The Resistance Committee

Committee Chairman: Dr.Emilio F.Campana
Session Chairman: Dr.In-Young Koh

1. DISCUSSIONS

1.1 Discussion to the 25th ITTC Resistance Committee by Tao Xing and Fred Stern, IIHR – Hydroscience & Engineering

The purpose of this discussion is to bring to the attention of the 25th ITTC Resistance Committee (1) the Symposium on Computational Uncertainty NATO-AVT-147 held in Athens, Greece on 3-7 December 2007 and in particular the paper by Stern (2007); (2) the improved factor of safety (FS) for Richardson Extrapolation for industrial applications by Xing and Stern (2008); and (3) the investigation of approaching the asymptotic range (AR) for practical applications in ship hydrodynamics by Xing et al. (2008).

1. Stern (2007) provides concepts, definitions, equations and procedures for quantitative assessment of numerical (verification) and modelling (validation) errors and uncertainties for CFD simulations and of intervals of certification for CFD codes at 95% level of confidence. Examples are provided for ship hydrodynamics, including certification of CFD codes for CFD Workshop Tokyo 2005. Comparisons are made with alternative approaches.

2. The correction factor (CF) method has variable FS with distance to the AR, which is a "common-sense" advantage compared with the grid convergence index (GCI) as it provides a quantitative metric to determine proximity of the solutions to the AR and approximately accounts for the effects of higher-order terms. One deficiency for both methods is that the estimates of grid/time-step uncertainties Uk are too conservative when the estimated order of accuracy is larger than the theoretical order of accuracy ($p_k > p_{k_{th}}$), which has been observed in previous verification studies. For the CF method, this deficiency is due to the assumption that the FS which is based on analytical benchmarks that approach the AR with $p_k < p_{k_{th}}$ can be reflected for $p_k > p_{k_{th}}$. An improved approach is to reflect the uncertainty itself with respect to the distance from the AR (Xing and Stern, 2008):

$$U_k = \begin{cases} \left[2(1-C_k)+1\right] \left|\delta^*_{RE_{k_1}}\right| & 0 < C_k \le 0.875 \\ \left[-25.6(1-C_k)^3 + 12.8(1-C_k)^2 + 1.1\right]\left|\delta^*_{RE_{k_1}}\right| & 0.875 < C_k \le 1.0 \\ \left[-135.8(C_k-1)^3 + 49.4(C_k-1)^2 + 1.1\right]\left|\delta^*_{RE_{k_1}}\right| & 1.0 < C_k < 1.125 \\ \left\{\frac{C_k}{2-C_k}\left[2\left(C_k-1\right)+1\right]\right\}\left|\delta^*_{RE_{k_1}}\right| & 1.125 \le C_k < 2 \end{cases} \quad (1)$$

The improved CF method is only applicable for $0 < Ck < 2$. $Ck = 0$ is the border of convergence and divergence such that grid errors/uncertainties are infinite due to infinite $\delta^*_{RE_{k1}}$ as a result of $pk = 0$, i.e., solution changes for the medium and fine grids are equal to those for the coarse and medium grids. For $Ck > 2$, solutions are too far from the AR and also regarded as divergent. Figure 1 compares the original CF (Wilson et al. 2004), improved CF, and GCI methods. The improved CF is shown to provide more reasonable intervals of uncertainty estimates for

$p_k > p_{k_{th}}$ and $1<Ck < 2$.

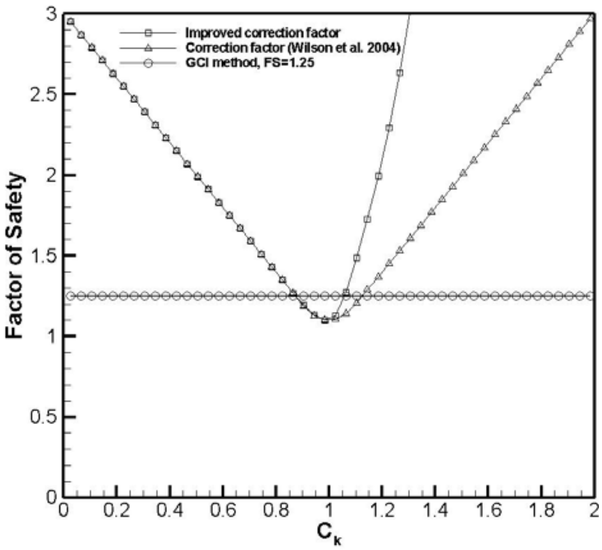

Figure 1. Factors of safety for correction factor and GCI verification methods.

3. Achieving the AR for practical applications, at least for ships, has not yet been demonstrated. Xing et al. (2008) investigated the issue of achieving the AR by continuously refining the grid from the coarsest grid (grid 7 with 360,528 points) to the finest grid (grid 1 with 8.1 million points) for the Athena bare hull with skeg with 2 degrees of freedom (pitch and heave) at Froude number (Fr) 0.48. The grids are designed with a systematic grid refinement ratio $r_G = 2^{1/4}$, which allows 9 sets of grids for verification and validation (V&V) with 5 sets with $r_G = 2^{1/4}$ (5,6,7; 4,5,6; 3,4,5; 2,3,4; ad 1,2,3), 3 sets with $rG = 2^{1/2}$ (3,5,7; 2,4,6; and 1,3,5), and 1 set with $r_G = 2^{3/4}$ (1,4,7).

