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Determination of Underwater Radiated Noise of a Marine Propeller Using Different Prediction Methods

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ABSTRACT
The significant environmental impact of underwater radiated noise (URN) on marine life due to on-going increase in shipping noise worldwide is recognized by International Maritime Organization (IMO) as a harmful form of pollution. Machinery, hull vibration and propellers have been identified as sources for shipping noise as the major stressor to the marine fauna. As one of the dominant sources of URN of ships is propeller cavitation, this paper follows the validation of selected methods to derive sound pressure signals from cavitation volume. Therefore, different numerical methods such as RANS and panel method are used to compute the cavitation volume for a chosen number of test cases. The results are further processed by analytical calculation of sound pressure by deriving the numerically computed volume. Using the Ffowcs Williams-Hawkings (FWH) method, the numerical evaluation will be used for verification of the analytical approach. The overall findings respective predicted sound levels are compared with data from full-scale measurements. The results will be discussed also in respect to the usage in the design process. An inclusion of the most efficient, feasible and reliable noise predicting method into the design process shall be enabled by the findings of this paper.

Keywords
Underwater Radiated Noise; Propeller; Cavitation; CFD.

1 INTRODUCTION

As environmental consciousness has increased worldwide, research has been funded to underline the hypothesis of URN to compromise and being harmful to marine life (Wright 2008). It has been shown that there is a strong coherence between the increase of noise pollution in oceans and the increase of commercial shipping traffic (Sonic Sea 2016). With the noise pollution becoming a growing concern, IMO released guidelines for the reduction of URN in 2023 (IMO 2023), although not mandatory yet. Recommended mitigation measures include machinery noise reduction, flow noise reduction as well as propeller noise reduction. With the propeller operating in an inhomogeneous wake field of the ship hull and thus developing cavitation, the propeller is the most dominant noise source within ship's operation. Propeller noise reduction can be achieved by a cavitation reducing propeller design, choosing characteristics carefully based on noise prediction. Research targeting verification and improvement of methods to predict noise induced by marine propellers is highly demanded.

Experimental prediction methods like model tests as well as full-scale measurements can be considered the most accurate methods available for assessment during or after the propeller design process. However, due to the requirement of a physical model of ship and propeller it is cost- and time-intensive. For fast results in the early stages of propeller design, both numerical and analytical methods have been developed for the prediction of hydroacoustic emissions. In this context the coupling of Computaional Fluid Dynamics (CFD) with acoustic analogies gained a certain popularity. Being a generalization of the Lighthill analogy the FWH analogy is increasingly applied.

URN mainly affects marine life in far field distance. Therefore, perspectively a method shall be used, that takes into account direct sound path as well as interferences caused by reflections from the free surface and seabed. Göttsche (2020) implemented the FWH-equation into the panel method *panMARE* and thus provided a method to evaluate acoustic pressure at far-field observer positions.

Aimed to reduce storage- and time-intensive numerical calculations Wang et al. (2022) coupled the FWH acoustic analogy with RANS simulations with a dual mesh technique for the acoustic assessment. The proposed method was verified by comparison of acoustic and hydrodynamic pressures at near field and far field positions.

Averson and Vendittis (1999) analysed full-scale underwater noise measurement data from merchant ships in regards to cavitating propellers and cavitation volume. They used the analytical correlation between volume acceleration and the radiated free-field acoustic pressure to produce a time signal of the cavitation volume of the acoustic source.

Kleinsorge et al. (2017) used URN measurement and calculation methods in order to evaluate the URN of a container ship. A sound correlation between panel method, model test and full-scale measurement was demonstrated.

2 METHODOLOGY

The suitability of the presented methods to predict underwater radiated noise for propeller in the early stages of the design process shall be validated by reference to results from full-scale measurements of a designated test case.

2.1 Full-Scale Measurements

The full-scale measurements have been performed with a General Cargo Ship (GCS) whose particulars are given in Table 1. The installed propulsor is a four-bladed Controllabe Pitch Propeller (CPP). Measurements were performed at the North Sea close to the island Helgoland, Germany, resulting in a rather low water depth of 30 m. For the purpose of collecting as much data as possible, six different operational conditions were run in generator mode by passing by a locally installed hydrophone.

