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Specialist Committee on Performance of Ships in Service 27th ITTC	27th ITTC 2012
Date 2012	Date 2012

Analysis of Speed/Power Trial Data

1. PURPOSE

This procedure concerns the method of analysis of the results obtained from the speed/power trials as conducted according part1 of this procedure.

The descriptions for the calculation methods of the resistance increase due to winds, due to waves and the analysis procedure for speed corrections based on relevant research results are modified from ITTC recommended procedures and guidelines (7.5-04-01-01.2/2005), and to fit IMO purposes.

The primary purpose of speed trials is to determine the ship's performance in terms of speed, power and propeller frequency of revolutions under prescribed ship conditions, and thereby to verify the satisfactory attainment of the contractually stipulated ship speed.

The purpose of this procedure is to define procedures for the evaluation and correction of speed/power trials covering all influences which may be relevant for the individual trial runs with assurance of the highest accuracy of speed and power determination in contractual and stipulated conditions.

The applicability of this procedure is limited to commercial ships of the displacement type.

2. TERMS AND DEFINITIONS

For the purposes of this procedure, the following terms and definitions apply:

- **Brake Power**: Power delivered at the output coupling of the propulsion machinery.
- **Delivered Power**: Power delivered to the propeller.
- **Shaft Power**: Net power supplied by the propulsion machinery to the propulsion shafting before passing through all speed-reducing and other transmission devices and after power for all attached auxiliaries has been taken off.
- **Ship Speed** is that realized under the contractually stipulated conditions. Ideal conditions to which the speed should be corrected are
  - no wind
  - no waves
  - no currents
  - deep water
  - stipulated displacement and trim

  with smooth hull and propeller surfaces.

3. RESPONSIBILITIES

The trial team is responsible for carrying out the trials and for correcting the data received. Preferably before the sea trials start, but at the latest when the trial area is reached and the environmental conditions can be studied, agreement between the trial team, shipyard and ship-owner should be obtained concerning the limits of wind forces, wave heights and water depths up to which the trials should be performed. Agreement should be obtained concerning the methods used to correct the trial data. The measured data, analysis process and the results should be transparent and open to the trial team.

4. ANALYSIS PROCEDURE

4.1 General Remarks

This document describes different methods to analyse the results of speed/power tests as conducted in part 1. The choice, which method to be used is given in the matrix of Table 1.

The recommended procedure for the analysis of speed trials is the direct power method and requires displacement / power / rate of revolutions / η_D and η_S as input values.

4.2 Description of the Analysis Procedure

The analysis of speed/power trials should consist of

- evaluation of the acquired data
- correction of ship performance for resistance increase due to wind, waves, water temperature and salt content
- elimination for current
- correction of the speeds at each run for the effect of shallow water
- correction of ship performance for displacement and trim
- presentation of the trial results

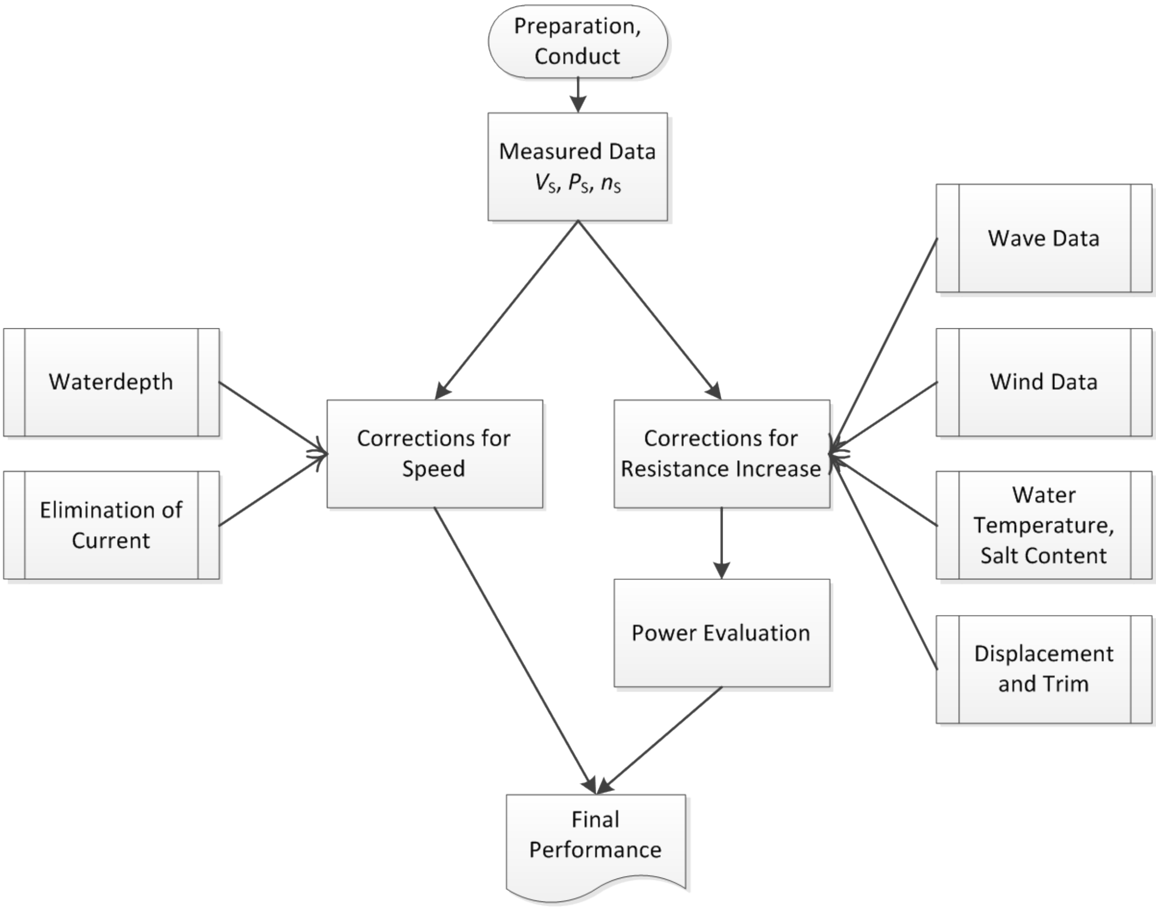

Fig.1 Flowchart of speed/power trial analysis

In the following chapters details of the methods are given. For wave and wind corrections the methods depend on the level of information which is available to the conducting party of the speed/power sea trials. The choice of the correction method should be made according to Chapter 3 of this procedure.

Evaluation

For the evaluation the direct power method is to be used.

Wind Correction

In calculating resistance increase due to wind, four methods can be used, depending whether there are wind tunnel measurements available or not:

If **wind tunnel measurements** are **available**:

Same method as with dataset on the wind resistance coefficient (Appendix C.2)

If **wind tunnel measurements** are **not available**:

Data set on the wind resistance coefficient (Appendix C.2)

or

Regression formula by Fujiwara et al.(Appendix C.3)

<table>
<tr><th colspan="4" rowspan="2">Condition</th><th colspan="8">Evaluation / Correction Method</th></tr>
<tr><th>Evaluation</th><th>Waves</th><th>Wind</th><th>Current</th><th>Air Resistance</th><th>Temper-ature, Density</th><th>Water Depth</th><th>Dis-placement Trim</th></tr>
<tr><td rowspan="2">Load variation test available</td><td colspan="3">yes</td><td>4.2.3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">no</td><td>4.2.3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Ship Lines available to all par-ties</td><td colspan="3">yes</td><td></td><td>D1or D2,D3</td><td></td><td></td><td></td><td>4.3.3</td><td>4.3.4</td><td>4.3.5</td></tr>
<tr><td rowspan="2">no</td><td rowspan="2">heave and pitch</td><td>yes</td><td></td><td>D2</td><td rowspan="2"></td><td rowspan="2">Includ-ed in method</td><td rowspan="2"></td><td rowspan="2">4.3.3</td><td rowspan="2">4.3.4</td><td rowspan="2">4.3.5</td></tr>
<tr><td>no</td><td></td><td>D3</td></tr>
<tr><td rowspan="3">Dataset of wind re-sistance coeffi-cients available</td><td colspan="3">Wind Tunnel Tests</td><td></td><td></td><td>C.1</td><td></td><td>Included in method</td><td>4.3.3</td><td>4.3.4</td><td>4.3.5</td></tr>
<tr><td colspan="3">Data set of STA</td><td></td><td></td><td>C.2</td><td></td><td>Included in method</td><td>4.3.3</td><td>4.3.4</td><td>4.3.5</td></tr>
<tr><td colspan="3">no</td><td></td><td></td><td>C.3 - C.5</td><td></td><td>Included in method</td><td>4.3.3</td><td>4.3.4</td><td>4.3.5</td></tr>
</table>

Table 1

where
the numbers identify the method by the chapters in which the methods are described,

e.g.: 4.2.3 Evaluation based on direct power method
D.1 Theoretical method with simplified tank tests
etc.

