

# Experimental Investigation of the Effect of Waves and Ventilation on Thruster Loadings

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## ABSTRACT

In order to obtain insight into the effect of waves and ventilation (air drawing) on propeller loading and dynamic fluctuations, tests of a model open pushing thruster were performed at different immersion ratios in different regular waves at different advance speeds. A high sampling frequency was employed for measurements, and wireless transmission was used to minimise data transfer noise. The objective of the study was to help to understand the dynamics of forces which in turn can improve the design of mechanical components for realistic loads. In addition results of the study provide knowledge for improved dimensioning of the thruster and more robust thrust allocation algorithms for dynamic positioning mode. The test set up is described briefly. Measurements of the total thrust from the thruster and propeller thrust and torque, together with underwater photographs of ventilated propeller at different submersion positions, are presented and discussed. Findings in this paper are – to some extent – also valid for podded propulsion units.

## Keywords

Ventilation; Waves; Dynamic forces; Propeller; Thruster; Pod

## 1 INTRODUCTION

Thrusters are widely used as manoeuvring and dynamic positioning propulsion units. Thrusters are also installed as main propulsion units of vessels. Vertical motions of the vessel and waves bring the thrusters closer to the surface and make them more susceptible to ventilation. In extreme cases, the propellers may partly or fully emerge from the water. MARINTEK has been performing several research programs related to thrusters and pods. These research programs involve both numerical and experimental research and development. On the numerical side, tools and methods are developed for design and analysis of podded propulsors. The main focus of the experimental investigation has been the dynamics

of these propulsors. However it has also been in a focus to provide a test series with a wide range of test parameters to assist thruster manufacturers with high quality empirical prediction tools. Koushan and Krasilnikov (2008) presented some of the research results regarding the hydrodynamic characteristics of open thrusters in oblique flow. Both numerical and experimental results were presented and discussed.

Kempf (1934) was a pioneer of the study of ventilation effects on propellers. He tested three- and four-bladed propellers at different revolutions and immersion ratios, and showed the negative effects of ventilation on thrust and torque. The effects of ventilation on average thrust and torque were studied by Shiba (1953), who also studied the effect of different propeller design parameters as well as the rate of revolutions and speed on ventilation. Gutsche (1967) presented the test results of partially submerged propellers and suggested a procedure for calculating the out-of-water effect on average thrust. Fleischer (1973) presented average thrust and torque measurements that demonstrated interactions between propeller and hull when the propeller is partly submerged. He also studied the effect of the rate of revolutions on ventilation. The effect of ventilation on average thrust and torque of propellers operating in waves has been discussed by Faltinsen et al. (1981) and Minsaas et al. (1987).

Koushan (2004) presented a study of total dynamic loadings of ventilated propellers, and showed that total propeller dynamic fluctuations during one ventilation cycle can range from 0 to 100% of the average force of a non-ventilated propeller. He also discussed the effect of partial submergence on the average thrust and torque of propellers at different advance coefficients and described thrust and torque estimation procedures as well as hysteresis around the critical advance coefficient.

Koushan (2006a) presented experimental results on the effects of ventilation on the dynamics of single-blade axial force (blade thrust) of the open propeller of a pulling thruster running at constant revolutions under

different constant immersion conditions at bollard condition. He showed that measured fluctuations were quite significant. Standard deviations of single-shaft frequency fluctuations in the blade thrust were almost equal to average blade thrust under partially submerged conditions. Measurements of average blade thrust showed that ventilation causes more than 40% loss under well submerged conditions and approximately 90% loss in partially submerged conditions. He discussed ventilation inception with the aid of photographs taken by an underwater high speed camera and scale effects in ventilation tests.

Koushan (2006b) described the effect of ventilation on the dynamics of axial force (thrust) of a single blade of the open propeller of a pulling thruster moving with forced sinusoidal heave motion under bollard condition. The highest position of the propeller varied from completely out of water to fully submerged. It was shown that fluctuations of blade axial force (blade thrust) are quite significant when the propeller is ventilated during a heave motion. It is the ventilation that is the main cause of fluctuations rather than the heave motion itself, though heave motion acts as generator and convector of ventilation. Koushan (2006b) also showed that the inception of ventilation leads to the highest dynamic fluctuations and results in a sudden large drop in blade thrust in the course of a single propeller revolution.

Koushan (2006c) has also discussed the effects of ventilation on the dynamics of thrust and torque of a single blade of the propeller of a pushing ducted thruster running at constant revolutions under various constant immersion conditions at bollard condition. He presented average duct and total thrust as well as the average propeller torque of a ducted thruster under various submergence conditions. A duct loses approximately 95% of its thrust at a propeller shaft immersion of one radius while 80% propeller thrust loss is measured at this submergence. The paper offered a comparison with the average loadings of a ventilated open thruster.

Koushan (2007) focused on the effect of ventilation on the dynamics of blade axial force (blade thrust), on blade moment about propeller shaft (corresponding to propeller torque), on duct thrust and on total thrust of a pushing ducted thruster moving with forced sinusoidal heave motion at bollard condition. The highest position of the propeller varied from completely out of water to fully submerged. Koushan shows that variations in relative blade torque are almost identical to variations in relative blade thrust under all ventilated conditions when the ducted thruster undergoes forced periodic heave motion. More ventilation leads to less available blade thrust, blade torque, duct thrust and consequently total thrust. Duct thrust suffers the largest relative losses due to ventilation. A duct loses half of its average thrust during one heave

cycle when the propeller at its highest position is just fully submerged and is touching the surface, i.e.  $h/R=1$ . Under such conditions, the available average propeller thrust during one heave cycle is just above 70%. Available duct and propeller thrust are negligible when the propeller is completely out of the water at its highest position during the heave cycle (i.e.  $h/R = -1$ ), even though it is fully submerged at its lowest position in the cycle.

This paper concentrates on the effect of waves and on propeller loadings of an open pushing thruster. These tests were conducted in the large towing tank at MARINTEK. A high sampling frequency was used during measurements. A propeller balance capable of measuring propeller thrust and torque was used, as was a novel wireless transmission system, to minimise data transmission noise.

