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Thrusters

Dynamics of Propeller Blade and Duct Loading on Ventilated Thrusters in Dynamic Positioning Mode

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Abstract

In order to obtain insight into the dynamics of propeller blade and duct loading fluctuations and ventilation phenomenon of thrusters in dynamic positioning (DP) mode, dynamic model tests of a ducted pushing thruster and an open pulling thruster were performed. Tests are performed under both constant immersions and with forced sinusoidal heave motion at bollard condition. High-speed cameras were used to visualize the ventilation phenomena. A high sampling frequency was employed for measurements, and wireless transmission was used to minimize 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 and possibly avoid the most harmful operating conditions. In addition test results deliver crucial information required for better management of different DP scenarios in the event of thruster ventilation/aeration. The test set up is described briefly. Measurements of the single blade axial force (blade thrust) and single blade moment about the propeller shaft (corresponding to propeller torque) as well as duct thrust and total thrust of thrusters, together with photographs of ventilated propellers at different submersion positions, are presented and discussed. Hydrodynamic characteristics of ducted thrusters are compared with those of open thrusters. Findings in this paper are – to some extent – also valid to podded propulsion units.

Keywords: Ventilation; Aeration; Air Drawing; Dynamic forces; Propeller; Thruster; Pod; Blade loadings; Duct

1 Introduction

Both ducted and open thrusters are widely used as manoeuvring and dynamic positioning and main propulsion units. Specially ducted pushing thrusters are installed as main propulsion units of vessels with high thrust requirements at low and zero speeds, like seismic vessels and tug-boats. Due to their high duty and varying load operation features, these thrusters are often subject to partial or full ventilation (air drawing). Vertical motions of the vessel relative to the free surface brings thrusters closer to the surface and makes them more susceptible to ventilation. In extreme cases, the propellers may partly or fully emerge from the water. There have been incidents of mechanical failure of power transmission components of thrusters that are believed to be related to ventilation.

Kempf [4] was a pioneer of the study of ventilation effects on propellers back in 1934. 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 [9], who also studied the effect of different propeller design parameters as well as the rate of revolutions and speed on ventilation. Gutsche [3] presented results of tests of partially submerged propellers and suggested a procedure for calculating the out-of-water effect on average thrust. Fleischer [2] 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. [1] and Minsaas et al. [8].

Koushan [5] 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 [6] presented experimental results of 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. He discussed ventilation inception with the aid of photographs taken by an underwater high speed camera and scale effects in ventilation tests. Koushan [7] has also discussed in detail 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 under bollard condition.

This paper focuses on thrust loss due to ventilation and the effect of ventilation on the dynamics of blade thrust, on blade moment about propeller shaft (corresponding to propeller torque), on duct thrust and on total thrust of both a pushing ducted thruster and an open pulling thruster moving with forced sinusoidal heave motion at bollard condition (zero advance speed). In addition hydrodynamic characteristics of ventilated ducted and open thrusters under constant immersion conditions are compared. Findings in this paper are – to some extent – also valid to podded propulsion units.

These tests were conducted in the Marine Cybernetic Laboratories at the Norwegian University of Science and Technology in Trondheim. A high sampling frequency was used during measurements together with high-speed video acquisition. These model tests are performed as part of the author's research at Rolls-Royce University Technology Centre "Performance in a Seaway" in Trondheim, Norway.

FX is single-blade axial force and is referred to as blade thrust in this paper. *MX* is the single blade moment about the propeller shaft and is referred to here as blade torque. *Duct_X* is the duct thrust and *Total_Thrust* is the thrust of the whole unit including propeller, duct and thruster body. The suffix *"0"* denotes the time-averaged value in well-submerged non-ventilated condition without heave motion (*FX0, MX0, Duct_X0 & Total_Thrust0*). Immersion is referred to immersion of the propeller shaft centre-line and is denoted *h* (positive downwards). Immersion ratio is the ratio between *h* and the propeller radius *R*.

2 Propellers, duct and thrusters

Two propellers were manufactured for the tests, one for ducted thruster tests and another for open thruster tests. Both propellers have principally same blade design. Ducted propeller has a larger hub than open propeller due to a larger blade dynamometer applied for ducted tests. The design is a compromise between an open and a ducted four-bladed right-handed propeller. Propeller drawings are presented by Koushan [6]. Blades are made of aluminium alloy, in order to avoid unnecessary additional mass forces, which could affect the measurements. The propellers have a diameter of 250 mm. The design pitch ratio is 1.1 and the blade area ratio approximately 0.6. Figure 1 illustrates the pressure side photograph of the propeller in the duct and the suction side photograph of the open propeller.

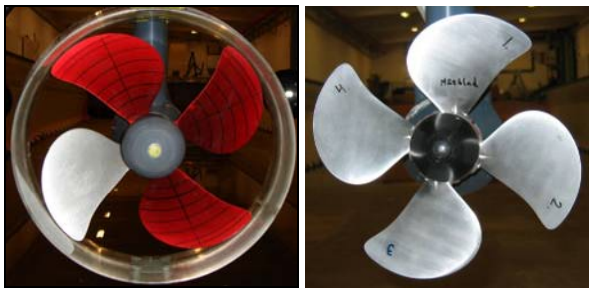

Figure 1 Pressure side view of the ducted propeller (left) and suction side view of the open propeller (right)

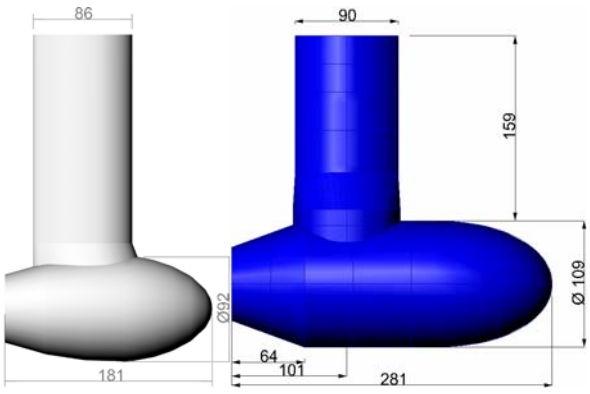

Figure 2 Rendered drawings of thruster bodies (side view), ducted thruster body (left) and open thruster body (right)

Figure 2 shows rendered drawings including main dimensions of the ducted and open thruster bodies. The ducted thruster body is 181 mm long and has a maximum diameter of 92 mm. Whereas the open thruster body is 281 mm long and has a maximum diameter of 109 mm. The duct is a typical 19A design with a length–diameter ratio of 0.5.

3 Test set up and performed model tests

Blade loadings of one of the four blades of the propeller of the open pulling thruster were measured using a blade dynamometer provided by Rolls-Royce Hydrodynamic Research Centre in Sweden that also provided thruster drive for these tests. This dynamometer measures blade axial and radial forces as well as moments about all three axes.

