ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

1978 ITTC Performance Prediction Method

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Disclaimer

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Resistance and Propulsion Committee of the 29th ITTC	29th ITTC 2021
Date: 03/2021	Date: 06/2021

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1978 ITTC Performance Prediction Method

1. PURPOSE OF PROCEDURE

The procedure gives a general description of an analytical method to predict delivered power and rate of revolutions for single and twin screw ships from model test results.

2. DESCRIPTION OF PROCEDURE

2.1 Introduction

The method requires respective results of a resistance test, a self-propulsion test and the characteristics of the model propeller used during the self-propulsion test,

The method generally is based on thrust identity which is recommended to be used to predict the performance of a ship. It is supposed that the thrust deduction factor and the relative rotative efficiency calculated for the model remain the same for the full scale ship whereas on all other coefficients corrections for scale effects are applied.

In some special cases torque identity (power identity) may be used, see section 2.4.4.

2.2 Definition of Variables

C_A	Correlation allowance
C_AA	Air resistance coefficient
C_APP	Appendage resistance coefficient
C_D	Drag coefficient
C_{DA}	Air drag coefficient of the ship above the water line
C_F	Frictional resistance coefficient
C_FC	Frictional resistance coefficient at the temperature of the self-propulsion test
C_{NP}	Trial correction for propeller rate of revolution at power identity
C_P	Trial correction for delivered power
C_N	Trial correction for propeller rate of revolution at speed identity
C_W	Wave resistance coefficient
C_T	Total resistance coefficient
D	Propeller diameter
F_D	Skin friction correction in self-propulsion test
J	Propeller advance coefficient
J_T	Propeller advance coefficient achieved by thrust identity
J_Q	Propeller advance coefficient achieved by torque identity
K_T	Propeller thrust coefficient
K_{TQ}	Thrust coefficient achieved by torque identity
K_Q	Propeller torque coefficient
K_{QT}	Torque coefficient achieved by thrust identity
k	Form factor
k_P	Propeller blade roughness
k_S	roughness of hull surface
N_P	Number of propellers
n	Propeller rate of revolution
n_T	Propeller rate of revolution, corrected using correlation factor
P	Propeller pitch
P_D, P_P	Delivered Power, propeller power
P_DT	Delivered Power, corrected using correlation factor
P_E, P_R	Effective power, resistance power
Q	Torque
R_C	Resistance corrected for temperature differences between resistance and self-propulsion test
Re	Reynolds number
$Re_{0.7}$	Propeller Reynolds number at 0.7 R
R_T	*Total* resistance
S	Wetted surface area

S_{WBK}	Wetted surface of bilge keels	
T	Propeller thrust	
t	Thrust deduction factor	
V	Speed	
V_A	Advance speed of propeller	
w	Taylor wake fraction in general	
w_Q	Taylor wake fraction, torque identity	
w_R	Effect of the rudder(s) on the wake fraction	
w_T	Taylor wake fraction, thrust identity	
Z	Number of propeller blades	
β	Appendage scale effect factor	
ΔC_F	Roughness allowance	
ΔC_{FC}	Individual correction term for roughness allowance	
Δw_C	Individual correction term for wake	
η_D	Propulsive efficiency or quasi-propulsive coefficient	
η_H	Hull efficiency	
η_0	Propeller open water efficiency	
η_R	Relative rotative efficiency	
ρ	Water density in general	
R_0	Full scale resistance without overload	(N)
F_x	External tow force	(N)
F_D	Skin friction correction force	(N)
λ	Scale ratio	(-)
C_{TAdd}	Added resistance Coefficient	(-)
ΔR	Added resistance	N)
ΔV	Added velocity	(m/s)
Δn	Added rpm	
ξ_n	Load variation coefficient of the shaft revolution speed	
ξ_v	Load variation coefficient of the ship speed	
ξ_P	Load variation coefficient of the delivered power	

Subscript “M” signifies the model

Subscript “S” signifies the full scale ship

2.3 Analysis of the Model Test Results

The calculation of the residual resistance coefficient C_R from the model resistance test results is found in the procedure for resistance test (7.5-02-02-01).

Thrust T_M, and torque Q_M, measured in the self-propulsion tests are expressed in the non-dimensional forms as in the procedure for propulsion test (7.5-02-03-01.1).

$$K_{TM} = \frac{T_M}{\rho_M D_M^4 n_M^2} \quad \text{and} \quad K_{QM} = \frac{Q_M}{\rho_M D_M^5 n_M^2}$$

Using thrust identity with K_{TM} as input data, J_{TM} and K_{QTM} are read off from the model propeller open water diagram, and the wake fraction

$$w_{TM} = 1 - \frac{J_{TM} D_M n_M}{V_M}$$

and the relative rotative efficiency

$$\eta_R = \frac{K_{QTM}}{K_{QM}}$$

are calculated. V_M is model speed.

Using torque identity with K_{QM} as input data, J_{QM} and K_{TQM} is read off from the model propeller open water diagram, and the wake fraction

$$w_{QM} = 1 - \frac{J_{QM} D_M n_M}{V_M}$$

and the relative rotative efficiency

$$\eta_R = \frac{K_{TM}}{K_{TQM}}$$

are calculated. V_M is model speed.

The thrust deduction is obtained from

$$t = \frac{T_M + F_D - R_C}{T_M}$$

where F_D is the towing force actually applied in the propulsion test. R_C is the resistance corrected for differences in temperature between resistance and self-propulsion tests:

$$R_C = \frac{(1+k)C_{FMC} + C_W}{(1+k)C_{FM} + C_W} R_{TM}$$

where C_{FMC} is the frictional resistance coefficient at the temperature of the self-propulsion test.

