J Mar Sci Technol (2010) 15:108–118
DOI 10.1007/s00773-009-0077-y

ORIGINAL ARTICLE

Study on the form factor and full-scale ship resistance prediction method

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Received: 23 October 2008 / Accepted: 26 October 2009 / Published online: 2 December 2009

Abstract To consider the resistance component due to hull geometry, the International Towing Tank Conference (ITTC) adopted the resistance test method in 1978, introducing the form factor concept with two basic assumptions, i.e., the form factor of a model ship is the same as that of a full-scale ship and the form factor is independent of ship speed. However, it is not only very difficult to determine the form factor using the ITTC '78 method, but also there have been questions regarding the basic assumptions. Therefore, the authors carried out three basic studies on the form factor concept and proposed a new extrapolation procedure for the prediction of full-scale ship resistance performance. The validity of the proposed procedure is being investigated by comparing sea trial and model test results. The results of this investigation will be presented in the near future.

Keywords Form factor · Total resistance · Frictional resistance · Wave resistance · Model test · Froude number · Reynolds number · Terminal form factor · Form factor correction factor

1 Introduction

Since ships are generally large-scale high-value movable structures, it is customary to confirm the performance characteristics of full-scale ships by model tests before construction. In order to accurately predict the performance characteristics of full-scale ships by model tests, the flow characteristics around a full-scale ship and that around the model ship should be made as similar as possible, i.e., dynamic similitude should be assured. In the case of the resistance test in particular, the complete satisfaction of such dynamic similitude requires that two kinds of nondimensionalized quantities, i.e., the Froude number and the Reynolds number, should be made the same for the full-scale ship and the model ship.

As is well known, however, the simultaneous scaling of both Froude and Reynolds numbers between two geosims is practically impossible. Therefore, early naval architects had come to realize the necessity of idealizing or simplifying the system to overcome such conflicts in achieving dynamic similitude and to make experimental methods applicable. From the viewpoint of such practical necessity, William Froude introduced the so-called Froude assumption in 1867, separating the total resistance into the frictional resistance and residual resistance components and proposing that the resistance test be conducted based on identical Froude numbers, with a correction for the different Reynolds number effects.

Basically, the same traditional method has been applied until now. In order to improve the traditional method, however, the International Towing Tank Conference (ITTC) Resistance and Propulsion Performance Committee adopted the following method in 1978, introducing the form factor concept as the performance prediction method for single-screw ships [1]:

$$C_{TS} = (1 + k) \cdot C_{FS} + C_W + \Delta C_F + C_{AA} \quad (1)$$

where C_T is the total resistance coefficient, k is the form factor, C_F is the frictional resistance coefficient, C_W is the wave-resistance coefficient, ΔC_F is the additional frictional resistance coefficient due to roughness, and C_{AA} is the air-resistance coefficient. Subscript S denotes full-scale ships.

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As shown in Eq. 1, the ITTC has adopted the method of separating viscous resistance and wave resistance using the form factor as the standard extrapolation method. Therefore, determination of the form factor is very important in the prediction of full-scale ship resistance characteristics.

The form factor, k, adopted by ITTC in 1978, is defined as follows with two basic assumptions:

$$1 + k = \lim_{F_N \to 0} \frac{R_T}{R_F} = \lim_{F_N \to 0} \frac{C_T}{C_F} \tag{2}$$

- The form factor of the model ship is the same as that of a full-scale ship, i.e., $(1 + k)_M = (1 + k)_S$
- The form factor is independent of ship speed.

In Eq. 2, F_N is the Froude number, R_T is the total resistance, and R_F is the frictional resistance. In the first assumption, subscript M denotes model ships.

In this study, the ITTC '57 correlation line was utilized as the frictional resistance coefficient, i.e.,

$$C_F = \frac{0.075}{(\text{Log}\, R_N - 2)^2} \tag{3}$$

and

$$R_N = \frac{VL}{\nu} \tag{4}$$

where R_N is the Reynolds number, V is the ship speed, L is the ship length, and ν is the kinematic viscosity.

Despite the standard method adopted by the ITTC Performance Committee, however, the results of performance predictions for full-scale ships using model tests generally vary considerably from basin to basin. This phenomenon has been well known among experts involved in this work. Such a phenomenon may be considered to occur for two main reasons. The first is the determination of form factors. It is very difficult to measure resistance at low speeds, and hence it is difficult to determine the form factor accurately according to its definition. The second is whether or not the basic assumptions are correct.

In fact, the authors support the form factor concept itself, because it is meaningful to be able to identify the resistance component related to the hull geometry in the total resistance by any means. However, it is considered necessary to investigate the validity of the present ITTC form factor concept. Therefore, the authors carried out the following three basic studies:

- The method of form factor determination according to the ITTC definition
- The relation between form factor and Reynolds number
- The method of form factor determination at the design speed.

This study was carried out over 15 years from 1992 to 2006. Table 1 shows the selected ships in chronological order for this study, and Table 2 shows the period of the model tests. All the basic and required tests were conducted at the deep-water towing tank of the Maritime Research Institute, Hyundai Heavy Industries (HMRI). The deep-water towing tank of HMRI is 220 m long, 14 m wide, and 6 m deep. Some limited tests were also conducted at the Hamburg Ship Model Basin (HSVA) and the SSPA in Sweden for confirmation. In this article, however, only the test results from the HMRI towing tank are presented.

