Preprint submitted to the Journal of Applied Ocean Research
DOI: 10.1016/j.apor.2016.08.009

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 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 presence of waves.

Keywords: Propulsion in Waves, Cavitation, Pressure Pulses, Marine Propeller, Propeller Performance in Waves, Propeller Design

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 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, Steen *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 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, Wu *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.

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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 Figure 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 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

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-

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

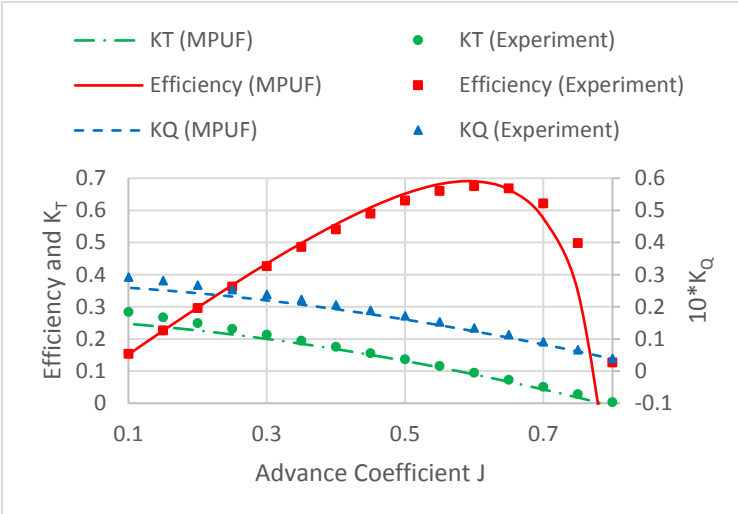


Figure 1 Comparison of open water data of KVLCC2 using MPUF-3A and model tests

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 Presence of Waves

Experiments were performed by Sadat-Hosseini, Wu *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 Figure 2.

Table 2 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 (knots)	15.5

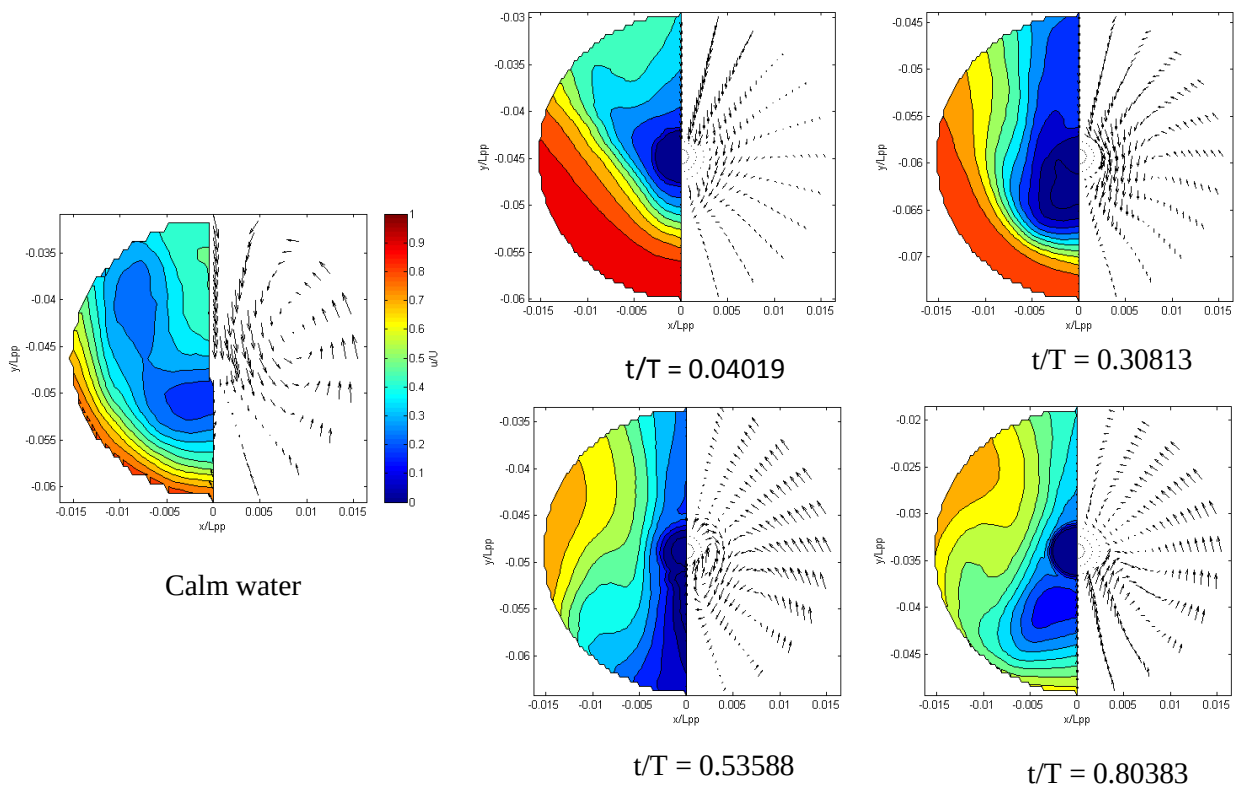


Figure 2 Wake in calm water compared to the wake in presence of wave having wavelength ratio λ/L = 1.1

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 the exact amount of cavitation and pressure pulses in full scale. We think that the use of model scale wake is sufficient for the qualitative study of the effect of waves on propeller performance.

Time-varying potential wake in presence of waves has been calculated using Shipflow Motions [16]. Simulations were performed at design speed in three different wavelengths (λ/L = 0.6, 1.1, 1.6), free to heave and pitch. Wake variation obtained using the potential flow calculation has been compared with the wake data obtained from CFD to investigate the appropriateness of computing the wake variation in waves using potential flow theory. The motivation for this being the excessive computational expense of seakeeping calculations with CFD.

2.3. Calculation of ship motions and added resistance

Ship motion RAOs (Response amplitude operators) were calculated using linear strip theory, utilizing potential theory and pressure integration, implemented in the ShipX Veres software. Using the motion response of the vessel, added resistance coefficients have been calculated using the method by Loukakis

and Sclavounos [17] (which is an extension of the classical Gerritsma and Beukelman's method) also implemented in ShipX Veres. Heave RAO, pitch RAO and added resistance calculations have been compared with the experimental investigations performed by Wu [18]. These comparisons can be seen in Figure 3. Added resistance was then computed in irregular waves for different peak frequencies using the Pierson-Moskowitz wave spectrum. Speed loss for a particular wave condition (e.g. λ/L=1.1, wave amplitude=3m) has been calculated in irregular waves having a peak frequency equal to the regular wave frequency and significant waveheight equal to the height of the regular wave. The reason behind using irregular waves for the computation of speed loss is to avoid getting unreasonably low ship speeds as a results of added resistance in regular waves which is often much larger than the added resistance in corresponding irregular waves.

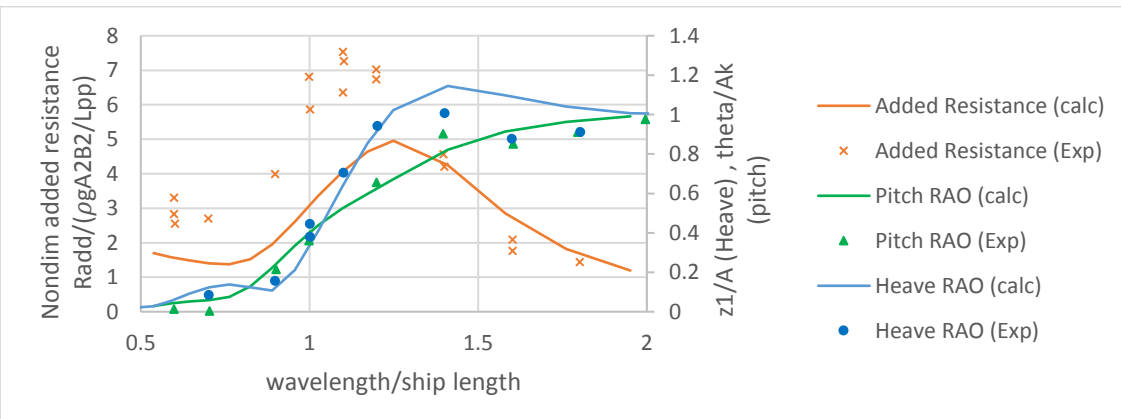


Figure 3 Added resistance and ship motions calculation compared with the experimental measurements

2.4. Calculation of propeller RPM fluctuation

In order to calculate the RPM fluctuation, a coupled engine-propeller model of Taskar, Yum *et al.* [19] [20] has been utilized. The study analyzes the engine-propeller interaction in the presence of waves considering a fluctuating wake field, propeller emergence, and free surface effects. Simulations in regular

head waves of 3 m wave amplitude showed around 3% fluctuation in RPM. Hence, propeller cavitation has been analyzed in 3% higher RPM to calculate the possible change in pressure pulses and cavitation.

2.5. Pressure Pulse calculation

Pressure pulses have been computed using HULLFPP [21] which calculates field point potential induced by a cavitating propeller using a potential based boundary element method. Time series of cavity shapes, cavity volumes and pressure distribution on blades calculated by MPUF-3A are used as an input to this code. In the computations, the hull was assumed to be a flat plate at a distance of 30% of the propeller diameter from the blade tip. Tip clearance of 30% is commonly seen on ships.

