Calculation of Principal Parameters of a Shallow Draft Vessel to be Fitted with Two Surface Piercing Propellers

Ahammad Abdullah
Naval Architect
Department of Naval Architecture and Marine Engineering
Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh

Zobair Ibn Awal
Assistant Professor
Department of Naval Architecture and Marine Engineering
Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh

Abstract

This research work attempts to develop a method to design a high-speed shallow draft vessel. The work is fundamentally performed into three segments: developing a performance prediction method for propeller where the data of a surface piercing propeller is collected from a convenient source, secondly calculation of the resistance of the vessel at designed ship speed and finally the principal parameters of the vessel are determined, where the resistance experienced by the vessel at design ship speed is balanced by the thrust developed by the propeller at the appropriate operating condition. The developed method is a different way to find the principal particulars of a ship which is distinct (reverse method) from the traditional approach. Predicted resistance from the performance prediction method and traditionally calculated resistance from the selected vessel are almost same which indicates that this method is suitable for designing high-speed shallow draft vessel.

Keywords: Performance prediction method, Surface Piercing Propeller, Shallow draft vessel design

I. INTRODUCTION

A surface propeller or surface piercing propeller is a screw propeller which operates partly submerged in water so that the propeller blades enter and leave the surface of water once in every revolution. Surface propellers are fitted just behind the hull of the ship instead of under it. As a result, the underwater appendages required for supporting the propeller are eliminated leading to a sharp drop in appendage resistance, which can be considerable in a small high speed vessel, as much as 30% of the total in some cases. At the same time, the decrease in efficiency due to the propeller not being fully submerged is not very large. Therefore, the total power required to attain a given speed with a surface propeller may be substantially less than the power required with a conventional fully submerged propeller.

In this paper the calculation of propeller performance characteristics such as thrust developed and torque experienced by a propeller, horizontal and vertical components of the force normal to the axis of the propeller of a partially submerged propeller is done. Also the calculation of hydrodynamic characteristics such as thrust and torque coefficients and efficiency of the propeller at the operating condition is done. The combination of hull-propeller is such that, two surface piercing propellers are fitted in a high speed shallow draught vessel.

After the prediction of the performance of the surface piercing propeller, the problem becomes to find the principal parameters of the vessel [7]. For this purpose, the calculation of resistance of the vessel at designed ship speed is done. Next a procedure is followed for the determination of principal parameters of the vessel which will balance this [4]. The principal dimensions such as length, breadth and draught of the vessel and form parameters such as prismatic coefficient, mid-ship section coefficient and block coefficient of the vessel are fixed by trial and error method.

II. LITERATURE REVIEW

Lots of researchers have already worked on the problem of how to calculate the principal parameters of ships. Through their research work formulae are now available for estimating the principal dimensions of shallow draft vessel depending on previous data of existing ships. Munro-Smith in his book [8] has shown different approach to get the principal dimensions of vessel based on different empirical formulae. Usually propeller calculation are done after selecting these dimension. But in our case a reverse approach is developed where first the performance of the propeller will be calculated and then the dimensions of vessel will be found based on calculated propeller thrust.

Several studies have been published for the performance calculation of surface piercing propellers (SPP). Many of these studies focus was to determine the time-averaged thrust, torque, bending moment, and transverse forces. In this paper, approached presented by Ghose & Gokran [2] will be used for the performance prediction of SPP.
III. PERFORMANCE CALCULATION PROCEDURE OF SURFACE PIERCING PROPELLER

The calculation of propeller performance characteristics such as thrust developed and torque experience by the propeller, horizontal and vertical component of the force normal to the axis of a propeller of partially submerge propeller is required. The calculation of hydrodynamic characteristics such as thrust and torque coefficient and efficiency of the propeller at the operating condition at certain advance coefficient is also required. Before developing the calculation procedure the following matters are taken into consideration:

- Two surface piercing propellers are to be fitted in a shallow draught vessel
- The shaft and propeller system should be such that, the submergence depth of the
- Propeller is h (figure 1) and inclination angle of the propeller axes, hence propeller shafts are horizontal (figure 1) but outwards aft to the vessel centre line is Ψ (figure 2)
- The axial and tangential forces per unit immersed blade length are constant
- The propeller blades are narrow and that the induced velocities can be neglected

The calculation is performed [2] sequentially as follows:

1) Calculation related to first blade of the propeller
2) Calculation related to all the blades of the propeller
3) Calculation of hydrodynamic characteristics of the propeller

Fig. 1: Shaft and Propeller system (h = depth of submergence) [3]

Fig. 2: Shaft and Propeller system (Ψ = inclination angel of the propeller axes which are horizontal but outwards aft to the vessel centre line [3]

A. Calculation related to first blade of the propeller

The geometrical parameters related to partially submerged propeller are illustrated in a figure in [3] and the calculation procedure is developed using information from [2]. If the angle with the upward vertical at which each blade enters and leaves the surface of water are Θ₁ and Θ₂ then,
\[ \theta_1 = 90^\circ + \sin^{-1} \frac{a}{R} \]  
\[ \theta_2 = 90^\circ + \sin^{-1} \frac{a}{R} \]  

Where,

- \( a \) = propeller axis above water line = \( R - h \)
- \( h \) = propeller depth of submergence
- \( R \) = propeller radius = \( \frac{D}{2} \)
- \( D \) = propeller diameter

At any angle \( \Theta \), \( \Theta_1 \leq \Theta \leq \Theta_2 \) radius at inner edge of immersed blade,

\[ r_0 = \frac{a}{\cos(180^\circ - \Theta)} = \frac{a}{\cos \Theta} \]  

Length of immersed blade = \( R - r_0 \)

Now, if it is assumed that the axial and tangential forces per unit immersed blade length are constant then thrust of the blade,

\[ T_i = \frac{dT}{dr} (R - r_0) \]  

Blade torque,

\[ Q_i = \int r \frac{dQ}{dr} dr = \frac{1}{r} \int \frac{dQ}{dr} r dr = \frac{1}{r} \int dQ \left[ \frac{R^2 - r_0^2}{2} \right] \]  

Tangential force,

\[ F_i = \frac{1}{r} \frac{dQ}{dr} (R - r_0) \]  

Horizontal component of tangential force,

\[ F_{iH} = F_i \times \cos(180^\circ - \Theta) = -F_i \times \cos \Theta \]  

Vertical component of tangential force,

\[ F_{iV} = F_i \times \sin(180^\circ - \Theta) = -F_i \times \sin \Theta \]  

The diagram of velocities and forces for a propeller blade element is illustrated in figure 3.

In equation (4),

\[ \frac{dT}{dr} = \frac{dL}{dr} \cos \beta + \frac{dD}{dr} \sin \beta \]  

In equation (5),

\[ \frac{dQ}{dr} = \left[ \frac{dL}{dr} \sin \beta - \frac{dD}{dr} \cos \beta \right] \times r \]

Here,

\[ \frac{dL}{dr} = C_L \times \frac{1}{2} \rho \times c \times V_r^2 \]  

\[ \frac{dD}{dr} = C_D \times \frac{1}{2} \rho \times c \times V_r^2 \]  

Where,

- \( C_L \) and \( C_D \) depends on the angle of attack (\( \alpha \)) of the section,
- \( P \) = density of water
- \( C \) = section chord length
- \( V_r = \) resultant inflow velocity to the section at an angle \( \beta \) with the transverse direction = \( \sqrt{(V_A \cos \psi)^2 + (ar)^2} \)

Further if it is assumed that the propeller blades are narrow and that the induced velocities can be neglected then, Hydrodynamic pitch angle at any radius, \( r \) is

\[ \beta = \tan^{-1} \left( \frac{V_A \cos \psi}{ar \times r} \right) \]  

