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Numerical investigation of tip vortex bursting and induced hull pressure pulses on a container vessel

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Abstract: A rotating marine propeller generates pressure pulses on the hull above it. The dynamics of cavitation, especially the tip vortex cavitation (TVC) bursting and TVC destruction by sheet cavity collapse have been found to induce high levels of pressure pulses on the ship hull body. The present study is focused on the numerical prediction of propeller induced pressure pulses on the hull with analysis on the interactions between ship wake, sheet cavitation and TVC. The predicted 1st – 2nd order Blade Passing Frequency (BPF) agree well with experimental measurements and higher order BPF pressure pulses are reasonably predicted as well. The study shows that the re-entrant jet, which can be related to the propeller inflow and convex shaped sheet cavity closure line, plays an important role regarding sheet cavitation collapse as well as violent TVC dynamics, and induce significant levels of hull pressure pulses.

Keywords: Tip vortex bursting; re-entrant jet; cavitation; pressure pulse

1. Introduction

A cavitating marine propeller is an effective source of hull pressure pulse generation. RANS based numerical simulation has been used for pressure pulse prediction [1,2], believed to be able to predict acceptable hull pressure pulse levels up to 2nd-order BPF (Blade Passing Frequency) induced by propeller sheet cavitation dynamics. Experimental studies [3-5] suggest Tip Vortex Cavitation (TVC) may lead to significant levels of pressure pulse from 3rd to 13th BPF, while scale resolving simulations have also been used and predictions of higher-order BPF pressure pulses were reported[6,7]; here for these cases the propellers were operating inside a wake and TVC was found to be bursting. The existence of upstream disturbances, i.e. upstream wake or sheet cavity dynamics is seemingly a pre-requisite for TVC bursting [8]. TVC bursting can induce high levels of hull pressure pulses, firstly reported by [9] and the TVC destruction by sheet cavity collapse is a common phenomenon on ship propellers, which might be related with re-entrant jet underneath the blade sheet cavity [10]. Converged side re-entrant jets may lead to strong cavitation dynamics including shedding and collapsing for twisted foils [11].

In the present study, a model scale container vessel with a single five-bladed high-skew fixed pitch propeller is studied. The vessel was used in the VIRTUE and SONIC EU project with model scale experiments carried out in the cavitation tunnel HYKAT at HSVA. The ship model was manufactured by HSVA with scale ratio of 1:29.1 and was installed according to even keel draft of 11.3 m. There were 13 pressure sensors installed on the ship hull above the propeller to measure propeller induced pressure pulses. The shaft speed of the model propeller was fixed to n = 28 rps during the experiments which result in a blade Reynolds number of Re = 1.52×10^6. The inlet velocity of the cavitation tunnel was adjusted to match desired non-dimensional thrust coefficient K_T, and the pressure was adjusted to the specific non-dimensional cavitation number σ at 0.8R with blade at 12 o'clock position. The considered operating condition in the present study corresponds to the designed service condition with full scale ship cruising speed of $V_S = 23.76$ Knots, thrust coefficient $K_T = 0.2234$ and cavitation number of $\sigma = 0.2354$.

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2. Simulation design

The commercial package Star-CCM+ is used for conducting numerical simulations. The simulation domain is chosen to be identical with the main dimensions of the cavitation tunnel HYKAT, sized 11 × 2.8 × 1.6 m. The propeller rotation speed was fixed to 28 rps and inlet velocity was adjusted to 7.27 m/s based on the desired propeller thrust coefficient K_T. Computational mesh was generated using Star-CCM+ building polyhedral mesher with totally 67 million cells, with 39 million cells for the propeller rotation region and 28 million cells for the cavitation tunnel test section. $k-\omega\ SST$ based IDDES turbulence model and Schnerr Sauer cavitation mass transfer model are used.

3. Results

The predicted hull pressure pulse levels are shown in Figure 1 with the 13 pressure transducer measurements for 1st-5th BPFs, with the predicted time history pressure signal on transducer 7 shown in Figure 2. The total vapor volume is integrated over the whole simulation domain as $V_{vapor} = \sum_1^n \alpha_{vi} V_{celli}$. For a breathing spherical monopole, the induced pressure fluctuation can be correlated with its volumetric variation as $p' \approx \frac{\rho}{4\pi r}\frac{\partial^2 V_{b,\left(t-\frac{r}{c}\right)}}{\partial t^2}$, which is also shown in Figure 2 and it can be found to be highly correlated with the induced pressure history.