2.4 Full Scale Predictions

2.4.1 Total resistance of ship

The total resistance coefficient of a ship without bilge keels is

$$C_{TS} = (1+k)C_{FS} + \Delta C_F + C_A + C_W + C_{AAS}$$

where

- k is the form factor determined from the resistance test, see ITTC standard procedure 7.5-02-02-01. Additionally, the determination can be supported by CFD calculation according to ITTC Guideline 7.5-03-02-04, “Practical Guidelines for Ship Resistance CFD”, and following ITTC Recommended Procedure 7.5-03-01-02, “Quality Assurance in Ship CFD Application”, using model scale benchmark data as well as full scale data for the demonstration.
- C_{FS} is the frictional resistance coefficient of the ship according to the ITTC-1957 model-ship correlation line
- C_W is the wave resistance coefficient calculated from the total and frictional resistance coefficients of the model in the resistance tests:

$$C_W = C_{TM} - C_{FM}(1+k)$$

The form factor k and the total resistance coefficient for the model C_{TM} are determined as described in the ITTC standard procedure 7.5-02-02-01.

The correlation factor for the calculation of the resistance has been separated from the roughness allowance. The roughness allowance ΔC_F per definition describes the effect of the roughness of the hull on the resistance. The correlation factor C_A is supposed to allow for all effects not covered by the prediction method, mainly uncertainties of the tests and the prediction method itself and the assumptions made for the prediction method. The separation of ΔC_F from C_A was proposed by the Performance Prediction Committee of the 19th ITTC. This is essential to allow for the effects of newly developed hull coating systems.

The 19th ITTC also proposed a modified formula for C_A that excludes roughness allowance, which is now given in this procedure.

- ΔC_F is the roughness allowance

$$\Delta C_F = 0.044\left[\left(\frac{k_S}{L_{WL}}\right)^{\frac{1}{3}} - 10 \cdot Re^{-\frac{1}{3}}\right] + 0.000125$$

where k_S indicates the roughness of hull surface. When there is no measured data, the standard value of k_S=150×10^{-6} m can be used. For modern coating different value will have to be considered.

- C_A is the correlation allowance

C_A is determined from comparison of model and full scale trial results. When using the roughness allowance as above, the 19th ITTC recommended using

$$C_A = (5.68 - 0.6 \log Re) \times 10^{-3}$$

It is recommended that each institution maintains their own model-full scale correlation. See section 2.4.4 for a further discussion on correlation.

- C_{AAS} is the air resistance coefficient in full scale

$$C_{AAS} = C_{DA} \frac{\rho_A \cdot A_{VS}}{\rho_S \cdot S_S}$$

where, A_{VS} is the projected area of the ship above the water line to the transverse plane, S_S is the wetted surface area of the ship, ρ_A is the air density, and C_{DA} is the air drag coefficient of the ship above the water line. C_{DA} can be determined by wind tunnel model tests or calculations. Values of C_{DA} are typically in the range 0.5-1.0, where 0.8 can be used as a default value.

If the ship is fitted with bilge keels of modest size, the total resistance is estimated as follows:

$$C_{TS} = \frac{S_S + S_{BK}}{S_S}\left[(1+k)C_{FS} + \Delta C_F + C_A\right] + \\ + C_R + C_{AAS}$$

$$C_{TS} \\ = \frac{S_S + S_{WBK}}{S_S}\left[(1+k)C_{FS} + \Delta C_F + C_A\right] + C_R \\ + C_{AAS}$$

where S_{WBK} is the wetted surface area of the bilge keels.

When the model appendage resistance is separated from the total model resistance, as described as an option in the ITTC Standard Procedure 7.5-02-02-01, the full scale appendage resistance needs to be added, and the formula for total resistance (with bilge keels) becomes:

$$C_{TS} \\ = \frac{S_S + S_{BK}}{S_S}\left[(1+k)C_{FS} + \Delta C_F + C_A\right] + C_W \\ + C_{AAS} + C_{APPS}$$

$$C_{TS} \\ = \frac{S_S + S_{WBK}}{S_S}\left[(1+k)C_{FS} + \Delta C_F + C_A\right] + C_W \\ + C_{AAS} + C_{APPS}$$

There is not only one recommended method of scaling appendage resistance to full scale. The following alternative methods are well established:

1) Scaling using a fixed fraction:

$$C_{APPS} = (1-\beta)C_{APPM}$$

where $(1-\beta)$ is a constant in the range 0.6-1.0.

2) Calculating the drag of each appendage separately, using local Reynolds number and form factor.

$$C_{APPS} = \sum (1-w_i)^2 (1+k_i) C_{FSi} \frac{S_i}{S_S}$$

$$Re = \frac{V\left(\frac{S_{APP}}{2}\right)^{\frac{1}{2}}}{\upsilon} \quad or \quad Re = \frac{VL}{\nu}$$

where index i refers to the number of the individual appendices. w_i is the wake fraction at the position of appendage i. k_i is the form factor of appendage i. C_{FSi} is the frictional resistance coefficient of appendage i, and S_i is the wetted surface area of appendage i. Note that the method is not scaling the model appendage drag, but calculating the full scale appendage drag. The model appendage drag, if known from model tests, can be used for the determination of e.g. the wake fractions w_i. Values of the form factor k_i can be found from published data for generic shapes, see for instance Hoerner (1965) or Kirkman and Klöetsli (1980). L is the characteristic length of appendage.

