DESIGN METHOD FOR MARINE PROPELLER/STATOR PROPULSORS

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Abstract

This paper describes a procedure for marine screw propeller design and its application in combination with stator device based on lifting line methodology. In accordance with the lifting line methodology, the design procedure presented in this paper involves the realistic representation of the slipstream deformation. The slipstream shape is allowed to deform and to align with the direction of local velocity which is the sum of the inflow wake velocity and induced velocity. As the slipstream deformation is the key parameter in the design of performance improvement devices, the propeller design methodology is combined with a stator device behind the propeller and the hydrodynamic performance of the combined system is analyzed in terms of effect of variation of the axial distance between the propeller and stator and the number of stator blades. In this it will be shown that the use of this combination is more efficient than the propeller alone.

Introduction

During the evolution of propeller design procedures from the simple Momentum Theory to more elaborate Lifting Surface Theory, the Lifting Line design procedure has occupied the designers more than any other method. Therefore today lifting line methods still have the most respected place amongst the others. This is not only because they have the advantage of being widely used and well established procedure due to their long service history.

From the above point of view, it could be well justified to seek for the further improvements in the present lifting line procedures by taking advantage of further advances in computational hydrodynamics. Indeed if one investigates the earlier lifting line models, it is found that a number of simplifying assumptions were necessary in order to derive a solution with the available computational tool. One of the these assumptions is that the propeller is moderately loaded and that the downstream variation in induced velocities and the resulting slipstream deformation can be neglected, Lerbs[4]. Later development of the lifting line methods has tackled the slipstream deformation by taking into account the self induced velocities, Glover[3]. But none of these methods included the effect of the local inflow velocities in the slipstream which would contribute to the deformation of the slipstream.

In order to achieve the goal of an improved propulsive efficiency some alternative propulsors have been proposed, the aim of which is to reduce the energy losses associated with the action of the propeller. These losses are due mainly to the transfer of energy to the water in the slipstream of the propeller, the axial energy loss arising from the acceleration of the water necessary to create thrust and the rotational energy loss from the transfer of torque from the propeller to the water. Recovery of the rotational energy loss and therefore significant gains in efficiency and balancing torque could be achieved by using the using the propeller/stator combination.

Propeller Design Procedure

In this section a description will be given of advanced lifting line procedure, Güner[1], based on the assumption that the blades are replaced by lifting lines with zero thickness and width along which the bound circulation is distributed. The free vortex sheets shed from the lifting lines lie on helical surface, the shape of which is function of velocities induced in the slipstream by the propeller and the body wake velocities.

The aim of the design is solution of the vortex model of the propeller and in particular the determination of the distribution of the bound circulation on the lifting line such that it absorbs a given power at a specified rate of rotation and propeller advance speed. This requires the following design parameters:

- Delivered power, P_D kW
- Propeller rate of rotation, N rpm
- Vehicle speed, V_S
- Torque identity wake fraction, w_Q
- Number of blades, Z

Using the above data and an appropriate B_P-δ diagram the optimum diameter, D, and the mean face pitch ratio of a "basic" propeller to satisfy the design condition can be determined.

When the propeller operates in the proximity of the sea surface, the necessary blade surface area required to minimise the risk of cavitation can be determined using an appropriate cavitation criteria, such as that due to Burrill[(2)]. The distribution of this area on an appropriate blade outline gives the blade chord widths at the design radii.

A simple stressing calculation can be used to calculate the blade section thickness and drag coefficient determined as function of the section thickness ratios.

The wake-adaptation of the design, i.e. optimisation with respect to the radial wake distribution in which the propeller is assumed to work, is then carried out using the improved lifting line procedure.

In this procedure the above design conditions are represented by the requirement that the propeller should achieve a torque coefficient, K_Q, given by

$$K_Q = \frac{33.55\,P_D}{\left[\frac{ND}{10}\right]^3 D^2} \qquad (1)$$

Optimisation of the design, i.e. the determination of the radial loading distribution corresponding to maximum efficiency, is achieved by introducing a minimum energy loss condition into the solution of the lifting line model. In this work the condition derived by Burrill[(5)] is used, in which the vortex sheets in the ultimate wake are assumed to have uniform pitch radially, i.e.:

$$x_i \pi \tan \varepsilon_i = \text{const.} \qquad (2)$$

Where $x_i = r_i / R$ is the non-dimensional form the i^{th} section radius, R is the propeller radius and ε_i is the pitch angle of helical vortex sheets at infinity.