$T$  is the propeller thrust.  $Q$  is the propeller torque.  $TTOT$  is the total thrust of the whole unit including propeller and thruster body. Propeller immersion refers to immersion of the propeller shaft centre-line relative to the undisturbed free surface (without waves) and is denoted  $h_0$  (positive downwards).  $h$  is the instantaneous propeller shaft immersion (positive downwards) and is referred to as dynamic immersion in the paper. Immersion ratio is the ratio between immersion and the propeller radius  $R$ .  $H$  is the wave height and  $T$  is the wave period. Wave height ratio is the ratio between  $H$  and radius  $R$ .  $V$  is the advance speed,  $n$  is the propeller rate of revolutions and  $D$  is the propeller diameter.  $\rho$  is the water density. Following standard coefficients are used in the paper:

$$\text{Propeller thrust coefficient: } KT = \frac{T}{\rho \cdot n^2 \cdot D^4}$$

$$\text{Total thrust coefficient: } KTTOT = \frac{TTOT}{\rho \cdot n^2 \cdot D^4}$$

$$\text{Propeller torque coefficient: } KQ = \frac{Q}{\rho \cdot n^2 \cdot D^5}$$

$$\text{Advance coefficient: } J = \frac{V}{n \cdot D}$$

## 2 PROPELLER AND THRUSTER

The propeller used is of a generic design. Since this propeller is also used for thruster tests with ducted propellers, the design is a compromise between an open and a ducted four-bladed right-handed propeller. Propeller drawings are presented by Koushan (2006b). The propeller has a diameter of 250 mm. Design pitch ratio is 1.1 and the blade area ratio is approximately 0.6. Figure 1 illustrates the pressure side photograph of the propeller.

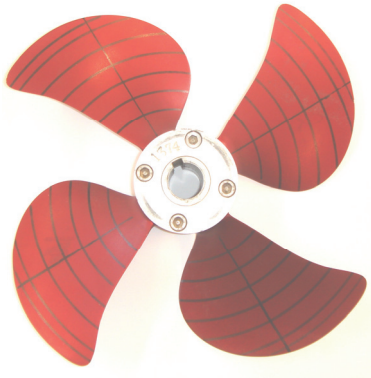


Figure 1 Pressure side view of the propeller

Figure 2 shows a rendered drawing including main dimensions of the thruster body. The thruster body is 181 mm long. The maximum diameter of the thruster body is 92 mm. A top view drawing of the model thruster is presented in Figure 3.



Figure 2 Rendered drawing of thruster body (side view)

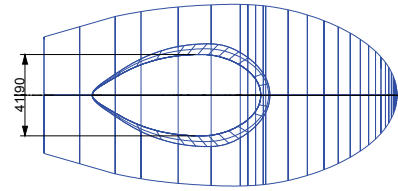


Figure 3: Top view drawing of model thruster

### 3 TEST SETUP AND INSTRUMENTATION

Tests were conducted in the MARINTEK large towing tank. This tank is 260 m long, 10.5 m wide and 5.6 to 10 m deep. The propeller was driven with an electric motor on top of the thruster. The propeller was mounted on a propeller balance designed and manufactured by MARINTEK. Thrust and torque of the propeller were measured using the propeller balance. A six-component balance was positioned on top of the thruster unit, measuring forces and moments on the whole unit including the propeller. To avoid measurement noise generated by slip-rings, an in-house developed wireless transmission system was used to transfer the data from the propeller balance to the data acquisition system. A pulse meter provided propeller rate of revolutions. Figure 4 shows a picture of the test set up.



Figure 4 Test setup

### 3 PERFORMED MODEL TESTS

Tests were performed at different propeller immersion ratios in several regular waves. All presented tests were carried out with a propeller rate of revolutions of 14 Hz. Therefore all tests are above the critical Weber number (Ref. Koushan 2006a).

Table 1 shows a list of selected model tests that are discussed in this paper. Conditions 1 to 5 refer to an initial propeller immersion ratio of 1.2 related to the undisturbed free surface while conditions 6 to 10 refer to immersion ratio of 1.6 related to the undisturbed free surface. Wave height ratio varies from 1 to 3.3, which results in partial or full emergence of the propeller during a wave cycle. Conditions 1 and 2 refer to same wave height but different wave period. This is also the case for conditions 6 and 7.

**Table 1 Performed model tests**

Condition	Immersion ratio $h_0/R$	Wave height ratio $H/R$	Wave period $T$ (s)
1	1.2	1	1.5
2	1.2	1	2.5
3	1.2	2	2
4	1.2	2.5	2
5	1.2	3.3	2
6	1.6	1	1.5
7	1.6	1	2.5
8	1.6	2	2
9	1.6	2.5	2
10	1.6	3.3	2

### 5 EFFECT OF WAVES AND VENTILATION ON TIME AVERAGED PROPELLER LOADINGS

Time averaged values of propeller thrust coefficient versus advance coefficient are presented in Figure 5 to Figure 14 for propeller immersion ratios 1.2 and 1.6 and for different wave heights and wave periods. For comparison purposes, measurements with a non ventilated deeply submerged propeller as well as measurements with propeller immersion ratios of 1.2 and 1.6 without waves are also presented. For all ventilated conditions, it can be observed that a sudden drop in thrust is measured when the advance coefficient becomes less

than 0.4, which is the so called critical advance coefficient for this propeller pitch setting. This phenomenon is discussed by Koushan (2004) and Shiba (1953). For the sub critical region, i.e. for advance coefficients larger than the critical advance coefficient, propeller thrust of a ventilated propeller can be roughly estimated using out-of-water and Wagner effects as explained by Koushan (2004).

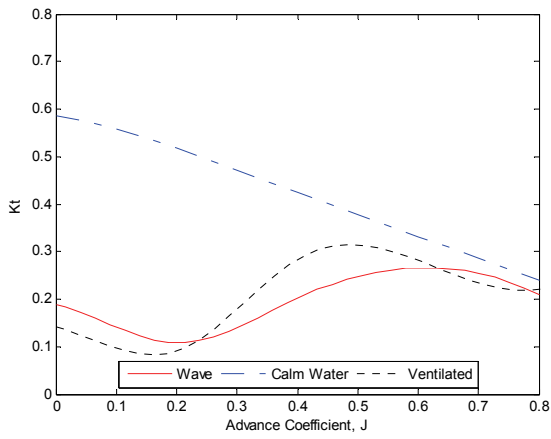
From critical advance coefficient  $J=0.4$  down to advance coefficient  $J=0.2$ , further reduction of the thrust of ventilated propeller is measured while from advance coefficient  $J=0.2$  down to bollard condition ( $J=0$ ) some thrust recovery for ventilated conditions is registered. This thrust drop and recovery is observed both with and without waves, though amount of thrust recovery is more pronounced in the case of ventilation in waves. In general, a larger thrust recovery is observed for immersion ratio  $h_0/R=1.6$  than for immersion ratio  $h_0/R=1.2$ .

