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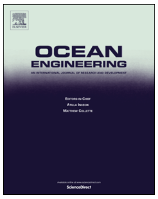

Estimation of full-scale propeller torque and thrust using free-running model ship in waves

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ABSTRACT

The authors propose a method to estimate full-scale propeller torque and thrust consisting of low-frequency and high-frequency components in waves by free-running model ship test. The duct fan auxiliary thruster (DFAT) (Tsukada et al., 2013, 2014) and the rudder-effectiveness and speed correction (RSC) (Ueno and Tsukada, 2015; Suzuki et al., 2014, 2015) ensure similar model ship motion to full-scale in wind and waves, where RSC controls the model ship propeller rate of revolution and the auxiliary thrust depending on instantaneous model ship speed. Analyzing wave component in the effective inflow velocity to propeller, the method estimates full-scale fluctuating propeller torque and thrust in waves. Trial application of the method exemplifies the property of full-scale fluctuating propeller torque and thrust comparing with those of a model ship.This method also makes it possible to incorporate into free-running model ship tests any engine model simulating interaction between propeller torque and engine torque.

1. Introduction

Ships in actual seas experience speed decrease, and torque and thrust increase comparing with those in calm water due to wind and waves. The torque and thrust not only vary on average but also fluctuate at encounter wave frequencies. Assessing correctly the variation of torque and thrust of full-scale ship fluctuating at actual seas has essential importance for ship, including propeller and engine, designers and operators as well. Numerous researches so far have confirmed that theories based on potential flow explain successfully the oscillation of ship speed, or surging motion, in waves. They assumed no significant scale effect on the oscillating components of motion. On the other hand, researches on scale effect on fluctuating torque and thrust are quite limited.

Yamanouchi and Ando (1966) carried out free-running model tests using Series 60 model ship in oblique regular waves and reported ship motion; mean of propeller torque, thrust, and propeller shaft revolution; and fluctuating component of torque and thrust. Although they pointed out the difference of engine characteristics between model and full-scale ships, they did not pay any attention to the scale effect on measured propeller torque and thrust originated in hydrodynamic phenomena. Yoshino et al. (1974) carried out free-running model test of container ship models with single and twin propellers and reported ship motion and fluctuating propeller torque and thrust in regular waves. They, however, did not refer to the scale effect of propeller torque and thrust. Sluijs (1972) carried out captive model test in head and following waves in which the propeller rotated at model ship self-propulsion point (MSSP) and the model was free in surge, pitch, and heave motion. He scaled up measured data including fluctuating component of propeller torque and thrust to full-scale by Froude's law of similarity without any other consideration of scale effect. Nakamura et al. (1975a) carried out captive model test, resistance and self-propulsion tests, of a container ship in head waves in which the model was in two modes; free in surge, pitch, and heave; and the motion restrained. They pointed out the fluctuation of propeller torque and thrust correlated closely with the fluctuation of inflow velocity to propeller, and wake coefficient tended to grow in high waves. They estimated the fluctuation of propeller torque and thrust considering characteristics of the driving motor of propeller and the decrease of incident wave amplitude at stern for which they assumed a simple function of wavelength to ship length ratio. They, however, did not discuss the scale effect of fluctuating propeller torque and thrust in waves. Ogawara et al. (1981) reported full-scale measurement of fluctuating propeller torque and propeller rate of revolution caused by propeller racing in wind and waves. They discussed the engine governor control to reduce the fluctuation of propeller rate of revolution. Tasaki (1957) discussed the scale effect originated in the difference of engine response of full-scale and model ships on fluctuation of propeller torque, thrust, and rate of revolution. He approximated the fluctuation of propeller torque and thrust linear

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to the fluctuation of ship speed and propeller rate of revolution, and modelled an engine as a first-order lag system of propeller torque to propeller rate of revolution. Nakamura and Naito (1977) approximated fluctuation of engine torque linear to fluctuation of engine rate of revolution and fuel injection. They discussed in model scale the effect of engine characteristics on fluctuating propeller torque, thrust and propeller rate, based on the comparison of numerical calculation and tank test data of a model ship in three different conditions; model ship with constant propeller rate of revolution, with constant propeller torque, and with constant engine power. Ikegami and Imaizumi (1978) developed a self-propulsion apparatus simulating an engine response and demonstrated fluctuating propeller torque and thrust in waves of a mode ship running at MSSP. They pointed out measured speed decrease in waves were not similar to full-scale because of the scale effect. Kitagawa et al. (2015) carried out free-running model test in head waves using a container ship model equipped with a diesel engine simulator and the duct fan auxiliary thruster (DFAT) (Tsukada et al., 2013, 2014) running at full-scale ship self-propulsion point (FSSP). They adopted an engine model of Bondarenko and Kashiwagi (2012), quasi steady model describing average response during a cycle of crank shaft of unit cylinder. Their test procedure takes into account the scale effect on mean of propeller torque and propeller rate of revolution but not on the fluctuating components. The authors proposed a method to embody full-scale equivalent propeller torque in free-running model ship testing (Ueno and Tsukada, 2014), making use of DFAT (Tsukada et al., 2013, 2014). DFAT, consisting of a duct fan, load cell for measuring auxiliary thrust, and a control PC, assists model ship propeller and controls propeller load at any designated time varying value without generating unnecessary lateral force. The method, however, assumes only slowly varying or low-frequency component of time varying propeller torque due to transition of environmental condition or manoeuvring motion, but does not take into account high-frequency component due to encounter waves.