The distribution of iterative errors $0.1\%S_{fine} \le U_I \le 0.3\%S_{fine}$ for grids 1 to 7 is shown in Figure 2(b) for resistance coefficients. U_I is of the same order of magnitude for all the grids, which suggests that it is mainly determined by the iterative method applied and independent of grid resolutions. As shown in Table 1, C_{TX} monotonically converges for grids (2,4,6), (1,3,5), (4,5,6), (3,4,5), (2,3,4), and (1,2,3), of which grids (1,2,3) have the smallest grid uncertainty and grids (3,4,5) are closest to the asymptotic range based on C_G closest to one. C_{TX} oscillatory diverges on grids (5,6,7), and monotonically diverges on grids (3,5,7) and (1,4,7). All the diverged solutions involve the coarsest grid 7, which is likely due to the insufficient resolution of the coarsest grid 7.

As shown in Figure 2(a), C_{TX} for grid 7 does not follow the trend as shown for grids 6-1. Figure 2(a) also shows frictional and pressure resistance coefficients C_{fX} and C_{PX} on all the grids. Figure 2(b) shows the magnitudes of the relative changes of solutions ε_N between two successive grids with respect to the solutions on the finest grid 1. When grids are refined from 5 to 1, ε_N systematically decreases for C_{TX} and C_{fX} while oscillatory decreases for C_{PX}. U_G for grids (4,5,6) is unreasonable large as it is too far away from the asymptotic range. U_G for grids (1,2,3) using the original CF is unreasonable small due to the deficiency discussed above. Excluding these two numbers, the average U_G are 2.53%, 4.39%, and 6.11% for the GCI, original CF, and new CF methods, respectively. Figure 2(b) shows that separating iterative errors from grid uncertainties is problematic for the finer grids since iterative and grid uncertainties are of the same order of magnitude. Implementation of more accurate and efficient iterative methods to speed up the convergence (e.g., multi grid) will be necessary.

However, ε_N of the current study does show systematic decreasing for C_{TX} and C_{fX} and oscillatory decreasing for C_{PX}. C_{TX}, C_{fX}, and C_{PX} show different rates of approaching the asymptotic range and CG shows a large range of values, which suggests that the finest grid is still out of the asymptotic range. Further refinement with y+ of the first grid point away from the wall less than 1 may help but requires a minimum of 38 million grid points. This number will be doubled if a whole domain simulation is conducted. Solutions on such fine grids are not trivial and raise issues of code efficiency and available computer resources. Validation is also shown in Table 1. The average E between the fine grid solution and the EFD data is about 2% and is insensitive to the grid refinement.

Since grid study (4,5,6) is too far away from the AR and U_I contaminates U_G for grid study (1,2,3), they are discarded for validation, which results in the average UV = 6.42% using the new CF method. It should be noted that although further reduction of U_I and further grid refinement are required to achieve the AR it does not reduce the interval of validation since U_G<<U_D.

References

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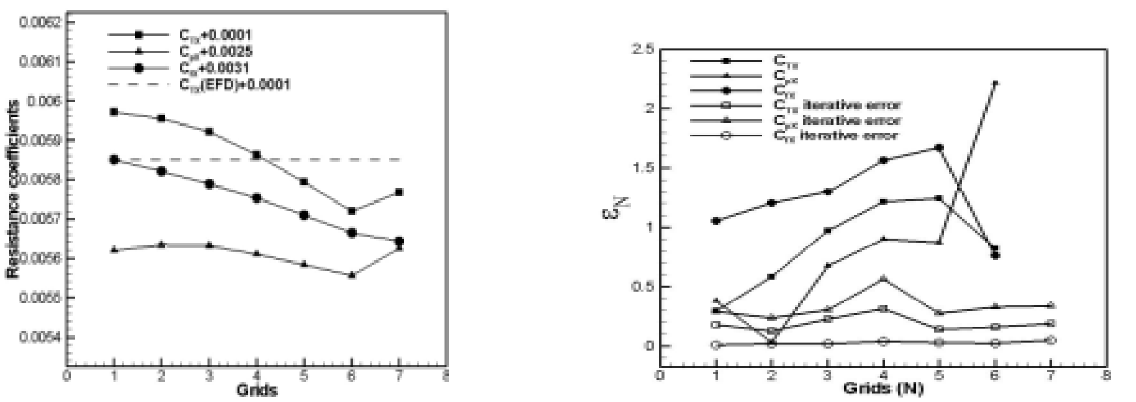

(a) (b)

Figure 2. Verification for resistance coefficients and motions for Athena bare hull with skeg (Fr=0.48):
(a) resistance coefficients,
(b) relative change N=|(SN-SN+1)/S1|×100 and iterative errors for resistance coefficients.

