Numerical analysis for the prediction of hull pressure fluctuation and underwater radiated noise induced by marine propeller cavitation

[1]Jeong-yong Park*; [2]Milovan Peric; [2]Mark Farrall; [3]Cheolsoo Park;

[1]Maritime Research Institute, Hyundai Heavy Industries Co., Ltd., Ulsan, Republic of Korea;
[2]Siemmens Industry Software Limited, London, United Kingdom;
[3]Korea Research Institute of Ships & Ocean engineering, Daejeon, Republic of Korea;

Abstract

In this study, viscous flow analysis by computational fluid dynamics (CFD) was performed on a five bladed conventional marine propeller in behind condition on the purpose of predicting hull pressure fluctuations and underwater radiated noise (URN) induced by the propeller. The computation was conducted in model and full scale using the total underwater geometrical model of the propeller, hull and rudder for the direct comparison with the experiment and full scale measurement, respectively. The cavitation pattern and subsequent fluctuating pressure were investigated in model scale. A good agreement in cavitation pattern was found between the numerical analysis and experiment, yet the resolution of tip vortex cavitation needs to be improved. The tendency and amplitude of pressure fluctuations were reasonably predicted, especially for the 1st blade passing frequency (BPF). For the prediction of sound pressure level (SPL) in full scale, a hybrid approach based on CFD and Ffowcs-Williams and Hawkings (FW-H) method is applied. In case of URN for full scale, SPL from the numerical computation was compared with the result from full scale measurement. The numerical analysis generally underestimated SPL in comparison with the result of full scale measurement. For the validation of numerical analysis, only the computational result of propeller and rudder radiated noise is compared with the result from the full scale measurement.

Keywords: Marine propeller, Cavitation, Hull pressure fluctuation, URN, RANS, CFD, FW-H, SPL

Introduction

A rotating marine propeller and unsteady cavitation induce pressure fluctuations on a ship. They can cause the deterioration of comfort on board and the fatigue damage on the ship structure. In addition, ship radiated noise has been of a significant interest to international maritime community in terms of passenger’s comfort as well as environmental protections. The propeller cavitation is also the main source of ship radiated noise. In this point of view, International Maritime Organization (IMO) released guidelines for the reduction of underwater noise in 2014 even if it is non-mandatory [1]. Also, considerable studies have been recently conducted in the European research project like AQUO and SONIC to improve both experimental and numerical prediction method of cavitation noise. For these reasons, the prediction of unsteady cavitation, hull pressure fluctuation and URN by propeller is very essential in the propeller design phase. Regarding the prediction of hull pressure fluctuation, Paik [2] showed that Reynolds Averaged Navier-Stokes (RANS) equation provides a good agreement with experimental results in the 1st BPF of hull pressure fluctuations. Another recent study presents numerical simulations for the prediction of hull pressure fluctuation induced by cavitation on propeller with capturing the tip vortex [3]. Concerning the numerical analysis for URN by a propeller, it can be calculated by complementary use of CFD and FW-H equation [4].

In this study, numerical analyses are conducted for the prediction of hull pressure fluctuations and underwater radiated noise induced by marine propeller cavitation. For the validation, numerical results are compared with the hull pressure fluctuation by model test and URN from the full scale measurement on a modern ultra large container carrier Especially, the URN is directly predicted by flow analysis and FW-H in full scale while most of previously conducted researches focused on the analysis in model scale or its scale up results. And the current work presented in this paper is an exploration study of the feasibility to predict the URN by a ship propeller from a practical perspective for the propeller design, using a commercial CFD tool STAR-CCM+ which provides flow simulation and acoustic analogy.