Utilizing the results of the three basic studies, the authors have made an effort to prepare an improved prediction method of full-scale ship resistance performance, basically maintaining the ITTC 1978 concept. This is the ultimate purpose of this study.

2 Suggestion of form factor determination by ITTC definition

2.1 Synopsis

The total resistance coefficient of a model ship is expressed as follows:

$$C_{TM} = (1 + k) \cdot C_{FM} + C_W \tag{5}$$

The most accurate method to determine the form factor is to utilize Eq. 5 if simultaneous measurements of total resistance and wave resistance are possible. Due to the difficulty and inaccuracy of measuring wave resistance, however, this method has no practical meaning. It is also impossible to measure the form factor directly according to the definition given in Eq. 2. In practice, therefore, the form factor is indirectly determined from the measurements of low-speed resistance. The problem is that accurate measurement of low-speed resistance of a model ship is very difficult.

Therefore, the authors have made an effort to prepare a method of determining the form factor consistently in accordance with the ITTC definition. The authors' method is briefly discussed. For the successful determination of the form factor from the ITTC definition, it is necessary to execute low-speed resistance tests very carefully, to select the measured data properly, and to utilize a suitable analysis method.

2.2 Direct method

First, data sets, i.e., sets of very low Froude numbers versus C_{TM}/C_{FM} values, should be prepared from a series of low-

Table 1 Ships studied in chronological order

Stage of selection	Year	Ship type	LPP_M (m)
First	1992	ITTC STD Ship 1 (series 60, $C_B = 0.6$)	2.0/4.0/8.0
		4,410-TEU C/C	2.0/4.0/8.0
		ITTC STD Ship 2 (series 60, $C_B = 0.8$)	2.0/4.0/8.0
		150,000-TDW B/C	2.0/4.0/8.0
Second	2003	5,600-TEU C/C	6.528
		137,300-m^3 LNG/C	7.647
		76,000-TDW B/C	6.865
		314,000-TDW VLCC	6.349
Third	2006	8,600-TEU C/C	2.0/4.0/7.584/10.0
		155,000-m^3 LNG/C	2.0/4.0/7.674/10.0
		317,000-TDW VLCC	2.0/4.0/6.775/10.0
		Mid-sized high-speed C/C	2.0/5.52/8.0/12.0

LPP_M, length between perpendiculars for the models; ITTC STD, International Towing Tank Conference standard; C/C, container carrier; B/C, bulk carrier; LNG, liquefied natural gas; VLCC, very large crude carrier; C_B

Table 2 Period of model tests

Test no.	Year	Number of ships	Model length (m)
1	1992	The first stage, 4 ships	2/4/8
2	1998	The first stage, 4 ships	2/4/8
3	2001	The first stage, 4 ships	2/4/8
4	2003	The first and the second stage, 8 ships	8
5	2006	The third stage, 4 ships	2/4/8/10

speed resistance tests. Here, the following symbols are used for the sake of convenience:

$$x = F_N, \quad y = C_{TM}/C_{FM} \tag{6}$$

The data sets are curve-fitted to the following polynomial equations by the least-squares method:

$$\text{Second order}: \quad y = ax^2 + bx + c \tag{7}$$

$$\text{Third order}: \quad y = ax^3 + bx^2 + cx + d \tag{8}$$

By definition, the form factor could be expressed as:

$$1 + k = \lim_{F_N \to 0} \frac{C_{TM}}{C_{FM}} = \lim_{x \to 0} y \tag{9}$$

The form factor thus becomes the constant term, i.e., c or d, in Eqs. 7 and 8. The third-order polynomial equation was simply used to check and to compare the results from the second-order polynomial equation.

2.3 Indirect method

The indirect method is based on the following approximate expression for the low-speed resistance:

$$C_{TM} = (1 + k) \cdot C_{FM} + aF_N^n \tag{10}$$

In Eq. 10, "a" is a constant related to the wave resistance coefficient.

In the method of Prohaska [2], the exponent "n" in Eq. 10, representing the amount of wave resistance, is fixed. In the linearized thin-ship theory, the asymptotic expansion of the wave resistance expression for small Froude number shows that wave resistance varies as the 6th power of the Froude number [3]. From the physical viewpoint, the exponent generally varies between 4 and 6, depending on the ship form. In this study, therefore, the exponents 4, 5, 6 were tested to investigate the effect of different exponents.

In this method, data sets of F_N^n/C_{FM} versus C_{TM}/C_{FM} are prepared from a series of low-speed resistance tests. Also, the following symbols may be used for the sake of convenience:

$$x = F_N^n/C_{FM}, \quad y = C_{TM}/C_{FM} \tag{11}$$

The data sets are curve-fitted to the second-order or the third-order polynomial equations by the least-squares method, as before. Then, the form factor becomes the constant term by definition.

3 Suggestion for the form factor determination at design speed

As mentioned above, the form factor concept was introduced to consider the resistance component due to hull geometry in ship resistance. It has also been assumed that the form factor is mainly related to the viscosity of the fluid. Since form resistance or wave resistance cannot be measured independently, in general, the only way to determine the form factor is by measuring the resistance in the low-speed region where wave resistance can be neglected. This is the concept of the ITTC.