Wave correction

In calculating resistance increase due to waves, three methods can be used:

In the case the **ship geometry is available** to all parties involved, the transfer functions of sea keeping tests can be used to analyze the speed / power tests, but also the theoretical method with simplified tank tests as prescribed in Appendix D.1 can be used.

If ship **geometry can't be made available** to all involved parties an empirical estimation method for the frequency response function, prescribed in D.2, should be used for the analysis. This empirical transfer function covers both the mean resistance increase due to wave reflection and the motion induced resistance

Under the condition that the pitching and heaving are small the simplified estimation method, prescribed in D.3, can be used.

To correct for shallow water effect the method proposed by Lackenby should be applied to the ship speed measured during each run.

Table 1 shows which method should be used, depending on the information available.

4.2.1 Resistance data derived from the acquired data

The resistance values of each run should be corrected for environmental influences by estimating the resistance increase ΔR as,

$$\Delta R = R_{AA} + R_{AW} + R_{AS} \tag{1}$$

with

R_{AA}: resistance increase due to relative wind,

R_{AS}: resistance increase due to deviation of water temperature and water density,

R_{AW}: resistance increase due to waves.

4.2.2 Evaluation of the acquired data

The evaluation of the acquired data consists of the calculation of the resistance value associated with the measured power value separately for each run of the speed trials.

The reason that the associated resistance/power should be calculated for each run is that a careful evaluation should consider the effects of varying hydrodynamic coefficients with varying propeller loads. The recommended correction methods except for the ones used for shallow water effect and for displacement and trim are applicable to resistance values.

4.2.3 Evaluation based on Direct Power Method

To derive the speed/power performance of the vessel from the measured speed over ground, shaft torque and rpm, the Direct Power Method is to be used. In this method[19] the measured power is directly corrected with the power increase due to added resistance in the trial conditions:

$$P_{SC} = P_{SM} + \Delta P \tag{2}$$

$$\Delta P = \frac{\Delta R V_S}{\eta_S \eta_D} \tag{3}$$

with

P_{SC}: corrected power,

P_{SM}: measured power,

V_S: ship speed through the water,

ΔP: required correction for power,

ΔR: resistance increase,

η_D: propulsion efficiency coefficient.

where ΔR is identical to the formula (1) and the corrected power P_{SC} is the power in no air and no other disturbance. The added resistance due to wind, waves, temperature and water density is estimated according section 4.3. For shallow water a speed correction is applied according to 4.3.4. Deviations in displacement are corrected for according to 4.3.5.

In the Direct Power Method the current is eliminated by averaging the results of double runs. Per set of measurements for one engine setting, after power correction, the average is determined by calculating the "mean of means" of the corrected speed and power points. By this procedure the first order current effects are corrected automatically.

From the corrected trial points the differences in speed with the fitted curve at the same power are derived. Plotting these speed differences on the basis of time for each trial run, a tidal curve can be fitted through these points. The purpose of creating this tidal curve is to have a quality control on the measured data.

The effect of added resistance on the propeller loading and thus on the propulsion efficiency coefficient η_D is derived from the results of load variation tank tests.

The correction of the propeller frequency of revolution is also based on the results of the load variation tank tests. If these are not available formula (4) based on statistics should be used

$$\Delta n = \left(0.1 \frac{\alpha_{ov} \cdot \Delta P}{P_{SM}} + 0.03 \frac{\beta_{ov} \cdot \Delta V}{V_{SM}} \right) n_M \qquad (4)$$

with

n_M: measured propeller frequency of revolution,

V_{SM}: measured ship speed,

α_{ov}: overload factor on power variation; the statistical value is 0.022 per 10% power correction from tank test,

β_{ov}: overload factor on speed variation; the statistical value is -0.01 per 3% power correction from tank test,

Δn: correction for propeller frequency of revolution.

4.2.4 Prediction of power curve from ballast condition to full load or stipulated condition

For dry cargo vessels it is difficult to conduct speed trials at full load condition. For such cases speed trials at ballast condition are performed and the power curve is converted to that of full load or of stipulated condition using the power curves based on the tank tests for these conditions.

The conversion method from ballast condition to full load or stipulated condition is shown in APPENDIX A.

4.2.5 Presentation of the trial results

The corrected shaft and/or delivered power values, together with the associated, corrected speed values of runs at almost identical power level, but in opposite directions (double run), should be combined and the mean values of speed, power and propeller rate of revolutions should be used to fair the final results.

4.3 Calculation methods for resistance increase and other corrections

4.3.1 Resistance increase due to the effects of wind

The resistance increase due to relative wind is calculated by

$$R_{AA} = \frac{1}{2}\rho_A V_{WR}{}^2 C_{AA}(\psi_{WR}) A_{XV} \tag{24}$$

with

A_{XV}: area of maximum transverse section exposed to the wind,

C_{AA}: wind resistance coefficient,

V_{WR}: relative wind speed,

ρ_A: mass density of air,

ψ_{WR}: relative wind direction; 0 means heading wind.

By nature wind speed and direction vary in time and therefore these are defined by their average values over a selected period.

For speed/power trials it is assumed that the wind condition is stationary i.e. that the speed and direction are reasonably constant over the duration of each double run. The average speed and direction during the double run are then determined for the duration of each measurement run.

The wind speed and direction are usually measured by the on-board anemometer, positioned mostly in the radar mast on top of the bridge. Both wind speed and direction at this location may be affected by the geometry of the vessel in particular the shape of the superstructure and the wheel house.

The true wind vector for each speed-run is found from the speed and heading of the vessel and the measured wind speed and direction. By averaging the true wind vectors over both speed-runs of the double run, the true wind vector for the run-set is found. This averaged true wind vector is then used to recalculate the relative wind vector for each speed-run of the set. This procedure is explained in detail in Appendix B-1.

The wind speed as measured by the anemometer should be corrected for the wind speed profile taking into account the height of the anemometer and the reference height for the wind resistance coefficients (normally 10 m) according to Appendix B-2.

The wind resistance coefficient should be based on the data derived from model tests in a wind tunnel.

In cases where a database is available covering ships of similar type, such data can be used instead of carrying out model tests. Besides, a wide range of statistical regression formulae concerning wind resistance coefficients of various ship types have been developed.
The methods are mentioned in Appendix C.

4.3.2 Resistance increase due to the effects of waves

The most reliable way to determine the decrease of ship speed in waves is to carry out sea keeping tests in regular waves of constant wave height, and different wave lengths and directions at various speeds.

Irregular waves can be represented as linear superposition of the components of regular waves. Therefore the mean resistance increase in short crested irregular waves R_{AW} is calculated by linear superposition of the directional wave spectrum E and the response function of mean resistance increase in regular waves R_{wave}.

$$R_{\mathrm{AW}} = 2\int_0^{2\pi}\int_0^{\infty}\frac{R_{\mathrm{wave}}(\omega,\alpha;V_{\mathrm{S}})}{\zeta_{\mathrm{A}}^{2}}E(\omega,\alpha)d\omega d\alpha \quad (25)$$

with

R_{AW}: mean resistance increase in short crested irregular waves,
R_{wave}: mean resistance increase in regular waves,
ζ_{A}: wave amplitude,
ω: circular frequency of regular waves,
α: angle between ship heading and incident regular waves; 0 means heading waves,
V_{S}: ship speed through the water,
E: directional spectrum; if the directional spectrum is measured at sea trials by a sensors and the accuracy is confirmed, the directional spectrum is available. If the directional spectrum is not measured it is calculated by the following relation:

$$E = S_{\mathrm{f}}(\omega)G(\alpha) \quad (26)$$

with

G: angular distribution function.
S_{f}: frequency spectrum, for ocean waves modified Pierson-Moskowitz type.

