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Numerical analysis of acoustic radiation efficiency of plate structures with air bubble layers

기포층을 갖는 판 구조물의 음향 방사 효율에 관한 수치해석

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ABSTRACT: Underwater noise pollution has a significant impact on the marine environment. This study proposed a simple approach to estimate the acoustic radiation efficiency of structures with air bubble layers. The method considered the insertion loss caused by the air bubble layer through post-processing of numerical results, assuming that insertion loss is equivalent to attenuation as demonstrated by previous studies. The proposed approach was validated by comparing it with a fully coupled analysis for plate structure models. The commercial finite element program COMSOL Multiphysics was used for the acoustic-structure interaction analysis, and the acoustic characteristics of air bubble layer for the fully coupled analysis was simulated by on the Commander and Prosperetti theory. The trends indicated good agreement between the simple approach and the fully coupled analysis in terms of radiation efficiency. It is confirmed that the proposed method is providing insight into the principal mechanism of underwater noise reduction for the bubble layer on the wedge-shaped structure.

Keywords: Radiation efficiency, Simple approach, Acoustic-structure fully-coupled analysis, Air bubble, Plate structure

PACS numbers: 43.30.Jx., 43.30.Ky

초 록: 수중 소음 공해는 해양 환경에 막대한 영향을 미친다. 본 연구에서는 기포층을 갖는 구조물의 음향 방사 효율을 추정하기 위한 간이 해석법을 제안하였다. 선행 연구 결과를 바탕으로 공기층에 의한 삽입 손실은 감쇠량과 동등하다고 가정하고, 기포층에 의한 삽입 손실은 수치해석 결과의 후처리 기법을 사용하여 계산되었다. 제안된 방법의 검증을 위해 판 구조물에 대한 음향-구조 완전 연성 해석을 수행하였다. 음향-구조 완전 연성 해석은 상용 유한 요소 프로그램 COMSOL Multiphysics를 사용하여 수행되었으며, 기포층의 음향 특성은 Commander 및 Prosperetti 이론을 사용하여 구현하였다. 음향 방사 효율 비교를 통해 간이 해석법과 완전 연성 해석 결과의 경향이 유사함을 확인하였다. 이러한 결과를 바탕으로 기포층을 갖는 쐐기 구조물의 방사 효율 메커니즘을 예측할 수 있음을 확인하였다.

핵심용어: 방사 효율, 간이 해석법, 음향-구조 완전 연성 해석, 기포층, 판 구조물

I. Introduction

Air-bubble curtains are commonly used to reduce underwater noise levels. The interaction between radiated sound and air bubbles has been extensively studied in engineering applications. Wursig *et al.*[1] measured sound intensities near pile-driving in the sea and demonstrated the effectiveness of air-bubble curtains in reducing radiated noise. Park *et al.*[2] developed an analytic solution to examine the insertion loss of fluid-loaded plates with bubble layers, while Lee *et al.*[3] studied the behavior of elastic shell models surrounded by air-bubble layers.

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“이 논문은 24th ICA 2022 국제학술대회에서 발표한 논문을 바탕으로 보완 연구한 결과임.”

We proposed simple approach to estimate the radiation efficiency for plate structures with air bubble in the previous study.[4] To validate the proposed method, it was compared with numerical analysis.

II. Theoretical background

2.1 Finite element method for acoustic-structure interaction

The inhomogeneous Helmholtz equation is commonly used in acoustics in the frequency domain for describing the propagation of sound waves in inhomogeneous media, including sources of sound, and takes the form:

$$\nabla \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q_d})\right) - \frac{k^2 p_t}{\rho} = \mathrm{Q_m}, \tag{1}$$

where $k^2 p_t/\rho$ is the total acoustic pressure field (p_t) multiplied by the wave number (k) squared and divided by the fluid density (ρ). This term represents the propagation of the sound waves in the fluid medium. The Q_m and $\mathbf{q_d}$ are the monopole and diploe domain sources, respectively.