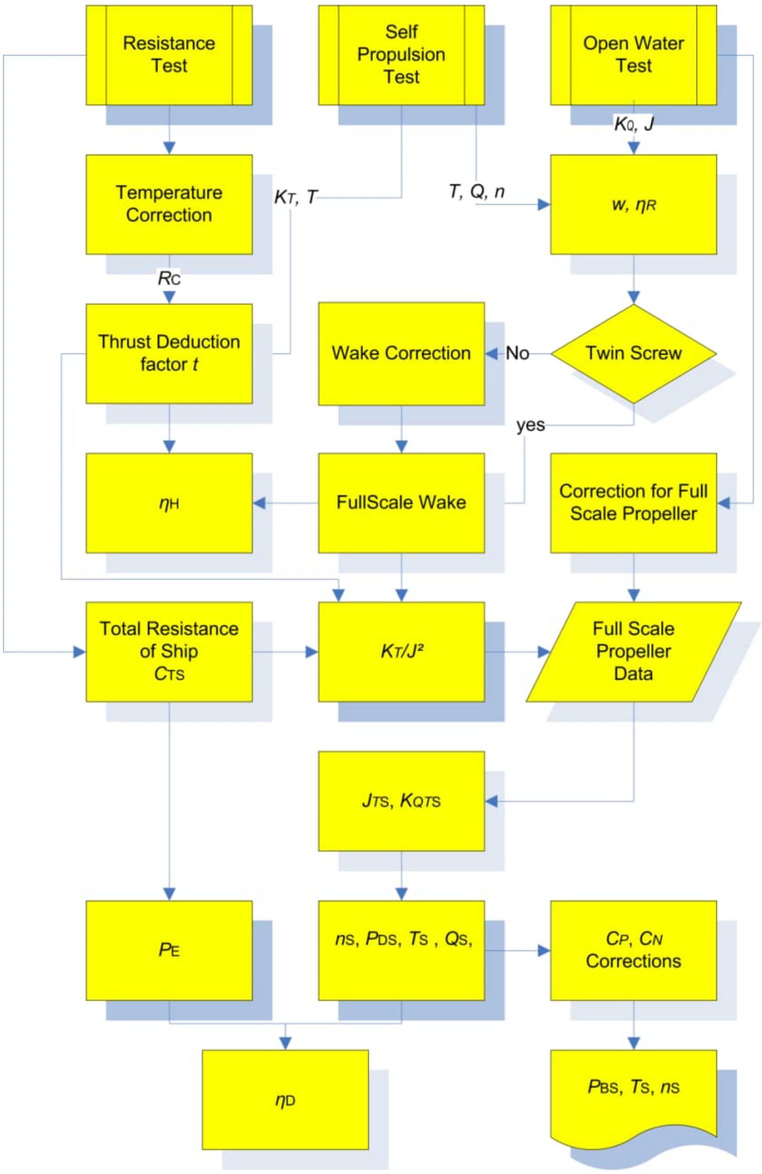

Figure 1 Flow chart of full scale predictions

2.4.2 Scale effect corrections for propeller characteristics

The characteristics of the full-scale propeller are calculated from the model characteristics as follows:

$$K_{TS} = K_{TM} - \Delta K_T$$

$$K_{QS} = K_{QM} - \Delta K_Q$$

where

$$\Delta K_T = -\Delta C_D \cdot 0.3 \cdot \frac{P}{D} \cdot \frac{c \cdot Z}{D}$$

$$\Delta K_Q = \Delta C_D \cdot 0.25 \cdot \frac{c \cdot Z}{D}$$

The difference in drag coefficient ΔC_D is

$$\Delta C_D = C_{DM} - C_{DS}$$

where

$$C_{DM} = 2\left(1 + 2\frac{t}{c}\right)\left[\frac{0.044}{(Re_{0.7})^{\frac{1}{6}}} - \frac{5}{(Re_{c0})^{\frac{2}{3}}}\right]$$

and

$$C_{DS} = 2\left(1 + 2\frac{t}{c}\right)\left(1.89 + 1.62 \cdot log\frac{c}{k_P}\right)^{-2.5}$$

In the formulae listed above *c* is the chord length, *t* is the maximum thickness, *P/D* is the pitch ratio and $Re_{0.7}$ is the local Reynolds number with Kempf's definition at the open-water test. They are defined for the representative blade section, such as at *r/R*=0.7. k_P denotes the blade roughness, the standard value of which is set k_P=30×10^{-6} m. $Re_{0.7}$ must not be lower than 2×10^5.

2.4.3 Full scale wake and operating condition of propeller

The full-scale wake is calculated by the following formula using the model wake fraction w_{TM}, and the thrust deduction fraction *t* obtained as the analysed results of self-propulsion test:

$$w_{TS} = (t + w_R) + (w_{TM} - t - w_R)\frac{(1 + k)C_{FS} + \Delta C_F}{(1 + k)C_{FM}}$$

where w_R stands for the effect of rudder on the wake fraction. If there is no estimate for w_R, the standard value of 0.04 can be used.

If the estimated w_{TS} is greater than w_{TM}, w_{TS} should be set as w_{TM}.

The wake scale effect of twin screw ships with open sterns is usually small, and for such ships it is common to assume $w_{TS} = w_{TM}$.

For twin skeg-like stern shapes a wake correction is recommended. A correction like the one used for single screw ships may be used.

The load of the full-scale propeller is obtained from

$$\frac{K_T}{J^2} = \frac{1}{N_P} \cdot \frac{S_S}{2D_S^2} \cdot \frac{C_{TS}}{(1 - t) \cdot (1 - w_{TS})^2}$$

where N_P is the number of propellers.

With this K_T/J^2 as input value the full scale advance coefficient J_{TS} and the torque coefficient K_{QTS} are read off from the full scale propeller characteristics and the following quantities are calculated.

- the rate of revolutions:

$$n_S = \frac{(1-w_{TS})\cdot V_S}{J_{TS}\cdot D_S} \qquad \text{(r/s)}$$

- the delivered power of each propeller:

$$P_{DS} = 2\pi\rho_S D_S^5 n_S^3 \frac{K_{QTS}}{\eta_R} \cdot 10^{-3} \qquad \text{(kW)}$$

- the thrust of each propeller:

$$T_S = \left(\frac{K_T}{J^2}\right) \cdot J_{TS}^2 \rho_S D_S^4 n_S^2 \qquad \text{(N)}$$

- the torque of each propeller:

$$Q_S = \frac{K_{QTS}}{\eta_R} \cdot \rho_S D_S^5 n_S^2 \qquad \text{(Nm)}$$

- the effective power:

$$P_E = C_{TS} \cdot \frac{1}{2}\rho_S V_S^3 S_S \cdot 10^{-3} \qquad \text{(kW)}$$

- the quasi-propulsive efficiency:

$$\eta_D = \frac{P_E}{N_P \cdot P_{DS}}$$

- the hull efficiency:

$$\eta_H = \frac{1-t}{1-w_{TS}}$$

2.4.4 Model ship correlation factor

The model-ship correlation factor should be based on systematic comparison between full scale trial results and predictions from model scale tests. Thus, it is a correction for any systematic errors in model test and powering prediction procedures, including any facility bias.