Table 1: Vessel Characteristics for GCS

General Cargo Ship	
Length between perpendiculars	148.31 m
Breadth	24 m
Design Draught	7.5 m
Displacement	21400 t
Maximum Continous Rating	12600 kW
Rpm at MCR	129.68 min^{-1}
Controllable Pitch Propeller	
Diameter	5.5 m
Number of blades	4
Expanded area ratio	0.598

The measuring conditions relevant for this paper are specified in Table 2, selected from the six run-throughs performed during the full-scale measurements according to classification recommendation.

Table 2: Full-Scale Measurement Conditions for GCS

Nominal shaft speed	129 min^{-1}
Ship speed (over ground)	19 kts
Water depth	60 m
Draught	7.5 m
Distance Hydrophone	92 m
Depth Hydrophone	30 m

2.2 Boundary Element Method

Due to low computational effort and cost Boundary Element Methods (BEM) work well to quickly generate results and integrate those into the design process. Thus, the panel code *panMARE* is initially used for numerical simulation of the cavitating test case propeller. The URN shall be predicted by a hybrid method based off the coupling of the FWH analogy with the BEM approach as described by Göttsche (2020). The ship's wake is calculated by the BEM such that the hull surrounding flow and the propeller including sheet cavitation are represented.

In order to reduce computational time, the mesh has been chosen as rough as possible on the basis of a mesh convergence study. The panel mesh per blade is defined by 16x14 panels on either side. The mesh is refined towards the leading edge as well as the tip. The panel mesh of the blade is shown in Figure 1.

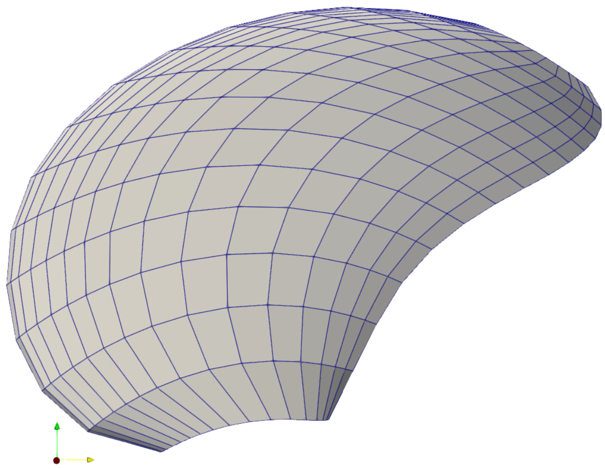

Figure 1: panMARE mesh of propeller blade

For time discretization a time stepping of 3 degrees per time step is chosen. The number of simulated propeller revolutions is 16 to realise at least 12 converged propeller revolutions for the FWH analysis. With respect to the evaluation using Fast-Fourier-Transformation (FFT), the last 12 propeller revolutions are considered in the FWH post-processing. The acoustic pressure values are tracked for a set number of 23 measure points in the far field distance, which is defined by a minimum distance of $1xLPP$. Although the position of the hydrophone used in the full-scale measurements is considered near field in regards to the FWH method implemented by Göttsche (2020), the observer points are used to retain direct comparability. The simulation of the propeller is performed in full-scale. The simulation set up is shown in Figure 2.