Table 1 Verification and validation study for integral resistance coefficient C_{TX} of Athena bare hull with skeg (*Fr*=0.48). U_G is %S_{fine}. Others are %EFD (C_{TX}=0.00575); C_{TX} is based on static wetted area; Factor of safety for GCI is 1.25

Grids	Refinement ratio	R_G	P_G	C_G	U_G (%)			E (%)	U_V (%)	U_D (%)
					Original CF	New CF	GCI		New CF	
2, 4, 6	$2^{0.5}$	0.63	1.32	0.58	4.90	4.90	3.34	1.83	5.21	1.5
1, 3, 5	$2^{0.5}$	0.40	2.66	1.51	1.16	3.59	0.72	2.10	3.96	1.5
4, 5, 6	$2^{0.25}$	0.97	0.16	0.07	125.2	125.2	52.7	0.24	125.5	1.5
3, 4, 5	$2^{0.25}$	0.80	1.27	0.59	7.23	7.23	4.98	1.23	7.47	1.5
2, 3, 4	$2^{0.25}$	0.60	2.98	1.64	4.27	8.73	1.07	1.83	9.02	1.5
1, 2, 3	$2^{0.25}$	0.50	4.00	2.42	1.11	—	0.58	2.10	—	1.5

1.2 Discussion to the 25th ITTC Resistance Committee by Keh-Sik Min,Hyundai Heavy Industries Co., Ltd. Korea

Study on the Form Factor and Full Scale Ship Resistance Prediction Method

In order to consider the resistance component due to hull geometry, ITTC adopted the resistance test method in 1978 introducing the form factor concept with two basic assumptions. However, it is not only very difficult to measure the form factor by the ITTC '78 method, but also there has been a skepticism on the basic assumptions. Therefore, the author have made three basic studies on the form factor concept and ultimately tried to prepare a improved resistance prediction method.

Introduction. Since ships are generally large-scale high-valued 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 the model ship should be made as similar as possible, that is, the dynamic similitude should be arranged. In the case of resistance test particularly, the complete satisfaction of such dynamic

similitude requires that two kinds of nondimensionalized quantities, that is, the Froude Number(F_N) and the Reynolds Number(R_N) should be made the same for a full scale ship and the model ship.

As-well-known, however, the simultaneous scaling of both Froude and Reynolds Numbers between two geosims is practically impossible. Therefore, the early naval architects had become to realize the necessity to idealize or simplify the system to overcome such a conflict in dynamic similitude and to make experimental methods applicable. From the view point of such practical necessity, William Froude introducted the so-called "Froude Assumption" in 1867 separating the total resistance into components of frictional resistance and residual resistance, and proposed the resistance test to be conducted based on the identical Froude Number with the correction for the different Reynolds Number effect.

Basically the same traditional method has been applied till nowadays. In order to improve the traditional method, however, 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.

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

As shown in equation (1), ITTC has adopted the method of separating viscous resistance and wave resistance using form factor as the standard extrapolation method. Therefore, determination of 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:

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

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

In spite of the standard method adopted by ITTC performance committee, however, the results of performance predictions for full scale ships by model tests sometimes vary considerably from basin to basin. Such a phenomenon of different results may be considered to come from two main reasons. The first one is the measurement of form factors. It is very difficult to measure resistance at low speeds, and hence, difficult to determine the form factor accurately according to definition. The next reason is whether or not the basic assumptions are correct.

Therefore, the author has made following three basic studies:

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

This study had been carried out for the duration of 15 years from 1992 to 2006. Table 2 shows the selected ships in chronological

Table 2 Selected Ships in Chronological Order

Stage of Selection	Time	Ship Type	LPP_M(m)
1ST	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
2ND	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
3RD	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-Size High-Speed C/C	2.0 / 5.52 / 8.0 / 12.0

order for this study, and Table 3 shows the period of model tests.

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

Table 3 Period of Model Tests

Test No	Year	No. of Ships	Model Size
1	1992	The 1ST Stage 4 Ships	2 m, 4 m, 8 m
2	1998	The 1ST Stage 4 Ships	2 m, 4 m, 8 m
3	2001	The 1ST Stage 4 Ships	2 m, 4 m, 8 m
4	2003	The 1ST and the 2ND Stage8 Ships	8 m
5	2006	The 3RD Stage 4 Ships	2 m, 4 m, 8 m,10 m

Suggestion of Form Factor Determination Method by ITTC Definition.

1. Synopsis

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

$$C_{TM} = (1+k)\cdot C_{FM} + C_w \qquad (3)$$

The most accurate method to determine form factor shall be to utilize equation (3) if simultaneous measurements of total resistance and wave resistance are possible. Due to difficulty and inaccuracy of measuring wave resistance, however, this method has no practical meaning. It is also impossible to measure form factor directly according to the definition expressed by the equation (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 author has made an effort to prepare a method of determining form factor consistently in accordance with ITTC definition. The author's method shall be briefly discussed.

2. Direct Method

First of all, data sets, that is, sets of very low Froude number versus C_T/C_F value should be prepared from a series of low-speed resistance tests. Here, the following symbols may be used for the sake of convenience:

$$x = F_N\ , \qquad y = C_T / C_F \qquad (4)$$

The data sets are to be curve-fitted to the following polynomial equations by the least-square method.

- 2nd order : $y = ax^2 + bx + c$ (5)
- 3rd order : $y = ax^3 + bx^2 + cx + d$ (6)

By the definition, form factor could be expressed by,

$$1+k = \lim_{F_N \to 0} \frac{C_T}{C_F} = \lim_{x \to 0} y \qquad (7)$$

Obviously, form factor becomes the constant term, that is, c or d in equations (5) and (6).