In the following, several different alternative concepts of correlation factors are presented as suggestions. It is left to each member organisations to derive their own values of the correlation factor(s), taking into account also the actual value used for C_A.

(1) Prediction of full scale rates of revolutions and delivered power by use of the C_P – C_N correction factors

Using C_P and C_N the finally predicted trial data will be calculated from

$$n_T = C_N \cdot n_S \qquad \text{(r/s)}$$

for the rates of revolutions and

$$P_{DT} = C_P \cdot P_{DS} \qquad \text{(kW)}$$

for the delivered power.

(2) Prediction of full scale rates of revolutions and delivered power by use of ΔC_{FC} - Δw_C corrections

In such a case the finally trial predicted trial data are calculated as follows:

$$\frac{K_T}{J^2} = \frac{1}{N_P} \cdot \frac{S_S}{2D_S^2} \cdot \frac{C_{TS} + \Delta C_{FC}}{(1-t)\cdot(1-w_{TS}+\Delta w_C)^2}$$

With this K_T/J^2 as input value, J_{TS} and K_{QTS} are read off from the full scale propeller characteristics and the following is calculated:

$$n_T = \frac{(1-w_{TS}+\Delta w_C)\cdot V_S}{J_{TS}\cdot D_S} \qquad \text{(r/s)}$$

$$P_{DT} = 2\pi\rho_S D_S^5 n_T^3 \frac{K_{QTS}}{\eta_R} \cdot 10^{-3} \qquad \text{(kW)}$$

(3) Prediction of full-scale rates of revolutions and delivered power by use of a C_{NP} correction

For prediction with emphasis on stator fins and rudder effects, it is sometimes recommended to use power identity for the prediction of full scale rates of revolution.

At the point of K_T-(J)-Identity the condition is reached where the ratio between the propeller induced velocity and the entrance velocity is the same for the model and the full scale ship. Ignoring the small scale effect ΔK_T on the thrust coefficient K_T it follows that J-identity correspond to K_T- and C_T-identity. As a consequence it follows that for this condition the axial flow field in the vicinity of the propeller is on average correctly simulated in the model experiment. Also the axial flow of the propeller slip stream is on average correctly simulated. Due to the scale effects on the propeller blade friction, which affect primarily the torque, the point of K_Q-identity (power identity) represents a slightly less heavily loaded propeller than at J-, K_T- and C_T-identity. At the power identity the average rotation in the slipstream corresponds to that of the actual ship and this condition is regarded as important if tests on stator fins and/or rudders are to be done correctly.

In this case, the shaft rate of revolutions is predicted on the basis of power identity as follows:

$$\left(\frac{K_Q}{J^3}\right)_T = \frac{1000 \cdot C_P \cdot P_{DS}}{2\pi \rho_S D_S^2 V_S^3 (1 - w_{TS})^3}$$

$$\frac{K_{Q0}}{J^3} = \left(\frac{K_Q}{J^3}\right)_T \cdot \eta_{RM}$$

$$n_S = \frac{(1 - w_{TS}) \cdot V_S}{J_{TS} \cdot D_S}$$

$$n_T = C_{NP} \cdot n_S$$

2.5 Load Variation Test

2.5.1 Purpose of load variation test

Load variation test is conducted to find out the variation of performance such as the efficiency, speed of revolution, propeller torque and thrust according to the variation of load on ship resistance. The self-propulsion test is normally conducted in calm water however the actual ship operates in non-still sea. The load variation test therefore is necessary to be carried out in self-propulsion condition to find out performance dependency on different loading conditions at same speed.

2.5.2 Method of load variation test

A load variation test is carried out at the selected draught and at minimum one speed. This speed shall be one of the speeds tested in the normal self-propulsion test. The load variation test includes at least 4 self-propulsion test runs, each one at a different rate of revolution while keeping the speed constant. The rate of revolutions are to be selected such that

$$\frac{\Delta R}{R_0} \approx [-0.1,0,0.1,0.2]\text{`} \qquad (1)$$

Where

$$\Delta R = (F_D - F_X)\,\lambda^3 \frac{\rho_S}{\rho_M} \qquad (2)$$

R_0 is full scale resistance without overload.r0

With reference to the resistance tests and in order to fulfil (1), the target tow force (F_x) can be calculated as follows:

$$F_X = F_D - [-0.1,0,0.1,0.2](R_{TM} - F_D) \qquad (3)$$

$$F_x = F_D - [-0.1,0,0.1,0.2](R_{TM} - F_{Dskin})$$

It is noted that F_{Dskin} is skin friction correction force defined as F_D in ITTC Recommended Procedure 7.5-02-03-01.1.

The “added resistance” in the load variation test has to be accounted for in the post processing. The measured data is processed according to ITTC Recommended Procedure 7.5–02–03–01.4 (1978 ITTC Performance Prediction Method), from section 2.4.3 and onwards, prepared for the standard self-propulsion test at tow force F_D with one modification. That C_{TS} is replaced by C_{TAdd}

with

$$C_{\mathrm{TAdd}} = C_{\mathrm{TS}} + \frac{\Delta R}{1/2\,\rho_S V_S{}^2 S_S} \qquad (4)$$

2.5.3 Dependency of propulsion efficiency with resistance increase

The fraction between the propulsion efficiency considering the load variation effect η_D and that in ideal condition η_{D0} is plotted against the fraction between the resistance increase ΔR and resistance in ideal condition R_0. Figure 3 shows an example. The variable ξ_P is the slope of the linear curve ideally going through {0, 1} and fitted to the data points with least square method.

$$\frac{\eta_D}{\eta_{D0}} = \xi_P \frac{\Delta R}{R_0} + 1 \tag{5}$$

2.5.4 Dependency of shaft rate with power increase

Similarly, the effect on shaft rate $\Delta n/n$ (the fraction between the deviation of shaft rate due to load variation effect Δn and the shaft rate in ideal condition n) is plotted against $\Delta P/P_{D0}$ (the fraction between power increase ΔP and the power in ideal condition P_{D0}). The variable ξ_N is the slope of the linear curve ideally going through {0, 0} and fitted to the data points with least square method. Figure3 gives an example.