Based on the assumptions that the circulation of the lifting line, or bound circulation, is assumed to go continuously to zero at both the tip and the boss, the associated expression for the circulation can be defined by a Fourier sine series and written in non-dimensional form as follows

$$G_i = \frac{\Gamma_i}{\pi D V_s} = \sum_{n=1}^{\infty} A_n \sin(n\phi_i) \qquad (3)$$

Where Γ_i is the bound circulation at x_i and A_n is the bound circulation coefficient whose value is to be determined.
The angular coordinate, ϕ_i, is defined in terms of the radial coordinate, x_i, as follows,

$$x_i = x_h + \left(\frac{1 - x_h}{2}\right)\left(1 - \cos\phi_i\right) \qquad (4)$$

Where x_h is the non-dimensional hub radius and ϕ_i varies from 0 at the hub to π at the tip.

The problem is now determination of the unknown A_n's. Once these values are calculated, the axial, tangential and radial induced velocities at any point of the lifting line can be estimated and finally the hydrodynamic pitch angle, lift coefficient and torque & thrust coefficients can be calculated..

The solution of the lifting line design problem reduces to the determination of the values of the coefficients, A_n, such that the design conditions and a prescribed condition for minimum energy loss are satisfied. To effect the solution the series is truncated to 9 terms and expressions for induced velocity components are derived at 9 reference points along the lifting line in terms of A_n's and the induction factors, I. The induction factors depend only the geometry of slipstream and can be derived from an application of the Biot-Savart Law [(1)].

At a point x_{ij} a distance y_{ij} downstream from the lifting line, the slope of the vortex line is given by

$$\tan\alpha_{ij} = \frac{U_{r_{ij}} + u_{r_{ij}}}{U_{a_{ij}} + u_{a_{ij}}} \qquad (5)$$

Where $U_{a_{ij}}, U_{r_{ij}}$ are the local wake velocities in the axial and radial directions and $u_{a_{ij}}, u_{r_{ij}}$ propeller induced velocities in the axial and radial directions.

The radius of the vortex line can be then determined from the following equation:

$$x_{ij} = x_i + \int_0^{y_{ij}} \tan(\alpha_{ij}) d\alpha_i \qquad (6)$$

The hydrodynamic pitch angle of the trailing vortices in the slipstream becomes

$$\beta_{ij} = \tan^{-1}\left[\frac{U_{a_{ij}} + u_{a_{ij}}}{\pi x_{ij} nD - u_{t_{ij}}}\right] \qquad (7)$$

Where n is the propeller rate of rotation per second.

As it can be seen from (6) and (7), the deformed slipstream shape depends on the total velocity on the vortex lines. The total velocity can be defined as the sum of velocities induced at the point by the trailing vortices in the slipstream, bound vortices at the lifting line and the local wake velocities. As long as the total velocity at the point is calculated correctly, the true shape of the slipstream can be obtained.

The above design methodology is applied for the two design cases using the input data given on Table 1 and the local wake velocities shown in Figure 1 and Figure 2.

The present method with these set of data gave an efficiency, η=0.697 for Propeller-1 and η=0.467 for Propeller-2.

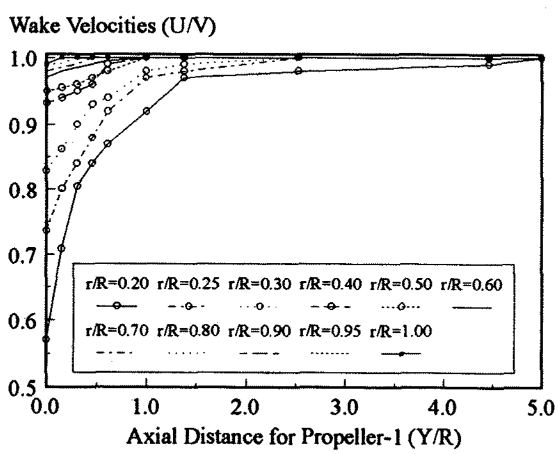

FIGURE 1- Wake Velocities for Propeller-1

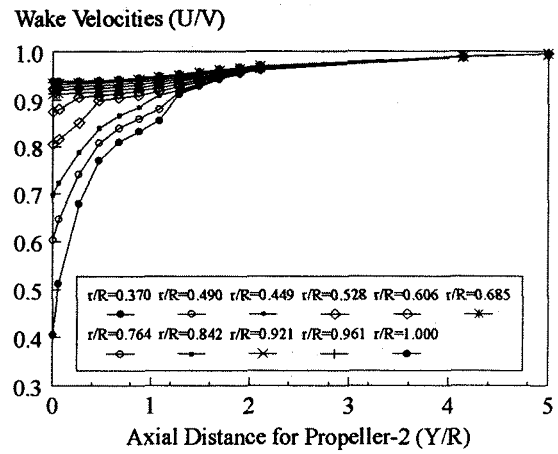

FIGURE 2- Wake Velocities for Propeller-2

TABLE 1- Design Input Data

	Propeller-1	Propeller-2
Delivered Power, P_D (kW)	28000	260
Design Speed, V_S (Knot)	32	15
Rate of rotation, RPM	170	2000
Propeller Diameter, D (m)	5.30	0.490
Number of Blades, Z	5	3

