DEVELOPMENTS IN MODELLING SHIP RUDDER-PROPELLER INTERACTION

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Abstract

A review is made of the physics of the flow between a rudder and propeller and the parameters governing their interaction. Recent developments in predicting rudder forces and rudder-propeller interaction are described. These entail treating the rudder-propeller combination as the overall manoeuvring and propulsion device. Reference is made to on-going research at the University of Southampton which has included wind tunnel experimental investigations of the basic rudder-propeller interaction characteristics, oblique flow and the influence of the hull, together with theoretical modelling of a number of these aspects. Proposals are made as to how the rudder-propeller interaction data may be used both as a rudder design tool and in ship manoeuvring simulation.

1 Introduction

1.1 General

Although research into ship manoeuvring has been on-going over many years there is still a lack of fundamental knowledge of the forces and moments developed on a vessel while it manoeuvres and, in particular, the interaction between the rudder, propeller and hull.

There is a general drive towards improving ship safety, and moves are being made towards the introduction of international legislation concerning manoeuvring and coursekeeping requirements. These moves have led to the need for an improved understanding of rudder operation and the prediction of rudder performance.

1.2 Physics of Interaction

When a ship is moving ahead the flow passing through the propeller is accelerated and rotated. The swirl and acceleration induced in the flow by the propeller alters the speed and incidence of the flow arriving at a rudder aft of the propeller. This controls the forces and moments developed by the rudder. These forces are important in determining the overall performance and manoeuvring characteristics of the vessel. The rudder itself influences the upstream flow onto and through the propeller which in turn affects the thrust produced and torque developed by the propeller. In a similar manner, the rudder-propeller combination influences the sideforce developed by the hull.

The parameters governing rudder-propeller interaction are described in some detail in Refs. [1] and [2]. These parameters can be divided into four main groups which can then be used to assess their effect on developed rudder forces. In the case say of rudder sideforce (lift) coefficient where for ease of explanation the propeller and rudder are assumed to have a fixed sectional geometry, it is found that:

$$C_L = f\left\{ \begin{array}{l} [\ J,\ Rn,\ \beta\ ],\ [\ \alpha,\ AR,\ t/c\ ], \\ [\ P/D\ ],\ [\ X/D,\ Y/D,\ Z/D,\ \lambda D/S\ ] \end{array} \right\}$$

where the first group includes the main flow variables, the second group describes the rudder geometry variables, the third group the propeller variable (this is often combined with the advance ratio to give a parameter K_T/J^2 based on propeller thrust loading), and the fourth group representing the relative position and size of the rudder and propeller. It follows that, for a given ship, modelling of rudder-propeller interaction should consider the relative importance of the above parameters.

1.3 Approach

A number of mathematical models of rudder-propeller interaction have been developed over the years. These have normally entailed treating the rudder and propeller separately, relying heavily on the use of rudder free-stream characteristics and using propeller actuator disc theory to model the rudder axial inflow velocity. This approach, together with a relatively large number of empirical modifications, can achieve reasonable predictions in simulations. It is however limited in that it does not correctly model the basic physical behaviour, and its use is generally restricted to the origins of the empiricism. In particular, the influence of the propeller induced rotational velocities are normally neglected, as are the spill over effects when the propeller slipstream is not completely covering the rudder span.

It is in the light of these deficiencies that a more physically correct approach is postulated. The overall strategy for such an approach entails identifying the influence of the propeller on the rudder, the rudder on the propeller and the rudder-propeller combination on the hull. Due to the complex nature of the interaction between the rudder and propeller it is further argued that the rudder plus propeller should be treated together as a combination, considering the action of the combination in its roles as a manoeuvring device and as a propulsion device. Work has been carried out at the University of Southampton over a number of years developing such an approach. Descriptions of its development, practical implications and applications are given in the following sections.