$$\frac{\Delta \mathrm{n}}{\mathrm{n}} = \xi_N \frac{\Delta \mathrm{P_D}}{\mathrm{P_{D0}}} \tag{6}$$

2.5.5 Dependency of shaft rate with speed change

The dependency of shaft rate with speed is derived through the following steps:
The shaft rate n in ideal condition is plotted against the resistance $R_0+\Delta R$ $(\Delta R=0)$ for a number of speeds in the same graph (in Figure 5). The shaft rate n considering the load variation effect is plotted against the resistance $R_0+\Delta R$ $(\Delta R\neq 0)$ for the speed closest to the predicted EEDI (Dashed line in Figure 5). In addition, the linear curve going through $\{R_0, n\}$ and fitted to the data points $\{R_0+\Delta R, n\}$ is obtained with least square method. Lines going through the point $\{R_0, n\}$ for each speed and parallel to the linear curve obtained above are plotted. A vertical line going through the resistance in ideal condition for the speed closest to the predicted EEDI speed is plotted in the graph (in Figure 5) From the intersections of lines (square □), the shaft rate for the corresponding speed of the each line can be obtained.

For each of the intersection points, compute $\Delta V/V_S$ relative to the speeds which is closest to the predicted EEDI speed. For each of the intersection points, compute $\Delta n/n$ relative to the n-values which is closest to the predicted EEDI speed. These points in a $\Delta n/n$ over $\Delta V/V_S$ graph (Figure 6) are plotted. This gives the rpm dependency of speed. The slope of the $\Delta n/n$ - $\Delta V/V_S$ curve fitted with least square method is ξ_V (Figure 6).

