Open water propeller characteristics testing engineering essay

Introduction

In order to obtain movement of a ship in the sea, some form of reaction force has to be present between the ship and the fluid. When considering ships, this reaction is normally either due to air, such as in the case of sail boats, or due to water, such as in the case of ships using a screw propeller. Propellers however, are far more common and are considered as the main type of propulsor used in ships. The thrust present due to the propeller, the torque which is developed in the shaft and the rotational speed of the propeller shaft and the propeller need to be known such that the open water propeller characteristics can be obtained. These are coefficients which are then used to determine the efficiency of the propulsor.

Project Objectives

The objectives of the project are:

To investigate model propellers following the standards set out by the International Towing Tank Conference (ITTC);

To obtain an ‘ open-water’ testing area using available resources;

To investigate modifications or upgrades on the existing resources.

Literature Review

Fig. 1 – Types of propeller tests

3. 1 Open Water Tests

The term ‘ open water’ refers to the condition where the propeller is not obstructed by the hull and is fully exposed to the water around it. Open water tests are carried out to obtain different coefficients which are then used to find the open water efficiency of a propeller, η_o. This efficiency can be used to estimate the power that the propeller would require [1]. These tests allow uniform comparison between propellers due to the nature of the dimensionless coefficients [2].

Towing Tank Tests: A towing tank is a tank containing calm water through which models are towed by a carriage. Propeller models are mounted on shafts which are driven by a motor inside some housing. The carriage tows the housing along the tank with a known velocity. The amount of readings possible in such a facility depends on the length of the tank, thus for a considerable amount of values to be collected at each run, a very long tank is needed. To avoid so much space being consumed, a circulating water tank can be used. This achieves a relative velocity between the propeller and the water while keeping the housing stationary [3], [4].

Cavitation Tunnel Tests: A cavitation tunnel consists of a water channel which is completely closed, equipped with an impeller to circulate the water in it. Since uniform flow is very difficult to attain, conditions close to uniform are normally accepted. The tunnel is closed so scaling of pressure is possible; this is quite useful when seeking similarity between full-scale and model propellers, which is usually required. When the propeller is mounted with the propeller shaft downstream, the propeller can be regarded as being in open water and therefore an open water test can also be performed in a cavitation tunnel [5].

3. 2 Self-Propulsion Tests

This type of test requires that a model hull has a propulsion unit added to it and this setup is then mounted onto a carriage. The model hull is run at the corresponding speed, which can be found after applying laws of similarity. The test would actually require both Froude and Reynolds similarity but propulsion tests conform to Froude similarity since Reynolds Number similarity cannot be achieved simultaneously with the first condition [6], [7].

Constant Speed Method: A specific speed is chosen and kept constant while varying the load. The test can be repeated for different velocities while taking readings for varying loads.

Constant Loading Method: In this case, the loading is chosen and set before the start of the experiment and the speed is varied throughout the experiment for a range of values to be obtained.

Mixed Loading Method: This method is nothing but the use of both constant speed and constant loading methods in combination [8].

3. 3 Cavitation Tests

Cavitation is the physical process which occurs in areas of localized high velocity or low pressure. Due to high velocities, there is a fall in pressure and if this results in a low enough pressure, formation of cavities is witnessed. Air bubbles which come out of solution and vapour then fill the cavities which can consequently grow very quickly [9]. As fluid flows past an aerofoil, there is a pressure reduction over the back face. Bubbles form and move to the trailing edge to collapse at higher pressure areas. This contributes to noise, reduction in efficiency and even physical damage to the propeller blades [10].

Cavitation tests investigate this physical phenomenon and are usually carried out in cavitation tunnels. The propeller is mounted onto a shaft in the cavitation tunnel and the impeller speed can be varied in order to vary the speed of the water. The rotational speed of the propeller can be varied independently. The water pressure can also be varied to obtain a similar bubble formation between the model and the full-scale propeller [5].

The cavitation number and the velocity of the incoming fluid are set before the test. The rotational speed of the propeller is varied during the test until cavitation can be witnessed visually both on the face and the back of the propeller. Since the result of this method depends on visual inspection, it is not very repeatable. Automatic detection systems have been implemented recently so that results are based on physical phenomena rather than on the visual capacity of the tester [11].

