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Ventilated Propeller Blade Loadings and Spindle Moment of a Thruster in Calm Water and Waves

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ABSTRACT

This paper presents experimental results of the forces and moments acting on a single propeller blade running in ventilated conditions in calm water and in waves. A model of a Rolls-Royce Azipull thruster with a four-blade propeller was tested with provisions to measure three orthogonal moments including spindle moment and two forces, on a single blade. The centrifugal force was not measured. High speed video is included to help gain a clearer understanding of the ventilation phenomena. The primary purpose of these tests is to establish a dataset for comparison with CFD calculations. They are also of use in structural design of propeller blades and improvement of dynamic positioning systems. Time averaged and dynamic measurements are presented, with the influence of various conditions such as static immersion, wave height, wave period, and propeller loading analyzed with respect to reduction in forces and moments. Comparisons are made with both ventilated and unventilated calm water cases.

Keywords

Thruster, Ventilation, Waves, Spindle Moment, Blade Loadings

1 INTRODUCTION

Current practice for design of propulsion systems is based mainly on analysis of calm water performance. The effects of seaways and motions of the ships and floating offshore structures are supposed to be taken into account by using high safety factors. The same applies for classification of the propulsion systems. However experience has shown that the problems are not necessarily solved by simply oversized dimensioning of the propulsors and machinery. The effects of excessive ship motions on extreme loads of propulsion units have not been studied in details.

Kempf (1934), Shiba (1953), Gutsche (1967) and Fleischer (1973) were pioneers of the study of ventilation effects on propellers. They tested and studied effect of different design, geometrical and operational parameters on ventilation effect in calm water, including number of blades, immersion ratio, rate of revolutions and speed, and propeller-hull interaction. The effect of ventilation on propellers operating in waves has been discussed by Faltinsen et al (1981) and Minsaas et al (1987). All these studies were focused on time averaged thrust and torque.

Koushan (2004) presented a study of total dynamic loadings of ventilated propellers, and showed that fluctuations during one ventilation cycle can range from 0 to 100% of the average force of a non-ventilated propeller. He also discussed 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 under different static immersion conditions at bollard condition. He showed quite significant measured fluctuations and that ventilation causes more than 40% loss of thrust under well submerged conditions and approximately 90% loss in partially submerged conditions. Koushan (2006b) presented results of tests performed under forced sinusoidal heave motion. The highest position of the propeller varied from completely out of water to fully submerged. Also in this case, significant loading fluctuations were measured 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 (2006c) discussed experimental results of a pushing ducted thruster under various static immersion conditions at bollard condition. He presented average duct and total thrust as well as the average propeller torque 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 forced sinusoidal heave motion. 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 heave motion. Also in this case, 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 thrust 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.

Koushan et al (2009) studied effect of ventilation and waves on thrust and torque of a pushing thruster at different advance speeds and immersion ratios. 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 tested propeller pitch setting. Further reduction of the thrust is measured down to advance coefficient J=0.2, while from advance coefficient J=0.2 down to bollard condition (J=0) some thrust recovery is registered. This is observed both with and without waves, though amount of thrust recovery is more pronounced in waves. The effect of wave height is significant especially for the sub-critical region i.e., advance coefficients larger than 0.4. 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.

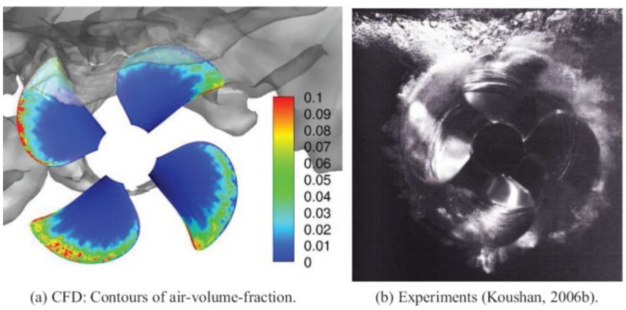

Figure 1: Comparison between calculated flow field and ventilation (a) model test observation (b) (Califano 2010)

More recently, there is significant research on numerical prediction of hydrodynamic performance of ventilated propellers. Califano (2010) performed numerical analysis of ventilated propellers using CFD during his PhD research. Figure 1 shows a comparison between CFD calculated and experimental results.

