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Analysis of Propulsion Performance of KVLCC2 in Waves

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ABSTRACT

In this paper, we have analyzed the propulsion performance of KVLCC2 in presence of waves. Different factors affecting the propulsion performance have been studied. Analysis of the extent of change in wake quality and its effect on the cavitation of propeller has been presented. Effect of wake change alone was separately calculated to analyze its importance in the design process, as wake data in waves is usually not available. It was observed that wake change itself does not significantly affect the amount of cavitation hence; cavitation margin should be considered only to handle increased load and relative stern motion.

Keywords

Cavitation Analysis in Seaway, Propeller in Waves, Performance in Off-Design Conditions.

1 INTRODUCTION

Currently, propellers are designed using wake, thrust deduction and relative rotative efficiency obtained in calm water conditions. These factors vary when ship is subjected to waves (Moor and Murdey 1970). Wake distribution also changes due to waves and ship motion (Nakamura and Naito 1975). Similar results were obtained in the RANS simulation carried out by Guo, Steen et al. (2012) where the nominal wake field was obtained in the presence of waves. In this simulation, axial wake velocities increased up to 35% of ship speed in some regions. Such changes in the wake distribution of a ship travelling in waves were experimentally confirmed by Wu (2013) using KVLCC2 ship model. PIV measurements of wake field found strong variation in presence of waves.

In view of this recently obtained data, which demonstrates significant effect of waves on wake, a possible drop in the performance of the propeller should be calculated. Full-scale experiments performed by Kayano, Yabuki et al. (2013) found a discrepancy between the calculated and obtained performance of the ship. This can be due to inability of prediction methods to take into account the effect of waves on the propulsion performance. Currently, off-design conditions are covered by simple sea margin, which may result in overdesign or failure in off design conditions. Therefore, previously considered assumptions and margins should be revisited and updated by detailed knowledge of propeller performance in waves.

Along with the efficiency of the propeller, cavitation and vibration characteristics should be studied in presence of waves as they depend on the wake distribution (Odabasi and Fitzsimmons (1978) and Huse (1974)). Moreover, a change in wake distribution changes the angle of attack and the cavitation number of the propeller blades as shown by Albers and Gent (1985). Chevalier and Kim (1995), Jessup and Wang (1996) studied the cavitation of a propeller operating in waves by calculating wake velocities using potential flow calculations. Drop in the cavitation inception speed of a vessel was observed in waves.

The cavitation characteristics of propellers designed using calm water wake data must be studied in order to validate currently used cavitation margins, so that future propellers can be designed for low cavitation and noise along with acceptable performance even in rough weather.

In this paper, we have evaluated the performance of the KVLCC2 propeller operating in waves. Time varying wake data in three different wavelengths provided by Sadat-Hosseini, Wu et al. (2013) have been used. The effect of waves on changes in the angle of attack and the cavitation number of propeller blade sections has been studied. The effect of wake change and relative stern motion has been separately observed to decide the order of importance of each effect. The effect of this time varying wake on vibration and noise characteristics of the propeller has been calculated using the BSRA wake criteria given by Odabasi and Fitzsimmons (1978). Other possible factors causing changes in propulsion performance in waves have been noted.

2 METHODS AND VALIDATION

2.1 Wake Data in Presence of Waves

Experiments were performed by Sadat-Hosseini, Wu et al. (2013) 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 model scale of 1:100. Ship particulars are given in Table 1 (SIMMAN 2008). 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 existing data from PIV experiments. Since the CFD data are smoother and less noisy, we have used them in our calculations. These results were available for waves $\lambda/L =$ 0.6, 1.1 and 1.6 at 8, 12 and 6 time intervals respectively in one wave period. Waveheight of these waves correspond to the full-scale waveheight of 3m.

Table 1 Ship Particulars

Length beween 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)	312622
Block coefficient (C_B)	0.8098
Design Speed (m/s)	7.97

Table 2 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

2.2 Wake Quality Assessment

In the preliminary investigation of the wake data in waves, the quality of wake was assessed and compared with the quality of the calm water wake using the BSRA wake criteria proposed by Odabasi and Fitzsimmons (1978). These criteria are based on a large collection of wake distribution data and noise and vibration characteristics of full-scale ships. Five conditions are mentioned for assessing the wake. Although satisfying these conditions does not guarantee good vibration and noise characteristics, it is recommended to be extra careful when the conditions are not met. For our purpose, these simple criteria are useful to assess the extent to which waves can affect vibration and noise characteristics without using any particular propeller geometry.

2.3 Wake Contraction Method

For further investigation of the performance of the propeller operating in waves, scaling of wake data from model scale to full scale was required. According to ITTC (2011), the wake scaling procedure given by Sasajima, Tanaka et al. (1966) is most commonly used and gives reasonable results. In this method, only viscous wake is scaled and a correction is applied to the potential component. However, in the absence of potential wake data, we have contracted the whole wake field towards the center plane by the ratio of viscous resistance coefficient between model and full scale. Hence, the difference between potential wake component of model and ship has been neglected.