The acoustic-structure coupling includes both the fluid load acting on the structure and the structural acceleration caused by the fluid. The acoustic-boundaries condition, which describes the interaction between sound wave and surface in the acoustic medium, are expressed as:

$$-\mathbf{n} \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q_d})\right) = -\mathbf{n} \cdot \mathbf{u_{tt}}. \tag{2}$$

$$\mathbf{F_A} = p_t \mathbf{n}$$

$\mathbf{n}$ is normal vector to the surface, and $\mathbf{u_{tt}}$ is the structural acceleration. $\mathbf{F_A}$ is the force per unit area by the surface. The internal boundary condition expressed by:

$$-\mathbf{n} \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q_d})\right)_{up} = -\mathbf{n} \cdot \mathbf{u_{tt}}. \tag{3}$$

$$-\mathbf{n} \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q_d})\right)_{down} = -\mathbf{n} \cdot \mathbf{u_{tt}}. \tag{4}$$

$$\mathbf{F_A} = (p_{t,down} - p_{t,up})\mathbf{n}. \tag{5}$$

$p_{t,down}$ and $p_{t,up}$ mean the acoustic pressure on the down and up sides of the interior boundary [shown in Fig. 1(a)].

2.2 Acoustic property of bubble layers: Commander and Prosperetti

According to Commander and Prosperetti,[5] the equivalent wave number k_m of bubbly fluid provides the following relationship for a pressure wave with a time dependence proportional to:

$$k_m^2 = \frac{\omega^2}{c^2} + 4\pi \int_0^\infty \frac{a f(a)}{\omega_0^2 - \omega^2 + 2i\delta\omega} da. \tag{6}$$

The function $f(a)$ represents the bubble distribution, and can be used to quantify the number of bubbles per unit volume, while a is a radius of bubble. δ is the damping coefficient of the bubble and ω_0 is the resonant frequency of the bubble. The damping coefficient of the mixed medium of bubble and water, α, is expressed as the imaginary part of the equivalent wave number:

$$\alpha = -Im(k_m) \text{ [nepers/m]}. \tag{7}$$

when the wave is propagated to a h [m], the attenuation α_e is equal to 8.686 αh[dB]. In this study, the bubble distribution was followed by a normal distribution.[3]

2.3 Simple approach: radiation efficiency prediction of structure with air bubble

Insertion loss is a measure of the reduction in sound power level (SPL) caused by an acoustic barrier, such as air bubble, wall, panel, and etc. It is expressed in decibels (dB) and is calculated as the difference between the sound power level of the source without the barrier ($\mathrm{SPL_I}$) and the sound power level of the source with the barrier ($\mathrm{SPL_{II}}$).

$$\mathrm{IL} = \mathrm{SPL_I} - \mathrm{SPL_{II}}. \tag{8}$$

In a previous study,[2] it was demonstrated that the insertion loss is equal to the attenuation of the air bubble layer ($\mathrm{IL} \approx \alpha_e$). Therefore, the $\mathrm{SPL_{II}}$ can be obtained by difference between $\mathrm{SPL_I}$ and α using Eq. (8).

$$\mathrm{SPL_{II}} = \mathrm{IL} - \mathrm{SPL_I} \approx \alpha_e - \mathrm{SPL_I}. \tag{9}$$

$\mathrm{SPL_I}$ was obtained from numerical analysis.

The acoustic radiation efficiency σ is defined as the sound power emitted by the vibrating structure, the mean square velocity in the entire area of the surface.

$$\sigma = \frac{W}{\rho c S \langle \overline{v}^2 \rangle}, \tag{10}$$

where ρ is the density of the fluid, W is the sound power emitted by the vibrating structure. $\overline{v}^2$ is the mean square velocity in the entire area of the surface S. The simple approach was briefly summarized as follows:

1. Calculate the attenuation, which was assumed to be equivalent to the insertion loss caused by the transmission through the bubble layer.
2. Obtain the sound pressure level from Finite Element Analysis without including the bubble layer model.
3. $\mathrm{SPL_{II}}$ is calculate by differences between $\mathrm{SPL_I}$ and IL

It is possible to obtain insertion loss and radiation efficiency using fully coupled analysis, but it needs more time to generate Finite Element (FE) model and compute results. Therefore, we proposed a procedure of simple approach for reducing computing power.

III. Numerical examples

3.1 Numerical models

To validate proposed approach, the fully coupled analyses were performed for the fluid-loaded plate models with air bubble. As shown in Fig. 1(a) ~ (b), a two-dimensional axisymmetric acoustic-structure interaction analysis were carried out for two type plates: finite and infinite plates. A point load was applied at the center of the plate.

