Investigation on Correlation Lines through the Analyses of Geosim Model Test Results

by Naoji Toki*, *Member*

Summary

The present paper, at first, presents the author's understanding of the problem caused by the use of ITTC (International Towing Tank Conference) 1957 Line in conjunction with three-dimensional analysis. Then, how the ideal friction line should be within the range of model Reynolds number is discussed.

As a conclusion of this paper, the answer to the question "Should ITTC 1957 Line be revised?" is as follows. It is "Yes" in a sense that ITTC 1957 Line prepared for two-dimensional analysis should be revised, if we employ three-dimensional analysis. It is "No" in another sense that the expected gain by the revision of the friction line would be almost negligible and, on the other hand, we have to expect the setback caused by changing from the well-accustomed line to new one.

1. Preface

Several papers were presented discussing what correlation line is most suitable for the separation of resistance components, on the basis of Geosim (Geometrically similar) model test results. For examples, Tanaka et.al.[1] pointed out that the values of form factor decreased for the larger model when Geosim model test results of Wigley hull form were analysed by three-dimensional analyses using Schoenherr Line, and Gometz [2] pointed out that the values of form factor obtained by the analyses of several Geosim model test results using ITTC 1957 Line increased when the larger model was used.

There have been successive discussions in ITTC conferences whether ITTC 1957 Line is an appropriate line to estimate frictional resistance of ship hull forms. Even if they might not create major activities of research work, it is truly a fundamental issue for the estimation of propulsive performance of ships through model tests. Then, it is very important to try to make the reality as clear as possible.

1.1. Common Claims

Most common claim seems to be that form factors analysed for test results of Geosim series models suffer scale-effect of the model size. However, because many of model test specialists know that the values of form factor varies time to time even when the resistance tests of a same model ship were repeated, it might be too hasty to conclude that ITTC 1957 Line is not appropriate only by the variation of form factor in a certain trend.

Another common discussion is that flat-plate friction line should be used for the separation of resistance components. However, the author considers the basis of this discussion is quite weak by the following two reasons.

(1) It is only the assumption made by William Froude that total resistance coefficient obtained by model test ($C_{T,M}$) can be separated into residual resistance coefficient (C_R) and frictional resistance coefficient (C_F), and that the extrapolation to the full-scale total resistance coefficient can be made by the application of the obtained C_R and C_F calculated by the same friction line used for the separation of resistance components.

(2) There are various proposals for the friction line of flat-plate. Then, even when we can suppose Froude's assumption would give definitely correct result, we cannot obtain one definite friction line for the separation of resistance components.

The author considers we should carefully examine the data obtained up to present from various directions before making any decisions on whether ITTC 1957 Line is appropriate or not.

1.2. Historical Review

At the time of the first ITTC, Froude's friction formulae together with Froude's assumption are used everywhere. During the World War II, Schoenherr line became popular on the American continent, and the first ITTC after the War (5th ITTC,

* Nagasaki Experimental Tank, Mitsubishi Heavy Industries, Ltd.

原稿受理 平成 20 年 8 月 25 日

London 1948) approved the use of Schoenherr line together with Froude’s friction formulae. However, because the two formulae are so different, ITTC formed the Committee on Skin Friction and Turbulence Stimulation to seek the friction formula which can be used consistently. The fundamental question is “By using what line we can get the reasonably well agreed residual resistance coefficients even when we test the different scale models of the same hull form?” It is the reason why Geosim model tests were performed quite intensively in 1950s.

ITTC 1957 Line is a correlation line proposed at 8th ITTC in Madrid through the analyses of Geosim model test results available at the time. The committee report [3] stated that it was formulated so as to minimize the model scale effect on residual resistance coefficients obtained by two-dimensional analysis. ITTC 1957 Line and Schoenherr Line are defined as follows

$C_F = 0.075/(\log Re - 2.0)^{2.0}$: ITTC 1957 Line (1)

$C_F = 0.0463/(\log Re)^{2.6}$: Schoenherr Line (Approx.) (2)

For an example of Geosim model test results, total resistance coefficients of model ($C_{T,M}$) of “Victory” data obtained at the Netherlands Ship Model Basin (NSMB) and reported by van Lammeren et.al. [4] are shown in Fig.1 being plotted over logarithm of Reynolds number (Re). Residual resistance coefficients (C_R) obtained from the results by two-dimensional analysis seem to have no scale effect of model size as shown in Fig.2 being plotted over Froude number (Fr).

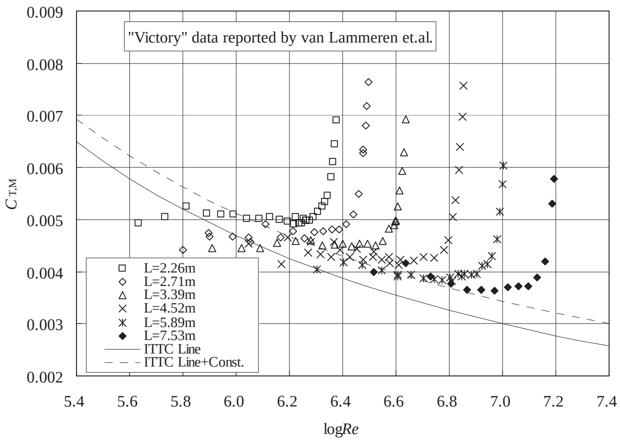

Fig.1 Example of Geosim Test Results ($C_{T,M}$ vs. log Re)

As shown in Fig.2, the value of C_R does not tend to zero when Froude number tends to zero. It means that total resistance coefficients obtained by Geosim series model test tend to a line which is shifted parallel above ITTC 1957 Line when Froude number tends to zero, as shown in Fig.1. Because the value of C_F becomes smaller when Reynolds number becomes greater, the value of form factor obtained by the test of larger model ship tends to be greater. Therefore, it is a matter of course that there would be scale effect on form factor, whether it is significant or not, when three-dimensional analysis was applied to Geosim model test results by using ITTC 1957 Line. However, about 20 years later, ITTC 1957 Line is used in combination with three-dimensional analysis in ITTC 1978 method.