The effect of wave period is not very dominant when comparing measurements for conditions 1 and 2 (Figure 5 and Figure 6) corresponding to immersion ratio  $h_0/R=1.2$  and wave periods 1.5 s and 2.5 s respectively. The same conclusion is valid for conditions 6 and 7 (Figure 10 and Figure 11) corresponding to immersion ratio  $h_0/R=1.6$  and wave periods 1.5 s and 2.5 s respectively. However a general conclusion can not be drawn because these tests are performed at a low wave height ( $H/R=1$ ).

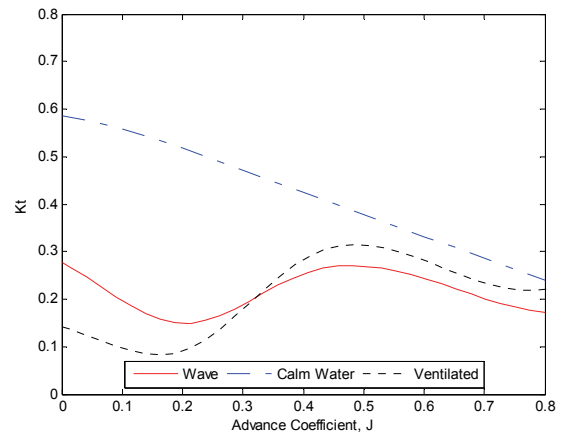
Experimental results for tests in waves for both immersion ratios  $h_0/R=1.2$  and  $h_0/R=1.6$  show that the effect of wave height is significant especially for the sub critical region i.e. advance coefficients larger than 0.4, where higher waves lead to larger thrust loss.

Introduction of waves results in even larger thrust loss due to ventilation for immersion ratio  $h_0/R=1.6$  compared to immersion ratio  $h_0/R=1.2$ . For immersion ratio  $h_0/R=1.2$ , introduction of waves contributes to some thrust recovery for advance coefficients less than 0.2, whereas for advance coefficients above 0.2 less thrust is measured compared to ventilated case without waves.

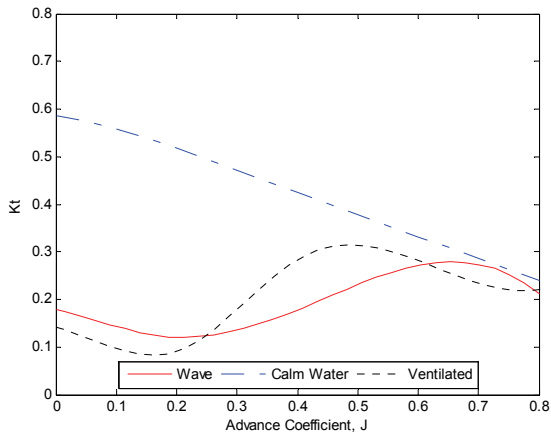
The effect of waves and ventilation on propeller torque coefficient follows the same trends as on propeller thrust coefficient. Propeller torque measurements are presented in Figure 23 to Figure 32 (ref. appendix). The same conclusion is valid for the effect of waves and ventilation on total thrust (ref. Figure 33 to Figure 42 presented in appendix).



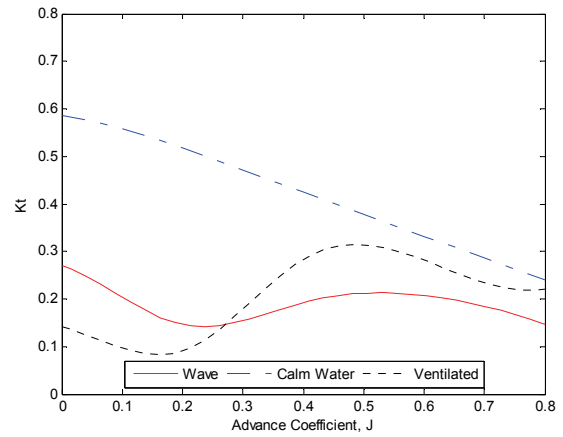
**Figure 5 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=1$ , wave period  $T=1.5$  s.**



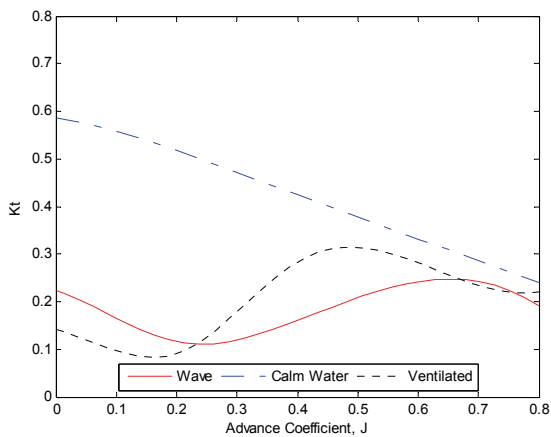
**Figure 8 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=2.5$ , wave period  $T=2$  s.**



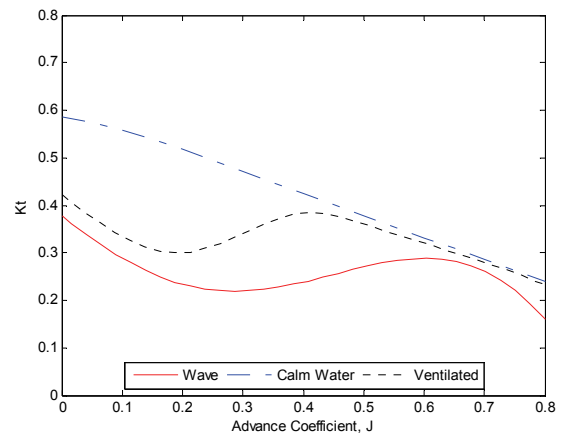
**Figure 6 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=1$ , wave period  $T=2.5$  s.**



