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Effect of waves on cavitation and pressure pulses

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ABSTRACT

In view of environmental concerns, there is increasing demand to optimize the ships for the actual operating condition rather than for calm water. Now, in order to apply this for propeller design, a first step would be to study the effects of waves on propeller operation. Therefore, the aim of this paper is to identify and quantify the effect of various factors affecting the propeller in waves. The performance of KVLCC2 propeller in the presence of three different waves has been compared with calm water performance. Changes in performance in terms of cavitation, pressure pulses, and efficiency have been studied. Significant increase in pressure pulses has been observed due to wake change in waves even though cavitation did not show any significant change. An analysis using cavitation bucket diagram in different wave conditions indicates that a propeller optimized for calm water wake may perform much worse in the presence of waves. Therefore, having wake variation at least in critical wave conditions (where the wavelength is close to ship length) in addition to calm water wake could be very useful to ensure that the propeller performs equally well in the presence of waves.

1. Introduction

Traditionally, propellers have been optimized for calm water conditions partly because one has not had the knowledge and tools to optimize propellers for operations in waves. However, with increasing environmental concerns and emission regulations, there is growing demand for the propulsion being optimized for the actual operating conditions, which typically include waves.

Currently, propellers are designed using wake, thrust deduction and relative rotative efficiency obtained in calm water conditions. Moor and Murdey [1] have shown through model tests of multiple ship hulls in calm water and in waves that wake, thrust deduction and propeller efficiency change in the presence of waves. Circumferentially averaged wake also changes due to waves and ship motions as demonstrated by Nakamura and Naito [2]. They also found that wake velocities increase in waves, and it is primarily caused due to pitching motion of the ship. Similar results confirming significant wake variation in waves were obtained in the RANS simulation carried out by Guo et al. [3] where the nominal wake field was obtained in the presence of waves. In these simulations, the axial wake velocities increased with up to 35% of ship speed in some regions. Such changes in the wake distribution of a ship traveling in waves were experimentally confirmed by Hayashi [4] using a model of the KVLCC2 ship. Strong variation of wake was observed in the presence of waves through the PIV (Particle Induced Velocimetry) measurements.

Change in wake distribution changes the angle of attack and the cavitation number of the propeller blades as shown by Albers and Gent [5]. Chevalier and Kim [6], Jessup and Wang [7] studied the cavitation of a propeller operating in waves by calculating wake velocities using potential flow calculations and observed a drop in the cavitation inception speed of the vessel in waves.

Due to increasing demand for efficiency, it is no longer possible to design the propellers without cavitation. Cavitation can lead to erosion on the propeller blades. Moreover, the pressure pulses can cause vibration in the ship structure thus affecting passenger comfort and in severe cases damage the structural integrity of the hull. In merchant ships, about 10% of propeller-induced vibration velocities are caused by bearing forces, whereas approximately 90% are due to pressure fluctuations, or hull surface forces [8]. Survey of 47 ships with vibration problem has shown that around 80% of the cases could be traced back to pressure pulses as a source of vibration problems. Based on reported cracks in the aft peak of 20 ships, strong correlation between fatigue damages in the afterbody and the amplitude of pressure pulses at blade harmonic frequency was observed [9]. Therefore, it is necessary to avoid cavitation erosion

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Table 1
Propeller Geometry.

Diameter (D) (m)	9.86
No of blades	4
Hub diameter (m)	1.53
Rotational speed (RPM)	76
A_e/A_0	0.431
$(P/D)_{mean}$	0.690
Skew (°)	21.15
Rake (°)	0

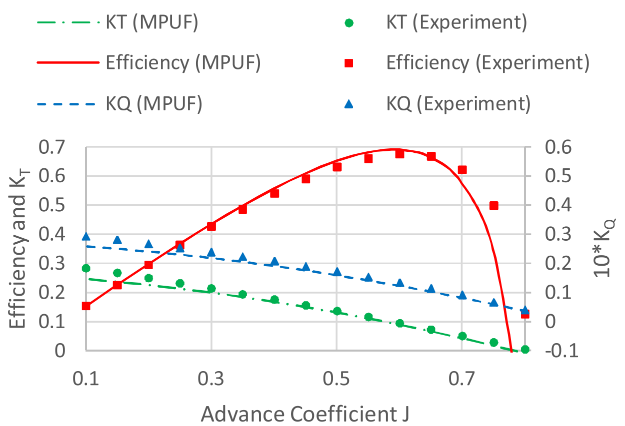

Fig. 1. Comparison of open water data of KVLCC2 using MPUF-3A and model tests.

and high pressure pulses even when the cavitation is present. It is achieved by adapting the propeller design to calm water wake as cavitation and pressure pulses depend on the wake distribution [10,11]. However, given the significant wake variation, it is essential to investigate the performance of propeller in the presence of waves. Moreover, lowering the pressure pulses comes at the expense of efficiency. Therefore, accurate estimation of pressure pulses in realistic operating condition can help us maximize the efficiency while still avoiding the unwanted consequences.