Where,

- \( V_A = \) Speed of advance in a horizontal direction parallel to the center line of the vessel. (Figure 1)
- \( \psi = \) Inclination angle of the propeller axes which are horizontal but outwards aft of the vessel centre line. (Figure 2)
Blade pitch angle at any radius \( r \) is,

\[
\phi = \tan^{-1}\left[ \frac{p}{2\pi r} \right]
\]

Angle of attack at any radius \( r \) is, \( \alpha = \phi - \beta \)

**B. Calculation related to all the blades of the propeller**

After finishing the calculation according to section 3.1 for each blade of the propeller we need to combine the effect of all blade of the propeller. The thrust, \( T \) of all the blades is calculated as follows:

\[
T_{i1}(\theta) = T \left[ \theta + (2\pi / z) \right]
\]

\[
T(\theta) = \sum_{i=1}^{z} T_{i}(\theta)
\]

\[
T_{average} = \frac{1}{2\pi} \int_{0}^{2\pi} T(\theta) d\theta
\]

Similarly, the variation of torque, \( Q \) and the horizontal and vertical components of the tangential force \( F_{H} \) and \( F_{V} \) can be obtained and their average values calculated.

**C. Calculation of hydrodynamic characteristics of the propeller**

The hydrodynamic characteristics of the propeller such as thrust and torque coefficients and efficiency at the operating condition i.e. at certain advance coefficient are expressed as,

Advance coefficient,

\[
J = \frac{V_{c} \cos \psi}{nD}
\]

Thrust coefficient,

\[
K_{T} = \frac{T}{\rho n^{3} D^{5}}
\]

Torque coefficient,

\[
K_{Q} = \frac{Q}{\rho n^{3} D^{4}}
\]

Efficiency,

\[
\eta = \frac{J}{2\pi} K_{T} K_{Q}
\]

**IV. CASE STUDY**

For the case study we are considering two surface piercing propellers are fitted in a shallow draught vessel. The detail particulars of the propeller is provided in table 1 which is taken from [2,3]. The propeller axes are horizontal but inclined at 10 degree outwards aft of the vessel centre line and are 0.1941m above the waterline. The axial and tangential forces per unit immersed blade length are constant and equal to the value at 0.7R.
V. CALCULATION OF THE PRINCIPAL PARAMETERS OF SHALLOW DRAFT VESSEL

To design any particular vessel a lot of calculations have to be done. Actually the calculation never stops before construction. Every time the dimensions are changed to fit the data. Overall cost estimation, rules and regulation, safety purpose and profit are the main criteria. In determining for a particular design guidance is taken from a ship similar to the proposal and for which the details are known.

In section 3, the performance of a surface piercing propeller is predicted. Two surface piercing propellers are fitted in a shallow draught vessel. Now the problem is to find the principal parameters of the vessel. The steps to be followed are:

1) Calculation of the resistance of the vessel at designed ship speed.

From table 1, the speed of advance of the propeller in the horizontal direction parallel to the center line of the vessel is

\[ V_A = 5 \, \text{m/s} \]

The wake fraction, \( \omega = 0.05 \)

The ship speed can be calculated as,

\[ V_S = V_A \sqrt{1 - \omega} = 5 \sqrt{1 - 0.05} = 5.2632 \, \text{m/s} \quad (13) \]

The average thrust, \( T_{\text{average}} \) of the propeller along the direction of the shaft axis is, \( T_{\text{average}} = 28.6447 \, \text{KN} \) from Table 2.

The total thrust of two propellers along the ship direction is,

\[ T = 2 \times T_{\text{average}} \times \cos \Psi \]

\[ = 2 \times 28.6447 \times \cos 100 \]

\[ = 56.4190 \, \text{KN} \]

Now the ship resistance is,

\[ R = T (1-t) \]

\[ = 56.4190 (1 - 0.02) \]

\[ = 55.2907 \, \text{KN} \]

The principal parameters of the vessel are to be determined such that the vessel will encounter resistance of 55.2907 KN at speed of 5.2632 m/s.