Potential wake is almost constant in a horizontal section in the propeller plane as seen from the typical ship scale wake presented in ITTC (2011). In such cases, the same full-scale total wake would be obtained by scaling the total wake or just the frictional component of the model-scale wake. The only error would be due to the neglected correction in the potential wake.

2.4 Software Validation Using Existing Data

After the initial wake assessment, a detailed study of propeller operating in presence of waves was performed. Existing KVLCC2 propeller design was analyzed in time varying wake. Details about propeller geometry can be seen in Table 2 (more details can be obtained from SIMMAN (2008)). The open source program Openprop based on vortex lattice lifting line theory (Epps 2010) has been used for this purpose.

Openprop requires blade section details, corresponding frictional drag coefficient, advance coefficient, axial and tangential wake velocities and at each radial location for the analysis. Blade section details can be found in SIMMAN (2008). *Javafoil* was used for the calculation of frictional drag at each radial section for the given Reynolds number. It uses panel method to calculate velocity profile and pressure distribution over the foil section. Using these pressure and velocity distributions, boundary layer calculations are performed where drag is calculated using momentum loss in the boundary layer (Hepperle).

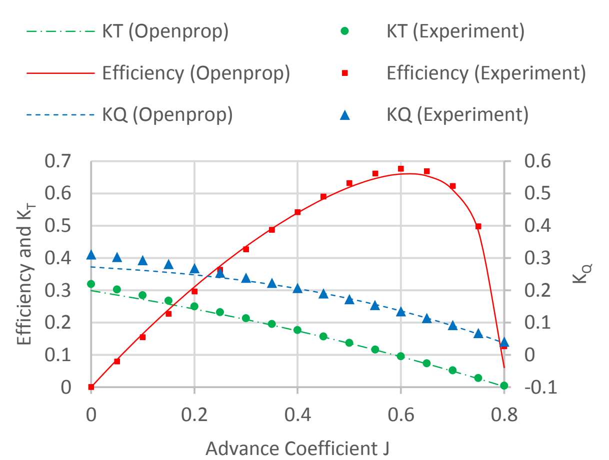

Figure 1 Comparison of Openprop and open water data of KVLCC2 propeller

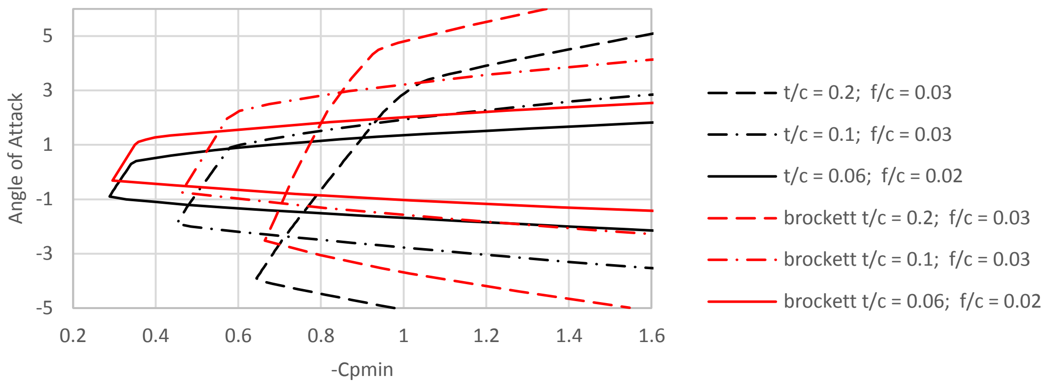

Figure 2 Comparison of cavitation bucket diagrams obtained from Openprop with those calculated by Brockett (1966)

Openprop is based on steady lifting line theory. As we know, a propeller operating even in calm water condition faces time varying inflow due to spatial variation of wake. Such cases should ideally be analyzed with unsteady calculations. Gaggero and Brizzolara (2009) have shown that a quasi-steady approach also gives good results compared to fully unsteady calculations. In their research, the quasi-steady approach was seen to correctly predict the change in thrust, torque and efficiency between propeller and its modified version. Hence, we have used quasi-steady approach for our analysis. Openprop analyzes propeller in a steady flow with only radial wake variation, however, in reality there is angular as well as radial variation of wake. Hence, performance of the propeller with four blades facing different radial wake distribution was assumed to be the average performance of four hypothetical propellers, each facing the radial wake distribution faced by each blade.

Performance of Openprop with frictional drag obtained from *Javafoil* was validated by comparing open water characteristics with the experimental data. Thrust, torque and efficiency in open water condition obtained using this approach match well with the experimental data as can be seen from Figure 1.

