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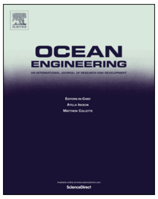

# Possibility of air-filled rubber membrane for reducing hull exciting pressure induced by propeller cavitation

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To mitigate hull excitation induced by the propeller cavity, our previous work proposed a single-nozzle air injection scheme based on the principle of acoustic destructive interference. Although inefficient energy consumption in a conventional air-carpet system could be reduced significantly, the proposed method was still hindered by the continuous usage of an air compressor and maintenance of the nozzle exposed to sea water.

In this study, we take advantage of the acoustic properties of rubber-like materials, which are similar to that of water. Accordingly, a rubber layer existing at the water-to-air interface appears to be transparent in the propagation of acoustic waves. More specifically, a rubber membrane filled with air could be anticipated to act only the role of air-packing without influencing the desired acoustic phenomenon, i.e., destructive interference. Hence, the purpose of this work is to provide analytical evidence to prove that an air-filled rubber membrane is capable of replacing the previous effort of air-injection. A design strategy for tuning the frequency of maximum destructive interference to an exciting frequency is also presented, which can be accomplished by adjusting the rubber membrane size. Finally, two experimental demonstrations conducted in a water tunnel verified the suggested scheme.

## 1. Introduction

A marine propeller operating in a non-uniform wake field generates periodic occurrences of cavitation, exerting a low frequency hull-excitation force at several orders of blade passing frequency (BPF). A certain degree of cavitation is generally tolerated for the sake of optimizing propulsion efficiency, but stringent demands on efficiency in recent years have inevitably driven further offsets in cavitation. Apart from influencing the wake field (Lindgren and Johnsson, 1980; Friesch, 1992) and modifying the propeller geometry (Cumming et al., 1972), external devices that are able to moderate the excitation of the propeller while maintaining the efficiency at a desired level have been studied.

In the early 2000s, the air-carpet system shown in Fig. 1(a) (Ukon et al., 2000) was introduced to achieve this goal. By exploiting the air-cushioning effect (Lee and Kim, 2007, 2009), a copious flow of compressed air was continuously distributed around the whole wetted stern-hull surface so that cavity-induced pressure waves could be isolated across the layer. However, the system was not suitable for widespread use because the isolation performance was mainly effective at high frequencies above several multiple orders of the BPF (Krüger et al., 2004; Ødegaard, 2006), and also because considerable energy consumption was inevitable as a result of using a huge air compressor.

The abovementioned critical bottlenecks were defeated by a single-nozzle air-injection scheme shown in Fig. 1(b) (Lee et al., 2014a). The underlying principle was an acoustic phenomenon known as destructive interference: if a pressure wave propagating in water meets air, and the acoustic impedance (characterized by the product of density and speed of sound) of air is far less than that of water, scattering (or reflection) occurs at the interface. At a certain frequency designated as the frequency of destructive interference, the scattered wave is totally out of phase with respect to the incident wave. Consequently, the incident and the scattered pressure wave cancel each other in the total field, which leads to pressure reduction outside the air-layer. Although significant energy savings in accordance with the simplification of the relevant design were definitely possible, the single-nozzle arrangement was brought under criticism because of the following two issues: (1) the fatigue of the air-compressor that arises as a result of its continuous usage and (2) the fouling accumulations in the protruded nozzle.

Noting that destructive interference emerges due to the large difference between the acoustic impedance of water and air,

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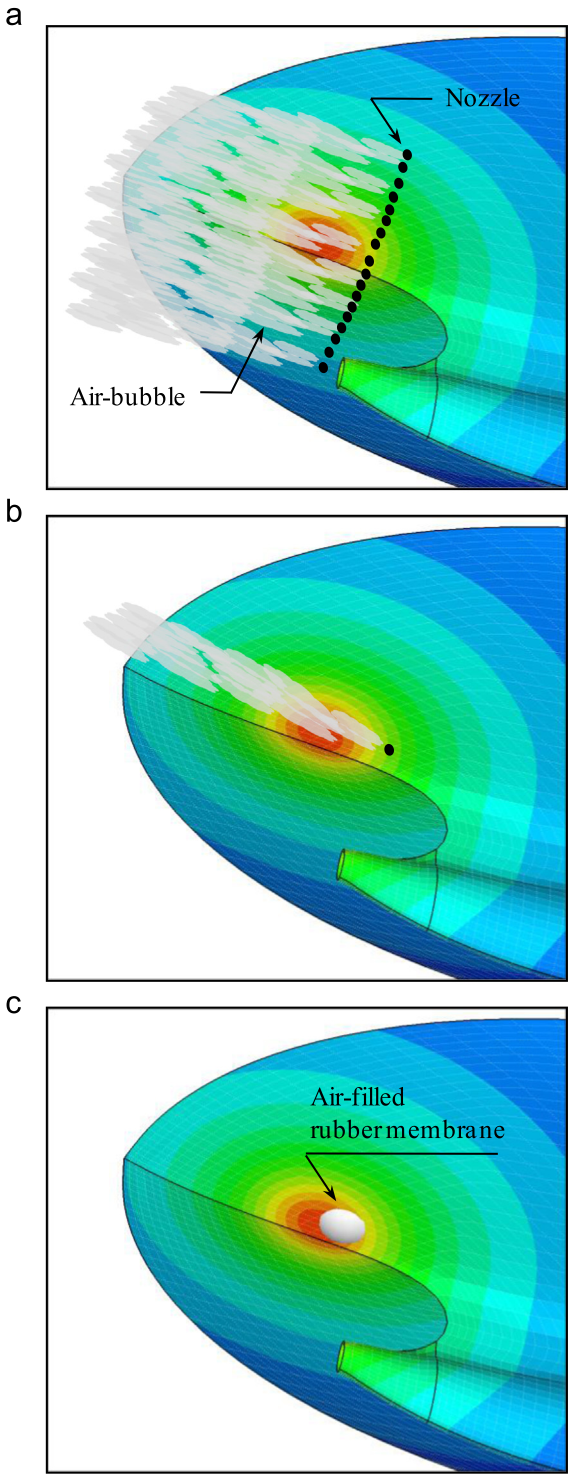