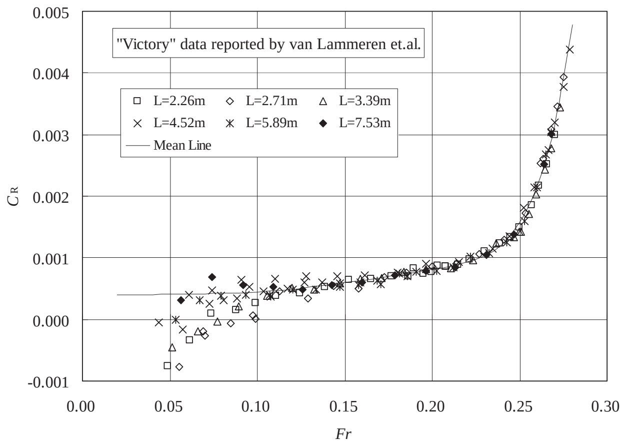

Fig.2 Example of C_R vs. Fr Plot

If the value of form factor k is not equal to zero, the slopes of a C_F curve and the curve of the C_F curve multiplied with (1+k) are different. Therefore, generally speaking, the correlation lines which can minimize the model scale effect on residual resistance coefficients obtained by two and three-dimensional analyses must be different each other.

1.3. The Scope of the Present Study

Reflecting the above, the author considers that the following investigations are necessary to make clear whether we should revise the current ITTC correlation line or not.

(1) Analyses of several sets of Geosim model test results (mainly obtained in 1950s) using ITTC 1957 Line. From the result, we can confirm to what extent the conclusion of 8th ITTC can be applied. At the same time, we can check the magnitude of model-size dependency of the values of form factor, k.

(2) Analyses of the sets of Geosim model test results, using a series of supposed friction lines which have different slope at model-scale Reynolds number while having almost the same values at full-scale Reynolds number, to investigate whether a new correlation line can be proposed or not. The procedures of two- and three-dimensional analyses should be applied.

1.4. Source Data

For the purpose, the raw data of the following Geosim model test results could be collected and were re-analysed.

(a) “Victory” data reported by van Lammeren et.al.[4]

(b) “Lucy Ashton” data reported by Lackenby [5]

(c) “BSRA (British Ship Research Association) C_b=0.75 series” data for three drafts reported by Hughes [6)]

(d) "Veedol" class tanker data obtained by MHI (Mitsubishi Heavy Industries), and partially presented by Watanabe [7)]

(e) "710 Class US Navy destroyer data" obtained at DTRC (David Taylor Research Center)

(f) "LPG Carrier" data obtained at Marintek

In the cases of (a), (b), (c), the references contain the paired values of model speed and total resistance, together with model particulars and tank water temperature. The reference of (d) does not contain the raw data, and the author analysed the in-house data. In the cases of (e) and (f), the raw data were offered to the author from DTRC and Marintek. Although the references of (a), (b), (c), (d) are rather old from the days of two-dimensional analysis, the used models were equipped with some turbulence stimulator like "Trip Wire" or "Plate Stud", and the data can be considered to keep the same level of quality as the present ones.

Throughout the following explanations, as well as Figures 1 and 2, "Victory" data obtained at NSMB and reported by van Lammeren et.al. [4)] are shown as examples.

1.5. Blockage Correction

The test results of "Victory" obtained at NPL (National Physical Laboratory) reported by Hughes [8)] are also analysed during the study. However, plot of C_R vs. Fr showed distinct differences in some cases, as shown in Fig. 3, which is a clear contrast with the results shown in Fig.2. At NPL, models of "Victory" with almost the same specifications as those at NSMB were tested in No. 1 and No. 2 tanks which have much smaller dimensions than the tank of NSMB.

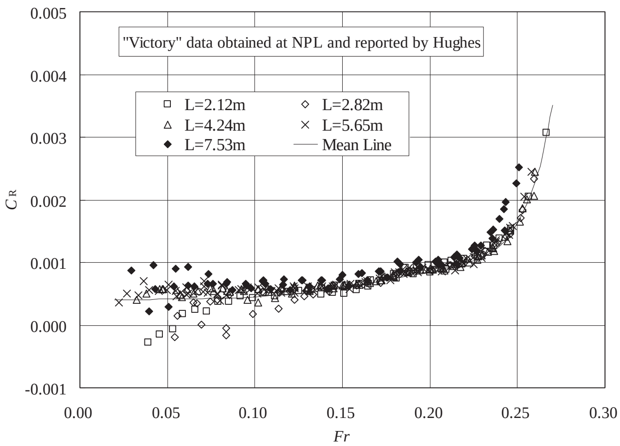

Fig.3 C_R vs. Fr Plot before Blockage Correction

In such cases where distinct differences are observed, blockage coefficients (the ratio of maximum transverse section area of model ship to transverse section area of tank) are larger than 1%, and up to more than 3%. So, blockage effects were corrected to no blockage by use of the first term of Tamura's corrector [9)]. The rest of three terms of Tamura's corrector are solely to take care of the corrections for shallow water conditions.

$$\frac{\Delta U}{U} = 0.51 \cdot m \cdot \left(\frac{2 \cdot L}{b} \right)^{0.8-4.76 \cdot m} \cdot \frac{1}{1 - Fr_h{}^2} \quad (3)$$

where, U, ΔU: Model speed and its increment due to the blockage effect, m: Blockage defined by the ratio of areas of maximum transverse section of model ship and the tank, L: Model length, b: Breadth of the tank, Fr_h: Froude number of water depth.