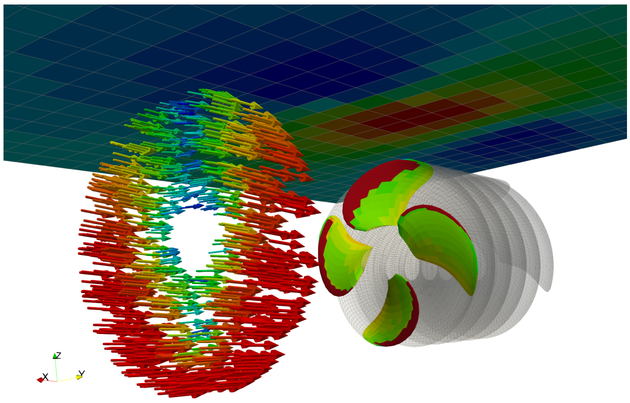

Figure 2: Simulation set up for BEM with *panMARE*

2.3 Coupled RANS Method

The CFD RANS computations have been performed with the CFD software OpenFOAM. The simulation is using dynamic mesh technique. The propeller is meshed in a cylindrical rotor domain, which consists of approximately 14.7 mill. cells. The cells are refined towards the propeller geometry. A non-dimensional first cell high of y+=30 is adopted together with a prism-layer near the wall surfaces in order to capture the boundary layer. The stator mesh around the propeller has also a cylindrical shape with a propeller shaft. It is cut at the top. The overall amount of cells is approximately 1.7 mill. cells. These are refined near the rotor mesh and along the wake flow. To the outer boundaries of the flow a slip condition is applied. The ship's wake is given as an inlet condition to the domain. Figure 3 shows the fluid domain setup. To solve the fluid flow the OpenFOAM *interphaseChangeDyMFoam* solver is chosen, which is a two phase solver for incompressible fluid. A Volume-of-Fluid (VOF) approach coupled with the Schnerr-Sauer cavitation model is used to capture the phase change. The k-ω-SST model is employed as turbulence solver. Wall-functions are applied, too. The simulation of the propeller is performed in full-scale. Results of the calculations are logged for the same measurepoints as used in the method of Section 2.2. The computational setup is according to the CFD simulations in Kleinsorge et al. (2022).

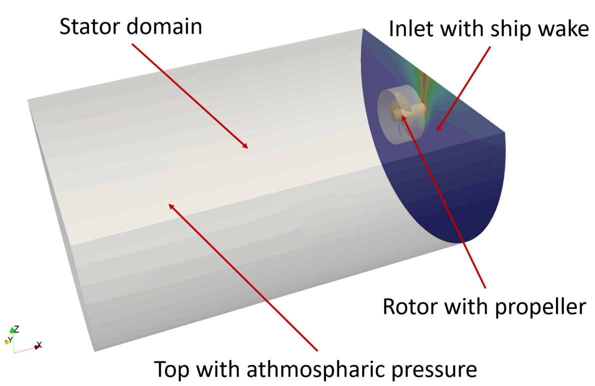

Figure 3: Simulation set up for RANS with OpenFOAM

2.3.1 FWH Approach

The FWH analogy was used according to the implementation of Wang et al. (2022a, 2022b) resulting in acoustic pressure data to be analysed as described in chapter 3. In order to calculate the acoustic pressures a coarse acoustic mesh with 12000 cells is placed around the rotor domain. The acoustic pressure in the observer points is tracked over one propeller rotation.

2.3.2 Analytical Approach

Propeller noise mainly originates in two effects. As the propeller operates behind a ship's hull it runs through a non-uniform wake inflow due to the hull's geometry and through a varying hydrostatic pressure as a function of water depth. With sufficiently high rotation speed cavitation occurs where the pressure is the lowest, meaning in the upper region of the wake field. When pressure increases, the cavity rapidly collapses. This cycle repeats with every blade passing. The change in cavity volume influences the distribution of blade rate harmonics (Averson and Vendittis 1999).
As in this study solely the propeller with sheet cavitation is investigated as a source of underwater radiated noise, it is assumed to function as a pulsating monopole sound source. The monopole acoustic pressure $p(t)$ is directly proportional to the second derivative of the change of cavity volume (Arverson & Vendittis 1999), which is given by

$$p(t) = \frac{\rho V^{''}(t)}{4\pi r}. \qquad (1)$$

where $V^{''}$ is the cavity volume acceleration, ρ is the fluid density, which is assumed to be constant, and r is the distance from the source.
From the results of the CFD RANS simulation performed with OpenFOAM the cavity volume can be extracted. The time dependent data are filtered to smoothen the waveform (see Figure 4). A python code is implemented to read the filtered data, generate a spline based waveform as an approximation of the cavitation volume over time and finally differentiate in time domain (see Figure 5).