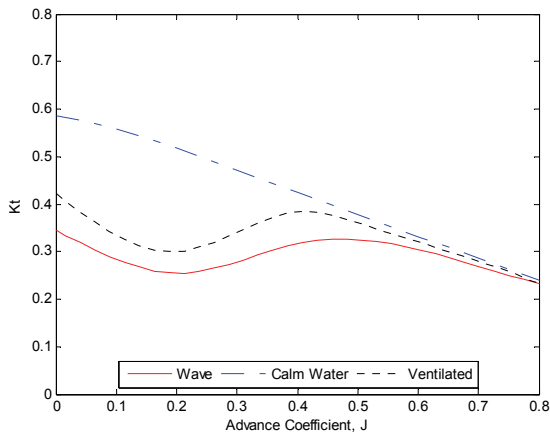
**Figure 9 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=3.3$ , wave period  $T=2$  s.**



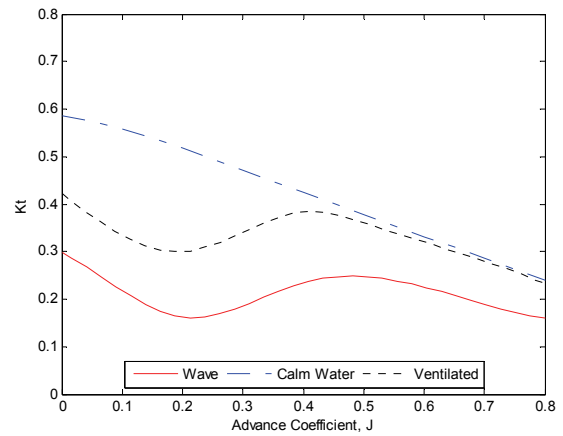
**Figure 7 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=2$ , wave period  $T=2$  s.**



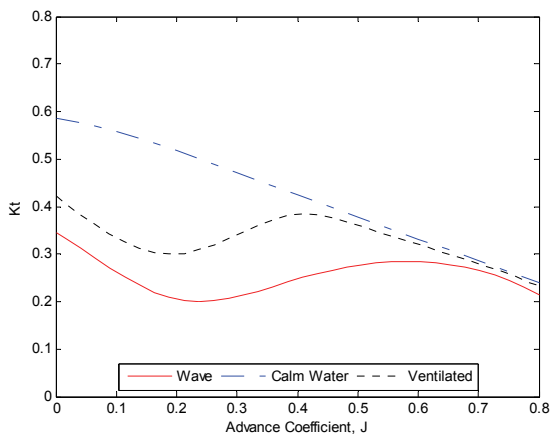
**Figure 10 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=1$ , wave period  $T=1.5$  s.**



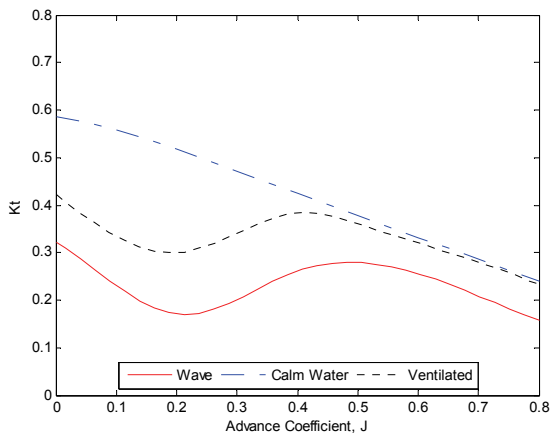
**Figure 11 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=1$ , wave period  $T=2.5$  s.**



**Figure 14 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=3.3$ , wave period  $T=2$  s.**



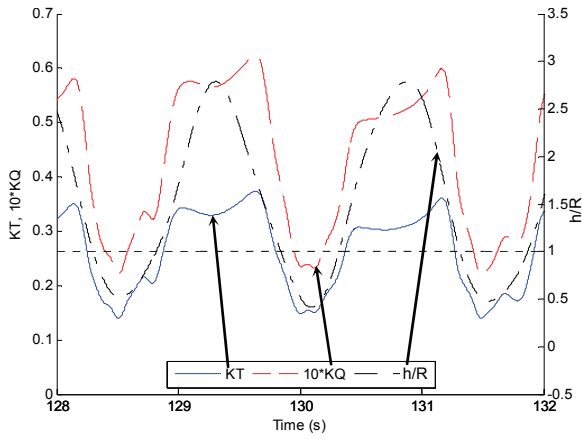
**Figure 12 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=2$ , wave period  $T=2$  s.**



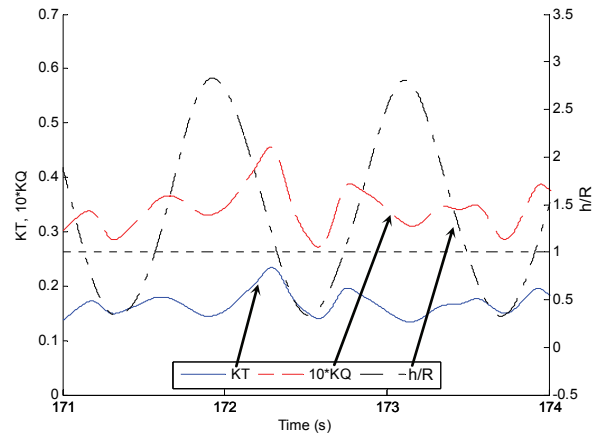
**Figure 13 Thrust coefficient  $KT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=2.5$ , wave period  $T=2$  s.**

#### 4 DYNAMIC EFFECTS OF WAVES AND VENTILATION ON PROPELLER LOADINGS

Figure 15 and Figure 16 show the time series of measured propeller thrust and torque coefficients and dynamic propeller immersion for propeller immersion ratios  $h_0/R=1.6$  and  $h_0/R=1.2$  respectively. During these tests, the advance coefficient was 0.4, which is close to the critical advance coefficient. Measurements are filtered using a low frequency pass filter. These figures show that propeller thrust and torque variations follow the same trends; thrust and torque follow surface elevation. Highest values are registered in the vicinity of the wave crest (propeller fully submerged) and lowest values are measured close to the wave trough where maximum ventilation happens. Once the propeller is ventilated, it keeps ventilated even as its emergence decreases. A similar phenomenon was observed during tests with a thruster under forced sinusoidal heave motion (ref. Koushan 2006b). Additional humps are registered when the propeller is coming out of the water and the blades are slamming the water free surface. Relative differences between minimum and maximum measured values are quite large, from 55% to 150% of the time averaged value for propeller immersion ratio  $h_0/R=1.6$  and from 40% to 150% of the time averaged value for immersion ratio  $h_0/R=1.2$ .