In this paper, we have analyzed the performance of the KVLCC2 propeller operating in waves. Time-varying wake data in three different head waves provided by Sadat-Hosseini et al. [12] have been used. Effect of various factors affecting propeller performance in waves like wake change, ship motions, wave dynamic pressure, added resistance and RPM fluctuation has been studied separately to decide the order of importance of each factor. Cavitation and pressure pulses have been calculated in different wave conditions and compared with that in calm water wake. An analysis of propeller blade sections using a cavitation bucket diagram was performed to explore the possibility of improving propeller design to ensure optimized performance not just in calm water but also in the presence of waves.

2. Methods and validation

2.1. Propeller analysis tools

The KVLCC2 propeller has been analyzed using the vortex lattice method implemented in MPUF-3A [13]. Details about the propeller geometry are given in Table 1 [14]. The fine grid has been used on the key blade while coarse grid has been used on other blades. Open water curves obtained using MPUF-3A for the KVLCC2 propeller are compared with experimentally obtained open-water data [14] in Fig. 1. When the propeller was analyzed in waves, the variation in inflow caused by waves and ship motions is taken into account in a quasi-steady manner, meaning that for each time instant, the flow field entering the propeller disk is treated as time-invariant. The propeller is then analyzed at each time instance in time-invariant wake using unsteady calculations. This approach is justified by the fact that the wave encounter frequency is much lower than the propeller rotation frequency.

Table 2
Ship Particulars.

Length between perpendiculars (m)	320.0
Length at water line (m)	325.5
Breadth at water line (m)	58.0
Depth (m)	30.0
Draft (m)	20.8
Displacement (m^3)	312,622
Block coefficient (C_B)	0.8098
Design Speed (knots)	15.5

For the analysis of propeller blade section in calm water and in waves, the lift coefficient has been obtained for the propeller blade section at 0.7R from MPUF-3A calculations. Cavitation bucket has been calculated by giving the blade section shape at 0.7R as an input to Xfoil [15]. While cavitation number (Sigma) is calculated as follows-

$$\text{Sigma} = \frac{P_0 + \rho g h - P_v}{0.5\rho[V_a^2 + (0.7\pi n D)^2]}$$

where P_0 is atmospheric pressure, ρ is the density of water, g is acceleration due to gravity, h is the instantaneous submergence of the blade section at 0.7R, P_v is the vapour pressure of water, V_a is average propeller inflow velocity, n is propeller rps and D is diameter of the propeller. It should be kept in mind that since both h and V_a varies in waves, the cavitation number varies with time.

2.2. Wake data in the presence of waves

Experiments were performed by Sadat-Hosseini et al. [12] to obtain wake data in three different wavelengths in head sea condition at design speed. A model of KVLCC2 was used for this purpose with the model scale of 1:100. Ship particulars are given in Table 2 [14]. In these experiments, PIV (Particle Image Velocimetry) was used to obtain time-varying nominal wake field in the propeller plane. CFD simulations were also performed and results were validated using the data from the PIV measurements. Since the CFD data are smoother and less noisy, we have used them in our calculations. These results were available for waves λ/L = 0.6, 1.1 and 1.6 at 8, 12 and 6 time intervals respectively in one wave encounter period. Wakes at different time intervals have been denoted by t/T, which is a fraction of time 't' in one wave encounter period 'T'. Note that 'T' is different in each wave case. At t/T = 0 the wave crest is located at the forward perpendicular of the ship. Waveheight of these waves corresponds to a full-scale wave amplitude of 3m. Wake fields in calm water and at four instances in λ/L = 1.1 can be seen in Fig. 2.

Due to the higher friction coefficient of the model scale ship, the wake field calculated in model scale should be contracted (scaled) for analyzing the propulsion performance in full scale. However, it is not uncommon that propellers are evaluated in model scale wake as far as pressure pulses are concerned. It is partly because the model scale hull is used in the tests carried out in the cavitation tunnel for the measurement of pressure pulses, which means that the propeller is analyzed in model scale wake to prove that the pressure pulses in full scale are within the contractual requirements. The general experience is that analyzing the propeller in model scale wake gives a conservative estimate of cavitation and pressure pulses.

The analysis in model scale wake also avoids the complexity and uncertainty of the wake scaling procedure. Moreover, for this study, it is more important to compare the propeller cavitation and pressure pulses in calm water with that in waves than predicting