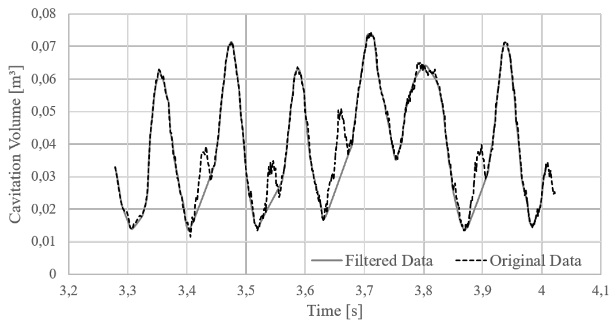

Figure 4: Cavitation volume from RANS simulation with OpenFOAM: Comparison between original and filtered data

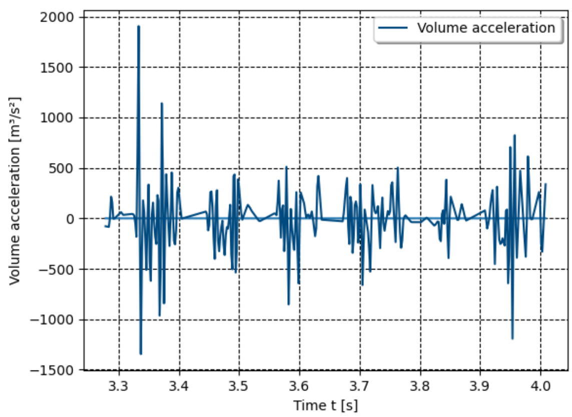

Figure 5: Cavitation volume acceleration generated by second derivative of cavitation volume by time

For the test case the sea water density is taken as $1025\ kg/m^3$. The distance varies for each measurepoint used in the simulation set up. Following equation (1), the sound pressure data for each measurepoint can be used for further evaluation.

3 EVALUATION

For each of the presented different methods predicting acoustic pressure values the results are handled as described in the following.

The acoustic pressure values of each of the measurepoints are processed via a standard Fast-Fourier-Transformation (FFT). Therefore, depending on the number of simulated propeller revolutions, the FFT algorithm is applied to the last number of revolutions being a multiple of 2^n, where n is a positive integer. Following with a Hanning window function the far-field data in frequency domain need to be transformed into sound pressure level (SPL). A reference value of $p_{ref} = 1 \cdot 10^{-6}\ Pa$ is used to transfer the acoustic pressure amplitude spectrum into SPL in decibels (dB). For full comparability of the results of the different methods the acoustic pressure data have been generated with, a normalization by distance is applied. The distance correction reveals the radiated noise level (RNL), which is mathematically given as

$$RNL = SPL + 20 \cdot log_{10}\left(\frac{D}{D_{ref}}\right)\ dB \qquad (1)$$

where D is the distance from the sound source, respectively from the ship, and $D_{ref} = 1\ m$ is the reference value for distance (IMO 2023). For a comparison of the $1/3$ octave bands the results are converted to equivalent $1\ Hz$ bandwidth.

3.1 Full-Scale Measurements

The full-scale measurement of the radiated noise from the General Cargo Ship were gained in the North Sea in a region of comparably shallow waters close to the island of Helgoland. Seabed conditions were assumed to be gravel. The measurements took place during beneficial weather and sea state conditions with no wind and minor wave height, although a strong tide current was present. As described, different operating conditions have been performed by the crew onboard ship aiming to remain a constant distance to the locally installed hydrophone. Due to the nature of maneuvering, correcting rudder movements to steer the course were necessary. These environmental conditions producing background noise have been considered in the analysis and evaluation conducted by DW ShipConsult. The results are depicted in Figure 6.