3. Indirect Method

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

$$C_{TM} = (1+k)\cdot C_{FM} + a \cdot F_N^n \qquad (8)$$

In equation (8), a is some constant related to wave resistance coefficient.

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

$$x = F_N^n / C_F\ , \qquad y = C_T / C_F \qquad (9)$$

The data sets are to be curve-fitted to the 2nd order or the 3rd order polynomial equations by the least-square method as before. Then, form factor becomes the constant term by the definition.

Suggestion for the Form Factor Determination at Design Speed.

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 the measured value. Therefore, the author has tried to prepare a method to be able to determine form factor at any speeds.

The following expression regarding wave resistance coefficient has been introduced with the assumption that form factor remains almost constant within very small speed intervals in the vicinity of the design speed.

$$C_F \cdot (1+k) + C_W = C_T$$

$$C_w = aF_N^n \ , \quad n = 4 \sim 6 \tag{10}$$

Using large-scale model ships, resistances were measured at several different speeds with very small interval in the vicinity of design speed. The form factor and the wave resistance coefficient were calculated by solving simultaneous equations formed at two neighbouring speeds.

Relation between Form Factor and Reynolds number.

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

In order to investigate the relation between form factor and Reynolds number, form factors should be measured with the variation of Reynolds number. In case of resistance tests with a model ship of fixed scale ratio, towing speeds, and hence, Froude number should be increased to increase Reynolds number. In this case, determination of form factor by ITTC definition is impossible.

In model tests, however, there is a way of varying Reynolds number at the same Froude number by varying scale ratio between full-scale ship and model ship. When scale ratio is denoted by λ, the change of Reynolds number due to change of scale ratio at the same Froude number becomes to be proportional to $\lambda^{1.5}$.

In order to investigate the relation between form factor and Reynolds number, therefore, the method of varying Reynolds number by the variation of the scale ratio has been adopted in this study. This is the very reason why several different model ships in size were constructed for the same kind of ship.

Model Tests.

For this study, 12 different ships were selected as shown in Table 2. Model tests had been carried out for the duration of 15 years from 1992 to 2006 as shown in Table 3. In order to systematically analyze test results, 12 selected ships have been classified into four groups such as fine higher-speed ship group, gas carrier group, full slow-speed ship group and special ship group as shown in Table 3.

Considering that this study was to be performed for an extended period, all the model ships had been strongly constructed with woods.

Table 4 Main characteristics of the object ships

Ship Type	Kind of Ship	Full-Scale Ship							Model Ship Length (m)
		LPP (m)	B (m)	T (m)	CB	VS (kts)	FN	RN×10-9	
Fine Higher-Speed Ship	ITTC STD 1 (Series 60, CB=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 Carrier	137,300 m3 LNG/C	274.0	48.0	11.25	0.671	19.7	0.196	2.316	7.647
	155,000 m3 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 Ship	ITTC STD 2 (Series 60, CB=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-Size High-Speed Container Carrier		276.0	27.6	9.0	0.475	35.0	0.346	4.182	2.0/ 5.52/ 8.0/ 12.0

Furthermore, deformation of model ships were always measured before tests, and corrected if the degree of deformation was beyond tolerance.

Low-speed resistance tests for the determination of form factor by ITTC definition were conducted for all 32 model ships, and resistance tests at the vicinity of design speed were conducted for 12 large-scale model ships. All the basic and required tests were conducted at the deep-water towing tank of Maritime Research Institute, Hyundai Heavy Industries. For conformation, some limited tests were also conducted at HSVA and SSPA.

Figures 3 shows four different model ships in size of 155,000 m^3 LNG carrier.

Figure.3 Models of 155,000 m^3 LNG carrier.

Test Results and Analyses.

1. Low-Speed Resistance Tests and Determination of Form Factors

As mentioned, low-speed resistance tests for the determination of form factors were carried out repeatedly for all 32 model ships, and vast amount of test results were prepared. Figure 4 shows the typical test results for 155,000 m^3 LNG carrier.

With the low-speed resistance test results, form factors were determined following the method discussed in section 2. Table 5 shows the typical result of analysis for the LNG carrier.

In the analysis of test results, both of methods, that is, direct method and indirect method produce generally acceptable good results. However, more consistent results could be derived from the indirect method. Particularly, indirectly method has advantages that the derived results do not much depend on either exponent n or form of polynomial.

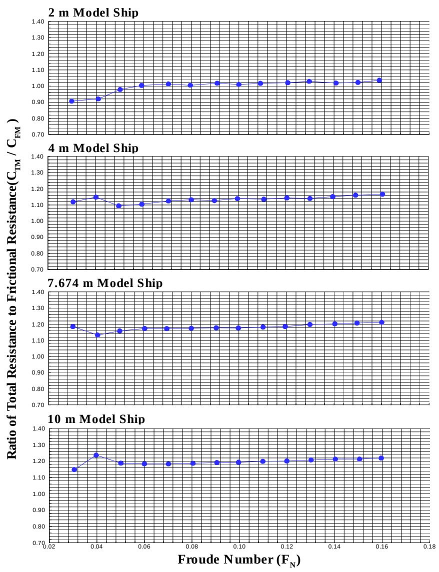

Figure. 4 Low-speed resistance test result of 155,000 m^3 LNG carrier

Table 5 Example of form factors determination from low-speed resistance test for 155,000 m^3 LNG Carrier