2 Interaction Model

2.1 Overall Philosophy

A physically correct, logical and practical solution to the rudder-propeller interaction problem is firstly to model the rudder plus propeller as a combination in isolation, attempting to take account of all the governing parameters described in Section 1.2. The influences of an upstream hull and drift angle β can then be applied in the form of velocity and flow straightening inputs to the basic isolated model of the rudder-propeller combination. The feasibility of this approach has been demonstrated through experimental work by the authors which has indicated, for example, that a systematic change in drift angle applied to the rudder-propeller combination leads to an effective shift in the sideforce characteristics of the combination by an angular offset, Fig. 1. Thus if these stages in the procedure can be modelled in the manner described, with sufficient detail and adequate accuracy, then a very versatile and physically correct model can be evolved which has immediate applications to manoeuvring simulations and detailed rudder design.

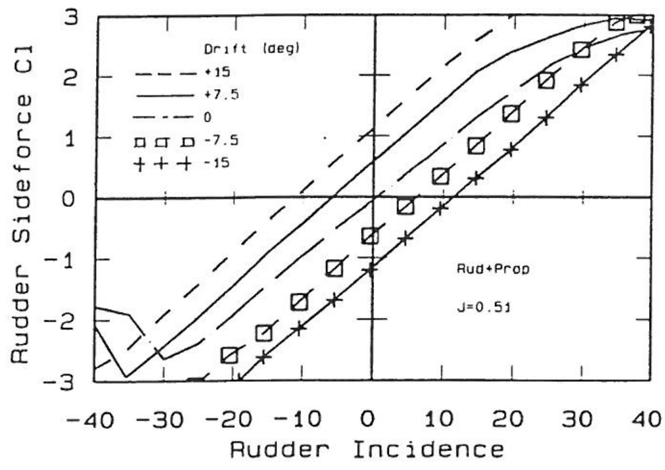

Figure 1 Effect of Drift Angle on Rudder Sideforce

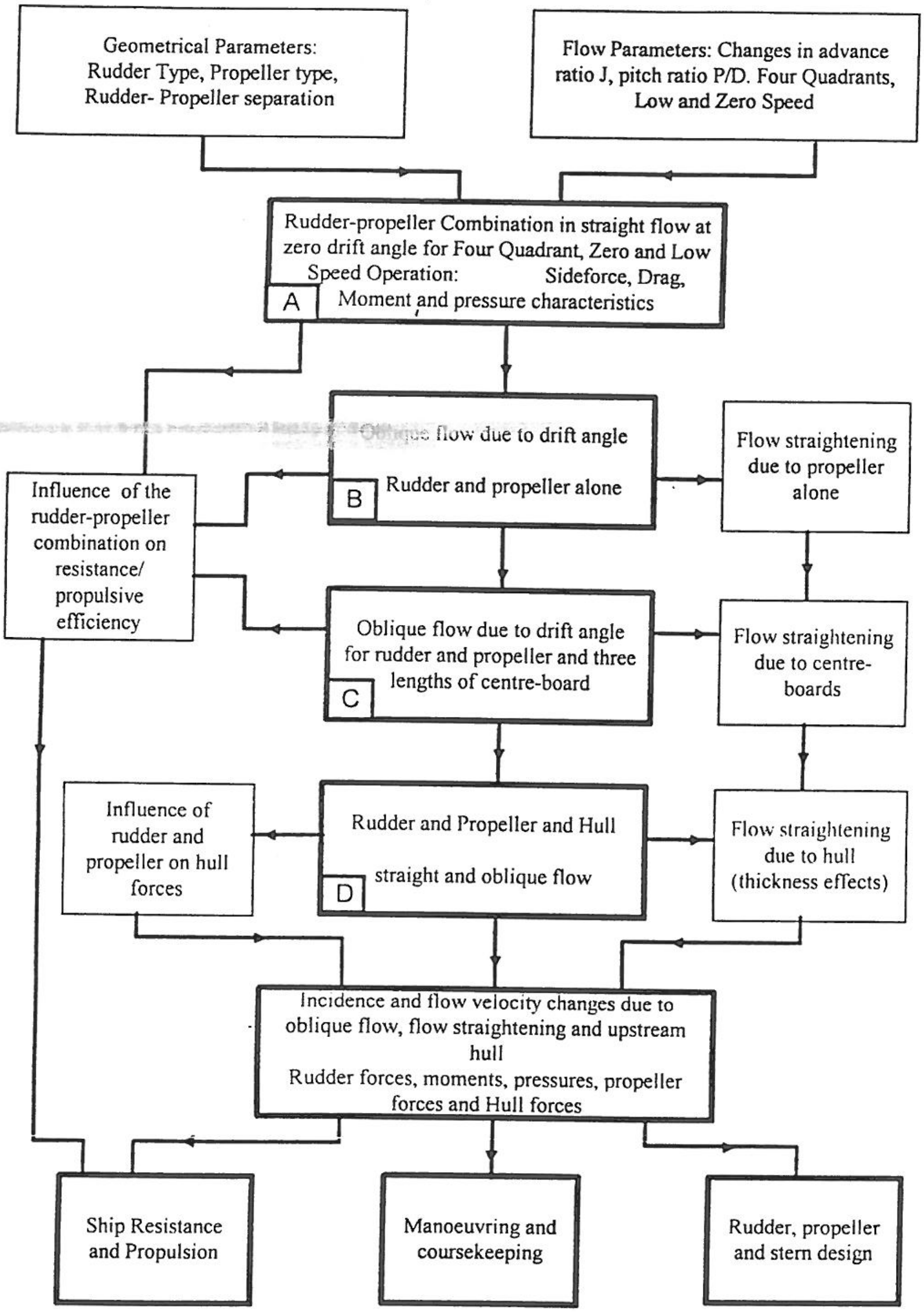

Figure 2 Components of Rudder-Propeller-Hull Interaction

2.2 Implementation