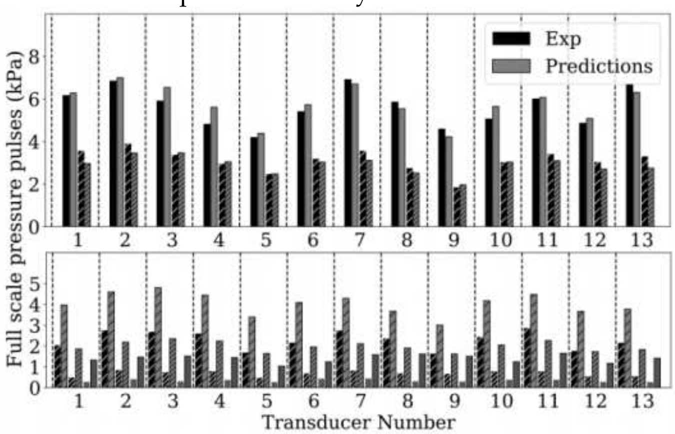

Figure 1 Predicted hull pressure pulses and comparison with experimental measurements. Upper frame: 1st and 2nd BPF; lower frame: 3rd to 5th BPF. Values are reported in full scale.

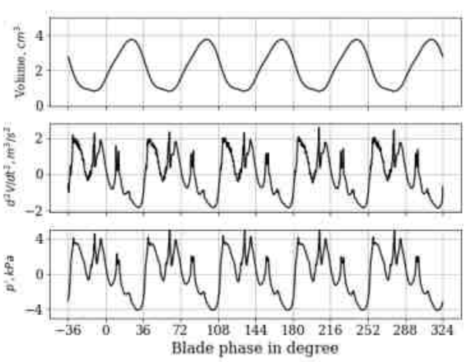

Figure 2 Vapor volume and hull pressure pulse in blade phase series. Top frame: integrated total vapor volume; middle frame: second order derivative of total vapor volume; bottom frame: pressure history at transducer No. 7.

The predicted cavitation patterns are shown in Figure 3 with the iso-surface of $\alpha_v = 0.5$ as well as the contour lines of propeller inflow U_x/U_{in}. The sheet cavitation is firstly showing up with convex shaped closure line and a re-entrant jet underneath it, indicated by a lighter blue color. The re-entrant jet is travelling from leading edge to the blade tip. The shape of the sheet cavity and its closure line has local maximum at about center plane where lowest U_x/U_{in} can be found. The gradient of U_x/U_{in} can be interpreted by the spatial density of contour lines, and at locations with larger U_x/U_{in} gradients (denser contour lines) a larger curved sheet cavity closure line can be found. If the cavitation iso-surface can be regarded as a surface with uniform pressure, local velocity has potential perpendicular to the cavitation surface. The curved sheet cavitation closure line, for the present case, lead to the re-entrant jet as shown in Figure 3 with 10 and 20 degrees.

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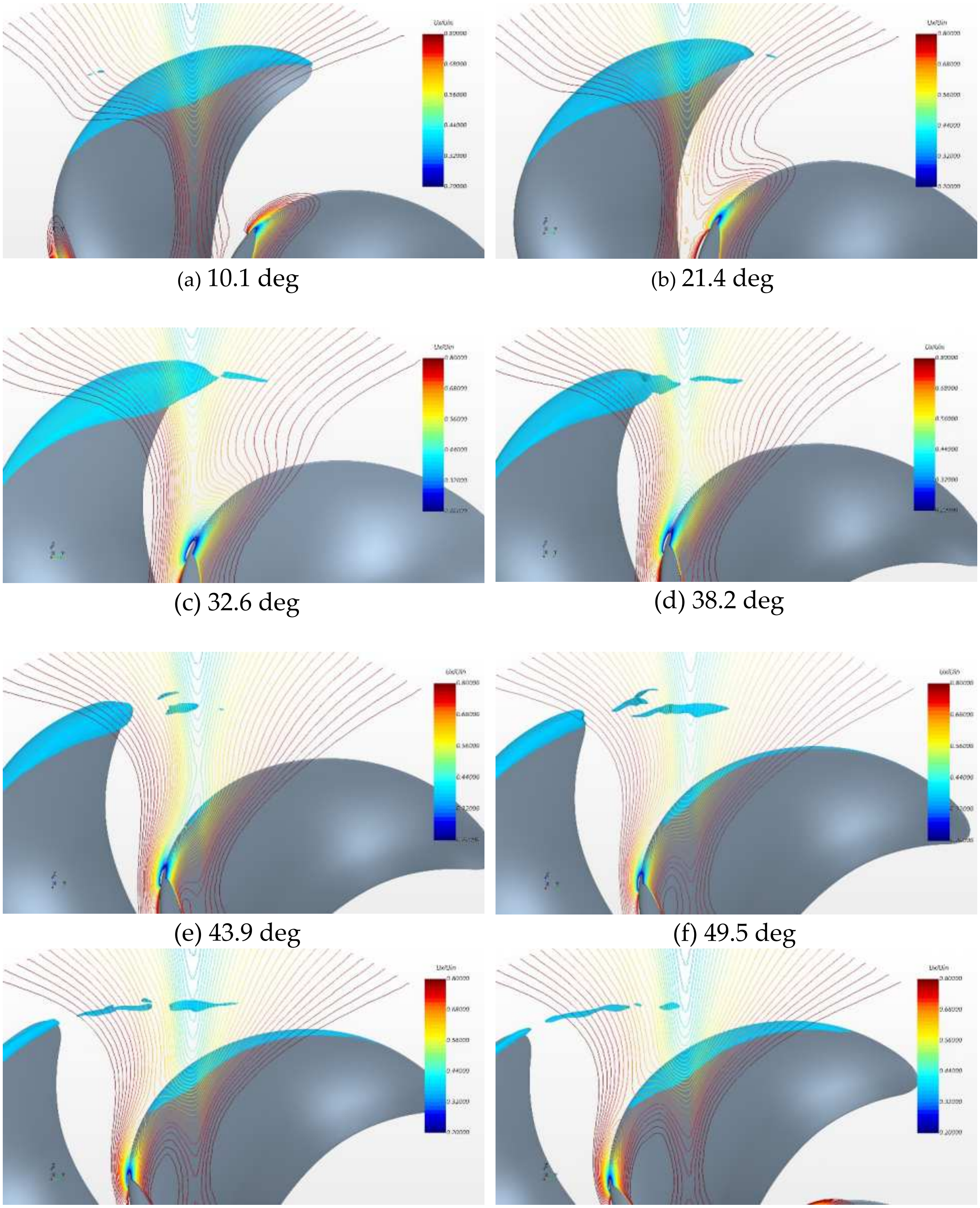