In the propeller design methodology, prediction of pressure pulses plays an important role. The propeller geometry should be such that the level of pressure pulses is below the specified threshold. The method proposed by Holden, Fagerjord *et al.* [22] is often used to analyze pressure pulses in the initial design stage. This method is based on numerous experimental studies and experiences with full-scale pressure pulses. The applicability of Holden's method for the analysis of propeller in waves has been tested by comparing the results with more accurate HULLFPP calculations. A comparison of pressure pulses predicted by both methods has been presented in Figure 4.

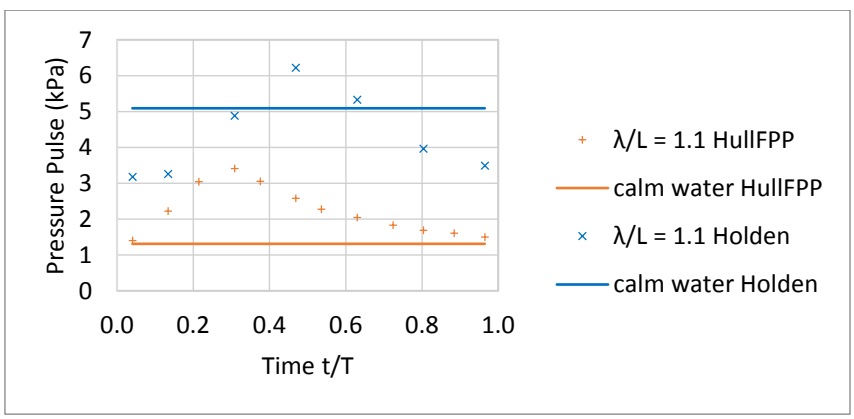


Figure 4 Comparison of pressure pulses calculated using Holden method and HULLFPP code

In Figure 4, it is evident that pressure pulses predicted by Holden's method are much higher than those predicted by HULLFPP. Moreover, the trend of variation in pressure pulses in different wake fields is different in two cases, as seen for λ/L=1.1. Therefore, analysis using a simple method like Holden's might not be a good idea. A more detailed analysis like the one using HULLFPP is required to capture the effects of minor variations in wake structure. An explanation for the large over-prediction by Holden's method compared to HULLFPP might be that it is based on data from old propellers, typically with little skew.

2.6. Calculation of unsteady wave pressure

Propeller cavitation can get affected by the change in cavitation number caused by ship motions as well as dynamic wave pressure. To study this effect, the total pressure was calculated at the location of the propeller shaft, considering the instantaneous depth of propeller and the phase of the passing wave. The total pressure was then used in the calculation of cavitation number for analyzing time-varying cavitation and pressure pulses in waves.

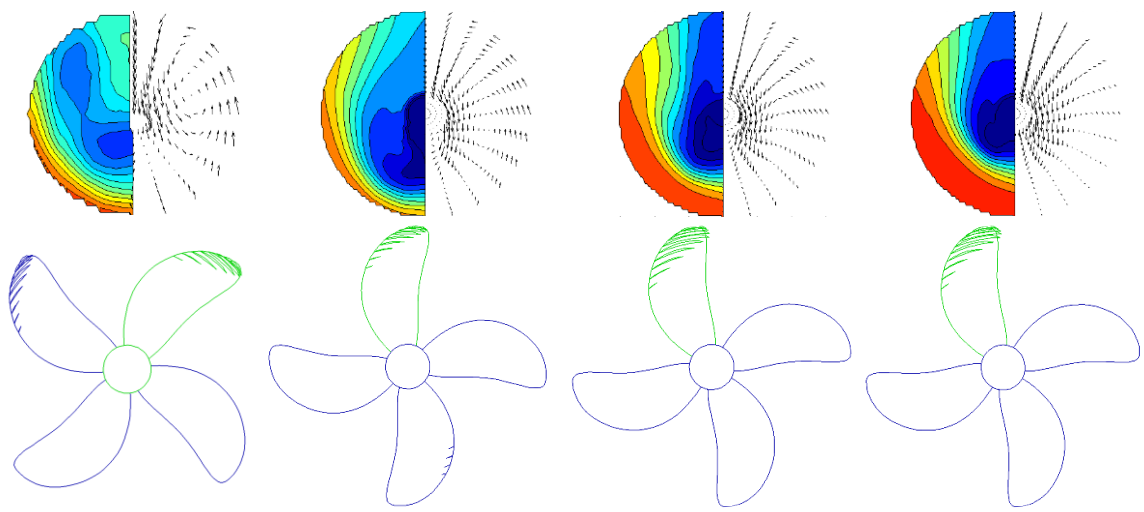
3. Analysis

Initially, the propeller was analyzed in the calm water wake field to observe the cavitation pattern and pressure pulses in calm water condition. The influence on cavitation and pressure pulses of the factors affecting propeller in waves i.e. wake variation, ship motions, dynamic wave pressure, speed loss and RPM fluctuations has been studied. The analysis was also performed using cavitation bucket diagram to observe the effect of these factors on lift coefficient and cavitation number. The analysis has been divided into three parts where the influence of each factor has been considered separately.

1. Wake variation and change in cavitation number due to ship motions and waves
2. Increased loading due to speed loss
3. RPM fluctuations due to engine propeller interactions and average wake variation

3.1. Effect of wake variation and change in cavitation number

The KVLCC2 propeller has been analyzed using MPUF at multiple time intervals in the presence of three different regular waves. In order to observe the effect of wake variation alone, the propeller immersion was assumed constant at 15.1m depth, equal to that in calm water. The maximum amount of cavitation in each case can be seen in Figure 5. In calm water, the blade position at which maximum cavitation occurs has been plotted. However, in presence of waves, cavitation depends not only on the location of the blade but also on the phase of the passing wave. Maximum cavitation with respect to blade position as well as time instant (or wave phase) can be seen in Figure 5.



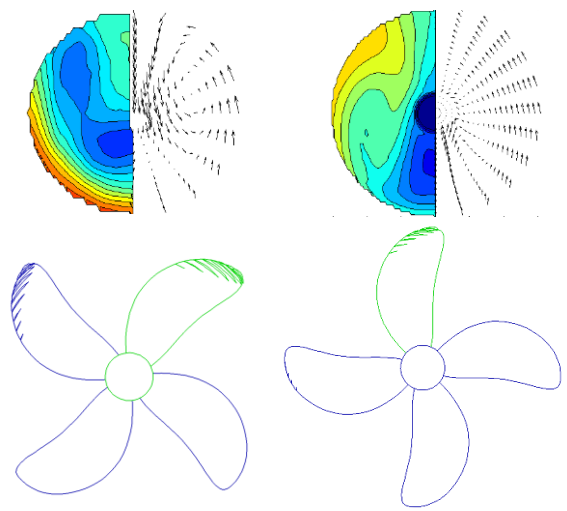
Calm water | λ/L = 0.6, t/T = 0.90936 | λ/L = 1.1, t/T = 0.30813 | λ/L = 1.6, t/T = 0.92454

Figure 5 Maximum suction side cavitation seen in each wavelength considering only wake change compared to cavitation in calm water wake

It can be seen from Figure 5 that for three wavelengths, maximum cavitation occurred at different blade positions although the location of cavitation on the blade was similar. Maximum cavitation is observed in the case of λ/L = 1.1 i.e. when the wavelength is close to ship length. Here, it is important to note that the maximum cavitation in presence of waves is occurring at one blade location at one instant in a single wave period. In presence of waves, maximum cavitation is observed when the stern of the ship is moving down causing low wake velocities in the upper part of the propeller disc close to the centerline. The

DOI: 10.1016/j.apor.2016.08.009

maximum cavitation seen in one full rotation of the blade varies as the wave passes, it can be as low as that shown in Figure 6. It was also observed that in calm water, cavity is present on a couple of blades simultaneously for a significant amount of time whereas in other cases, as the cavity on one blade vanishes, the next blade starts cavitating. This may have an effect on the behavior of pressure pulses.



Calm water λ/L = 1.6, t/T = 0.41445

Figure 6 Minimum suction side cavitation seen in presence of wave among all three waves considering only wake change

In addition to the effect of wake variation, change in cavitation number can also affect propeller cavitation and pressure pulses. In the presence of waves, varying propeller immersion due to ship motions and dynamic wave pressure lead to a change in cavitation number. Therefore, the propeller has been analyzed to see the combined effect of variation in cavitation number and wake variation on the cavitation and pressure pulses.

The total pressure, including the dynamic pressure, at the location of the propeller, was expressed in terms of an equivalent height of water column. The propeller was analyzed in wakes at different time instances at calculated equivalent propeller depth. Therefore, comparing the cavitation and pressure pulses using fixed cavitation number with that in varying cavitation number will show the effect of a change in cavitation number in waves.