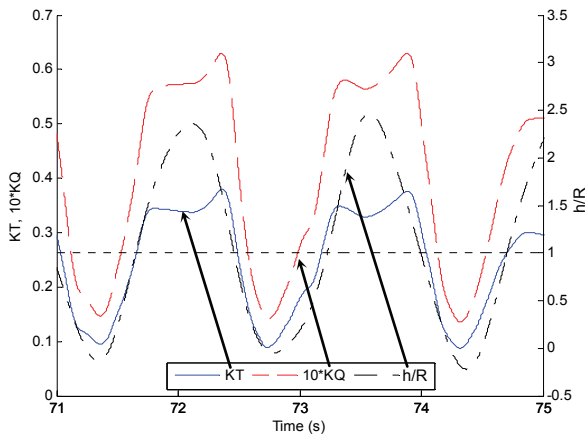
**Figure 15** Time series of propeller thrust and torque coefficients and dynamic propeller immersion. Propeller immersion ratio  $h_0/R=1.6$ , Wave height ratio  $H/R=2.5$ , Wave period  $T=2$  s, Advance coefficient  $J=0.4$



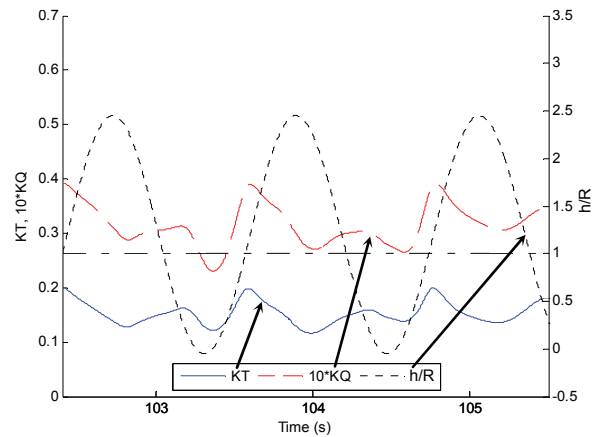
**Figure 17** Time series of propeller thrust and torque coefficients and dynamic propeller immersion. Immersion ratio  $h_0/R=1.6$ , Wave height ratio  $H/R=2.5$ , Wave period  $T=2$  s, Advance coefficient  $J=0.8$

Time series measurements of the propeller thrust and torque coefficients and dynamic propeller immersion for propeller immersion ratios  $h_0/R=1.6$  and  $h_0/R=1.2$  are shown in Figure 17 and Figure 18 respectively. The advance coefficient was 0.8 during these tests, which is in the sub critical ventilation region. Therefore less variation in propeller loading was measured compared to those registered for advance coefficient  $J=0.4$ . Variations in this case are mostly around  $\pm 20\%$  of the time averaged values. Humps are still registered when the propeller is coming partially out of the water or when the propeller is immersed again, due to the fact that the blades are slamming the water free surface.

Selected underwater video captures of tests discussed in this section are presented in Figure 19 to Figure 22. Pictures close to the wave trough (left picture) and the wave crest (right picture) are presented for advance coefficients 0.4 and 0.8 under propeller immersion ratios of  $h_0/R=1.2$  and  $h_0/R=1.6$ . During the wave trough, full ventilation is observed in all mentioned conditions due to partial emergence of the propeller. During the wave crest (fully submerged propeller) at the sub critical advance coefficient of 0.8, clear ventilation of the trailing edge of the thruster leg is observed. This ventilation reaches the propeller tip and inclines towards the free surface behind the propeller. However the propeller is hardly ventilated in this condition. At the critical advance coefficient of 0.4, during the wave crest, no thruster leg ventilation is seen. The propeller tip still ventilates in this condition.



**Figure 16** Time series of propeller thrust and torque coefficients and dynamic propeller immersion. Immersion ratio  $h_0/R=1.2$ , Wave height ratio  $H/R=2.5$ , Wave period  $T=2$  s, Advance coefficient  $J=0.4$



**Figure 18** Time series of propeller thrust and torque coefficients and dynamic propeller immersion. Immersion ratio  $h_0/R=1.2$ , Wave height ratio  $H/R=2.5$ , Wave period  $T=2$  s, Advance coefficient  $J=0.8$

## 6 CONCLUSIONS

For all ventilated conditions, it can be observed that a sudden drop in thrust is measured when the advance coefficient becomes less than 0.4, which is the so called critical advance coefficient for this propeller pitch setting. From critical advance coefficient  $J=0.4$  down to advance coefficient  $J=0.2$ , further reduction of the thrust is measured while from advance coefficient  $J=0.2$  down to bollard condition ( $J=0$ ) some thrust recovery is registered. This thrust drop and recovery is observed both with and without waves, though amount of thrust recovery is more pronounced in the case of ventilation in waves. The effect of wave height is significant especially for the sub critical region i.e. advance coefficients larger than 0.4, where higher waves lead to larger thrust loss. The effect of waves and ventilation on propeller torque follows the same trends as on propeller thrust.

Dynamic variations of thrust and torque follow surface elevation. Highest values are registered in the vicinity of the wave crest (propeller fully submerged) and lowest values are measured close to the wave trough where maximum ventilation happens. Once the propeller is ventilated, it keeps ventilated even as its emergence decreases. Additional humps are registered when the propeller is coming out of the water and the blades are slamming the water free surface.