*Corresponding Author, Jeong-yong Park: pjy6262@hhi.co.kr

Prediction of cavitation and hull pressure fluctuation in model scale

For the numerical analysis, RANS is applied for the prediction of cavitation and hull pressure fluctuation in model scale. The cavitation is simulated by using the Schnerr-Sauer model which is based on a simplified form derived from the general Rayleigh-Plesset model by excluding higher order terms, viscous and surface tension effects. For the propeller rotation, overlapping grids are adopted. The background grid includes hull and rudder and is meshed as if the propeller was not present, while a separate grid region is created around the propeller and rotates with it. Table 1 describes the detailed numerical setup and analysis condition. In this table, T, ρ, n and D represent thrust, density, rps and propeller diameter, respectively. $P_{0.7R}$ is a static pressure at the 70 % of propeller radius above the propeller shaft center and P_v is a vapor pressure.

Software	STAR-CCM+ (v12.02)
Turbulence Model	RANS (k-ε model)
Cavitation model	Schnerr-Sauer
Wall treatment	All y+ wall treatment
Propeller rotation rate (rps)	40 rps
Time step	2.5E-5s (0.36 deg/s)
Inflow velocity	7.5 m/s
Thrust oe i ient $\left(K_T = \frac{T}{0.5\rho n^2 D^4}\right)$	0.1850
Cavitation number $\left(\sigma_{0.7R} = \frac{P_{0.7R} - P_v}{0.5\rho n^2 D^2}\right)$	1.45
Scale ratio	45.7613
Draft	Ballast draft
Power	85% MCR
Free surface	Neglected
No. of cells	Abt. 12.5 millions

Table 1 Numerical setup and analysis condition

For the validation of numerical analysis, the predicted cavitation pattern is compared with the result from the model test performed at Large Cavitation Tunnel (LCT) in KRISO. Figure 1 depicts the cavitation pattern. A good agreement was found between the numerical analysis and experiment, yet the resolution of tip vortex cavitation needs to be improved. Also, the predicted pressure fluctuation by computation is also compared with the model test results on several sensor locations as shown in Figure 2. Figure 3 shows that the tendency and amplitude of hull pressure fluctuations are reasonably predicted, especially for the 1st BPF. In this figure, the hull pressure fluctuation is expressed as pressure coefficient, $K_P \left(= \frac{\Delta p}{\rho n^2 D^2}\right)$ where Δp is the pressure lu t uation amplitude rom the mean pressure.

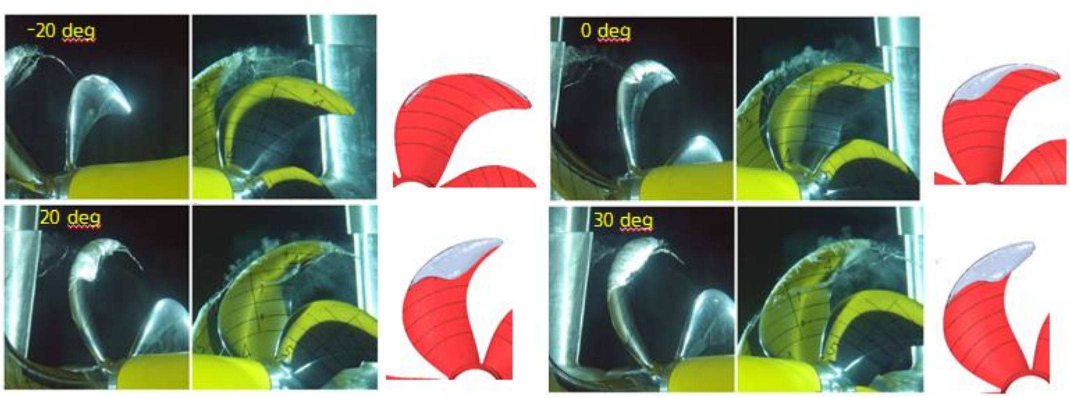

Figure 1 Comparison of cavitation between experiment and numerical analysis
[left: experiment (starboard side view), center: experiment (portside view), right: numerical analysis]