Size of Model Ships (m)	Order of Polynomial	n = 4	n = 5	n = 6
2.0	2nd	1.00977	1.00978	1.00996
	3rd	1.00954	1.00963	1.00979
4.0	2nd	1.12269	1.12490	1.12636
	3rd	1.12262	1.12435	1.12565
7.674	2nd	1.17261	1.17284	1.17319
	3rd	1.16995	1.17122	1.17199
10.0	2nd	1.18156	1.18355	1.18495
	3rd	1.17825	1.18076	1.18245

2. Resistance Tests in the vicinity of Design Speed and Prediction of Form Factors

In order to predict the form factor at the design speed, resistance tests in the vicinity of design speed were carried out for 12 large-scale model ships. Figure 5 shows the typical test result for 317,000 TDW crude oil carrier(VLCC).

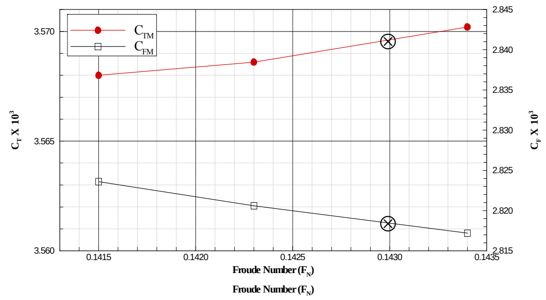

Figure. 5 Resistance test result in the vicinity of the design speed for 317,000 TDW VLCC

With the test results in the vicinity of design speed, form factors have been calculated following the method discussed in section 3. All the form factors determined from the low-speed resistance tests and the tests in the vicinity of the design speed have been summarized in Table 6. Table 6 may be regarded as the overall summary of all the test results.

It was in general very difficult to derive meaningful form factors consistently at the design speed due to scattering of measured resistance at very close vicinity of the design speed. As shown in Table 6, however, the potentiality of obtaining practically useful value has been confirmed.

In the case of deriving form factors at the design speed, it should be recognized that there is an additional hydrodynamic problem. Different from the low-speed range, hull wave shall be generated in the design speed range, and affect the form resistance. In other words, not only Reynolds number, but also Froude number will affect the form resistance simultaneously.
However, there is no possible way to estimate the interrelation of form factor, Reynolds number and Froude Number. This is the present state-of-art of technology in ship hydrodynamics.

Table 6 Examples of Selected form factor

Ship Type	Kind of Ship	Type of Test	Size of Model Ships (m)	RNM×10-7	Form Factor
Fine Higher-Speed Ship	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	155,000 m3 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	317,000 TDW Crude Oil Tanker	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

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 number have been well arranged in Table 6. As shown in Table 6, form factor is increased with increased model ship length, that is, with increased Reynolds number. The trend of increase in form factor is considered to be rather consistent. From the result of this study, it could be realized that form factor of the full-scale ship is different from that of the model ship. Therefore, the ITTC '78 assumption should be corrected.

When the influence from hull wave is neglected, however, the form factor will reach constant at the Reynolds number where flow characteristics around a ship hull becomes fully turbulent. With the assumption that this Reynolds number region is 10^9, the author tried to find out the ratio of change of form factor according to the change of Reynolds number. In order to do that, it was decided to perform regression analysis for the form factors determined from the results of low-speed resistance tests. For the sake of convenience, the form factor whose corresponding Reynolds number is greater than 10^9, that is, the ultimate form factor practically reached to constant value shall be termed as "Terminal Form Factor."

The regression analysis has been performed in the form of the relative value, that is, the ratio of form factor with respect to the terminal form factor. Two different regression equations have been prepared as follows:

$$FCF = \tanh x, \quad x = a(\mathrm{Log}\, RN)n \qquad (11)$$

$$FCF = \frac{a + b(\mathrm{Log}\ R_N)^n}{c + b(\mathrm{Log}\ R_N)^n} \qquad (12)$$

The form factors for 12 large-scale model ships were utilized as the basic reference points with the assumption that they were determined properly.

From the view points of accuracy and convenience in use, it has been decided to select the equation (11). The result of the regression analysis is as follows:

$$FCF = \tanh x, \quad x = a\,(\mathrm{Log}\, RN)n$$
$$a = 0.015064 \qquad (13)$$
$$n = 2.6752$$

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

Table 7 Comparison of measured and corrected form factors

Ship Type	Kind of Ship	2 m Class Model Ship			4 m Class Model Ship			6 - 8 m Class Model Ship			10 - 12 m Class Model Ship	Terminal Form Factor
		Mea-sured	Corrected	% Differ-ence	Mea-sured	Corrected	% Differ-ence	Mea-sured	Corrected	% Differ-ence		
Fine Higher-Speed Ship	ITTC STD 1 (Series 60, CB = 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 m3 LNG Carrier	-	-	-	-	-	-	1.114	1.114	0.00	-	1.134
	155,000 m3 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, CB = 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 Crude Oil Tanker	-	-	-	-	-	-	1.194	1.194	0.00	-	1.220
	317,000 TDW Crude Oil Tanker	1.012	1.164	15.02	1.113	1.209	8.63	1.238	1.229	-0.73	1.238	1.252
Mid-Size 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