A novel blade dynamometer capable of measuring forces and moments in all six degrees of freedom was designed for the ducted pushing thruster tests in cooperation between MARINTEK and the Norwegian University of Science and Technology. The dynamometer is miniaturised and can be fitted into the propeller boss. A reliable wireless transmission system was developed to transfer the data from the blade dynamometer to the data acquisition system. This was also done in cooperation between MARINTEK and the University.

Tests were conducted in the Marine Cybernetics Laboratory in Trondheim. This tank is 40 m long, 6.45 m wide and 1.5 m deep. The test rig of the tank can be moved in all six degrees of freedom.

The propellers were driven by electric motors on top of the thrusters. Blade loadings on one of the four propeller blades were measured. A six-component balance was positioned on top of the thruster unit, measuring loadings on the whole unit including the propeller (but excluding the duct). Data are collected at a high sampling rate. Two force transducers measured axial and transverse forces on the duct. A pulse meter indicated the angular position of the reference blade. Figure 3 shows a picture of the test set-up for ducted thruster and Figure 4 illustrates test set-up for open thruster. Underwater high-speed digital cameras were used to take pictures of interesting events. The cameras were mounted in streamlined underwater housings upstream of the propellers.

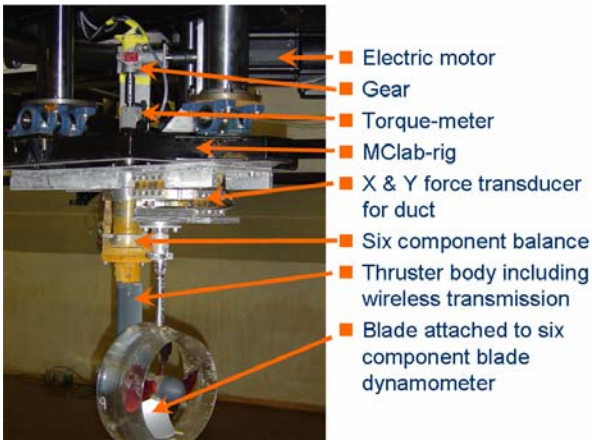

Figure 3 Test set up for ducted thruster

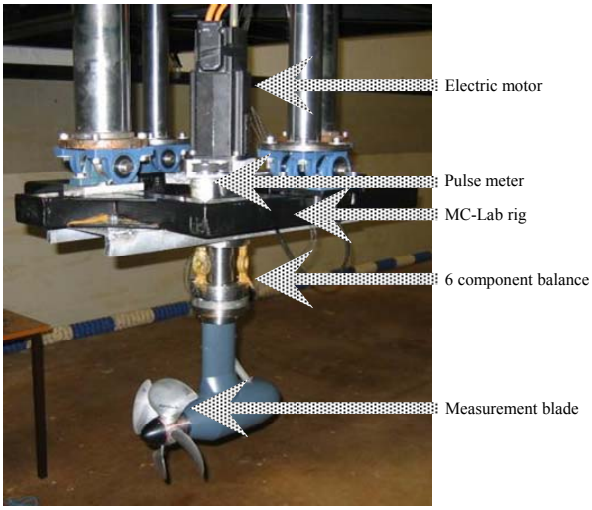

Figure 4 Test set up for open thruster

Tests were performed at different revolution rates and carriage speeds both at constant submersions and with periodically varying submersions, at constant azimuth angles and periodically varying azimuth angles. This paper presents the results of tests with constant and periodically varying submersions at zero speed and a revolution rate of 14 Hz. Of the measured components, propeller blade thrust, blade torque, duct thrust and total thrust are discussed. Alternative configurations and

other measured loading components will be presented in future publications.

4 Effect of immersion ratio on average loadings

Figure 5 shows the effect of propeller immersion on the average loadings (blade thrust *FX*, blade torque *MX*, duct thrust *Duct_X* and total thrust *Total_Thrust*) when the ducted propeller is ventilated. The thruster is not moving under these conditions. A curve showing the out-of-water effect is also shown. Out-of-water effect is a theoretical model that refers to static loss of thrust due to emergence of a part of the propeller when it is partly submerged and non-ventilated. This simple model does not take into account surface effect. It is merely the ratio of submerged area of the propeller to total area of propeller disc. The procedure to calculate out-of-water effect is described by Koushan [5]. The out-of-water effect underestimates propeller thrust loss under ventilated conditions. This effect shows no loss when the propeller is completely submerged, i.e. $h/R \geq 1$.

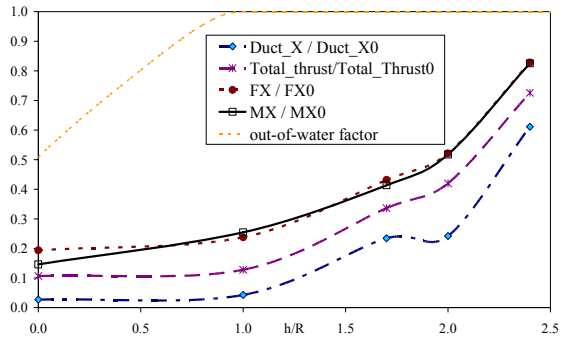

Figure 5 Time-averaged relative ducted thruster loadings versus shaft immersion ratio

At low immersion where the propeller is partly out of water or blade tip is just touching the free surface ($0 \leq h/R \leq 1$), average thrust and average blade torque are approximately 20% of the values under fully submerged non-ventilated condition. Relative duct thrust is less than 5% whereas relative total thrust is approximately 10%. With increasing immersion ($1 \leq h/R \leq 2.4$), both blade thrust and the torque as well as total and duct thrust keep growing with the exception of stagnation of duct thrust between immersion ratios 1.7 and 2. Relative duct thrust is approximately 15 to 20% lower than relative blade thrust independent of immersion ratio, whereas relative total thrust is around 10% lower than relative blade thrust.