Openprop has also been used to predict the cavitation on the propeller blades. In order to calculate the cavitation, pressure distribution over the foil has been calculated using linear foil theory; possible effects of viscosity have been neglected. Areas where pressure falls below the vapor pressure is assumed to cavitate. The cavitation bucket can be obtained by observing the angle of attack and cavitation number at which cavitation starts. Cavitation buckets were plotted for foils with three different combinations of camber and thickness. These plots were compared with those obtained by Brockett (1966) where minimum pressure envelopes were calculated for steady two dimensional flow with an empirical correction for the viscosity. There is discrepancy in the exact values of the angle of attack where cavitation inception is predicted. However, Openprop correctly predicts the cavitation inception trends as seen in Figure 2. Even though more complicated and accurate theories like lifting surface theory and cavitating foil theory are available to predict exact cavitation pattern, change in efficiency, thrust and torque of a cavitating propeller; we have used this simple theory since we are interested in comparing the performance of a propeller in waves with that in calm water, rather than very accurately predicting the performance in cavitating condition. Thus, correct prediction of trends would serve the purpose.

While calculating the cavitation pattern, depth variation of the propeller due to ship motion was also taken into account. Relative stern motion was calculated using the motion response of the ship. All the analysis was performed at constant rpm. Hence, variation of rpm due to time varying torque was neglected in the analysis, which may cause some inaccuracies.

3 ANALYSIS

3.1 Wake Assessment in Presence of Waves

Vibration and noise characteristics of a propeller depend on the wake field in which it operates. Odabasi and Fitzsimmons (1978) have listed certain criteria to be fulfilled by the wake distribution for low noise and vibration. Time varying wake in waves will now be compared with the calm water wake field considering four out of five BSRA wake criteria.

Criterion 1 –

The maximum wake measured inside the angular interval $\theta_B = 10 + 360/Z$ degrees and in the range $0.4 - 1.15R$ around the top dead center position of the propeller disc should satisfy the following:

$$Wmax < 0.75 \; or \; Wmax < C_B$$

whichever is smaller. Where Z is the number of blades. $Wmax$ has been obtained at given locations at different times in one wave period to compare with the value observed in calm water. Values greater than that in calm water can increase vibration and noise.

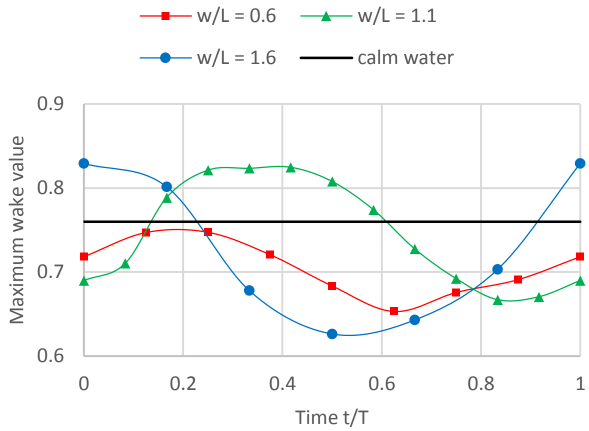

Figure 3 Comparison of wake peak observed in waves and in calm water

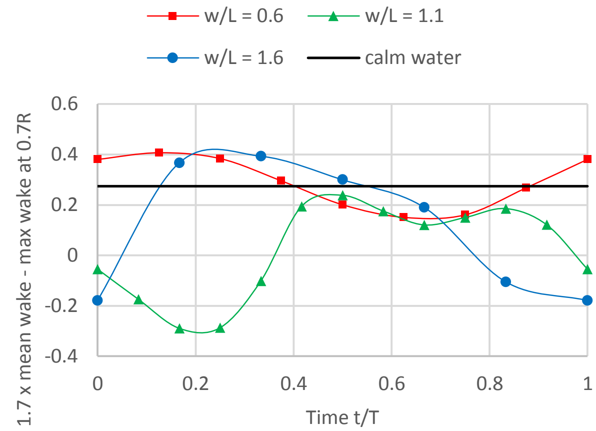

Figure 4 Comparison of wake with respect to criterion 2

Variation of $Wmax$ in different waves can be seen in Figure 3. When the wave is shorter than the ship, the maximum value of wake is always smaller than in calm water. In the longest wavelength, only few values are greater than that in calm water. While, when wavelength is close to ship length, $Wmax$ in wave is higher than that in calm water for almost 50% of the time as seen from Figure 3. Hence, this condition is not greatly affected due to waves except in case of wavelength close to ship length.

Criterion 2 –

The maximum acceptable wake peak should satisfy the following relationship with respect to the mean wake at $0.7R$:

$$Wmax < 1.7\overline{W}_{0.7}$$

Therefore, $(1.7\overline{W}_{0.7} - Wmax)$ was plotted in different wavelengths, at different times in time varying wake and compared with the calm water condition (Figure 4). Value of this variable should be positive for the criterion to be satisfied.

Figure 4 shows that this condition would be most stringent if it is to be satisfied in wavelength $\lambda/L = 1.1$. Since, all the values of $(1.7\overline{W}_{0.7} - Wmax)$ are lower than that in calm water and many of them are negative. Also in the wavelength $\lambda/L = 1.6$, values lower than that in calm water are observed for almost 50% of the time period. Hence, in case of designs where this condition is just satisfied in calm water, its violation is highly probable in presence of waves. This gives us an idea about the margin to be considered while satisfying this condition in realistic sea when only calm water wake data is available.