$$\frac{\Delta n}{n} = \xi_V \frac{\Delta V}{V_S} \tag{7}$$

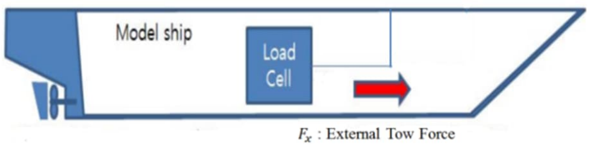

Figure 2 Typical Measurement System

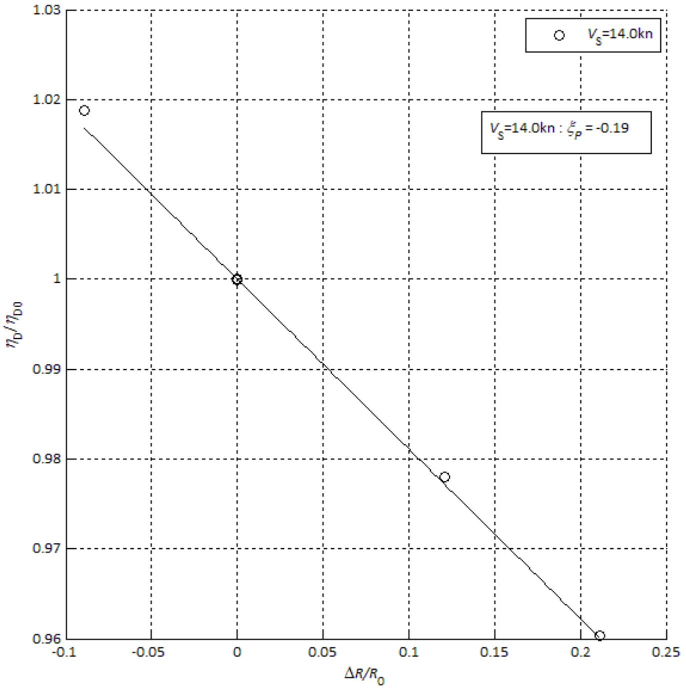

Figure 3 Relation between propeller efficiency and resistance increase

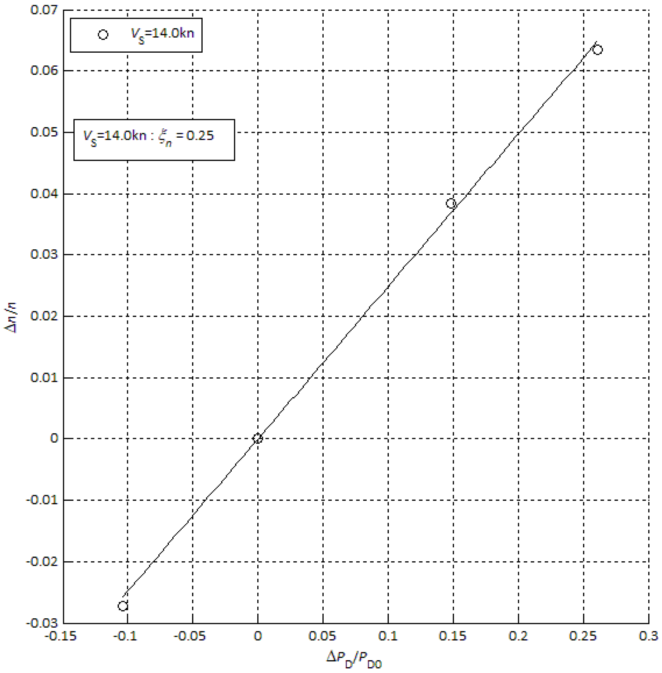

Figure 4 Relation between propeller rate and power increase

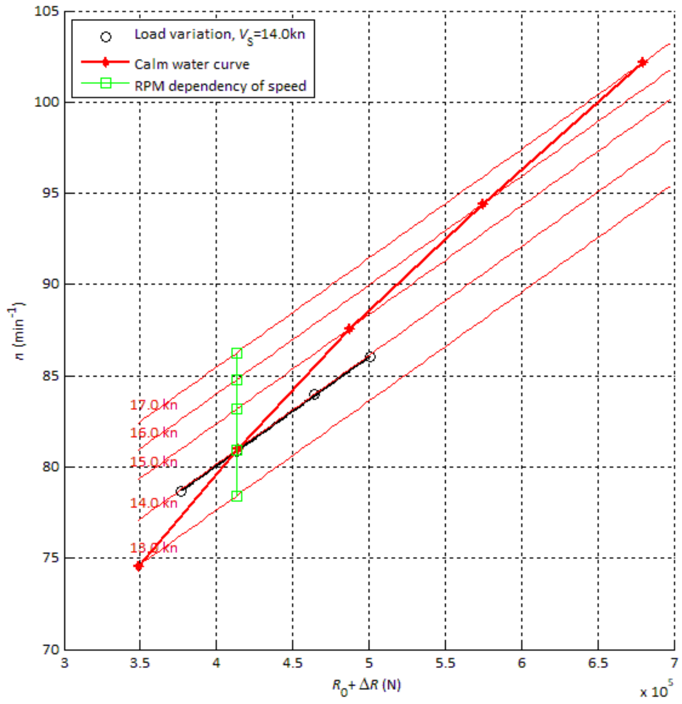

Figure 5 Relation between propeller rate and speed change

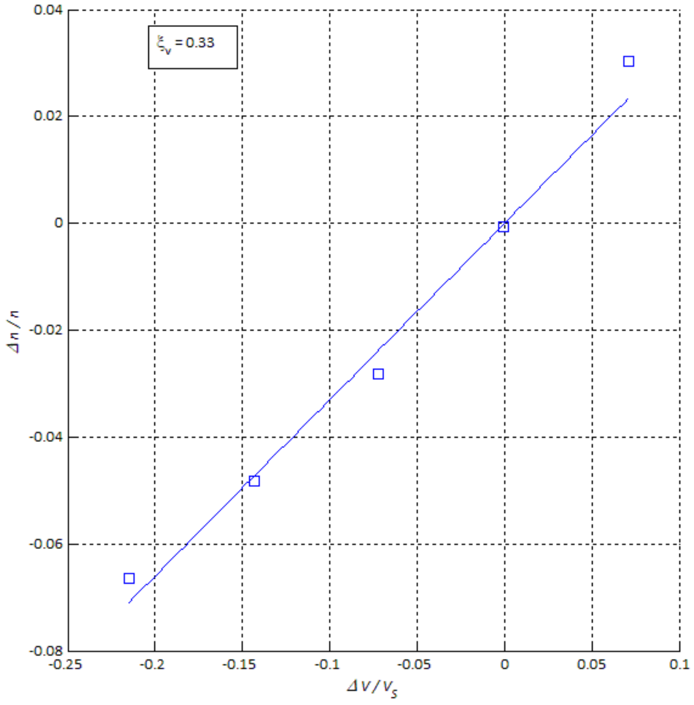

Figure 6 Relation between propeller rate and speed change, second step

2.6 Documentation

The results from the test should be collated in a report which should contain at least the following information:

- Model Hull Specification:
    - Identification (model number or similar)
    - Draughts and Displacement volume
    - Turbulence stimulation method
    - Model scale
    - Model material
- Main dimensions and hydrostatics (see ITTC Recommended Procedure 7.5-01-01-01 Hull Model).
- Model Propeller Specification
    - Identification (model number or similar)
    - Model Scale
    - Main dimensions and particulars (see ITTC Recommended Procedure 7.5-01-01-01 Propeller/Propulsion unit model)
    - Model material
- Particulars of the towing tank, including length, breadth and water depth
- Test date
- Parametric data for the test:
    - Water temperature in towing tank
    - Water density in towing tank
    - Kinematic viscosity of the water
    - Form factor (even if (1+*k*) = 1.0 is applicable, this should be stated)
    - Roughness of hull and propeller
    - Water temperature of full-scale
    - Water density of full-scale
- For each speed the following data should be given as a minimum:
    - External tow force
    - Sinkage fore and aft, or sinkage and trim
    - Propeller thrust, torque and rate of revolutions.
    - Correlation allowance C_A
    - Propulsive efficiency
    - Hull efficiency
    - Relative rotative efficiency
    - Taylor wake fraction
    - Thrust deduction factor
    - Trial prediction with C_P, C_N
    - Ship service prediction(ship speed, rate of revolution, delivered power, Sea Margin)
    - Overload factors(ξ_N, ξ_P, ξ_V), only used for attaining EEDI speed

3. VALIDATION

3.1 Uncertainty Analysis

Not yet available

3.2 Comparison with Full Scale Results

The data that led to 1978 ITTC performance prediction method can be found in the following ITTC proceedings:

1. Proposed Performance Prediction Factors for Single Screw Ocean Going Ships (13th 1972 pp.155-180) Empirical Power Prediction Factor (1+X)
2. Propeller Dynamics Comparative Tests (13th 1972 pp.445-446)
3. Comparative Calculations with the ITTC Trial Prediction Test Programme (14th 1975 Vol.3 pp.548-553)
4. Factors Affecting Model Ship Correlation (17th 1984 Vol.1 pp274-291)

4. REFERENCES

(1) Hoerner, S.F. (1965) “Fluid-Dynamic Drag”. Published by the author.

(2) Kirkman, K.L., Klöetsli, J.W. (1980) “Scaling Problems of model appendages”, 19th American Towing Tank Conference, Ann Arbor, Michigan

(3) "Guideline on the determination of model-ship correlation factors", 2017, Revision04

Appendix A. EXAMPLE OF ANALYSIS OF LOAD VARIATION TEST

This appendix gives the details of a load variation test for the SSPA benchmark data used in the exemplified figures in section 2.5. The data is analysed using the ITTC 1978 performance prediction method version 0, as published in 1999, in the same way of the original report by Werner,S. (2018).

Table A1 shows principal particulars of the ship and propeller. Table A2 shows the open water characteristics in model and full scale. The resistance and self-propulsion test results in the load variation test are shown in Table A3. By assuming the form factor k =0.240, the full-scale performance is calculated as shown in Table A4. The values in ideal condition are written with bold letters in the table.