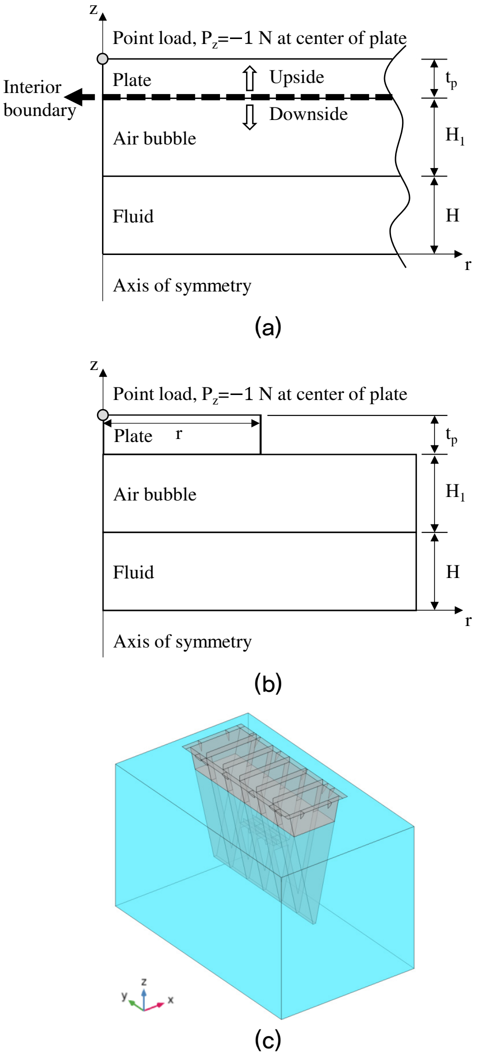
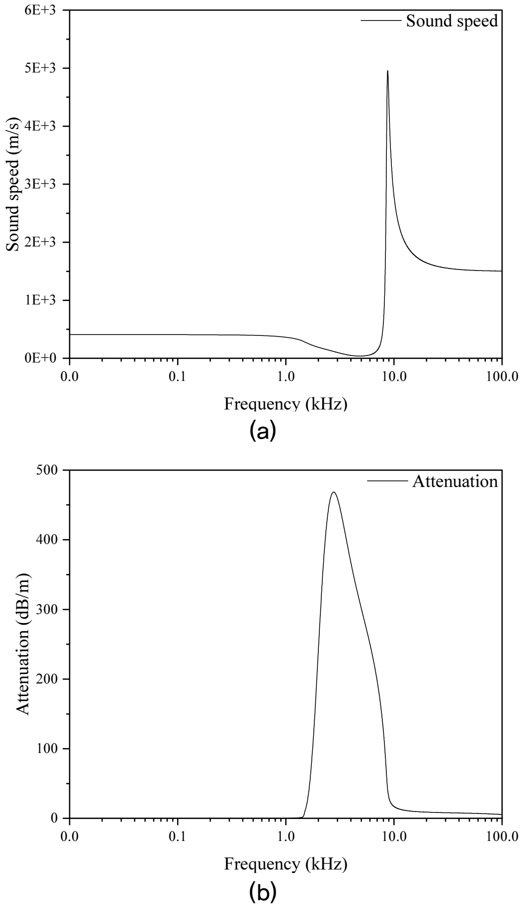


Fig. 1. (Color available online) Illustration of numerical models (a) infinite plate (b) finite plate (c) wedge-shaped structure.

Furthermore, the simple approach was conducted to investigate the radiation efficiency characteristics of composite plate stricture, which was the wedge-shaped structure [see Fig. 1(c)]. The length, width, and height were defined by the x, y, and z-directions. A unit load was applied to the inner stiffener. The parameters for numerical analysis are presented in Table 1. The Perfectly Matched Layer (PML) was added to the absorbing boundary to make the domain infinite. The convergence study was conducted

Table 1. Parameters for numerical models.

Medium	Parameter	Value
Steel	Young's modulus	19.5×10^{10} N/m^2
	Poisson's ratio	0.3
	Density	7,800 kg/m^3
	Compressional sound of speed	5801.2 m/s
	Structural loss factor	0.005
Plate	Thickness, t_p	0.015 m
	Radius, r	1.25 m
Wedge-shaped structure	Weight	3419.7 kg
	Buoyancy	2997.0 kg
	Height	2500.0 m
	Draft	2000.0 m
	Width	1337.7 m
	Length	3000.0 m
Fluid	Depth, H	3.0 m
	Density	1,000 kg/m^3
	Sound of speed, c_w	1,500 m/s
Air- bubble	Bubble radius	0.5 mm ~ 2.5 mm
	Specific heat ratio	1.4
	Layer thickness, H_l	0.1m
	Wave Speed	c_w/f
	Density	999 kg/m^3



(a)

(b)

Fig. 2. The pressure acoustic model parameters for bubble layer. (a) sound speed (b) attenuation.

to determine the appropriate element size, and one bending wave of the plate was discretized with eight elements. The acoustic property of the bubble layer was defined by the sound speed and attenuation coefficient (see Fig. 2).