The standard form of the frequency spectrum and the angular distribution function are assumed for the calculation. For seas the modified Pierson-Moskowitz frequency spectrum of ITTC 1978 shown in formula (27) is recommended. For swells JONSWAP frequency spectrum is generally applied.

$$S_{\mathrm{f}}(\omega) = \frac{A_{\mathrm{f}}}{\omega^{-5}}\exp\left(-\frac{B_{\mathrm{f}}}{\omega^{4}}\right) \quad (27)$$

with

$$A_{\mathrm{f}} = 173\frac{H_{\mathrm{W1/3}}{}^{2}}{T_1^{4}} \quad (28)$$

$$B_{\mathrm{f}} = \frac{691}{T_1^{4}} \quad (29)$$

$$T_1 = 2\pi\frac{m_0}{m_1} \quad (30)$$

where

$H_{\mathrm{W1/3}}$: significant wave height,
m_n: n^{th} moment of frequency spectrum.

For the angular distribution function the cosine-power type shown in formula (31) is generally applied; e.g. s=1 for seas and s=75 for swells are used in practice.

$$G(\alpha) = \frac{2^{2s}}{2\pi}\frac{\Gamma^{2}(s+1)}{\Gamma(2s+1)}\cos^{2s}\left(\frac{\theta-\alpha}{2}\right) \quad (31)$$

where

s: directional spreading parameter,
Γ: Gamma function,
θ: primary wave direction; 0 means heading waves.

For seas and swells R_{AW} is calculated for each run with different wave height, period and direction.

The resistance increase due to waves should be determined by tank tests or formulae shown in Appendix D.

4.3.3 Resistance increase due to water temperature and salt content

Both, water temperature and salt content, affect the density of the sea water and thus the ship resistance; usually the prediction calculations of speed trials are based on a temperature of the sea water of 15°C and a density of 1025 kg/m³.

The effects of water temperature and salt content are calculated as follows[1].

$$R_{AS} = R_{T0}\left(1-\frac{\rho}{\rho_0}\right) - R_F\left(1-\frac{C_{F0}}{C_F}\right) \quad (32)$$

with

$$R_F = \frac{1}{2}\rho S\, V_S^{\,2} C_F \quad (33)$$

$$R_{F0} = \frac{1}{2}\rho S V_S^{\,2} C_{F0} \quad (34)$$

$$R_{T0} = \frac{1}{2}\rho_0 S\, V_S^{\,2} C_{T0} \quad (35)$$

where

C_F: frictional resistance coefficient for actual water temperature and salt content,

C_{F0} : frictional resistance coefficient for reference water temperature and salt content,

C_{T0} : total resistance coefficient for reference water temperature and salt content,

R_{AS} : resistance increase due to deviation of water temperature and water density,

R_F : frictional resistance for actual water temperature and salt content,

R_{F0} : frictional resistance for reference water temperature and salt content,

R_{T0} : total resistance for reference water temperature and salt content,

S : wetted surface area,

V_S: ship's speed through the water,

ρ : water density for actual water temperature and salt content,

ρ_0 : water density for reference water temperature and salt content.

4.3.4 Correction of the ship performance due to the effects of shallow water.

The formula (36) by Lackenby for the correction of shallow water effects results in a correction to the ship's speed.

$$\frac{\Delta V}{V} = 0.1242\left(\frac{A_M}{H^2} - 0.05\right) + 1 - \left(\tanh\frac{gH}{V^2}\right)^{1/2} \quad \text{for } \frac{A_M}{H^2} \geq 0.05 \quad (36)$$

where

A_M: midship section area under water,
g: acceleration due to gravity,
H: water depth,
V: ship speed,
ΔV: decrease of ship speed due to shallow water.

4.3.5 Correction of the ship performance due to the effects of displacement and trim

Displacement and trim are, in general, factors that can be adjusted to stipulated values at the time of the trials but there may be substantial reasons for discrepancies.

Trim shall be maintained within very narrow limits. For the even keel condition the trim shall be less than 1.0% of the mid-ships draught. For the trimmed trial condition, the immergence of the bulbous bow on the ship should be within 0.1 m compared to the model test condition, whereas the displacement should be within 2% of the displacement of the model tested condition.

Ship resistance is known to be sensitive for trim in particular for cases where the bulbous bow or the transom are close to or protrude the waterline. For such effects no reliable correction methods exist and therefore trim deviations should be avoided during speed/power trials.

A very simple formula which can be applied either to resistance- or power values is the Admiral-formula which has to be used in case the displacement of the vessel at the speed/power trial differs from the displacement at the relevant model test within the above mentioned limits.

$$\frac{P_1}{V_1^3 \Delta_1^{2/3}} = \frac{P_2}{V_2^3 \Delta_2^{2/3}} \tag{37}$$

where

P_1: power corresp. to displacement Δ_1,
P_2: power corresp. to displacement Δ_2,
V_1: speed corresponding to displacement Δ_1,
V_2: speed corresponding to displacement Δ_2.

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Appendix

A. CONVERSION FROM BALLAST SPEED/POWER TEST RESULTS TO OTHER STIPULATED LOAD CONDITIONS

For dry cargo vessels it is difficult or unfeasible to conduct speed trials at full load condition. For such cases speed trials at ballast condition are performed and the result of the speed trials is converted to that of full load/stipulated condition using tank test results.

The power curve at full load/stipulated condition is obtained from the results of the speed trials at ballast condition using the power curves predicted by model tank tests. The tank tests should be carried out at both draughts: ballast condition corresponding to that of the speed trials and full load/stipulated condition.

Using the power curve obtained by the speed trials at ballast condition, the conversion on ship speed from ballast condition to full load condition to be carried out by the power ratio α_P defined in formula (A-1). The adjusted power at full load condition ($P_{\mathrm{Full,S}}$) is calculated by formula (A-2).

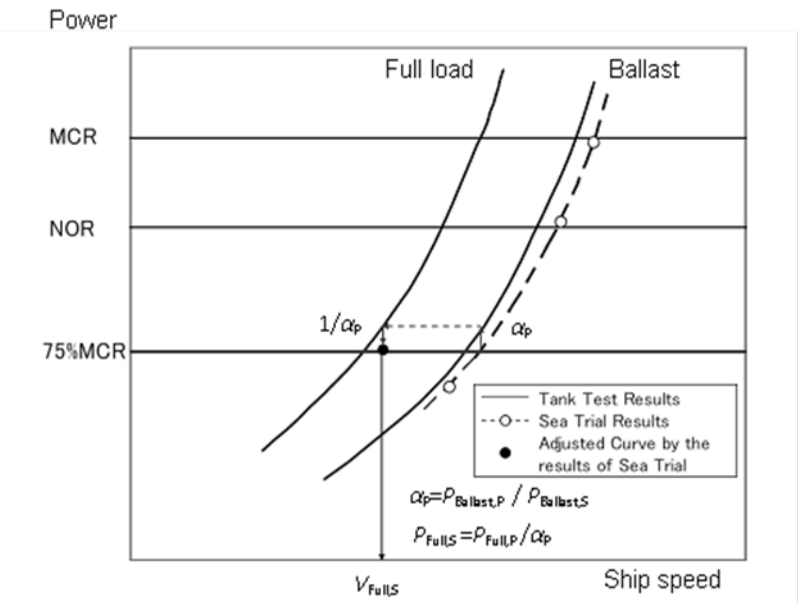


Fig.A-1 An example of ship speed adjustment using power ratio.

$$\alpha_{\mathrm{P}} = \frac{P_{\mathrm{Ballast,P}}}{P_{\mathrm{Ballast,S}}} \tag{A-1}$$

$$P_{\mathrm{Full,S}} = \frac{P_{\mathrm{Full,P}}}{\alpha_{\mathrm{P}}} \tag{A-2}$$

where

$P_{\mathrm{Ballast,P}}$: predicted power at ballast condition by tank tests,
$P_{\mathrm{Ballast,S}}$: power at ballast condition obtained by the speed trials,
$P_{\mathrm{Full,P}}$: predicted power at full load condition by tank tests,
$P_{\mathrm{Full,S}}$: power at full load condition,
α_{P}: power ratio.