MARINTEK has been performing several research programs related to thrusters and pods performance in seaways. One of them is the cooperative European research project PropSeas. Other Norwegian partners are Rolls-Royce Marine, NTNU and Farstad Shipping while German partners are Germanischer Lloyd, Technical University of Hamburg, University of Duisburg-Essen and Develogic. The project is sponsored by The Research Council of Norway and German Federal Ministry of Economics and Technology in addition to contributions from industrial partners. Activities in the project include numerical analyses, model testing and unique full scale long term monitoring of propeller blade loadings of an offshore vessel operating in seaways. Results of the project can then be applied to revise classification and design guidelines.

In this paper, authors present the results of part of the model experimental investigations performed at MARINTEK. Tests were conducted with a scaled model of a Rolls Royce Azipull pulling thruster in waves and in calm water at different immersion ratios and various advance coefficients. Single propeller blade loadings were measured using an in-house developed blade dynamometer. Tests were documented using high-speed video cameras above and underwater. Global loadings on the thruster were measured by a 6-component balance. Data acquisition was done with high sampling frequency to capture the dynamics. For the first time, results of blade spindle moment of these model tests are presented.

2 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 10m deep.

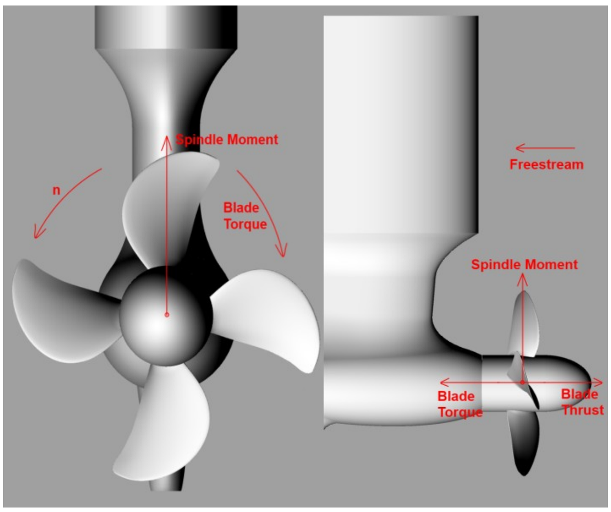

Figure 2: Coordinate System

The tests were conducted using a model of a Rolls-Royce Azipull pulling thruster, as seen in Figure 3. The thruster housing was modified slightly to accommodate the required instrumentation, and the uppermost part of the thruster housing was extruded up to the above the free surface. The right-handed propeller was 4-bladed with pitch ratio of 1.2 and blade area ratio of 0.447. The diameter of the model propeller is 200 mm.

Standard sign conventions are used for thrust and torque, while spindle moment is defined as being positive in the direction of increasing blade pitch (see Figure 2).

Figure 3: Model Azipull thruster

The measurement blade (red) was mounted on a five-component force balance, designed and manufactured by MARINTEK, capable of measuring two forces and three moments (centrifugal force is not included). The propeller was driven with an electric motor on top of the thruster. 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 high resolution rotary encoder provided propeller angular position and rate of revolutions. High speed video cameras above and underwater documented ventilation events.

Following standard coefficients are used in the paper:

$$J = \frac{V}{n \cdot D}$$ advance coefficient

$$K_T = \frac{T_{BLADE}}{\rho \cdot n^2 \cdot D^4}$$ blade thrust coefficient

$$K_Q = \frac{Q_{BLADE}}{\rho \cdot n^2 \cdot D^5}$$ blade torque coefficient

$$K_{SM} = \frac{SM}{\rho \cdot n^2 \cdot D^5}$$ spindle moment coefficient

D	Propeller diameter
H	Wave height
H	Instantaneous propeller shaft immersion
$h0$	Immersion of the propeller shaft centre-line relative to the undisturbed free surface (without waves), positive downwards
N	Propeller rate of revolution
Q_{BLADE}	Single blade torque
R	Propeller radius
SM	Blade spindle moment
T	Wave period
T_{BLADE}	Single blade thrust
V	Advance speed
ρ	Water density

Immersion ratio is the ratio between immersion and the propeller radius *R*. Wave height ratio is the ratio between *H* and *R*. *OW* annotation refers to average value for given advance coefficient for fully submerged non-ventilated case. Standard deviation is denoted as *S.D.*

3 PERFORMED MODEL TESTS

Tests were performed in calm water and one set of regular waves. All presented tests were carried out at a propeller rate of revolutions of 18 Hz. Therefore, all tests are above the critical Weber number (ref. Koushan 2006a). Table 1 provides a list of selected model tests which are discussed in this paper.