After the blockage correction, the relationship between Fr and C_R were very much improved, as shown in Fig. 4. Throughout the analyses, the blockage correction was applied to all the test cases where the blockage coefficient is larger than 1%.

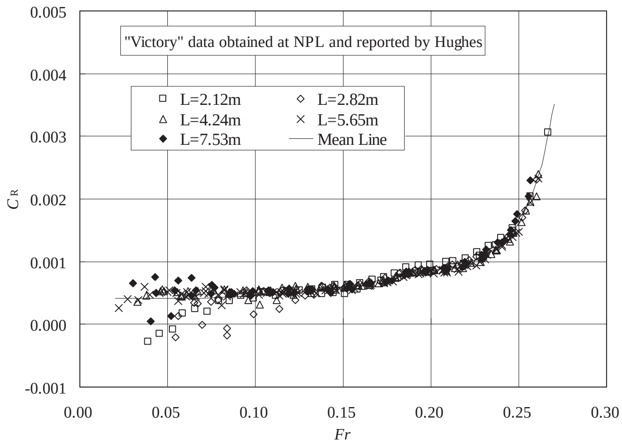

Fig.4 C_R vs. Fr Plot after Blockage Correction

2. Analyses by Use of ITTC 1957 Line

2.1. Procedure of Two-Dimensional Analysis and Examples of the Results

At first, total resistance coefficients of model ($C_{T,M}$) were plotted over the corresponding values of logRe, and an example is shown in Fig. 1. Then, the values of C_F calculated by ITTC 1957 Line were subtracted and the obtained values of C_R are plotted over Froude number (Fr), as shown in Fig.2.

$$C_{T,M} = C_F + C_R \quad (4)$$

The figures for all the analysed data obtained in 1950s seem to show that the committee of 8th ITTC really accomplished well their intention; "The newly proposed line must produce, on the average, better correlation among Geosim models of a variety of forms at different scale than does the Schoenherr line", by proposing ITTC 1957 Line.

The test data of all sizes for Fr>0.11 were fitted by the formula (5), and the fitted result is shown in Fig.2 by the solid line. The original formula of the formula (5) is the asymptotic expansion formula of wave-making resistance coefficient presented by Inui et.al.[10]. The author added constant term: $C_{R,0}$ to follow a tendency that C_R does not necessarily approach to zero in this case when Fr approaches to zero.

$$C_{R,\text{ mean line}} = C_{R,0} + a\times Fr^4 + b\times Fr^8 + c\times Fr^{12} + d\times Fr^{16} \quad (5)$$

2.2. Procedure of Three-Dimensional Analysis and Examples of the Results

$C_{T,M}$ for Fr>0.11 were fitted by use of Inui's asymptotic expansion formula [10] of wave-making resistance coefficient (C_W), as follows;

$$C_{T,M} = (1+k)\times C_F + C_W = (1+k)\times C_F + a\times Fr^4 + b\times Fr^8 + c\times Fr^{12} + d\times Fr^{16} \quad (6)$$

As the result, the value of k was obtained. This method is denoted as "Asymptotic". Data at Fr<0.11 were neglected because of comparatively big scatter of $C_{T,M}$.

Taking the first two terms of the formula (6), the following linear relationship is obtained between $C_{T,M}/C_F$ and Fr^4/C_F.

$$C_{T,M}/C_F = (1+k) + a\times Fr^4/C_F \quad (7)$$

Prohaska proposed his analysis method of form factor using this relationship and test data at low speed only, which was adopted as the present ITTC recommended procedure. However, because the data obtained at low speed have too much scatter, data obtained for 0.11<Fr<0.16 were used in the analysis here. This method is denoted as "Prohaska".

As explained in 2.1., the author could obtain $C_{R,\text{ mean line}}$ by the analyses of Geosim series data. Then, the most probable estimation of $C_{T,M}$ can be obtained from $C_{T,M} = C_{F,\text{ittc}} + C_{R,\text{ mean line}}$ as a function of Re and Fr. From this function, the scale effect on form factor can be estimated by the followings.

(a) The values of $C_{T,M,\text{ mean line}}$ (= $C_{F,\text{ ittc}}$ + $C_{R,\text{ mean line}}$) were calculated for several values of Fr for each model.

(b) The calculated $C_{T,M,\text{ mean line}}$ /$C_{F,\text{ ittc}}$ and $Fr^4/C_{F,\text{ ittc}}$ were fitted by a straight line and (1+k) can be obtained by Prohaska's method.

This method is denoted as "Mean line".

2.3. Scale Effect on Form Factor

The values of form factor were estimated by the above three methods, and an example of the results is shown in Fig.5 being plotted over log(Re, Fr=0.1). Re, Fr=0.1 is Reynolds number corresponding to Fr=0.1 and is dependent on model size. Similar figures to Fig.5 were obtained from the analyses of the other Geosim series test data.

From these figures, it can be concluded;

(1) Scatter of k obtained by "Prohaska" is considerably big due to the relatively low reliability of $C_{T,M}$ values at low speed. Reliability of each value of k is questionable and only the general tendency can be meaningful.