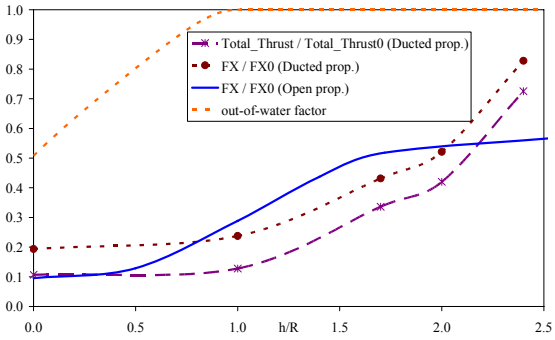

Figure 6 Comparison of time-averaged loadings of ducted and open thrusters

Figure 6 shows comparison between relative blade thrust of an open pulling thruster and relative blade thrust as well as relative total thrust of the ducted pushing thruster. None of thrusters is moving under these conditions. Propellers used have the same geometry and pitch ratio in both cases. Relative blade thrust of open propeller shows a loss of around 40% at high immersion ratios ($h/R > 1.6$) when it is ventilated. Whereas loss of relative blade thrust of ducted propeller is less than 20% at immersion ratio of 2.4. It is expected that this loss is decreased further with increasing immersion. Relative total thrust of ducted propeller follows same trend as relative blade thrust but it is approximately 10% lower. Relative blade thrust of open propeller is higher than relative total thrust of ducted thruster for immersion ratios lower than 2.2.

Figure 7 shows the effect of the highest position (during a heave cycle) of the propeller shaft of the ducted pushing thruster on time-averaged blade thrust *FX* and blade torque *MX* as well as duct thrust *Duct_X* and total thrust of the unit, including duct *Total_Thrust*. Results are normalized with averaged values in non-ventilated condition without heave motion, i.e. *FX0*, *MX0*, *Duct_X0* and *Total_Thrust0*. A curve showing the out-of-water effect is also shown.

This diagram shows that all force components follow the same trend. Thrust and torque losses are also similar. The torque measurements show a few percent more loss than thrust loss. Duct thrust

suffers from highest losses. Values for the available total thrust of the unit lie somewhere between duct thrust and blade thrust.

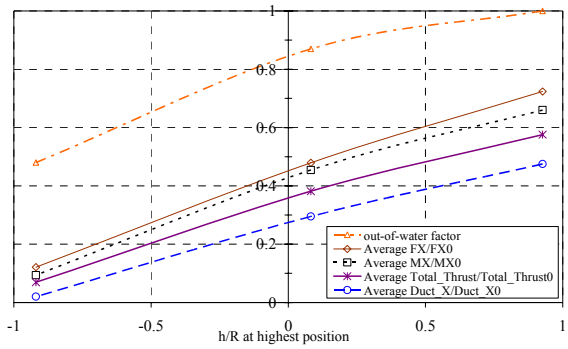

Figure 7 Time-averaged relative ducted thruster loadings versus shaft immersion ratio at its highest position during a heave cycle

Approximately 30% loss of blade thrust and torque was observed where propeller was subjected to sinusoidal heave motion with an immersion ratio of 0.93 at the highest position of a heave cycle. Available duct thrust was already more than halved at this condition. Losses came to more than half of blade thrust and torque and 70% of duct thrust where almost half of the propeller is out of the water at its highest position during a heave cycle, i.e. at h/R=0.08. The available average blade thrust and torque were approximately 10% when the propeller is nearly fully out of water at its highest position during a heave cycle, i.e. h/R=−0.92, though the propeller was completely submerged at its lowest position. Available duct thrust was practically negligible at this condition. Under all conditions, losses of blade thrust and torque were 30 to 40% more than out-of-water effect.

Figure 8 presents the effect of highest position (during a heave cycle) of propeller shaft of the open pulling thruster on time-averaged blade thrust. Results are normalized with averaged blade thrust under non-ventilated condition without heave motion *FX0*.

5% loss of blade thrust is observed where the open thruster undergoes sinusoidal heave motion without any ventilation, which is the case for the test with immersion ratio of 2.2 at highest position of heave cycle. Whereas 25% loss of blade thrust is measured for the case that the propeller is partially ventilated under an immersion ratio of 1.1 at highest position. Losses count to more than half of blade thrust where more than half of the propeller is out of the water at its highest position during a heave cycle. Available average blade thrust is less than 20%, where the propeller is completely out of water at its highest position during a heave cycle, though the propeller is completely submerged at its lowest position. Under ventilated conditions, losses of blade thrust were about 30 to 40% more than out-of-water effect.

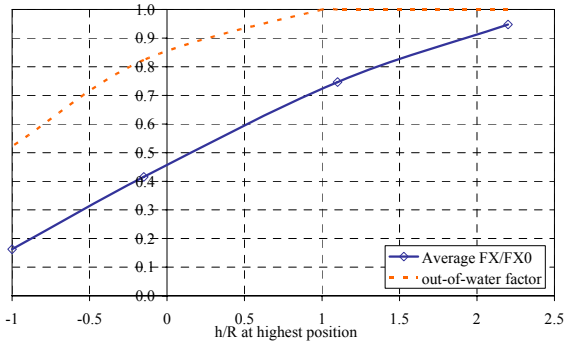

Figure 8 Time-averaged relative blade thrust of open thruster versus shaft immersion ratio at its highest position during a heave cycle

Losses of blade thrust of open pulling thruster due to ventilation are very similar to those of ducted pushing thruster shown in Figure 7.

5 Dynamics of forced heave motion of the open thruster, non-ventilated case

Measured instantaneous blade thrust of the open pulling thruster relative to time-averaged blade thrust (for the whole time series) are shown in Figure 9 for the test condition that the highest position of propeller shaft during a heave cycle was h/R=2.2. Amplitude of heave motion was $1.1 R$ with period of 1.9 s. No ventilation was observed during this test. Instantaneous propeller shaft immersion is also presented in the same figure. This figure shows that measured blade thrust oscillates approximately ±35% of time-averaged thrust. It can be seen that there are both low- and high-frequency fluctuations. For a better understanding of the dynamics involved, various fluctuation frequencies were identified and analyzed. Spectral analysis showed that low-frequency fluctuations coincided with heave motion variations while dominant high-frequency

fluctuations varied mainly with shaft frequency of single blade (or the blade frequency of the propeller because measurements were performed on a single blade).

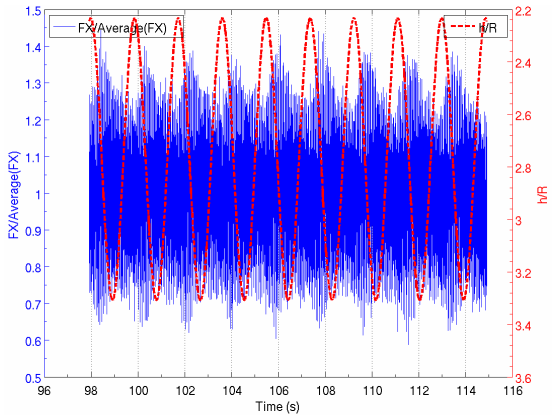

Figure 9 Relative blade thrust of open thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=2.2; amplitude/R=1.1; period=1.9 s

Figure 10 shows time series of relative blade thrust measurements for non-ventilating case that are filtered with a 12 Hz low pass filter. Low-frequency fluctuations are moderate and vary mostly ±2% of the average blade thrust. However there are clear sudden drops of blade thrust at highest and lowest thruster positions where direction of heave motion changes. Otherwise, blade axial force increases when propeller is moving downwards and decreases when the propeller is moving upwards.

