

Accuracy Improvement for Propeller Cavitation Noise Prediction Using UDF

IlGuk Song, JungHun Pae, PokHyon Om, KwangIl Ri*

Abstract

Recently, there has been an increase in demand for propulsion systems with higher hydrodynamic performance and lower underwater-radiated noise, as environmental issues are gaining more attention in addition to the traditional military necessity. It is important to reduce cavitation noise when designing propellers of the ships, especially for oceanographic research vessels because they use acoustic instruments and cavitation noise can interfere with their operation. It is well known that, when the cavitation occurs on the propeller, the tonal and broadband noise increase rapidly in the wide frequency range. Therefore, it is indispensable to quantitatively predict the propeller cavitation noise. In the previous papers, the prediction of cavitation noise using the Schnerr-Sauer cavitation model, which was constructed by neglecting the second-order and viscous terms of the Rayleigh-Plesset bubble dynamics equation, resulted in large errors compared with the experimental data. In this study, we have used numerical simulations using MRF (Multiple Reference Systems) technique to predict cavitation and cavitation noise around propellers. The formulation of Reynolds-averaged Navier-Stokes (RANS) with k - ω shear transport and fast Fourier transform is applied to the simulation. The far-field radiation under different operating conditions is calculated by the Efwocs Williams-Hawkings (FW-H) equation. The model defined by the user-defined function (UDF) considering the second-order terms and surface tension terms in the Rayleigh-Plesset bubble dynamics equation is used as a cavitation model. The effect of the advance coefficient on the cavitation and cavitation noise is simulated. The validity of the present numerical method is verified by comparing the predicted sound pressure spectrum with the measured sound pressure spectrum. Finally, Results by Schnerr-Sauer model and UDF model are compared of experiment result. Results by UDF model are in better agreement with experimental results than by Schnerr-Sauer. The obtained UDF model and results can be used to optimize the operating parameters of the induced pattern of noise radiation in underwater vehicles.

Keywords: Underwater propeller, fluent, cavitation, numerical simulation, propeller cavitation noise, UDF

INTRODUCTION

The performance and noise characteristics of ship propellers using numerical simulations have been extensively studied by many researchers. Purwana predicted the performance and noise of the propeller with the formulation of RANS and FW-H equations [1]. Williams and Hawkings reported acoustic predictions using a method for computational noise in which any body in a fluid moves; this method is still applied in hydroacoustic predictions as a useful tool in computational numerical practice [2]. Huang and Shi studied the underwater radiant noise of a SUBOFF model propeller by a pump jet without tip clearance [3]. The analysis of time-varying unsteady propeller forces was then carried out and the FW-H equation was then employed to predict

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the far-field sound radiation of the propeller using a planar element method. The underwater-radiated noise from underwater propellers can be grossly categorized into two parts: one is non-cavitation noise, and the other is cavitation noise.

Propeller cavitation is known as one of major sources of vibration and noise of ships and submarines. Especially, it is important to reduce cavitation noise when designing propellers for the ships such as oceanographic research vessels, because they use acoustic instruments, and cavitation noise is harmful to their operation. Therefore, it is indispensable to quantitatively predict propeller cavitation noise.

Lafeber and Bosschers predicted propeller cavitation noise using a low-fidelity model derived from multiple computational regression analysis [4]. Salvatore and Ianniello predicted instantaneous cavitating-plate propeller noise with a hydrodynamic model coupled with a hydroacoustic model in a nonuniform inviscid flow based on the FW-H equation corresponding to the Bernoulli equation model [5]. In this study, we have performed a cavitation noise simulation using the Schnerr-Sauer cavitation model in Fluent. However, there was a large difference between the experimental results and the simulation results.

The Rayleigh-Plesset bubble dynamics equation which is used to derive Schnerr-Sauer cavitation model is as follows [6]:

$$\frac{p_B - p_\infty}{\rho_l} = R_B \frac{d^2 R_B}{dt^2} + \frac{3}{2} \left(\frac{dR_B}{dt} \right)^2 + 4 \frac{\nu}{R} \frac{dR_B}{dt} + 2 \frac{\sigma}{\rho R_B} \quad (1)$$

Where,

- p_B : bubble surface pressure,
- p_∞ : local far-field pressure,
- ρ_l : liquid density,
- R_B : bubble radius,
- ν : liquid kinematic viscosity, and
- σ : liquid surface tension coefficient.

