Investigation on Components of Added Resistance in Short Waves

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Summary

In order to estimate decrease of ship speed in actual seas, it is important to calculate added resistance in waves with accuracy. Especially added resistance in short waves is one of the predominant factors inducing the decrease of speed for a large ship in relation to wave spectrum. Various calculation methods have been proposed for the added resistance in short waves. However those methods are proposed for blunt and low-speed ships, for example, tanker, bulk carrier, etc. Those methods give poor agreement with experimental data for fine and high-speed ships. To improve the estimation method, firstly numerical investigation on the effect of draft and frequency was carried out. Thereafter experiments of wall-sided models with motion fixed were conducted. From these results a new formula is proposed, which gives good agreement with the experimental results.

1.Introduction

When a ship sails in waves, the resistance is larger than that in still water. The phenomenon is called added resistance in waves, and it is caused by energy dissipation when a ship generates waves due to ship motion or reflection of incident waves. Added resistance in waves should be accurately estimated to evaluate decrease of speed and fuel consumption in actual seas. Especially added resistance in short waves is one of the predominant factors inducing the decrease of speed for a large ship in relation to wave spectrum. It is known that calculated results of added resistance in short waves give poor agreement with the experimental data. Fujii and Takahashi1) considered the reason for the discrepancy as added resistance due to wave reflection, and they proposed a semi-empirical formula. Thereafter, Takahashi2) revised the formula. Faltinsen et al.3) proposed a formula based on the theory for a limiting case of wave length. Ohkusu4) developed an estimation method by unsteady wave analysis. Nakamura et al.5) carried out an experiment on diffraction condition for added resistance in short waves. Naito et al.6) calculated added resistance by ray theory. However, those methods are not aiming at a fine and high-speed ship such as a container ship.

The calculation methods for added resistance due to wave reflection are based on an equation for drift force acting on an object upstanding in short waves, and are composed of bluntness coefficient, effect of draft and frequency, and effect of advance speed. The variable parameters in the calculation are ship speed, draft, wave frequency and shape of water plane. In order to investigate effects of these parameters, experiments in regular heading waves were conducted with two types of wall-sided models.

2.Estimation Method of Added Resistance due to Wave Reflection

2.1 Conventional Method

According to the proposal of Fujii and Takahashi, added resistance due to wave reflection R_{AWr} is expressed by the following equation.

$$R_{AWr} = \frac{1}{2}\rho g \zeta_a^2 B \cdot B_f \alpha_d \left(1 + \alpha_U\right) \tag{1}$$

ρ; fluid density, g; gravitational acceleration,
ζ_a; amplitude of regular waves, B; ship breadth

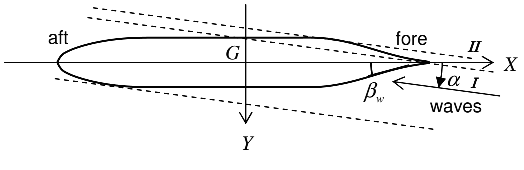

Fig. 1 Coordinate system.

Fig.1 shows a coordinate system of the wave reflection. A ship is running to the positive X direction in regular waves with incident angle α (heading direction: 0 deg).

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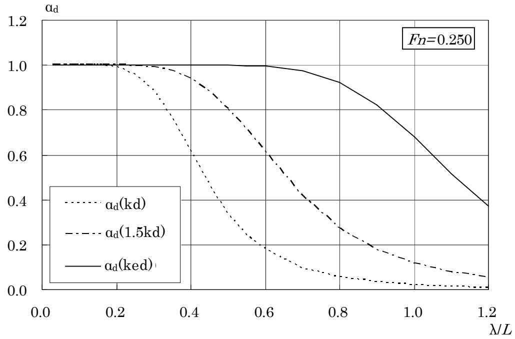


Fig. 2 Comparison of effect of draft and frequency.

In this paper, following investigations are carried out based on Eq.(1).

Eq.(1) is composed of effect of draft and frequency (α_d), effect of advance speed ($1+\alpha_U$), and bluntness factor B_f.

The components of Eq.(1) are expressed as follows:

(i) Bluntness coefficient (B_f)

Bluntness coefficient is determined by a shape of water plane and it is expressed by the following equation.

$$B_f = \frac{1}{B}\left\{ \int_I \sin^2(\alpha+\beta_w)\sin\beta_w dl + \int_{II} \sin^2(\alpha-\beta_w)\sin\beta_w dl \right\} \tag{2}$$

I, II; domains of integration in Fig.1, dl; line element

β_w; slope of line element

(ii) Effect of draft and frequency (α_d)

According to Fujii-Takahashi or Takahashi, effect of draft and frequency is expressed as follows.

