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REPORT OF PROPELLER COMMITTEE

APPENDIX 3

PROPELLER BEHAVIOUR UNDER OPERATIONAL CONDITIONS

by Koichi Koyama and Tatsuo Ito
(Ship Research Institute)

INTRODUCTION

The study of marine screw propellers is usually based on the study of the propeller alone in the absence of the hull and appendages. Experimentally the study has been performed by means of open water propeller tests, while theoretically it has been developed by means of the lifting line theory and, recently, lifting surface theory which is more suitable for marine screws with wide blades.

The screw propeller is installed behind a hull together with the rudder and, therefore, it works in the complex wake flow field. Moreover, the ship is operated in seaway and manoeuvred in harbour. Consequently, the following items are of great importance for the hydrodynamic problems of propeller: (a) propulsive efficiency, (b) cavitation, (c) vibratory forces and moments, (d) behaviour in seaway, (e) propeller-rudder interaction, and (f) stopping ability.

Among these items, this appendix deals with the state-of-the-art of propeller/rudder interaction and the use of a propeller in stopping.

PROPELLER/RUDDER INTERACTION

The problem of the unsteady hydrodynamic interference between a propeller and a rudder, when both lifting surfaces are located in the wake of a hull, is of considerable interest to naval architects since it is directly connected with the manoeuvring of a ship and with its propulsive efficiency. Furthermore, an adequate estimate of the vibratory loadings on propeller blades and rudder is essential information for the study of hull vibration, etc.

The early studies of the mutual interaction between propeller and rudder were based on propellers and rudders designed to operate in isolation. This work was aimed at improving propulsive efficiency. In the design of a rudder, however, the influence of the propeller cannot be ignored. Therefore, many studies (1-4) have dealt with the characteristics of a rudder in the slipstream of a propeller. On the other hand, however, there are few studies (5-9) dealing with the propeller placed before a rudder from a viewpoint of propeller design. This is because it is usually assumed that the influence of the rudder on the flow field of a propeller can be ignored.

Isay (10) studied the mutual interaction theoretically using the assumptions that, the number of propeller blades was infinite, and the rudder had no thickness. He solved the integral equation relating rudder circulation and upwash on the surface of a rudder behind a propeller with infinite number of blades. Then he estimated the effects of the presence of the rudder circulation on the propeller circulation. He found two effects. The first one is the circumferential variation of propeller circulation. Though the variation is very small at zero helm angle, it cannot be ignored at large helm angles. The second one is the small reduction of mean values of the propeller circulation at each radius, though the reduction near the hub is remarkable. At zero helm angle, the thrust of the rudder is larger than the thrust reduction of propeller due to the existence of the rudder. So, the total thrust of the propeller and the rudder is larger than the thrust of the propeller alone. But at large helm angle, the total thrust becomes less than the thrust of the propeller alone.

It has been shown by Isay, therefore, that neglecting the influence of a rudder at zero helm on propeller performance is justified.

Nakanishi, et al (11,12) studied the mutual interaction between a rudder with thickness and a propeller with an infinite number of blades. They solved the problem using a set of simultaneous equations and boundary conditions at both propeller and rudder by means of an iteration procedure. They found that the mutual interaction between a propeller and a thin rudder at zero helm angle could be ignored, and that the mutual interaction was mainly due to the thickness of the rudder. They also found that with a reducing axial distance between the propeller and a thick rudder the propeller thrust and the rudder drag increased and that the thrust is larger than the drag.

Brunstein (13) studied the mutual interaction between a propeller with a finite number of blades and a thick rudder. The propeller, working in the wake of a hull, was treated by means of unsteady lifting surface theory. The rudder in the propeller slipstream was treated by means of the steady method. Calculations based on a propeller with a simplified form, gave the following results. The thrust of a thick rudder behind a propeller was a few per cent of the propeller thrust at zero helm angle, while it became smaller or negative at large helm angle. With a thin rudder the propeller thrust decreased at zero helm angle and it decreased remarkably at large rudder helm. However, with a rudder of conventional thickness, the propeller thrust increased.