Neglecting the second-order terms, the surface tension force and viscosity term, Eq. (1) is simplified to:

$$\frac{dR_B}{dt} = \sqrt{\frac{2(p_B - p)}{3\rho_l}} \quad (2)$$

The final form of Schnerr-Sauer cavitation model can be obtained by replacing the Eq. (2) with Eq. (3):

$$\begin{cases} R_e = \frac{\rho_v \rho_l}{\rho} \alpha (1 - \alpha) \frac{3}{R_B} \frac{dR_B}{dt}, (p \leq p_v) \\ R_c = \frac{\rho_v \rho_l}{\rho} \alpha (1 - \alpha) \frac{3}{R_B} \frac{dR_B}{dt}, (p \geq p_v) \end{cases} \quad (3)$$

Like this, the simulation was not sufficiently accurate because the second-order terms, the surface tension force and viscosity term in Rayleigh-Plesset equation had been neglected.

Therefore, in this study, a numerical simulation method considering second-order term and surface tension term is proposed to improve the accuracy of cavitation noise prediction for user-defined function (UDF).

NUMERICAL SIMULATION

UDF Definition

Consider a spherical microbubble containing an equilibrium gas and vapor within a stationary liquid (Figure 1). It is assumed that the liquid can withstand the vapor pressure p_{g0} , even under tension.

Assuming an adiabatic transformation of the cavitation bubble collapse, the cavitation surface pressure is related to the initial pressure p_{g0} by the following expression:

$$p_B = p_v + p_g \quad (4)$$

$$p_g(t) = p_{g0} \left[\frac{R_0}{R_B} \right]^{3\gamma} \quad (5)$$

Where, γ is the ratio of heat gas capacities c_{pg} and c_{vg} and p_g stand for the partial pressure of the gas inside the bubble.

Substituting Eqs. (4) and (5) into Eq. (1) gives the following:

$$R_B \frac{d^2 R_B}{dt^2} + \frac{3}{2} \left(\frac{dR_B}{dt} \right)^2 = \frac{p_v + p_{g0} \left[\frac{R_0}{R_B} \right]^{3\gamma} - p_\infty}{\rho_l} - 2 \frac{\sigma}{\rho R_B} - 4 \frac{v}{R} \frac{dR_B}{dt} \quad (6)$$

In most cases, viscosity does not play an effective role. So, let us neglect the last term in Eq. (6) and solve the equation.

Converting to $\frac{dR_B}{dt} = U$, $\frac{p_{g0}}{\rho_l} = C_0^2$,

Eq. (6) can be written as follows:

$$R_B \frac{d^2 R_B}{dt^2} + \frac{3}{2} \left(\frac{dR_B}{dt} \right)^2 = \frac{1}{2R_B^2 U} \frac{d}{dt} (R_B^3 U^2) = C_0^2 \left(\frac{R_0}{R_B} \right)^{3\gamma} - \frac{2\sigma}{\rho R_B} - \frac{1}{\rho} (p_\infty - p_v) \quad (7)$$

The integration of the Eq. (7) is as follows:

$$U = \frac{dR_B}{dt} = \left\{ \frac{2C_0^2}{3(1-\gamma)} \left[\left(\frac{R_0}{R} \right)^{3\gamma} - \left(\frac{R_0}{R} \right)^3 \right] + \frac{2\sigma}{\rho R} \left[\left(\frac{R_0}{R} \right)^2 - 1 \right] + \frac{2(p_\infty - p_v)}{3\rho} \left[\left(\frac{R_0}{R} \right)^3 - 1 \right] \right\}^{\frac{1}{2}} \quad (8)$$

Eq. (8) can be numerically solved by using the 4th order Runge-Kutta method. As a result, the cavitation radius and cavitation radius change with respect to time can be obtained.

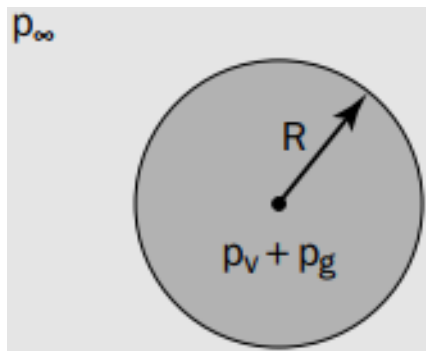


Figure 1. Microbubble in a liquid.