**Fig. 1.** Design improvement of the air bubble layer system (propeller is not shown). The contour coloring on the hull surface represents an example of the pressure fluctuation distribution: (a) and (b) were reproduced from Lee et al. (2014a). (a) Air-carpet system: spatial arrangement of several nozzles, (b) single-nozzle air-injection scheme, (c) Air-filled rubber membrane attached on the hull-surface.

**Table 1**
Comparisons of acoustic impedance.

| Medium | Density, $\rho$ [kg/m$^3$] | Sound speed, $c$ [m/s] | Acoustic impedance, $\rho c$ [kg/(m$^2$s)=Rayls] |
|---|---|---|---|
| Air | 1 | 340 | 340 |
| Water | 1000 | 1500 | $1.50 \times 10^6$ |
| Rubber-like material[a] | 900–1300 | 1300–1700 | $(1.17-2.21) \times 10^6$ |

[a] Cited from Wiley (2011). By appropriate selection of its composition, the rubber can match the acoustic impedance of water. In this case, the material is called Rho-c rubber.

Table 1 provides key data indicating that rubber-like materials and water have similar acoustic properties. More specifically, a rubber layer existing at the water-to-air interface appears to be transparent for the propagation of acoustic waves. The air-filled rubber membrane shown in Fig. 1(c) is then expected to just retain air without influencing the desired destructive interference, while eliminating the necessity of an air compressor and a nozzle. Accordingly, the aim of this paper is to propose a practical design strategy by establishing a theoretical justification for the air-filled rubber membrane in a spherical shape.[2]

The notion of acoustic transparency is not new, and is commonly exploited in various underwater applications such as anechoic coatings for submarines (Meng et al., 2012), shielding for a hydrophone (Montgomery et al., 1982), and mitigation of man-made underwater noise (Lee et al., 2011, 2014b). Moreover, the proposed idea undoubtedly resembles the ultrasound contrast agent used to enhance the visibility of blood vessels in medical imaging (Calliada et al., 1998). To encapsulate a microbubble, the agent employs a thin polymer shell that allows no significant loss of acoustic echo from a bubble. The regime works in the several megahertz frequency band where the shear wave effect in the shell cannot be ignored. This may stiffen the free-bubble, resulting in deviation from ideal behavior. That is the reason why most relevant literatures focus on the influence of the encapsulating material. Previous studies (de Jong et al., 1992; de Jong and Hoff, 1993) have shown how encapsulating the shell increases the resonance frequency through experimental measurements, and thereby proposed ad hoc consideration of the elastic parameter for the shell. Using the generalized Rayleigh–Plesset equation, Church (1995) derived a more well-founded theoretical model, in which the shell is described by a shear modulus and a shear viscosity.

The frequency-dependent nature of a viscoelastic material reveals that its shear modulus in low frequencies is much lower than that in the ultrasonic range (Capps et al., 1981; Nashif et al., 1986). As an example, the commercially available rubber Anti-phone has a shear modulus of 95 MPa at 1 MHz at normal sea water temperature, but this value significantly decreases to 0.8 MPa at 10 Hz. For this material, it would therefore be reasonable to neglect the shear effect at low frequencies of interest. A current effort further ignores the viscous damping factor of the shell; diminishing the resonance peak, the role of damping would be significant only around the resonance frequency (Crandall, 1970). The membrane design that we eventually seek is concerned with the frequency points of resonance and destructive interference, and not with their associated amplitudes.

Compared to Church's approach, in short, the shell in the present study can be regarded as a lossless fluid-like medium supporting a longitudinal (or compressional) wave only. Hence, we can tackle the problem in a simple and effective manner. The developed model leads to a straightforward design method that tunes the frequency of the destructive interference to an exciting frequency by adjusting the membrane size. This aspect will be explored in Section 2. The proposed scheme is validated in Section

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[2] Low frequency scattering is mainly affected by an effective volume of the object, not by a shape (Weston, 1967). Thus, the membrane under consideration can be modeled as a simple sphere.