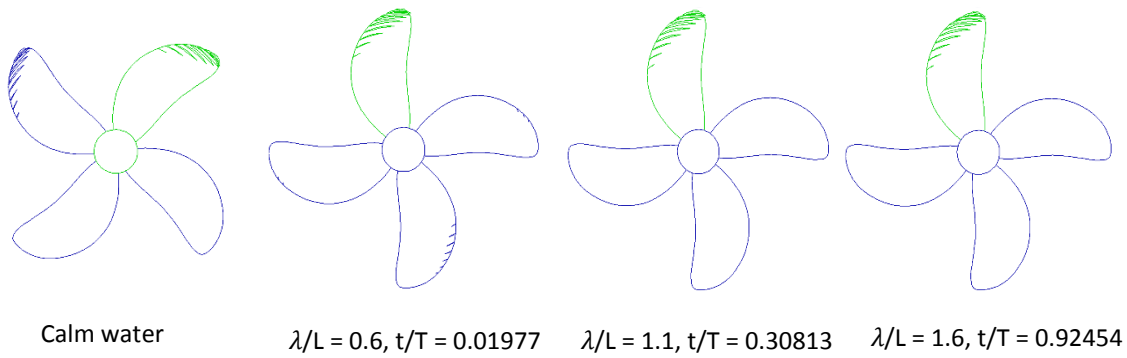


Figure 7 Maximum suction side cavitation seen in each wave considering wake change, ship motions and dynamic wave pressure

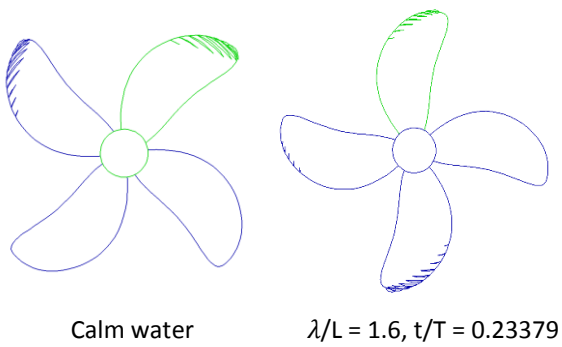


Figure 8 Minimum suction side cavitation seen in presence of wave among all three waves considering wake change, ship motions and dynamic wave pressure

As in the earlier case, the cavitating propeller has been presented at the angle and time instant of maximum cavitation in each wave in Figure 7. Comparing maximum cavitation in λ/L=1.1 and 1.6 in Figure 7 with Figure 5, it seems that including the variation in cavitation number reduces the maximum volume of cavitation. This is because the variation in cavitation number is favorable for the instances of unfavorable wake variation. In other words, the worst possible wake in waves occurs at a cavitation number higher than that in calm water. Whereas, in λ/L=0.6, the amount of cavitation is higher when the variation of cavitation number is taken into account. The amount of cavitation varies as the wave passes, the minimum cavitation in presence of waves can be observed in Figure 8. In this case, although the blade at 12 o'clock position shows minimum cavitation, blade at 6 o'clock position has higher cavitation. This happens when the stern of the ship is moving up (note Figure 9), causing low wake velocities in the

lower part of propeller disc close to the centerline. Hence, propeller blade starts cavitating even when it is at 6 o'clock position.

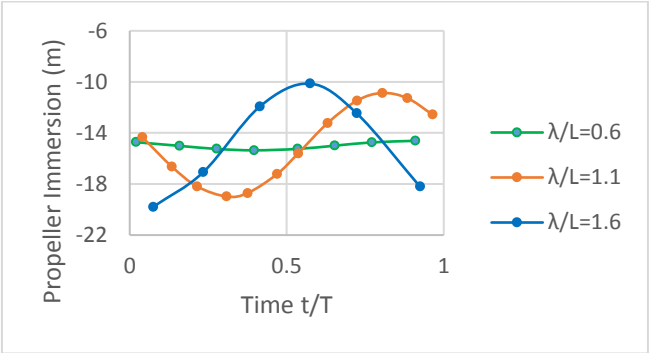


Figure 9 Variation of propeller immersion in waves measured from calm water line (Propeller immersion in calm water is 15.1m)

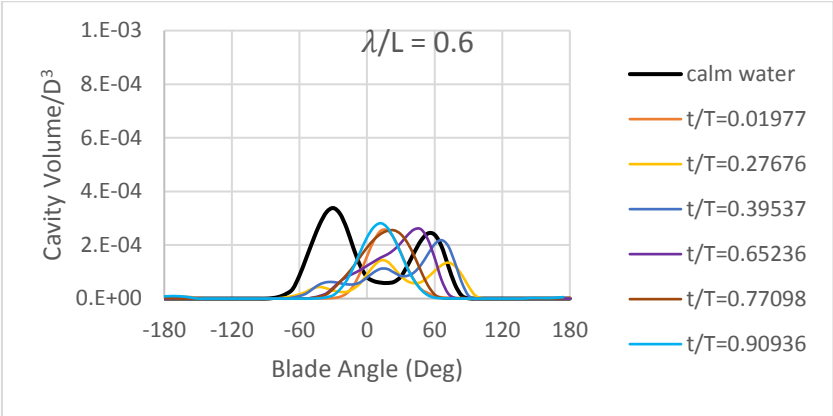


Figure 10 Cavitation volume variation in λ/L=0.6 at different times as wave passes considering only wake change

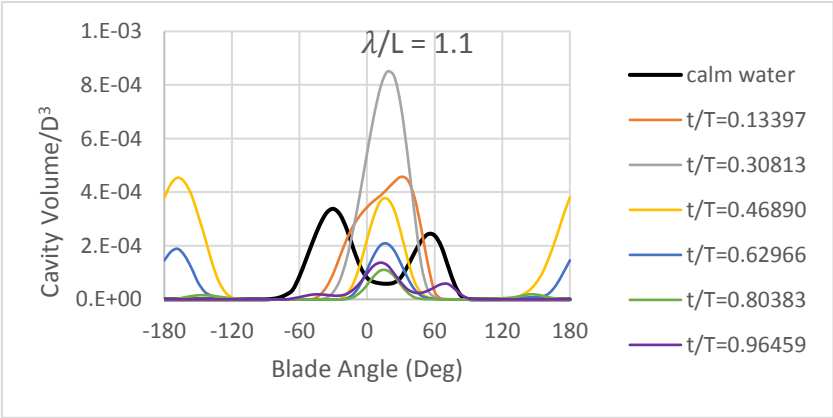


Figure 11 Cavitation volume variation in λ/L=1.1 at different times as wave passes considering only wake change

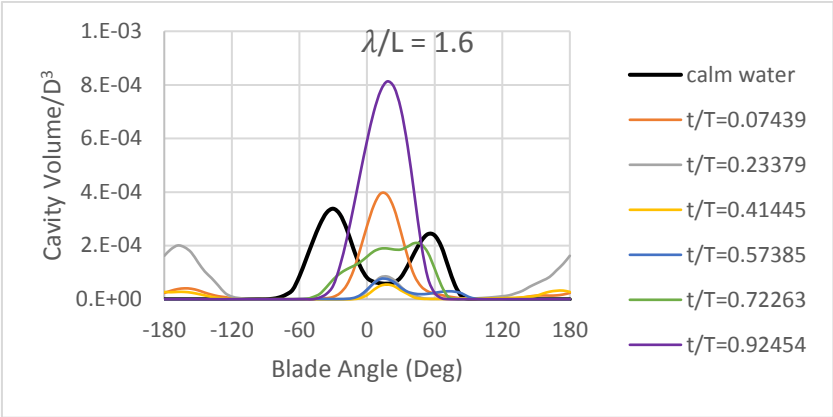


Figure 12 Cavitation volume variation in λ/L=1.6 at different times as wave passes, considering only wake change

To compare the cavitation in calm water with that in waves, it would be more appropriate to compare the time history of cavitation volume in calm water with that in waves. Therefore, cavitation volume on a single blade has been plotted as a function of blade position in the calm water and different times in each wave condition. Cavitation volumes with constant cavitation number have been presented in Figure 10 to Figure 12 and those considering the variation in cavitation number have been plotted in Figure 13 to Figure 15.

First, coming to the computations at fixed cavitation number. In λ/L=0.6, at all times, maximum cavitation is lower than the amount of cavitation in calm water. Whereas, in λ/L=1.1 and λ/L=1.6 maximum cavitation volume is as high as twice the amount of maximum cavitation in calm water. However, this happens only for one time instance. In most other cases, the amount of cavitation is either comparable or lower than the calm water cavitation. In cases λ/L=1.1 and λ/L=1.6 cavitation sometimes appears on the blade at 6 o'clock position which is not seen in the calm water and the λ/L=0.6 case. In cases of λ/L=1.1, t/T= 0.46890 and λ/L=1.6, t/T= 0.23379, the volume of cavitation is higher at 6 o'clock position than at 12 o'clock position. These are the instances when the stern of the ship is moving upwards as noted earlier.

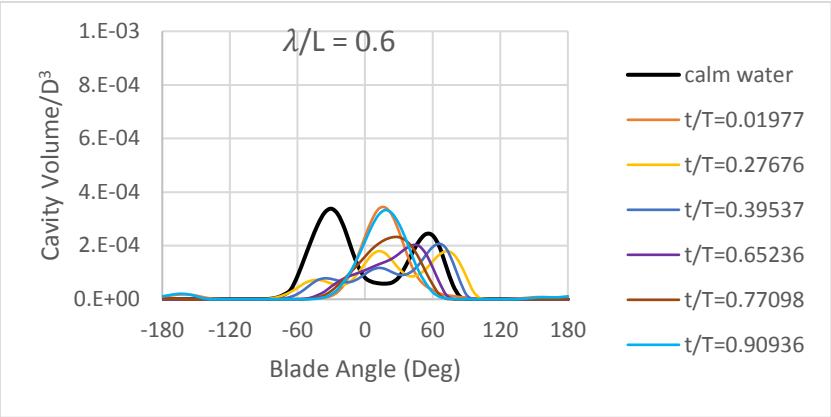


Figure 13 Cavitation volume variation in λ/L=0.6 at different times as wave passes, considering wake change, ship motions and dynamic wave pressure