Substituting the obtained results into Eq. (3), we obtain a new cavitation model with higher accuracy than the Schnerr-Sauer cavitation model. This model is suitable for cavitation bubble collapse problems including cavitation noise because the second-order term and surface tension term are not neglected here in comparison with Schnerr-Sauer cavitation model.

This model was implemented using UDF. Radius and radius ratio with respect to time was inputted to computational fluid dynamics for unsteady calculation based on a UDF.

Propeller Model and Simulation Method

Propeller data and 3D model of the propeller are presented in the Table 1 and Figure 2.

As shown in Figure 3, the fluid uniform flow of the propeller is modeled numerically divided into dynamic and static cylinders. When the diameter of the propeller is D , the static cylinder is $3D$ in diameter, $2D$ from the inlet and $5D$ from the outlet, so the total length is $7D$. The rotating speed is changed to different work conditions. And the contacting surface between the rotating and static domain is set as the interface to enable the exchange of information between the two sub domains. Cavitation model is chosen to model defined by UDF.

After conducting steady state calculation, the DES simulation is carried out for noise prediction based on the FW-H equation with the initial value of steady flow. Density is 1026 kg/m^3 and velocity of sound is 1500 m/s . The reference pressure for calculation of the Sound Pressure Level is set to $p_{ref} = 1 \mu\text{pa}$.

Table 1. Propeller data.

Classification	Value
Diameter (mm)	200
Hub/Diameter Ratio	0.3
Expanded blade area Ratio	0.88
Pitch at $r=0.7R$	0.816

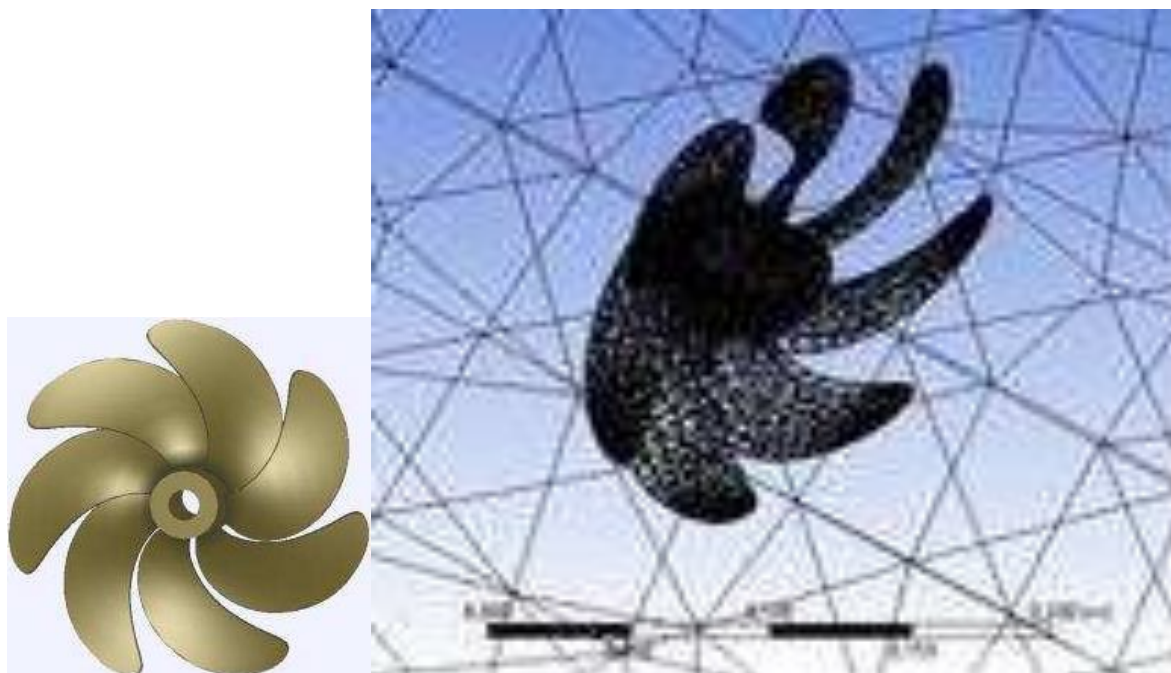


Figure 2. Propeller: (a) 3D Model; (b) Meshing.

