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## **[N689] Prediction of Underwater Propeller Noise & Hydrofoil Cavitation Bubble Behavior and Noise**

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### **ABSTRACT**

Sound generated by a propeller is critical in underwater detection and is often related to the survivability of the vessel especially for military purposes. Marine propeller noise might be classified into comprising two principal constituents (non-cavitating and cavitating components). The main purpose of this research is to analyze these noise sources from marine propeller. The approach for the investigation is a potential based panel method coupled with acoustic analogy. The flow field is analyzed with potential based panel method and then the time dependent pressure data are used as the input for Ffowcs-Williams Hawkins formulation to predict the far-field acoustics. To predict propeller cavitation noise, the blade

surface cavity considered as a single valued pulsating volume of vapor attached to the blade surface. The time dependent cavity volume data are used for noise prediction. Furthermore, we analyze hydrofoil cavitation bubble behavior and noise using Eulerian/Lagrangian approach. Through this study, we can analyze dominant noise source of marine propeller and provide a basis for proper noise control strategies.

**KEYWORDS:** Underwater Propeller Noise, Acoustic Analogy, Cavitation Noise

## INTRODUCTION

Sound generated by a propeller is critical in underwater detection and is often related to the survivability for vessels especially for military purposes. Marine propeller noise can be classified into cavitating and non-cavitating noise. Cavitation of the marine propeller is the most prevalent source of underwater sound in the ocean and is often the dominant noise source of a single marine vehicle. However submarines and torpedoes are usually operated under the deep sea enough to avoid cavitation[1]. Therefore both cavitating and non-cavitating noise are also important. The approach for the investigation of the non-cavitating noise is potential based panel method coupled with the acoustic analogy. Of the various types of cavitation, sheet cavitation on the suction surface and bubble cavitation produce the highest noise level [1]. So we developed computational method for the analysis of propeller surface cavitation noise. This method employed a potential or velocity based formulation. Cavity has been considered as a single pulsating volume attached to the surface, which can be calculated by the potential flow method. For blade sheet cavitation noise prediction, the time dependant cavity volume data are used. And hydrofoil bubble cavitation is analyzed using Eulerian/Lagrangian approach.

## NUMERICAL METHODS

### Flow Solver (Marine Propeller)

The flow solver method is based on Green's third identity for velocity potential  $\phi$ . The perturbation potential,  $\phi_p(t)$ , at any time  $t$  and any point on the wetted surface ( $S_{ws}(t)$ ) or the cavity surface ( $S_c(t)$ ) may be expressed by using Green's third identity [2].

$$2\pi\phi_p(t) = \int_{S_{ws}(t) \cup S_c(t)} \left[ \phi_q(t) \frac{\partial}{\partial n_q(t)} \left( \frac{1}{R(p; q)} \right) - \frac{\partial \phi_q(t)}{\partial n_q(t)} \frac{1}{R(p; q)} \right] dS + \int_{S_w(t)} \Delta \phi_w(t) \frac{\partial}{\partial n_q(t)} \left( \frac{1}{R(p; q)} \right) dS$$

To determine the unique potential flow solution, the boundary conditions have to be applied on the flow boundaries. However, since the geometry of the cavity surface is unknown, as initial flow boundaries the cavity surface on the blade is approximated to the blade surface and the cavity surface in the wake is approximated to the wake surface [2]. Kutta condition is used and the pressure equality at the trailing edge of the blade and duct is also enforced.

### Acoustic Analysis (Marine Propeller)

Ffowcs Williams and Hawkings formulated the equation for the manifestation of acoustic analogy proposed by Lighthill [3]. There are various ways to evaluate Ffowcs Williams-Hawkings equation and the three types of noise source term (monopole, dipole, and quadrupole) have been proposed. Farrasat proposed a time-domain formulation that can predict noise from an arbitrarily shaped object in motion without the numerical differentiation of the observer time [4]. The implementation of this formulation is quite straightforward because contributions from each panel with different retarded times are added to form an acoustic wave. Blade surfaces are divided into rectangular panels radiating noise as sources at different retarded times.