In most cases of low-speed resistance tests for form factor determination, the flow characteristics around model ships are not in the state of full turbulence, and hence, a discrepancy is expected both in the concept and in the measured value. Therefore, the authors have tried to prepare a method to determine the form factor not only for the limiting case of zero speed, but also for any speed.

When the Reynolds number is greater than 10^7, the flow may be assumed to be fully turbulent and the form factor may approach an almost constant value. Therefore, it was decided to conduct resistance tests as much as possible at speeds where the Reynolds number was greater than 10^7. Fortunately, this condition is mostly satisfied at the model ship speed corresponding to the full-scale ship's design speed for large-scale model ships with a length greater than 6.0 m.

The following expression regarding the wave resistance coefficient was introduced with the assumption that the form factor remains almost constant within very small speed intervals close to the design speed:

$$\begin{aligned}(1+k)\cdot C_{\mathrm{FM}}+C_{\mathrm{W}}&=C_{\mathrm{TM}}\\ C_{\mathrm{W}}=aF_{\mathrm{N}}^{n},\quad n&=4\text{–}6\end{aligned} \tag{12}$$

Using large-scale model ships, resistances were measured at several different speeds within very small intervals close to the design speed. The form factor and the wave resistance coefficient were calculated by solving simultaneous equations formed from data obtained at two neighboring speeds.

4 Relation between form factor and Reynolds number

As the ship speed increases, a hull wave is generated and affects the form resistance. In other words, the form factor begins to be affected by the Froude number as well as by the Reynolds number. In order to investigate the effect of the hull wave on form resistance, however, very serious basic research needs to be performed. For the progress of this study, therefore, the effect of the hull wave on the form resistance has been excluded. In other words, it has been assumed that form resistance depends on the Reynolds number only.

In order to investigate the relation between the form factor and Reynolds number, form factors should be measured at different Reynolds numbers. For resistance tests with a model ship of fixed scale ratio, the towing speeds, and hence the Froude number, should be increased to increase the Reynolds number. In this case, determination of the form factor by using the ITTC definition is impossible. In model tests, however, there is a way of varying the Reynolds number at the same Froude number, i.e., by varying the scale ratio between the full-scale ship and the model ship. With the scale ratio denoted by λ, the change of Reynolds number due to a change of scale ratio at the same Froude number is proportional to $\lambda^{1.5}$.

In order to investigate the relation between the form factor and Reynolds number, therefore, the method of varying the Reynolds number by using models with different scale ratios was adopted in this study. This is the reason why several model ships of different sizes were constructed for the same kind of ship.

5 Model tests

For this study, 12 different ships were selected, as shown in Table 1. Model tests were carried out over 15 years from

Table 3 Main characteristics of the object ships

Ship type	Kind of ship	Full-scale ship							Model length (m)
		LPP (m)	B (m)	T (m)	C_B	V_S (knots)	F_N	$R_N \times 10^{-9}$	
Fine higher-speed ships	ITTC STD 1 (series 60, $C_B = 0.6$)	121.92	16.25	6.5	0.60	20.0	0.295	1.073	2.0/4.0/8.0
	4,410-TEU C/C	263.0	37.1	12.5	0.591	25.4	0.257	2.903	2.0/4.0/8.0
	5,600-TEU C/C	271.0	40.0	12.5	0.589	25.0	0.250	2.924	6.528
	8,600-TEU C/C	319.0	42.8	13.0	0.656	25.2	0.233	3.458	2.0/4.0/7.584/10.0
Gas carriers	137,300-m^3 LNG/C	274.0	48.0	11.25	0.671	19.7	0.196	2.316	7.647
	155,000-m^3 LNG/C	275.0	44.2	11.47	0.757	20.0	0.199	2.351	2.0/4.0/7.674/10.0
Full slow-speed ships	ITTC STD 2 (series 60, $C_B = 0.8$)	121.92	18.76	7.5	0.80	14.0	0.207	0.751	2.0/4.0/8.0
	76,000-TDW B/C	221.0	32.25	12.4	0.845	14.5	0.159	1.411	6.865
	150,000-TDW B/C	270.0	45.0	16.5	0.823	14.5	0.144	1.723	2.0/4.0/8.0
	314,000-TDW VLCC	320.0	70.0	16.76	0.810	16.9	0.154	2.393	6.349
	317,000-TDW VLCC	319.0	60.0	21.0	0.814	15.7	0.143	2.216	2.0/4.0/6.775/10.0
Mid-sized high-speed container carriers		276.0	27.6	9.0	0.475	35.0	0.346	4.182	2.0/5.52/8.0/12.0

F_N Froude number, R_N Reynolds number, B beam, T draft, V_S ship speed

1992 to 2006 as shown in Table 2. In order to systematically analyze the test results, the 12 selected ships were classified into four groups, i.e., the fine higher-speed ship group, the gas carrier group, the full slow-speed ship group, and the special ship group as shown in Table 3. Since this study was expected to be performed over an extended period, all the model ships were constructed using wood. Furthermore, hull geometry was always checked for deformation before tests, and was corrected if the level of deformation was beyond the tolerance. For the sake of consistency, no turbulence stimulators were fitted to any of the model ships.