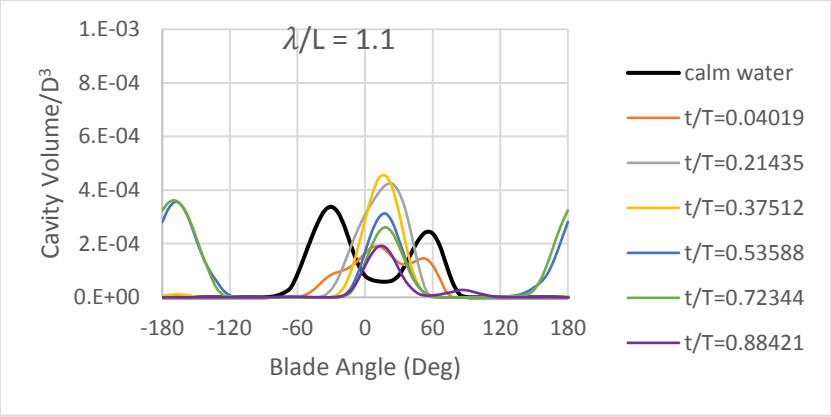


Figure 14 Cavitation volume variation in λ/L=1.1 at different times as wave passes, considering wake change, ship motions and dynamic wave pressure

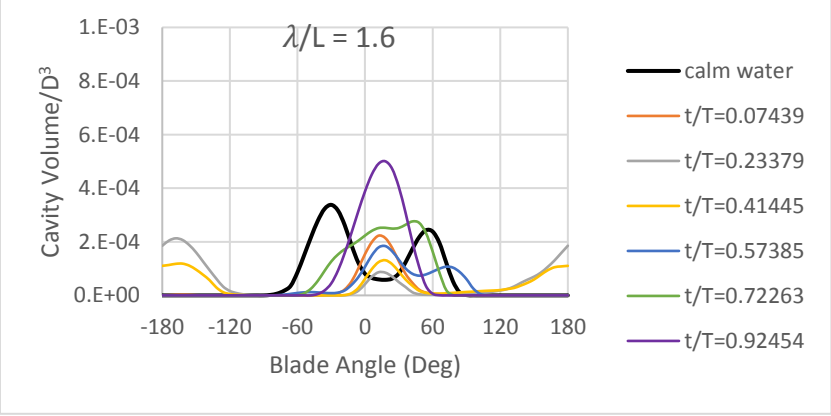


Figure 15 Cavitation volume variation in λ/L=1.6 at different times as wave passes, considering wake change, ship motions and dynamic wave pressure

Cavity volume variation considering variation in cavitation number has been plotted in Figure 13, Figure 14 and Figure 15. Comparing these plots with Figure 10, Figure 11 and Figure 12, it can be observed that maximum cavitation volume is lower by about 45% in λ/L=1.1 and by about 38% in λ/L=1.6 when the effect of variation in cavitation number is included. Therefore, the change in cavitation number due to waves and ship motions seems to favor the propeller performance for these wavelengths. Whereas, for λ/L=0.6, the maximum cavitation volume is 18% higher when the cavitation number variation is included. Considering all the factors affecting propeller in waves, only in a few time instances, the cavitation volume is larger than the maximum cavitation volume in calm water. Thus, presence of waves does not significantly affect average cavitation volume.

In all the cases, the pattern of the cavity volume varies in a much different way than in the calm water case. In calm water, the cavity volume variation shows double peaks whereas, in the presence of waves, cavity volume has just a single maximum in most of the cases. This, as explained earlier, is due to low-speed area developed close to propeller centerline due to the motion of the stern. This behavior suggests that pressure pulses are affected by operation in waves as they primarily depend on cavity volume variation and distance to the hull. Therefore, it is important to see how pressure pulses are affected in the presence of waves.

Pressure pulses were analyzed in waves and in calm water using HULLFPP as already mentioned. Variation of the first, second and third harmonics in waves has been compared with those in calm water. Usually, the amplitude of the first harmonic i.e. pressure pulses of blade pass frequency is highest and most significant from the hull vibration point of view. Pressure pulses in calm water and in waves considering constant cavitation number have been compared in Figure 16. For λ/L=1.1 and 1.6, the first harmonic of pressure pulses is higher than in calm water for almost all time instances. Maximum pressure pulses in these wave conditions are more than double of those in calm water. In the case of

λ/L=0.6, pressure pulses are higher than calm water for 50% of the time. Thus, it is clear that wake variation does significantly affect pressure pulses.

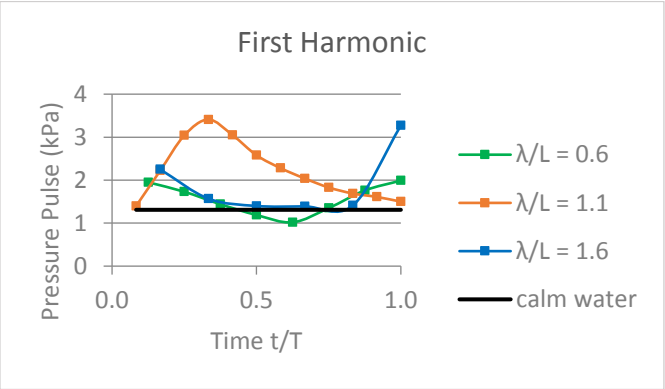


Figure 16 First harmonic of pressure pulses in waves considering only wake change

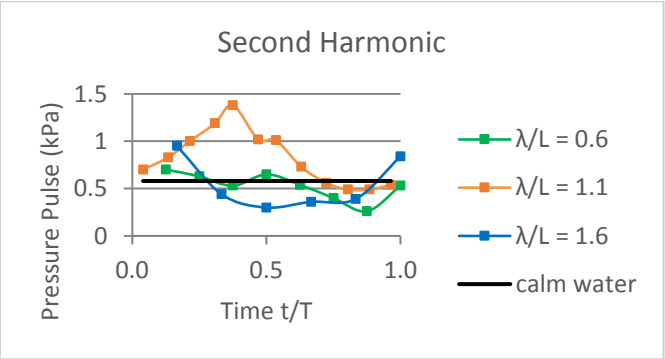


Figure 17 Second harmonic of pressure pulses in waves considering only wake change

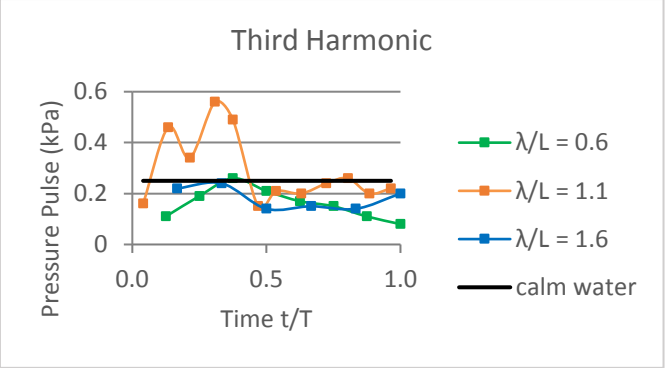


Figure 18 Third harmonic of pressure pulses in waves considering only wake change

Coming to second and third harmonic of pressure pulses, they are considerably higher than calm water value only for λ/L=1.1 as seen in Figure 17 and Figure 18. Moreover, for λ/L=1.1 the maximum value of the second harmonic is close to the first harmonic amplitude of pressure pulses in calm water. For the other waves, the second and third harmonic pressure pulses are either comparable or lower than the calm water value.

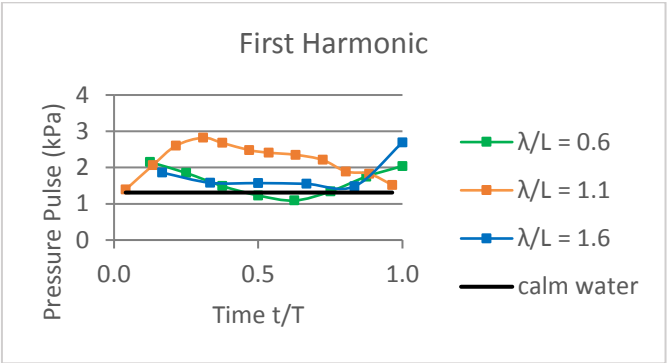


Figure 19 First harmonic of pressure pulses in waves considering wake change, ship motions and wave dynamic pressure

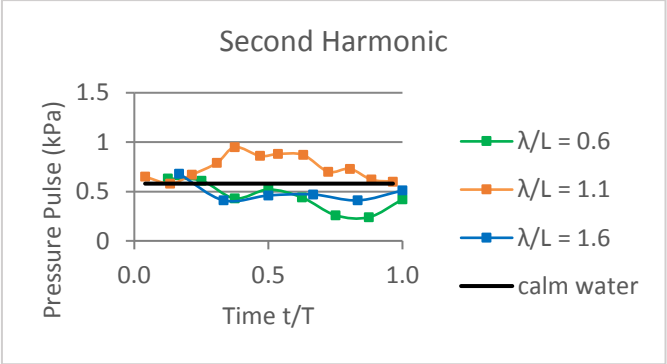


Figure 20 Second harmonic of pressure pulses in waves considering wake change, ship motions and wave dynamic pressure

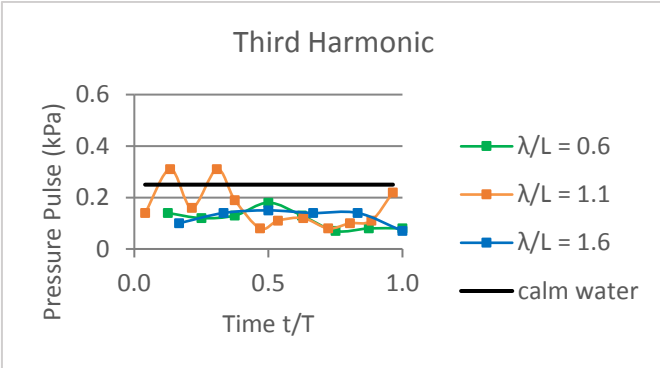


Figure 21 Third harmonic of pressure pulses in waves considering wake change, ship motions and wave dynamic pressure

In Figure 19, Figure 20 and Figure 21 pressure pulses considering the effect of wake variation, ship motions, and dynamic wave pressure have been plotted. In the case of waves with λ/L=1.1 and 1.6 maximum values of first harmonic of pressure pulses is lower than that observed using wake change alone, which is in line with the change in cavitation volume as discussed above. However, pressure pulses in Figure 19 are higher than that in Figure 16 for approximately 50% of the times in all three waves. The maximum 0.4kPa increase in the first harmonic of pressure pulses is observed due to the effect of variation in the cavitation number (in the case of λ/L=1.6, t/T= 0.57385).