Criterion 3 –

Wake non-uniformity criterion is important to avoid unsteady cavitation and high levels of pressures on the hull. In this criterion, tip cavitation number is plotted against average non-dimensional wake gradient. Tip cavitation number is defined as-

$$\sigma_n = \frac{\left(9.903 - \frac{D}{2} - Z_p + T_A\right)}{0.051(\pi n D)^2}$$

while average non-dimensional wake gradient is defined as $(\Delta w/(1-\overline{w}))$, where D is the propeller diameter (m). Z_p is the distance between the propeller shaft axis and the base line (m). T_A is the ship's draught at the aft-perpendicular (m). n is the propeller rotational speed (rev/s). Δw is the wake variation. Plotted point should lie above the dividing line of Figure 5 to satisfy the criterion.

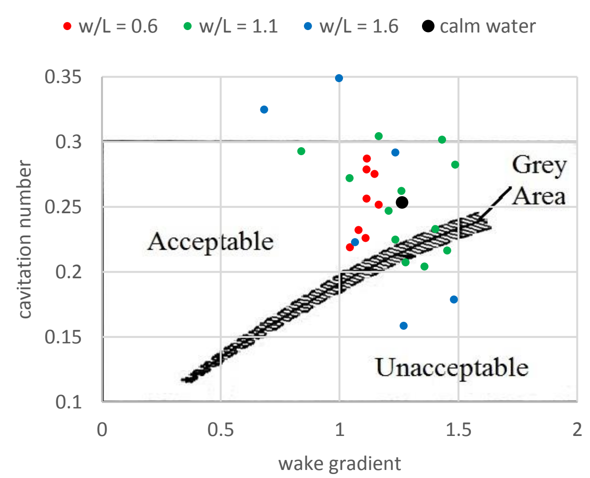

Figure 5 Wake non-uniformity criterion

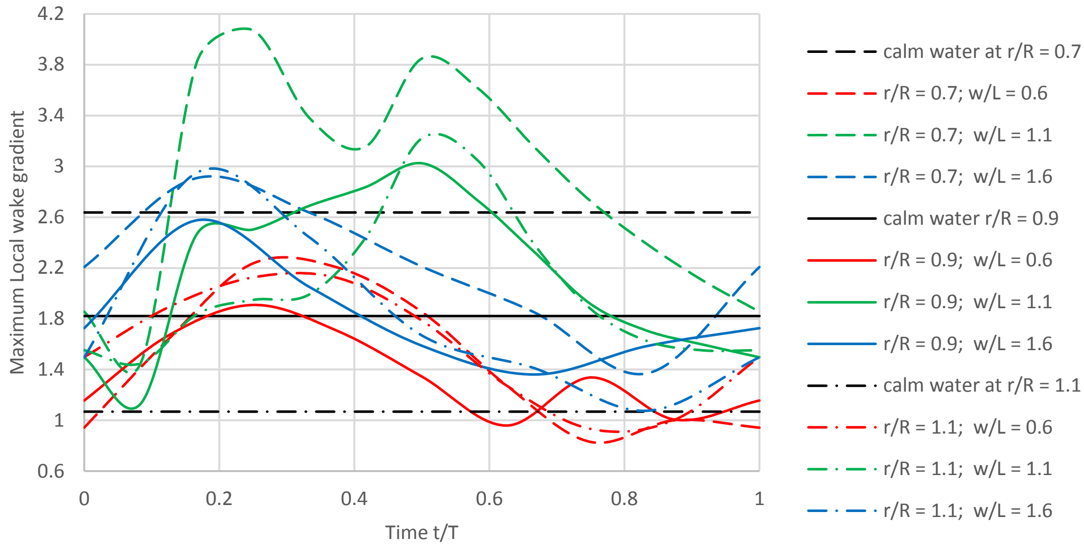

Figure 6 Maximum wake gradient at different time intervals in three different wavelengths

Figure 5 shows the plot for this criterion in three different head waves. Variation in cavitation number is due to change in the submergence of the propeller due to ship motion while change in the horizontal axis variable (wake gradient) is due to wake variations in waves. Wake gradient is becoming favorable (i.e. less) in more cases than in those it is getting worse than the calm water value. Some values are present in the unacceptable region, which may cause intermittent cavitation and vibration while ship is travelling in waves. Figure 5 also provides the information about the extent to which waves can worsen the cavitation and vibration characteristics of the propeller. Therefore, appropriate cavitation margin can be considered for the calm water design to have acceptable cavitation and vibration performance in waves.

Criterion 4 –

For the propellers susceptible to the cavitation, that is near the grey area of Figure 5, the local wake gradient per unit axial velocity for radii inside the angular interval θ_B in the range of $0.7 - 1.15R$ should be less than unity; that is,

$$\frac{1}{\left(\frac{r}{R}\right)}\left|\frac{\left(\frac{dw}{d\theta}\right)}{(1-w)}\right| < 1.0$$

where θ is in radians.