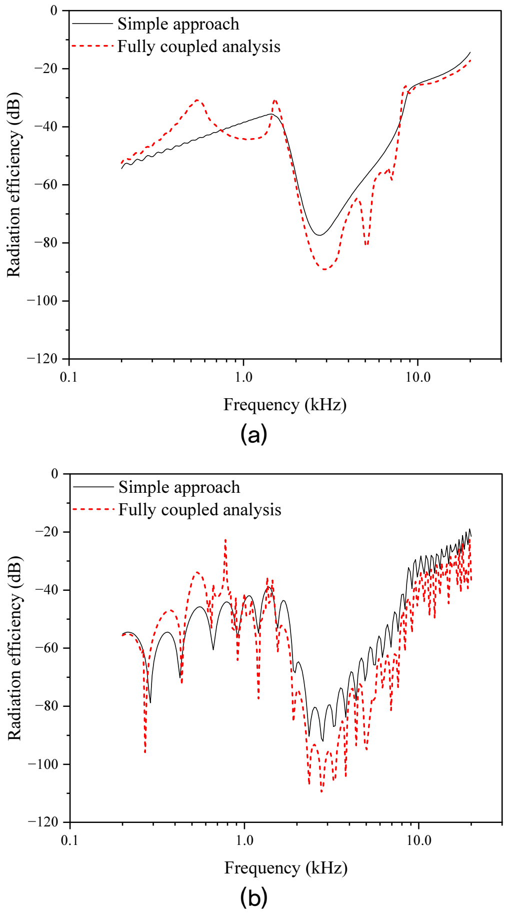
3.2 Numerical results

The radiation efficiency of plate models was compared between fully coupled analysis and simple approach from 200 Hz ~ 20,000 Hz, as presented in Fig. 3. The results indicate that, for finite plates, the simple approach underestimates the radiation efficiency above 1.5 kHz, which is the frequency range where the effect of a bubble layer begins to have an effect compared to the fully coupled analysis. In the fully coupled analysis, a rapid decrease in radiation efficiency was observed within a specific frequency range. Further studies are necessary to validate these results. Despite the differences between the two method, the trends in the results exhibit a relatively good match. The analysis for finite plates confirms that the characteristics of finite plates are accurately reflected in the results, which were compared based on peak values. Fig. 4 shows the radiation efficiency from simple approach compared with the numerical result without air bubble layer (w/o air bubble layer).

IV. Conclusion

This paper proposed a simple approach to investigate the radiation efficiency of a structure surrounded by an air bubble. The fluid-loaded plate models were selected to validate this method by comparing it to the fully coupled analysis results. The study shows that it is feasible to replace the insertion loss with attenuation.

In parallel to the numerical study, it is recommended to



(a)

(b)

Fig. 3. (Color available online) The radiation efficiency of numerical method and simple approach. (a) infinite plate (b) finite plate.

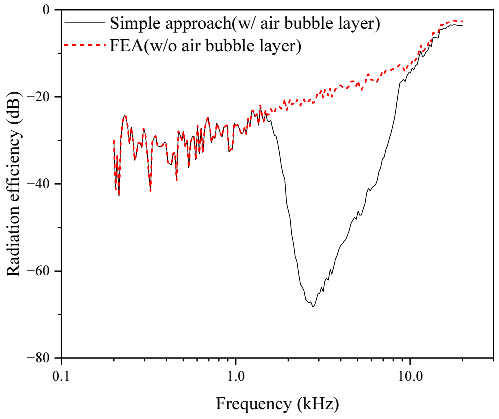


Fig. 4. (Color available online) The radiation efficiency of wedge-shaped structure surrounded air-bubble layer.

conduct experimental investigations to validate the proposed simple approach. The tests will be performed at the structural level, and the wedged shape structure surrounded by fluid has been designed for experimental validation. The radiation efficiency of this structure will also be investigated through numerical simulations.

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Profile

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