The second harmonic of the pressure pulses is higher than the calm water value only for λ/L=1.1 while in other waves, it is lower than in calm water. For third harmonic, hardly any time instances show higher pressure pulses than calm water. Thus, considering first, second and third harmonic of pressure pulses in waves, wave condition λ/L=1.1 seems critical for the analysis of propeller in presence of waves.

To separate the effect of variation in cavitation number from the effect of wake change, change in the first harmonic of pressure pulses are plotted in Figure 22 against equivalent propeller immersion. Change in pressure pulses has been calculated as the difference between the pressure pulses computed with fixed and with varying cavitation number i.e. difference between the level of pressure pulses in Figure 16 and Figure 19. The maximum increase of about 0.4kPa is observed due to the effect of variation in cavitation number.

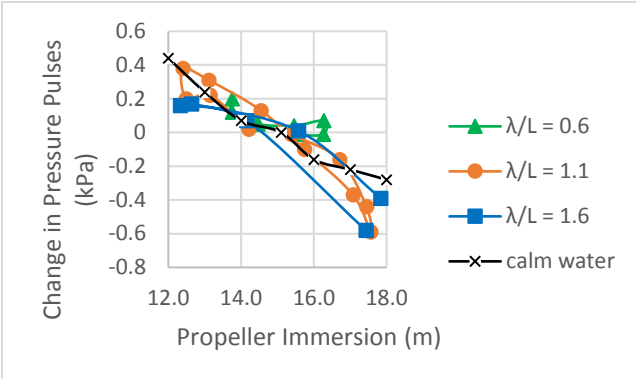


Figure 22 Variation of pressure pulses with change in propeller immersion (Propeller immersion in calm water is 15.1m)

The propeller was analyzed in calm water wake at different immersions to compare the rate of change of pressure pulses with respect to propeller immersion in calm water with that in waves. From Figure 22 it is seen that increase in pressure pulses due to change in propeller immersion is similar in calm water wake as well as in wake in the presence of waves. Therefore, possible increase in pressure pulses due to combined effect of waves and ship motions can be approximated by analyzing the propeller in calm water wake by varying the propeller immersion.

The lift coefficient obtained from MPUF-3A calculations has been plotted against cavitation number (sigma) for one full rotation of the blade section at 0.7R, thus forming a loop. Cavitation bucket obtained from Xfoil calculations has also been plotted for this propeller blade section. Operating loops in calm water as well as at the instant of maximum cavitation in each wavelength can be seen in Figure 23 along with the cavitation bucket. Comparing the operating loops and Xfoil calculations with MPUF results, there is a slight discrepancy since calm water operating loop is well inside the cavitation bucket predicted by Xfoil hence the section at 0.7R should be free of any cavitation in calm water whereas MPUF computations show the presence of cavitation at that section. This can be due to calculations being for 2D flow in Xfoil and 3D flow in MPUF. Therefore, the cavitation bucket should only be considered for the approximate estimation of the cavitation-free zone. The aim of plotting the operating loops is to compare the variation in cavitation number and lift coefficient in different wakes.

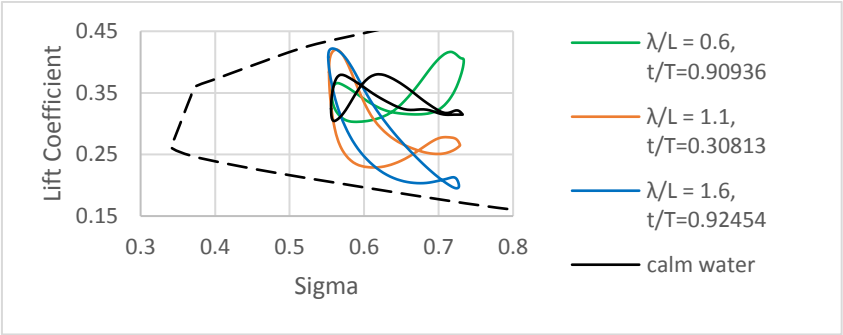


Figure 23 Variation in lift coefficient of blade section at 0.7R at the instance of maximum cavitation in each wave considering only wake change

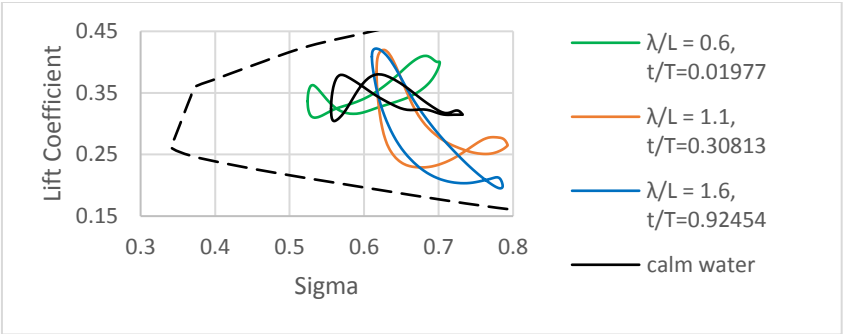


Figure 24 Variation in lift coefficient of blade section at 0.7R at the instance of maximum cavitation in each wave considering wake change, ship motions and dynamic wave pressure

In this case, the propeller depth was assumed constant, so the change in sigma is only due to change in instantaneous depth of the propeller blade as it rotates. Therefore, variation in sigma is similar in all the cases. However, the variation of lift coefficient changes drastically in the presence of waves. Variation in lift coefficient is much larger in λ/L=1.1 and 1.6 than in calm water. Hence, if propeller sections are designed considering only the calm water wake, performance could become much worse in presence of waves.

DOI: 10.1016/j.apor.2016.08.009

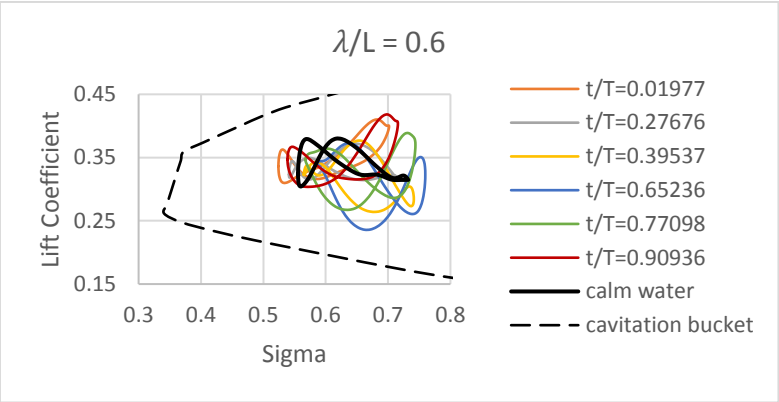


Figure 25 Variation in lift coefficient of blade section at 0.7R at different times as wave passes in λ/L=0.6 considering wake change, ship motions and dynamic wave pressure

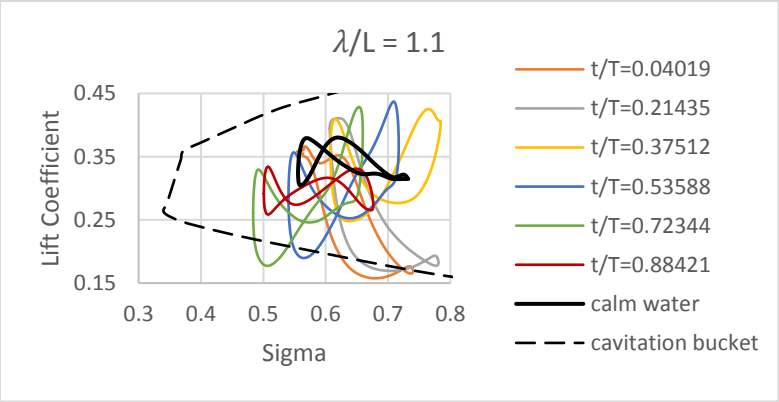


Figure 26 Variation in lift coefficient of blade section at 0.7R at different times as wave passes in λ/L=1.1 considering wake change, ship motions and dynamic wave pressure

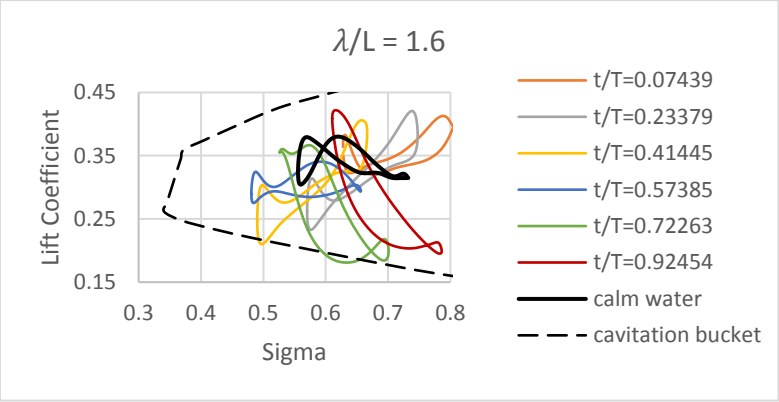


Figure 27 Variation in lift coefficient of blade section at 0.7R at different times as wave passes in λ/L=1.6 considering wake change, ship motions and dynamic wave pressure

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Similar Xfoil analysis considering the variation in cavitation number (due to varying propeller immersion) in addition to wake change (=angle of attack variation) at the instance of maximum cavitation has been presented in Figure 24. Comparing it with Figure 23, variation in sigma can be seen in addition to variation in lift coefficient. It can be observed that operating loops for wavelength ratios 1.1 and 1.6 have shifted towards higher sigma. This leads to a slight reduction in cavitation and pressure pulses (observed earlier) as cavitation bucket is slightly wider at higher sigma.