Fujii – Takahashi's formula;

$$\alpha_d = \frac{\pi^2 I_1^2(kd)}{\pi^2 I_1^2(kd) + K_1^2(kd)} \tag{3}$$

Takahashi's formula;

$$\alpha_d = \frac{\pi^2 I_1^2(1.5kd)}{\pi^2 I_1^2(1.5kd) + K_1^2(1.5kd)} \tag{4}$$

I_1;

Modified Bessel function of the first kind of order 1

K_1;

Modified Bessel function of the second kind of order 1

k; wave number of incident waves, d; draft

Eq.(3) is a square of the reflectance ratio of upstanding wall derived by Ursell[7]. In Takahashi's formula, $1.5kd$ is used instead of kd as a parameter of non-dimensional frequency to extend effect to long waves according to experimental data. Fig.2 shows calculated results of α_d for a ship of 300m length and 14m draft using kd or $1.5kd$ as the parameter of non-dimensional frequency; where λ is length of incident waves.

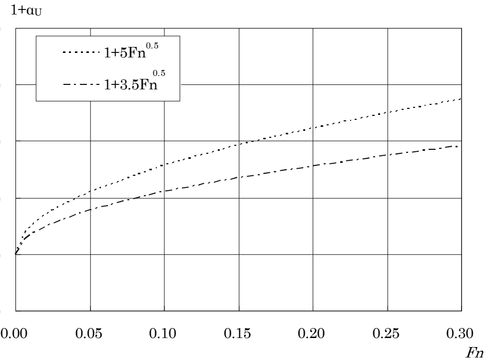


Fig. 3 Comparison of effect of advance speed.

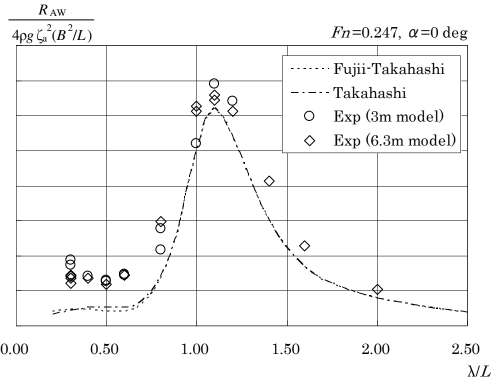


Fig. 4 Example of calculated results of added resistance in waves.

(iii) Effect of advance speed ($1+\alpha_U$)

In Fujii-Takahashi's formula and Takahashi's formula, effect of advance speed is given by following equations.

$$\text{Fujii – Takahashi's formula;}\ \alpha_U = 5\sqrt{Fn} \tag{5}$$

$$\text{Takahashi's formula;}\ \alpha_U = 3.5\sqrt{Fn}\cos\alpha \tag{6}$$

$Fn = \dfrac{U}{\sqrt{gL}}$; Froude number,

L; ship length, U; ship speed

The effect of advance speed α_U is expressed as an empirical formula which is derived from experiments of blunt ships. Fig.3 shows calculated results of $(1+\alpha_U)$ by Fujii-Takahashi's formula and Takahashi's formula, respectively.

As an applied example of Fujii-Takahashi's formula and Takahashi's formula, calculated results of added resistance in waves (R_{AW}) for a container ship of 300m length, 40m breadth and 14m draft shown in Fig.4[9]. Added resistance due to ship motion is calculated by Maruo's theorem[8]. In short waves, the calculated result gives poor agreement with experimental data. As shown here an example, it is well-known that there is a remarkable discrepancy particularly in the case of a high-speed ship such as a container ship. It is necessary to modify effect of draft and frequency and effect of advance speed.

2.2 Investigation in the Case of Zero Forward Speed

In order to examine effect of draft and frequency (α_d), numerical investigation is carried out.