The solution for the acoustic pressure can be obtained in the following form by using Green's function and coordinate transformations.

$$4\pi p'(\bar{x}, t) = \frac{1}{c_0} \frac{\partial}{\partial t} \int_{f=0} \left[ \frac{\rho_0 c_0 v_n + l_r}{r(1-M_r)} \right]_{ret} dS + \int_{f=0} \left[ \frac{l_r}{r^2(1-M_r)} \right]_{ret} dS$$

The subscript *ret* denotes that the integration is evaluated at the retarded time. The speed and accuracy of the numerical calculation is improved by eliminating the numerical differentiation. The final result is as follow.

$$p'(\bar{x}, t) = p'_T(\bar{x}, t) + p'_L(\bar{x}, t)$$

where,

$$4\pi p'_T(\bar{x}, t) = \int_{f=0} \left[ \frac{\rho_0 \dot{v}_n}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{\rho_0 v_n (r\dot{M}_i \hat{r}_i + c_0 M_r - c_0 M^2)}{r^2(1-M_r)^3} \right]_{ret} dS$$

and

$$4\pi p'_L(\bar{x}, t) = \frac{1}{c_0} \int_{f=0} \left[ \frac{\dot{l}_i \hat{r}_i}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{l_r - l_i M_i}{r^2(1-M_r)^2} \right]_{ret} dS + \frac{1}{c_0} \int_{f=0} \left[ \frac{l_r (r\dot{M}_i \hat{r}_i + c_0 M_r - c_0 M^2)}{r^2(1-M_r)^3} \right]_{ret} dS$$

Here  $p'_T$  and  $p'_L$  respectively denote the acoustic pressure due to thickness and loading, corresponding to the monopole and the dipole terms. Near-field and far-field terms are seen explicitly as  $1/r^2$  and  $1/r$  terms in the integrals, respectively.

## Hydrofoil Cavitation Bubble Behavior and Noise

Hydrofoil cavitation is numerically investigated using Eulerian/Lagrangian approach. Since cavitation bubbles are very small mass, momentum and energy of bubbles have little influence on flow field. For Eulerian/Lagrangian analysis, flow field is computed using Eulerian Reynolds-Averaged Navier-Stokes solver. The small bubbles are traced through the flow field based on the Newton's second law with models for various forces acting on the bubble.

$$\rho_b V_b \frac{d\vec{U}_b}{dt} = V_b (\rho_b - \rho) \vec{g} + V_b \nabla p + \frac{1}{2} \rho A_b C_D (\vec{U} - \vec{U}_b) |\vec{U} - \vec{U}_b| + \frac{1}{2} \rho V_b \left( \frac{d\vec{U}}{dt} - \frac{d\vec{U}_b}{dt} \right) + 6 A_b \sqrt{\frac{\rho \mu}{\pi}} \int_0^t \left( \frac{d\vec{U}}{d\tau} - \frac{d\vec{U}_b}{d\tau} \right) \frac{d\tau}{\sqrt{t - \tau}}$$

Also, the growth-collapse of bubble is modeled by Rayleigh-Plesset equation.

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho} \left[ p_v + p_{g0} \left( \frac{R_0}{R} \right)^{3k} - p - \frac{2\gamma}{R} - \frac{4\mu}{R} \dot{R} \right] + \frac{(\vec{U} - \vec{U}_b)^2}{4}$$

Therefore, flow field as carrier-flow is one-way coupled to bubble dynamics.

The acoustic pressure in the far away from the bubble is given by as follows.

$$p'(t) = \frac{\rho_0 \ddot{V}_b \left( t - \frac{r}{c} \right)}{4\pi r}$$

Since the bubble volume is  $V_b = 4/3\pi R^3$  and  $V_b'' = 4\pi R(2R' + RR'')$

Far away from the bubble, the acoustic pressure is as follows [5].

$$p'(r, t) = \rho \left[ \frac{R}{r} (2R'^2 + RR'') \left( t - \frac{r}{c} \right) \right]$$

where,  $p'$  is the acoustic pressure and  $c$  is the sound speed.

## RESULTS AND DISCUSSION

The propeller model is shown in Figure1. Flow fields are computed using this propeller model in non-uniform flow. Marine propeller flow analysis results are shown in Figure 2, which shows blade surface pressure distribution and converged sheet cavity planform. The cavity volumes from the present method are good agreement with other numerical results [2]. These results are used for noise prediction. Figure 3-(a) shows non-cavitating noise sound pressure level and directivity pattern. The directivity of the thickness noise is an 8-shaped with

maximum occurring on the propeller rotation plane. The unsteady loading noise is known to be dipole in nature, with a strong radiation tendency towards on the hub axis. These results are depicted well in Figure 3-(a). And as shown in these results under non-cavitating condition, unsteady loading noise is dominant. Figure 3-(b) shows blade sheet cavitation noise sound pressure level and directivity pattern. Generally, cavitation noise radiates sound as a monopole but our results show somewhat dipole characteristics. This result shows that rotating volume of vapor attached to blade effects noise directivity.

