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Design of air-balloons for suppression of propeller cavitation induced hull-excitation at multi-frequencies

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ABSTRACT

The main objective of the present study is to establish a practical design strategy of air-balloons for a suppression of the propeller cavitation induced hull pressures at multi frequencies. Theoretical foundation is initiated with the existing modal series solution of a multiple scattering problem. An approximated form is then derived by a monopole regime which is valid in a low frequency range. Subsequent parametric analysis with a variation of the separation distance between the balloons provides an analytical evidence that the mutual interaction can be neglected unless they are too close to each other. Hence it is addressed that the individual balloon can be designed separately without a consideration of their coupling characteristics. Finally, the water tunnel test with two balloons demonstrates noticeable vibration reductions at the first- and second- order of blade passing frequencies by 72% and 59%, respectively.

1. Introduction

The previous single nozzle air-injection scheme (Lee et al., 2014) discovered a possibility to suppress propeller-cavity induced hull exciting pressure by means of an acoustic phenomenon known as the destructive interference: When a pressure wave generated by cavitating propeller strikes on the injected air, whose acoustical impedance (i.e., a product of density and sound speed) is much less than that of water, the phase of scattered (or reflected) wave becomes totally reversed. This results in a cancellation of the incident- and the scattered-pressure in the total field.

As shown in Table 1, similar acoustic impedance between rubber and water motivated our recent work (Lee et al., 2015a). In this approach, a rubber layer at water-to-air interface appears to be acoustically transparent. It was shown that the air-filled rubber membrane (hereinafter the balloon) plays a specific role of air-packing without any influence on the desired destructive interference. Accordingly an effort of the air-injection could be made unnecessary by attaching such a simple air-balloon on the stern-hull surface, as shown in Fig. 1(a). For verifications in the full-scale ship, Lee et al. (2015b) presented sea-trial measurements by manufacturing $1.1\,\mathrm{m} \times 1.1\,\mathrm{m}$ sized inflatable balloon. The balloon showed its effectiveness by attaining a noticeable hull vibration reduction of 65% at the exciting frequency of interest. Based on the ideal gas law, a method of how to inflate the balloon to the design size and to keep it constant despite draught changes was treated as well.

The authors would like to emphasize that the phenomenon of acoustic cancellation takes place only at a certain frequency however. It is the so-called the frequency of destructive interference, which is inversely proportional to the balloon size. In other words, once a single balloon is tuned to a specific size, it alone has no choice but to counteract an excitation at a particular frequency. The marine propeller operating in a non-uniform wake field generates vibratory hull-exciting pressures at several orders of blade passing frequency (BPF) (Carlton, 2007; Weitendorf, 1981). The pressure amplitudes are normally descending with the order, but we often encounter an occurrence of large pressure amplitudes at higher harmonics. For example, an excessive tip vortex cavitation may provoke high harmonic amplitudes to be of the same level with that of the lowest order, or even higher (Friesch, 1995, 1998; Hämäläinen and van Heerd, 1998). Then, multi balloons shown in Fig. 1(b) can be a natural measure to control such excitations at several frequencies, as they are anticipated to make destructive interferences at different frequencies.

The scope of this research is interested in reaching a design methodology for the balloons using the multiple scattering theory. When two or more spherical[1] bodies are in close proximity to the others, there exist

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[1] The balloon objects in this study will be idealized to spheres for a mathematical convenience. Its reasoning will be given in Section 2.1.

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Glossary

a	Radius of spherical balloon [m]
c	Speed of sound [m/s]
C_q	q-th order scattering amplitude of an isolated air-balloon
d	Separation distance between the balloons [m]
f	Frequency [Hz]
ϕ	Azimuthal angle [rad]
g	Relative density, ρ_a/ρ_w
h	Relative sound speed, c_a/c_w
h_q	q-th order spherical Hankel function
i	$\sqrt{-1}$
j_q	q-th order spherical Bessel function
λ	Wavelength [m]
k	Wavenumber [rad/m]
n_q	q-th order spherical Neumann function
N	Number of spheres (or balloons)
p	Pressure, [Pa]
p_0	Amplitude of incident plane wave [Pa]
p_{total}	Total pressure ($=p_{inc} + p_{scat}$) [Pa]
P_q^p	q-th order associated Legendre function
p_{tunnel}	Pressure in tunnel [bar]
q	Order of wave
Q	Truncation order
$Q_{(pqpm)}$	Translational coefficient
θ	Polar angle [rad]
r	Radial distance from the origin of sphere [m]
ρ	Density [kg/m^3]
t	Time [s]
V_t	Water flow speed in tunnel [m/s]
ω	Frequency [rad/s]
Z	Impedance [Rayls = (kg/m^3)·(m/s)]