This criterion limits the wake gradient in order to reduce volume variations of the cavity. It is required only when the relation between wake gradient and cavitation number lies in the grey area in Figure 5. However, here we are more interested in comparing quality of wake in waves with calm water wake. Hence, local wake gradient for unit axial

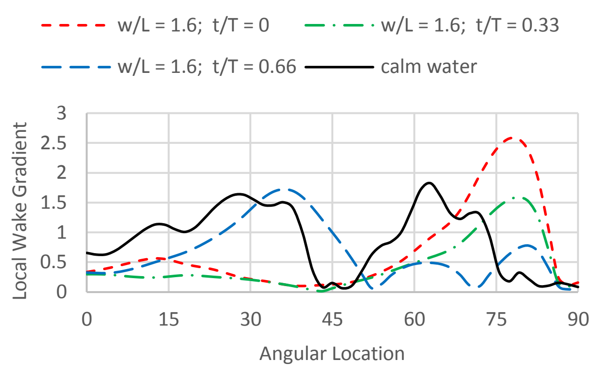

Figure 7 Wake gradient at w/L=1.6 at different time intervals as a function of angular position

velocity was calculated (Figure 7) and maximum value was obtained in the angular interval θ_B in the range 0.7R to 1.15R. This maximum value obtained at different time intervals of wave period is plotted in Figure 6.

As seen in Figure 6, from 0.7R to R, in wave $\lambda/L = 0.6$ values of wake gradient hardly exceed corresponding calm water value. While in wavelengths $\lambda/L = 1.1$ and 1.6 local wake gradient is higher than calm water value for approximately 66% and 33% of the time respectively. At r = 1.1R almost all the wake distributions in waves show higher local gradients. Amount of exceedance, whenever it occurs is considerable. Moreover, in this case, all the values including those in calm water exceed the criterion limit, i.e. all values are greater than one. Therefore, points lying in grey or unacceptable region in Figure 5 are the cause of concern. Since, unstable cavitation in large wake gradient can cause significant amount of noise due to the cavity volume

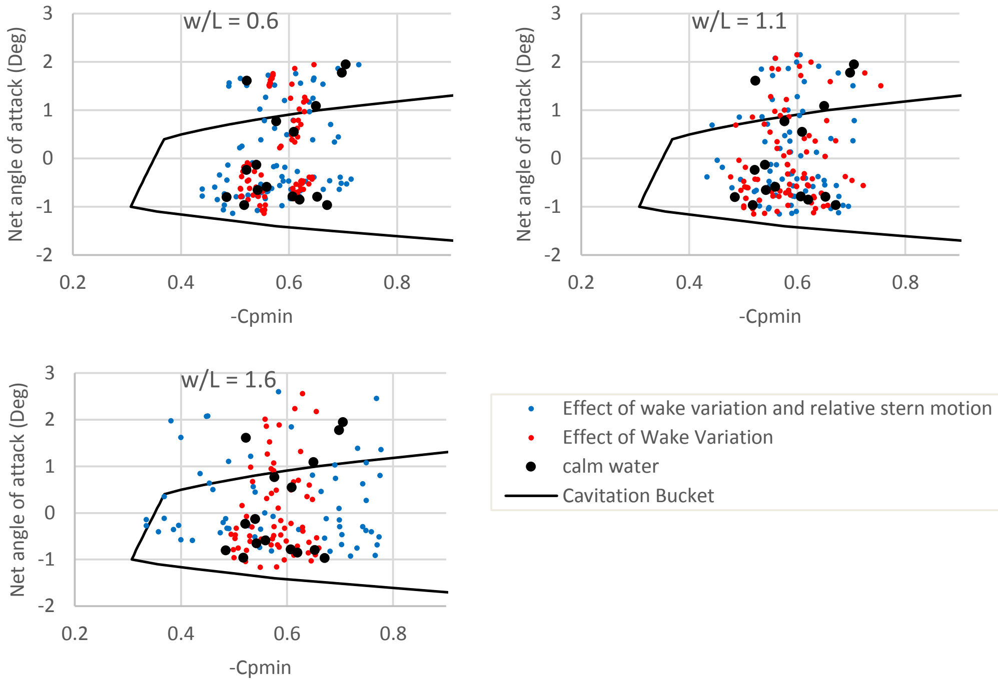

Figure 8 Cavitation number and angle of attack faced by propeller blade section at 0.7R in calm water and in waves

variation. Radial section r/R = 1.1 is analyzed since there is chance of wake at that location coming in way of propeller due to propeller action (contraction of stream tube).

3.2 Propeller Analysis Using Openprop

After analyzing the wake quality, propeller geometry of KVLCC2 ship was examined in time varying wake using Openprop. As noted earlier, significant change in the wake, observed in presence of waves is expected to affect the operation of wake-adapted propellers. Although wake assessment gives some idea about possible cavitation, examining the propeller geometry can reveal additional details like changes in the type and the extent of cavitation, thrust and torque fluctuations. Therefore, performance of the propeller in waves was compared with that in calm water.