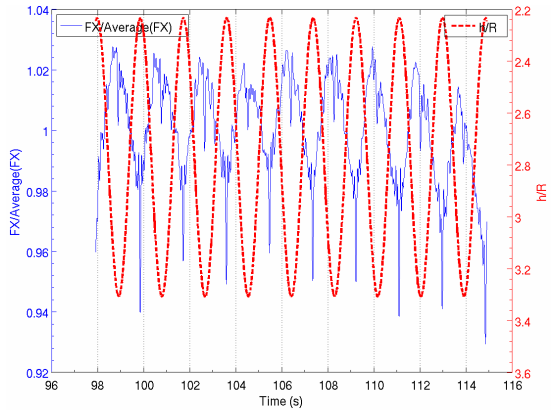

Figure 10 Low-pass (12 Hz) filtered relative blade thrust of open thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=2.2; amplitude/R=1.1; period=1.9 s

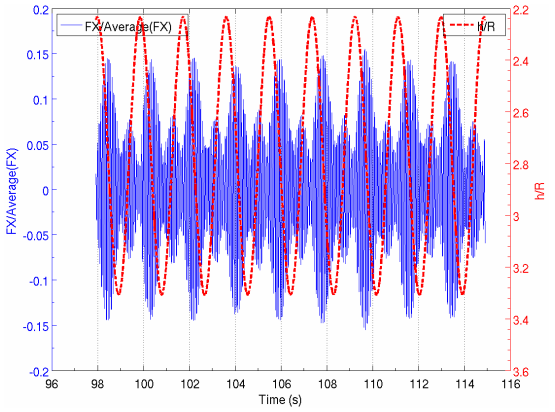

Figure 11 Shaft frequency fluctuations in relative blade thrust of open thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=2.2; amplitude/R=1.1; period=1.9 s

Shaft frequency fluctuations of blade thrust for mentioned case are illustrated in Figure 11. Variation range is approximately ±15% of average blade thrust. There is a clear correlation between the heave velocity and magnitude of shaft frequency fluctuations. In addition, motion direction affects the fluctuations. Lowest shaft frequency fluctuations (ca. ±5%) are measured at highest and lowest thruster positions where the heave velocity goes to zero and direction of heave motion changes. When the thruster is moving downwards, fluctuations increase to maximum midways downwards (where heave velocity is maximum) and decrease to minimum at lowest position during a heave cycle. Fluctuations increase again when the thruster is moving upwards up to midways upwards however this increase is only ±8%, i.e. approximately half of fluctuations at the same immersion position when the thruster was moving downwards. After passing midways upwards, fluctuations descend towards highest position during a heave cycle.

6 Dynamics of forced heave motion of the open thruster, ventilated case

Test analyzed in this section is performed with the open pulling thruster at highest propeller shaft immersion of h/R=−0.15 with heave motion amplitude of 2.15·R and heave period of 2 s. Some of the photographs taken by underwater camera are presented in Figure 19 (a to r). Measurement blade is at bottom position in these photographs. Propeller remains at least partially ventilated

during this test. More than half of the propeller is out of water at highest position of thruster during a heave cycle (Figure 19 a) and therefore the propeller is fully and uniformly ventilated at this position. As the propeller moves downwards, it keeps its ventilation (Figure 19 b to f). When the thruster nearly has reached its lowest position (Figure 19 h), connection to free surface is only through a funnel and the ventilation gets violent. At the lowest position of thruster (Figure 19 i), the air supply from the free surface is broken and ventilation gets more violent. Ventilation reduces to tip vortex ventilation as the thruster moves up (Figure 19 j & k). Propeller gets ventilated through free surface, first as the propeller shaft immersion ratio is approximately 1.5 (Figure 19 l). As the propeller moves further upwards, it gets fully ventilated.

Relative blade thrust of open pulling thruster and its shaft immersion ratio are shown in Figure 12. Blade thrust is measured close to zero at highest position of thruster during a heave cycle.

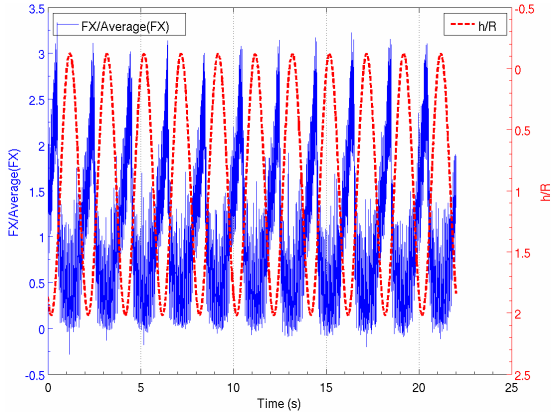

Figure 12 Relative blade thrust of open thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=−0.15; amplitude/R=2.15; period=2 s

Low pass (12 Hz) filtered blade thrust is illustrated in Figure 13. Minimum is reached as the propeller is mostly out of water at its highest position during a heave cycle. Blade thrust increases with increasing immersion. Measured thrust keeps increasing as the thruster moves upwards again and extent of ventilation keeps reducing until the propeller gets fully ventilated through the free surface where a sudden large drop of thrust is observed close to shaft immersion ratio of 1.5. This sudden drop happens just within a single revolution.

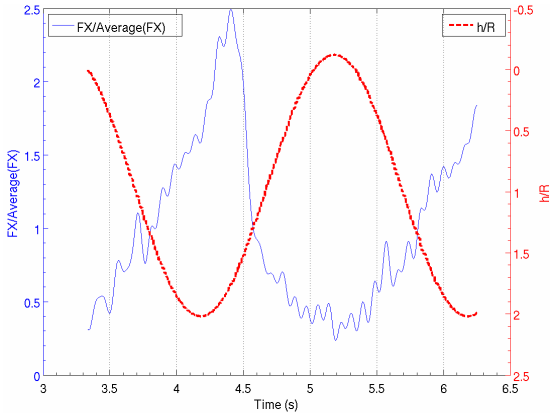

Figure 13 Low-pass (12 Hz) filtered relative blade thrust of open thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=−0.15; amplitude/R=2.15; period=2 s

Figure 14 illustrates shaft frequency fluctuations in blade thrust. Variations are nearly ±30%. However shaft frequency fluctuations are reduced to minimum, right after the thruster starts moving upwards from its lowest position where ventilation is limited to tip vortex ventilation. But a sudden increase is observed as the propeller gets fully ventilated on the way up at immersion ratio of approximately 1.5. At the same position, highest variation of low-frequency fluctuations was observed. Combination of these low- and high-frequency fluctuations at such a short time lead to high impact on mechanical parts of power transmission.