(2) Even if the data of higher Froude number are taken into account by applying Inui's asymptotic formula [10], the results obtained by "Asymptotic" show almost no improvement.

(3) The variations of k obtained by "Mean line", which is expected to show the most probable estimate of form factor scale effect, are almost buried in the scatter of k values obtained by "Prohaska" or "Asymptotic".

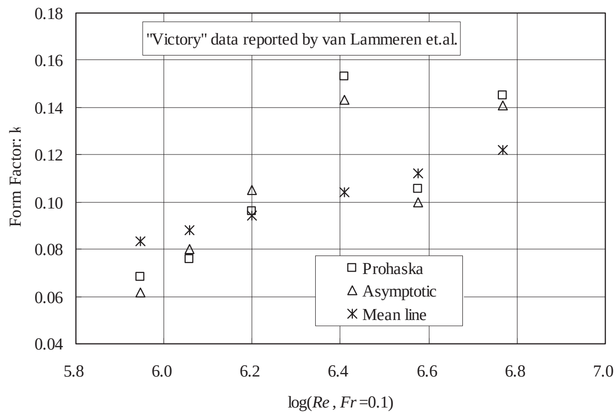

Fig.5 Form Factor: k vs. log(Re, Fr=0.1) (ITTC 1957 Line)

3. Supposed Series Friction Lines

In the above analyses, only one friction line i.e. ITTC 1957 Line is used. However, if we try to answer the question "By using what line we can get the best agreed residual resistance coefficients even when we test the models of different sizes?", the use of series friction lines is necessary.

3.1. Concept

In the report of 8th ITTC (1957), the committee proposed the new line (ITTC 1957 Line) which gives similar C_F values as Schoenherr line at Reynolds numbers corresponding to full-scale ships, and gives steeper slope at model Reynolds number. The author followed the idea. Also, the form of the series friction lines was set similar to ITTC 1957 Line as follows.

$$C_F = A/(\log Re\text{-}B)^C \quad \text{[A, B and C: Given coefficients]} \quad (8)$$

Because, practically speaking, it is troublesome to use slope of friction line as a parameter, the author re-wrote the conditions which should be satisfied by the series line as follows;

(1) The values of C_F at logRe=8.0 and 9.0 are the same as those of ITTC 1957 Line (and Schoenherr Line).

(2) The value of C_F at logRe=6.0 is varied as a parameter.

Then, slope of the lines can be controlled by the parameter.

3.2. The Obtained Series Lines

As the values of C_F at logRe= 6 of the existing friction lines are

0.00469, 0.00439 and 0.004335 by ITTC 1957, Shoenherr and Grigson Lines respectively, the lowest value of the parameter was set 0.0042, a little lower than Grigson Line, and the highest value was selected to be 0.0052, well beyond ITTC 1957 Line. Then, eleven lines were obtained corresponding to the values of parameter; 0.0042, 0.0043, 0.0044, • • • • •, 0.0052. The definition of i-th friction line used here is as follows;

$$C_{F,\,i} = 0.0042 + (i\text{-}1)\times 0.0001 \text{ at } Re = 10^6 \qquad (9)$$

The values of C_F calculated for these eleven lines are shown in Fig.6, being compared with ITTC 1957, Schoenherr and Grigson Lines. From this figure, the obtained series lines are considered to be suitable for the following analyses.

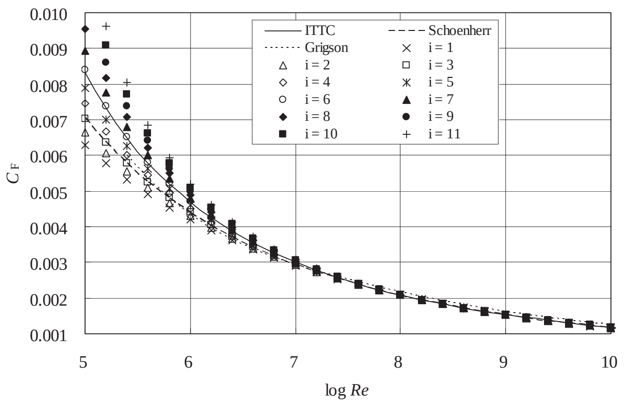

Fig.6 Series Friction Lines Set for the Analysis

For the calculation of C_F by Grigson Line, the Specialist Committee of Powering Performance Prediction of 24th ITTC presented the following approximate formula [11]. The formula was used in this paper.

$$C_F = 10^A, \qquad (10)$$

$A = 2.98651 - 10.8843 \times \log(\log Re) + 5.15283 \times \{\log(\log Re)\}^2$, when $2\times 10^5 \leqq Re \leqq 10^7$

$A = -9.57459 + 26.6084 \times \log(\log Re) - 30.8285 \times \{\log(\log Re)\}^2 + 10.8914 \times \{\log(\log Re)\}^3$, when $10^7 \leqq Re \leqq 6\times 10^9$

4. Analyses by use of the Series Friction Lines

In the following analyses, a best line is to be found for each set of Geosim model test results, which can minimize scale effect on residual resistance coefficients.

4.1. Two-Dimensional Analysis

4.1.1. C_R Deviation from Mean Line

When a set of Geosim model test data are given, total resistance coefficient of k-th Froude number using j-th model of the Geosim series is written as $C_{T,M,\,j,\,k}$. In the case where i-th friction line of the above series is applied, the value of $C_{F,\,i,\,j,\,k}$ corresponding to the value of $Re_{j,\,k}$ is obtained by the line and subtracted form the value of $C_{T,M,\,j,\,k}$. Then, the value of residual resistance coefficient $C_{R,\,i,\,j,\,k}$ is calculated. Namely;

$$C_{R,\,i,\,j,\,k} = C_{T,M,\,j,\,k} - C_{F,\,i,\,j,\,k} \qquad (11)$$

The obtained $Fr_{j,\,k}$ and $C_{R,\,i,\,j,\,k}$ correspondences are fitted by the formula (5), and the formula of $C_{R\ \text{mean line}}$ is obtained.