Added resistance due to wave reflection at zero forward speed is equal to wave drift force. By Fujii-Takahashi's formula, coefficient of drift force (C) is expressed by multiplying the effect of draft and frequency (α_d) for an upstanding wall, which is shown in Fig.5, and bluntness coefficient (B_f).

$$C = \frac{R_{AWr}}{1/2\rho g \zeta_a^2 B} = \alpha_d(kd) \cdot B_f \quad . \qquad (7)$$

To confirm a validity of the equation, a numerical calculation for a three dimensional curtain wall (3DCW) is carried out. The program was developed by one of the authors to calculate the wave field around a curtain wall type breakwater. It can be applied to an arbitrary upstanding wall of zero thickness in regular waves shown in Fig.6.

For a straight curtain wall shown in Fig.7, comparisons between coefficient of wave drift force of 3DCW and that of Eq.(7) are shown in Fig.8. In the three dimensional calculation, the length of a curtain wall is selected 5 times as long as wave length since the program requires a finite value. From Fig.8, both results give good agreement and these indicate the validity of Eq.(7).

Consequently a calculation is carried out for a boxy shape (depth;14m) shown in Fig.9. The calculated results for $\theta = 45$deg and $\theta = 90$deg are shown in Fig.10. Though the result of Eq.(7) is larger than that of 3DCW due to three dimensional effect, it well expresses the tendency.

We propose to use $k_e d$ instead of $1.5kd$ as the parameter of non-dimensional frequency.

$$\alpha_d(k_e d) = \frac{\pi^2 I_1^2(k_e d)}{\pi^2 I_1^2(k_e d) + K_1^2(k_e d)} \qquad (8)$$

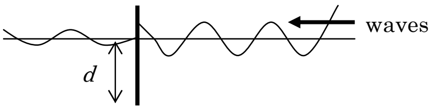


Fig. 5 Two dimensional upstanding wall.

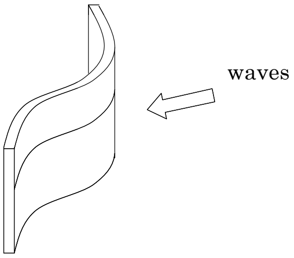


Fig. 6 Three dimensional curtain wall.

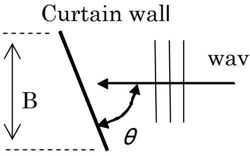


Fig. 7 Relation between waves and curtain wall.

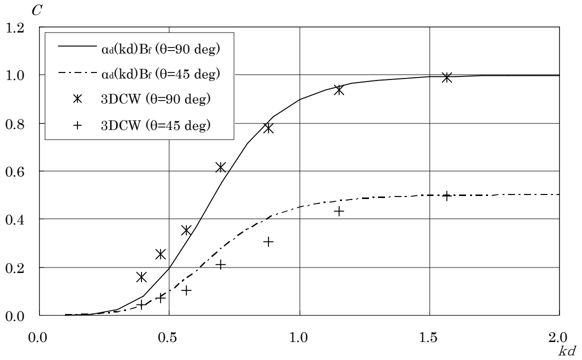


Fig. 8 Wave drift force (U=0).

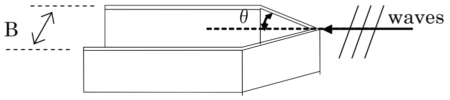


Fig. 9 Boxy shape.

$$k_e = \frac{\omega_e^2}{g} = k(1 + \Omega \cos\alpha)^2 \qquad (9)$$

$$\Omega = \frac{\omega U}{g}, \quad \omega_e = \omega + kU\cos\alpha \qquad (10)$$

It is considered as a rational method because the wave frequency of reflected wave is ω_e. The example of a calculation with $k_e d$ is shown in Fig.2. The applicability of the formula is to be confirmed by experiments.

3.Experiment using Wall-sided Models

Experiments using wall-sided models were conducted for added resistance in regular heading waves to clarify the contribution of the parameters of added resistance due to wave reflection.

3.1 Models

Two types of wall-sided models are used for the experiments; one is a container type and the other is a bulk carrier (BC) type. These models represent a bow part of each type. The actual length (L_T) of both models is 5.5m though the ship length (L) of the model is assumed to be 7.5m corresponding to a ship breadth (B). The aft part of the model is formed with simple straight shape, and both the models have the same shape at the aft part. In the following section Fn and λ/L are non-dimensionalized by the ship length 7.5m. The dimension and the shape of models are shown in Table 1 and Fig.11.