3.2.1 Effect of Waves on Cavitation

Propeller cavitation is affected by the following factors in the presence of waves:

1. Relative stern motion causing change in the cavitation number
2. Change in wake field leading to alteration of inflow velocities and blade angle of attack
3. Added resistance causing increased propeller loading

Out of these three, relative stern motion and added resistance of ship can be estimated at the design stage, while considering the effect of wake change is tough. Wake in waves can be obtained either experimentally or computationally. Experimentally finding time varying wake is not a common practice, it would require specialized instruments like PIV. Moreover, multiple runs would be required to find wake in different wavelengths. Computationally finding wake variation in waves is also expensive. Therefore, it is important to know the extent to which the wake change alone influences the propeller performance, especially due to significant changes in the wake field observed in presence of waves.

Therefore, propeller design was analyzed in time varying wake using the method based on the lifting line theory. These calculations were also used to predict the extent of cavitation on the propeller blade along with thrust and torque fluctuations in different conditions.

Cavitation Number and Blade Angle of Attack –

While designing the propeller, the knowledge of variation in the angle of attack and cavitation number is important to choose correct blade thickness. However, certain cavitation margin has to be assumed for possible off design conditions including the ship operation in rough sea, as wake in waves is rarely available. Therefore, since wake data in waves is available in this case, the correctness of cavitation margin has been analyzed further. This would help propeller designers to estimate the change in the extent of cavitation in presence of waves as compared to the calm water condition.

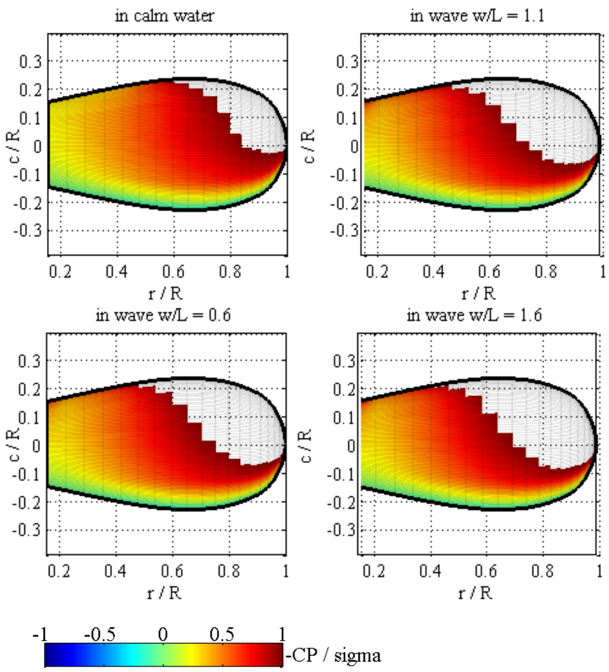

Figure 9 Propeller cavitation in different conditions

Cavitation characteristics of the propeller were examined in presence of waves. Cavitation numbers and angle of attacks faced by the blade section at 0.7R were plotted along with the cavitation bucket of the blade section. Plotted points for the calm water condition correspond to sixteen different angular positions of the blade as it rotates in the calm water wake. While points in waves correspond to eight different angular positions of the blade at ten different time intervals in one wave period. This can be seen in Figure 8.

In Figure 8, influence of wake change and relative stern motion was analyzed while effect of added resistance was not considered. Out of these two, relative stern motion only affects the range of –Cpmin and not angle of attack; since it affects only cavitation number. While, wake change can affect both the variables. Spread in the values of –Cpmin is predominantly due to relative stern motion. In all 3 cases, the effect of wake variation does not decrease the minimum value of –Cpmin seen in calm water. Maximum of half a degree increase in angle of attack can be seen due to wake variation only in wavelength w/L = 1.6. In other two waves, no significant change in maximum or minimum angle of attack is observed. Similar trends were observed at other blade sections as well.

Cavitation Due to Wake Variation –

Due to wake variation alone, there is no increase in the range of cavitation numbers while angle of attack increases slightly in some cases as compared to the calm water condition. Influence of this slight increase in the angle of attack (only due to wake variation) on the extent of cavitation can be seen in Figure 9 where maximum amount of cavitation in each condition has been plotted. No significant change in cavitation is seen due to the effect of wake variation. This observation is in line with the earlier result of cavitation bucket diagram. Since spread of operating points is similar to the one obtained in calm water wake, similarity in the extent and pattern of cavitation is expected.

