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Numerical Investigation of Full-Scale Cavitating Propeller Underwater Radiated Noise

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Abstract: This study aims to predict the full-scale propeller Underwater Radiated Noise (URN) in cavitating and non-uniform flow conditions using a viscous flow-based hybrid method. The recently introduced benchmark propeller of the research vessel, "The Princess Royal", was used for the numerical application to validate the methodology presented in this paper. The hybrid method constitutes a DES (Detached Eddy Simulation) solver coupled with a porous formulation of the Ffowcs Williams Hawking Equations (P-FWH) for the URN predictions. The Schnerr-Sauer cavitation model based on the reduced Rayleigh-Plesset equation was utilised to model the sheet and tip vortex cavitation (TVC). A vorticity-based Adaptive Mesh Refinement (V-AMR) technique was proposed and implemented for better modelling of the TVC in the propeller's slipstream. The hydrodynamic performance, including the cavity patterns and URN results, were compared with the full-scale URN data collected from the sea trials with The Princess Royal. The predicted propeller URN results show good agreement with the trials data except for some discrepancies in the high-frequency region of the noise spectra investigated.

Keywords: Underwater Radiated Noise (URN); Cavitation Noise; Computational Fluid Dynamics (CFD), Ffowcs Williams Hawkings Equation (FWH); Full-scale Propeller; The Princess Royal.

1. Introduction

Over the last decades, the increasing volume of commercial marine transport has caused a considerable rise in the emitted URN levels, and shipping generated noise has become a dominant anthropogenic noise source in the world's oceans, as reported in many references, e.g. [1]. The potentially harmful effects of the URN by ships on marine creatures have become a significant concern by international and regional authorities with a remarkable expansion of ship numbers and sizes [2]. This concern, in turn, has urged some regulatory authorities and classification societies to take leading roles to introduce some non-mandatory notations to reduce the ship radiated noise, including, e.g., the Det Norske Veritas Germanisher Loyd (DNV-GL) QUIET class, Registro Italiano Navale (RINA) DOLPHIN. Within the same context, the International Maritime Organisation (IMO) has prioritised superiorities this concern and published a non-mandatory guideline to minimise the URN levels, particularly induced by commercial ships [3].

The ship generated URN has three major contributions, including the machinery noise, hydrodynamic noise caused by the flow around the hull and its appendages, and the propeller radiated noise [4]. Amongst these contributions, the propeller induced noise, especially in the presence of cavitation, is the dominant one increasing the overall URN level significantly. Therefore, considerable efforts have been put into predicting the propeller induced URN using different approaches [5]. The model tests conducted in the cavitation tunnels and depressurised towing tanks have been one of the most reliable approaches to predict the propeller URN. However, the issues with the availability of these facilities, their higher costs and scale effects of the extrapolations, in recent years, have favoured the use of the state of art CFD tools with the significant progress achieved in the development of these tools to predict propeller URN (e.g. [10], [11]). However, the detailed validation and verification of the numerical results from these tools with the experimental and sea trial data are still limited, requiring further work as tackled in this study.

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The numerical simulations are being currently conducted using the potential flow-based boundary element methods or viscous flow-based CFD solvers (i.e., RANS, DES and LES) for the solution of cavitating flow around the marine propellers both in the model and full-scale. Using these methods, in general, the sheet cavitation on the propeller blades is modelled. In contrast, the TVC is neglected because of the complexity of the modelling to TVC. The complexity is associated with the fact that the accurate solution and observation of TVC are strongly dependent on cell size inside the vortex and the turbulence modelling in the viscous solvers. Thus, the scale resolving simulations (i.e., in DES or LES) using the advanced meshing techniques (e.g., Adaptive Mesh Refinement) are suitable methods for the accurate modelling of the tip vortex flow inside the vortex and hence TVC in the propeller slipstream.

One of the recent approaches in predicting the URN is the combined (or hybrid) use of the CFD and the Ffowcs Williams Hawking (FWH) equations based acoustic analogy method. In implementing this hybrid approach, while the noise source in the near field is determined by the CFD (viscous) solver, the propagation of the sound from the near field to the far-field is conducted by the use of the acoustic analogy. The most commonly used acoustic analogy is the Ffowcs Williams Hawkings (FWH) equation. In the literature, the cavitating propeller URN is generally predicted in the presence of only sheet cavitation (e.g., [6], [7], [8] and [9]); hence there is a lack of studies including the contribution of tip vortex cavitation on propeller URN apart from the sheet cavitation (e.g. [10], [11]) because of the earlier stated complexity of the TVC modelling.