3. 4 Recommendations and Guidelines for Testing

The International Towing Tank Conference (ITTC) is an association made up of organizations from all over the world. Its members seek to analyse the performance of ships and other related facilities through modelling, and then use the outcomes to predict the behavior of such installations. The ITTC also gives test guidelines and procedures one could follow for reliable results. Amongst the members of the ITTC one can find numerous universities as well as private companies. The last conference was the 25th International Towing Tank Conference which took place in Fukuoka, Japan in September of 2008.

The next conference will be held in 2011 in Rio de Janeiro, Brazil. The ITTC has set recommended procedures and guidelines for each of the propeller tests mentioned earlier.

Existing Testing Facilities in Europe

Towing Tanks: There are several towing tanks around the globe; two tanks amongst the longest in Europe [12] are:

QinetiQ Haslar (UK) – this is Europe's largest towing tank which is 270 m long, 12 m wide and 5. 5 m deep. It has been used for different purposes, such as in the development of wave energy devices and to ensure safety of submarines [13].

SSPA, Göteborg, Sweden – this tank is more generally used for propulsion and resistance tests as part of the optimisation of hull forms. The SSPA tank is 260 m long, 10 m wide and 5 m deep [14].

Fig. 2 – QinetiQ Haslar tank, UK [15] Fig. 3 – SSPA Towing tank, Sweden [14] [32]

Cavitation Tunnels: Some cavitation tunnels around Europe are the following:

MARIN Wageningen, Netherlands – Some tests carried out at this facility are cavitation observation and performance tests, propeller noise measurement tests and supercavitating propeller tests [16].

HSVA, Hamburg, Germany – has three cavitation tunnels available, the largest one, HYKAT, has its test section 11 m long, 2. 8 m wide and 1. 6 m deep. Between them, the three tunnels can accommodate propellers having diameters ranging from 230 to 400 mm [17].

Fig. 4 – MARIN Cavitation tunnel [18] Fig. 5 – HVSA HYKAT, Germany [17]

Choice of Test

4. Choice of Test

The choice of test that would eventually be carried out depended on the facilities available in the laboratories. These consisted of:

A cavitation tunnel which needed replacement of parts and maintenance

A wave-making tank

A circulating water channel

The circulating water channel was the most adequate facility since it needed very little maintenance and was also an ideal choice for an open water test.

Theoretical Analysis

The aim of an open water test is to obtain values of the open water efficiency of the propeller, η_o, for different values of the advance coefficient, J. Dimensional analysis was carried out after deducing that the thrust, T (N), depends on:

the diameter of the propeller, D (m)

the rate of revolutions of the propeller, n (rps)

the advance speed, V_a (m/s)

the kinematic viscosity of the fluid, ν (m2/s)

the density of the fluid, ρ (kg/m3)

the gravitational acceleration, g (m/s2)

Such that: (1)

is a function of the advance coefficient; is a function of the Reynolds Number whose effect is negligible since the viscous effect on the blades is quite small when compared to the other forces acting on the propeller; is a function of the Froude Number which is not required in open water tests since there is no wave-making included in the testing procedure.

Therefore (2)

The torque, Q (Nm) depends on the same parameters and dimensional analysis gives:

(3)

For the same reasoning as above, this becomes:

(4)

The advance coefficient, J, which is dimensionless, is described as: (5)

From the above equations: and (6), (7)

Where KT and KQ are the thrust and torque coefficients respectively.

The propeller efficiency is also required to describe the performance of the propeller.

(8)

(9)

(10)

Therefore: (11)

Substituting for J, T and Q from above:

(12)

This shows that the open water propeller efficiency is a function of the advance coefficient, the thrust coefficient and the torque coefficient.

Fig. 6 – KT-KQ diagram [19]

Design of Equipment

6. 1 Load Cell

Fig. 7 – Positioning of strain gauges

Load cells were needed for the open water test in order to obtain values of thrust and torque. To be able to obtain dimensions of a load cell to be made intentionally for the experiment, approximate values of the thrust and torque which would be expected in such a test were needed. Such values were T = 30 N and Q = 0. 5 Nm, which values were taken from dynamometer specifications used in the open water testing facility of Gent University

Maritime Technology Division [20]. Instead of having two different load cells, one for each parameter, a single reaction-torque and thrust load cell was designed. A circular cross section is the most adequate and reliable to measure torsional strain and strain gauges at 45° and -45° to the longitudinal axis of the shaft were to be fixed to read the torque. To also cater for the thrust, a strain gauge at 0° had to be added since this is the most effective reading for compressive strain. Thus, three strain gauges in a -45°, 0°, 45° configuration on a circular section would function as the required reaction-torque and thrust load cell.