In addition to the instant of maximum cavitation, the behavior of operation loops should be examined at other time instances to know the behavior of the operating loop as the wave passes. Therefore, Xfoil analysis has been carried out at different time instances in each wave as seen in Figure 25, Figure 26 and Figure 27. Wake variation, as well as variation in propeller immersion, has been considered in this analysis.

Comparing Figure 24 with Figure 26, it can be observed that the instance of maximum cavitation volume is not necessarily the worst condition for the propeller blade. Even though pressure side cavitation is not seen in the MPUF analysis at any time instance, Xfoil analysis tells us that at some time-instances the propeller operates very close to having pressure side sheet cavitation. (Cavitation bucket is only approximate as noted earlier. It has been provided as a reference to the comparison of different operating loops.) The maximum deviation from the calm water operating loop is seen in λ/L = 1.1. In this wave, maximum increase in suction side cavitation has been observed. Moreover, the propeller is more prone to pressure side cavitation as well as bubble cavitation at certain time instances in this wave as compared to calm water condition.

For the studied propeller, most of the operating points lie within the cavitation bucket, even in the presence of waves. This could be due to the general experience of the propeller designers about required margins for operation in waves and off design conditions, as they did not have the information

about wake field in waves at the time of designing the propeller. However, there are no clear guidelines regarding cavitation margins to avoid performance drop in waves, and when designing another propeller for another ship, the resulting propeller performance in waves might be less favourable.

3.2. Effect of increased loading

Added resistance due to waves leads to increased propeller load. This is likely to increase the amount of cavitation on the propeller. Moreover, pressure pulses are likely to vary if there is a significant change in the cavitation pattern. Hence, the sensitivity of cavitation and pressure pulses towards the increased propeller loading has been studied.

Ship motions depend on ship speed, therefore, wake variation will also change for different ship speed. However, in the absence of wake data at reduced speed, wake variation at design speed has also been used at reduced ship speed. The ship speed has been calculated in irregular waves of peak frequency 0.090, 0.067 and 0.055 Hz, corresponding to λ/L=0.6, 1.1 and 1.6 respectively with significant wave amplitude of 3m. Ship speed obtained using constant propeller RPM is 11.9, 11.3 and 11.6 knots for the three wave conditions. The propeller has been analyzed in each wave condition using the corresponding wake variation and ship speed. Propeller depth was assumed constant. The only difference between the computations in section 3.1 (with constant cavitation number) and these computations is the speed of the ship.

Increase in pressure pulses has been computed by comparing the pressure pulses in this analysis with those calculated considering wake change only (Figure 16). As seen in Figure 28, pressure pulses increased at maximum about 0.2kPa due to increased load. The maximum cavitation volume increased by about 10%. However, in some cases, maximum cavitation volume and pressure pulses decreased even after increasing the propeller load. This was observed in the instances of wake variation that caused high pressure pulses (λ/L=1.1, t/T= 0.30813and λ/L=1.6, t/T= 0.92454). It was observed that the cavity is

present for larger range of blade angles in presence of speed loss or increased loading, but maximum cavitation volume is lower. However, decrease in maximum cavitation volume is very small.

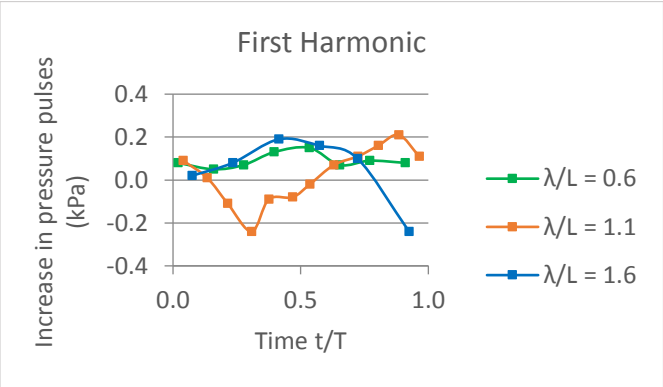


Figure 28 Increase in pressure pulses as a result of increased load on the propeller caused by the added resistance

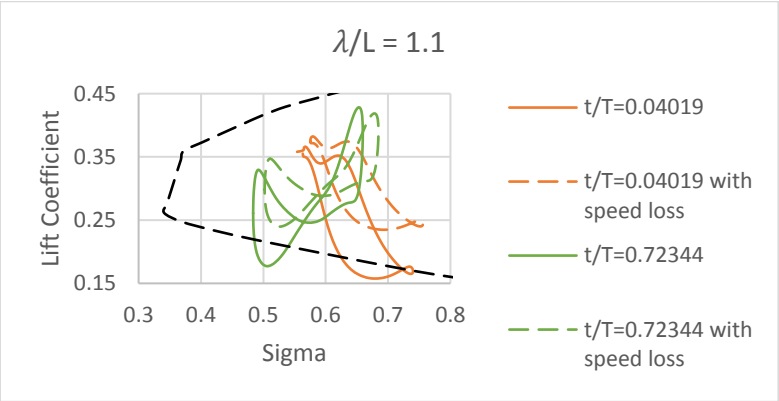


Figure 29 Comparison of variation in lift coefficient of blade section at 0.7R with and without speed loss

Variation in lift coefficient and cavitation number were also plotted to observe the effect of speed loss on operating loops. As seen in Figure 29 operating loops shift towards higher lift coefficient due to speed loss, which is expected since blade angle of attack increases due to decreased advance coefficient of the propeller as the ship speed reduces. The increased angle of attack leads to higher propeller loading. Also, note that the increase in lift coefficient is greater for the points at lower lift coefficient. Also, the operating loops shift towards higher sigma as the ship speed is reduced. Therefore, in the presence of speed loss, the probability of pressure side cavitation reduces. The presence of waves will often be

accompanied by speed loss thus, lowering the risk of pressure side cavitation, which looks imminent in Figure 26.

3.3. Effect of RPM fluctuations

As the ship travels in waves, wake fluctuates due to combined effect of waves and ship motions. This leads to varying propeller torque and therefore varying loads on the engine. Propeller RPM fluctuations depend on the engine control system, system inertia, and load variations. This RPM fluctuation might alter the cavitation pattern and pressure pulses. It was observed that RPM fluctuation is in phase with variation in the average wake. Whereas variation in pressure pulses is a function of wake distribution rather than the average wake.

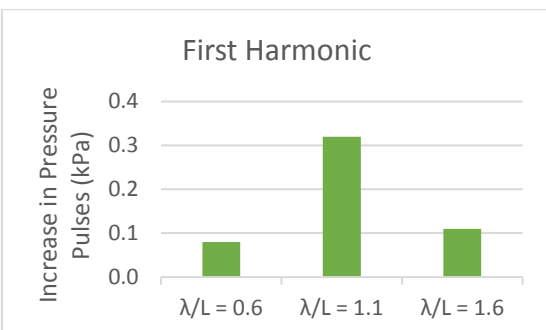


Figure 30 Increase in pressure pulses due to RPM fluctuations in waves

RPM fluctuation was calculated using engine-propeller coupled simulations, as described in section 2.4. In the presence of waves, the propeller speed was seen to fluctuate between 74 to 78 RPM at a constant ship speed of 15.5 knots. The propeller has been analyzed at the instant of 78 RPM in the corresponding wake in presence of wave at that instant. The instances of maximum propeller speed occur at t/T = 0.39537, 0.46890 and 0.72263 in λ/L=0.6, 1.1 and 1.6 respectively. Pressure pulses in these conditions were compared with those in the same instance of the wake but at 76 RPM, which is design RPM. About

0.3kPa increase in the first harmonic of pressure pulses can be observed in Figure 30. However, this increase is small as compared to increase in pressure pulses due to wake change in waves.

3.4. Summary of the factors affecting the pressure pulses in waves

The effect of wake change, ship motions, wave dynamic pressure, speed loss and RPM variation has been observed on cavitation and pressure pulses. All these effects have been considered in the presence of waves of 3m wave amplitude to be able to compare the influence of these effects. Figure 31 compares the maximum increase in the first harmonic of pressure pulse due to all four effects. The largest increase in pressure pulses is due to wake variation in waves. Effects of ship motions, RPM fluctuation, and speed loss are relatively small. Since wake variation is having a significant impact on the propeller performance, it should be taken into account while designing the propeller.

Also, note that considering the effect of wake variation in propeller design procedure is much more difficult than considering the effect of ship motions, added resistance and RPM fluctuations. Since obtaining reliable wake in waves is a challenging task in itself.