Table 1: Test conditions

Condition	Immersion ratio *h0/R*	Advance Coeff. *J* range	Wave height ratio *H/R*	Wave period *T* (s)
Calm water	2.5	0 - 1.2		
Calm water	1	0 - 1.2		
Regular wave	1	0 - 1.2	2	1.5

as given in histogram in Figure 8. Respective underwater photo is shown in Figure 11, which shows partial ventilation of the propeller.

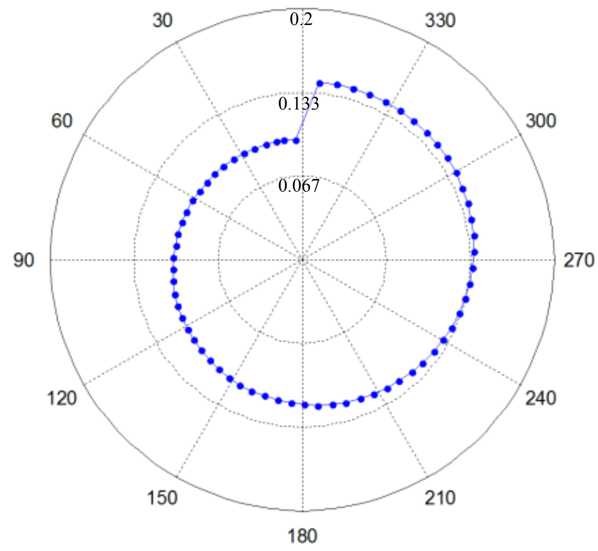

Figure 5: Polar diagram showing low pass filtered normalised thrust coefficient K_T/K_{TOW} in one single revolution, advance coefficient J=0, calm water, immersion ratio $h0/R$=1

Histogram for advance coefficient J=1.2 is given in Figure 9, which shows symmetrical variation of approximately ± 10% of the mean thrust, mainly due to propeller strut interaction. It can be seen from underwater photo shown in Figure 12 that there is no ventilation.

As histograms approximate the probability distribution, they show that the standard deviation values should be handled with some care as the data shows distributions that can be both highly skewed and non-Gaussian. Torque variations are similar to the thrust variations as shown in Figure 6.

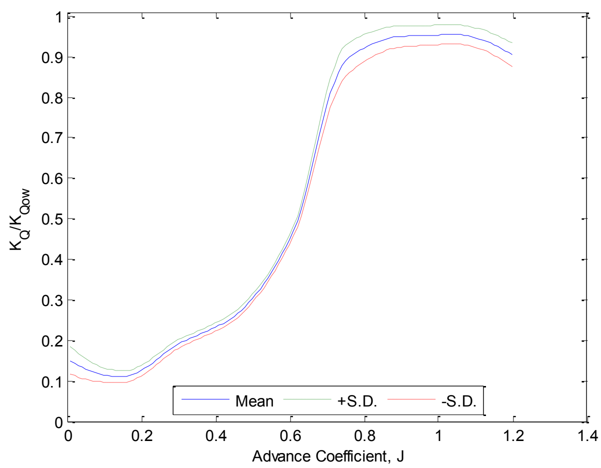

Figure 6: Normalised torque coefficient K_Q/K_{QOW} vs advance coefficient J, calm water, immersion ratio $h0/R$=1, Mean and Mean±Standard Deviation are shown.

4 RESULTS

Where noted in the relevant graph axes, results are presented in the form K/K_{ow}, where K_{ow} is the time averaged mean value of the relevant coefficient (Either K_T or K_Q), at the relevant advance coefficient J value, obtained from the results of first condition in Table 1 (i.e., calm water, deeply submerged and non-ventilated).