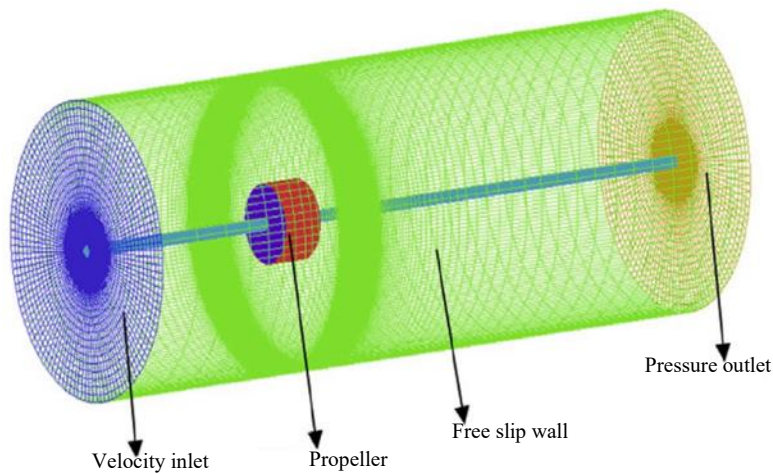


Figure 3. Computational domain around propeller and boundary condition.

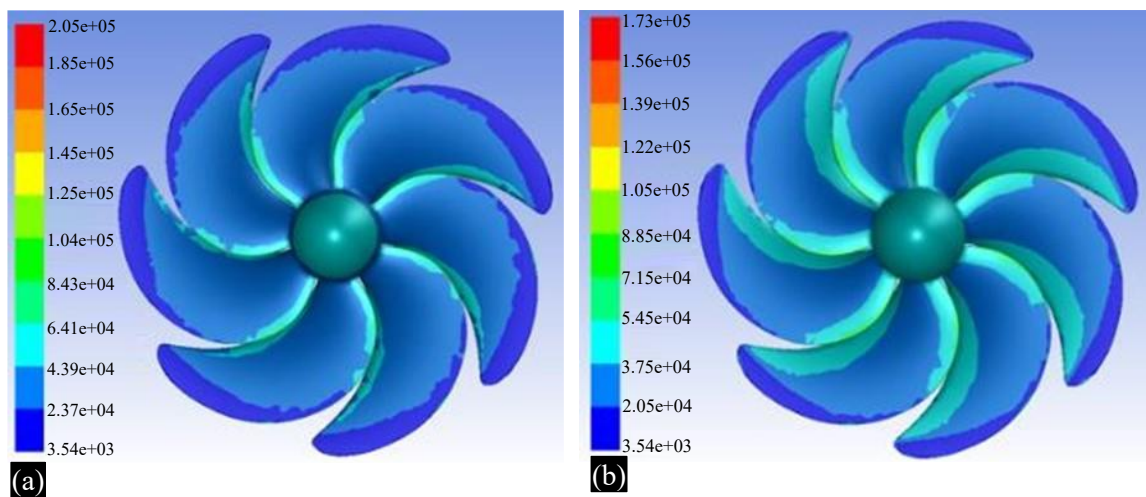


Figure 4. Pressure distribution of propeller blade surface: (a) $J=0.456$; (b) $J=0.529$.

Table 2. Numerical simulation results.

J	T	Q	K_t	$10K_q$	n
0.456	59.12	1.895	0.313	0.534	0.425
0.529	55.54	1.745	0.307	0.508	0.509
0.638	51.23	1.674	0.287	0.472	0.618
0.723	46.23	1.583	0.263	0.442	0.685
0.834	35.49	1.524	0.214	0.431	0.659
0.921	27.23	1.423	0.149	0.412	0.53
1.034	21.21	1.363	0.119	0.381	0.514
1.121	15.931	1.283	0.091	0.345	0.47

In the IHL (Indonesia Hydrodynamic Laboratory), experiments on cavitation flow and noise of the propellers were implemented [7].

RESULTS AND DISCUSSION

Propeller performance and noise characteristics were calculated under the condition of advance coefficient $J=0.456\sim 1.121$. In Figure 4, the pressure distribution on the propeller is shown under different advance coefficient conditions. In Table 2, the numerical simulation results are shown [8].

In Figure 5, the numerical results and experimental results for thrust, torque coefficient and efficiency are shown. The numerical results are in good agreement with the experimental data in the range of overall advance coefficient.

Figure 6 shows that cavitation occurs at the tip of the propeller blade at $J=0.529, 0.456, n=35$ and 40 rad/s. Hydrodynamic or acoustic fluid pressure changes greatly and very rapidly during cavitation. Cavitation collapses often change rapidly, are shortly lived and generate high acoustic pressure. When a cavitation bubble reaches the maximum radius in the high-pressure area, the bubble becomes collapsed [9]. Figure 7 shows SPL (Sound Pressure Level) measured by UDF model.