Fig.A-1 shows an example of the conversion to derive the resulting ship speed at full load condition ($V_{\mathrm{Full,S}}$) at 75%MCR.

B. EVALUATION OF WIND DATA

B.1 Averaging process for the true wind vectors

The true wind vectors in each run are found from the speed and heading of the vessel and the measured wind speed and direction. By averaging the true wind vectors over both runs of the double run, the true wind vector for the run-set is found. This averaged true wind vector is then used to recalculate the relative wind vector for each run of the set.

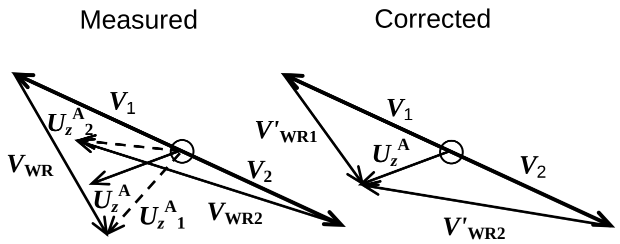


Fig.B-1 True wind vectors and relative wind vectors.

Fig.B-1 shows the averaging process to obtain the corrected relative wind vectors where

U_z^{A}: averaged true wind vector,
$U_z{}^{\mathrm{A}}{}_1$: true wind vector at a run 1,
$U_z{}^{\mathrm{A}}{}_2$: true wind vector at a run 2,
V_1: ship movement vector at a run 1,
V_2: ship movement vector at a run 2,
V_{WR1}: measured relative wind vector at run 1,
V_{WR2}: measured relative wind vector at run 2,
V'_{WR1}: corrected relative wind vector at run 1,
V'_{WR2}: corrected relative wind vector at run 2.

B.2 Correction for the height of the anemometer

The difference between the height of the anemometer and the reference height is to be corrected by means of the wind speed profile given by formula (B-1).

$$U_z{}^{\mathrm{A}}(z_{\mathrm{ref}}) = U_z{}^{\mathrm{A}}(z)\left(\frac{z_{\mathrm{ref}}}{z}\right)^{1/7} \tag{B-1}$$

where

$U_z^{\mathrm{A}}(z)$: wind speed at height z,
z_{ref}: reference height.

The reference height is selected as the corresponding height for the specific wind resistance coefficient from wind tunnel tests.

C. CORRECTION METHODS FOR RESISTANCE INCREASE DUE TO WIND

For calculating the resistance increase due to wind the following methods are to be used:

C.1 Wind resistance coefficients by wind tunnel test

If wind resistance tests have been performed in a wind tunnel the wind resistance coefficients evaluated by these tests have to be used.

C.2 Data sets of wind resistance coefficients

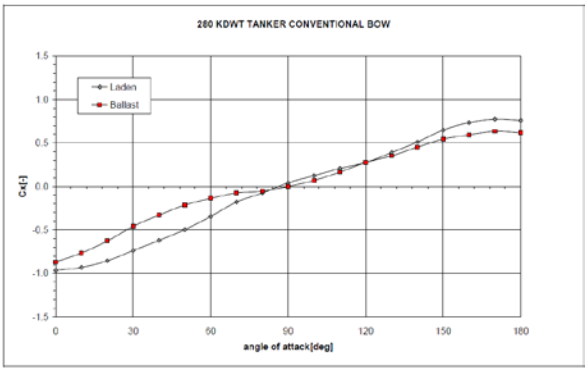
Data sets of the wind resistance coefficients have been prepared by STA-JIP[19].

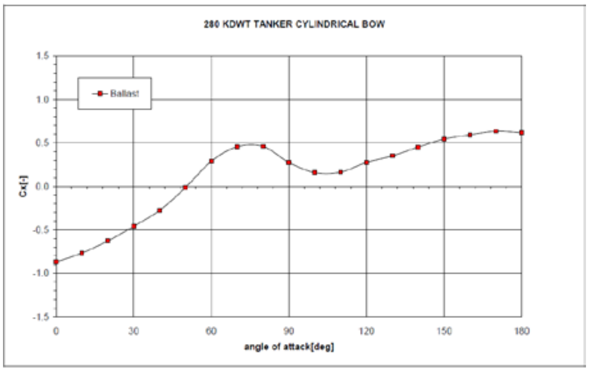
Data sets are available for tankers, LNG carriers, container ships, car carriers, ferries/cruise ships and general cargo ships as shown in Table C-1. The wind resistance coefficients for each ship type are shown in Fig. C-1.

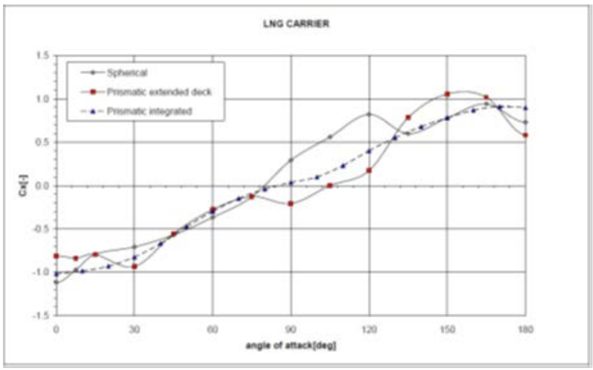
For the use of these coefficients the vessel type, shape and outfitting should be carefully evaluated and compared with the geometry of the vessel from the data set. The data provided are limited to the present-day common ship types. For special vessels such as tugs, supply ships, fishery vessels and fast crafts, the geometry of the vessel is too specific to make use of the available database.

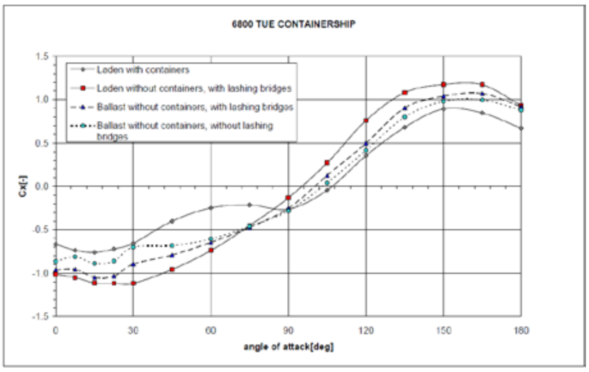
Ship type	Loading condition	Superstructure	Test vessel
tanker conventional bow	laden	normal	280kDWT
tanker conventional bow	ballast	normal	280kDWT
tanker cylindrical bow	ballast	normal	280kDWT
LNG carrier	average	prismatic integrated	125k-m^3
LNG carrier	average	prismatic extended deck	138k-m^3
LNG carrier	average	spherical	125k-m^3
container ship	laden	with containers	6800TEU
container ship	laden	without containers, with lashing bridges	6800TEU
container ship	ballast	with lashing bridges	6800TEU
container ship	ballast	without lashing bridges	6800 TEU
car carrier	average	normal	Autosky
ferry/cruise ship	average	normal	
general cargo ship	average	normal	