The vessel is supposed to be plying in fresh water region and the water temperature is Take as 30°c. The water properties are then,

Density, \( \rho = 996 \, \text{kg/m}^3 \)

Kinematic viscosity, \( \nu \approx 0.804 \times 10^{-6} \, \text{m}^2/\text{s} \)

The principal dimensions such as length, breadth and draught of the vessel and form Parameters such as prismatic coefficient mid-ship section coefficient and block coefficient of the vessel are fixed by trial and error method. The last and final calculation is provided here.

The prismatic coefficient is chosen as \( C_p = 0.8 \)

The midship section coefficient is chosen as \( C_m = 0.95 \)

So that block coefficient is \( C_b = C_p \times C_m = 0.76 \)

The speed length ratio is chosen such that the vessel may be considered as high-speed vessel,

\[ 1.0724 \times V_S / (\sqrt{L}) = 1 \]

So that,

\[ L = (1.0724 \times 5.2632)^2 \]

\[ = 31.8576 \, \text{m} \]

Next the displacement length ratio is chosen as

\[ (0.02789 \Delta) / (L/100)^3 = 250 \]

We get,

\[ \Delta = (250 \times (L/100)^3)/0.02789 \]

\[ = (250 \times (31.85/100)^3)/0.02789 \]

Table - 1

<table>
<thead>
<tr>
<th>Parameters of propeller</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blades</td>
<td>4</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Pitch ratio (P/D)</td>
<td>1.0</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>600 rpm</td>
</tr>
<tr>
<td>Velocity of advance</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Wake fraction (( \omega ))</td>
<td>0.05</td>
</tr>
<tr>
<td>Section chord length(at ( r=0.7R ))</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Lift coefficient, ( C_L)</td>
<td>0.015/deg. Angle of attack</td>
</tr>
<tr>
<td>Drag coefficient, ( C_D)</td>
<td>0.001/deg. Angle of attack</td>
</tr>
</tbody>
</table>
Calculation ofPrincipal Parameters of a Shallow Draft Vessel to be Fitted with Two Surface Piercing Propellers

Let us take length-breadth ratio as, \( L/B = 4 \)

Then,
\[ B = \frac{L}{4} = 7.9644 \text{ m} \]

As, \( \Delta = \rho . L . B . H . C_b \) we get,
\[ H = \frac{\Delta}{(L . B . C_b . \rho)} = \frac{289.8215}{(31.8576 \times 7.9644 \times 0.76 \times 0.996)} = 1.5090 \text{ m} \]

The breadth-draught ratio is,
\[ \frac{B}{H} = \frac{7.9644}{1.5090} = 5.2779 \]

VI. VESSEL RESISTANCE CALCULATION

The resistance of a ship at a given speed is the fluid force acting on the ship in such a way as to oppose its motion. The resistance will be equal to the component of the fluid forces acting parallel to the axis of motion of the ship.

The total resistance denoted by \( R \), can be split into a number of different components, which are due to variety of causes and which interact one with the other in an extremely complicated way. In order to deal with resistance in a practical way, it is necessary to consider the total resistance as being made up of components which can be combined in different ways. The components can be described as follows.

Initially the total resistance can be taken as,
\[ R = R_R + R_F \]

Where,
\( R_R \) = residual resistance
\( R_F \) = frictional resistance for smooth hull

The calculation procedure developed and presented in section 3 is applied for the prediction of the performance characteristics of a partially submerged propeller.

The residual resistance, \( R_R \) is calculated using Taylor’s Standard series [1] and the calculation method can be found in [2, 4]. The calculation of frictional resistance, \( R_F \) for smooth hull using ITTC formulation [5].

Calculation of total resistance for smooth hull,
\[ R = R_R + R_F = 36.4686 + 6.4233 = 42.8919 \text{ KN} \]

Now, some allowance is made for appendages, roughness allowance and weather allowance to have a reasonable correction to the previously calculated resistance for smooth hull condition [6].