Fig. 8 – Load cell

part on which strain gauges are fixed

part encasing

motor and gearbox

part to be fixed

to the housing

outlet for motor terminalsTwo rectangular strain rosettes were fixed on opposite sides of the load cell, the 0° being aligned with the longitudinal axis, that is, parallel to the axis of the thrust. To transfer the load from the propeller onto this load cell, the motor and gearbox used to power the propeller were incorporated with the cell. Since the expected loads were quite small, the readings from the load cell were also expected to be very small. To be able to improve this and get bigger numbers on the strain meters, the circular section was reduced to a hollow circular section since this has smaller cross sectional area and polar moment. The outer radius was chosen such that the strain rosettes would be adhered to a surface which has a large radius of curvature, preferably a plane surface. Aluminium was chosen as the load cell material since it has relatively low stiffness, which complements the idea of increasing the values of strain; it is widely and readily available in circular cross-sections and is also easily machined. The designed wall thickness of 1. 5 mm was decided by plotting curves for micro-strain against wall thickness for different outer radii of the load cell and choosing radii for maximum readings while keeping a thickness which is attainable with conventional machining. Turning, milling and drilling processes were used to machine the load cell.

The load cell had to be calibrated for both thrust and torque. This was accomplished by first loading the cell in compression, then subject it to a torque and finally, a combination of both compression and torsion. The output values from the Model P3 Strain Indicator and Recorder were recorded and compared to expected values. Equations were obtained from mechanics of materials analysis.

Where E is Young’s Modulus (N/m2)

ε is the strain, subscript denotes the orientation

Ro is the outer radius (m)

Ri is the inner radius (m)

G is the modulus of rigidity (N/m2)

ν is the Poisson ratio (13)

(14)

(15)

Fig. 10 – Graph of load cell torque calibration

Fig. 9 – Graph of load cell thrust calibration

6. 2 Jig for Pitot Tube

Fig. 11 – Pitot tube jig

To be able to obtain the velocity profile of the water passing through the channel, readings of differential pressure at various points across a section of the channel were taken using a pitot tube. Pitot tubes should have the shorter leg parallel to the flow when taking readings and are quite sensitive to misalignment [21]. For this reason a jig allowing adjustments in both directions was designed. Two blocks of steel clamp the Pitot tube securely using bolts. This assembly is then placed onto a mating part in which it can slide and another bolt secures the transverse position. This mating part is in turn bolted to the channel walls. Milling and drilling processes were used to machine this part.

The motor which provides power to the propeller shaft, and the gearbox which converts the speed, have to be encased in some housing together with the load cell. A streamlined housing would be preferred to induce less turbulence in the surrounding water. To obtain open water conditions, the ITTC recommends that the propeller is at least twice its diameter away from the housing while having an immersion of at least 1. 5 times its diameter. A stern tube was fitted in the housing for the shaft to rotate in and also to reduce vibrations due to the deflection of the Test Housing

protruding shaft. A model of the housing was made out of cardboard after its minimum dimensions were calculated after taking into consideration the channel dimensions, the dimensions of the motor, gear box and load cell and also the fact that the propeller shaft should be able to be changed when needed, therefore enough space for a hand to fit in was required. The cardboard model was then covered with layers of fibreglass and paint. In order to be able to fix the hull to the channel, attachments to be fixed to the sides of the housing had to be made. The attachments were designed so as to allow adjustments of propeller immersion.

Fig. 12 -Housing with stern tube and side attachments

Testing Methods

To be able to carry out the open water test, geometrical, kinematic and dynamic similarity had to be obtained. The models were compared to a full-size propeller of diameter 3 m, rotating at 110 rpm with an advance speed of 10 m/s bearing a thrust of 500 kN and a torque equivalent to 95 kNm [22]. Theory predicts that for geometrically similar models with a scaling factor of λ, model values of advance speed, Vam, rotational speed nm, thrust, Tm and torque, Qm are as given in Table 1.