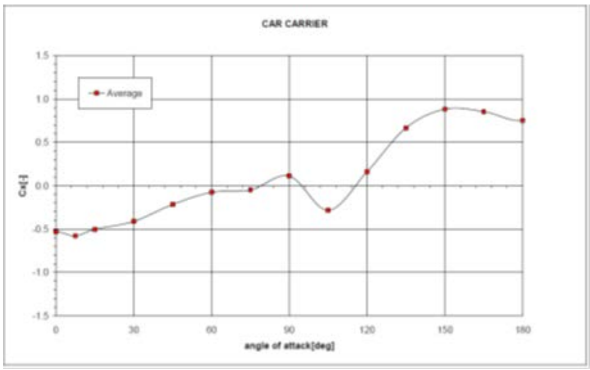
Table C-1 Ship type for the data set

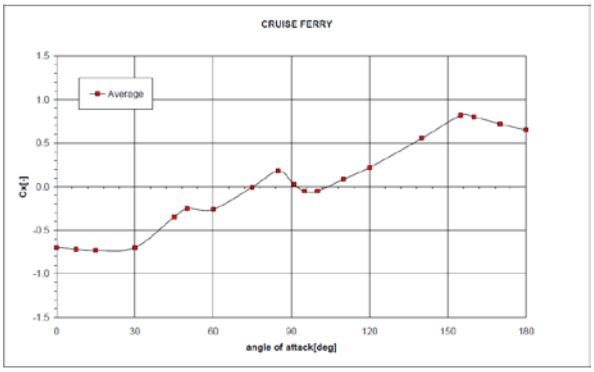












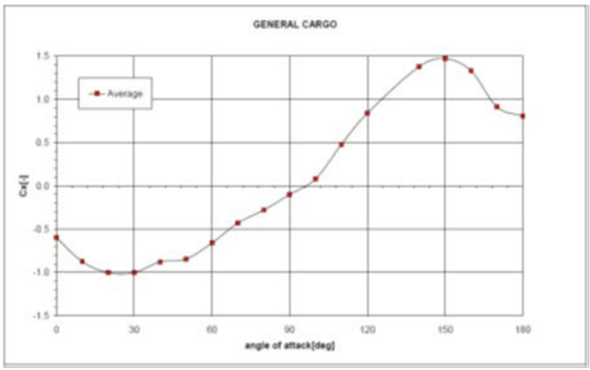


Fig.C-1 Wind resistance coefficients for ship types[19].

C.3 Regression formula by Fujiwara et al.

A regression formula based on model tests in wind tunnels has been developed by Fujiwara et al.[16].

$$C_{AA} = C_{LF}\cos\psi_{WR} + C_{XLI}\left(\sin\psi_{WR} - \frac{1}{2}\sin\psi_{WR}\cos^2\psi_{WR}\right)\sin\psi_{WR}\cos\psi_{WR} + C_{ALF}\sin\psi_{WR}\cos^3\psi_{WR} \quad \text{(C-1)}$$

with

for $0 \le \psi_{WR} < 90\text{(deg.)}$

$$C_{LF} = \beta_{10} + \beta_{11}\frac{A_{YV}}{L_{OA}B} + \beta_{12}\frac{C_{MC}}{L_{OA}} \quad \text{(C-2)}$$

$$C_{XLI} = \delta_{10} + \delta_{11}\frac{A_{YV}}{L_{OA}H_{BR}} + \delta_{12}\frac{A_{XV}}{BH_{BR}} \quad \text{(C-3)}$$

$$C_{ALF} = \varepsilon_{10} + \varepsilon_{11}\frac{A_{OD}}{A_{YV}} + \varepsilon_{12}\frac{B}{L_{OA}} \quad \text{(C-4)}$$

for $90 < \psi_{WR} \le 180\text{(deg.)}$

$$C_{\mathrm{LF}} = \beta_{20} + \beta_{21}\frac{B}{L_{\mathrm{OA}}} + \beta_{22}\frac{H_{\mathrm{C}}}{L_{\mathrm{OA}}} + \beta_{23}\frac{A_{\mathrm{OD}}}{L_{\mathrm{OA}}{}^{2}} + \beta_{24}\frac{A_{\mathrm{XV}}}{B^{2}} \qquad \text{(C-5)}$$

$$C_{\mathrm{XLI}} = \delta_{20} + \delta_{21}\frac{A_{\mathrm{YV}}}{L_{\mathrm{OA}}H_{\mathrm{BR}}} + \delta_{22}\frac{A_{\mathrm{XV}}}{A_{\mathrm{YV}}} + \delta_{23}\frac{B}{L_{\mathrm{OA}}} + \delta_{24}\frac{A_{\mathrm{XV}}}{BH_{\mathrm{BR}}} \qquad \text{(C-6)}$$

$$C_{\mathrm{ALF}} = \varepsilon_{20} + \varepsilon_{21}\frac{A_{\mathrm{OD}}}{A_{\mathrm{YV}}} \qquad \text{(C-7)}$$

for $\psi_{\mathrm{WR}} = 90(\mathrm{deg.})$

$$C_{\mathrm{AA}}\big|_{\psi_{\mathrm{WR}}=90(\mathrm{deg.})} = \frac{1}{2}\left(C_{\mathrm{AA}}\big|_{\psi_{\mathrm{WR}}=90(\mathrm{deg.})-\mu} + C_{\mathrm{AA}}\big|_{\psi_{\mathrm{WR}}=90(\mathrm{deg.})+\mu} \right) \qquad \text{(C-8)}$$

where

A_{OD}: lateral projected area of superstructures etc. on deck,

A_{XV}: area of maximum transverse section exposed to the winds,

A_{YV} projected lateral area above the waterline,

B: ship breadth,

C_{AA}: wind resistance coefficient,

C_{MC}: horizontal distance from midship section to centre of lateral projected area A_{YV},

H_{BR}: height of top of superstructure (bridge etc.),

H_{C}: height from waterline to centre of lateral projected area A_{YV},

L_{OA}: length overall,

μ: smoothing range; normally 10(deg.),

ψ_{WR}: relative wind direction; 0 means heading winds.

The non-dimensional parameters β_{ij}, δ_{ij} and ε_{ij} used in the formulae are shown in Table C-2.

	i	j = 0	1	2	3	4
β_{ij}	1	0.922	-0.507	-1.162	-	-
	2	-0.018	5.091	-10.367	3.011	0.341
δ_{ij}	1	-0.458	-3.245	2.313	-	-
	2	1.901	-12.727	-24.407	40.310	5.481
ε_{ij}	1	0.585	0.906	-3.239	-	-
	2	0.314	1.117	-	-	-

Table C-2Non-dimensional parameters

D. CORRECTION METHODS FOR RESISTANCE INCREASE DUE TO WAVES

D.1 Theoretical method with simplified tank tests

Applying the theoretical formula, the mean resistance increase in regular waves R_{wave} is calculated from the components of the mean resistance increase based on Maruo's theory R_{AWM} and its correction term which primarily is valid for short waves R_{AWR}.

$$R_{\mathrm{wave}} = R_{\mathrm{AWM}} + R_{\mathrm{AWR}} \qquad \text{(D-1)}$$

with

R_{AWM}: mean resistance increase in regular waves based on Maruo's theory(4), which is mainly induced by ship motion.

R_{AWR}: mean resistance increase due to wave reflection for correcting R_{AWM}.

R_{AWR} should be calculated with accuracy because the mean resistance increase in short waves is predominant one.

