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A study on high-lift rudder performance in adverse weather based on model tests under high propeller load

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ABSTRACT

High-lift rudder performance is studied on the basis of model test results with regard to the requirement of interim guidelines of International Maritime Organization for minimum propulsion power to maintain the manoeuvrability in adverse weather. Model tests of two types of high-lift rudder in flow behind highly loaded propeller in a cavitation tunnel have clarified their performance comparing with a conventional mariner rudder. The analysis of the test data presented here proposes a procedure to deduce the equivalent rudder areas to conventional rudders for estimating minimum propulsion power of ships equipped with high-lift rudders in adverse weather. The authors estimated the required minimum speed and the minimum propulsion power of ships equipped with the high lift rudders according to the interim guidelines using the equivalent rudder areas quantified by the model tests. The test data, the analysis method, and the estimates for the guidelines reveal how the high-lift rudders perform and contribute well to reduce the required minimum propulsion power.

1. Introduction

Ships having smaller propulsion power are expected to come out under the regulation of Energy Efficiency Design Index (EEDI) (IMO, 2011). Since operational limits decrease along with the decrease of engine outputs, these ships tend to have smaller propeller rotational speed in adverse weather. These ships, therefore, might have difficulty in coping with adverse weather due to small rudder force caused by the engine speed decrease. In the circumstance, the interim guidelines of the International Maritime Organization (IMO) (IMO, 2013) for determining the minimum propulsion power to maintain the manoeuvrability in adverse weather have been formulated (IMO, 2013).

High-lift rudders (HLRs) enable those ships to improve manoeuvrability without increasing their propulsion power. The assessment formula of the guidelines allows to use the equivalent rudder area of HLR to a conventional rudder for estimating the required minimum speed of a ship with HLR instead of the actual rudder area. However, the equivalent rudder area is not defined in the guidelines.

There are some experimental researches investigating performance of HLRs by model tests (Kato and Motora, 1968; Mukohara, 1992; Sakae, 2002; Yamamoto, 2004). Numerical studies on rudder performance including those in flow behind propeller also have been reported so far (El Moctar, 1999; Hirano et al., 1982; Lee et al., 2008; Liu et al., 2016). Pyo and Suh (2000) presented a numerical model to estimate performance of flap rudders in open water together with model experiment for comparison. They focus mainly on the performance in uniform flow or in flow behind propeller of which load is around design speed. Propeller load in adverse weather, however, increase significantly due to speed decrease even for ships having smaller engine complying with EEDI regulations. In such situations, rudder force is susceptible to accelerated propeller slipstream. Thus, the equivalent rudder area should be quantified by tests or estimates in flow behind highly loaded propeller.

The authors carried out model tests of two types of HLRs and a conventional mariner rudder in flow behind highly loaded propeller at a cavitation tunnel in order to deduce the equivalent rudder area. The analysis of the test data presented here makes it possible to compare the maximum lifts of the HLRs with that of the conventional rudder under high propeller loading condition, which tells the equivalent rudder areas of the HLRs and procedures to deduce them. Moreover, the minimum propulsion power of ships equipped with the HLRs in adverse weather was calculated in accordance with the interim guidelines (IMO, 2013) using the equivalent rudder areas quantified by the model tests. The discussion reveals how HLRs reduce the required minimum propulsion power.

Abbreviations: FREP, fishtail-sectioned rudder with end plates; HLR, high lift rudder; IMO, International Maritime Organization; ITTC, International Towing Tank Committee; LST, lifting surface theory; NMRI, National Maritime Research Institute, Japan

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Nomenclature

Greek symbols

α_R	effective inflow angle to rudder [deg]
$\|\delta\|$	absolute value of rudder angle [deg]
δ	rudder angle [deg]
δ_f	flap angle [deg]
η	ratio of propeller diameter to rudder height [-]
κ	coefficient representing increment of propeller slipstream at rudder position [-]
Λ	aspect ratio of rudder [-]
ν	coefficient of kinematic viscosity of water [m^2 s^{-1}]
ρ	water density [kg m^{-3}]
τ	propeller loading factor ($T/0.5\rho\pi(D_P/2)^2V^2$) [-]
τ_m	mean of propeller loading factor at the minimum required ship speed and the required rotational speed of a propeller defined in the interim guidelines [-]