Equation

Quantity

Model 1

Model 2

Dm (m)

0. 05

0. 035

(16)

λ

60

85. 7

(17)

Vam (m/s)

1. 29

1. 08

(18)

nm (rps)

14. 18

16. 98

(19)

Nm (rpm)

850. 80

1018. 80

(20)

Tm (N)

2. 32

0. 79

(21)

Qm (Nm)

0. 00733

0. 00176

Table 1 – Similarity of parameters between ship and model

In order to obtain the open water characteristics of the model propellers, the torque, thrust, rotational speed, and advance speed had to be measured. During normal operation, water hits the back of the propeller first and thus when performing an open water test, the propeller has to be mounted such that the water still hits the back first. For this reason, the propeller cap was cut off and fitted onto the back side of the hub. The propeller shaft was inserted from the stern tube to fit into a universal joint and fastened by a grub screw. The motor terminals were connected to the power supply and the voltage was set; the load cell was connected to the Model P3 Strain Indicator and Recorder and its settings were adjusted. The propellers had a piece of reflective tape stuck on the cap in order to reflect the laser emitted from Contact/Non-Contact Pocket Laser Tachometer which gives the rotational speed readings. The propeller was screwed onto the propeller shaft behind a lock nut which was tightened and the housing was fixed to the channel walls. The Pitot tube jig was mounted and the Pitot tube was connected to a differential manometer and zeroed. The water pump was switched on and left to settle to obtain steady flow.

Open water tests are carried out for a fixed rpm while varying the advance velocity, but the rotational speed settings were much more repeatable than the velocity settings with the available resources, and therefore this approach was not adequate. Instead, readings of thrust and torque strains were taken for a specific speed, while varying the rpm. The Pitot tube was used between readings to check the velocity of the water. Different values of advance speed were achieved and readings of thrust and torque were taken for rotational speeds equivalent to the designed rpm in Table 1, together with ±25%, ±50% and ±75% when possible.

Tests and Results

From the values obtained, the advance coefficient, J, the thrust, T and thrust coefficient, KT, the torque, Q and torque coefficient, KQ and the open water efficiency, ηo were computed. KT, KQ and ηo were plotted against J for each of the two propellers. The load cell was replaced with full-bridge load cell and the results of the new setup were plotted in Fig. 13 and Fig. 14.

Fig. 14 – Graph of KT, KQ and ηo against J for 50mm diameter propeller at designed speed Nm= 850. 8rpm

Fig. 13 – Graph of KT, KQ and ηo against J for 35mm diameter propeller at designed Nm= 1018. 8rpm

Discussion

The plots for both propellers show shapes in accordance with those in Fig. 6 but deviated from the magnitudes in these same plots. When Va = 0, J = 0 and KT and KQ have a maximum value. This is the static condition and occurs at 100% slip. When KT = 0, there exists a resultant velocity which produces no lift and therefore no thrust. This is the condition at 0% slip. The open water efficiency is reduced to zero at both extremes of slip. A factor strongly contributing to such results is the blockage factor of the housing in the channel since even though the dimensions of the housing were designed to be kept as small possible, there was a considerable amount of blockage in the tank and the water could not flow freely, contributing to more turbulence in the test section. The blockage factor during the tests ranged from 66% to 70% which is higher than required. Severe ventilation, which is the sucking down of air from the water surface, was occurring at the higher rpm settings, causing the motor to slip and loose thrust while readings from the strain indicator and tachometer fluctuated. Vibrations of the motor unit, which was in close proximity to the load cell, could have also affected the results, not only because of erroneous readings, but also because the load cell was noticed to unscrew itself slightly from the motor unit during operation, thus the transmission of the loads was possibly affected. The dimensions of the channel itself (width: 100mm, height 210mm) caused the testing area conditions to be far off from open water conditions and also to have a comparatively large boundary layer. The results were not as complete as would have been required because very few velocity settings could be attained in the available setup.

Conclusion

The aim of the dissertation was to investigate propellers by building an open water test area using available resources. Some improvements on the setup could be a wider, deeper section in the circulating water channel where the blockage effect is minimized together with the boundary layer effect. There could also be improvements in the design of the housing by having a more streamlined shape and also by reducing the size of the components inside the housing, namely the motor, gearbox and load cell, such that the housing is smaller and the blockage factor is reduced. The wave-making tank could also be used for open water tests by designing a towing carriage to tow the housing along with a constant velocity. For real-life simulation the test housing can be modified for tests to be carried out in the sea but this would involve more variables such as temperature, speed and waves and thus lack of repeatability.