can be attributed to the diffraction effect in the different fluid layer. This behavior was not in the theoretical results because the diffraction effect is neglected in the theoretical model.



(a) (b)

Figure 2 Enhancement ratio distribution along beam axis. (a: sum frequency, b: difference frequency)

6. Application

To verify the application of nonlinear parametric sound enhancement through different fluid layers, the technique is applied to the noninvasive measurement of a square cylinder made of aluminum as shown in Fig 1 (b) in water together with a shadow method [3, 5]. It was located at z = 200 mm in water behind the ethanol layer, and the hydrophone was at z = 300 mm. Figures 3 (a) and (b) show the B-mode images of nonlinear sound with and without different fluid layer in water, respectively. Three types of signal amplitude distributions were observed in the results both with and without the ethanol layer. The three types of waves were penetration waves through the cylinder, reverberation waves inside the cylinder and direct waves. These distributions are more clearly observed in the result with the ethanol layer than in water. The results indicate that the secondary waves from the parametric array are magnified by the ethanol layer.

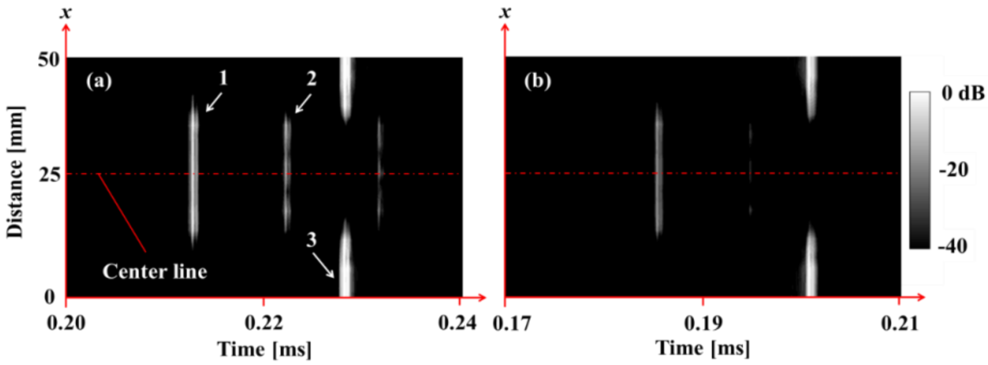


Figure 3 B-mode images after logarithmic data compression. (a: ethanol layer, b: water)

7. Conclusion

The mechanism of parametric sound enhancement through different fluid layers was derived theoretically and it was numerically and experimentally studied. In addition, the concept of different fluid layer was applied to the noninvasive measurement of structures in water environment. A theoretical analysis was carried out using the Burgers equation and numerical simulation was carried out using the hybrid model under the irradiation of two distinct primary frequencies from a circular sound source through different fluid layer. The results showed that the sound pressure at the sum and difference frequencies increases with increasing length of the different fluid layer. It was also found that the maximum enhancement ratio in the axial direction was 3.7 at the difference frequency, which is larger than 2.7 at the sum frequency due to the diffraction effect in the different fluid layer. Finally, the concept of nonlinear parametric sound enhancement through different fluid layer was applied to the noninvasive measurement of a target square cylinder in water. The measurement result with different fluid layer showed higher signal amplitude of target structure imaging than conventional nonlinear acoustic imaging.

References

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