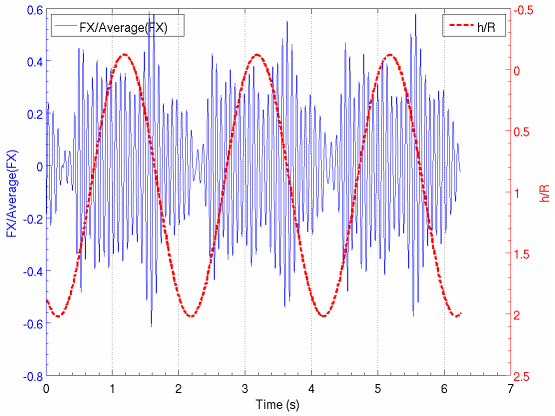

Figure 14 Shaft frequency fluctuations in relative blade thrust of open thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=−0.15; amplitude/R=2.15; period=2 s

Comparison of dynamic behavior of non-ventilated and ventilated thrusters under forced heave motion show that it is the ventilation which is the primary cause of fluctuations rather than the heave motion. Of course, the heave motion acts as a generator and transporter of ventilation.

7 Dynamics of forced heave motion of the ducted thruster, ventilated case

This section discusses the ducted pushing thruster test in which the highest position of the propeller shaft during the heave cycle, was h/R=0.08, i.e. with the top blade almost fully out of water. The amplitude of heave motion was 1.8$\cdot R$, with a period of 4 s. Some of the photographs taken by the portside underwater high-speed camera at different propeller immersions are shown in Figure 20 (a to l). The measurement blade is the lowest blade in these photographs.

Almost half of the propeller is out of the water at its highest position during the heave cycle and the propeller is fully and uniformly ventilated at this position (Figure 20 a). As the propeller moves downwards, the free surface is further deformed in the direction of the propeller shaft and the propeller keeps its full ventilation half-way down to its lowest position (Figure 20 b and c). The free surface has started moving back to normal and access to air from above is nearly cut when the propeller has moved down by 80% of the full distance. Ventilation has started to decline (Figure 20 d). When the thruster has reached almost its lowest position (Figure 20 e), the air supply from the free surface is broken and ventilation is reduced to tip vortex ventilation. At the lowest position of the thruster (Figure 20 f), the propeller is ventilation-free and the free surface is back to normal. However as the propeller moves up again to 19%, ventilation inception is observed via an air channel between the thruster stock and the duct (Figure 20 g). The direction of propagation of ventilation is once again in the direction of rotation of the propeller, as shown in Figure 20 h and i. Full and uniform ventilation is reached when the thruster has moved by 61% upwards (Figure 20 j). Full ventilation remains stable as thruster approaches its highest position (Figure 20 k and l).

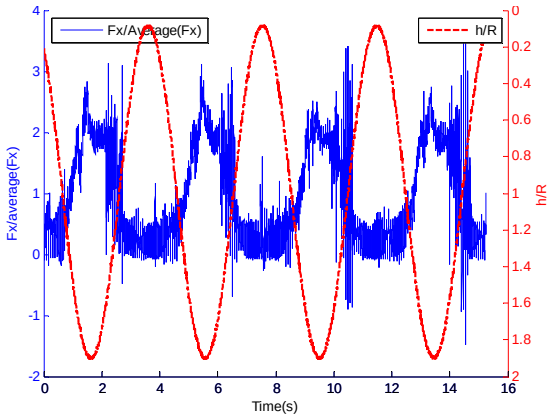

Figure 15 Relative blade thrust of ducted thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=0.08; amplitude/R=1.8; period=4 s

Figure 15 shows time-series of blade thrust relative to time-averaged blade thrust. The instantaneous propeller-shaft position is also presented in the same diagram. Large variations in blade thrust can be seen. Blade thrust approaches zero close to the highest position of the thruster, where the propeller is fully ventilated. Maximum blade thrust is reached near the lowest position of the propeller, where the propeller is not ventilated.

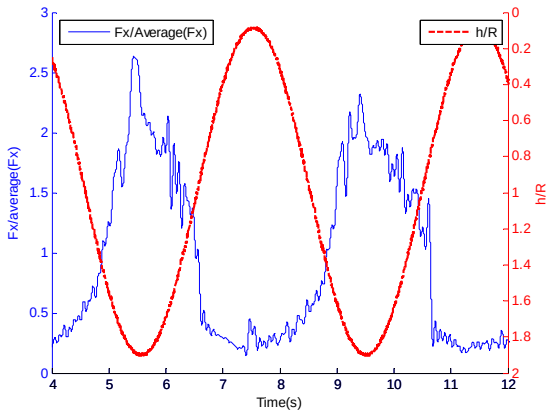

Figure 16 Low-pass (12 Hz) filtered relative blade thrust of ducted thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=0.08; amplitude/R=1.8; period=4 s

Figure 16 shows a time-series of relative blade thrust which has been filtered with a 12 Hz low-pass filter. In this case too, variations are related to the ventilation. A minimum is reached as the propeller starts cutting through the free surface on the way up at a propeller shaft immersion ratio h/R lower than 1. This minimum level is maintained

while the propeller moves to the top and moves downwards again until ventilation starts to decay. As the thruster continues to move downwards, blade thrust rises with increasing immersion because of the reduction in ventilation. The highest level of blade thrust is obtained when the propeller is ventilation-free, close to its lowest position in the heave cycle.

Shaft frequency fluctuations in blade thrust are shown in Figure 17. Lowest fluctuations are measured when the thruster moves downwards and the propeller is fully submerged. The level of fluctuations rises as the propeller becomes ventilated on the way up. Maximum variation in shaft frequency is reached when the thruster is moving upwards and the starboard half of the propeller is fully ventilated while the port half is ventilation free. This illustrates the hysteresis of the ventilation effect, i.e. both minimum and maximum variations happen at almost the same immersion ratio *h/R* of approximately 1, minimum while the thruster is moving downwards and maximum while it is moving upwards.