Tsakonas, et al, (14), studied the propeller-rudder interaction problem by means of the unsteady-lifting surface theory. They carried out a comprehensive investigation, treating realistic flow conditions and accurate geometry of lifting surfaces. Their numerical solution provided means for a systematic study of the effects of all parameters, such as number of blades, geometry of the lifting surfaces, axial clearance, and wake flow. From the small number of calculations performed it was seen that the mean thrust and torque were not affected by the presence of the rudder, in contrast to the corresponding vibratory components and to the steady and unsteady transverse forces and moments. The axial clearance played an important role in evaluating both steady and unsteady hydrodynamic forces and moments on both lifting surfaces.

There are cases where the unsteady rudderstock moment is of the same order or larger than the steady-state moment, and neglect of this time-dependent component will lead to erroneous conclusions.

Their study provides a clear understanding of the nature of the interaction effects and more information of practical interest for design of hull-propeller-rudder configurations than do the methods currently used. For greater precision in estimating the magnitudes of the interaction effects it is suggested that this study be complemented by a study of the effects of thickness of both lifting surfaces.

Lindgren (15) carried out experiments on the effects of the presence of the rudder as well as the effects of propeller position and clearance on the propulsive characteristics. Open water propeller tests were carried out in the normal manner (without a rudder) and also in conjunction with rudders of different thicknesses. The importance of the rudder thickness in relation to the propulsive characteristics of single screw ships was observed.

Løtveit (16) made some investigations to clarify the action of a rudder working in the propeller slipstream of a single-screw ship. In this work he measured the pressure distribution over the surface of a rudder placed in the slipstream of a propeller on a model of a tanker. From the pressure distributions obtained the flow field behind the propeller can be visualised.

Lewis (17) studied propeller vibration forces in single-screw ships and found that the rudder clearance was a very critical factor. He also found that a low transverse force level could be obtained with the correct positioning of the rudder.

THE USE OF PROPELLER IN STOPPING

The study on the stopping abilities of ships was carried out very early (18). Recently, the very rapid increase in the size of tankers, accompanied by a significant decrease in the ratio of installed power per unit of displacement, has emphasised the need to examine the stopping ability of this type of ship.

The phenomena of stopping manoeuvres are so complicated that the problem must be simplified for the purpose of estimating the stopping ability. There are many methods for estimating stopping distance by solving the differential equation on the proper assumptions (19-23). Following example is the method by Clarke and Wellman (23).

To calculate the stopping distance of a ship, it is necessary to solve the following differential equation;

$$\frac{\Delta\,(1+k_1)}{g}\frac{dV}{dt} = -T(n,V)-R(V)$$

where

Δ : Ship displacement

k_1 : Added mass coefficient

g : Acceleration due to gravity

V : Ship speed

t : time

T : Propeller thrust

R : Hull resistance

n : Propeller speed of rotation

To solve this a number of assumptions have been made. These are justified by available experimental evidence.

(a) The hull resistance is proportional to the square of the ship speed

(b) The propeller thrust changes linearly from the ahead value to the astern value during the time taken to reverse the shaft, and then remains constant throughout the whole stopping manoeuvre. The astern thrust being equal to that produced by the screw running astern with the ship dead in the water.

(c) The engine settings remain constant and the rudder is held amidships following the astern order, until the ship becomes dead in the water.

(d) The ship remains on its original course throughout the stopping manoeuvre.

(e) The longitudinal added mass coefficient is assumed to be constant throughout the stopping manoeuvre.

Results of a number of stopping trials of ship have been published (24-32). There are, however, few results on the effects of shallow water (32). The track of the ship during the stopping manoeuvre is completely erratic and the track cannot be predicted (33). For the purpose of complementing the information from the sea trials, model tests in the towing tank (28, 34, 35) have been carried out and they provide qualitative results. The quantitative correlation between the model and the full scale is not satisfactory when the quasi-stationary approach (35) is used. For the purpose of improving the stopping ability from a viewpoint of safety, the use of many auxiliary devices to reduce the stopping distance of a ship as well as of propeller is examined (23, 28, 36, 37).