4.1 Load Fluctuations in Calm Water

Figure 4 shows normalised thrust vs. advanced coefficient J, for tests performed in calm water at immersion ratio $h0/R$=1 (blade tip at its highest point touches the undisturbed free surface). Mean values as well as standard deviation about mean values are shown. At J values above 0.8 (light loading), hardly any ventilation is observed. Measured thrust is close to values for deeply submerged case. Standard deviation in this region is relatively low. A sudden drop in thrust is measured in the vicinity of critical advance coefficient ($J \approx 0.6$). Measured thrust continues declining toward bollard condition (J=0), where highest relative standard deviations are observed, though slight thrust recovery is measured below advance coefficient $J \approx 0.15$.

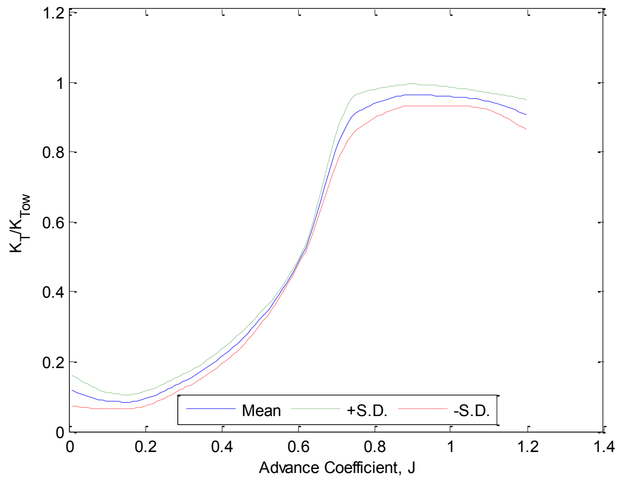

Figure 4: Normalised thrust coefficient K_T/K_{TOW} vs advance coefficient J, calm water, immersion ratio $h0/R$=1, Mean and Mean±Standard Deviation are shown.

The propeller is fully ventilating in bollard condition as shown in Figure 10. A histogram of the normalised thrust coefficient for this case is shown in Figure 7. Histograms summarise variations for the whole period of measurements. It is clear that the effect of ventilation is dynamic and is not necessarily repeatable from one revolution to the other. In some propeller revolutions, thrust peaks up to twice the mean value are measured at bollard condition. As an example, filtered blade thrust variation for a single revolution is given in Figure 5. However, this could be different for successive revolutions, though the trend would be similar. High peak values are also measured at advance coefficient of J=0.6

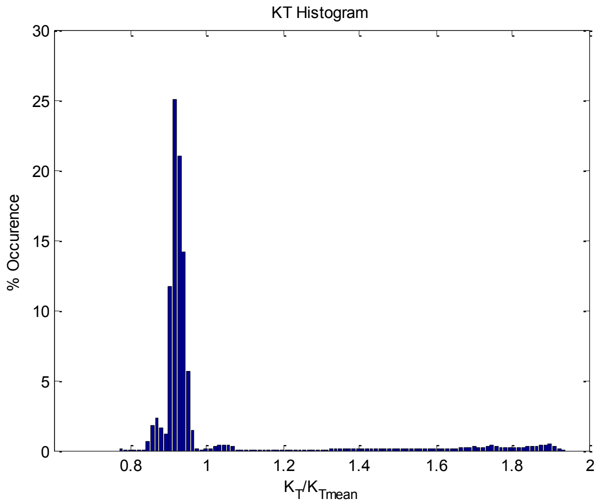

Figure 7: Histogram of normalised thrust coefficient K_T/K_{TOW}, advance coefficient J=0, calm water, immersion ratio $h0/R$=1