Figure A1 shows the relation between propulsion efficiency and resistance increase from those in the ideal condition. The variable ξ_P is determined to be -0.19, which is the slope of the linear curve going through {0,1} and fitted to the data points with least square method. Similarly, the relation between propeller rate and power increase is plotted in Figure A2. The variable ξ_N is determined to be 0.25, which is the slope of the linear curve going through {0,0} and fitted to the data points with least square method.

The propeller rate n_S is plotted against the resistance R_{TS} as circle marks in Figure A3. The linear curve is obtained with least square method. n_S and R_{TS} in Table A5 obtained in the normal propulsion test are plotted in the same figure. The lines going through the points $\{R_{TS}, n_S\}$ for each speed are drawn with the same slope of the linear curve. The propeller rates corresponding to the resistance at the reference speed = 13.990 knots are intersected for each speed (square marks). Figure A4 shows the propeller rate and speed change at the reference speed. The variable ξ_V is determined to be 0.32, which is the slope of the linear curve fitted to the data points with least square method.

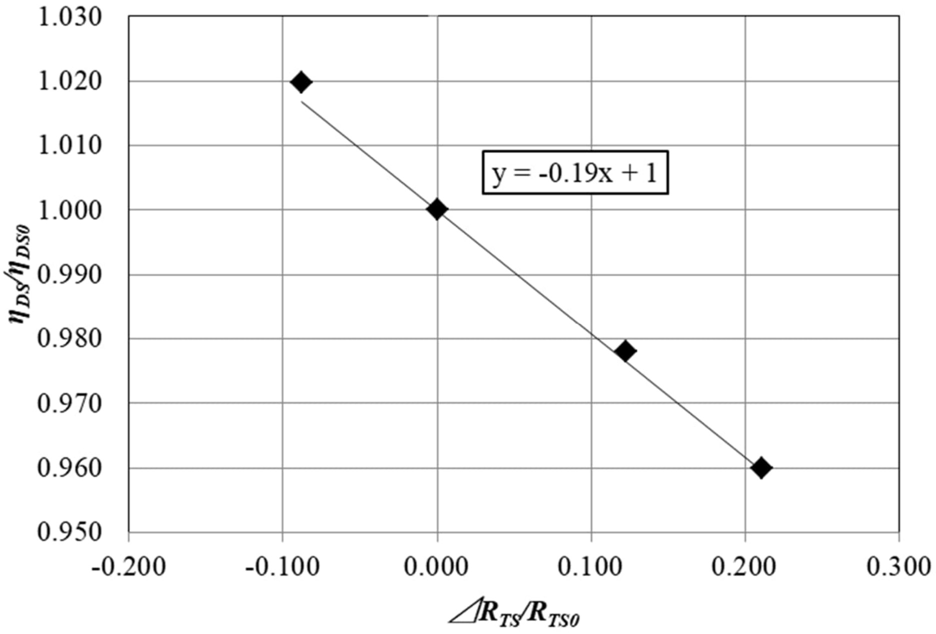

Figure A1 Relation between propulsion efficiency and resistance increase

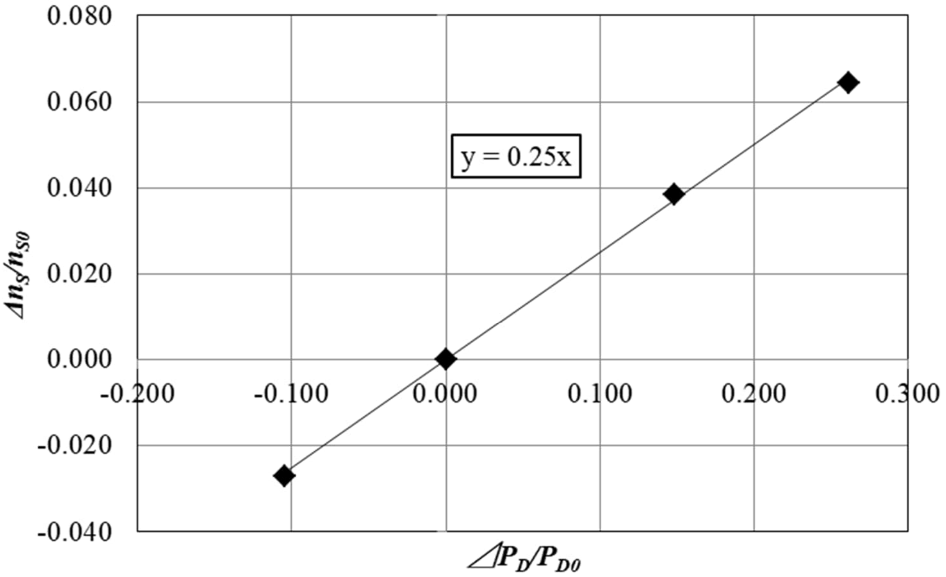

Figure A2 Relation between propeller rate and power increase

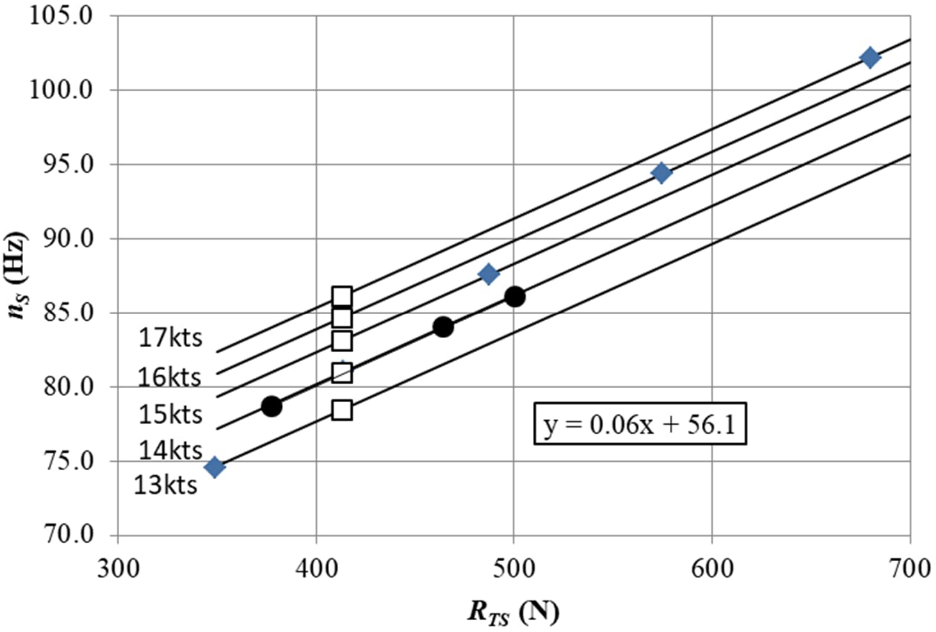

Figure A3 Relation between propeller rate and speed change

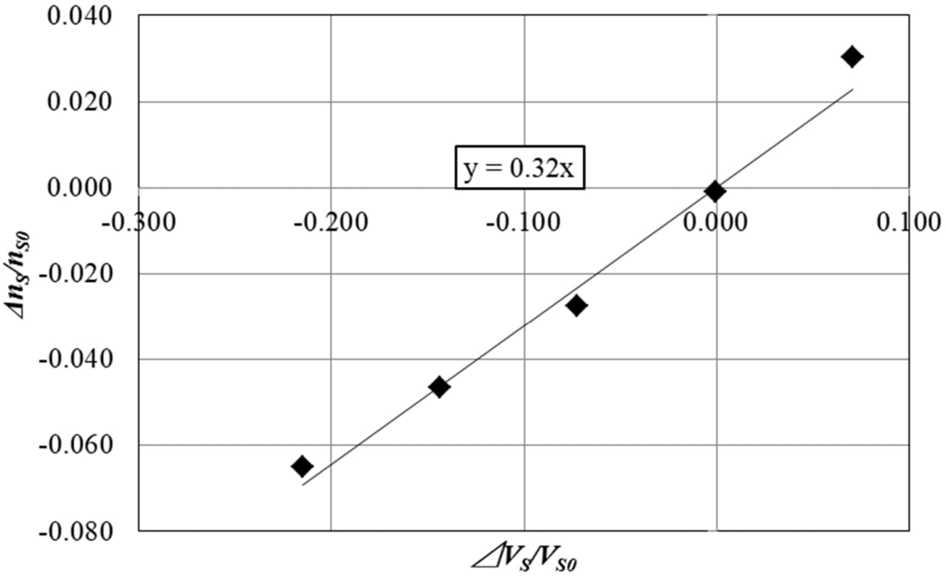

Figure A4 Relation between propeller rate and speed change, second step

Table A1 Principal particulars of ship and propeller and water property

(Ship)

Scale	26.25
L_{BP} [m]	178
L_{WL} [m]	176
T_F [m]	6.3
T_A [m]	7
B [m]	27
S_{Hull} [m^2]	5770
S_{Rudder} [m^2]	60
$S_{bilge\ keel}$ [m^2]	75