In order to identify and understand the various components of the interaction model a long term programme of research is being conducted at theUniversity of Southampton, entailing both experimental and theoretical work. An outline description of the various components which make up the overall model, and inputs/outputs at the various stages , are given in Fig. 2. The main phases of the work in the course of the investigation are designated Blocks A, B, C, and D.

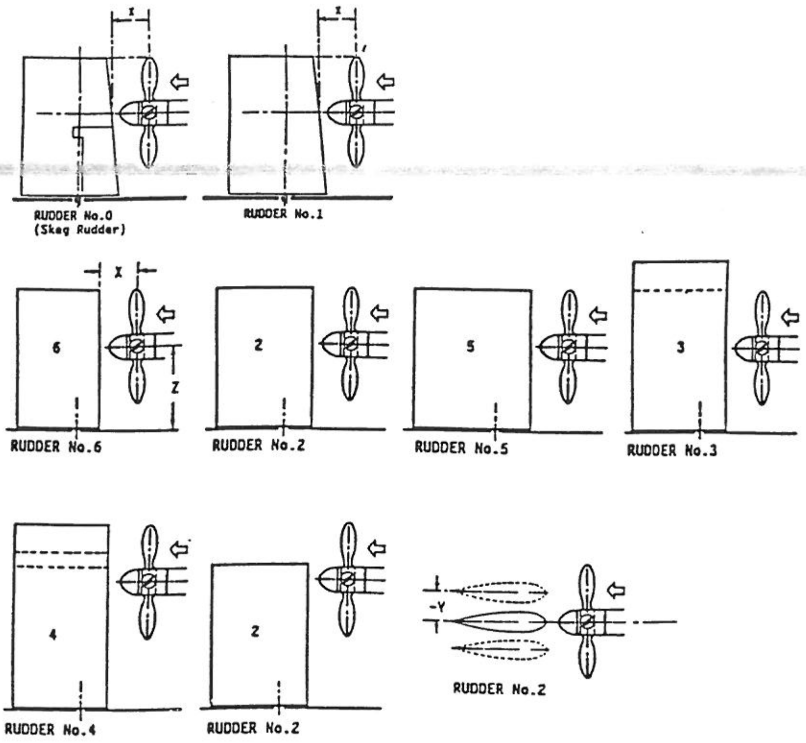

Figure 3 Alternative Rudder-Propeller Arrangements Tested

The first phase of the work, (Block A), entailed extensive experimental and theoretical modelling of the rudder and propeller combination in isolation. This included experimental testing of eight rudder models at various longitudinal, lateral and vertical separations from the propeller over a range of rudder incidence for various propeller thrust loadings, Fig. 3. The tests included measurements of rudder forces and moments and pressure distributions which indicated the distribution of loading. Typical results for such tests are shown in Fig. 4, and many of the basic data for the rudder plus propeller combination in isolation are described in Refs. 1 and 3. More recent tests have extended the investigation of the rudder plus propeller combination in straight flow to include operation in four quadrants and

at low and zero ship speed. In all tests, the propeller thrust, torque and rpm were measured.