The expression of R_{AWM} is given in the following formulae.

$$R_{wm} = 4\pi\rho\left(-\int_{-\infty}^{m_3} + \int_{m_4}^{\infty}\right)\left|H_1(m)\right|^2 \frac{(m+K_0\Omega_{\text{E}})^2(m+K\cos\alpha)}{\sqrt{(m+K_0\Omega_{\text{E}})^4 - m^2K_0^{\ 2}}}dm$$

$$\text{for } \Omega_{\text{E}} \leq \frac{1}{4} \qquad \text{(D-2)}$$

$$R_{wm} = 4\pi\rho\left(-\int_{-\infty}^{m_3} + \int_{m_4}^{m_2} + \int_{m_1}^{\infty}\right)\left|H_1(m)\right|^2 \frac{(m+K_0\Omega_{\text{E}})^2(m+K\cos\alpha)}{\sqrt{(m+K_0\Omega_{\text{E}})^4 - m^2K_0^{\ 2}}}dm$$

$$\text{for } \Omega_{\text{E}} > \frac{1}{4} \qquad \text{(D-3)}$$

with

$$\Omega_{\text{E}} = \frac{\omega_{\text{E}}V_{\text{S}}}{g} \qquad \text{(D-4)}$$

$$K = \frac{\omega^2}{g} \qquad \text{(D-5)}$$

$$K_0 = \frac{g}{V_{\text{S}}^{\ 2}} \qquad \text{(D-6)}$$

$$\omega_{\text{E}} = \omega + KV_{\text{S}}\cos\alpha \qquad \text{(D-7)}$$

$$m_1 = \frac{K_0\left(1-2\Omega_{\text{E}} + \sqrt{1-4\Omega_{\text{E}}}\right)}{2} \qquad \text{(D-8)}$$

$$m_2 = \frac{K_0\left(1-2\Omega_{\text{E}} - \sqrt{1-4\Omega_{\text{E}}}\right)}{2} \qquad \text{(D-9)}$$

$$m_3 = -\frac{K_0\left(1+2\Omega_{\text{E}} + \sqrt{1+4\Omega_{\text{E}}}\right)}{2} \qquad \text{(D-10)}$$

$$m_4 = -\frac{K_0\left(1+2\Omega_{\text{E}} - \sqrt{1+4\Omega_{\text{E}}}\right)}{2} \qquad \text{(D-11)}$$

where

- g: gravitational acceleration,
- $H(m)$: function to be determined by the distribution of singularities which represents periodical disturbance by the ship,
- V_{S}: ship speed through the water,
- α: encounter angle of incident waves (0 deg. means heading waves),
- ρ: density of fluid,
- ω: circular wave frequency,
- ω_{E}: circular wave frequency of encounter.

The expression of R_{AWR} is given by Tsujimoto et al.[20] The calculation method introduces an experimental coefficient in short waves into the calculation in terms of accuracy and takes into account the effect of the bow shape above the water.

$$R_{\text{AWR}} = \frac{1}{2}\rho g \zeta_{\text{A}}^{\ 2} B B_{\text{f}} \alpha_T (1 + C_U Fr) \qquad \text{(D-12)}$$

where

- B: ship breadth,
- B_{f}: bluntness coefficient,
- C_U: coefficient of advance speed,
- Fr: Froude number,
- α_T: effect of draught and encounter frequency,
- ζ_{A}: wave amplitude.

with

$$\alpha_T = \frac{\pi^2 I_1^{\ 2}(k_e T)}{\pi^2 I_1^2(k_e T) + K_1^2(k_e T)} \qquad \text{(D-13)}$$

$$k_{\text{e}} = k\left(1 + \Omega\cos\alpha\right)^2 \qquad \text{(D-14)}$$

$$\Omega = \frac{\omega V_{\text{S}}}{g} \qquad \text{(D-15)}$$

$$B_{\mathrm{f}} = \frac{1}{B}\left\{\int_I \sin^2\left(\alpha+\beta_{\mathrm{w}}\right)\sin\beta_{\mathrm{w}}dl + \int_{II} \sin^2\left(\alpha-\beta_{\mathrm{w}}\right)\sin\beta_{\mathrm{w}}dl\right\} \quad \text{(D-16)}$$

where

- I_1: modified Bessel function of the first kind of order 1,
- K_1: modified Bessel function of the second kind of order 1,
- k: wave number,
- T: draught; for a trim condition T is the deepest draught,
- β_{w}: slope of the line element dl along the water line,

and domains of the integration (I & II) are shown in Fig.D-1. When $B_{\mathrm{f}}<0$, then $B_{\mathrm{f}} = 0$ is assumed.

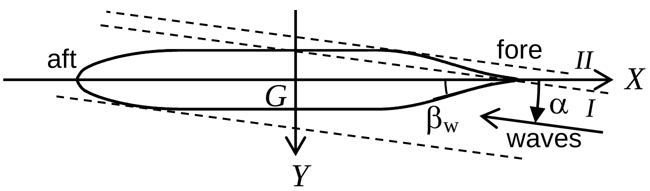


Fig.D-1 Coordinate system for wave reflection.

The coefficient of the advance speed in oblique waves $C_U(\alpha)$ is calculated on the basis of the empirical relation line shown in Fig. D-2[1], which has been obtained by tank tests of various ship types following to the procedures in the next paragraph. When $C_U(\alpha=0)$ is obtained by tank tests the relation used in oblique waves is shifted parallel to the empirical relation line. This is illustrated in Fig.D-3 for both fine and blunt ships.

The aforementioned coefficient $C_U(\alpha=0)$ is determined by tank tests which should be carried out in short waves since R_{AWR} is mainly effected by short waves. The length of short waves should be $0.5L_{\mathrm{PP}}$ or less. The coefficient of advance speed C_U is determined by the least square method through the origin against Fr; see Fig.D-4.

The tank tests should be conducted for at least three different Froude Numbers Fr. The Fr should be selected such that the speeds during the sea trials lie between the lowest and the highest selected Fr.

---

[1] The empirical relation line in Fig.D-2 was obtained as follows. C_U is derived from the result of tank tests and R_{AWM}, as formula (D-17).

$$C_U = \frac{1}{Fr}\left\{\frac{R_{\mathrm{wave}}^{\mathrm{EXP}}(Fr) - R_{\mathrm{AWM}}(Fr)}{\frac{1}{2}\rho g \zeta_{\mathrm{A}}{}^2 B B_{\mathrm{f}} \alpha_{\mathrm{T}}} - 1\right\} \quad \text{(D-17)}$$

with

$R_{\mathrm{wave}}^{\mathrm{EXP}}$: mean resistance increase in regular waves measured in the tank tests.

In calculating R_{AWM} the strength of the singularity σ is calculated by the formulation of slender body theory as formula (D-18) and the singularity is concentrated at depth of $C_{\mathrm{VP}}T_{\mathrm{M}}$.

$$\sigma = -\frac{1}{4\pi}\left(\frac{\partial}{\partial t} - V_{\mathrm{S}}\frac{\partial}{\partial x}\right)\left\{Z_{\mathrm{r}}(x)B(x)\right\} \quad \text{(D-18)}$$

with

- $B(x)$: sectional breadth,
- C_{VP}: vertical prismatic coefficient,
- t : time,
- T_{M}: draught at midship,
- x: longitudinal coordinate,
- Z_{r}: vertical displacement relative to waves in steady motion.

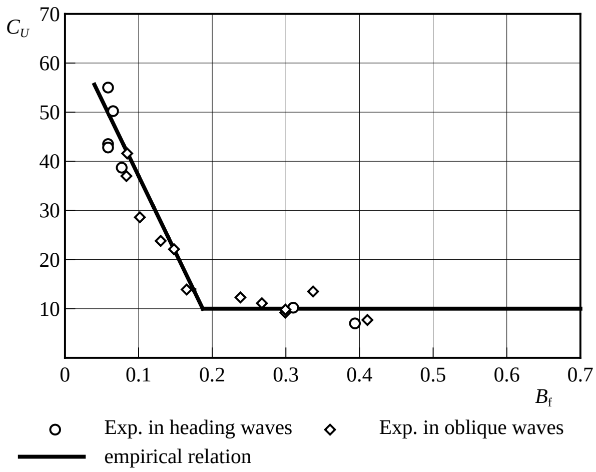
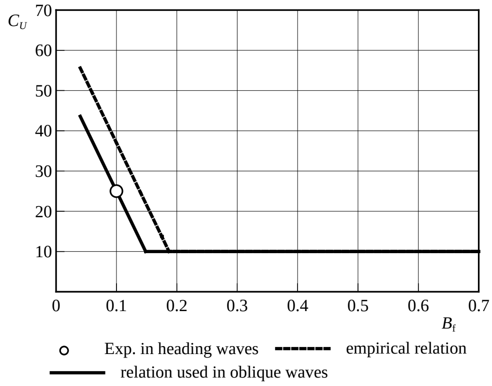


Fig.D-2 Relation between the coefficient of advance speed on added resistance due to wave reflection and the bluntness coefficient for conventional hull form above water.