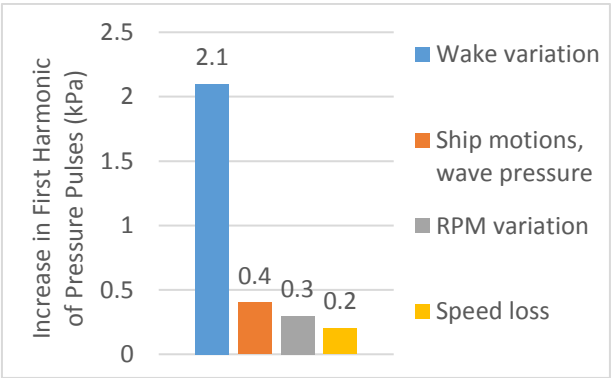


Figure 31 Comparison of maximum increase in the first harmonic of pressure pulses due to different factors in presence of waves

3.5. Efficiency variation in waves

As wake varies significantly in waves, propeller efficiency also varies with time. The propeller has been analyzed in different wakes in waves at design RPM, constant cavitation number, and design ship speed. Variation in propeller efficiency due to wake variation has been plotted in Figure 32. When K_T, K_Q and efficiency in presence of waves is plotted against the corresponding advance coefficients, data-points in presence of waves follow propeller open water curves as observed in Figure 33. From this, we can conclude that the efficiency is primarily affected by the average change in wake fraction and not much by wake distribution. Whereas cavitation and pressure pulses are directly related to wake distribution, and they depend less on average wake at least in the vicinity of operating point, as we have argued earlier.

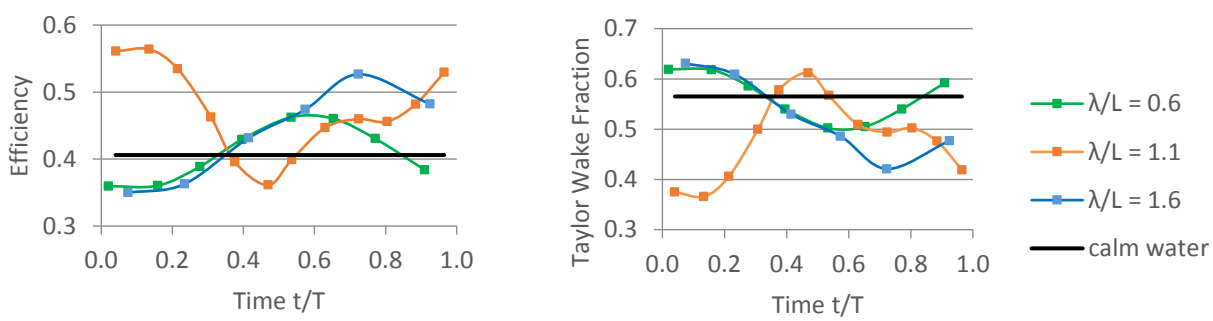


Figure 32 Variation in efficiency and Taylor wake fraction at different times in presence of waves considering only wake variation

In addition to the wake variation in waves, wake fraction averaged over one wave encounter period is lower than the calm water Taylor wake fraction due to the pitching motion of ship leading to increased propeller inflow as described by Faltinsen, Minsaas *et al.* [23].

Since average wake is different in the presence of waves, this can affect the choice of optimum propeller diameter and RPM. Choosing the optimum diameter for the wake in waves can lead to better propeller efficiency in presence of waves rather than in calm water. Doing so, propeller efficiency may reduce in

calm water but the vessel will perform better in waves. A further study is required to quantify total gain in efficiency considering different weather conditions.

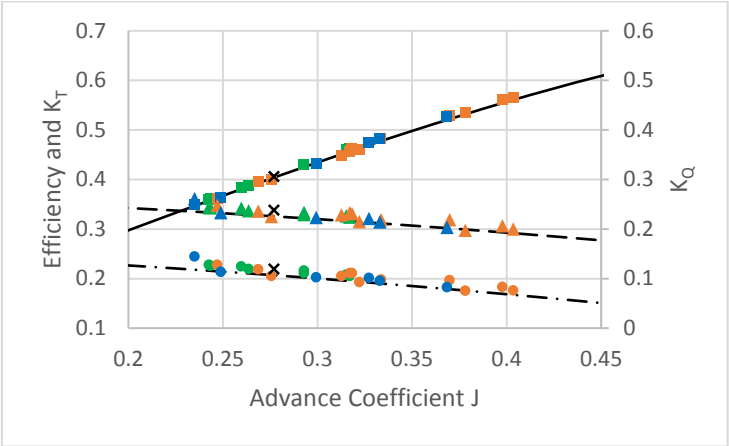


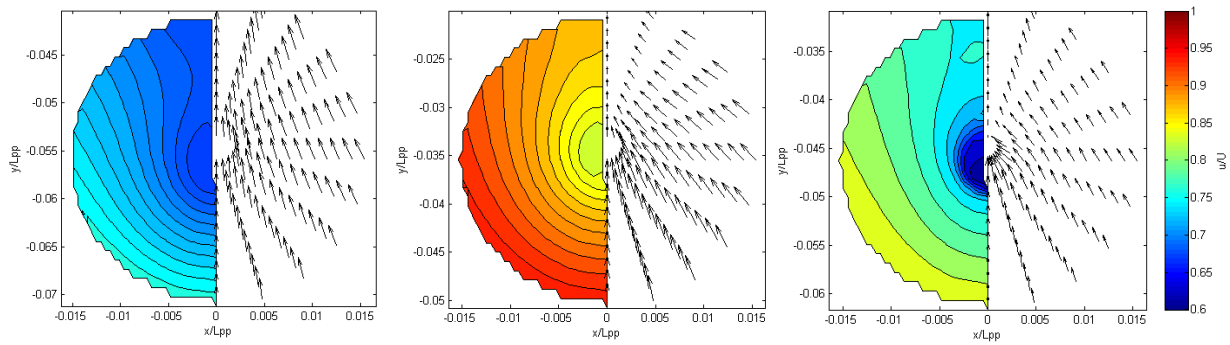
Figure 33 Propeller efficiency, K_T and K_Q in presence of waves along with propeller open water data. Propeller open-water efficiency, K_T and K_Q have been shown using solid, dash-dot and dashed lines respectively. Efficiency, K_T and K_Q in waves has been denoted by square, circle and triangle respectively. (λ/L=0.6 – Green; λ/L=1.1 – Orange; λ/L=1.6 – Blue). Performance in calm water wake has been denoted by cross mark.

3.6. Computation of wake in waves

From the presented analysis, it is evident that the propeller should be analyzed not just in calm water but also in presence of waves. Moreover, propeller optimization should also consider the operation in realistic weather conditions, since calm water is rather an exception at sea. However, to achieve this, the first step would be to obtain the wake distribution in waves, as wake variation has more impact than the other effects of waves on the propeller. Currently, it is not a standard practice to obtain wake in waves. Thus, to analyze and optimize a propeller in presence of waves, we need to have a tool or a method to calculate wake in waves.

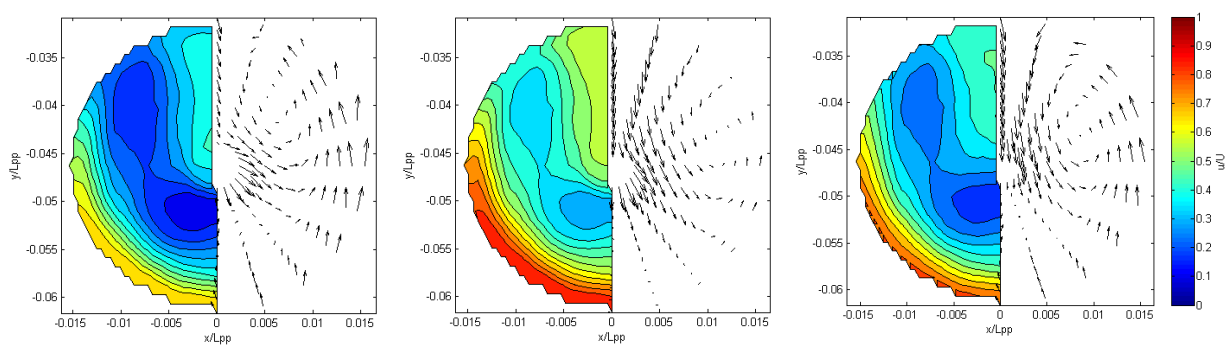
The variation of spatially averaged wake in waves can be divided into two factors: a) Mean change in wake due to pitching motion of ship, as explained by Faltinsen, Minsaas *et al.* [23] and b) Wake fluctuation due to induced particle velocities caused by incoming waves and surge motion of ship, as discussed by Ueno, Tsukada *et al.* [24]. Both these factors are caused by potential effects. Therefore,

although wake itself is a viscous phenomenon, wake change could be primarily due to potential effects. Chevalier and Kim [6], Jessup and Boswell [25] have studied cavitation of a propeller operating in waves by calculating wake velocities using potential flow calculations. Thus, we will proceed to check if potential flow calculations are suitable for finding the change in wake distribution due to waves for our current case vessel.



t/T = 0.53588 t/T = 0.04019 Calm water

Figure 34 Potential calm water wake and wake in λ/L=1.1 at a couple of instances



t/T = 0.53588 t/T = 0.04019 Calm water

Figure 35 Wakes in wave λ/L=1.1 obtained using potential flow calculations at a couple of instances

We checked if potential flow calculations can be used to estimate the change of wake distribution due to waves using the Shipflow software. First, the KVLCC2 hull was simulated in calm water to obtain the potential wake. The hull was then analyzed using Shipflow Motions to get the potential wake in waves. Potential wakes in calm water and in waves can be seen in Figure 34. The potential calm water wake has

been subtracted from the calm water wake distribution and potential wake in a particular wave has been added to it to get total wake in a wave. Wake distribution obtained using this procedure can be seen in Figure 35 at a couple of instances in wave λ/L=1.1. It can be observed that wake obtained using this method does not resemble the wake distribution obtained from CFD computations as seen in Figure 1. One of the reasons is that the difference between potential wake in waves and in calm water is almost constant over the plane of propeller disc. Hence, wake variation obtained using this methodology adds or subtracts a constant value from the calm water wake. Therefore, contours of wake plots remain almost unaltered while just the level of contours changes.