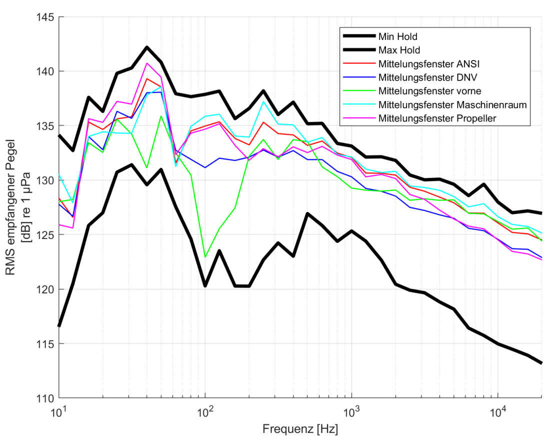

Figure 6: Results of Full-Scale Measurements: RMS sound pressures

For comparison of the received SPL by acoustic source, the acoustic signals are shown in Figure 6, which provides information as to the distribution of the far-field root-mean-square (RMS) sound pressure subject to source and frequency. Looking at e.g. the purple line, the significant hump in sound pressure between $40 - 50\ Hz$ is a common observation in full-scale measurements of merchant ships, although mostly for container vessels rather than general cargo vessels. Figure 6 conveys the dominant role of the propeller in the overall radiated noise alongside the engine room. Generally speaking, at higher speeds the propulsion related sources are dominant in the ship's radiated noise. In the light of this paper, the focus is laid on the propeller radiated noise. Therefore, considerable data with regards to the RMS sound pressure shall be highlighted: The peak value is reached at $50\ Hz$ with 140.7 dB $re\mu Pa$, followed by an instant decrease at around $68\ Hz$, which represents the 8^{th} multiple of the blade frequency. Over the higher frequencies the RMS sound pressure consistently decreases at a slow rate.

3.2 Numerical Methods

3.2.1 panMARE and FWH

For evaluation of the acoustic pressure data generated with the described panel code in combination with the FWH method the last 12 simulated propeller revolutions are considered for the application of the FFT algorithm. This results in a narrow frequency range from $0 - 100\ Hz$ that can be mapped and compared to other results. In regard to a comparison with limiting curves given by classification societies and the frequency range used by marine life for communication, the small frequency range limits the evaluation of the propeller induced noise. For this paper, only sheet cavitation has been simulated. As vortex cavitation is assumed to mainly show in and influence higher frequencies, a coupling of a method taking vortex cavitation effects into account with the hybrid model of *panMARE* and FWH analogy is proposed to be investigated further.

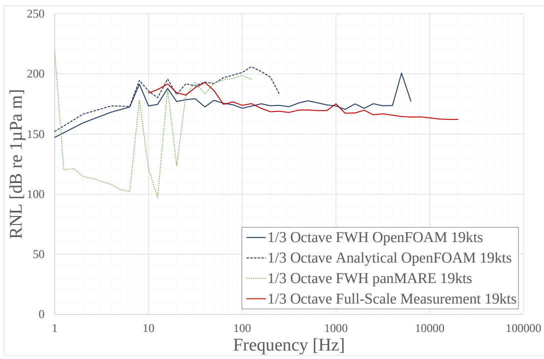

Figure 7: Comparison of $1/3$ Octave bands of full-scale measurement data with URN predicted with presented methods

The resulting $1/3$ octave band presented in Figure 7 shows the characteristic distribution of RNL generated with the hybrid method. Significant peaks show at blade frequency harmonics. It appears, that the RNL is not highest at blade frequency as assumed. Within the presented frequency range the maximum RNL peaks at 100 Hz with 198 dB $re\mu Pa$. The trend of the predicted radiated noise level is difficult to decipher as the data range ends after its peak. In the narrow range of comparable frequencies, the hybrid method does show a certain correlation with full-scale measured RNL, although increasing towards frequencies over 50 Hz. Furthermore, the characteristic hump cannot be seen in the dataset.

3.2.2 OpenFOAM and FWH

Due to high computational effort, approximately one propeller revolution has been simulated. For each measurepoint in the far-field the acoustic pressure data for one revolution are processed via the Hanning window function for the application of FFT. It is common knowledge that the quality of FFT increases and results are more refined with an increased number of evaluated periods. Therefore, a careful extension of the dataset processed through a window function becomes necessary. As this was not done in the process of this paper, it remains subject for further investigations.

Following the coupled procedure proposed by Wang et al. (2022a) acoustic pressure data can be directly used for further post-processing. The resulting $1/3$ octave band is presented in Figure 7. The first harmonics of the blade frequency are significantly apparent. As supposed and contrary to the results generated by panel code method the peak at blade frequency (8.6 Hz) illustrates the highest RNL with a value of 191 dB $re\mu Pa$. Equally to the panel code predicted RNL, the current sound pressure data do not display a hump at 50 Hz. The peak RNL at around 5000 Hz is understood as a numerical anomaly. Besides, the graph shows a steady trend to slowly decrease in radiated noise level in good correlation to the results of the full-scale measurement.