Within the above framework, this study aims to predict the full-scale propeller URN using a state of art commercial CFD solver and an advance meshing technique to include the TVC under the effect of non-uniform wake flow. The developed Vorticity-based Adaptive Mesh Refinement (V-AMR) technique, which is successfully applied in different model scale propellers by the authors (e.g.,[12], [13], [14]), was also applied for the full-scale propeller. In this way, a better realisation of the TVC in the propeller slipstream was achieved. This was followed by the prediction of the propeller URN using the porous formulation of the FWH equation. The propeller hydrodynamic characteristics and URN were predicted, and results were compared with those of the sea-trial data.

2. Test Case Description

In the numerical simulations, the recently introduced benchmark propeller of "The Princess Royal" was used for the propeller induced URN in the presence of cavitation [15]. This propeller has also been the test propeller of a presently ongoing round-robin (RR) test campaign. Hence, the hydrodynamic and hydro-acoustic performance of this benchmark propeller has been investigated comprehensively in model scale by the participation of many different facilities worldwide [16] (e.g., the University of Strathclyde, The University of Genoa, NMRI, SSPA, KRISO, CNR-INM, and MARIN). In complementing the RR test campaign results, the full-scale URN data is also available for this benchmark propeller from the FP7 SONIC Project results (e.g., [17]). The Princess Royal's propeller is a fixed pitch with five blades with a diameter of 0.75m. The detailed geometrical features of the vessel and its propeller can be found in Atlar et al. [15].

One of the typical full-scale operational conditions (i.e., Condition 4) of The Princess Royal was used for the simulations in this study, as given in Table 1. Condition 4 presented the strongest tip vortex cavitation during the sea trial [17].

Table 1. Full-scale operational conditions during sea trials.

Condition	Engine RPM	Propeller RPM	V_S (knot)	σ_N
4	2000	1141.5	15.11	1.07

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3. Numerical Model

The cavitating flow around the full-scale propeller was solved using the commercial CFD solver (Star CCM) [18]. In the numerical simulations, the DES solver was used together with the k-ω SST turbulence model and the wall function approach. DES is a hybrid method by the combined use of the RANS in the boundary layer and LES in the free-field region. The segregated flow model was used with a SIMPLE algorithm. The second-order scheme was used for both the convection term and time discretisation to increase the accuracy of the solution. The time step was selected to correspond to 0.5^0 of the propeller rotational angle rate (i.e., $7.3*10^{-5}$ s). The sliding mesh approach was used to model the propeller rotational motion. The CFD simulations were conducted with the measured wake data in the ITU (Istanbul Technical University) towing tank.

In modelling the cavitation, the Schnerr-Sauer cavitation model based on the reduced Rayleigh Plesset equation was used for the sheet and tip vortex cavitation [18]. In this model, seeds are assumed to be spherical and uniformly distributed in the liquid, and all seeds initially have the same radius. The Volume of Fluid (VOF) method was employed to describe the phase transition between the liquid and vapour.

As stated earlier, for the URN prediction, the FWH equation, which is the rearranged form of continuity and momentum equations into the inhomogeneous wave equation, was used [19]. Two different types of FWH formulation are present, namely, impermeable and porous (or permeable). As also stated earlier, although cavitation is the most dominant noise source, the vorticity and turbulent structure in the propeller's slipstream as a non-linear noise source also contribute significantly to the overall noise level. The non-linear noise contributions can be included either directly computing the quadrupole noise terms or using the porous formulation of the FWH equation. However, the quadrupole noise terms' direct solution using volume integrals is computationally expensive, and its solution is more sensitive to numerical errors and accuracy of the hydrodynamics inputs. Thus, the porous form of the FHW (P-FWH) was utilised to solve the quadrupole noise sources using the surface integrals instead of directly solving them using volume integrals. The porous formulation of FWH was applied by Ffowcs Williams and Hawkings [19] in their original study and also proposed as a possible numerical solution of the FWH equation by Di Francescantonio [20]. In this approach, the noise region surrounds the propeller blades to account for the contribution of non-linear noise sources induced by the propeller's slipstream.

