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Rudder effectiveness correction for scale model ship testing

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ABSTRACT

The authors propose an idea of rudder effectiveness correction for free-running manoeuvring tests using scale models. The idea aims to realize the full-scale-equivalent manoeuvring motion with scale models using the auxiliary thruster that the authors developed. The auxiliary thruster can generate time varying forward force needed for the rudder effectiveness correction. The auxiliary thrust is represented by the force required for the skin friction correction multiplied by the newly defined rudder effectiveness correction factor. The propulsive performance of the model and full-scale ships in steady straight running determines a value of the factor. Theoretical calculations using the modular mathematical model applied to a container ship and a tanker clarify characteristics of the factor. The tank tests and numerical simulations confirm the feasibility of the idea.

1. Introduction

The difference of Reynolds number between model and full-scale ships violates the similarity of resistance, propeller load, and, therefore, rudder force in free-running model tests. This is the reason why the manoeuvring motion of free-running model ships is not similar to full-scale ships'.

Followings are among numerous reports on the model-ship correlation in manoeuvrability. Kawano et al. (1963) carried out full and model scale manoeuvring tests and discussed the full-scale equivalent rudder area of model ships. They reported the full-scale equivalent rudder area for model ships is around 70% the geometrically similar rudder. Yumuro (1975) pointed out based on a theoretical calculation the rudder force of mode ship with skin friction correction (SFC) is around 70% the estimated value of full-scale ship. He noted SFC in captive model tests modified model ships rudder effectiveness but significant difference still remains between model and full-scale ships. He proposed captive model tests with such propeller rate as made the rudder effectiveness similar to the full-scale ship, though he did not indicate how to settle such propeller rate. These reports above imply the similarity of rudder effectiveness is neither at the model ship self-propulsion point (MSPP) nor at the ship self-propulsion point (SSPP). In general, the propeller rate at MSPP is higher than at SSPP because of the relatively larger resistance in model scale than in full scale.

Researchers had tried to realize the similar manoeuvring motion to full-scale ships' using scale models. Fujii (1960) used an air-propeller generating auxiliary thrust to make the model ship propeller rate similar to the full-scale ship's, based on the Froude's similarity law, and studied the rudder torque. He states he placed the air-propeller at the pivoting point without describing any reason. The authors deduce the reason is to avoid producing the lateral force due to lateral inflow velocity to the air propeller because the unnecessary lateral force could result in dissimilar manoeuvring motion. The pivoting point is the point on the centerline where the lateral velocity component is zero. Since the pivoting point does not stay at a fixed point but moves during unsteady motion, the method using air-propeller is effective only in steady turning, but not in general manoeuvring motion. Bindel (1966) summarized SFC on captive and free-running model tests with the air-screw, stating SFC makes the turning radius larger, the speed decrease and drift angle smaller, but no significant difference in the directional stability. Oltmann et al. (1980) investigated the propeller load effect on manoeuvrability with the aid of the computerized planar motion carriage (Grim et al., 1976) that was able to provide a free-running model ship with prescribed constant force during tracking the model. They compared full-scale ship data with the numerical simulations results of several different model propeller loads. They stated the easiest way to compensate for the scale effect in manoeuvrability is to choose the propeller rate which best generates the corresponding rudder inflow velocity of the full-scale. They, anyway, could not reach any concrete proposal how to settle the propeller rate. Crane et al. (1989) state the model propeller slip ratio should be identical to the full-scale ship propeller slip ratio and this can be fulfilled by an

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air propeller providing part of the thrust. They point out the air force can be measured and dynamically changed as a function of measured model speed to improve results, but do not discuss on the lateral force of the air-propeller. Kobayashi et al. (2000) developed an air-jet mechanism placed at the aft end of a model ship for providing with additional forward force. The mechanism should not generate the unnecessary lateral force, but a relatively large air cylinder on a carriage tracking a model ship is indispensable. They carried out free-running model tests in which the air-jet system was applied and compared the test results with full-scale trial data. Although the air-jet force seems not to have been controlled depending on instantaneous model ship speed but to be kept constant, they stated the free-running model test with SFC is suitable for predicting full-scale manoeuvring motion. Son et al. (2010) developed a towing device consisting of a servo motor on a tracking carriage and wire connected to a load cell placed at the center of gravity of the model ship. The device can provide a free-running model ship with additional longitudinal force. Kajita et al. (1975) carried out a free-running model test using several different scale models with rudders of different areas. The test results clarified the smaller models are the more stable their directional stability becomes. They compared the rudder normal force of these models based on the mathematical model and demonstrated the large scale models with reduced rudder area had showed similar manoeuvrability to the full-scale ship. In spite of all these efforts described above, there is no standardized or generally accepted free-running model test procedure to realize full-scale equivalent manoeuvring motion yet.