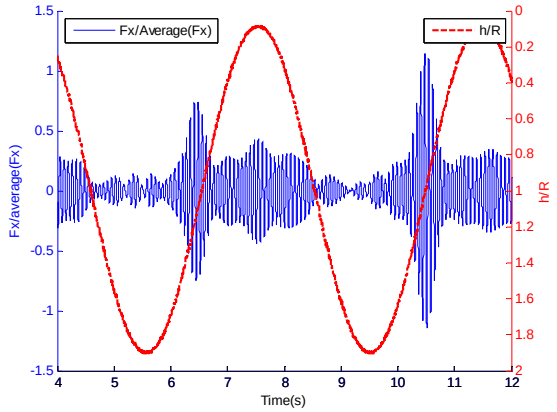

Figure 17 Shaft frequency fluctuations in relative blade thrust of ducted thruster and relative propeller shaft immersion; propeller shaft at highest position h/R=0.08; amplitude/R=1.8; period=4 s

Relative blade torque measurements are almost identical to those of relative blade thrust. This is illustrated in the diagrams of Figure 18. The left-hand diagram shows low-pass variations which are similar to blade thrust variations presented in Figure 16, while the right diagram shows shaft frequency fluctuations in blade torque which are similar to shaft frequency fluctuations in blade thrust (Figure 17).

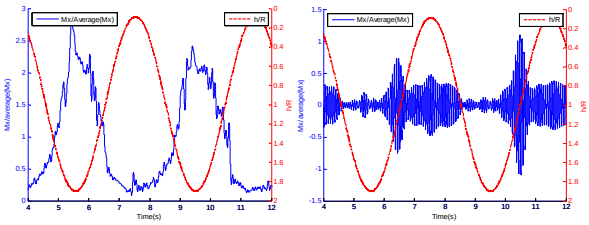

Figure 18 Low-pass filtered data (left) and shaft frequency fluctuations (right) of relative blade torque of ducted thruster; propeller shaft at highest position h/R=0.08; amplitude/R=1.8; period=4 s

8 Comparison between open and ducted thruster ventilation

There are clear distinctions between ducted and open thrusters under ventilated conditions. Ducted propeller is ventilated in the direction of rotation of propeller that leads to asymmetry of ventilation about a vertical plane through the propeller shaft centre line, where as open propeller ventilation is more spread over a rotation of propeller or under conditions close to free surface, upper part of the open propeller faces more intensive ventilation than the lower part which is due to the fact that free surface is deformed downwards.

Generally, ventilation of open propeller gets more violent than that of ducted propeller. This phenomenon can be clearly observed under larger submergence conditions when the propeller is ventilated. Open propeller can get ventilated in larger depths than ducted propeller and keeps ventilation down to larger depths when it is moving downwards than ducted propeller.

These differences are reflected in the dynamic forces of these two types of thruster. It is clear from two preceding chapters that on one hand, the open propeller suffers under larger sudden falls of relative blade thrust than the ducted propeller though the relative variation levels are similar (compare Figure 12 with Figure 15 and compare Figure 13 with Figure 16). On the other hand relative blade thrust of the ducted propeller experiences larger local shaft frequency variations than that of open propeller when it gets ventilated on the way up (compare Figure 14 with Figure 17).

9 Concluding remarks

Fluctuations in blade thrust are quite significant when a thruster is ventilated. Ventilation affects both the dynamic and static loadings on thrusters. Variations in relative blade torque are almost identical to variations in relative blade thrust under ventilated conditions.

There are clear differences between ventilation of open and ducted propellers. Ventilation of ducted propeller starts in the direction of rotation of the propeller while open propeller ventilation is distributed around the rotation of the propeller. Open propeller ventilation can get more violent, specially at deeper immersions. Open propeller has a loss of blade thrust of around 40% under large immersion ratios (h/R>1.6) when it is ventilated while loss of blade thrust of ducted propeller is less than 20% under immersion ratio of 2.4. Duct thrust suffers the largest relative losses due to ventilation.

When a thruster undergoes heave motion, it is the ventilation which is the primary cause of loading fluctuations rather than the heave motion. Of course, the heave motion acts as a generator and transporter of ventilation. Ventilation inception leads to highest dynamic fluctuations. It results in sudden large drop of blade thrust.

10 Acknowledgement

The author would like to acknowledge gratefully the post-doc. fellowship from his employer MARINTEK within the Rolls-Royce University Technology Centre in Trondheim, which made this research possible. The author acknowledges thankfully also support of the Rolls-Royce Hydrodynamic Research Centre in Sweden on the tests with the open pulling thruster.

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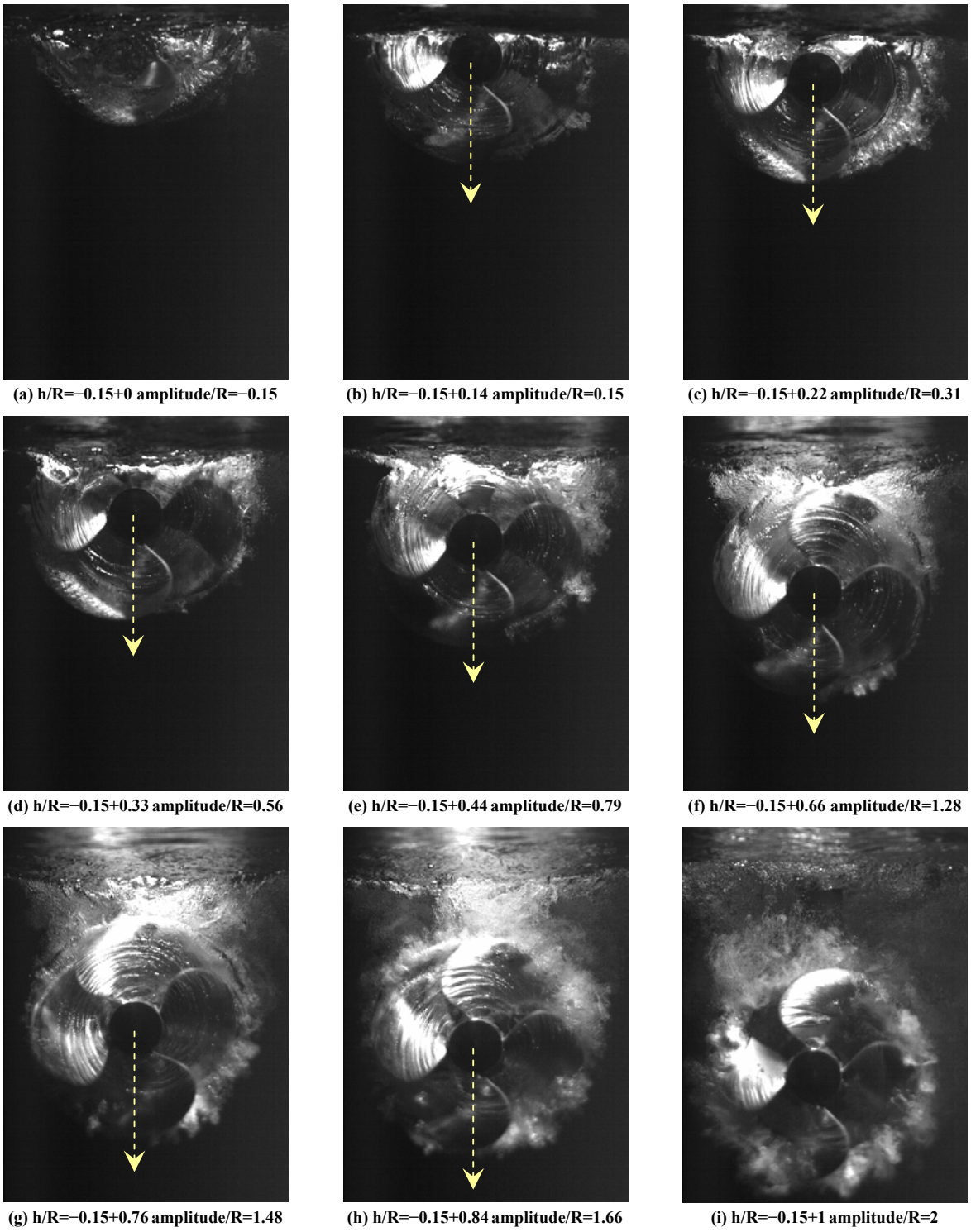
12 Photographs