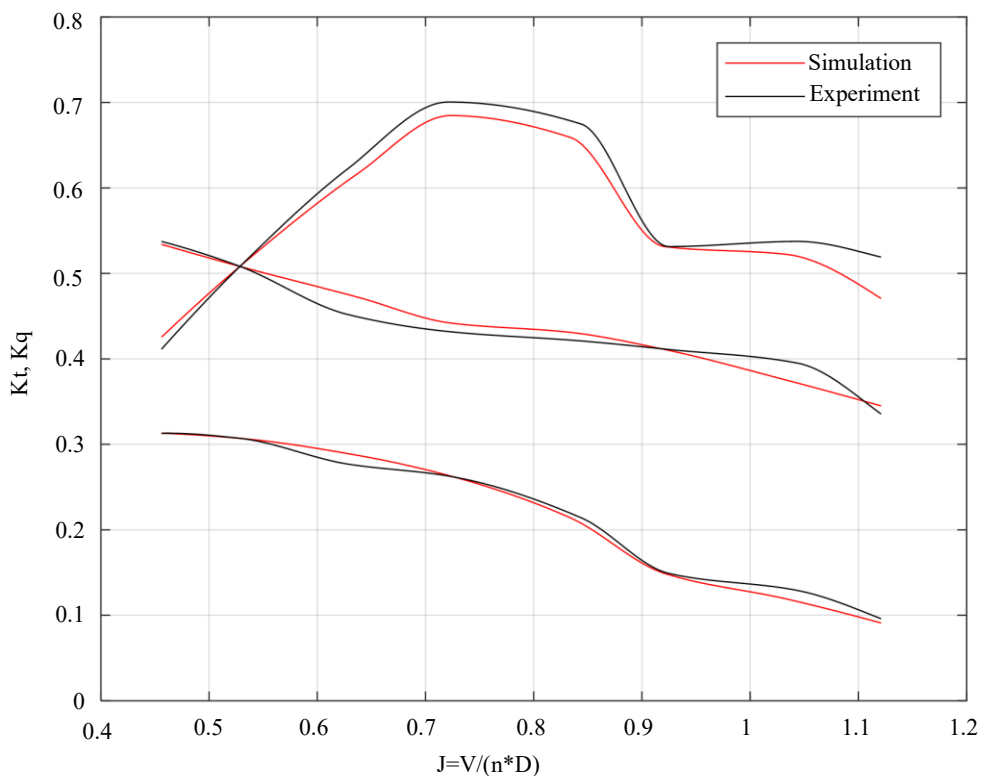
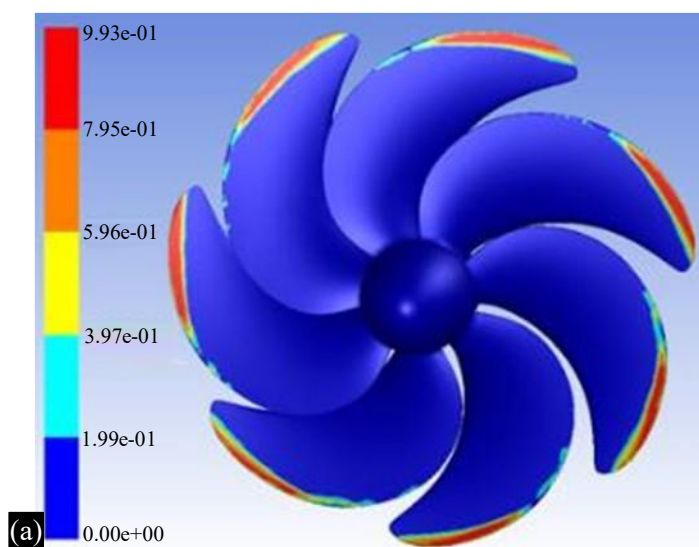


Figure 5. Thrust coefficient, torque coefficient and efficiency for propeller.