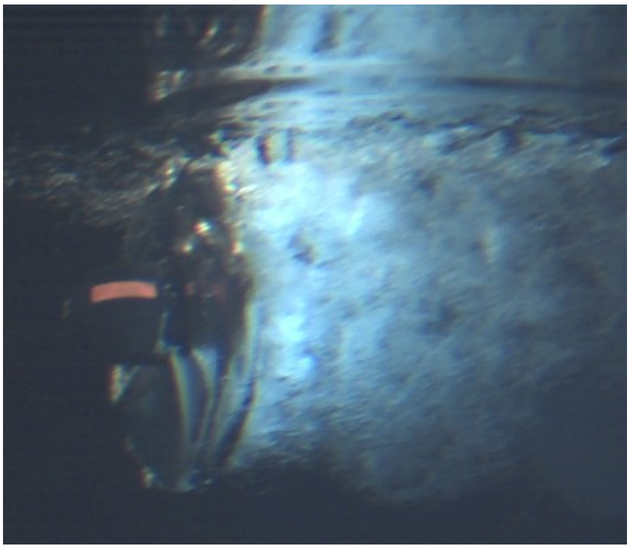

Figure 10: Underwater Photo, J=0

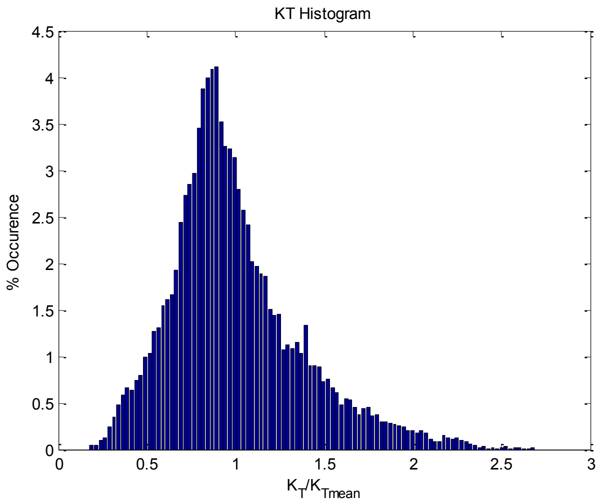

Figure 8: Histogram of normalised thrust coefficient K_T/K_{TOW}, advance coefficient J=0.6, calm water, immersion ratio $h0/R$=1

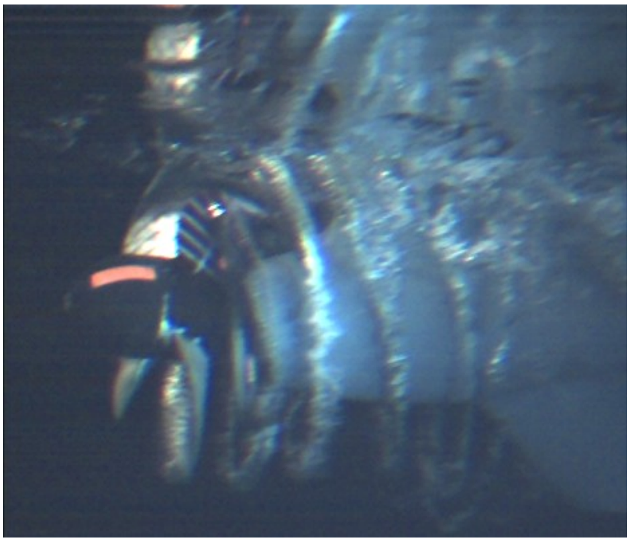

Figure 11: Underwater photo, J=0.6

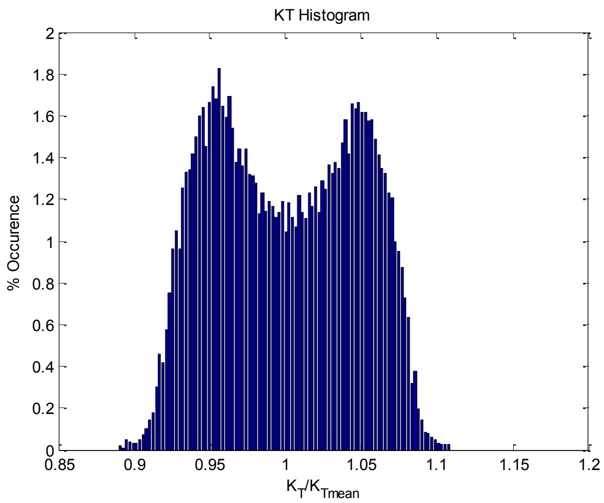

Figure 9: Histogram of normalised thrust coefficient K_T/K_{TOW}, advance coefficient J=1.2, calm water, immersion ratio $h0/R$=1