Stator Design

The downstream stator can be designed to remove the unbalanced torque reaction and to reduce the rotational energy loss as proposed by Glover [3] as with other energy saving propulsors, the use of a stator is only worthwhile where the energy losses in the slipstream are significant i.e. the propeller loading is moderate to high. Where the propeller loading is light, as in the case of a torpedo, the use of a stator may result in reduced propulsor efficiency, but they provide a cheap and effective means of removing the unbalanced torque.

The stator has a negligible effect on the propeller forces but, for the appropriate propulsor loading, the stator produces a net positive thrust and the propulsor efficiency becomes greater than that of the equivalent conventional propeller.

The stator is modelled by a system of lifting lines. Since the stator does not rotate, the path of trailing vortices behind the stator is different than that of the propeller the trailing vortices are no longer taken to be helical, but rather consist of semi-infinite line vortices. The velocities induced by each horseshoe vortex, consisting of a bound vortex segment and its accompanying trailing vortices is calculated by the application of Biot-Savart Law.

The following assumptions are also made in designing the downstream stator:

- The blades of the stator are considered to have an equal angular spacing
- The stator is assumed to have zero skew and rake.
- The tip of the stator is kept within the propeller slipstream and for that reason the tip radius of the stator is set equal to the radius of contracted propeller slipstream at the plane of the stator.

Having established the stator hub and tip radii from the propeller slipstream shape, 37 field points are distributed between the hub, x_h, and the tip x_t, with 5° spacing between the points in angular coordinate. As in the case of the propeller, this spacing was found to give good accuracy and acceptable computation time. The locations of the field points are determined by following equation,

$$x_f(i) = x_h + 0.5(1 - x_t)(1 - \cos\theta_i) \quad (8)$$

where $\theta_i = \frac{\pi}{36}(N - 1)$ (N=1,2,3,......37)

Since there are no rotational induced velocities downstream of the stator, the free vortex lines shed by the stator are directed axially downstream on surfaces of cylinders which contract with the propulsor slipstream. On each of the trailing vortex lines shed from the stator 30 vortex elements and control points are considered and the non-dimensional axial location of these points is determined as below:

$$Y_i = 5(1 - \cos\theta_i) \quad (9)$$

where $\theta_i = \frac{\pi}{60} N$ (N=1,2,3,......30)

Having done this, 1110 points are obtained to model the slipstream shape behind the stator. The next step is to determine the bound vortices of the stator in order to achieve the design of the stator. Once the bound circulation of the stator is established, the velocity induced by the stator can be calculated in axial, radial and tangential directions using Biot-Savart Law. The applications of the law gives the following equations in non-dimensional form the lifting line and from the hub to the tip for each blade are considered. The total velocity induced at $P(x_p,y_p)$ by Z_s vortex lines is written as follows:

$$\left.\begin{aligned} u_a &= \sum_1^{Z_s} \frac{G}{2}\int_{x_h}^{x_t}\int_0^{\infty}\frac{1}{a^3}\Big[\big(x_p - x\cos(\theta + \phi_z)\big)\tan\alpha \\ &\quad \sin(\theta + \phi_z) + \tan\alpha\cos(\theta + \phi_z)\cdot x\sin(\theta + \phi_z)\Big]dydx \\ u_r &= \sum_1^{Z_s} \frac{G}{2}\int_{x_h}^{x_t}\int_0^{\infty}\frac{1}{a^3}\Big[-(y_p - y)\tan\alpha\sin(\theta + \phi_z) + \\ &\quad x\sin(\theta + \phi_z)\Big]dydx \\ u_a &= \sum_1^{Z_s} \frac{G}{2}\int_{x_h}^{x_t}\int_0^{\infty}\frac{1}{a^3}\Big[x_p - x\cos(\theta + \phi_z) + (y_p - y) \\ &\quad \tan\alpha\cos(\theta + \phi_z)\Big]dydx \end{aligned}\right\} \quad (10)$$

where

$$a = \sqrt{\left[x^2 + x_p^2 + (y_p - y)^2 - 2xx_p\sin(\theta + \phi_z)\right]}$$