The unstructured hexahedral elements were adopted to discretise the computational domain, which is shown in Figure 1. Trimmer mesh was used with minimal skewness of the cells by the combination of the V-AMR technique. AMR is a dynamic method that refines or coarsens the cells at the specified region according to refinement criteria. In this study, the gradient quantity (i.e., vorticity) was used as a refinement criterion for the AMR procedure. Another difficulty for the AMR procedure is the determination of the required cell size in the vortex region. By implementing the useful suggestions of the available literature (e.g., [21], [22]) and our further investigations (e.g., [13]), the TVC can be observed for the model scale propeller if the grid size inside the vortex is between 0.2mm-0.25mm. In a full-scale propeller, the tip vortex diameter is larger than those of a model scale propeller; hence, the grid size will not have to be the same order as the model scale propeller. However, it should be in a similar order relative to the propeller diameter. Therefore, the grid size in the vortex region was enlarged with the scale ratio ($i.e., \lambda = 3.41$), and it was set to 0.68mm for the full-scale propeller.

The proposed V-AMR procedure is composed of two stages. When the flow field converged using the initial mesh, tip vortex development is visualised using the Q criterion for the 1st stage V-AMR procedure. In this way, the threshold value of the Q criterion can be set based on the region where is of great interest (in our case Q_1=40.000 1/s^2). The helical structures of the tip vortex show the regions where the magnitude of the Q criterion is higher than the determined threshold value. When the field of interest was determined, the refinement table was generated using the user-based field functions in all directions. At the 1st stage of

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the V-AMR application, the tip vortex trajectory was determined using relatively coarse grids. Following the two or three propeller revolutions, the process was repeated for the 2nd stage of the V-AMR application with the new threshold value and grid size (in our case Q_2=500.000 1/s²). Implementing two stages of the V-AMR technique provides a considerable reduction of total element count and hence computational cost. The implemented grid structure around the propeller blades, computational domain & boundary conditions is shown in Figure 1.

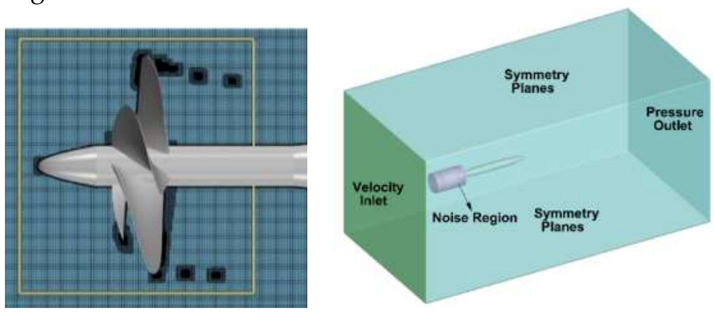

Figure 1. Grid structure around the propeller blades and computational domain & boundary conditions.

3. Results

Figure 2 compares the sheet and tip vortex cavitation obtained by CFD and sea trial data (Sampson et al.,[23]). As shown in Figure 2, the large extent of suction side sheet cavitation (i.e., around 25-30% of the blade area) was observed during the sea trials. In the CFD computations, the sheet cavitation on the propeller blades is slightly underpredicted compared to the sea-trial. Although the complex cavity dynamics associated with the cloudy appearance and unstable dynamics of tip vortex cavitations are present in the sea-trial, the same TVC dynamics could not be observed in the CFD calculations. Thus, the sheet and tip vortex cavitation are simulated by the considerably less intense cavity dynamics in the CFD when compared to sea trial observations. Nevertheless, the appearance and deformation of TVC could be simulated successfully using the V-AMR technique.