When tank tests are not carried out, the coefficient of advance speed in heading waves $C_U(\alpha = 0)$ is calculated by the following empirical relations, formulae (D-19) and (D-20), shown in Fig.D-2. The formulae are suitable for all ships.

$$C_U(\alpha = 0) = -310B_f + 68 \quad \text{for } B_f < 58/310 \tag{D-19}$$

$$C_U(\alpha = 0) = 10 \quad \text{for } B_f \geq 58/310 \tag{D-20}$$



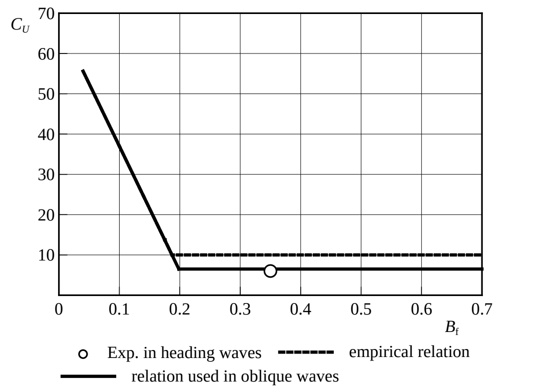


Fig.D-3 Shift of the empirical relation in oblique waves (upper; for fine ship $B_f < 58/310$, lower; for blunt ship $B_f \geq 58/310$).

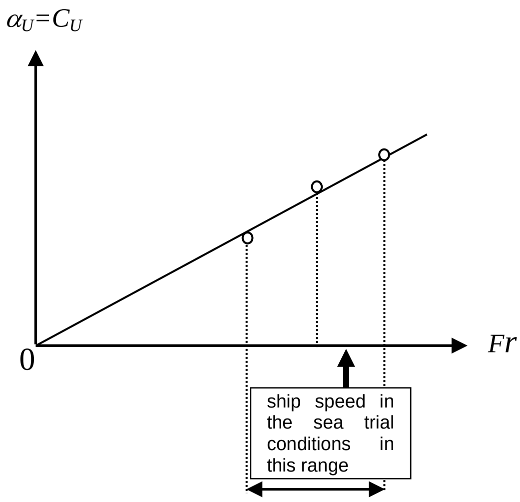


Fig.D-4 Relation between effect of advance speed ($\alpha_U = C_U Fr$) and Froude number Fr.

D.2 Empirical correction method with frequency response function for ships which heave and pitch during the speed runs (STA 2)

An empirical method(19) has been developed to approximate the transfer function of the mean resistance increase in heading regular waves by using the main parameters such as ship dimensions and speed, see Fig.D-5.

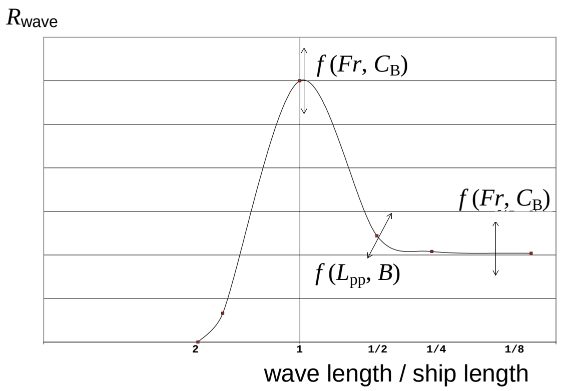


Fig.D-5 Parametric transfer function of mean resistance increase in regular waves.

This empirical transfer function covers both the mean resistance increase due to wave reflection R_{AWR} and the motion induced resistance R_{AWM}.

$$R_{\mathrm{AWM}} = 4\rho g \zeta_{\mathrm{A}}{}^2 B^2 / L_{\mathrm{pp}} \overline{raw}(\omega) \quad \text{(D-21)}$$

With

$$\overline{raw}(\omega) = \bar{\omega}^{b_1} \exp\left\{\frac{b_1}{d_1}\left(1-\bar{\omega}^{d_1}\right)\right\} a_1 Fr^{1.50} \exp\left(-3.50 Fr\right) \quad \text{(D-22)}$$

$$\bar{\omega} = \frac{\sqrt{\frac{L_{\mathrm{PP}}}{g}}\sqrt[3]{k_{yy}}}{1.17 Fr^{-0.143}}\omega \quad \text{(D-23)}$$

$$a_1 = 60.3 C_{\mathrm{B}}{}^{1.34} \quad \text{(D-24)}$$

$$b_1 = \begin{cases} 11.0 & \text{for } \bar{\omega} < 1 \\ -8.50 & \text{elsewhere} \end{cases} \quad \text{(D-25)}$$

$$d_1 = \begin{cases} 14.0 & \text{for } \bar{\omega} < 1 \\ -566\left(\frac{L_{\mathrm{PP}}}{B}\right)^{-2.66} & \text{elsewhere} \end{cases} \quad \text{(D-26)}$$

and

$$R_{\mathrm{AWR}} = \frac{1}{2}\rho g \zeta_{\mathrm{A}}{}^2 B \alpha_1(\omega) \quad \text{(D-27)}$$

$$\alpha_1(\omega) = \frac{\pi^2 I_1{}^2(1.5kT_{\mathrm{M}})}{\pi^2 I_1^2(1.5kT_{\mathrm{M}}) + K_1^2(1.5kT_{\mathrm{M}})} f_1 \quad \text{(D-28)}$$

$$f_1 = 0.692\left(\frac{V_{\mathrm{S}}}{\sqrt{T_{\mathrm{M}} g}}\right)^{0.769} + 1.81 C_{\mathrm{B}}{}^{6.95} \quad \text{(D-29)}$$

where

C_{B}: block coefficient,
k_{yy}: non dimensional radius of gyration in lateral direction,
L_{pp}: ship length between perpendiculars,
T_{M}: draught at midship,

with the following restrictions

1. $75(\mathrm{m}) < L_{\mathrm{pp}} < 350(\mathrm{m})$,
2. $4.0 < \frac{L_{\mathrm{pp}}}{B} < 9.0$,
3. $2.2 < \frac{B}{T} < 5.5$,
4. $0.10 < Fr < 0.30$,
5. $0.50 < C_{\mathrm{B}} < 0.90$ and
6. wave direction is heading (within 0 to ±45 (deg.)).

The method is applicable to the mean resistance increase in long crested irregular head waves R_{AWL}, formula (D-30). The application is restricted to waves in the bow sector to ±45 (deg.) off bow waves which are treated as head waves for this method. Waves outside the ±45 (deg.) sector are omitted from the wave correction in this method.

$$R_{\mathrm{AWL}} = 2\int_0^\infty \frac{R_{\mathrm{wave}}(\omega;V_S)}{\zeta_{\mathrm{A}}^2} S_{\mathrm{f}}(\omega)d\omega \qquad \text{(D-30)}$$

D.3 Simplified correction method for ships that do not heave and pitch during the speed runs (STA 1)

Specifically for speed trial conditions with present day ships a dedicated and simplified method has been developed [(19)] to estimate the added resistance in waves with limited input data.

Speed trials are conducted in low to mild sea states with restricted wave heights. In head waves the encounter frequency of the waves is high. In these conditions the effect of wave induced motions can be neglected and the added resistance is dominated by the wave reflection of the hull on the waterline. The water line geometry is approximated based on the ship beam and the length of the bow section on the water line (Fig D.6).

Formula (D-31) estimates the resistance increase in head waves provided that heave and pitching are small. The application is restricted to waves in the bow sector (within +/-45 deg. off bow). For wave directions outside this sector no wave correction is applied.

$$R_{\mathrm{AWL}} = \frac{1}{16}\rho g H_{\mathrm{W1/3}}^2 B \sqrt{\frac{B}{L_{\mathrm{BWL}}}} \qquad \text{(D-31)}$$

Where

B: beam of the ship
$H_{\mathrm{W1/3}}$: significant wave height,
L_{BWL}: distance of the bow to 95% of maximum breadth on the waterline, shown in Fig.D-6,

with the following restrictions

1. significant wave height ($H_{\mathrm{W1/3}}$); $H_{\mathrm{W1/3}} < 0.015 L_{\mathrm{PP}}$,
2. wave induced motion is small (pitch < 0.5(deg.) and roll < 1(deg.)),
3. wave direction is heading (within 0 to ±45 (deg.))