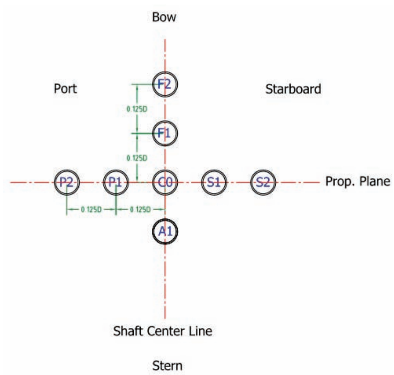

Figure 2 Sensor locations to measure hull pressure fluctuation

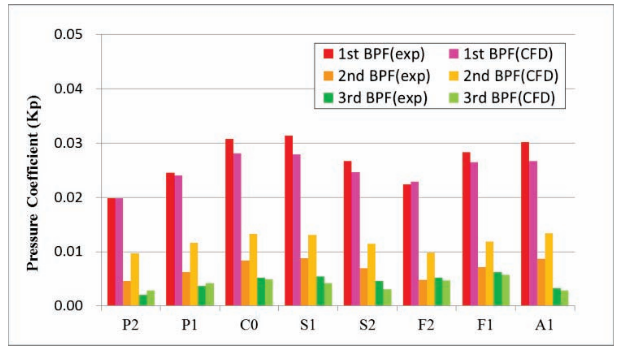

Figure 3 Comparison of Pressure Coefficient

Prediction of cavitation and SPL in full scale

Numerical predictions on cavitation and SPL were conducted in full scale using a grid with about 19.5 million cells. Unlike the computation in model scale, free surface was considered as shown in Figure 4. The ship speed and propeller rotation rate was about 25 knots and 79 rpm, respectively. The simulation was first carried out with larger time steps until free surface waves were developed and became nearly steady; the time step was then gradually reduced to values suitable to resolve propeller rotation and unsteady cavitation (2.5E-4s). Figure 5 indicates the computed cavitation pattern in full scale. The transient data obtained by CFD is transferred and used in FW-H formulation as the acoustic solver. In this study, FW-H embedded in STAR-CCM+ was also used. Monopole and dipole are included while quadrupole is excluded in the numerical simulation. The impermeable surfaces were selected as shown in Figure 6.

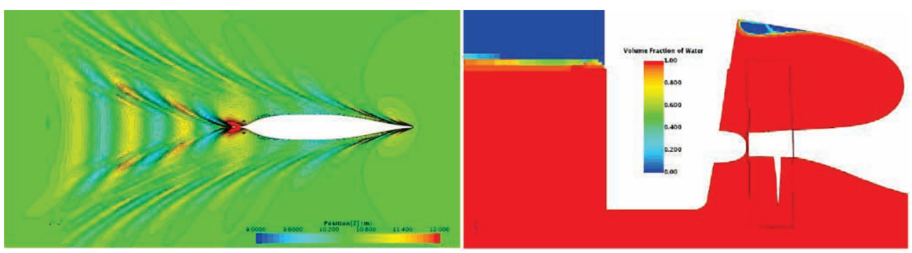
Figure 4 Predicted free surface waves

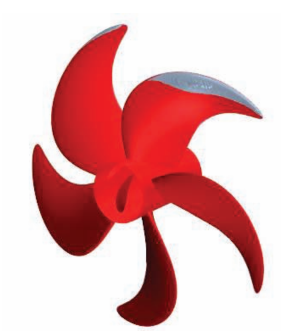
Figure 5 Cavitation pattern


Figure 6 Defined impermeable surfaces

For the validation of numerical analysis, only the computational result of propeller radiated noise is compared with the result from the full scale measurement because cavitation observation and measurement of hull pressure fluctuations were not carried out. The obtained data from computation is corrected to an equivalent 1 Hz bandwidth and 1 m source spectrum level. ITTC suggests that the sound pressure level be corrected to a standard measuring distance of 1m using the following relationship: SPL = SPL_1 + 20log(r), where SPL and SPL_1 are the sound pressure level in 1 Hz band in dB relative to 1 μPa at 1 m and 1 Hz band in dB relative to 1 μPa, respectively; r is the distance of the location of the receiver distance from the propeller center. This correction is adopted in this study.