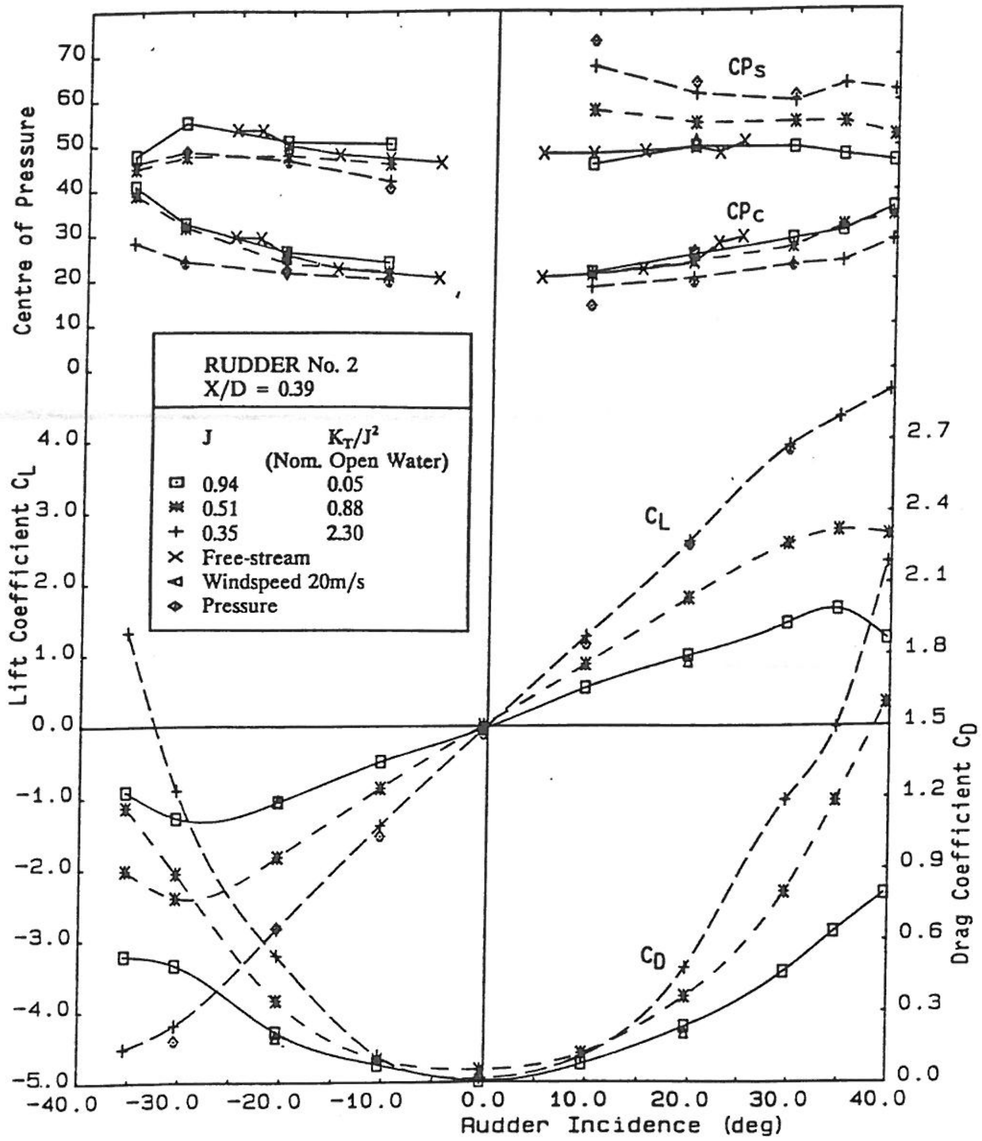

Figure 4 Example Sideforce, Drag, CPc, and CPs Characteristics

In order to provide a basic understanding of flow straightening due to propeller alone, the next phase of the work (Block B) entailed experimental testing of the rudder and propeller combination alone in oblique flow. An example of such an investigation, for a particular J value, is given in Fig. 1 which illustrates the sideforce characteristics over a range of drift angles. The deficit between the set drift angle and rudder incidence for zero sideforce provides the flow straightening due to the propeller.