For each pair of $Fr_{j,\,k}$ and $C_{R,\,i,\,j,\,k}$, the value of $C_{R\ \text{mean line}}$ corresponding to the value of $Fr_{j,\,k}$ is calculated and subtracted from the value of $C_{R,\,i,\,j,\,k}$. Thus "C_R deviations" are obtained.

$$(C_R \text{ deviation})_{i,\,j,\,k} = C_{R,\,i,\,j,\,k} - C_{R\ \text{mean line}\ i,\,j,\,k} \qquad (12)$$

In the case of i=3, the values of $(C_R \text{ deviation})_{3,j,k}$ are shown, being plotted over Fr in Fig.7.

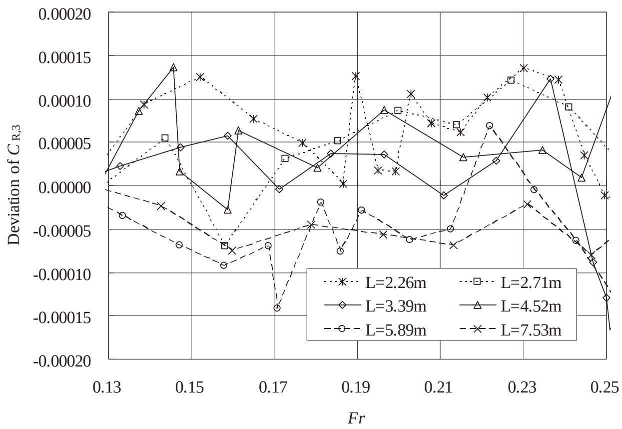

Fig.7 $(C_R \text{ Deviation})_{3,j,k}$ Plotted over Fr

In this figure, generally speaking, deviations of $C_{R,\,3}$ for relatively smaller models (L=2.26m and 2.71m) have positive values, and those of larger models (L=7.53m and 5.89m) have negative values. It means the most suitable friction line should have larger slope of C_F curve (larger value of C_F at Re=10^6) than the 3rd friction line.

4.1.2. Deviation Index

Variance of C_R deviation obtained for j-th model: $(\text{VR } C_R)_{i,j}$ and deviation index of the Geosim series for i-th friction line are calculated as follows;

$$(\text{VR } C_R)_{i,j} = \frac{\sum_{k=1}^{N_j} (C_R \text{deviation})_{i,j,k}^{\ 2}}{N_j} \qquad (13)$$

$$(\text{Deviation index})_i = \sqrt{\frac{\sum_{j=1}^{M} (\text{VR } C_R)_{i,j}}{M}} \qquad (14)$$

where, N_j: number of model test data of j-th model, M: number of tested models.

Deviation index of Geosim series is expected to have minimum value where the characteristics of the friction line are most suitable to the resistance characteristics of the data. Then, the most suitable friction line can be found by examining the Geosim series test data as explained here.

The values of Deviation index of Geosim series are plotted over the parameter of series friction line, and shown in Fig8. In this example, deviation index has minimum value around the friction line corresponding to C_F = 0.0047 at Re=10^6. The fitted result of the variation around the minimum point by a quadratic function is shown by the solid line in Fig.8.

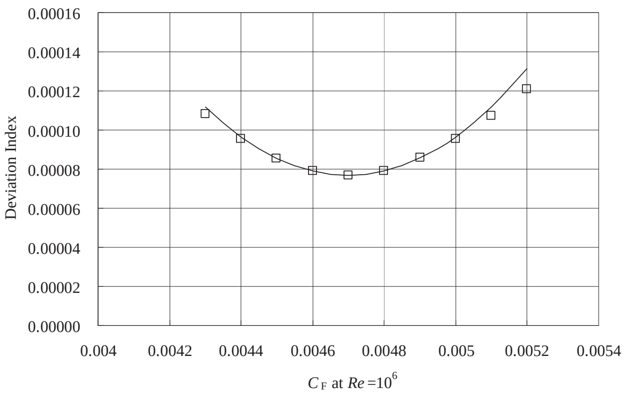

Fig.8 Variation of Deviation Index Plotted over C_F at Re=10^6 (Two-Dimensional Analysis)

Thus, we can find out the most suitable line anyhow. However, we have to realize the obtained result must have considerable uncertainty associated with the scatter of "(C_R deviation)$_{i,j,k}$", as an example of scatter is shown in Fig.7.

4.1.3. Obtained Results of Most Suitable Friction Line

In Fig.9, the values of C_F at Re=10^6 of the most suitable friction line are plotted by ■ for the analysed eight Geosim series models over $k_{est,ITTC}$ (MHI).

