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Rudder effectiveness and speed correction in practice at tank test

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ABSTRACT

The rudder effectiveness and speed correction (RSC) is a control method to ensure the similarity of manoeuvring motion of a free-running model ship to full-scale. RSC tells how to control a model propeller rate of revolution and auxiliary thrust depending on a model ship speed. The rudder effectiveness correction (REC) is a simplified method of RSC, controlling only the auxiliary thrust. This paper presents tank test data that show a clear difference between RSC and REC and confirm how well RSC works in practice. The tank test employed a duct fan type auxiliary thruster for RSC, REC, and the skin friction correction (SFC) for comparison. The ordinary free-running model ship not using the auxiliary thruster or with no correction (NC) are also in the test program. Comparisons are made in turning and zigzag manoeuvres in calm water, and course keeping manoeuvres in regular waves. Numerical simulations verify that RSC compensates for the scale effect with higher precision than REC, and also well explain the difference of tank test data characteristics among RSC, REC, SFC and NC.

1. Introduction

It is well known that a free-running model ship (FMS) running at a model ship self-propulsion point (MSPP) does not tell directly full-scale ship manoeuvrability. The reason is the scale effects originated in the difference of Reynolds number R_n between model and full-scales. The difference of R_n leads to the dissimilarities of hull resistance and propeller load that affect the rudder effectiveness (Liu and Hekkenberg, 2017; Suzuki et al., 2017). Several types of auxiliary thruster (Fujii, 1960; Kobayashi et al., 2000; Tsukada et al., 2013, 2014) including those using computerized carriage systems (Grim et al., 1976; Son et al., 2010) tried to compensate for the scale effect by exerting additional forward force on FMS. Yumuro (1975) and Oltmann et al. (1980) had found that neither MSPP nor full-scale ship self-propulsion point (FSPP) resolves the scale effects. However, most of the auxiliary thrusters developed afterwards aimed at the skin friction correction (SFC) of which propeller rate of revolution is FSPP. This fact indicates how controversial the problem on the propeller rate of revolutions of FMS has been so far.

Facing to this problem in the midst of their development of a duct fan type auxiliary thruster (DFAT) (Tsukada et al., 2013, 2014), Ueno et al. (2014) proposed the rudder effectiveness correction (REC) method. According to a mathematical model of manoeuvring motion (Kose et al., 1981), they approximated the similarity of rudder effectiveness by the similarity of the longitudinal component of the effective inflow velocity to a rudder. In their proposal, they defined the auxiliary thrust factor f_{TA} that represents the ratio of the auxiliary thrust (T_A) to the additional force for SFC (T_{SFC}). f_{TA} equal to 0 corresponds to FMS with no correction (NC) or running at MSPP, while f_{TA} equal to 1 corresponds to FMS with SFC or running at FSPP. By solving the simultaneous equations for the similarity of rudder effectiveness and the similarity of longitudinal force acting on a ship at a designated ship speed in calm water, REC determined a model propeller rate of revolution n_m and f_{TA}. f_{TA} of a container ship and a tanker were both intermediate values between 0 and 1, which means REC gives n_m between MSPP and FSPP. Although n_m and f_{TA} of REC are both constants, T_A varies in manoeuvring motion because T_{SFC} depends on a model ship speed. This means that REC does not control n_m and f_{TA} but controls T_A using a measured instantaneous model ship speed. Numerical simulations well explained the tank test data comparing with NC, REC, and SFC (Ueno et al., 2014), and confirmed REC gives the best estimates of full-scale manoeuvrability. However, slight differences remain between FMS with REC and a full-scale ship in the numerical simulations.

To fill the gap in the numerical simulations between FMS with REC and full-scale Ueno and Tsukada (2015) proposed the rudder effectiveness and speed correction (RSC), an improved REC method. RSC controls both n_m and f_{TA} depending on a longitudinal model ship speed u using solutions of the simultaneous equations same as those of REC for arbitrary u, not for a designated ship speed. Fig. 1 illustrates the flow into a rudder of FMS comparing with that of full-scale. The longitudinal component of the effective inflow velocity to a rudder u_R is a root of weighted mean of squares of the wake flow and the propeller race. The

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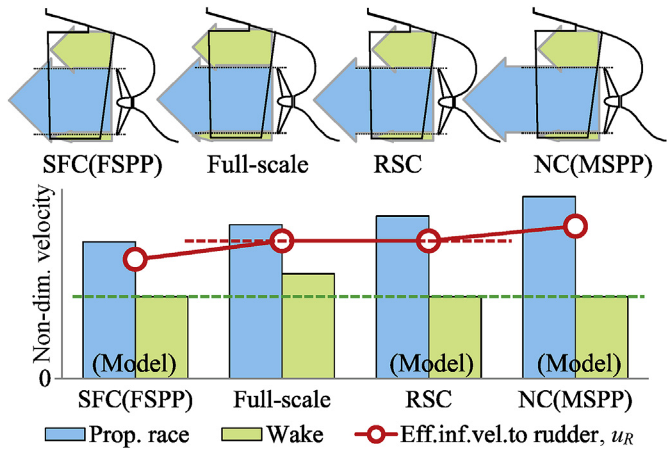

Fig. 1. Schematic illustration of non-dimensional velocity of propeller race and wake flow into rudder, and the longitudinal component of effective inflow velocity to rudder u_R, of a model ship with SFC, NC, and RSC comparing with full-scale ship.