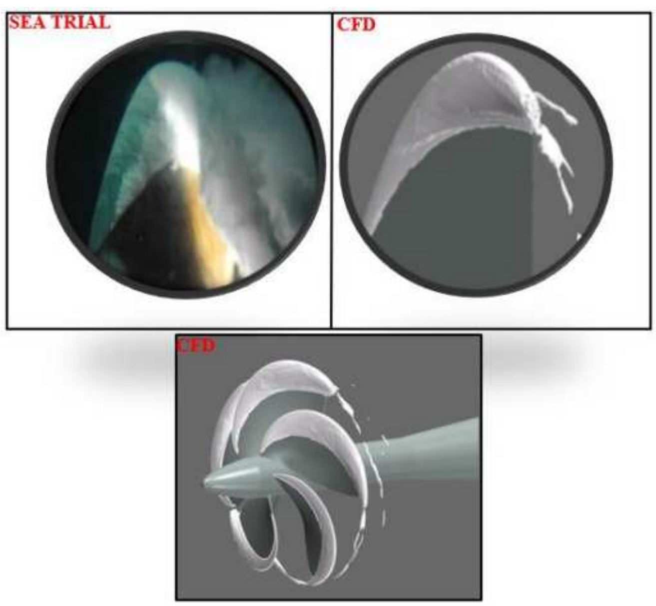

Figure 2. Comparison of cavity pattern between sea trial observations [23] and CFD simulations (vapour volume fraction (α_V=0.1).

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Due to the lack of sea-trial data for the thrust coefficient, the numerical results were only compared with the sea-trial data in terms of torque coefficient. The comparison showed that the torque coefficient is overpredicted with the CFD around 9%.

The Princess Royal propeller's full-scale noise measurements were made by CETENA in the FP7-SONIC project. After that, the noise levels were extrapolated to a 1m reference distance using the ITTC distance normalisation procedure and presented in One-Third Octave (OTO) band levels. In the CFD calculations, the receiver was located at 1m from the propeller's blade centre at the propeller plane to compare the numerical results with those of the sea-trial data. The noise data was recorded during the seven propeller rotations, and 3dB were added as the catamaran vessel has two propellers. Following this, the narrowband data was converted to OTO band levels. As shown in Figure 3, there is a good agreement between the CFD predictions and the full-scale measurements up to 2kHz, and the BPF values (i.e., 1st and 2nd BPF) were well predicted in the CFD calculations. However, the numerical calculation underpredicted the noise levels approximately 10-15dB after 2kHz. The reason is that the broadband part of the noise spectrum is strongly affected by the cavitation dynamics. The interaction between the sheet and tip vortex cavitation and unstable tip vortex cavitation dynamics could not be observed in the CFD calculations. Hence, these lack of reproduction of the cavity dynamics can lead to the underprediction of the noise levels in the high-frequency region.

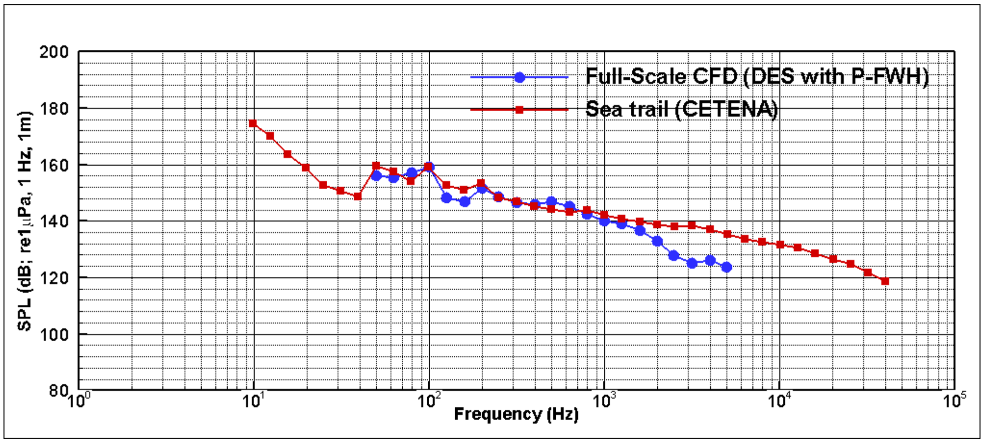

Figure 3. Comparison of sound pressure levels between sea trial and CFD (OTO).

4. Conclusions

This paper presented the URN prediction induced by the cavitating propellers of The Princess Royal and compared with the full-scale URN measurements. The hybrid method (i.e., DES with P-FWH equation) was used to predict the propeller URN in full-scale. The accurate modelling of the TVC in the propeller's slipstream was achieved using the developed V-AMR technique in the numerical predictions. By using the V-AMR technique, the formation of the TVC was somewhat predicted successfully. However, unstable cavitation dynamics could not be predicted as in the full-scale observations using the CFD. However, the noise prediction obtained by CFD showed good agreement with the sea trial data. The work presented in this paper is currently being extended to predict propeller URN in full-scale in the presence of a hull. Thus, the acoustic analogy's effectiveness will be shown for the receivers located in the far-field where the sea-trial data was collected.

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