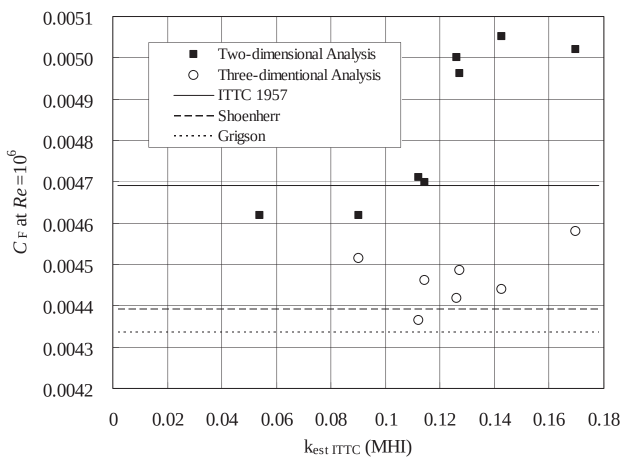

Fig.9 Most Suitable Values C_F at Re=10^6 for Various Hull Forms

The plot sequence of hull forms in the figure from left to right is "710 Class US Navy destroyer", "Lucy Ashton", "BSRA75 LW2", "Victory", "BSRA75 LWL", "BSRA75 LW1", "Veedol", "Marintek LPGC". From the figure, it can be concluded that the slope of friction line should be steeper for the full hull forms than fine hull forms.

$k_{est,ITTC}$ (MHI) is the values of form factor estimated for ITTC 1957 line by MHI's empirical formula, which is written as follows.

$$k_{est,ITTC}\ (\mathrm{MHI}) = 36.89 \times \nabla/L^3 + 516.8 \times \nabla^2/L^6 - 3.368 \times d/L - 0.2864 \times B/L + 0.1291 \quad (15)$$

where, ∇: displacement volume of model, B, d: breadth and draft of model.

The reason why the results are not plotted over more simple fullness parameters, such as ∇/L^3, is that uniform increasing tendency as shown by ■ in Fig.9 was not obtained in such cases.

4.2. Three-Dimensional Analysis

4.2.1. Difference from Two-Dimensional Analysis

The value of residual resistance coefficient $C_{R,\,i,\,j,\,k}$ is usually calculated using a value of form factor: k decided by the analysis of the measured data (by Prohaska's method, for example). Then, residual resistance coefficient is calculated as follows;

$$C_{R,\,i,\,j,\,k} = C_{T,M,\,j,\,k} - (1+k) \times C_{F,\,i,\,j,\,k} \quad (16)$$

However, because of the facts that scatter of the low-speed model test data are much bigger than those of higher speed data, the usual procedure of obtaining the value of form factor from low-speed model test data is abandoned in the analysis here. Instead, it is temporarily given for the analysis.

The value of form factor depends on friction line used for the analysis. In this paper, it is considered the value of form factor defined by ITTC 1957 line is given, and it is converted into the value defined by the other friction line by the following formula.

$$(1+k_{ITTC}) \times C_{F,\,ittc} = (1+k_{FL\,i}) \times C_{F,\,i}\ (= C_{T,M\ \mathrm{at\ Low\ speed}}) \quad (17)$$

where, k_{ITTC}: Form factor defined by ITTC 1957 line, $k_{FL\,i}$: Form factor defined by i-th friction line.

Another point is at what Reynolds number the above formula is applied. As the effect of the difference of Re is expected negligible when i-th friction line is the most suitable friction line, form factor is converted at logRe=6.75 which corresponds roughly to low speed test condition of 7m class model.

When a value of k_{ITTC} is supposed, characteristics of the most suitable friction line can be obtained through the calculation procedure explained in 4.1. The characteristics are represented by the values of C_F at Re=10^6 and $C_{R,0}$ in the formula (5). For a few supposed values of k, the process is repeated and combinations among values of k, C_F at Re=10^6 and $C_{R,0}$ are obtained. When the values of the given k and the obtained C_F at Re=10^6 are plotted over the obtained $C_{R,0}$, two curves can be drawn as shown in Fig.10.

Then, the final results of the values of k and C_F at Re=10^6 are obtained at the intersection with $C_{R,0}$=0 and these two curves. Thus, the most suitable friction line and the value of form factor, which satisfy the condition that C_R tends to zero when *Fr* tends to zero, can be obtained.

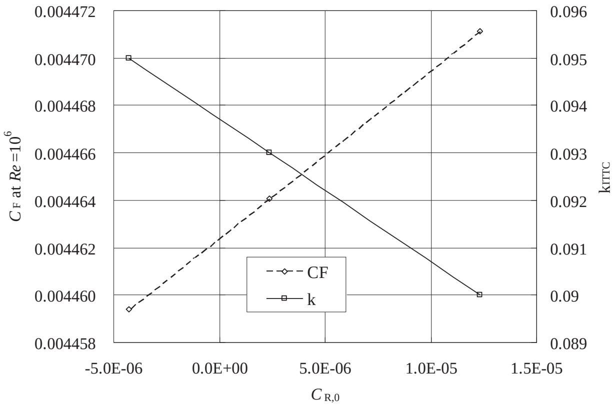

Fig.10 Combinations among Values of k, C_F at $Re=10^6$ and $C_{R,0}$

Figure corresponding to Fig.8 is shown in Fig.11. When Fig.11 is compared with Fig.8, the most suitable value of C_F at $Re=10^6$ decreased from around 0.0047 (two-dimensional analysis) to around 0.0045 (three-dimensional analysis).