## ACKNOWLEDGEMENT

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APPENDIX

UNDERWATER PICTURES



Figure 19 Underwater picture, left: wave trough, right: wave crest, propeller immersion ratio  $h_0/R=1.6$ , advance coefficient  $J=0.4$



Figure 20 Underwater picture, left: wave trough, right: wave crest, propeller immersion ratio  $h_0/R=1.2$ , advance coefficient  $J=0.4$



Figure 21 Underwater picture, left: wave trough, right: wave crest, propeller immersion ratio  $h_0/R=1.6$ , advance coefficient  $J=0.8$



Figure 22 Underwater picture, left: wave trough, right: wave crest, propeller immersion ratio  $h_0/R=1.2$ , advance coefficient  $J=0.8$

TORQUE COEFFICIENT DIAGRAMS

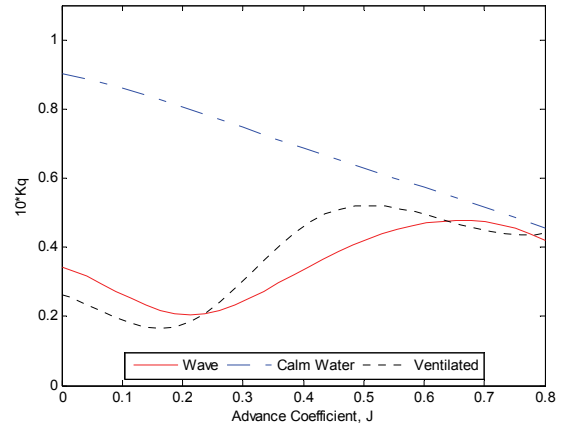


Figure 23 Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=1$ , wave period  $T=1.5$  s

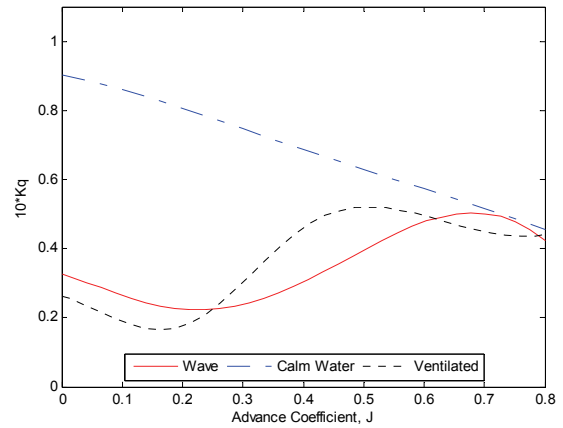


Figure 24 Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=1$ , wave period  $T=2.5$  s

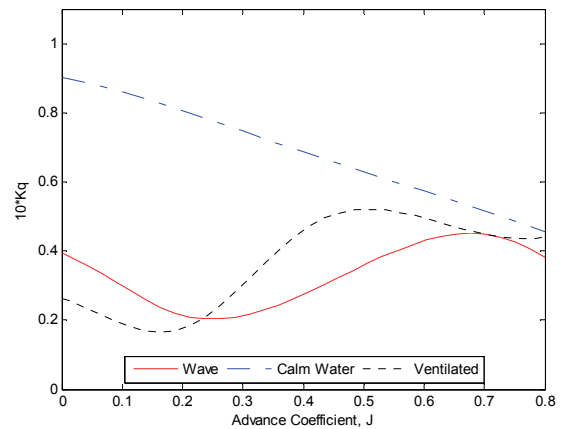
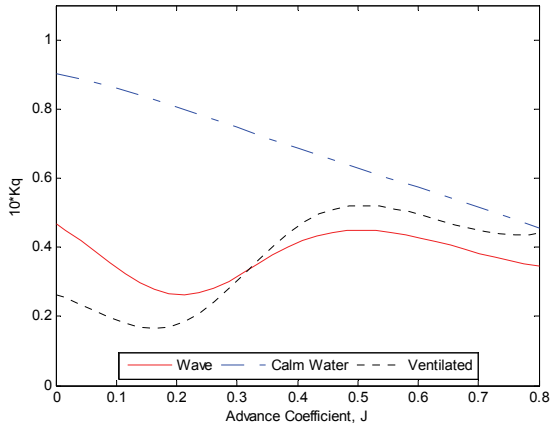
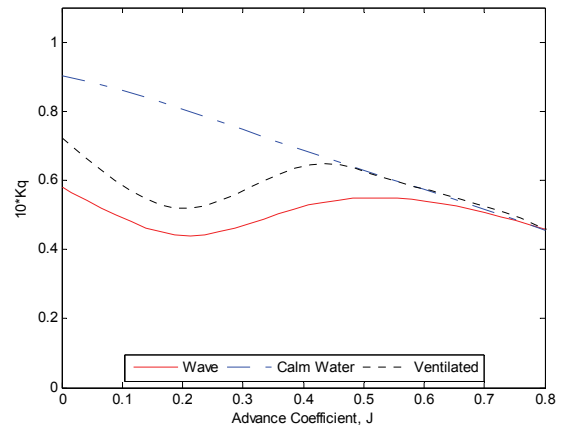


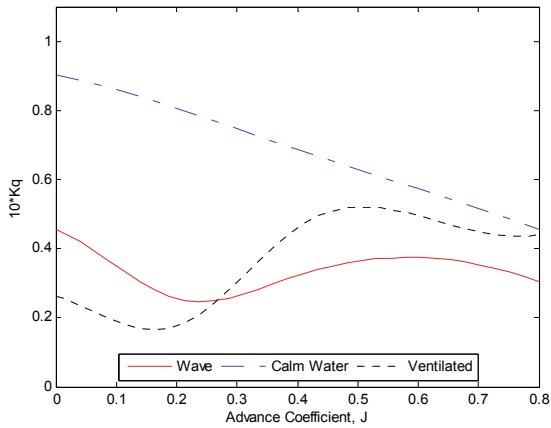
Figure 25 Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=2$ , wave period  $T=2$  s



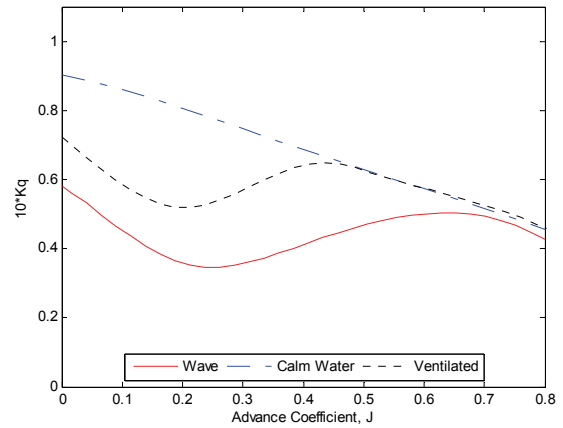
**Figure 26** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=2.5$ , wave period  $T=2$  s