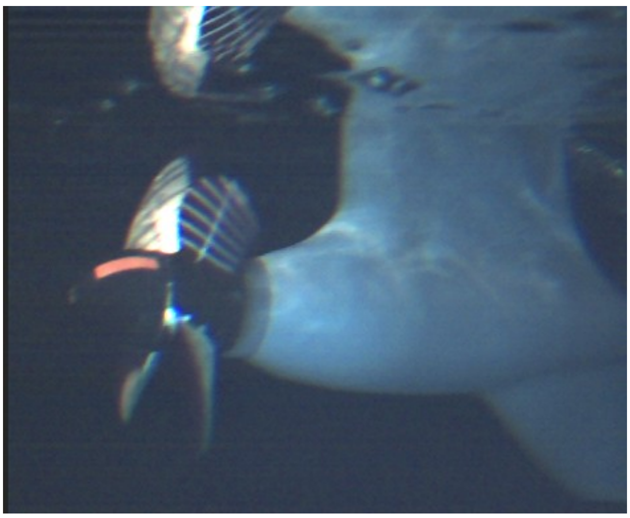

Figure 12: Underwater photo, J=1.2

Spindle moment coefficient K_{SM} is normalised by torque coefficient of the single blade K_Q. This is to enable the results from this paper to be referenced against the results from a standard open water propeller test for a propeller with an arbitrary number of blades. Normalised spindle moment coefficient K_{SM}/K_{QOW} vs. advance coefficient J is given in Figure 13. It is observed that the spindle moment changes sign from positive to negative at high J values. Normalised spindle moment increases from bollard condition towards critical advance coefficient ($J \approx 0.6$).

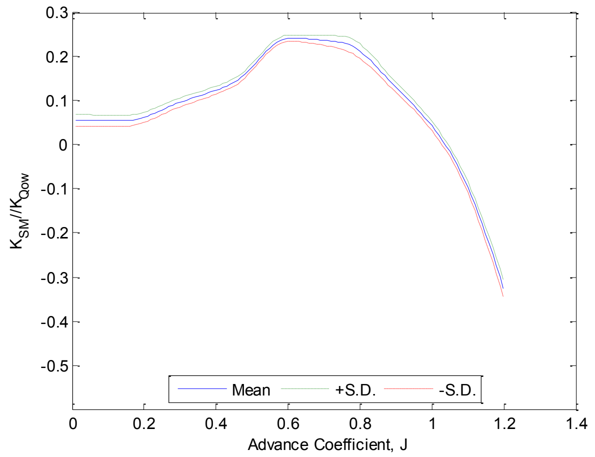

Figure 13: Normalised spindle moment coefficient K_{SM}/K_{QOW} vs advance coefficient J, calm water, immersion ratio $h0/R$=1, Mean and Mean±Standard Deviation are shown.

4.2 Load Fluctuations in Regular Waves

Tests were also performed in a regular wave, with wave height ratio H/R=2 and wave period T=1.5 s. Static immersion ratio of propeller shaft centre line was the same as for the calm water test at $h0/R$=1. These tests were also conducted in advance coefficient range of 0 to 1.2. Normalised thrust coefficient K_T/K_{TOW} vs. advance coefficient J is presented in Figure 14. The trend is to some extent similar to the calm water results (Figure 4); however, thrust drop happens at a lower advance coefficient and is more sudden. Noteworthy is the magnitude of dynamic fluctuations, shown by standard deviation. Standard deviations are in general much higher than those observed during calm water tests and low immersion. Also in wave tests, maximum relative fluctuations happen at bollard condition. Some thrust recovery is observed below advance coefficient $J \approx 0.1$ towards bollard condition. Lowest fluctuations are measured in the vicinity of critical advance coefficient ($J \approx 0.5$). Figure 15 shows normalised torque coefficient K_Q/K_{QOW} vs. advance coefficient J. The trend is similar to normalised thrust shown in Figure 14. Mean value of normalised spindle moment coefficient K_{SM}/K_{QOW} as well as mean value±standard deviation vs. advance coefficient J are given in Figure 16. Also in this case, higher fluctuations are measured compared to calm water tests (Figure 13). Normalised spindle moment increases towards critical advance coefficient ($J \approx 0.5$).