Furthermore, hydrofoil bubble cavitation is predicted using Eulerian/Lagrangian approach. Figure 4 shows each bubble trajectory and growth-collapse.

## CONCLUSIONS

The non-cavitating and cavitating noise generated by underwater propeller and hydrofoil bubble cavitation have analyzed numerically in this study. Potential based panel method coupled with time-domain acoustic analogy is used to predict the noise generated by marine propeller in non-uniform inflow condition. For the noise prediction, Ffowcs Williams-Hawkings equation is applied as Farrasat proposed. Under non-cavitating condition, the noise directivity pattern is a direct result of dipole dominating overall noise level. In addition to sheet cavitation and hydrofoil bubble cavitation behavior and acoustics are also analyzed. Through this study, we can analyze dominant noise source of marine propeller.

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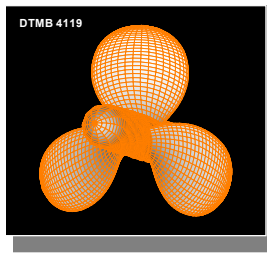


Figure 1: Propeller Models and conditions

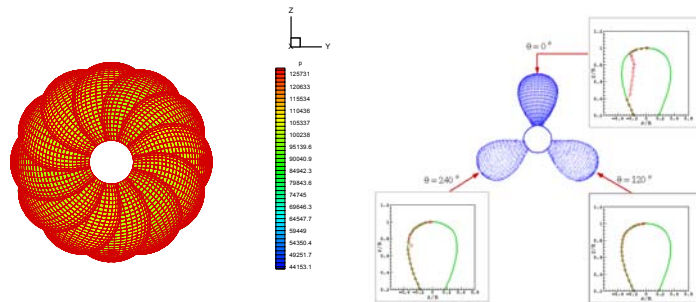


Figure 2: Propeller Blade Surface Pressure Distribution and Blade Sheet Cavity Planform

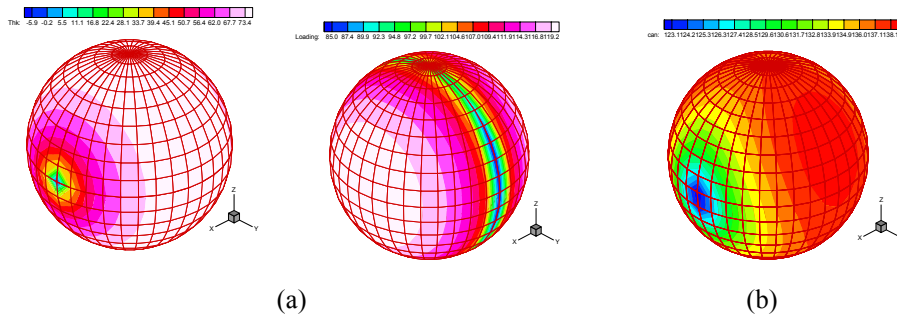


Figure 3. : Non-Cavitating and Sheet Cavitation Noise SPL and Directivity 3D Contour.

- (a) Non-cavitating Noise : Thickness , Loading
- (b) Cavitating Noise : Sheet Cavitation

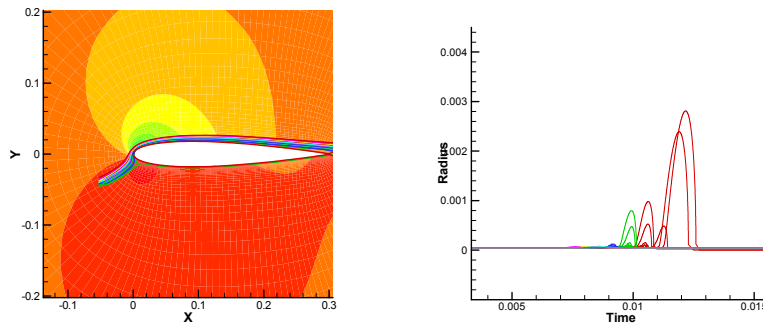


Figure 4. : Hydrofoil Cavitation Bubble Trajectory and Behavior