These results obtained using quasi-steady approach were validated using fully unsteady simulations with cavity volume calculations. The unsteady panel method software AKPA, developed by MARINTEK and University of St. Petersburg, was used to simulate the propeller in calm water

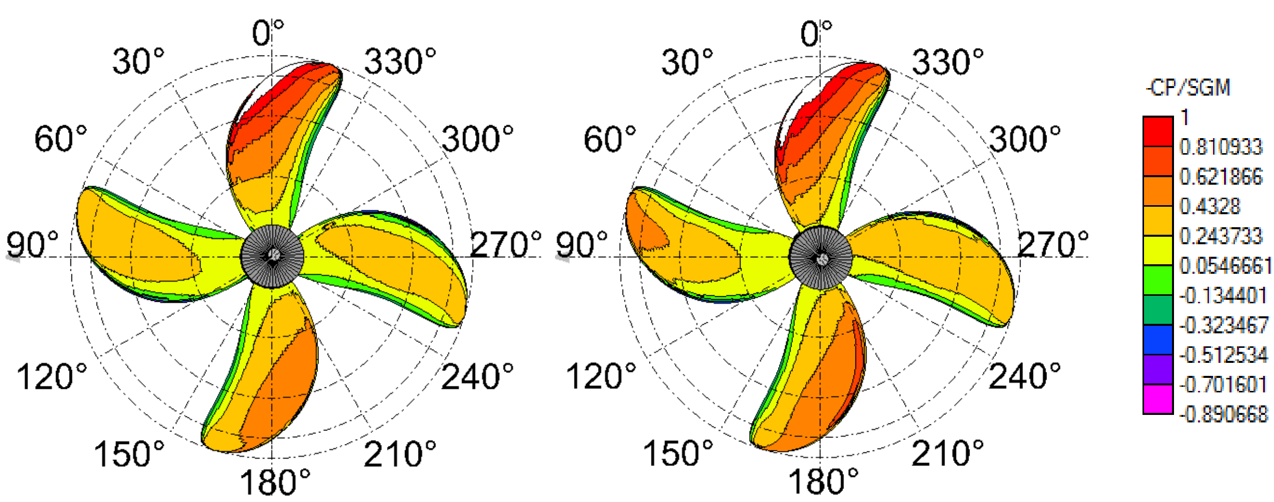

Figure 10 Unsteady simulation results of propeller in calm water and in wave

wake and in case of $\lambda/L = 1.6$ where maximum increase in cavitation volume was observed in Figure 9. Effect of wake change alone was considered in order to compare the results with those in Figure 9. For the simulation in presence of wave, wake at the time instance showing maximum cavitation in Openprop simulation was chosen. Time period of the propeller being much smaller than that of wake variation, wake field was assumed constant in this unsteady simulation. Cavitation pattern obtained from this analysis can be seen in Figure 10.

Unsteady panel method (Figure 10) show significantly less cavity volume as compared to Openprop (Figure 9). However, maximum cavitation seen in presence of waves hardly differs from the cavitation in calm water, as can be observed in Figure 10.

Effect of Waves on Cavitation –

Therefore, the effect of wake change, excluding other factors, on the cavitation is minor in spite of significant changes observed in the wake field. This can be due to the large induced velocities as compared to the wake velocities, and that even though the change of wake pattern due to waves is quite significant, the critical features, like maximum wake and wake gradient don't worsen much. The effect of such wake variation could be more pronounced in case of a lightly loaded propeller. It is important to note that this analysis has been performed using wake data in regular waves of fixed waveheight. Therefore, influence of waves can increase in case of higher waves. However, effects are expected to be less severe in irregular waves with significant waveheight equal to the height of the regular wave.

Increased load caused by added resistance increases the angle of attack of blade sections making them susceptible to backside sheet cavitation. In this case, since propeller is already cavitating in calm water wake, increased load will increase the extent of this cavitation. However, as noted earlier, this effect can be easily taken into account while designing the propeller, since the increased propeller load can be calculated from the added resistance.

3.2.2 Thrust and torque fluctuations in waves

Along with the changes in cavitation and vibration characteristics, wake variation also causes thrust and torque to fluctuate. The amount of these fluctuations should be examined to see if they affect the operation of the engine. Fluctuations of K_Q at constant propeller rpm obtained using Openprop can be seen in Figure 11 for three different wavelengths. Maximum fluctuation is evident when wavelength is equal to the ship length. Change in mean value of K_Q as compared to the calm water value is due to the increase in average inflow to the propeller caused by the pitching motion of ship.

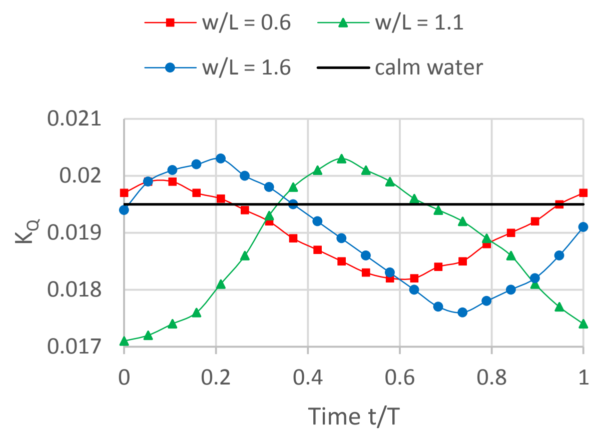

Figure 11 Variation of K_Q in waves

Fluctuations in K_Q have been calculated assuming constant propeller rpm while in reality rpm is a function of torque and engine behavior.