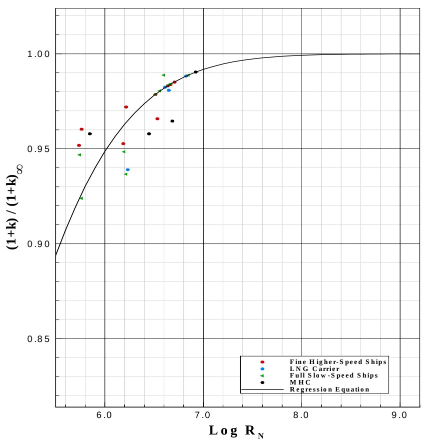

Figure. 6 Form factor correction factor curve

Suggestion for Full-Scale Ship Resistance Extrapolation Method. Form factors according to ITTCU'78 definition could be determined consistently if,

- low-speed resistance tests are conducted carefully with a suitable dynamometer,
- test data are properly selected
- and data sets are analyzed by the indirect method suggested by the author.

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

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

1) Conduct low-speed resistance test using large-scale model ships (6 ~ 8 m) and determine the form factor by ITTC '78 definition. Obtain form factors at the design speeds, that is, at the identical design Froude number for the model ship and for the full-scale ship using the regression equation (13).

2) Conduct regular resistance test and find total resistance coefficients of the

model ship at the various corresponding ship speeds including the design speed.

3) Calculate Reynolds number at the various model ship speed corresponding to full-scale ship speed and correct the form factors. Obtain Wave-resistance coefficient using the corrected form factors as follows :

$$C_W = C_{TM} - (1 + k)_M \quad C_{FM} \qquad (14)$$

The form factor of the model ship, that is, $(1+k)_M$ varies with varying ship speed till Reynolds number reaches the region where the state of flow around the model ship becomes fully turbulent.

4) Using the form factor for full-scale ship obtained in step 1) and wave-resistance coefficient found in

step 3), find total resistance coefficient for full-scale ship as follows :

$$C_{TS} = (1 + k)_S \quad C_{FS} + C_W \qquad (15)$$

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

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

$$CTS = (1 + k)S \quad CFS + CW + \Delta CF + CAA \qquad (16)$$

In equation (16), ΔC_F and C_{AA} have been described in equation (1). For almost all cases, Reynolds number at the design speed of full-scale ships is greater than 10^9, and hence, the corresponding form factor, that is, $(1 + k)_S$ becomes the terminal form factor that could be regarded as constant.

Table 8 Examples of full-scale ship resistance prediction

Kind of Ship	Extrapolation Method	LPPM (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
	Min	1.549	1.688	1.662	1.668
155,000 m3 LNG Carrier	Froude	1.674	2.110	2.109	2.080
	ITTC '78	1.646	1.859	1.850	1.842
	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
	Min	1.687	1.836	1.842	1.807

Conclusions.

Systematic study on the form factor and the extrapolation method for the prediction of full-scale ship resistance performance has been performed. Since it is not easy to measure low-speed resistance or to measure resistance at the vicinity of the design speed, tests had been repeated several times to obtain reasonably satisfiable measurements. Various meaningful results have been derived from this study. Among them, the following important conclusions shall he stated:

- ITTC '78 definition and assumptions regarding form factor do not agree with physical phenomena. Nevertheless, this method has been being used, because no better method of determining form factor at the design speed is available. Therefore, study should be performed to prepare improved prediction method than ITTC '78 method.

- Form resistance is also related to hull wave generated by moving ship hull as well as viscosity. In other words, form factor is affected by Froude number as well as by Reynolds number. This phenomenon becomes more noticeable as speed increases. However, it is extremely difficult to quantitatively predict the effect of Reynolds number. Furthermore, simultaneous influence from both of Reynolds number and Froude number is not known at all. This is the present state-of-art of technology in ship hydrodynamics.

- With the assumption that form factor becomes constant when the state of flow around a ship hull is fully turbulent neglecting the influence from hull wave, the author has suggested new extrapolation procedure for the prediction of full-scale ship resistance performance together with form factor correction factor according to Reynolds number. The investigation on the validity of the author's suggested method has been being carried out presently.

  It is recommended to perform basic researches on the physical insight into flow characteristics around a ship hull to eliminate nowadays many assumptions and questions in ship hydrodynamics.

1.3 Discussion to the 25th ITTC Resistance Committee by Ahmed Derradji, NRC-IOT, Canada

Worldwide facility bias in Resistance Committee report. The RC used Eq.7.1 to estimate mean values, and also through Eq.7.2 the uncertainty in the mean value is given by combination of precision and bias uncertainties using SSR(Sum Square Roots).

However, several international organizations such NIST recommend Youden testing as the method for estimating facilities bias. Youden testing was published in the 1960 and survived the test of time over the years also UAC recommends that. My question is: Is the R/C aware of Youden test? If yes, why not Youden testing?

1.4 Discussion to the 25th ITTC Resistance Committee by A.F. MOLLAND, University of Southampton, UK

It is noted that this is the first time that airflow around ship superstructures has been dealt with in a formal manner by ITTC, and a very useful review of the subject area has been carried out. The two main aspects of concern are considered, that is the prediction of the flow regime and the prediction of aerodynamic forces. As the conclusions recommended more work on new ship concepts, such as multi hull ships, attention is drawn to the existing results of tests by Molland and Barbeau (2003) on the air drag on the superstructures of fast commercial catamarans.