Low-speed resistance tests for the determination of the form factor using the ITTC definition were conducted for all 32 model ships, and resistance tests at speeds close to the design speed were conducted for 12 large-scale model ships. Figures 1, 2, and 3 show four model ships of different sizes for an 8,600-TEU container carrier, a 155,000-m^3 liquefied natural gas (LNG) carrier, and a 317,000-TDW very large crude carrier (VLCC), respectively.

Fig. 1 Models of the 8,600-TEU container carrier

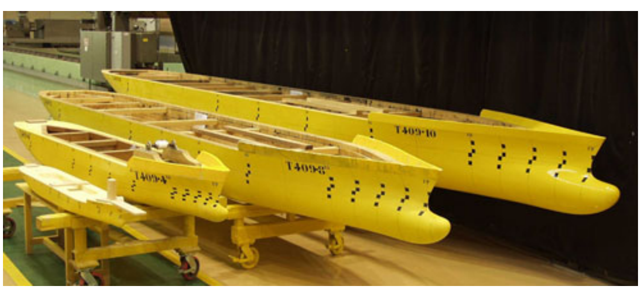

Fig. 2 Models of the 155,000-m^3 liquefied natural gas (LNG) carrier

Fig. 3 Models of the 317,000-TDW very large crude carrier (VLCC)

6 Test results and analyses

6.1 Low-speed resistance tests and determination of form factors

As mentioned, low-speed resistance tests for determination of the form factor were carried out repeatedly for all 32 model ships. Figures 4, 5, and 6 show the typical test results for the three ship types mentioned above. Figures 4, 5, and 6 also show the general trend of the form factor by the ITTC definition according to the ship length, i.e., according to the Reynolds number at the equivalent Froude numbers.

In Fig. 4, it can be seen that the low-speed resistance behaviors for smaller model ships are somewhat different to those of larger model ships. This phenomenon has been rather commonly experienced during tests. Since the Reynolds numbers for these tests are in the order of 10^5, it is considered that the flow around the model ships is mostly laminar or in transition.

With the low-speed resistance test results, form factors were determined following the method discussed in Sect. 2. In general, data for Froude numbers in the range 0.12–0.07