Roman symbols

A_H	projected lateral area of the rudder horn below the top end of movable rudder part [m^2]
A_L	lateral windage area [m^2]
$A_{LS,cor}$	submerged lateral area of a ship corrected for breadth effect [m^2]
A_{PD}	propeller disc area [m^2]
A_R	sum of the projected lateral area of movable rudder part and the rudder horn [m^2]
A_{RO}	projected lateral area of movable rudder part [m^2]
A_{RC}	area of conventional rudder (=A_{RO}) [m^2]
A_{RE}	equivalent rudder area [m^2]
A_T	longitudinal windage area [m^2]
B	ship breadth [m]
BHP_{limit}	operation limit of engine [kW]
BHP_m	required brake power [kW]
BHP_{MCR}	maximum continuous rating [kW]
BHP_{MEP}	mean effective pressure limit [kW]
BHP_{OLP}	torque/speed limit [kW]
C_D	rudder drag coefficient (=D/0.5$\rho A_{RO}V^2$) [-]
$\|C_L\|$	absolute value of rudder lift coefficient [-]
C_L	rudder lift coefficient (=$L/0.5\rho A_{RO}V^2$) [-]
C_{LMAX}	maximum lift coefficient [-]
$\|C_{LMIN}\|$	maximum lift coefficient in case of negative rudder angle [-]
C_N	rudder normal force coefficient (=$F_N/0.5\rho A_{RO}V^2$) [-]
$C_{N\infty}$	rudder normal force coefficient with infinite aspect ratio [-]
$C_{0.7R}$	chord length at 70% propeller diameter [m]
D	rudder drag [N]
d_{mid}	ship draft at midship [m]
D_P	propeller diameter [m]
f_α	gradient of rudder normal force coefficient [-]
F_N	rudder normal force [N]
$F_N{}^{with\ Horn}$	rudder normal force including horn part [N]
F_T	rudder tangential force [N]
H_R	rudder height [m]
H_W	significant wave height [m]
J	propeller advance ratio (=V/N_PD_P) [-]
$J_{\delta 0}$	propeller advance ratio at zero rudder angle [-]
k	form factor [-]
K_T	thrust coefficient (=$T/\rho N_P{}^2D_P{}^4$) [-]
L	rudder lift [N]
L_{PP}	length between perpendiculars [m]
N_{MCR}	propeller rotational speed at maximum continuous rating [rpm]
N_P	propeller rotational speed [rpm]
N_{Pm}	propeller rotational speed to achieve required propeller thrust [rpm]
P_S	pressure at upstream of propeller and rudder positions in the cavitation tunnel [Pa]
Q	propeller torque [Nm]
R_{air}	aerodynamic resistance [N]
R_{app}	resistance due to appendages [N]
R_{aw}	added resistance in long-crested irregular waves [N]
R_{cw}	resistance in calm water [N]
t	thrust deduction fraction [-]
T	propeller thrust [N]
T_m	required propeller thrust [N]
T_P	peak wave period [s]
V	speed of advance referred to open water [ms^{-1}]
V_A	advance speed of propeller (=V , in this paper) [ms^{-1}]
V_{ck}	minimum course keeping speed [knot]
$V_{ck,ref}$	reference course keeping speed [knot]
V_m	required minimum speed to maintain manoeuvrability [knot]
V_{nav}	minimum navigational speed [knot]
V_R	effective inflow velocity to rudder [m/s]
V_V	velocity of main flow in the cavitation tunnel measured by Venturi tubes located upstream of propeller and rudder positions [ms^{-1}]
1-w_P	wake fraction at propeller position [-]

2. Model test

2.1. Concept of study and model test planning

Model tests are case studies to quantify the equivalent rudder areas of typical HLRs to a conventional rudder using rudder models, all of which were designed for the same supposed ship. The supposed ship is a bulk carrier of 12,000 dead weight tons (DWT). Principal particulars are in Table 1. The rudders are a typical mariner rudder that is widely used as a conventional rudder; and two HLRs; a fishtail-sectioned rudder with end plates (FREP) (Japan Hamworthy; Mukohara, 1992), and a flap rudder (Becker marine systems, 2013; Sakae, 2002).

Model tests were in flow behind highly loaded propeller assuming in adverse weather condition, and the maximum lift of rudders at large angle range is the focal point of this study. However, rudder performance in uniform flow including characteristics in small rudder angle range is indispensable for understanding what the tested rudders are like. Appendix A shows such fundamental test results together with validation comparing with numerical and theoretical studies (Hirano et al., 1982; Liu et al., 2016).

The tests were carried out in the cavitation tunnel at the National Maritime Research Institute, Japan (NMRI). The measuring part is circular and the diameter of the measuring part is 0.75 m. Cavitation tunnels, in general, can achieve high Reynolds number comparing with towing tanks, though attention should be paid to wall and blockage effects. The tests were conducted without a ship model and wake behind ship was not simulated, since the tests aimed at investigating relative performance of the HLRs to that of the conventional rudder.

2.2. Rudder models

Configurations and sections of the rudder models are shown in