References.

Molland, A.F. and Barbeau, T-E., 2003, 'An investigation into the aerodynamic drag on the superstructures of fast catamarans'.

Transactions of the Royal Institution of Naval Architects, Vol.145.

1.5 Discussion to the 25th ITTC Resistance Committee by Naoji Toki, Mitsubishi Heavy Industries, Ltd., Japan

Purpose of Facility Bias World wide Campaign. Although I think this kind of cooperative work is very important, I am afraid the Purpose of the Campaign is not explained in the committee report, clearly enough. I can understand the purpose, if the committee focused on uncertainty of the test results. But, I hope the basic question on facility bias concerning the average values of the results has already been resolved.

As an example, I like to explain the Goesim model test results in 1950s, analysed by two-dimensional analysis using ITTC 1957 Line. Geosim test results of "Victory" ship were presented by van Lammeren et.al. in TINA (1955). The analysed results of CR values are shown in Fig.7 with a mean line. Another Geosim test results of "Victory" ship were presented by Hughes in TINA (1956) and the results of CR values obtained by a simple analysis are shown in Fig.8. Although Fig.8 show much bigger scatter than Fig.7, it is mainly caused by the fact that the models were tested in smaller tank than that of NSMB. So, after a correction of blockage effect, the analysed results turned to be as shown in Fig.9, which is much better than Fig.8 and similar to Fig.7.

The mean lines of Fig.7 and Fig.9 are compared in Fig.10 and there can be observed only slight difference between the two. We have another example of 10th ITTC standard model tests, where the results from three Japanese tanks (Nagasaki, Mejiro and Meguro) were compared each other and reasonable coincidence was obtained.

Reflecting the information, I hoped that the basic question on facility bias was resolved during this period.

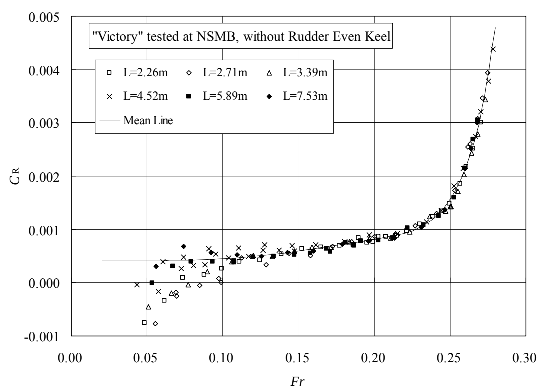

Figure.7 Analysed results of “Victory” Geosim test results presented by van Lammeren et.al.

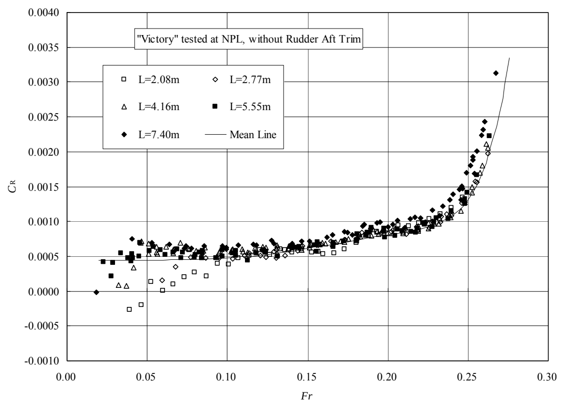

Figure.8 Simply analysed results of “Victory” Geosim test results presented by Hughes

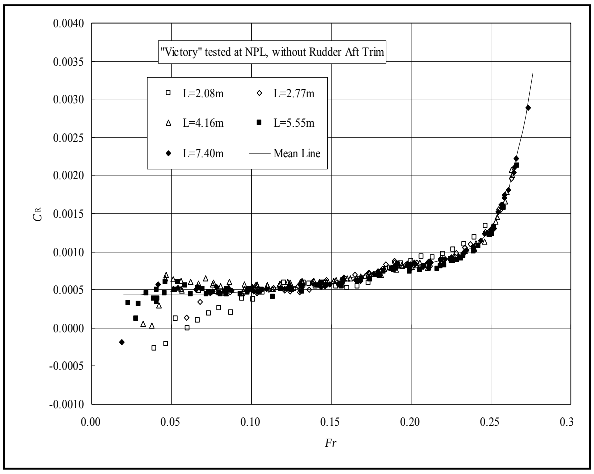

Figure.9 Analysed results of “Victory” Geosim test results presented by Hughes (after blockage correction)

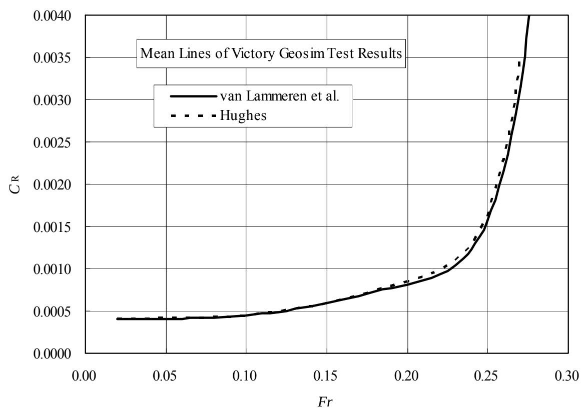

Figure.10 Comparison of mean lines derived from the two “Victory” Geosim test results

1.6 Discussion to the 25th ITTC Resistance Committee by Sverre Steen, Norwegian University of Science and Technology, Norway

The resistance committee has performed an analytical study of different friction lines.