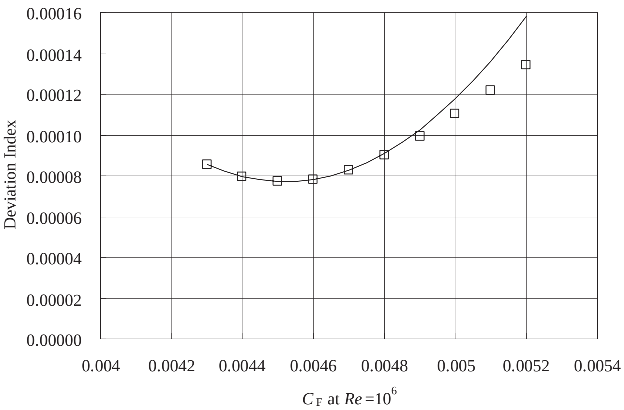

Fig.11 Variation of Deviation Index Plotted over C_F at $Re=10^6$ (Three-Dimensional Analysis)

4.2.2. Obtained results of Most Suitable Friction Line

In Fig.9, the values of C_F at $Re=10^6$ of the most suitable friction line are plotted by ○ for the analysed seven Geosim series models over $k_{est,ITTC}$ (MHI). Test results of "710 Class US Navy destroyer" Geosims could not be analysed in this case, because of the lack of low speed test data.

In this case, the scatters of the values of C_F at $Re=10^6$ become much smaller in comparison to the former results obtained by two-dimensional analyses. There is no clear dependency between the value of C_F at $Re=10^6$ and the fullness of hull form represented by $k_{est,ITTC}$ (MHI).

4.3. Conclusions from the Study using Series Friction Lines

From the above analyses, it can be concluded as follows;

(1) When two-dimensional analysis is employed, the value of C_F at $Re=10^6$ of the most suitable friction line varies depending on the fullness of the hull form.

(2) When three-dimensional analysis is employed, scatter of C_F at $Re=10^6$ of the most suitable friction line becomes much smaller than the case of two-dimensional analysis.

(3) The above two results may indicate the concept of three-dimensional analysis is more rational than that of two-dimensional analysis, at least within the model-scale Reynolds number.

5. New Correlation Line and the Analyses by use of It

From the above results, it is reasonable to pick up a new correlation line which corresponds to the average of the ○ marks in Fig.9. It can be written as follows;

$$C_F = 0.30478/\{\log Re - 0.4763\}^{2.4705} \qquad (18)$$

This line is shown being compared with other friction lines and recently proposed Katsui's formula [12)]

$$C_F = \frac{0.0066577}{(\log Re - 4.3762)^{0.042612 \log Re + 0.56725}}$$

$$(10^6 \leqq Re \leqq 7 \times 10^9) \qquad (19)$$

in Fig.12. All but ITTC 1957 Line and the new correlation line are the formulae of a flat plate friction line. It can be noticed from this figure, the New Proposal lies very close to Prandtle-Schlichting, Schoenherr and Katsui's lines.

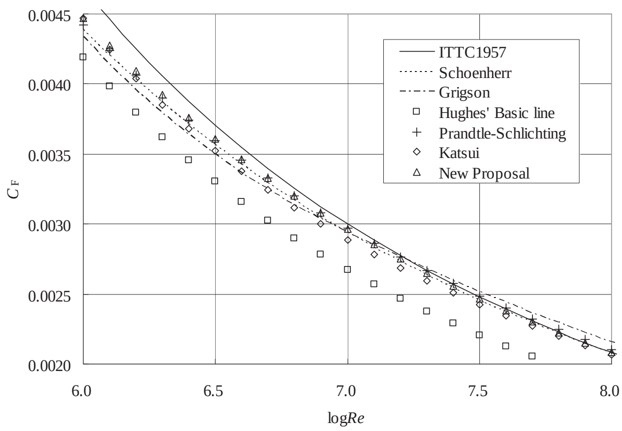

Fig.12 Comparison of the Newly-Proposed Correlation Line with the Existing Lines

By use of this new proposal, the author analysed the Geosim test results where the form factor: k is estimated from each model test results as explained in 2.2. By the results, scale effect on form factor could be checked.

Then, total resistance coefficients of full-scale ship ($C_{T,S}$) were estimated by three-dimensional analysis with k estimated by "Asymptotic". $C_{T,S}$ were estimated in both cases where the New Proposal and ITTC 1957 Line were applied and the results were compared.

5.1. Scale-Effect on Form Factor

The figure corresponding to Fig.5 is shown in Fig.13. When compared with Fig.5, Fig.13 shows that model scale effect on form factor [variations of k values obtained by "Prohaska", "Asymptotic" and "Mean line" vs. log(Re, Fr=0.1)] decreased significantly, and model scale effect on k values obtained by "Mean line" is almost negligible.

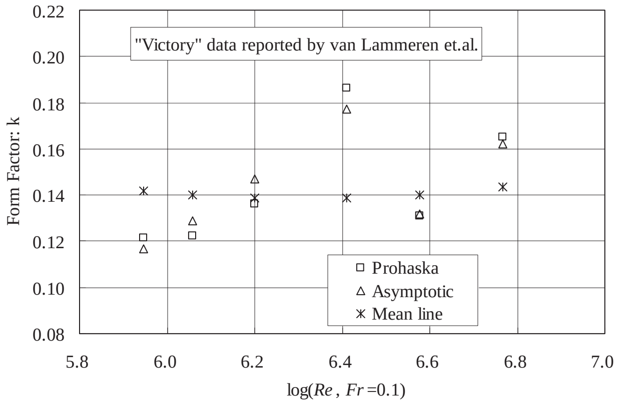

Fig.13 Form Factor: k vs. log(Re, Fr=0.1) (New Line)

5.2. Total Resistance Coefficient of Full-Scale Ship

C_R and $C_{T,S}$ were estimated by three-dimensional analysis with k estimated by "Asymptotic" and shown in Figs.14 and 15. In these figures, there can be observed no significant scale-effects.