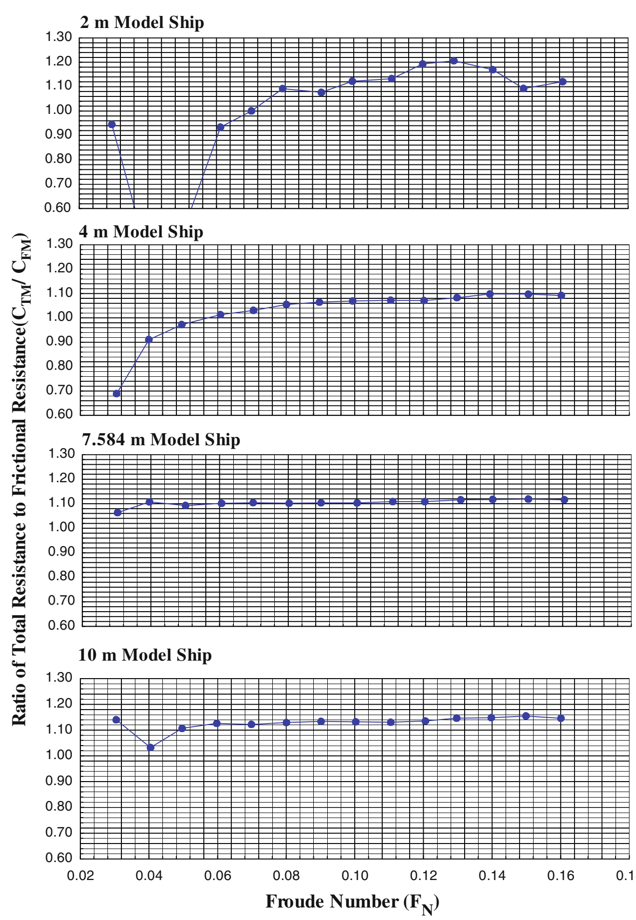

Fig. 4 Low-speed resistance test results for the 8,600-TEU container carrier

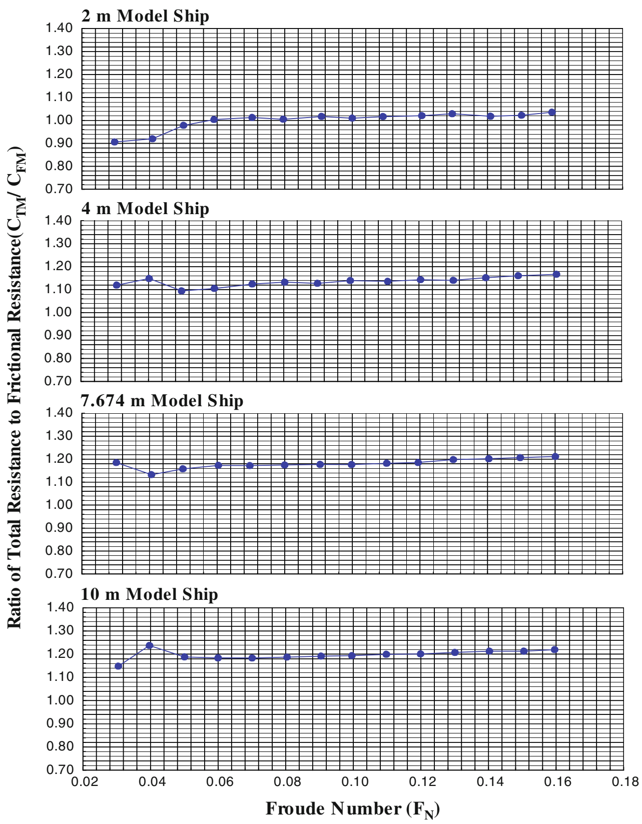

Fig. 5 Low-speed resistance test results for the 155,000-m^3 LNG carrier

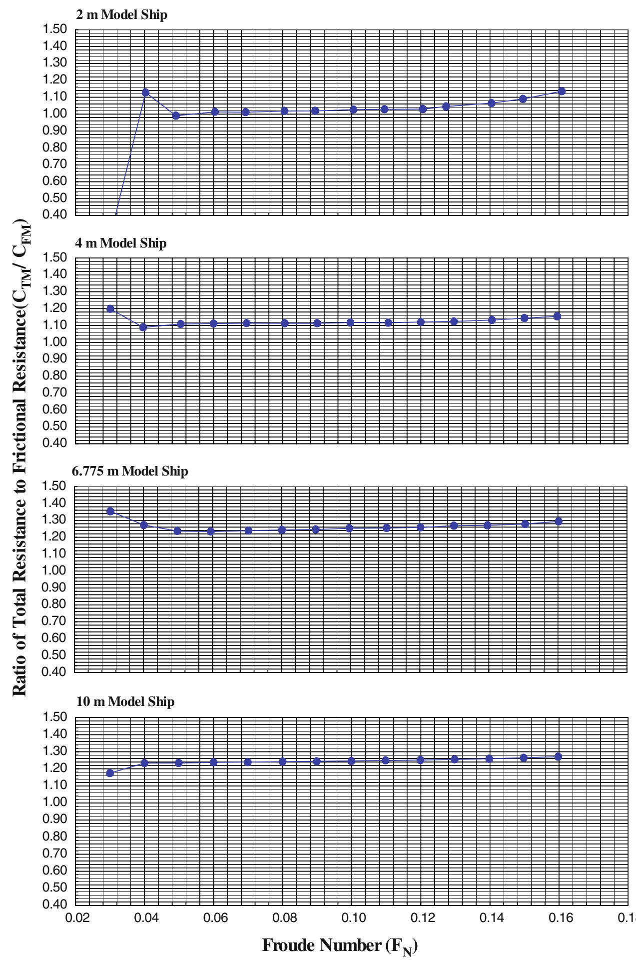

Fig. 6 Low-speed resistance test results for the 317,000-TDW VLCC

were utilized. Table 4 shows a summary of the form factors determined from low-speed resistance test results using different methods for three different ship types. As shown in Table 4, both the direct method and the indirect method produce good generally acceptable results, except for the very small model ships. However, more consistent results could be derived using the indirect method. In particular, the indirect method has advantages that the derived results do not much depend on either exponent n or the form of the polynomial equation. However, it was decided to select the following case as the standard procedure, considering the association with low-speed approximation from the linearized thin-ship theory:

- indirect method
- exponent $n = 5$
- second-order polynomial.

6.2 Resistance tests at speeds close to the design speed and prediction of form factors

In order to predict the form factor at the design speed, resistance tests at speeds close to the design speed were carried out for 12 large-scale model ships. With the test results for speeds close to the design speed, form factors were calculated following the method discussed in Sect. 3. For reference, the method of calculating form factors at the design speed is summarized again as follows:

$$(1 + k) \cdot C_F + C_W = C_T$$
$$C_W = aF_N^n, \quad n = 6 \qquad (13)$$

In Eq. 13, a different exponent, i.e., $n = 6$ instead of 5, was selected based on the wave-resistance theory for the different speed range. All the form factors determined from the low-speed resistance tests according to the standard procedure and from the tests at speeds close to the design speed are summarized in Table 5. In general, it was very difficult to derive meaningful form factors consistently at the design speed due to the scattering of measured resistance values at speeds very close to the design speed. As shown in Table 5, however, the possibility of obtaining practically useful values has been confirmed.