The third and fourth phases of the work, Blocks C and D, investigated in a systematic manner the influence of an upstream body on flow straightening effects. This firstly entailed experimental tests using two-dimensional centre boards of different lengths upstream of the rudder-propeller combination, which provided basic information on the influence of upstream body length. This was followed by oblique flow tests with a representative hull upstream of the rudder-propeller combination (see Fig. 5).

Figure 5 Simulated Hull Upstream of Rudder-Propeller Rig

The hull was pressure tapped which allowed hull developed sideforce due to the rudder-propeller combination to be derived for change in drift angle, rudder incidence and propeller thrust loading.

The experimental investigations have been supported by theoretical work using lifting line and surface panel theories (Refs. 2, 4). The developed theories have proved to be useful tools, allowing interpolation and some extrapolation of the existing data, hence broadening the potential applications of the overall strategy.

3 Practical Implications and Applications

3.1 Rudder Design

The extensive experimental measurements and theoretical prediction of rudder forces, moments and pressure distributions provide a wide range

of necessary data for use in detailed rudder design. In particular, their use is important in establishing suitable rudder scantlings and stock diameter and likely torques for the design of the steering gear.

3.2 Manoeuvring and Coursekeeping

The application of the philosophy and strategy described in Section 2 allows a more fundamentally correct approach to the modelling of rudder-propeller interaction in manoeuvring and coursekeeping simulations. It offers the facility to eliminate much of the corrective empiricism and approximation traditionally employed.

A good base of experimental data has already been established for the performance of rudder-propeller combinations in isolation together with good indications of flow straightening, hence rudder incidence corrections, due to the propeller and upstream bodies when in oblique flow. These data, together with a broadening of the base through theoretical modelling, provide the necessary components for the implementation of the proposed approach.

3.3 Resistance and Propulsion

The monitoring of rudder drag, propeller thrust, torque and rpm during all the experimental tests has provided a good indication of the influence of rudder-propeller interaction on propulsive effects. For example, the presence of the rudder leads to increases in propeller thrust and torque whilst the influence of the propeller leads to changes in rudder drag with the possibility of rudder thrust at high propeller thrust loadings. The results are broadly in line with those derived by Stierman[5] indicating changes in propulsive effects for different rudder geometries and relative position of rudder and propeller. Such influences on propulsion have also been identified by Suhrbier[6] and Kracht[7]. The results suggest that due to the interaction of the rudder and propeller it would be more correct to treat the rudder and propeller as a combined propulsive device. To this end, English[8] argues a strong case for a reappraisal of the traditional approach to the analysis and scaling of combined rudder-propeller propulsive effects.

4 Conclusions

The approach described, treating the rudder-propeller combination as the overall manoeuvring and propulsion device, provides a more rational and physically correct approach to the rudder-propeller interaction problem. Its application offers scope for improvements in detailed rudder design, the prediction of rudder-propeller propulsive effects and the modelling of manoeuvring and coursekeeping.

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Nomenclature

A	Rudder Area	AR	Effective Aspect Ratio $(2S^2/A)$
c	Rudder Chord	C_D	Drag Coefficient
C_L	Lift (sideforce) Coeff'.	D	Propeller Diameter
J	Advance Ratio (V/nD)	K_T	Thrust Coefficient $(T/\rho n^2 D^4)$
n	Rate of revolution	P	Propeller pitch
Rn	Reynolds No. $(\rho Vc/\mu)$	S	Rudder span
t	Rudder thickness	V	Flow speed
α	Rudder incidence	β	Yaw or drift angle
ρ	Density	μ	Dynamic viscosity
λ	Proportion of propeller race diameter impinging on rudder		
X	Longitudinal distance, propeller plane to rudder leading edge		
Y	Lateral distance between propeller axis and rudder stock		
Z	Vertical distance between rudder root and propeller axis		

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