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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 the Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{FC}$</td>
<td>Frictional resistance coefficient at the temperature of the self propulsion test</td>
</tr>
<tr>
<td>$C_{NP}$</td>
<td>Trial correction for propeller rate of revolution at power identity</td>
</tr>
<tr>
<td>$C_{F}$</td>
<td>Trial correction for delivered power</td>
</tr>
<tr>
<td>$C_{N}$</td>
<td>Trial correction for propeller rate of revolution at speed identity</td>
</tr>
<tr>
<td>$C_R$</td>
<td>Residual resistance coefficient</td>
</tr>
<tr>
<td>$C_T$</td>
<td>Total resistance coefficient</td>
</tr>
<tr>
<td>$D$</td>
<td>Propeller diameter</td>
</tr>
<tr>
<td>$F_D$</td>
<td>Skin friction correction in self propulsion test</td>
</tr>
<tr>
<td>$J$</td>
<td>Propeller advance coefficient</td>
</tr>
<tr>
<td>$J_T$</td>
<td>Propeller advance coefficient achieved by thrust identity</td>
</tr>
<tr>
<td>$J_Q$</td>
<td>Propeller advance coefficient achieved by torque identity</td>
</tr>
<tr>
<td>$K_T$</td>
<td>Thrust coefficient</td>
</tr>
<tr>
<td>$K_{TQ}$</td>
<td>Thrust coefficient achieved by torque identity</td>
</tr>
<tr>
<td>$K_Q$</td>
<td>Torque coefficient</td>
</tr>
<tr>
<td>$K_{QT}$</td>
<td>Torque coefficient achieved by thrust identity</td>
</tr>
<tr>
<td>$k$</td>
<td>Form factor</td>
</tr>
<tr>
<td>$k_P$</td>
<td>Propeller blade roughness</td>
</tr>
<tr>
<td>$k_s$</td>
<td>Roughness of hull surface</td>
</tr>
<tr>
<td>$N_P$</td>
<td>Number of propellers</td>
</tr>
<tr>
<td>$n$</td>
<td>Propeller rate of revolution</td>
</tr>
<tr>
<td>$n_{PT}$</td>
<td>Propeller rate of revolution, corrected using correlation factor</td>
</tr>
<tr>
<td>$P$</td>
<td>Propeller pitch</td>
</tr>
<tr>
<td>$P_D$, $P_P$</td>
<td>Delivered Power, propeller power</td>
</tr>
<tr>
<td>$P_{DT}$</td>
<td>Delivered Power, corrected using correlation factor</td>
</tr>
</tbody>
</table>
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).

\[
K_{TM} = \frac{T_M}{\rho_M D_M^2 \eta_M^2} \quad \text{and} \quad K_{QM} = \frac{Q_M}{\rho_M D_M^2 \eta_M^2}
\]

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

\[
w_{TM} = 1 - \frac{J_{TM} D_M \eta_M}{V_M}
\]

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 $K_{QTM}$ is read off from the model propeller open water diagram, and the wake fraction

\[
w_{QM} = 1 - \frac{J_{QM} D_M \eta_M}{V_M}
\]

and the relative rotative efficiency

\[
\eta_R = \frac{K_{QTM}}{K_{QM}}
\]

are calculated. $V_M$ is model speed.

The thrust deduction is obtained from
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:

\[
R_C = \frac{(1+k)C_{FMC} + C_R}{(1+k)C_{FM} + C_R} R_{TM}
\]

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

\[
C_{TS} = (1+k)C_{FS} + \Delta C_F + C_A + C_R + C_{AAS}
\]

where

- \( k \) is the form factor determined from the resistance test, see ITTC standard procedure 7.5-02-02-01.
- \( C_{FS} \) is the frictional resistance coefficient of the ship according to the ITTC-1957 model-ship correlation line.
- \( C_R \) is the residual resistance coefficient calculated from the total and frictional resistance coefficients of the model in the resistance tests:

\[
C_R = C_{TM} - (1+k)C_{FM}
\]

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 \( \Delta C_F \) 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 \( \Delta C_F \) from \( C_A \) was proposed by the Performance Prediction Committee of the 19\textsuperscript{th} ITTC. This is essential to allow for the effects of newly developed hull coating systems.