When deriving form factors at the design speed, it should be recognized that there is an additional hydrodynamic problem. In contrast to the situation in the low-speed range, a hull wave is generated at the design speed and this

Table 4 Sample form factors determined from low-speed resistance tests

Ship type	Model length (m)	Order of polynomial	Method			
			Direct	Indirect		
				$n = 4$	$n = 5$	$n = 6$
8,600-TEU container carrier	2.0	Second	0.7436	1.0076	1.0245	1.0360
		Third	0.8158	1.0000	1.0127	1.0267
	4.0	Second	0.7591	1.0121	1.0217	1.0277
		Third	0.9690	1.0000	1.0081	1.0164
	7.584	Second	1.1153	1.1020	1.1020	1.1020
		Third	1.0931	1.1038	1.1034	1.1031
	10.0	Second	1.1347	1.1240	1.1252	1.1261
		Third	1.1035	1.1194	1.1216	1.1230
155,000-m^3 LNG carrier	2.0	Second	1.0604	1.0098	1.0098	1.0100
		Third	1.0335	1.0095	1.0096	1.0098
	4.0	Second	1.0779	1.1227	1.1249	1.1264
		Third	1.1652	1.1226	1.1244	1.1257
	7.674	Second	1.2201	1.1726	1.1728	1.1732
		Third	1.0974	1.1700	1.1712	1.1720
	10.0	Second	1.1643	1.186	1.1836	1.1850
		Third	1.1136	1.1783	1.1808	1.1825
317,000-TDW VLCC	2.0	Second	1.0139	1.0122	1.0139	1.0151
		Third	0.9621	1.0027	1.0075	1.0103
	4.0	Second	1.1150	1.1127	1.1128	1.1130
		Third	1.1135	1.1130	1.11307	1.1131
	6.775	Second	1.2301	1.2377	1.2397	1.2411
		Third	1.1933	1.2321	1.2355	1.2377
	10.0	Second	1.2312	1.2377	1.2388	1.2397
		Third	1.2054	1.2366	1.2378	1.2387

n exponent in Eq. 10

affects the form resistance. In other words, not only the Reynolds number, but also the Froude number will affect the form resistance simultaneously. However, there is no possible way to estimate the interrelation of the Reynolds number, the Froude number, and the form factor using the results of the present research. This is the present state of the art of ship hydrodynamics. It is considered that very serious basic research is required to investigate the simultaneous effect of the Reynolds number and the Froude number on the form resistance.

6.3 Relation between form factor and Reynolds number

The form factors determined from the results of low-speed resistance tests and their approximate range of Reynolds numbers are given in Table 5. As shown in Table 5, the form factor increases with increasing model ship length, i.e., with increasing Reynolds number. The trend of the increase in form factor is considered to be rather consistent. From the results of this study, it could be realized that the form factor of a full-scale ship is likely to be different from that of the model ship; therefore, the ITTC '78 assumption should be corrected.

When the influence of the hull wave is neglected, however, the form factor will reach a constant value at the Reynolds number where the flow characteristics around the ship's hull become fully turbulent. With the assumption that this Reynolds number is in the region of 10^9, the authors tried to elucidate the relation between the form factor and the Reynolds number. In order to do that, it was decided to perform regression analysis on the form factors determined from the results of the low-speed resistance tests.

For the sake of convenience, the form factor with a corresponding Reynolds number greater than 10^9, i.e., the ultimate form factor that has practically reached a constant value, was called the terminal form factor.

The regression analysis was performed using a relative value, i.e., the ratio of form factor with respect to the terminal form factor; we call this ratio the form factor correction factor (FCF). The FCF asymptotically approaches unity as the Reynolds number increases; it is practically 1.0

Table 5 Selected form factors

Ship type	Kind of ship	Type of test	Model length (m)	$R^*_{NM} \times 10^{-7}$	Form factor
Fine higher-speed ship	ITTC STD 1 (series 60, $C_B = 0.6$)	Low speed	2.000	0.058	1.064
			4.000	0.164	1.077
			8.000	0.464	1.090
		Design speed	8.000	1.571	1.099
	4,410-TEU container carrier	Low speed	2.000	0.055	1.067
			4.000	0.154	1.068
			8.000	0.436	1.102
		Design speed	8.000	1.577	1.087
	5,600-TEU container carrier	Low speed	6.528	0.327	1.095
		Design speed	6.528	1.129	1.117
	8,600-TEU container carrier	Low speed	2.000	0.054	1.008
			4.000	0.132	1.012
			7.584	0.342	1.102
			10.000	0.511	1.124
		Design speed	10.000	1.913	1.116
Gas carrier	137,300-m^3 LNG carrier	Low speed	7.647	0.408	1.114
		Design speed	7.647	1.002	1.128
	155,000-m^3 LNG carrier	Low speed	2.000	0.060	1.010
			4.000	0.171	1.123
			7.674	0.447	1.173
			10.000	0.669	1.182
		Design speed	10.000	1.902	1.187
Full slow-speed ship	ITTC STD 2 (series 60, $C_B = 0.8$)	Low speed	2.000	0.058	1.165
			4.000	0.164	1.181
			8.000	0.464	1.241
		Design speed	8.000	1.100	1.253
	76,000-TDW bulk carrier	Low speed	6.865	0.361	1.204
		Design speed	6.865	0.717	1.206
	150,000-TDW bulk carrier	Low speed	2.000	0.055	1.157
			4.000	0.156	1.159
			8.000	0.442	1.202
		Design speed	8.000	0.815	1.215
	314,000-TDW VLCC	Low speed	6.349	0.323	1.194
		Design speed	6.349	0.621	1.206
	317,000-TDW VLCC	Low speed	2.000	0.062	1.012
			4.000	0.177	1.113
			6.775	0.396	1.238
			10.000	0.704	1.238
		Design speed	10.000	1.439	1.224
Mid-sized high-speed container carrier		Low speed	2.000	0.070	1.000
			5.520	0.281	1.000
			8.000	0.485	1.007
			12.000	0.894	1.034
		Design speed	12.000	4.412	0.967