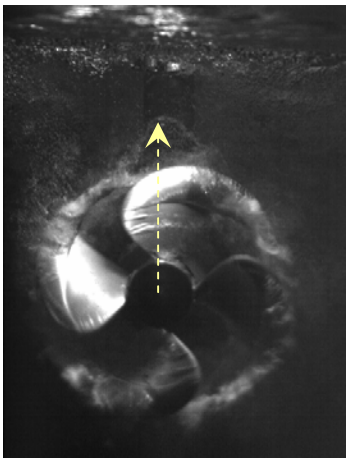


(a) h/R=−0.15+0 amplitude/R=−0.15 (b) h/R=−0.15+0.14 amplitude/R=0.15 (c) h/R=−0.15+0.22 amplitude/R=0.31

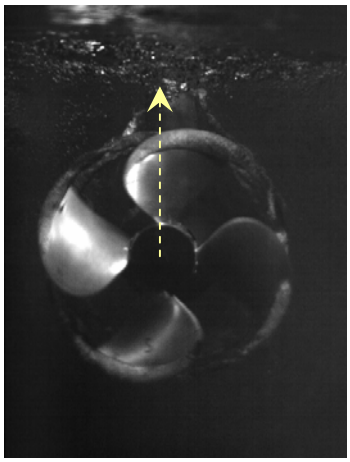
(d) h/R=−0.15+0.33 amplitude/R=0.56 (e) h/R=−0.15+0.44 amplitude/R=0.79 (f) h/R=−0.15+0.66 amplitude/R=1.28

(g) h/R=−0.15+0.76 amplitude/R=1.48 (h) h/R=−0.15+0.84 amplitude/R=1.66 (i) h/R=−0.15+1 amplitude/R=2

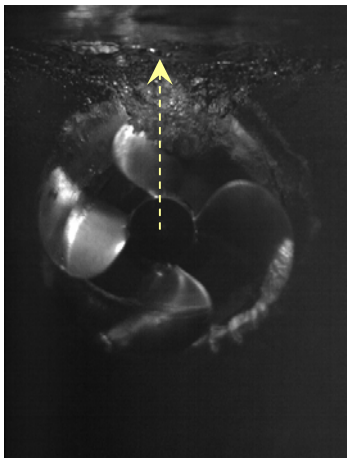
Figure 19 (a to i) Open thruster suction side under various immersion conditions; propeller shaft immersion ratio at highest position h/R=−0.15, amplitude/R=2.15, period=2s. Direction of vertical motion is shown by an arrow. Continuation on next page...