Resistance for smooth hull, \( R = 42.8919 \text{ KN} \)

Allowance for appendages, say 5% of \( R = 2.1446 \text{ KN} \)
\[ \therefore R_1 = 45.0365 \text{ KN} \]

Roughness allowance, say 15.97% of \( R \)
\( \text{(Equivalent to } \Delta C_F = 0.0003) \)
\[ \therefore R_2 = 46.0625 \text{ KN} \]

Weather allowance, say 20% of \( R_2 \)
\[ = 9.2125 \text{ KN} \]
\[ \therefore \text{Total} = 55.2750 \text{ KN} \]

VII. RESULTS

The following calculations are performed following the procedure developed and presented in section 3.

1) Thrust developed by the propeller
2) Torque experienced by the propeller
3) Horizontal component of the force normal to the axis of the propeller
4) Vertical component of the force normal to the axis of the propeller

The hydrodynamic characteristics such as \( J, K_T, K_Q \) and \( \eta \) of the propeller are also calculated and presented in Table 2.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{average}} )</td>
<td>28.6447 KN</td>
</tr>
<tr>
<td>( Q_{\text{average}} )</td>
<td>3.1142 KN.m</td>
</tr>
<tr>
<td>( F_{H(\text{average})} )</td>
<td>5.1451 KN</td>
</tr>
<tr>
<td>( F_{V(\text{average})} )</td>
<td>0 KN</td>
</tr>
<tr>
<td>The advance coefficient, ( J )</td>
<td>0.3333</td>
</tr>
</tbody>
</table>

All rights reserved by www.ijirst.org
Using the values in Table 2 and considering two surface piercing propellers will be fitted in a shallow draught vessel, the principal parameters of the vessel is calculated which is shown in section 5. Finally we get the principal parameters of the vessel which is given in the following Table 3.

<table>
<thead>
<tr>
<th>Principal parameters</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>31.8576 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>7.9644 m</td>
</tr>
<tr>
<td>Draught</td>
<td>1.5090 m</td>
</tr>
<tr>
<td>Length-breadth ratio</td>
<td>4.0</td>
</tr>
<tr>
<td>Breadth-draught ratio</td>
<td>5.2779</td>
</tr>
<tr>
<td>Prismatic coefficient</td>
<td>0.8</td>
</tr>
<tr>
<td>Midship-section coefficient</td>
<td>0.95</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>0.76</td>
</tr>
<tr>
<td>Displacement</td>
<td>289.8215 tonnes</td>
</tr>
</tbody>
</table>

Final step is to find the actual resistance of the vessel and to compare it with the previous results which is obtained from the performance prediction method. The calculated resistance is equal to 55.275 KN that can be used for powering calculation. This value is very close to the value of 55.2907 KN which can be found from the thrust produced by the two surface piercing propellers after thrust deduction.

**VIII. CONCLUSIONS**

There are many formulae for estimating the principal dimensions of shallow draft vessel depending on previous data of existing ships. Some formulae are not suitable for modern design, because of the great development in ship engineering. Therefore, it was necessary to get new method to estimate the principal dimensions of vessel. Main dimensions decide many of ship’s characteristics, e.g., stability, tanks capacity, power requirement, and even economic efficiency. Therefore estimating the main dimensions is a particularly important phase in the overall design procedure of a new ship especially in preliminary design stage to identify the main features of the ship. The aim of this paper is to introduce and update the method (Reverse) that can be used to determine the main dimensions of a shallow draft vessel in preliminary design stage. And from the results and discussion it is evident that our proposed way of calculating principal parameters of ship can be feasible. The overall evaluation of the work presented in the paper is that, a high speed shallow draught vessel is designed which is fitted with surface piercing propeller.

**ACKNOWLEDGMENTS**

Our deep gratitude goes to our BSc thesis supervisor Professor Dr. Md. Refayet Ullah for his initiation and supervision of this study and for his continuous support and engagement in the project. We would also like to acknowledge the effort and guidance of Dr. Zobair Ibn Awal who made it possible for us to write this research paper.

**REFERENCES**