R_{NM} Reynolds number of model

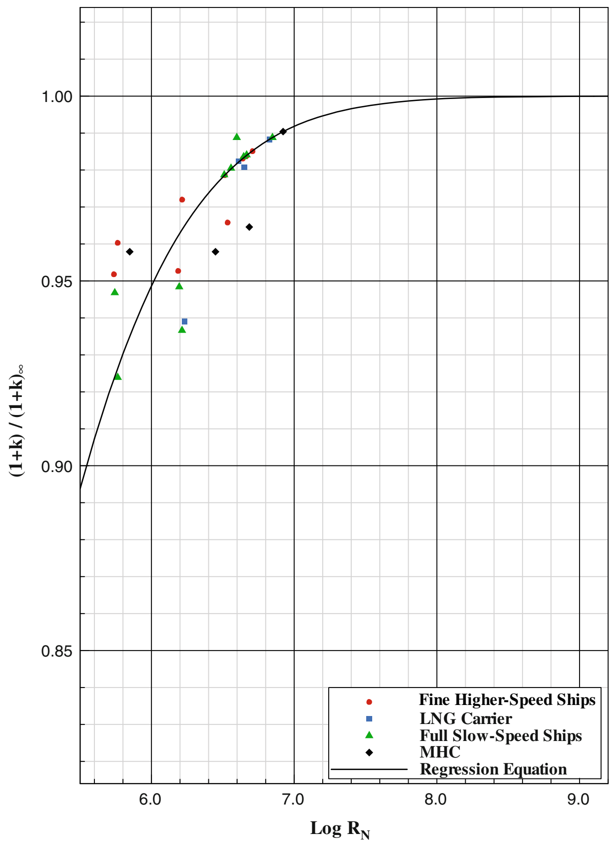

Fig. 7 Form factor correction factor curve. *MHC* mid-sized high-speed container carrier, R_N Reynolds number, k form factor

when the Reynolds number is greater that 10^9. Two different regression equations were prepared as follows:

$$\mathrm{FCF} = \tanh x, \quad x = \mathrm{a}(\mathrm{Log}\, R_\mathrm{N})^n \tag{14}$$

$$\mathrm{FCF} = \frac{a + b(\mathrm{Log}\, R_\mathrm{N})^n}{c + b(\mathrm{Log}\, R_\mathrm{N})^n} \tag{15}$$

The form factors for the 12 large-scale model ships were utilized as the basic reference points with the assumption that they were determined properly. From the viewpoint of accuracy and convenience of use, it was decided to select Eq. 14. The result of the regression analysis is as follows:

$$\mathrm{FCF} = \tanh x, \quad x = a(\mathrm{Log}\, R_\mathrm{N})^n$$
$$a = 0.015064 \quad n = 2.6752 \tag{16}$$

Figure 7 shows the FCF curve, i.e., the relative change of form factor with respect to Reynolds number. Table 6 shows the corrected form factors using the result of the regression analysis and the comparison with those determined from the results of low-speed resistance tests.

7 Suggestion for full-scale ship resistance extrapolation method

Form factors according to the ITTC '78 definition could be determined consistently. For almost all cases of such low-speed tests, however, the Reynolds number range is much lower than 10^7, and the flow around the model ship is not in the fully turbulent state. In this Reynolds number range, form factors are not constant, but vary with the Reynolds number. Therefore, the two basic assumptions made in the ITTC '78 definition do not agree with physical phenomena.

In this regard, the authors would like to suggest the following extrapolation procedure for the prediction of the full-scale ship resistance:

1. Conduct low-speed resistance tests using large-scale model ships (6–8 m in length) and determine the form factor by the ITTC '78 definition. Obtain form factors at the design speed, i.e., at the identical design Froude number for the model ship and for the full-scale ship using the regression Eq. 16. The form factor at the design speed for the full-scale ship becomes the terminal form factor, since the Reynolds number at the design speed for a full-scale ship is greater than 10^9 in general.
2. Conduct regular resistance tests and find the total resistance coefficients of the model ship at various corresponding ship speeds, including the design speed.
3. Calculate the Reynolds number at various model ship speeds corresponding to full-scale ship speeds and correct the form factors. Obtain the wave-resistance coefficient using the corrected form factors as follows:
$$C_\mathrm{W} = C_\mathrm{TM} - (1 + k)_\mathrm{M} \cdot C_\mathrm{FM} \tag{17}$$

The form factor of the model ship, i.e., $(1 + k)_\mathrm{M}$, varies with the ship speed until the Reynolds number reaches the region where the flow around the model ship becomes fully turbulent.

4. Using the form factor for the full-scale ship obtained in step (1) and the wave-resistance coefficient found in step (3), find the total resistance coefficient for the full-scale ship as follows:
$$C_\mathrm{TS} = (1 + k)_\mathrm{S} \cdot C_\mathrm{FS} + C_\mathrm{W} \tag{18}$$

Following the extrapolation procedure suggested by the authors, the total resistance coefficients for 12 full-scale object ships were analyzed and compared with those obtained by the existing method. Due to limited space, however, the results for the 8,600-TEU container carrier, the 155,000-m^3 LNG carrier, and the 317,000-TDW crude oil tanker (VLCC) only are summarized in Table 7 as examples.