Subscripts

a	Air
des	Destructive interference
eq	Equivalent
inc	Incident wave
res	Resonance
$scat$	Scattered wave
$total$	Total wave
w	Seawater

mutual interactions between them. The solution of multiple scattering requires satisfactions of appropriate boundary conditions on the surfaces of all spheres (Brunning and Lo, 1971). For this purpose, the so called "*addition theorem*" is inevitable to expand spherical wave solutions of the Helmholtz equation centered about a given origin into the ones centered about a shifted origin (Felderhof and Jones, 1987). Applying boundary conditions on each sphere yields a set of simultaneous equations where unknown scattering coefficients are coupled. The resulting equations for a general number of spheres are so complicated that it is difficult to get even a numerical solution. Alternatively, a reasonable approach to tackle is to focus on the two spheres problem which was treated in a large volume of published studies (Twersky, 1962; Brunning and Lo, 1971; Domany et al., 1984; Gaunaurd et al., 1995; Gabrielli and Mercier-Finidori, 2001; Gumerov and Duraiswami, 2002, 2005; Roumeliotis and Kotsis, 2007 and more). The very fundamental problem deserves a thorough investigation, because it permits not only an opportunity to explore characteristics of the mutual interaction but also an insight to attain a solution for the case of several spheres more than two.

To propose a practical design strategy, this paper begins with the simplest case of two interacting spherical balloons by employing the formulation of Gaunaurd et al. (1995). Rather than working with the exact solution to the problem, we derive its monopole approximation based on a low frequency assumption. Subsequent parametric study varying the distance between the balloons offers a critical clue that the interaction becomes weak for a large separation. This allows the solution even for the general case to be expressible by an algebraic sum of isolated balloon. Consequently it is addressed that the design strategy for the individual balloon exactly follows the single case.

This paper takes a structure of four sections, including this introductory section. Section 2 lays out the theoretical formulation, and presents the findings of the research. It goes on with experimental verifications in Section 3, wherein the propeller cavitation test with two balloons exhibits considerable vibration suppressions at the two target frequencies. Finally, this paper closes with conclusions in Section 4.

2. Theory of acoustic scattering for two spherical balloons

2.1. Problem formulation and analytic solution

As detailed in our previous studies (Lee et al., 2015a, 2015b), we are concerning for a low frequency range up to several multiples of blade rates so that the corresponding wavelengths can be assumed to be large enough compared to the size of balloon. For such an acoustically small object, a spherical-like wavefront can be approximated as a plane wave across the body's aperture. This enables to regard the pressure fluctuation from a cavitating propeller as a plane wave excitation.

The second assumption is to model the complicated shape of balloon as an ideal sphere. Scattering by an acoustically small object is insensitive to the shape, because details of the geometry are not resolved. That is, the scattering in the low-frequency range is mainly affected by an effective volume of the balloon rather than by its shape (Weston, 1967). Unless the aspect ratio of the balloon is too high (Strasberg, 1953), hence, the analysis for a spherical balloon would hold for a non-spherical case as well.

Owing to the acoustically transparent nature of rubber material, we will also not consider the rubber layer necessarily employed for an air-packing. Even if there is a slight difference of the acoustic impedance as usual, the resultant effect was found to be insignificant provided that the frequency range of interest is low. Further discussions on this matter can be found in the introduction part of Lee et al. (2015a).

Finally, the hull plate to which the balloon is attached will not be taken into account for simplicity. The presence of rigid wall is equivalent to the presence of a mirror balloon oscillating in phase with the true balloon (Feuillade, 1995). The in-phase motion induces a positive mass

Table 1
Comparisons of acoustic impedance.

Medium	Density, ρ [kg/m^3]	Sound speed, c [m/s]	Acoustic impedance, ρc [kg/(m^{2}s) = Rayls]
Water	1000	1500	1.50×10^6
Rubber material*	900–1300	1300–1700	$(1.17–2.21) \times 10^6$

(*) Cited from Wiley (2011).