(a) 10.1 deg
(b) 21.4 deg
(c) 32.6 deg
(d) 38.2 deg
(e) 43.9 deg
(f) 49.5 deg
(g) 55.1 deg
(h) 59.6 deg

Figure 1. Cavitation (iso-surface of $\alpha_v = 0.5$) history with axial propeller inflow slightly upstream the propeller blade.

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With the re-entrant jet traveling to the blade tip, between blade phase of 32 to 38 degrees, the sheet cavity aft part collapses violently and triggers tip vortex cavitation bursting at blade phase around 48 degrees. These two events can be correlated with the pressure pulse signal of the first peak around 45 degrees, and it worth mentioning this first peak contains two subtle sub-peaks with phase difference of 2~3 degrees. The triggered tip vortex cavitation is surrounded by multiple rolling sub-cavities and the main TVC is relatively larger in size at the mid-plane and relatively stronger dynamics at locations with large propeller inflow gradients. The TVC also behaves similarly as a breathing structure and lead to the series of pressure fluctuations observed in the pressure signal.

4. Conclusions

Satisfying numerical prediction of pressure pulse is achieved in the present study, and the predicted pressure pulse levels are highly correlated with the rate of cavitation volume growth/shrinkage. TVC bursting is found inducing significant levels of pressure pulses at higher orders BPF. The collapse of sheet cavity and generation and bursting of TVC is found to be triggered by the re-entrant jet underneath the blade sheet cavitation, and the formation of re-entrant jet can be related with the convex shaped sheet cavitation closure line, which is influenced by the propeller inflow gradients.

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References

1. P. Peraku, T. L. (2016). Comparison of urans and bem-bem for propeller pressure pulse prediction: E779a propeller in a cavitation tunnel. Proceedings of 19th Numerical Towing Tank Symposium. St. Pierre dOleron, France.
2. Paik, K.-J., Park, H.-G., & Seo, J. (2013). RANS simulation of cavitation and hull pressure fluctuation for marine proepller operating behind-hull condition. International Journal of Naval Architecture and Ocean Engineering, 502-512.
3. Berghult, L. (2000). Propeller induced tip vortex noise as function of blade area and blade tip loading, in Proceedings of the international conference on propeller cavitation (NCT's 50).
4. Aktas, B., Atlar, M., Fitzsimmons, P., Shi, W. (2018). An advanced joint time-frequency analysis procedure to study cavitation-induced noise by using standard series propeller data, Ocean Engineering, 170, 329-350.
5. Pereira, F., Salvatore, F., Di Felice, F., Soave, M. (2004). Experimental investigation of a cavitating propeller in non-uniform inflow, in Proceedings of the 25th ONR Symposium on Naval Hydrodynamics.
6. Li, D. Q, Hallander, J, Johansson, T. (2018). Predicting underwater radiated noise of a full scale ship with model testing and numerical methods. Ocean Engineering, 161, 121-135.
7. Sakamoto, N. K. (2018). Prediction of near field propeller cavitation noise by viscous CFD with semi-empirical approach and its validation in model and full scale. Ocean Engineering, 168, 41-59.
8. Pennings, P., Westerweel, J., T. Van Terwisga. (2016). Cavitation tunnel analysis of radiated sound from the resonance of a propeller tip vortex cavity, International Journal of Multiphase Flow, 83, 1-11.
9. English, J. W. (December 1979). Cavitation induced hull surface pressures measurements in a water tunnel. Symposium on propeller induced *ship vibration.* London
10. Kuiper, G. (2001). New developments around sheet and tip vortex cavitation on ships propellers. 4th international symposium on cavitation: lecture. Pasadena.
11. Hu, C., Chen, G., Yang, L., Wang, G. (2018). Large eddy simulation of turbulent attached cavitation flows around different twisted hydrofoils. Energies, 11(10), 2768.

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