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Influence of ducted propeller on seakeeping in waves

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ABSTRACT

It has been claimed that the use of a ducted propeller instead of an open propeller reduces the pitching motions of a ship, and the added resistance in waves. In addition, there is the potential benefit of smaller loss in propulsive efficiency when the propeller loading increases due to added resistance. Although little documentation for the validity of these claims is found, they look reasonable, since the duct has an effect similar to a passive foil, which is proven to reduce the vertical plane motions of high speed vehicles. This paper investigates the effect of a duct on the seakeeping of conventional ships. It is shown how the effect of the duct on the motions can be modelled by an equivalent flat foil. The effect of duct on motions and added resistance is investigated using linear strip theory. Results of model tests using a conventional 120 m single screw cargo vessel with a ducted and an open propeller are presented. The model test results confirm the findings from the numerical calculations, which is that the duct needs to be much larger than what is typical for such a ship in order to have a significant influence on the seakeeping performance.

1. Introduction

The most popular form of marine propulsion device is a screw propeller. It transforms the power generated by the main engine into the thrust force, and in this process some energy losses occur. *Ludwig* Kort (1934) demonstrated that in the case of heavily loaded propellers, an increase in propulsive efficiency could be achieved by surrounding the propeller with a foil-shaped shroud or an accelerating duct. As ducted propellers give increased thrust at low speed and/or high propeller loadings, they are adopted into a range of marine vessels, such as commercial ships, tugboats, bulk carriers, submarines, trawlers etc.

It has been claimed (for instance Minsaas, 1967) that ducted propellers contribute to reduce pitching motions in waves, and to reduce speed loss due to waves. Åkre (1984, 1985) performed model tests with models of trawlers and found that when the propeller was equipped with a duct, the pitching motion was reduced and the pitch axis was moved aftwards. His experiments also showed that the speed loss due to waves was reduced when a duct was applied. However, this last observation might partly be caused by the fact that addition of a duct to a propeller without changing other factors reduces the propeller loading, something that contributes in itself to lower speed loss in waves.

The choice of propeller type for any ocean-going vessel has been based on the calm water characteristics for the propulsors. The performance in waves is so far not considered during such selection, at least not quantitatively. The purpose of this work is to find out whether ducts can improve the seakeeping capabilities in a fairly general sense, which would be important for the choice of propulsion system for ships that are supposed to operate frequently in heavy seas.

2. Theoretical calculations

2.1. Estimation of lift for duct

The duct is treated as an annular foil with aspect ratio equal to the ratio of the inner diameter to the length of the duct. Morgan and Caster (1965) give the lift coefficient values at various angles of attack for three ducts of different annular NACA profiles and camber-chord ratios. Fletcher (1957) presents the plot of lift coefficients against angle of attack for a family of annular airfoils of different aspect ratio with same projected area (product of the inner diameter and the chord parallel to center line). The lift coefficient for the design duct can be estimated from the plot by interpolation for a specific aspect ratio value.

2.2. Determination of equivalent flat foil

For numerical calculations, the duct is modelled as an equivalent passive foil (flat plate) placed behind the hull at the propeller

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centre plane. The analysis is based on the principle that the static lift force generated by the duct and the equivalent plate is same.

The aspect ratio of the plate has been chosen to be equal to that of the design duct, where the aspect ratio of the duct is defined as diameter/chord. Hence, the basis of estimation of the dimensions for the flat plate can be written as follows:

$$L_a = L_p;\ (L = 0.5 C_L \rho V^2 S);\ \text{which gives} - C_{La} S_a = C_{Lp} S_p \tag{1}$$

L is the total lift force; S, the plan area (product of inner diameter and length for annular duct); subscripts 'a' and 'p' are used for annular and flat foil cases respectively. It is concluded by Fletcher (1957) that the lift coefficient curve slope of annular foil is approximately twice of slope for lift coefficient curve for rectangular plane airfoil if they have same aspect ratio. This conclusion appears well when the lift coefficient slopes of low aspect ratio straight wings, obtained by halving the corresponding values of annular foils, are compared to those obtained from the following expressions.

$$C_L = 2\pi\alpha\Lambda/(2 + \sqrt{\Lambda^2 + 4})$$

(Helmbold, 1942; Anderson, 2001)

$$C_L = 2\pi\alpha\Lambda(\Lambda + 1)/(\Lambda + 2)^2$$

(Søding, 1982)

Here Λ is the aspect ratio, and α is the angle of attack of the plane foil. The comparison plots are shown in Fig. 1 for validation.

2.3. Considering the effects of propeller on foil lift

So far, the lift of the duct without a propeller working inside has been considered. This might be a questionable assumption, but a discussion of this issue has not been found in open literature. Instead, the effect of the propeller on the duct lift is studied using a set of model tests with a ducted azimuthing thruster presented in MARINTEK Report (2007). The duct used here has a length of 125 mm, and an inner diameter of 252.78 mm.