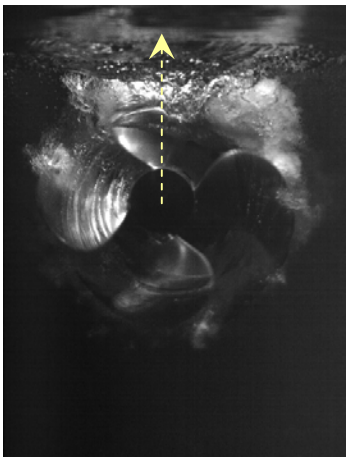
(j) h/R=−0.15+0.97 amplitude/R=1.95



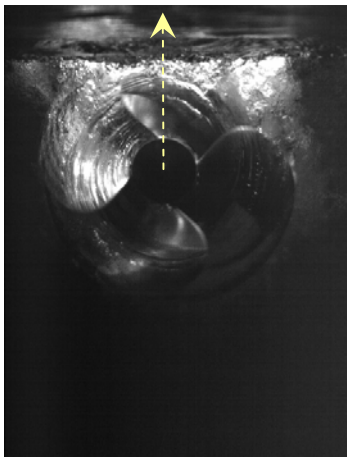
(k) h/R=−0.15+0.86 amplitude/R=1.7



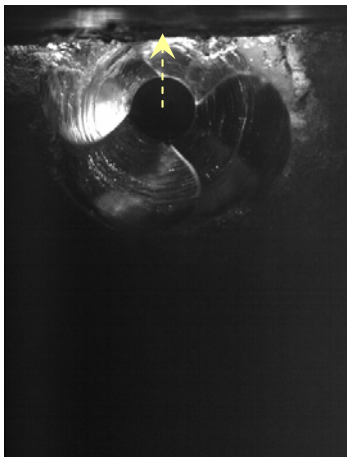
(l) h/R=−0.15+0.77 amplitude/R=1.5



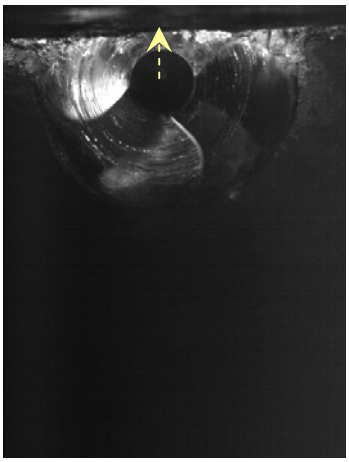
(m) h/R=−0.15+0.66 amplitude/R=1.26



(n) h/R=−0.15+0.56 amplitude/R=1.07

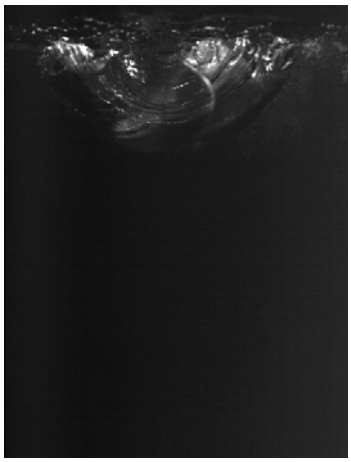


(o) h/R=−0.15+0.34 amplitude/R=0.58



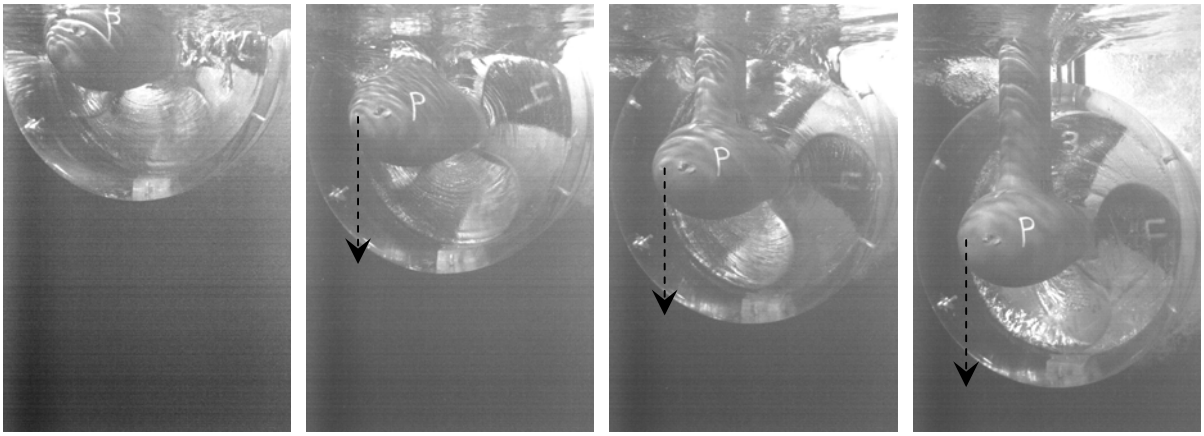
(p) h/R=−0.15+0.24 amplitude/R=0.37

(q) h/R=−0.15+0.14 amplitude/R=0.15



(r) h/R=−0.15+0 amplitude/R=−0.15

Figure 19 (j to r) (Continuation) Open thruster suction side under various immersion conditions; propeller shaft immersion ratio at highest position h/R=−0.15, amplitude/R=2.15, period=2s. Direction of vertical motion is shown by an arrow.

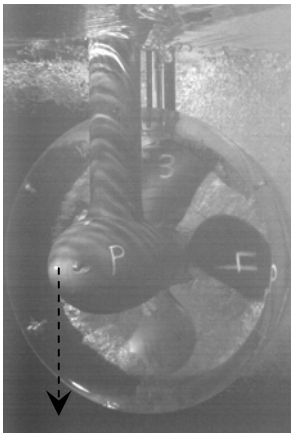


(a) h/R=0.08+0 amplitude/R=0.08

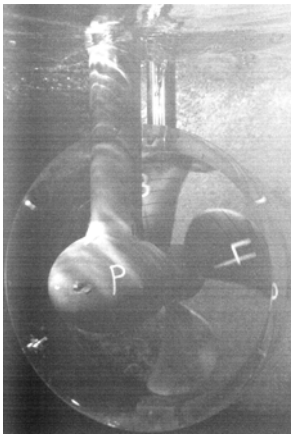
(b) h/R=0.08+0.3 amplitude/R=0.62

(c) h/R=0.08+0.52 amplitude/R=1.02

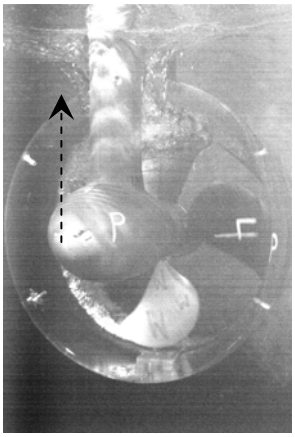
(d) h/R=0.08+0.8 amplitude/R=1.52



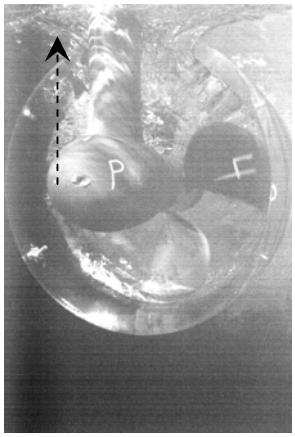
(e) h/R=0.08+0.92 amplitude/R=1.74



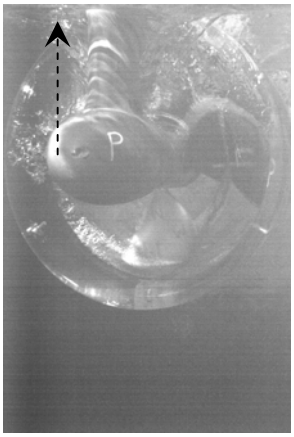
(f) h/R=0.08+1 amplitude/R=1.88



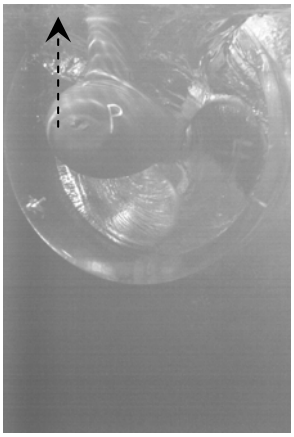
(g) h/R=0.08+0.81 amplitude/R=1.54



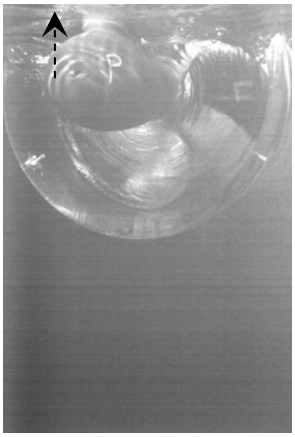
(h) h/R=0.08+0.6 amplitude/R=1.16



(i) h/R=0.08+0.5 amplitude/R=0.98



(j) h/R=0.08+0.39 amplitude/R=0.78



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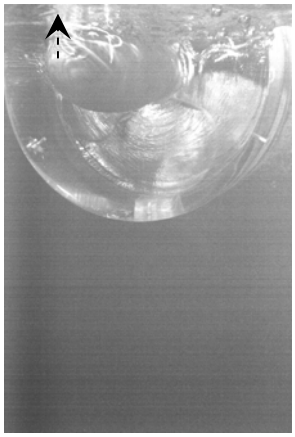

(l) h/R=0.08+0.1 amplitude/R=0.26

Figure 20 (a to l) Ducted thruster suction side under various immersion conditions; propeller shaft immersion ratio at highest position h/R=0.08, amplitude/R=1.8, period=4 s. Direction of vertical motion is shown by an arrow.