Figure 7 represents the comparison of source spectrum level between full scale measurement and numerical analysis plotted in narrowband and 1/3 octave band. BPF is clearly observed in the computational result from the narrowband plot. The SPL from numerical analysis is generally matched with that from full scale measurement, however, there are some discrepancies including 1^{st} BPF which is over estimated about 11dB. Additional peaks excluding BPF shown in full scale measurement results are regarded to be due to the excitation force from engine, diesel generator and etc. In 1/3 octave band plot, SPL from the numerical computation is generally in a good agreement with the result of full scale measurement but slightly underestimated. This underestimation can be related with the lack of machinery noise, the lack of predicted tip vortex cavitation, the exclusion of quadrupole source and etc.

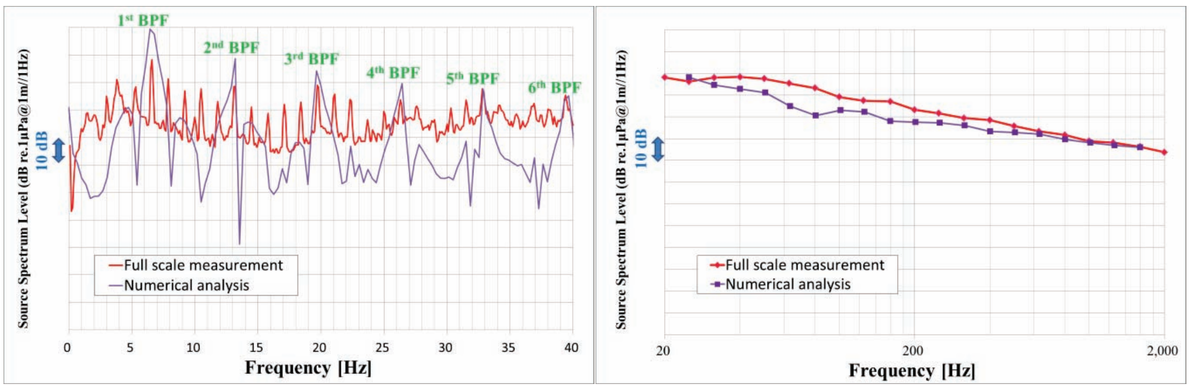

Figure 7 Source Spectrum Level (left: Narrowband, right: 1/3 octave band)

Conclusions

In spite of some limitations in capturing the growth and collapse of cavitation considering that Schnerr-Sauer model is used in this study, reasonable sheet cavitation and hull pressure fluctuation are obtained from the numerical analysis in model scale. It can provide useful information at propeller design stage. For the prediction of SPL in full scale, a hybrid approach based on CFD and FW-H is adopted. URN is predicted directly by flow analysis and FW-H in full scale. Although SPL from numerical analysis is somewhat underestimated in comparison with the result of full scale measurement, it may be the result of having the propeller and rudder as the only two sources of noise in the simulation while in reality there will be contribution from some other sources as well. We could find a possibility to obtain a reasonable SPL in full scale within practical use of commercial CFD software. However, it is necessary to perform additional works on the broadband noise source and other case studies in the future for making the current approach on prediction of URN more reliable. This approach is regarded as almost unprecedented in respect that URN is predicted directly by flow analysis and FW-H in full scale. It is also considered to be a challenging task in consideration of the fact we apply it to very large commercial ship and compare the computation results with those from full scale measurement.

Acknowledgement

This work was supported by the Ministry of Trade, Industry and Energy (MOTIE) (project code: 10045337, “Development of fundamental technology for ship propeller noise and key te hnology or noise redu tio n design”).

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