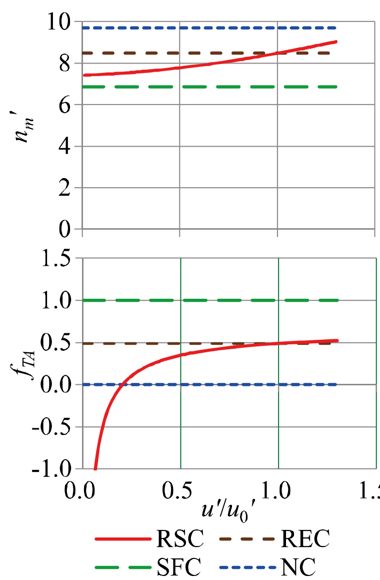

Fig. 2. Non-dimensional model propeller rate of revolution n_m' and auxiliary thrust factor f_{TA} for the tanker model of which scale ratio is 1/110, comparing RSC, REC, SFC, and NC depending on speed ratio u'/u_0' where u_0' is a designated ship speed corresponding 15.5 kn in full-scale.

weight depends on the ratio of propeller diameter to rudder height, which u_R in Eq. (10) concretizes later. RSC is for the similarities of u_R and the ship speed, respectively, and SFC is for the similarities of the effective propeller thrust and the ship speed, both using the auxiliary thruster. NC, however, is for the similarity of the ship speed only without using the auxiliary thruster. Since u_R squared approximates the rudder normal force, the similarity of u_R, leads to the similarity of the rudder effectiveness.

The formulation of RSC foresees that FMS with RSC tells full-scale manoeuvrability not only in calm water but also in wind and waves by ensuring both the similarity of the rudder effectiveness and the speed response at arbitrary u. Numerical simulations confirmed theoretically higher accuracy of RSC for estimating full-scale performance than REC both in calm water and in wind. The discrepancies between numerical estimates by RSC and by REC were not significant in calm water because REC has comparable high accuracy. These small numerical discrepancies in calm water without experimental validation might raise a following question. To what extent is RSC practical and reliable in tank tests to obtain more accurate estimates than REC? RSC must be worth a cost of the speed dependent control both of n_m and T_A, while REC controls only T_A.

This paper presents FMS tests of a tanker to confirm how RSC works well in practice. The tank tests used DFAT for RSC, REC, and SFC. DFAT (Tsukada et al., 2013, 2014) is a duct fan type auxiliary thruster of which feedback control employs measured auxiliary thrust and model ship speed data. Comparisons are in turning and zigzag manoeuvres in calm water and course keeping manoeuvres in regular waves. Numerical simulations for RSC, REC, SFC, NC, and for the full-scale ship confirm that both RSC and REC are effective to compensate for the scale effect on manoeuvrability. The clear differences observed in the tank test in manoeuvrability of RSC from SFC and NC, and a narrow difference from REC correspond well to those of the numerical simulations. These findings ensure that RSC works well in practice at tank tests and is a promising FMS control method to estimate directly full-scale manoeuvrability.

2. Outline of RSC

The concept of RSC (Ueno and Tsukada, 2015) is both the similarities of the rudder effectiveness and the longitudinal speed response ensure the similarity of manoeuvring motion of FMS to full-scale. This section summarizes RSC of which details are found in Ueno and Tsukada (2015).

The rudder normal force represents the rudder effectiveness. The longitudinal component of the effective inflow velocity to a rudder plays a dominant role for the rudder normal force comparing with the lateral component. Therefore, the similarity of the longitudinal component of the effective inflow velocity to a rudder can approximate the similarity of the rudder effectiveness that the similarities both of sway force and yaw moment require. On the other hand, the similarity of the longitudinal force consisting of propeller thrust, resistance, and external forces ensures the similarity of the longitudinal speed response. The similarity of manoeuvring motion ensures the similarity of external forces that depend on the relative motion to wind and waves. Therefore, the similarities of propeller thrust and resistance ensure the similarity of the longitudinal speed response, where T_A is indispensable. These considerations are for ships with conventional rudders and propellers. If the dependency of the similarity between model and full-scales on other factors was significant, the requirements to ensure the similarity should be examined in different ways.

Let us discuss the similarity between model and full-scales using non-dimensional variables defined as follows according to Froude's law of similarity.

$$\frac{Length}{L},\frac{Mass}{\rho L^3},\frac{Force}{\rho g L^3},\frac{Moment}{\rho g L^4},\quad \frac{Time}{\sqrt{L/g}},\frac{Translational\ \ speed}{\sqrt{Lg}},\frac{Angular\ \ speed}{\sqrt{g/L}}. \tag{1}$$

In Eq. (1), L, ρ, and g stand for ship length between perpendiculars, the density of water, and the gravitational acceleration, respectively. All the non-dimensional values are in accordance with Eq. (1) hereafter if not otherwise specified.

Following simultaneous equations are the governing equations of RSC embodying the above mentioned similarities. Prime $'$ stands for the non-dimensional variables according to Eq. (1), and subscripts m and s stand for model and full-scales values, respectively.

$$\begin{cases} u'_{Rm} = u'_{Rs} \\ (1-t_m)T'_m - (1-f_{TA})T'_{\mathrm{SFC}} = (1-t_s)T'_s \end{cases} \tag{2}$$

u_{R*}', where asterisk * stands for either m or s, is the longitudinal component of the effective inflow velocity to a rudder, a function of a propeller rate of revolution $n^{*\prime}$ and a longitudinal ship speed u'. Several mathematical models as those in Kose et al. (1981) for example are applicable to the u_{R*}' calculation if they represent characteristics of u_{R*}'