3.2.3 OpenFOAM and Analytical Approach

The posed difficulty of post-processing of the underlying RANS simulation results over solely one propeller revolution is as well applicable to the coupled approach with the analytical evaluation. Furthermore it has to be considered, that the chosen measurepoints are mirror-symmetric to the ship's centerline. Therefore, a disadvantage of equation 1 compared to the hybrid method is the neglect of the side of blade entry into or blade exit from the wake field dent as the equation solely takes the distance itself into account.

For the lower frequency the RNL derived from cavitation volume shows good correlation to results generated with the method of Wang et al. (2022a). Peak value at blade frequency accounts for 194 dB $re\mu Pa$, which is only 3 dB $re\mu Pa$ lower than the peak value from FWH analogy. This seems plausible as the results were generated from the same RANS simulation. Nonetheless, the graph shows quite different behavior for higher frequencies above 20 Hz. Surprisingly, the graph subsequently shows good correlation with results from the hybrid panel code method using the FWH analogy. In contrast to that, the RNL shows a downward trend above 100 Hz. Figure 8 indicates the radiated noise level after distance normalization for the aforementioned methods to predict underwater radiated noise of propellers. The observations made for the $1/3$ octave bands are underlined by the distribution shown in Figure 8.

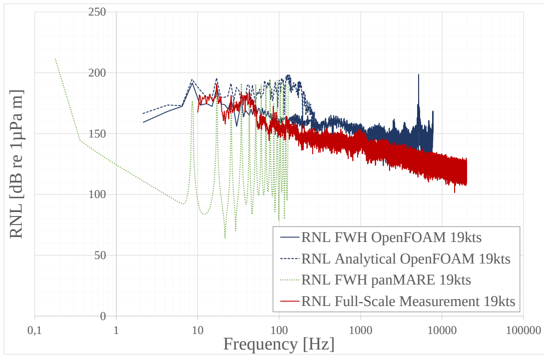

Figure 8: Comparison of full-scale measurement data with RNL predicted with presented methods

4 CONCLUSION

The study of three different methods to predict the underwater radiated noise of a cavitating controllable pitch propeller in a high speed operating condition concludes with an ambivalent impression on the applicability of one of the presented methods. Uncertainties remain in regards to the acoustic evaluation due to distinct discrepancies between full-scale measurements and numerically and analytically predicted URN. Thus, only an approximate conclusion can be made respectively to the practicalness within the design process.

The hybrid method consisting of sound pressure data derived through FWH analogy from simulations based on panel code distinguishes itself due to principally low computational effort. On the contrary, there is a great limitation of frequency range, narrowing the applicability down to research instead of commercial projects. The high discrepancy in results compared is surprising as experience showed good reliability when recalculating existing full-scale measurements. It is assumed that the chosen controllable pitch propeller shows unusual behavior within the panel code method. With the extension of the method by integrating vortex cavitation, the coupling of *panMARE* and the FWH analogy seems to be the most feasibly acoustic signals predicting method.

Wang's et al. (2022a) method for volumetric integration of FWH shows the best correlation with the validation basis consisting of the full-scale measurement data. The results ranging up to high frequencies as well as the extensive information that can be extracted from the simulation results are distinct advantages. In contrast, the high computational effort prevents the integration into the early stages of the design process. The usage within time-uncritical projects as well as in the detailed design process is encouraged.

The analysis of the cavitation volume and subsequently the

analytical derivation of the volume acceleration and therefore the acoustic pressure shows surprisingly good results for the lower frequencies. As the higher frequency ranges are more of interest, it could be beneficial to optimize the analytical post-processing with regards to the used derivation function and artificial extension of the dataset. Computational effort wise the method does not differ from the dual mesh using numerical approach proposed by Wang et al. (2022a).
It is proposed to further investigate a defined number of additional propellers for solidified assessment of the reliability of each method.

5 ACKNOWLEDGEMENT

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