The committee pointed out the importance of the friction line for the powering performance prediction.

However, as I presume you know, the boundary layer flow for full-scale ships is so-called fully rough flow. For fully rough flow the value of CF is no longer a function of Re but instead only a function of the roughness of the ship surface. Thus, I think that discussing the fine details of the friction line without considering roughness allowance will not lead to improved powering performance predictions. What is the opinion of the resistance committee on this issue?

2. COMMITTEE REPLIES

2.1 Reply of the 25th ITTC Resistance Committee to Tao Xing and Fred Stern

The Resistance Committee thanks Professors Xing and Stern for their contribution supplementing the report with the very latest developments in the field of verification and validation (V&V).

1. The work by Stern (2007) provides procedures for quantitative assessment of verification and validation errors related to uncertainties in CFD simulations. Furthermore, the paper provides considerations about the intervals of certification for CFD codes at 95% level of confidence.

2. Discussing the improvements in the correction factor (CF) approach for quantitative estimation of uncertainties, is particularly valuable for the development of the ITTC recommended Procedure 7.5-03-01-01.

   The CF method has a variable factor of safety which depends on the distance to the asymptotic range. The paper by Xing and Stern (2008) provides an improved approach when the estimated order of accuracy is larger than the theoretical order of accuracy, a problem observed in previous verification studies.

3. Regarding the last point raised by the discussers, they should be thanked for presenting a comprehensive example of an attempt to reach the asymptotic range for a practical ship application by continuously refining the grid from the coarsest level (with 360,528 points) to the finest level (with 8.1 million points) and for discussing the issues related to this.

2.2 Reply of the 25th ITTC Resistance Committee to Keh-Sik Min

The Resistance Committee thanks Dr. Min for his contribution supplementing the RC report with an interesting paper in the fundamental field of the form factor and ship resistance prediction method. The paper presents an experimental study aimed at improving the resistance prediction. While the RC strongly encourage this type of experimental studies, it is believed that the role of the CFD in improving significantly the ship resistance predictions will be soon recognized.

2.3 Reply of the 25th ITTC Resistance Committee to Ahmed Derradji

The Resistance Committee would like to thank Dr. Derradji for the interest in the report and for the question. The RC is perfectly aware of the Youden testing and totally agrees with the discusser about the fact that this procedure has survived the test of time and that it is very well known.

The reason for not using this procedure is quite simple though. The worldwide campaign is carried out in the interest of the ITTC members, and should follow, as much as possible, the standard procedures and rules that this community is currently adopting, including (*a fortiori*, we might add) the procedure already formally adopted for the uncertainty estimation in testing.

Finally, that RC wants to stress that the data from the worldwide test campaign will be available to the ITTC members and that these data can be analyzed with the Youden test as well.

2.4 Reply of the 25th ITTC Resistance Committee to A.F. MOLLAND

The Resistance Committee thanks Professor Molland for his contribution supplementing the RC report with an excellent paper in the field of the aerodynamic drag on the superstructures of fast catamarans. The paper presents an experimental and numerical study on a family of superstructure shapes. For each superstructure shape, drag coefficients are presented which should be useful for powering predictions.

2.5 Reply of the 25th ITTC Resistance Committee to Naoji Toki

The Resistance Committee thanks Dr. Toki for his question. The RC however do not agree with the statement made by Dr. Toki, that "the basic question on facility bias concerning the average values of the results has already been resolved".

Quite on the contrary, the RC believes that the detailed example provided by Dr. Toki represents a good example of the average facility bias. Indeed, in fig 4 of his discussion, Dr. Toki reports the comparison of the mean residual coefficients derived from two series of test made on two different towing tanks on the model "Victory". The curves show a nice similar behavior, from which the discusser argue that the facility bias is negligible.

The RC would like to highlight that, although the two curves show a similar behavior, they appear to be slightly shifted in the range above Fr=0.20. This shift produces an increasing relative error (it appear appears to be already of the order of 5% for Fr=0.20) when the two curves start to grow rapidly above Fr=0.23. The RC would like to stress that this shift between two towing tank results is exactly an indication of the facility bias. The relative error for higher Froude numbers appears to be up to 10 %.

The RC believes that the worldwide test campaign of great importance for the ITTC community because will not only give information about the average bias but, even more important, will assess the *Facility Bias Uncertainty.*

2.6 Reply of the 25th ITTC Resistance Committee to Sverre Steen

The Resistance Committee thanks Prof. Steen for his question. As he pointed out, inclusion of roughness effect is particularly important for prediction of ship-scale frictional resistance. Regarding this point, we believe that theoretical consideration of the effects based on boundary layer theory for smooth wall is still of great importance in practical design, and in practice, that is widely used in design along with consideration of roughness corrections (e.g., delta CF for part of paint toughness). However, we think the corrections must be more theoretical, and indeed, such studies have been recently getting more attentions not only in ship hydrodynamics but also in the aerodynamics field. Hopefully, RC task in next term will definitely cover those studies.