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

- \( \Delta C_F \) is the roughness allowance

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

where \( k_S \) indicates the roughness of hull surface. When there is no measured data, the standard value of \( k_S=150\times10^{-6}\) 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 19\textsuperscript{th} ITTC recommended using

\[
C_A = (5.68 - 0.6 \log Re) \times 10^{-3}
\]
to give values of $\Delta C_F + C_A$ that approximates the values of $\Delta C_F$ of the original 1978 ITTC method. 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, $\rho_A$ 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:

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

where $S_{BK}$ 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:

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

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:

$$C_{AppS} = (1 - \beta) \cdot C_{AppM}$$

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.

$$C_{AppS} = \sum_{i=1}^{n} (1 - w_i)^2 \cdot (1 + k_i) \cdot C_{FSi} \cdot \frac{S_i}{S_S}$$

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).
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 \( \Delta C_D \) is
\[ \Delta C_D = C_{DM} - C_{DS} \]

where

\[ C_{DM} = 2 \left( 1 + 2 \frac{t}{c} \right) \left[ \frac{0.044}{(Re_c)^{\frac{1}{5}}} - \frac{5}{(Re_c)^{\frac{2}{5}}} \right] \]

and

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

In the formulae listed above, \( c \) is the chord length, \( t \) is the maximum thickness, \( P/D \) is the pitch ratio and \( Re_c \) 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 \( r/R = 0.75 \). \( k_p \) denotes the blade roughness, the standard value of which is set \( k_p = 30 \times 10^{-6} \) m. \( Re_c \) must not be lower than \( 2 \times 10^5 \).

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 \( w_m \), and the thrust deduction fraction \( t \) obtained as the analysed results of self-propulsion test:

\[ w_T = (t + w_R) + (w_m - t - w_R) \left( \frac{1+k}{1+k} \right) C_p \Delta C_p \]

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 \( w_T \) is greater than \( w_M \), \( w_T \) should be set as \( w_M \).

The wake scale effect of twin screw ships with open stems is usually small, and for such ships it is common to assume \( w_T = w_M \).

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

\[ \frac{K_T}{J^2} = \frac{1}{N_p} \cdot \frac{S_S}{2D^2} \cdot \frac{C_{TS}}{(1-t) \cdot (1-w_T)^2} \]

where \( N_p \) is the number of propellers.

With this \( K_T / J^2 \) as input value the full scale advance coefficient \( J_T \) and the torque coefficient \( K_{QS} \) are read off from the full scale propeller characteristics and the following quantities are calculated.

- the rate of revolutions:
  \[ n_s = \frac{(1-w_T) \cdot V_S}{J_T \cdot D_S} \] (r/s)

- the delivered power of each propeller:
  \[ P_{DS} = 2\pi \rho S S^2 D_S^4 \frac{K_{QS}}{n_s} \cdot 10^{-3} \] (kW)

- the thrust of each propeller:
  \[ T_S = \left( \frac{K_T}{J^2} \right) \cdot J_T^2 \rho S D_S^4 n_s^3 \] (N)

- the torque of each propeller:
  \[ Q_S = \frac{K_{QS}}{\eta_R} \cdot \rho S D_S^4 n_s^2 \] (Nm)

- the effective power:
  \[ P_E = C_{TS} \cdot \frac{1}{2} \rho S V_S^3 S_S \cdot 10^{-3} \] (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

\[
n_T = C_N \cdot n_S \quad (r/s)
\]

for the rates of revolutions and

\[
P_{DT} = C_P \cdot P_{DS} \quad (kW)
\]

for the delivered power.

(2) Prediction of full scale rates of revolutions and delivered power by use of \(\Delta C_{FC} - \Delta w_{C}\) corrections

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

\[
\frac{K_T}{J^2} = \frac{1}{N_p} \cdot \frac{S_s}{2D_s^2} \cdot \frac{C_{TS} + \Delta C_{PC}}{(1 - t) \cdot (1 - w_{TS} + \Delta w_C)^2}
\]

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:

\[
n_T = \frac{(1 - w_{TS} + \Delta w_C) \cdot V_s}{J_{TS} \cdot D_s} \quad (r/s)
\]

\[
P_{DT} = 2\pi \rho_s D_s^3 n_T^3 \frac{K_{QTS}}{\eta_r} \cdot 10^{-3} \quad (kW)
\]

(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 \(\Delta K_T\) 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 \(K_T\)-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:

\[
\left( \frac{K_Q}{J^3} \right)_T = \frac{1000 \cdot C_p \cdot P_{DS}}{2 \pi \rho_s D_s^3 V_s^3 (1 - w_{TS})^3}
\]

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

\[
n_s = \frac{(1 - w_{TS}) \cdot V_s}{J_{TS} \cdot D_s}
\]

\[
n_T = C_{NP} \cdot n_s
\]

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:

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