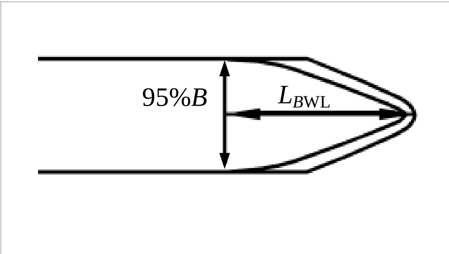


Fig.D-6 Definition for the distance of the bow to 95% of maximum beam on the waterline.

E. NOMENCLATURE

A_E/A_O	blade area ratio	[-]
A_{LV}	transverse area above water	[m^2]
A_{M}:	midship section area under water	[m^2]
A_R	rudder area	
A_T	submerged area transom	[m^2]
A_{XV}	area of maximum transverse section exposed to the winds	[m^2]
B	ship breadth	[m]
B_f	bluntness coefficient	[-]
b_R:	rudder span	[m]
C	coefficient for starboard and port rudder	[-]
C_{AAjj}	measured wind resistance coefficient at wind tunnel	[-]
$\hat{C}_{AAij}$	estimated wind resistance coefficient	[-]
$C_{AA}(\psi_{WR})$:	wind resistance coefficient	
C_B	block coefficient	
C_F	frictional resistance coefficient for actual water temperature and salt content,	[-]
C_{F0}	frictional resistance coefficient for reference water temperature and salt content.	[-]
C_M	midship area coefficient	[-]
$C_{nmargin}$	rpm margin in percent rpm at NCR	[%]
C_{PA}	prismatic coefficient of aft part (from midship to A.P.)	[-]
C_{SEAMAR}	sea margin in percentage NCR	[%]
C_{T0}	total resistance coefficient for reference water temperature and salt content,	[-]
C_U	coefficient of advance speed	[-]
C_{WA}	water plane area coefficient of aft part (from midship to A.P.)	[-]
C_{WL}	prismatic waterline coefficient	[-]
D	diameter of the actual full scale propeller	[m]
D	depth, moulded, of a ship hull	[m]
E:	directional sea spectrum	
Fr	Froude number	[-]
G	angular distribution function	[-]
g	gravitational acceleration	[m/s^2]
H	waterdepth	[m]
H_{ANEMO}	height anemometer above water	[m]
H_R	rudder height	[m]
$H_{S1/3}$	sum of significant wave height of swell and wind driven seas	[m]
$H_{W1/3}$	significant wave height	[m]

I_1	modified Bessel function of the first kind of order 1	[-]
J	propeller advance ratio	[-]
K_Q	propeller torque coefficient	[-]
K_T	propeller thrust coefficient	[-]
K_1	modified Bessel function of the second kind of order 1	[-]
k	wave number	[-]
k_{YY}	non dimensional longitudinal radius of gyration	[% of L_{PP}]
L_{CB}	longitudinal centre of buoyancy forward of midship	[% of L_{PP}]
L_{BWL}	distance of the bow to 95% of maximum breadth on the waterline	[m]
L_{PP}	length between perpendiculars	[m]
L_{WL}	length at waterline	[m]
MCR	maximum continuous rating	[kW]
NCR	nominal continuous rating	[kW]
N_{MCR}	rpm at MCR	[rpm]
N_{NCR}	rpm at NCR	[rpm]
N_P	number of propellers	[-]
N_S	number of ships	[-]
N_ψ	number of wind directions	[-]
n:	measured rate of revolution of propeller at each run	
n_C	corrected rpm (RPMC)	[rpm]
$n_{(i)}$	propeller frequency of revolutions at $(i)^{th}$ run	[rpm]
$n_{(i+1)}$	propeller frequency of revolutions at $(i+1)^{th}$ run	[rpm]
P	propeller pitch at 0.7 R	[m]
P_B	break horse power	[kW]
P_D	delivered power at propeller	[kW]
P/D	pitch/diameter ratio at 0.7R	[-]
P_S	ship shaft power	[kW]
P_{SC}	Corrected ship power (PSC)	[kW]
R_{AA}	resistance increase due to relative winds	[N]
R_{AS}	resistance increase due to deviation of water temperature and water density	[N]
R_{AW}	mean resistance increase in short crested irregular waves	[N]
R_{AWM}	mean resistance increase in regular waves based on Maruo's theory(4),	
R_{AWR}	mean resistance increase due to wave reflection for correcting R_{AWM}.	
R_T	total resistance in still water	[N]
R_{T0}	resistance for reference water temperature and salt content	[N]
R_{wave}	mean resistance increase in regular waves	[N]
$R_{\beta\beta}$	resistance increase due to drift	[N]
$R_{\delta\delta}$	resistance increase due to steering	[N]
S	wetted surface hull	[m^2]
S	frequency spectrum, for ocean waves modified Pierson-Moskowitz type	[-]
S_{APP}	wetted surface appendages	[m^2]
$\overline{SE}_{EST}$	averaged standard errors of wind resistance coefficient	[-]

T_A	draught at aft perpendicular	[m]
T_F	draught at forward perpendicular	[m]
T_M	draught at midships	[m]
t	thrust deduction fraction	[-]
t_{Aref}	reference air temperature	[°C]
t_{Sref}	reference sea water temperature	[°C]
V_{FM}	mean current velocity	[m/s]
$V_{G'(i+1)}$:	ship speed over the ground at $(i+1)^{th}$ run	[kn]
V_{KN}	ship speed over ground	[kn]
V_S	ship speed (VS)	[kn]
$V_{SC.}$	corrected ship speed (VSC)	[kn]
V_{WR}	apparent wind speed, relative wind velocity	[m/s]
w	wake fraction	[-]
w_m	mean wake fraction	
Z	number of propeller blades	[-]
α:	wave direction relative to bow, angle between ship heading and incident regular waves; 0 means head waves.	[deg]
α_T:	effect of draught and encounter frequency	[-]
β	drift angle	[deg]
β_w	slope of the line element dl along the water line	[deg]
β_{WR}	apparent wind direction relative to bow	[deg]
∇	displaced volume	[m^3]
Δ	displacement	[t]
ΔR	resistance increase	[N]
Δ_{ref}	reference displacement	[m^3]
ΔV_S	decrease of ship speed due to shallow water	[kn]
$\Delta\tau$	load factor increase due to resistance increase	[-]
δ	rudder angle	[deg]
δ_n	correction factor for RPM (DRPM)	[-]
δP_A	power correction factor for wind (DPWIN)	[kW]
δP_t	pwer correction factor for temperature (DPTEM)	[kW]
$\delta P\rho$	power correction factor for density (DPDEN)	[kW]
$\delta P\Delta$	power correction factor for displacement (DPDIS)	[kW]
δV_H	speed correction factor for depth (DVDEP)	[kn]
ζ_a	wave amplitude	[m]
η_R	relative rotative efficiency by use of the thrust identity	[-]
η_S	mechanical efficiency mechanical losses in shafting(s) and gear box(es).	[-]
Λ_R	aspect ratio of rudder	[-]
λ	model scale 1:	[-]
ρ	density of the sea water , water density for actual water temperature and salt content	[kg/m³]
ρ_A	mass density of air	[kg/m³]
ρ_{WSref}	sea water density according to contract	[kg/m^3]

ρ_{WS}	sea water density	[kg/m^3]
ρ_0	water density for reference water temperature and salt content	[kg/m^3]
ψ	heading of ship; compass course	[deg]
ψ_{WR}:	relative wind direction	[deg]
ω:	circular frequency of incident regular waves	[1/s]
ω:	circular frequency of incident waves.	