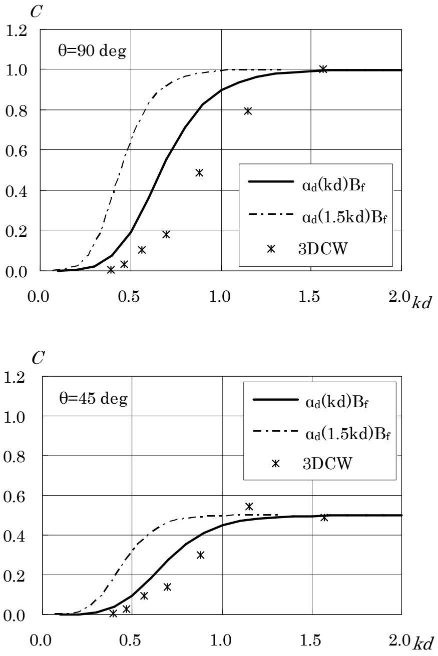


Fig. 10 Wave drift force of the curtain wall hull (U=0).

Table 1 Dimension of models.

	Container type	BC type
L_T(m)	5.5	5.5
B(m)	1.0	1.0
d(m)	0.35	0.35
Displacement;∇(m^3)	1.113	1.377
Wetted surface area;S(m^2)	6.621	7.307
B_f	0.056	0.382
※ L(m) (virtual)	7.5	7.5

3.2 Measurement System

The experiments are carried out at Mitaka No.3 Ship Model Basin in National Maritime Research Institute (length; 150m, width; 7.5m, depth; 3.5m with wave generators of plunger type).

Experimental system is shown in Fig.12. Resistance is measured by 2 load cells with 500N capacity at aft and fore positions. The ship motion in heading waves is fixed by 2 load cells. Gimbals set on the mount of the model remove static load due to longitudinal ship deformation.

3.3 Measurement Items

Following investigations through the experiments were carried out.

・Effect of advance speed $(1+\alpha_U)$ by towing the models with different speed.

・Relation between bluntness coefficient B_f and effect of advance speed $(1+\alpha_U)$ by using 2 models of different types of the hull form.

・Effect of draft and frequency (α_d) by towing the models in different wave frequency and draft.

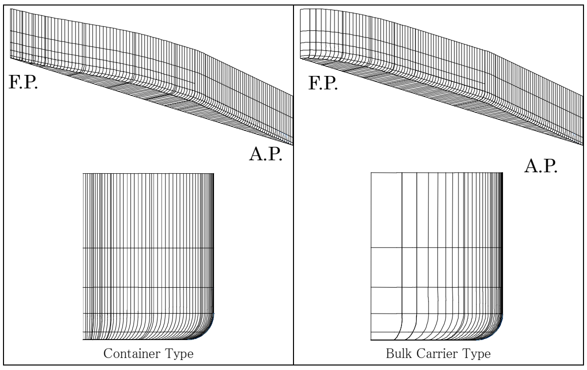
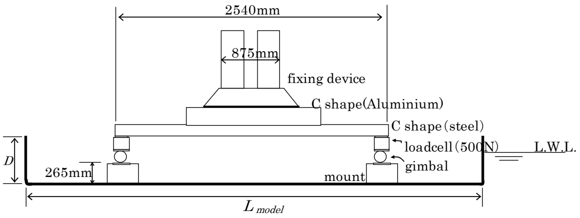


Fig. 11 Model ships.

(a) Side view



(b) Front view

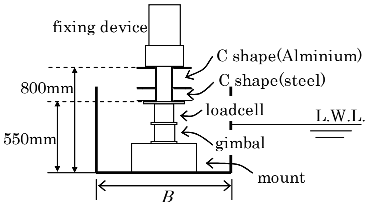


Fig. 12 Experimental system.

4.Results of Experiment

4.1 Effect of Advance Speed

In order to examine the effect of advance speed, the model is towed with different speed in regular heading waves of $\lambda/L = 0.3$. In such short waves, the effect of draft and frequency is considered as $\alpha_d \simeq 1$. Fig.13 and Fig.14 show results of $(1+\alpha_U)$ of a container type model and a bulk carrier type model, respectively.

α_U is expressed as the functions of $\sqrt{Fn}$ or Fn. The coefficients of the functions (C_U) in each case are shown in Table2. Both the coefficients have difference between the container type model and the bulk carrier type model. The coefficients will be represented by the bluntness coefficient. For various types of ships, the coefficients of advance speed are examined by Tsujimoto et al.$^{9)}$.