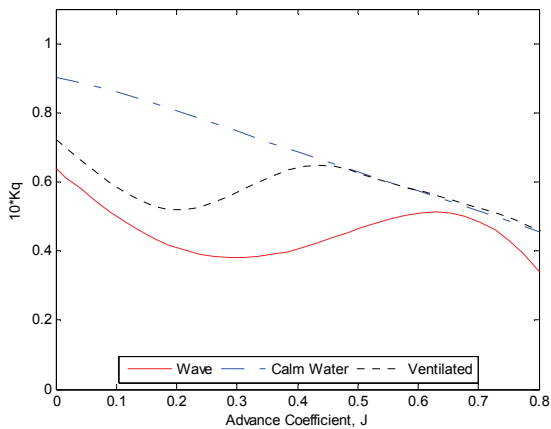
**Figure 29** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=1$ , wave period  $T=2.5$  s



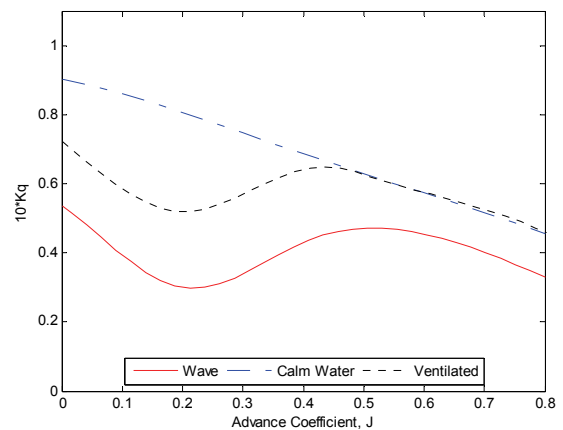
**Figure 27** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=3.3$ , wave period  $T=2$  s



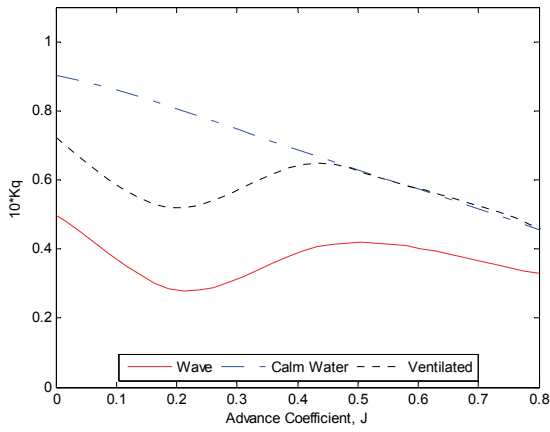
**Figure 30** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=2$ , wave period  $T=2$  s



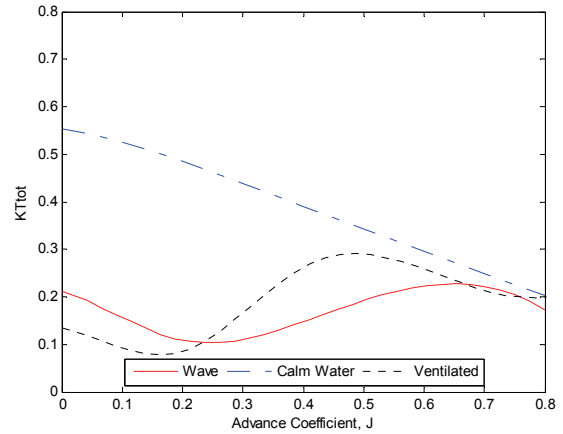
**Figure 28** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=1$ , wave period  $T=1.5$  s