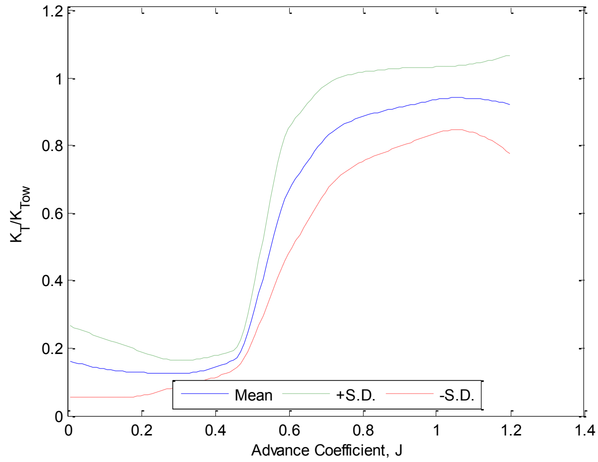

Figure 14: Normalised thrust coefficient K_T/K_{TOW} vs advance coefficient J, wave height ratio H/R=2, wave period T=1.5 s, immersion ratio $h0/R$=1, Mean and Mean±Standard Deviation are shown.

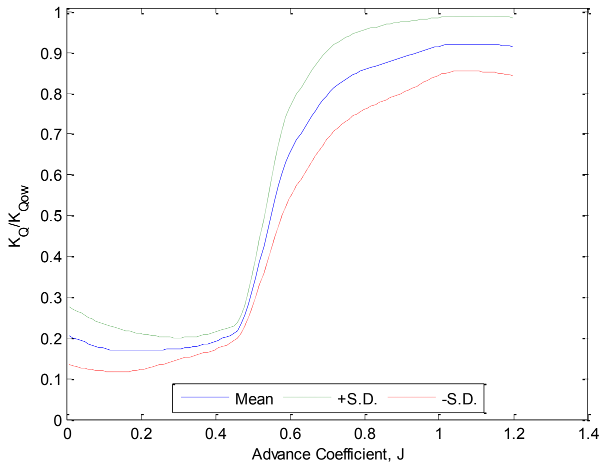

Figure 15: Normalised torque coefficient K_Q/K_{QOW} vs advance coefficient J, wave height ratio H/R=2, wave period T=1.5 s, immersion ratio $h0/R$=1, Mean and Mean±Standard Deviation are shown.

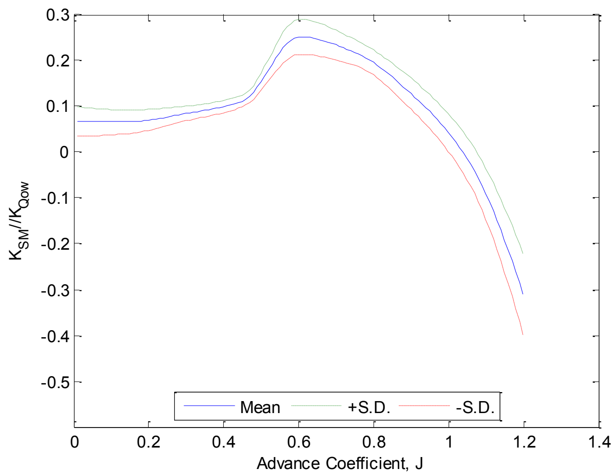

Figure 16: Normalised spindle moment coefficient K_{SM}/K_{QOW} vs advance coefficient J, wave height ratio H/R=2, wave period T=1.5 s, immersion ratio $h0/R$=1, Mean and Mean±Standard Deviation are shown.

5 CONCLUSIONS

Experimental results are presented for the thrust, torque, and spindle moment of a single blade of a propeller from a pulling thruster under various ventilated operating conditions and in waves. For all ventilated conditions, it can be observed that a sudden drop in thrust is measured when the advance coefficient becomes less than critical advance coefficient, which is $J \approx 0.6$ for calm water and $J \approx 0.5$ for wave condition. From critical advance coefficient down to bollard condition, further reduction of the thrust is measured, though slight thrust recovery is registered close to the bollard condition (J=0). Dynamic variations are analysed using standard deviation and histograms. As histograms approximate the probability distribution, they show that the standard deviation values should be handled with some care as the data shows distributions that can be both highly skewed and non-Gaussian. The effect of waves and ventilation on propeller torque follows the same trends as on propeller thrust. It is observed that the spindle moment changes sign from positive to negative at high J values.

ACKNOWLEDGEMENT

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