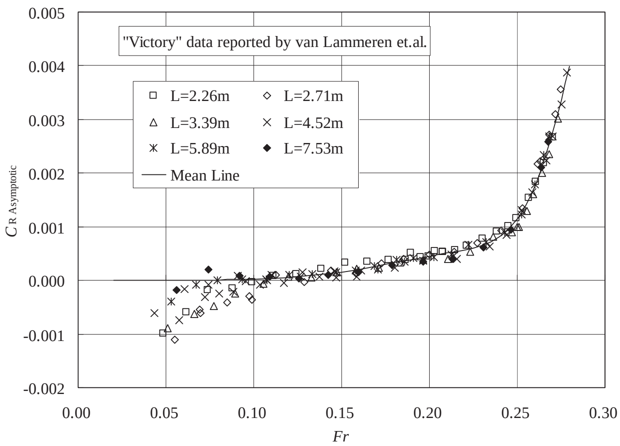

Fig.14 Residual Resistance Coefficients vs. Fr (New Line)

When Fig.14 is compared with Fig.2, the scatter of C_R obtained by three-dimensional analysis the results seems to be slightly larger than those by two-dimensional analysis. It is because the scatter of C_R in Fig.14 is partly derived from the scatter of form factor.

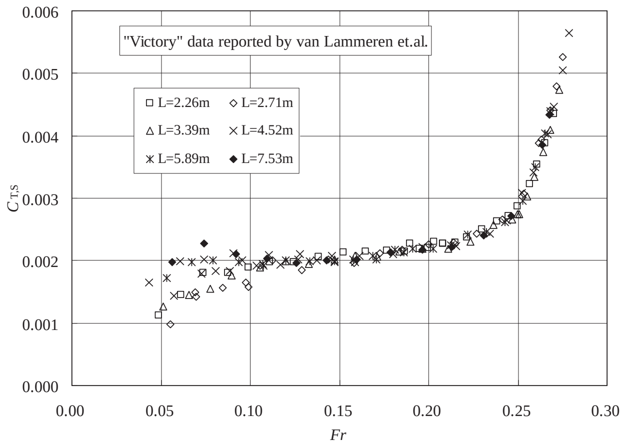

Fig.15 The estimated Total Resistance Coefficients of Full-Scale Ship vs. Fr (New Line)

$C_{T,S}$ were estimated by using ITTC 1957 Line and three-dimensional analysis with k estimated by "Asymptotic". The results are shown in Fig.16. When the figure is compared with Fig.15, there can be observed no significant difference so far as the scatter of the results is concerned. It means that almost no improvement shall be obtained by the introduction of the new correlation line.

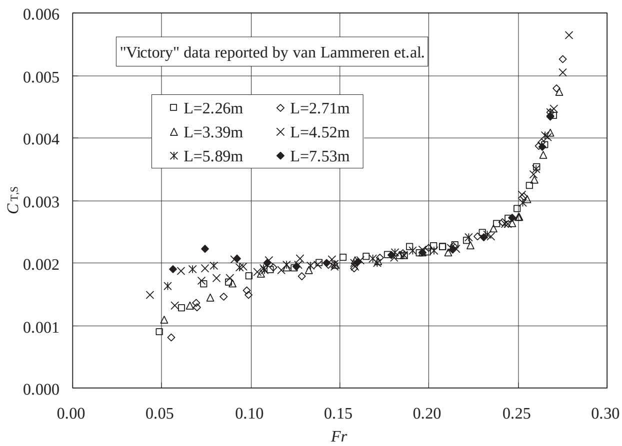

Fig.16 The Estimated Total Resistance Coefficients of Full-Scale Ship vs. Fr (ITTC 1957 Line)

The small difference of the mean level is created by the change of the friction line, and the effect on the estimated full-scale performance cannot be neglected on this point. However, if the friction line is revised, we have to re-analyse the full-scale trial results by using the new friction line and the values of a model-ship correlation factor shall be changed. Then, we can expect that the small difference of the mean level will be adjusted by the change of the model-ship correlation factor. Therefore, only scatter is important.

6. Concluding Remarks

Following to the discussions that there is significant model scale-effect on form factor analysed by use of ITTC 1957 Line, the author started this study from the historical review. It showed that model scale-effect on form factor is inevitable when three-dimensional analysis is employed with ITTC 1957 Line.

Then, formulating a series of parametric friction lines which has different slopes at model Reynolds number, the author investigated what friction line can minimize model scale-effect on the results of three-dimensional analysis. As a result, the author can conclude a line defined by the formula (18), which lies very close to Prandtle-Schlichting, Schoenherr and Katsui's lines, is appropriate on the basis of the available Geosim model test data.

Although it is confirmed that the scale effect on form factor can be reduced by the application of the new line, the estimated results of total resistance coefficients of full-scale ship by use of the new line and ITTC 1957 Line show no significant difference. Then, we can expect no improvement by the introduction of the formula (18).

For the future work and the further improvements, the author would like to express as follows;

(1) All the analysed Geosim model test results are for relatively older hull forms and they do not include really full hull forms of current design. We should encourage the formulation of Geosim model test program including modern full ships.

(2) The scatter of the analysed Geosim model test results is considerably big. We should initiate serious endeavor to improve the accuracy (or repeatability) of ship model tests.

Acknowledgements

The author would like to express, at first, his sincere thanks to Dr. Kin-ya Tamura, who taught the author a lot of the history of ITTC. He actually guided the author in due course of the investigation.

He also likes to express special thanks to the members of Specialist Committee on Powering Performance Prediction of 25th ITTC and the members of Nagasaki Experimental Tank. Through the discussions with them, this investigation was completed.

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