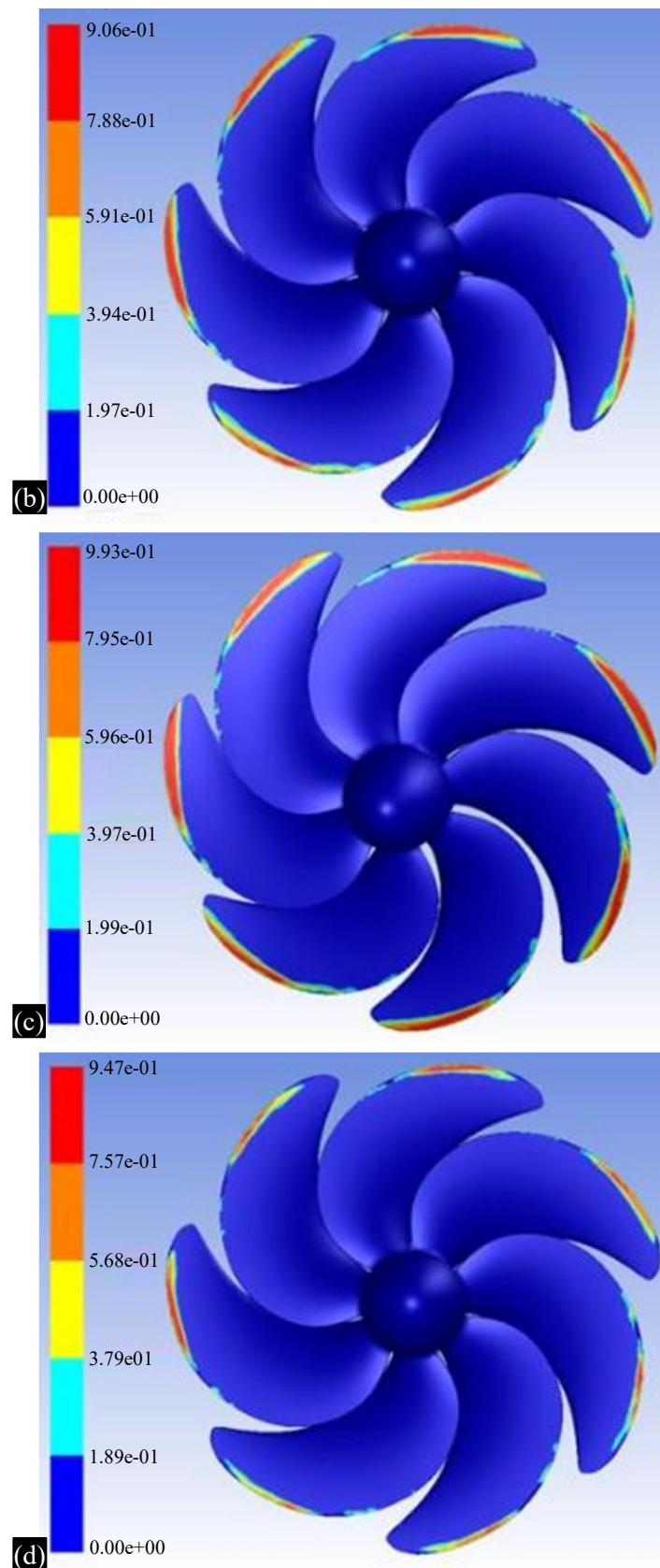


Figure 6. Volume fraction vapor distribution: (a) $J=0.529$, $n=40$ rps; (b) $J=0.529$, $n=35$ rps; (c) $J=0.456$, $n=40$ rps; (d) $J=0.456$, $n=35$ rps.