In above equations, the circulation G, is the only unknown which can be calculated such that the propeller induced tangential velocities far downstream of the propeller are cancelled. Having calculated the induced velocities, the thrust and torque are calculated for each section of the stator blade as follows:

$$dT = \frac{\frac{1}{4}\rho C Z_s D_s\left[u_{apm} + U_a\right]^2\left[\frac{C_L}{\tan\beta_i} - C_D\right]}{\sin\beta_i}dx$$

$$(11)$$

$$dQ = \frac{\frac{1}{8}\rho C Z_s D_s^2\left[u_{apm} + U_a\right]^2\left[C_L + \frac{C_D}{\tan\beta_i}\right]}{\sin\beta_i}dx$$

where ρ is water density, C stator chord lengths, D_s stator diameter, U_a wake velocity, u_{apm} propeller mean induced axial velocity, C_L stator lift coefficient, C_D stator drag coefficients.

In applying the above design procedure the main input data are the number of the blades, the chord lengths and the axial distance between the propeller and the stator.

Propulsor Design Study

In order to investigate the performance characteristics of the propeller/stator combination, two parameters are considered to be important and were therefore systematically varied for each set of data. These parameters are the number of the stator blades and the axial distance between the propeller and the stator.

In investigating the effect of the number of the stator blades, the blade number was varied from 3 to 15 in steps of 3. The main objective of this investigation is to determine the blade number beyond which the gain in performance becomes practically insignificant.

The axial distance (AXD) between the lifting line of the propeller and the stator would result in change in the stator diameter and propeller induced velocities. For each set of design data the axial spacing is varied from Y/R=0.2 to 0.8 in steps of 0.2.

In order to carry out the above outlined systematic investigation of the stator performance, firstly AXD was kept constant while the number of stator blades was changed. At each run of the program the geometry of the stator was modified to give lift coefficient of about 0.55 to 0.65 together with a fair blade outline. This smoothing process was carried out using a least square fitting routine. Following this process, 20 different stator designs were generated for each set of data and the respective gains due to the application of a stator behind the propellers were computed.

The result of the computations for Propeller-1 and Propeller-2 are presented in Figure 3 and Figure 4 as the gains against the number of stator blades for varying AXD. The figures suggest that the optimum number of the stator blades is nine and the gain in propulsor efficiency increases with the large AXD values. From the practical point of the view it was decided to select a nine blades stator at an axial distance of 0.60 which was considered to be reasonable upper limit to axial separation of the propeller and stator.

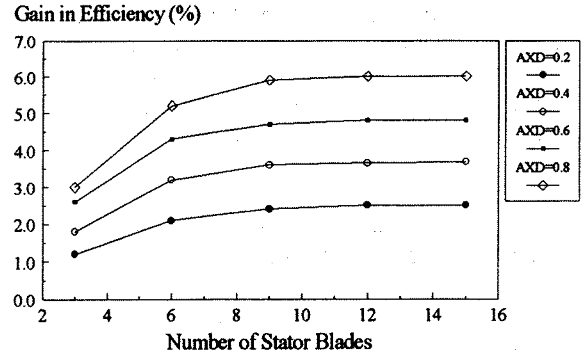

FIGURE 3. Variation of Number of Stator Blades for Propeller-1

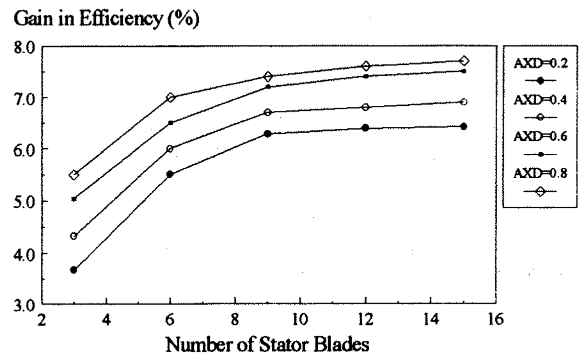

FIGURE 4. Variation of Number of Stator Blades for Propeller-2

Conclusions

- The improved design methodology reported in this paper could provide the designer with capability for more sound and efficient design of propeller and stator combination for surface and submerged ships.
- The performance analysis of the propeller combined with the stator locate behind the propeller indicated that the undesirable effect of the propeller torque can be avoided by the use of the stator. This is an important design requirement for directional stability of the high speed submerged bodies.
- Without paying attention to other engineering considerations the gain means the vessel would operate more efficient which would result in vessel speed increase for the same engine power.

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