The values of the duct side force and propeller thrust obtained by varying pitch ratios and heading angles have been used to plot curves of the duct lift coefficient (C_L) v/s heading angle for different thrust loading coefficients (C_T) given by $C_T = 4T/\pi\rho V^2 D^2$. Here, V is the incoming velocity and D, the propeller diameter. The slope of the linear part of each curve has been used to plot the duct lift coefficient curve slope as a function of C_T. Considering a particular range of C_T (0.2–9.0) a quadratic curve has been fitted through the points as shown in Fig. 2. It is to be noted that, due to the definition of the heading angle in the report, the lift coefficient slope values are negative.

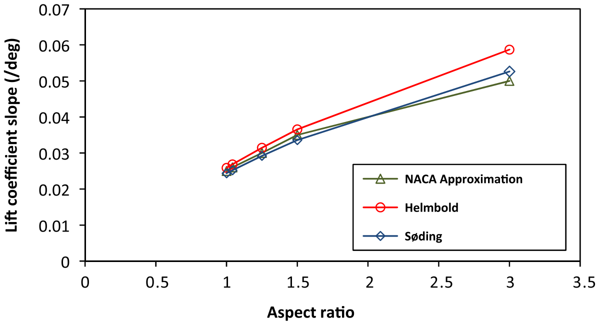

Fig. 1. Lift coefficient curve slope vs. aspect ratio for plane rectangular foils.

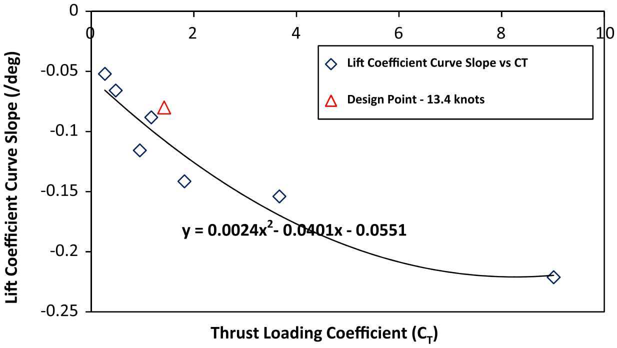

Fig. 2. Plot of lift coefficient slope vs. C_T – ducted azimuthing thruster tests (MARINTEK).

2.4. Formulation for the equivalent flat foil area considering thrust loading

The estimated value of lift coefficient curve slope for the ducted azimuthing thruster (as mentioned in Section 2.1) is shown as the design point in Fig. 2 at the corresponding C_T value for the case vessel at the primary design speed of 13.4 knots. The effect of the rotating propeller is included as an increment in the lift coefficient curve slope corresponding to the operation point C_T.

From the plot for ducted thruster tests (Fig. 2), the lift coefficient curve slope ($C_{L,S}$) for an annular foil considering propeller action is approximated as follows:

$$C_{La,prop,S} = 0.0024 C_T^2 - 0.0401 C_T - 0.0551 \quad (0.2 < C_T < 9.0) \tag{2}$$

The increment in lift coefficient curve slope due to propeller effect is given by the following equation:

$$\Delta C_{La,S} = C_{La,prop,S} - C_{La,S} \tag{3}$$

From the approximation mentioned in 2.2, $C_{Lp} = 0.5 C_{La}$, hence $C_{Lp,S} = 0.5 C_{La,S}$

Hence, for the same lift force on the annular foil and the equivalent flat rectangular plate

$$(C_{La,S} + \Delta C_{La,S}) S_a = C_{Lp,S} S_p = 0.5 C_{La,S} S_p$$

Rewriting for S_p gives the equivalent flat plate area for the duct as follows:

$$S_p = 2(1 + \Delta C_{La,S}/C_{La,S}) S_a \tag{4}$$

The ratio $\Delta C_{La,S}/C_{La,S}$ is obtained from the ducted thruster tests, which reflects the effect of propeller action on the lift coefficient curve slope for the duct. The value of this ratio calculated for the case vessel at the design speed is 0.3. As the change in lift coefficient curve slope considering propeller action depends on C_T, the calculated equivalent flat foil area depends on the propeller loading.

3. Numerical calculations

Numerical calculations for motions and added resistance are performed using the potential flow solver ShipX Veres plug-in (Fathi and Hoff, 2010). ShipX Veres is using linear strip theory based on the STF approach (Salvesen et al., 1970) to predict the motions of the ship. The viscous effects are neglected and the fluid motion can be assumed to be irrotational, so that the problem can be formulated in terms of potential flow theory. The oscillatory motions of the ship are assumed linear and harmonic. Fig. 3 shows the panels of the hull with a right-handed coordinate system (x; y; z) fixed with respect to the mean oscillatory position of the ship. The origin is located in the plane of the undisturbed free