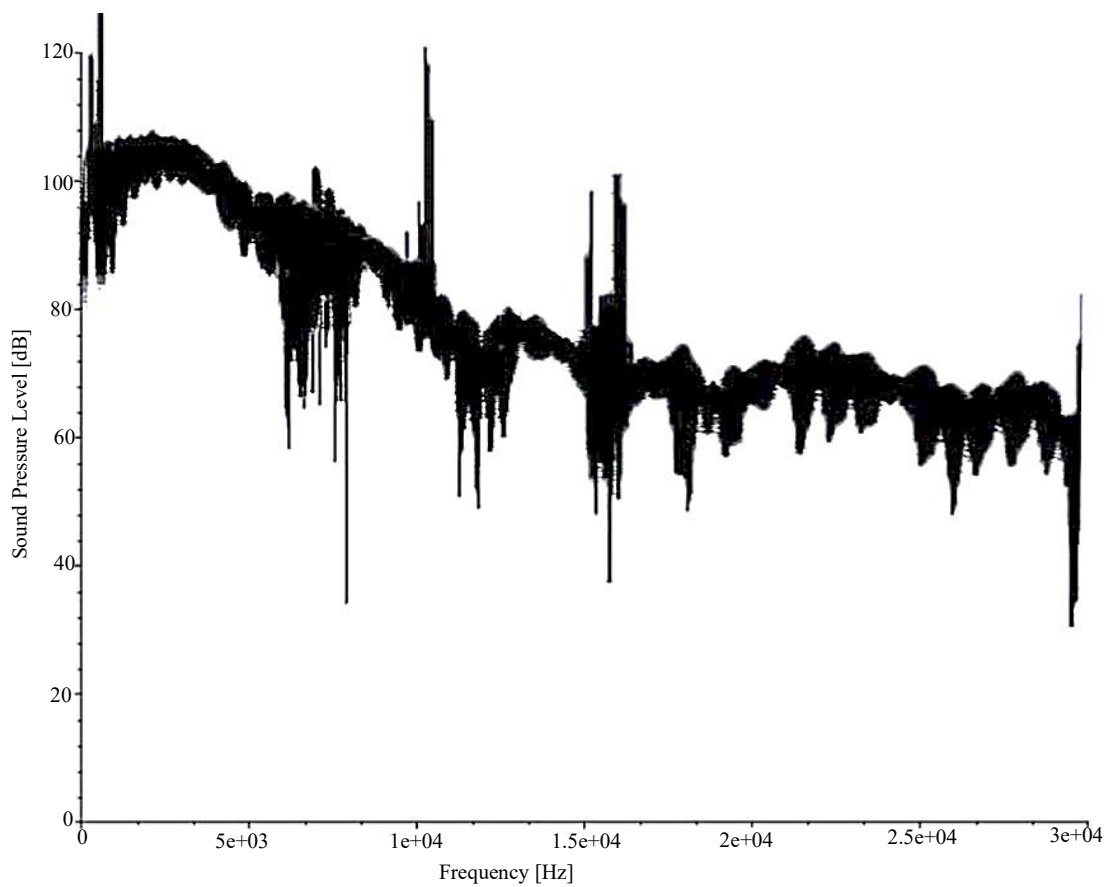


Figure 7. SPL using UDF.

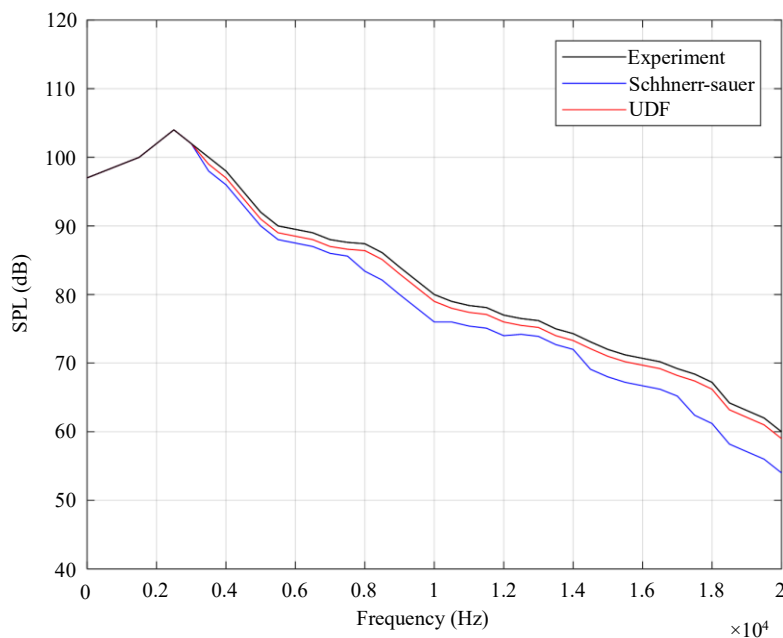


Figure 8. Comparison of experiment result with results by Schnerr-Sauer model and UDF model.

Figure 8 shows comparison of experiment result with results by Schnerr-Sauer model and UDF model. From Figure 8 we can know that results by UDF model are in better agreement with experimental results than by Schnerr-Sauer [10].

CONCLUSION

This study investigates the hydrodynamic performance and noise characteristics of propellers under cavitation operating conditions. The results of this study show that the numerical results are in good agreement with the experimental data. The obtained UDF model and results can be used to optimize the operating parameters of the induced pattern of noise radiation in underwater vehicles.

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