4.2 Effect of Draft and Frequency

The model is towed at constant speed in different wave length and draft in order to examine effect of draft and frequency (α_d). The results are shown in Fig.15 and Fig.16 as the function of λ/L at d=0.35m. The results as the

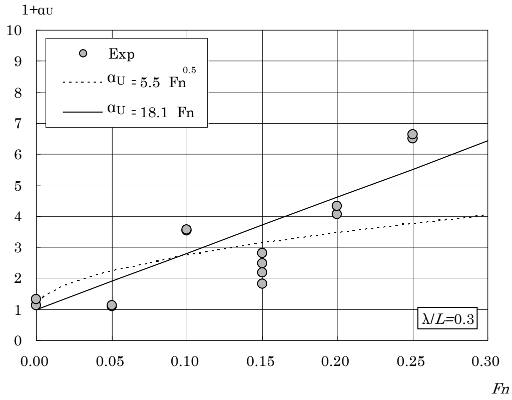


Fig. 13 Effect of advance speed; container type.

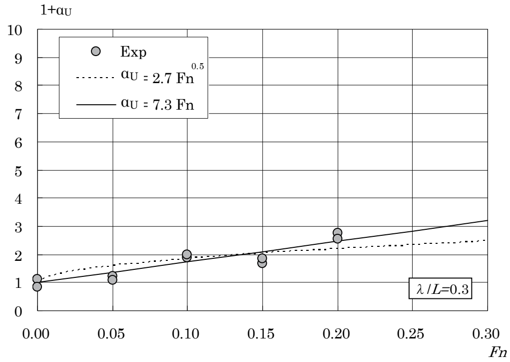


Fig. 14 Effect of advance speed; bulk carrier type.

Table 2 Comparison of coefficient (C_U) of effect of advance speed.

	Container type	Bulk carrier type
Coeff. of $\sqrt{Fn}$	5.5	2.7
Coeff. of Fn	18.1	7.3

function of d at λ/L=0.3 are shown in Fig.17 and Fig.18 as well.

From Fig.15 and Fig.16, it is obvious that the experimental results of α_d keeps a large value also in long waves. It is clear that the proposed formula Eq.(8) expresses better agreement with the experimental data than the other formulas.

In the case of the bulk carrier type model, there were difficulties to fix the model ship in long waves. The measurement at $\lambda/L = 0.75$ in Fig.16 has the influence because the wave exciting force is larger.

5.Effect of a Measurement System

In Fig.13 and Fig.14, experimental results are not smooth. To examine whether it is an error by the measurement system or not, the other experiment with motion free system (surge, heave, pitch and roll) was carried out in Mitaka No.2 Ship Model Basin in National Maritime Research Institute (length; 400m, width; 18m, depth; 8m). A load cell with 600N capacity is used. The container type model is towed with different speed in waves of $\lambda/L = 0.3$. The results of the experiments are shown in Fig.19. In Fig.19, the results of the fixed model are also plotted. The figure shows that both results have a similar tendency, it implies that there is no error caused by measurement system.

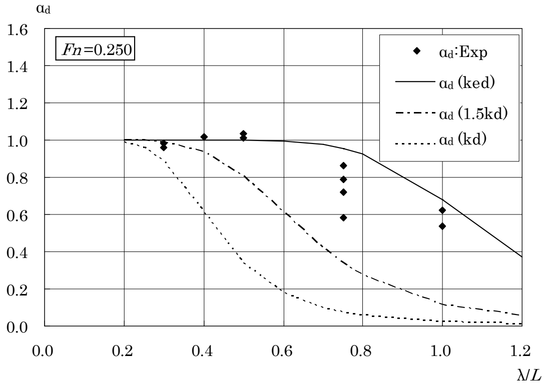


Fig. 15 Effect of draft and frequency; container type. ($d = 0.35$m)

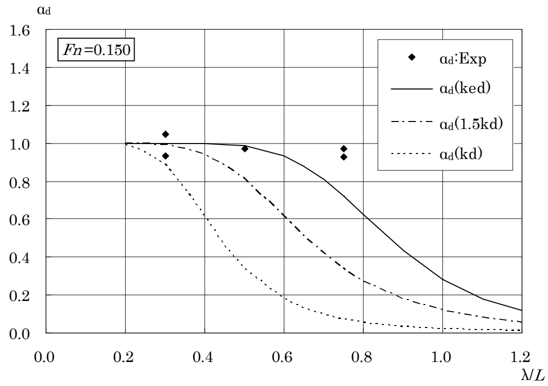


Fig. 16 Effect of draft and frequency; bulk carrier type. ($d = 0.35$m)

Experimental results of added resistance in waves are related to resistance in still water. For checking resistance in still water, the comparison of two measurement systems is shown in Fig.20. Resistance in still water is nondimensionalized by $0.5\rho SU^2$. Fig.20 shows little difference between the result of resistance in still water by vertical motion free system and that by motion fixed system.