Table 6 Comparison of measured and corrected form factors

Ship type	Kind of ship	2-m class model ship			4-m class model ship			6- to 8-m class model ship			10- to 12-m class model ship	Terminal form factor
		Measured	Corrected	Difference (%)	Measured	Corrected	Difference (%)	Measured	Corrected	Difference (%)		
Fine higher-speed ship	ITTC STD 1 (series 60, $C_B = 0.6$)	1.064	1.026	−3.57	1.077	1.068	−0.84	1.090	1.090	0.00	–	1.108
	4,410-TEU container carrier	1.067	1.035	−3.00	1.068	1.079	1.03	1.102	1.102	0.00	–	1.121
	5,600-TEU container carrier	–	–	–	–	–	–	1.095	1.095	0.00	–	1.119
	8,600-TEU container carrier	1.008	1.053	4.46	1.012	1.093	8.00	1.102	1.118	1.45	1.124	1.141
Gas carrier	137,300-m^3 LNG carrier	–	–	–	–	–	–	1.114	1.114	0.00	–	1.134
	155,000-m^3 LNG carrier	1.010	1.110	9.90	1.123	1.154	2.76	1.173	1.176	0.26	1.182	1.196
Full slow-speed ship	ITTC STD 2 (series 60, $C_B = 0.8$)	1.165	1.168	0.26	1.181	1.215	2.88	1.241	1.241	0.00	–	1.261
	76,000-TDW bulk carrier	–	–	–	–	–	–	1.204	1.204	0.00	–	1.228
	150,000-TDW bulk carrier	1.157	1.129	−2.42	1.159	1.176	1.47	1.202	1.202	0.00	–	1.222
	314,000-TDW VLCC	–	–	–	–	–	–	1.194	1.194	0.00	–	1.220
	317,000-TDW VLCC	1.012	1.164	15.02	1.113	1.209	8.63	1.238	1.229	−0.73	1.238	1.252
Mid-sized high-speed container carrier		1.000	1.000	0.00	1.000	1.019	1.90	1.007	1.028	2.09	1.034	1.044

Table 7 Examples of full-scale ship resistance prediction

Kind of ship	Extrapolation method	LPP_M (m)			
		2.0	4.0	8.0	10.0
8,600-TEU container carrier	Froude	1.501	1.776	1.795	1.839
	ITTC '78	1.478	1.751	1.636	1.669
	This study (min)	1.549	1.688	1.662	1.668
155,000-m^3 LNG carrier	Froude	1.674	2.110	2.109	2.080
	ITTC '78	1.646	1.859	1.850	1.842
	This study (min)	1.692	1.856	1.852	1.848
317,000-TDW VLCC	Froude	1.723	1.880	2.246	2.141
	ITTC '78	1.686	1.629	1.835	1.801
	This study (min)	1.687	1.836	1.842	1.807

In the case of actual constructions, the following relation is applied for the prediction of resistance performance of full-scale ships:

$$C_{TS} = (1 + k)_S \cdot C_{FS} + C_W + \Delta CF + C_{AA} \quad (19)$$

For almost all cases, the Reynolds number at the design speed of full-scale ships is greater than 10^9, and thus the corresponding form factor, i.e., $(1 + k)_S$, becomes the terminal form factor, which can be regarded as constant.

8 Conclusions

Systematic study of the form factor and the extrapolation method for the prediction of full-scale ship resistance performance was carried out. From the results of this study, the following conclusions could be derived:

- The form factor from the ITTC '78 definition could be determined consistently following the method suggested in this study.
- In general, it is very difficult to derive consistent results at the design speed. However, the possibility of obtaining practically useful values has been confirmed.
- The form factor increases with increasing Reynolds number when the flow around a ship hull is not fully turbulent. It is certain that there is a close relation between the form factor and the Reynolds number. In aeronautical science, it is well known that the form factor does not change, but remains constant if the flow around an airplane is fully turbulent, i.e., the Reynolds number is greater than 10^9. The form factor in this state is called the terminal form factor.
- The form resistance is also related to the hull wave generated by a moving ship hull as well as to the viscosity. In other words, the form factor is affected by the Froude number as well as by the Reynolds number. This phenomenon becomes more significant as the ship speed increases. However, the simultaneous influences from both the Reynolds number and the Froude number are not currently understood. This is the present state of the art in ship hydrodynamics.
- The ITTC '78 definition and assumptions regarding the form factor do not agree with physical phenomena. Nevertheless, this method has long been used because no better method is available.
- With the assumption that the form factor becomes constant when the flow around a ship hull is fully turbulent, neglecting the influence of the hull wave, the authors have suggested a new extrapolation procedure for the prediction of the full-scale ship resistance performance together with the FCF according to the Reynolds number. Investigation into the validity of the authors' suggested method is being carried out.

It is considered that basic studies on the physical insight of flow characteristics around a ship hull and ship resistance should be performed to prepare a more rational method of full-scale ship resistance prediction including the simultaneous influence of viscosity and the hull wave. It is the authors' desire that many current hypotheses and assumptions in ship hydrodynamics be clarified by successful performance of such basic studies.

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