A_V [m^2]	625
∇ [m^3]	24900
k_S [µm]	150

(Propeller)

Z	4
D [m]	6.3
P/D	0.832
$c_{0.75R}$ [m]	1.727
$t_{0.75R}$ [m]	0.059
k_P [µm]	30

(Water properties)

ρ_M [kg/m^3]	1000
ρ_S [kg/m^3]	1025
ν_M [m^2/s]	1.139E-06
ν_S [m^2/s]	1.188E-06

Table A2 Open water characteristics

J	K_{TM}	$10K_{QM}$	K_{TS}	$10K_{QS}$
0.181	0.3234	0.3874	0.3238	0.3838
0.252	0.2961	0.3612	0.2965	0.3576
0.323	0.2682	0.3347	0.2686	0.3311
0.393	0.2398	0.3077	0.2402	0.3041
0.464	0.2111	0.2803	0.2115	0.2767
0.534	0.1821	0.2519	0.1825	0.2483
0.605	0.1523	0.222	0.1527	0.2184
0.676	0.1213	0.1899	0.1217	0.1863
0.746	0.0883	0.1547	0.0887	0.1511
0.817	0.0524	0.1151	0.0528	0.1115

Table A3 Model test results in load variation test

V_S [knots]	R_{TM} [N]	F_D [N]	T_M [N]	Q_M [Nm]	n_M [Hz]	w_{TM} [-]	t [-]	η_R [-]
13.990	34.580	9.880	30.380	0.965	6.790	0.427	0.187	1.020
14.000	34.630	7.190	33.620	1.059	7.060	0.418	0.184	1.022
13.990	34.580	5.170	36.080	1.131	7.230	0.418	0.185	1.021
14.000	34.630	11.880	28.060	0.895	6.600	0.431	0.189	1.022

Table A4 Predicted performance in full scale (load variation test)

V_S [knots]	n_S [Hz]	R_{TS} [N]	η_D [-]	P_D [kW]	$\Delta n_S/n_{S0}$ [-]	$\Delta R_{TS}/R_{TS0}$ [-]	$\Delta\eta_D/\eta_{D0}$ [-]	$\Delta P_D/P_{D0}$ [-]
13.990	**80.9**	**413**	**0.810**	**3671**	**0.000**	**0.000**	**1.000**	**0.000**
14.000	84.0	464	0.792	4217	0.039	0.123	0.978	0.149
13.990	86.1	501	0.778	4632	0.064	0.211	0.960	0.262
14.000	78.7	377	0.826	3287	-0.027	-0.088	1.020	-0.105

Table A5 Predicted performance in full scale (normal propulsion test)

V_S [knots]	n_S [Hz]	R_{TS} [N]	η_D [-]	P_D [kW]	n_S at R_{TS0} [Hz]	$\Delta V_S/V_{S0}$ [-]	$\Delta n_S/n_{S0}$ [-]
13	74.6	349	0.815	2860	78.4	0.071	0.030
14	81.0	414	0.811	3676	81.0	-0.001	-0.001
15	87.6	487	0.807	4658	83.1	-0.072	-0.028
16	94.4	575	0.798	5926	84.7	-0.144	-0.047
17	102.2	680	0.781	7617	86.2	-0.215	-0.065