The other possible reason for the lack of smoothness expressed in Fig.13 and Fig.14 is effect by the shape of aft part. It remains to be investigated in the future.

6.Conclusions

In order to develop a method for estimating added resistance of a fine and high-speed ship, a numerical calculation of three dimensional curtain wall and experiments with fixed models were carried out.

As a result, we obtained following conclusions.

1) For the calculation of added resistance due to wave reflection with accuracy, effect of draft and frequency can be well explained by using $k_e d$ instead of kd as the parameter of non-dimensional frequency.

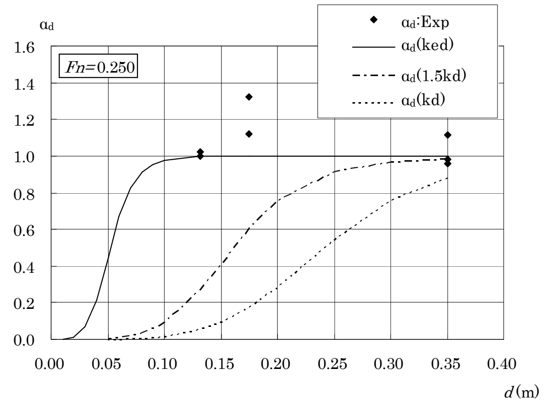


Fig. 17 Effect of draft and frequency; container type. ($\lambda/L = 0.3$)

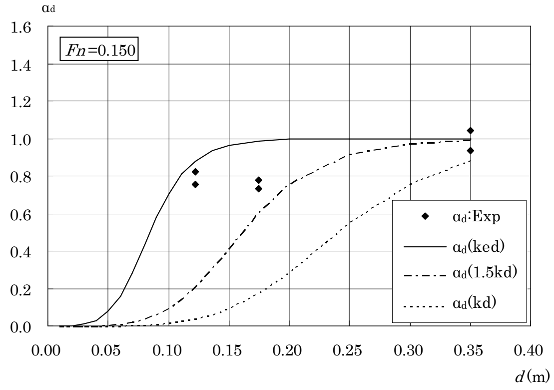


Fig. 18 Effect of draft and frequency; bulk carrier type. ($\lambda/L = 0.3$)

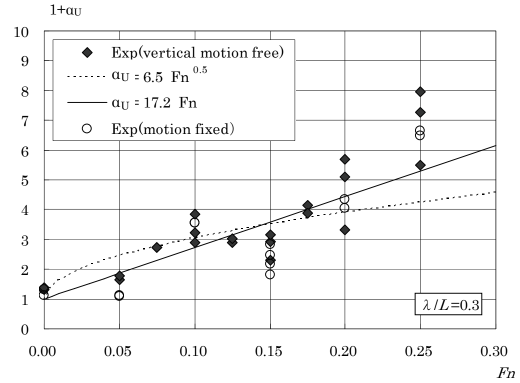


Fig. 19 Speed effect; container type (motion free). ($\lambda/L = 0.3$)

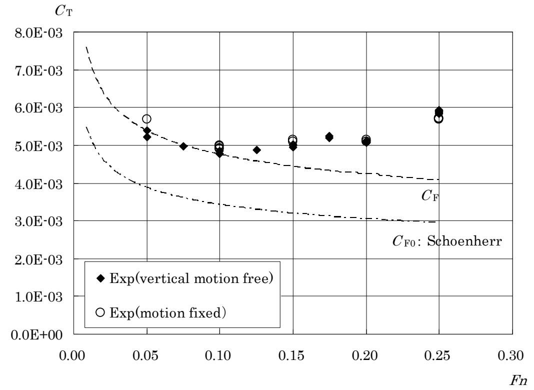


Fig. 20 Resistance in still water of the container type

2) The effect of advance speed is related to shape of ship hull. The term can be represented as $(1 + C_U Fn)$ or $(1 + C_U\sqrt{Fn})$, and C_U also varies due to shape of ship hull.

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