The propeller produces a reverse thrust during a ship stopping manoeuvre. For the effective use of the propeller it is desirable to understand how it works during the stopping manoeuvre. The following explanations are given in Ref 38.

Full scale experiments on intermediate tankers showed that any stopping manoeuvre may be subdivided into three successive periods:

— a first period beginning with the order "full astern" and ending when the astern revolutions reach the required rate,

— a second period extending until thrust and torque are stabilized,

— a third period covering the quasi-stationary decrease of the speed under steady astern power.

During the first period, conditions are varying at a high rate, the propeller acts like a plain disc of equal projected area, the resistance of which is only a small part of the whole braking force. During the second period, the propeller effect is relatively more important because the other braking forces are strongly decreasing, but this effect is not directly related to the propeller speed because of unsteady conditions in which ventilation and vortices play a major role. During the third period, the propeller works in the usual way as in model test with slow ahead advance and normal astern speed. The braking force on the hull due to the action of the propeller is given by the following expression;

$$F = 0.0111 \left[\frac{K_T}{K_Q^{2/3}} P_D^{2/3} D^{2/3} \right] \left[(1-t)\eta_R \right]$$

where F is in tons, D in feet, and P_D in hp. The terms in the first bracket refer to the propeller alone whereas the terms in the second bracket refer to the interaction between the hull and the propeller. Values of the factor $K_T/K_Q^{2/3}$ depend only on the geometry of the screw itself and a survey of available open water data showed that number of blades and shape and type of section had little influence on this factor. Even over a practical range of pitch ratio and blade area ratio, there was little change in this factor.

From this rough analysis it is concluded that, as far as propeller design is concerned, stopping ability is mainly dependent on screw diameter, the other propeller data being of interest only during the last period of the stopping manoeuvre. Now there is a general feeling among ship operators that the actual problem is not of stopping from full ahead, but from reduced speed. Then, the last period of the manoeuvre becomes the longest too, and the backing qualities of the propeller deserves attention.

The basis of the model test on the stopping ability of propellers is the open-water tests of propellers over the entire range of operations (39-40, 48). The test results show that astern thrust is dependent mainly on pitch-diameter ratio and blade area ratio, and the number or type of blades has little influence (23). The wake and thrust deduction fractions for various values of advance coefficient must be known. Harvald has carried out extensive experiments (45), the results of which show that both fractions change considerably with varying advance coefficient. The variation is dependent to some extent on whether the speed or rate of rotation is kept constant. A great part of the variation of the fractions is due to their definitions. In most of the investigations dealing with the hydrodynamic conditions of stopping of the ship, it is assumed that the wake and thrust deduction fractions are constant during the manoeuvre. That these assumptions are not correct may be seen from Harvald's investigation. However, it is possible to determine the values in the extreme conditions from the values of the fractions of a freely running ship. Consequently it is possible to construct a complete manoeuvre nomogram for preliminary designs, even if results of model tests are not available. Head reach and retardation time can be determined by graphic integration.

A quasi-stationary approach (35) is an attractive model test technique for qualitative conditions of the stopping abilities of large ships. However, in the present state of knowledge, a fair correlation between model trials and sea trials has not yet been reached (23). Hooft and van Manen have derived the stopping abilities of a 100,000 tons d.w. tanker equipped with different propeller types from model tests with the aid of a quasi-stationary method. Four propeller types have been examined i.e. (a) a conventional screw propeller, (b) a screw and nozzle system (ducted propeller), (c) a contra-rotating propeller system, and (d) a controllable pitch propeller. In conclusion it has been shown that the non-conventional propeller, especially controllable pitch propeller is superior in stopping abilities. Recently the superiority of the controllable pitch propeller in stopping abilities is verified also in a sea trial (47).

CONCLUSION

We find, from the above review that, (a) the development of a non-stationary lifting surface theory to solve the interaction problem between the propeller with a finite number of blades having thickness and the rudder with thickness is needed, and (b) it is necessary to continue work on the correlation between model and ship stopping ability.

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