The authors proposed rudder effectiveness correction (REC) (Ueno et al., 2014), for realizing full-scale equivalent manoeuvring motion of free-running model ship using DFAT (Tsukada et al., 2013, 2014). REC controls the thrust of DFAT to make the longitudinal component of inflow velocity to rudder similar to that of full-scale ship. They demonstrated by numerical simulation and tank test that model ships with REC show intermediate manoeuvring performance between those running at MSSP and those running at FSSP, and that REC gives better approximation of full-scale ship than others. Then, they proceeded to propose rudder effectiveness and speed correction (RSC) (Ueno and Tsukada 2015), an advanced REC taking account of time varying ship speed. RSC controls both the thrust of DFAT and the model propeller rate of revolution depending on the solutions of simultaneous equations for the similarity of rudder effectiveness and ship speed response, giving improved estimate of full-scale ship manoeuvring performance even in external forces. Suzuki et al. (2014) applied RSC in numerical simulation to ships in steady advancing condition in wind and waves and confirmed RSC can give good approximation. Suzuki et al. (2015) proposed a method to incorporate the limit for continuous engine operation into RSC and validated it by numerical simulation, which expanded the prospect of RSC. These researches indicate free-running model ships running at both MSSP and FSSP perform differently in general from full-scale ships and RSC ensures the similarity of manoeuvrability between model and full-scale ships in both transient and steady conditions.

The authors propose here a method to estimate full-scale propeller torque and thrust including its fluctuating or high-frequency component making use of free-running model test. In the method, RSC (Ueno and Tsukada, 2015; Suzuki et al., 2014, 2015) ensures similar ship motion and, therefore, similar propeller situation in waves. The procedure of the method based on some assumptions is as follows. Analysis at every time step of measured model propeller torque and thrust, and model ship speed estimates the effective inflow velocity to propeller of model ship. By replacing the model ship speed component by that of full-scale in the estimated effective inflow velocity to propeller of model ship one can estimate the effective inflow velocity to propeller of full-scale ship. The estimated full-scale effective inflow velocity to propeller and supposed full-scale propeller rate of revolution tell instantaneous full-scale propeller advance ratio and, accordingly, full-scale fluctuating propeller torque and thrust. Trial application of the method to existing tank test data by assuming hypothetical RSC condition exemplifies how the full-scale propeller torque and thrust in waves are different from those of model ship. The authors also propose a new free-running test procedure incorporating any engine model simulating interaction between propeller torque and engine torque.

2. Estimation of full-scale propeller torque and thrust

Let us consider phenomena in non-dimensional forms to discuss the correlation between model and full-scale ships. The representative length, mass, and time for transforming variables to their non-dimensional forms are ship length in perpendiculars L, ρL^3, and $(L/g)^{1/2}$, where ρ and g are the density of water and the gravitational acceleration, respectively. Non-dimensional speed, therefore, is equal to Froude number. Variables with prime' on their right shoulders represent non-dimensional values. Subscript m and s represent model and full-scale values, respectively, and subscript * stands for either of them when needed. Variables with neither subscript m nor s represent those assumed to have no scale effect, and have an identical non-dimensional quantity for both model and full-scale ships. Variables with tilde ~on top of them represent low-frequency components and those followed by Δ represent high-frequency components. Their conceptual definitions are as follows. The low-frequency component varies depending on manoeuvring motion or environmental change in terms of statistics while high-frequency component varies responding to discrete encounter waves or gusts of wind. Low-frequency and high-frequency components constitute corresponding whole value, though some consist of either low-frequency or high-frequency component.

2.1. Similarity of ship motion in external forces

RSC (Ueno and Tsukada, 2015; Suzuki et al., 2014, 2015) ensures similar model ship manoeuvring motion to full-scale even in external forces, which realizes similar encounter wave situation of a model ship propeller to that of full-scale propeller.

The concept of RSC (Ueno and Tsukada, 2015) is that the similarities of both effective inflow velocity to rudder and longitudinal speed response ensure the similarity of manoeuvring motion of a free-running model ship to full-scale. An auxiliary thruster, DFAT (Tsukada et al., 2013, 2014), puts the concept into practice. Governing equations of RSC are as follows.

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

u'_{R*} is the effective inflow velocity to rudder, a function of propeller rate of revolution n'_* and longitudinal component of ship speed u'. Several rational mathematical models are applicable to u'_{R*} calculation (Kose et al., 1981). 1–t is the thrust deduction coefficient. T'_* is the propeller thrust, a function of n'_* and u'. $T_{\mathrm{SFC}}{}'$ is the force required for the skin friction correction, varying depending