These variations in torque can cause transients in engine operations, and might influence engine performance negatively. Here it is important to observe the magnitude of torque fluctuations. Furthermore, engine simulation should be carried out with this torque input in order to calculate effect of torque fluctuation on engine operations, and its efficiency and emissions. The changes in the propeller speed due to engine response can be taken into account in the propeller analysis, in order to "close the loop".

4 CONCLUSION

We now have an information about an extent to which the criteria required for good noise and vibration characteristics get affected due to waves. Hence, in future designs appropriate margins can be considered for the similar type of vessels. However, such analysis should be performed for the variety of ships for multiple propeller loadings in order to generalize the results.

As per the analysis, it seems, presence of waves does not significantly affect cavitation in spite of large changes observed in the wake field. Thus, a margin for cavitation would mainly be required for increased loading, relative stern motion and not much for the wake change due to waves. Therefore, in practice the required margin can be estimated using added resistance and relative stern motions.

Vibration and noise characteristics have been analyzed using the BSRA wake criteria. However, more advanced techniques should be used to quantify the pressure pulses in different wakes. Pressure pulses may increase since higher wake gradients were observed in presence of waves.

Present analysis being in regular waves gives conservative estimate of the effect of waves on the propeller performance. We expect the effects to be less severe in case of irregular waves. It should also be mentioned that current wake field in waves is obtained at model scale corresponding to the actual waveheight of 3m for a 340m long ship. Hence, there is a possibility of larger performance changes in presence of higher waves. Thus, it would be of interest to perform a similar investigation, but for a significantly smaller ship.

Significant fluctuations observed in propeller torque in waves should be analyzed further to calculate its effect on the engine operation. Coupled response of engine and propeller should be obtained to examine the effect of waves on whole propulsion system.

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DISCUSSION

Question from Tom van Terwisga

Did you check the cavitation effect for the ship in waves considering an unsteady method and did you look at the corresponding unsteady pressure variations?

Author's Reply

Along with lifting line method, cavitation analysis was also performed using unsteady panel method with cavity volume calculations using the software AKPA as mentioned in the paper. However, wake was assumed quasi steady i.e. calculations were performed for wake distribution at different time intervals. Wake variation was assumed constant in time in each calculation. We believe that quasi-steady wake assumption is reasonable since the frequency of wake variation is much smaller than the frequency of propeller rotation.

The effect of change in cavitation number due to relative stern motion has been taken into account using hydrostatic approximation. Hence, the effect of dynamic pressure due to wave has been ignored. However, we agree that it would have been interesting to include the effect of unsteady pressure variations on the propeller performance.

Question from Johan Bosschers

Can you say something about the influence of the change in transverse velocities on the results? Is the influence of ship motions included?

Author's Reply

In some cases, transverse velocities show significant change. We believe, change in transverse can affect the tip vortex inception, which has not been studied in this paper. Transverse velocities can affect the cavitation due to change in the blade angle of attack. However, total induced velocities being much larger compared to the transverse velocities, any recognizable effect due to transverse velocities alone was not observed in the analysis.

Ship motions influences the propeller in two ways. Part of wake variation is due to ship motion and cavitation number changes due to change in propeller immersion. Influence of wake variation on propeller operation has been studied in detail in this paper as wake data in waves was obtained for the ship free to heave and pitch. The effect of variation in propeller immersion has been compared with the effect of wake variation in Figure 8.

Question from Moustafa Abdel Maksoud

Did you consider the effect of added resistance on the amount of cavitation on the propeller surface? Do you think that the following wave condition is more critical than the head waves one?

Author's Reply

In this paper, added resistance has not been considered, since wake data was available for the design speed of ship and since considering the added resistance would change the ship speed as well as motion response, leading to significant changes in wake. Even if the speed could be kept the same by increasing the shaft power to compensate for the added resistance, this change in propeller operating point means that we would not be able to single-out the effect of the wake change. However, the effect of added resistance is planned to be included in future studies.

Following wave condition can be more critical as waves would be directly affecting the propeller. However, authors are not aware of any measurement data or computations of wake in following waves. Limited availability of wake data is in general a limitation for analyzing propeller in waves.

Question from Mehmet Atlar

Interesting paper. The authors may also consider the BSRA criteria of Odabasi and Fitzimmons in terms of propeller-excited vibrations (PEV) since these two authors provided diagram (i.e. criteria) for cavitation and PEV assessment in their work (i.e. similar to the diagram in Figure 5 of the paper) that would be interesting to compare with the performance in waves.

Author's Reply

The paper mentions the Odabasi criterion. We believe, this is same as the BSRA criteria you mention. We have used the opportunity to update the paper so that it now also refers to this as the BSRA criterion.