Thus, it seems that viscous effects play a more significant role in wake variation than previously thought; partly due to the relatively high block coefficient of KVLCC2 hull. Therefore, any potential flow calculation method must be expected to fail to capture these effects, and therefore would fail to capture important wake features like wake peak. Hence, potential flow methods do not seem to be suited for calculation of the change of wake distribution due to waves, at least in the case of high block coefficient single-screw ships. However, it would be interesting to perform similar investigations for slender ships and twin-screw vessels.

4. Discussion

The analysis shows that the average amount of cavitation seen in the presence of waves is not significantly different from that in the calm water, even though the distribution of wake is very different. However, pressure pulses show a significant increase. Pressure pulses are proportional to the second derivative of the cavity volume. Therefore, higher cavity volume variations in the presence of waves lead to higher pressure pulses.

It was observed that average wake and wake distribution both change in the presence of waves. However, there is little or no correlation between the variation of Taylor wake fraction in Figure 32 and

the variation of pressure pulses in Figure 16. Therefore, pressure pulses vary primarily due to change in wake distribution rather than variation in the average wake.

The Xfoil analysis gives a clear picture of worst possible operating conditions in waves. However, these conditions would vary depending on vessel design. Therefore, instead of solely relying on the experience of propeller designers for the cavitation margins, it would be beneficial to have data of wake variation in at least one wavelength. Having wake data at least in one wavelength would be very useful, especially in the case of automated propeller optimization as described by Vesting [26], where the experience of the propeller designers is often missing.

In this study, the cavitation in different cases has been compared in terms of its volume. However, it is important also to look at the erosiveness of cavitation in waves compared to calm water. Since smaller volumes of cavitation can still be more erosive and therefore create more damage to the propeller.

Investigations in this paper are based on one hull and propeller design. We know that when it comes to propeller design and wake variation, each ship will have a different propeller and wake variation. Hence, in order to draw any generalized conclusions, more ships should be studied to check the general validity of our findings. Also, other wave conditions should also be analyzed e.g. irregular waves and following waves. Moreover, full-scale experimental measurements of pressure pulses in waves are required to confirm what is seen in the simulations, since there are complexities involved while going from model scale to full scale, like scale effects for wake variation and for the propeller itself. In spite of all this, the analysis in this paper strongly suggests that the conditions could become much worse in waves and much different from what is seen in calm water. When these conditions become clearer, it would be possible to extend the boundaries of propeller optimization by considering the conditions in the presence of waves.

5. Conclusions

The influence of operation in waves on the propeller performance, in terms of efficiency, cavitation extent and pressure pulses, has been investigated in this paper, using KVLCC2 as a case. The effect of wake change, ship motions, wave dynamic pressure, speed loss and RPM variation has been considered. It is found that the variation of wake distribution in waves has by far the largest impact on the propeller performance and the greatest change occurs for waves that have a length approximately equal to the ship length. However, getting wake data for operation in waves is hard. Also, the number of wake fields to be considered in a propeller design must be very limited - current practice is to consider only the calm water wake field at the design speed. Thus, we recommend that the wake field in a regular wave of wavelength to ship length ratio λ/L=1.1 is taken into account in the design, in addition to the calm water wake field. Knowing the wake distribution in worst intended operating condition can help us maximize the propeller efficiency while still avoiding the unwanted effects of cavitation and pressure pulses.

As our study has considered only one ship and propeller design, we recommend extending the study to more ship designs. Also, the effect of irregular waves and different wave headings on the wake distribution should be investigated.

6. Acknowledgement

The authors would like to thank Professor Frederick Stern from the University of Iowa for providing the wake data in waves used to analyze propeller in different conditions. We also thank Professor Bjørnar Pettersen for helping us obtain the wake data. This work is funded by the project 'Low Energy and Emission Design of Ships' (LEEDS, NFR 216432/O70) where the Research Council of Norway is the main sponsor. We are grateful to Rolls-Royce Hydrodynamic Research Centre along with the University Technology centers of Rolls Royce at NTNU and Chalmers University of Technology for their support. We

would also like to show our gratitude to Professor Carl-Eric Janson from Chalmers University of Technology for helping us with the Shipflow computations.

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APPENDIX A – Wake Fields

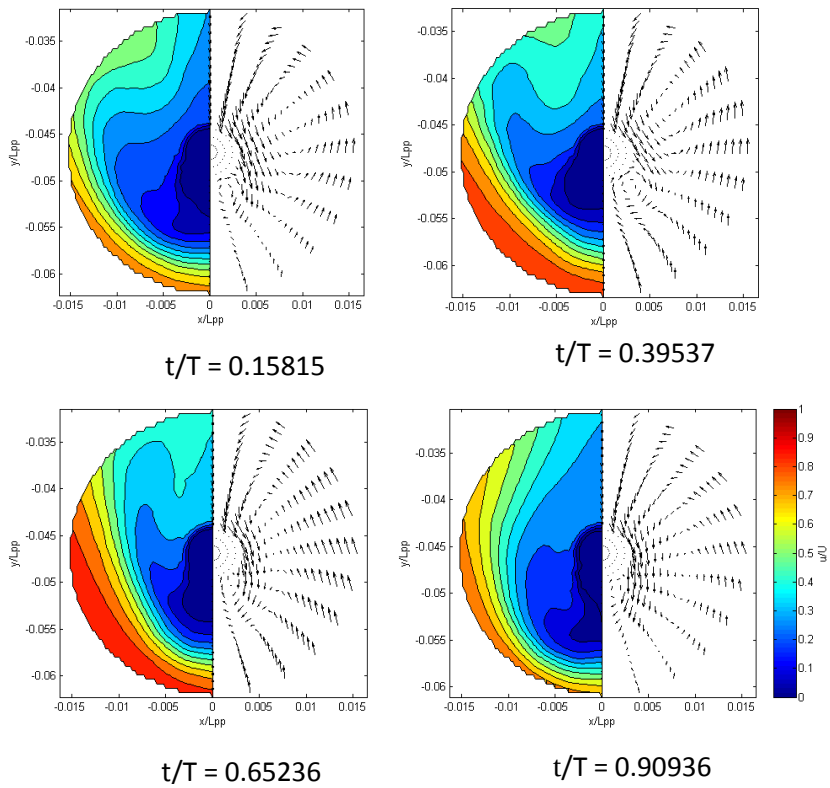

Figure A1 Wake in presence of wave having wavelength ratio λ/L = 0.6

DOI: 10.1016/j.apor.2016.08.009

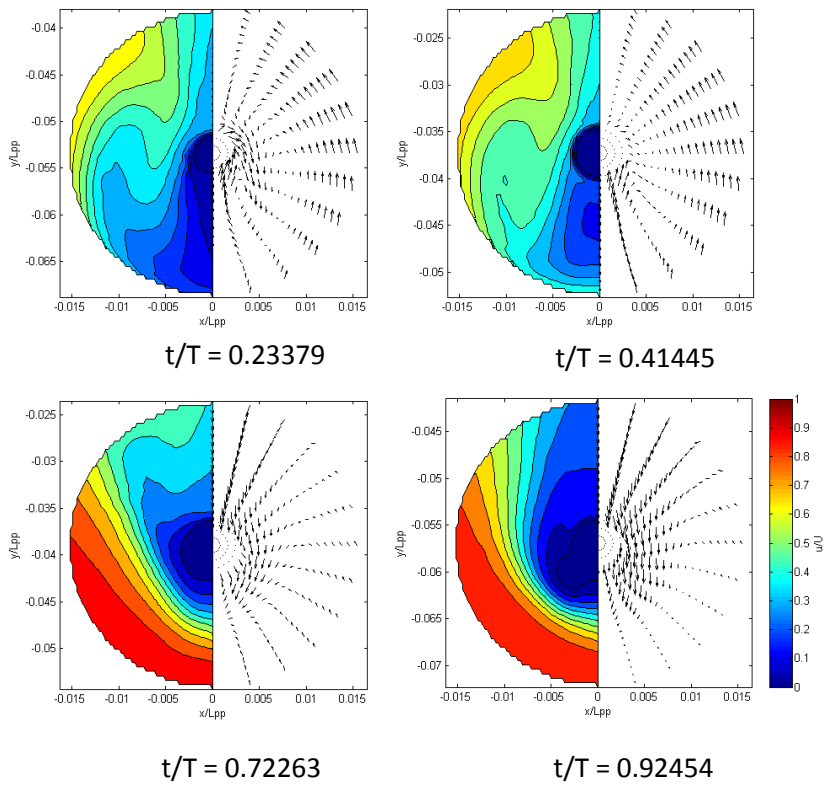

Figure A2 Wake in presence of wave having wavelength ratio λ/L = 1.6