Above examples on the free-running test procedure, apart from Kajita et al. (1975), shows different types and different uses of the auxiliary thrusters. Especially, an auxiliary thruster capable of providing a model ship with forward force depending on the instantaneous model ship speed without unnecessary lateral force is not familiar even today. This, the authors consider, implies neither a practical mechanism to generate the auxiliary thrust nor a method to use the mechanism is established yet except an example of Son et al. (2010) for SFC. As for the mechanism, Tsukada et al. (2013) developed a prototype of duct fan type auxiliary thruster (DFAT) being able to control its thrust and adjust the propeller load to designated time varying values depending on any measured data without generating the unnecessary lateral force. The prototype consists of a duct fan, a load cell measuring the auxiliary thrust, and a PC. The PC controls the auxiliary thrust of the duct fan depending on measured model ship speed. They demonstrated how the prototype works well by showing the tank test data with and without the speed dependent SFC, comparing also with theoretical calculations. The mechanism is compact enough to be loaded totally onboard if necessary and, the authors believe, can be a promising experimental tool to find a method for the objective, how to realize full-scale equivalent manoeuvring motion with scale model ships.

In this report the authors propose an idea of rudder effectiveness correction (REC) as an application of the DFAT to realize the full-scale equivalent manoeuvring motion using scale models. REC controls the auxiliary thrust to ensure the similarity of rudder normal force between model and full-scale ships approximately. REC factor, introduced here, characterizes the auxiliary thrust for REC. The authors assembled a new DFAT for practical use. Free-running model test using scale models of a container ship and a tanker with DFAT examine how REC works on the manoeuvrability. The authors add a term representing the effect of the auxiliary thrust into a modular mathematical model to look into the effect of REC theoretically and also to confirm whether or not the tank test was carried out as desired. Comparisons of the tank test data of model ships with REC, theoretical calculation for model ships with REC, and theoretical calculation for corresponding full-scale ships clarify how well REC works to compensate for the scale effect on manoeuvrability.

2. Rudder effectiveness correction

2.1. Basic idea

Since the origin of manoeuvring motion is the rudder force, the rudder normal force should be primarily responsible for the similarity of manoeuvring motion between model and full-scale ships. The basic idea of rudder effectiveness correction is to make the ruder normal force of model ships similar to full-scale ones using the auxiliary thruster.

Suppose the geometrically similar rudder angle and constant propeller rate by ignoring the effect of propeller torque variation on the propeller rate. Then, what we can do in the free-running test using geometrically similar scale models with the auxiliary thruster are to choose the constant propeller rate and to control the auxiliary thrust during manoeuvring motion.

Let us consider a model ship in steady straight running. The longitudinal equilibrium equation taking into account the auxiliary thrust is written as follows.

$$(1-t)T+T_A-R_{\mathrm{T}}=0 \tag{1}$$

T, t, and R_T stand for the propeller thrust, the thrust deduction factor, and the total resistance, respectively. T_A stands for the auxiliary thrust. Since R_T is constant at a speed satisfying the Froude's similarity law, T_A determines T and, therefore, the propeller rate being constant through the tank test.

Accordingly, the basic idea comes down to the problem how to designate the auxiliary thrust in a steady straight running condition and how to control it during the manoeuvring motion to follow so as to have the similar rudder normal force to the full-scale ship in the model test.

2.2. Definition of REC factor, f_{REC}

In the discussion concerning the auxiliary thrust the force required for SFC can be a unit of measurement. Let us introduce first the auxiliary thrust factor f_{TA}, defined in the following equation.

$$T_A=f_{TA}T_{\mathrm{SFC}} \tag{2}$$

T_{SFC} is the auxiliary thrust required for SFC, defined by the following formula.

$$T_{\mathrm{SFC}}=\frac{\rho_m}{2}S_m u_m^2\{(1+k)(C_{\mathrm{F0}m}-C_{\mathrm{F0}s})-\Delta C_{\mathrm{F}}\} \tag{3}$$

Subscripts m and s represent the values of model and full-scale ships, respectively. ρ, S, and u stand for the density of water, the wetted surface area, and the longitudinal component of ship speed, respectively. k stands for the form factor. C_{F0} and ΔC_{F} stand for the friction resistance coefficient of a corresponding plate and the roughness allowance, respectively. C_{F0} is a function of Reynolds number, R_n (Saunders et al., 1957) and ΔC_{F} a function of a full-scale ship length (ITTC performance committee, 1978). T_{SFC} is, therefore, a function of the longitudinal ship speed and full-scale ship length.

SFC makes the propeller rate at SSPP. Note that SFC, in spite of its literature, never corrects the skin friction but makes the model ship propeller load equal to the full-scale ship, where the propeller rate is at SSPP. The following equation defines the propeller load τ.

$$\tau=\frac{T}{(\rho/2)\pi(D/2)^2u^2} \tag{4}$$