**Figure 31** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=2.5$ , wave period  $T=2$  s

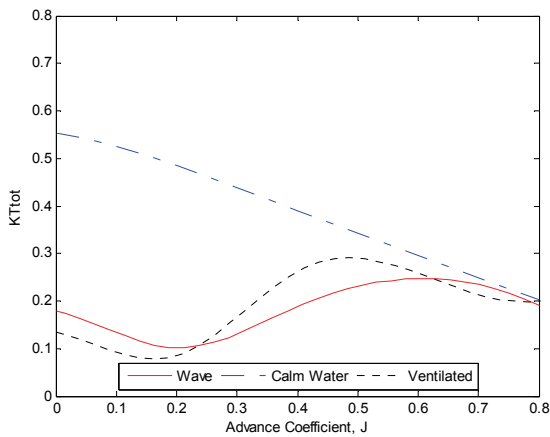


**Figure 32** Torque coefficient  $KQ$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=3.3$ , wave period  $T=2$  s

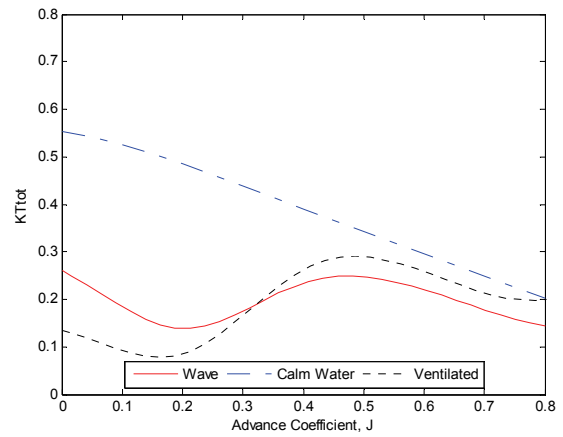


**Figure 35** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=2$ , wave period  $T=2$  s.

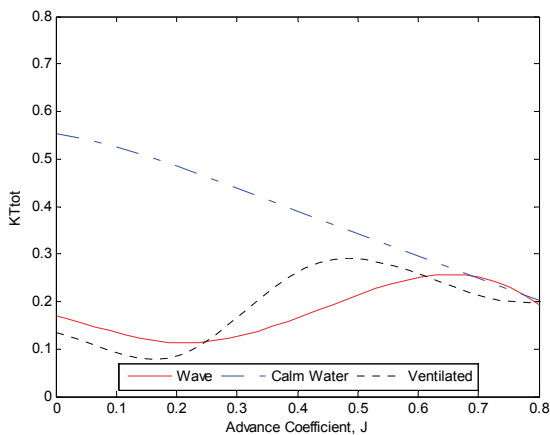
TOTAL THRUST COEFFICIENT DIAGRAMS



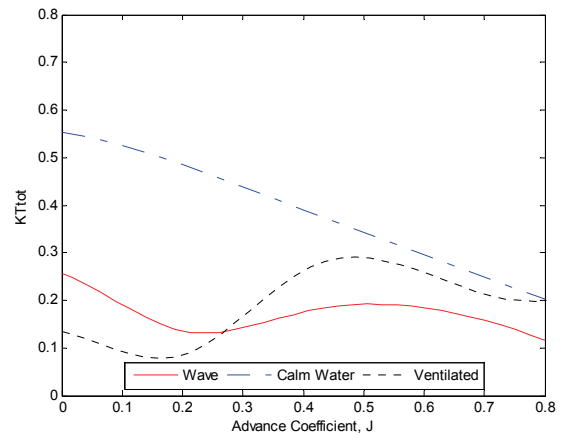
**Figure 33** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=1$ , wave period  $T=1.5$  s.



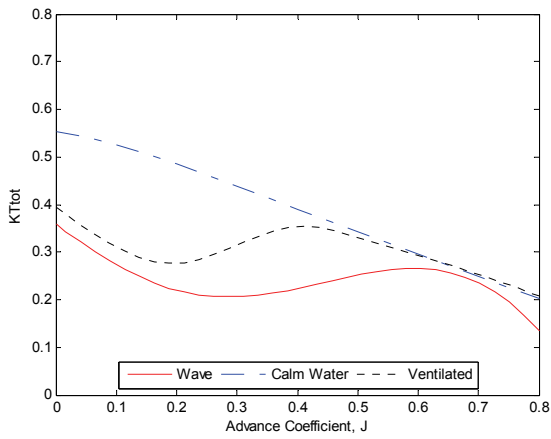
**Figure 36** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=2.5$ , wave period  $T=2$  s.



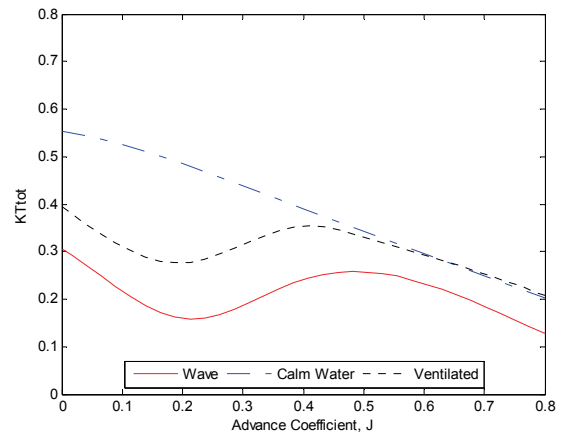
**Figure 34** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=1$ , wave period  $T=2.5$  s.



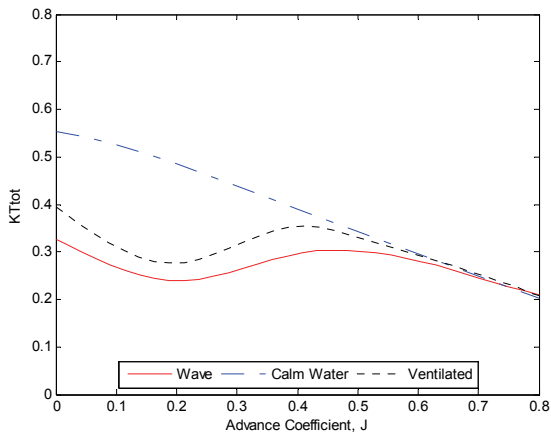
**Figure 37** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.2$ , wave height ratio  $H/R=3.3$ , wave period  $T=2$  s.



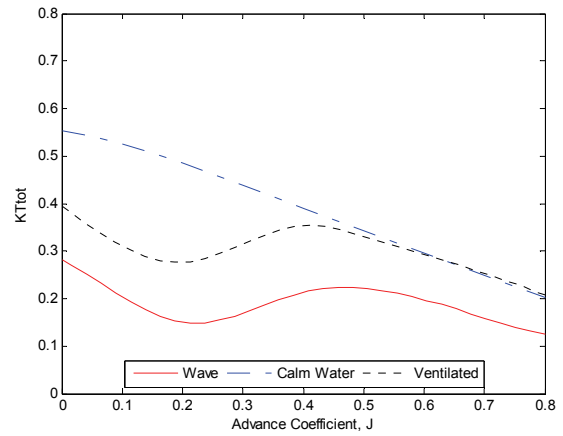
**Figure 38** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=1$ , wave period  $T=1.5$  s.



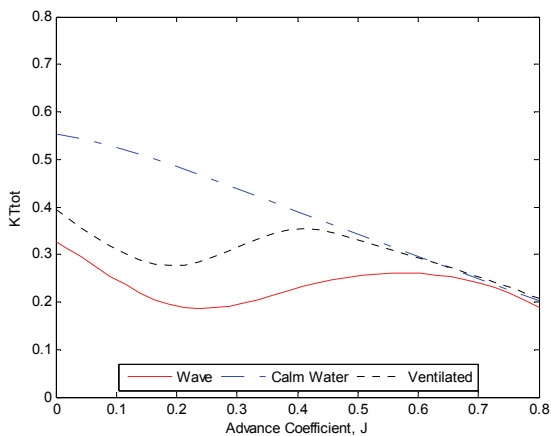
**Figure 41** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=2.5$ , wave period  $T=2$  s.



**Figure 39** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=1$ , wave period  $T=2.5$  s.



**Figure 42** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=3.3$ , wave period  $T=2$  s.



**Figure 40** Total thrust coefficient  $KTTOT$  versus advance coefficient  $J$ . Effect of wave and propeller immersion. Immersion ratio  $h_0/R=1.6$ , wave height ratio  $H/R=2$ , wave period  $T=2$  s.