ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Preparation, Conduct and Analysis of Speed/Power Trials

7.5	Process Control
7.5-04	Full Scale Measurements
7.5-04-01	Speed and Power Trials
7.5-04-01-01.1	Preparation, Conduct and Analysis of Speed/Power Trials

Updated / Edited by	Approved
Specialist Committee on Ships in Operation at Sea of the 29th ITTC	29th ITTC 2021
Date 04/2021	Date 06/2021

Table of Contents

Preparation, Conduct and Analysis of Speed/Power Trials

1. PURPOSE

The primary purpose of speed-power trials is to determine ship performance in terms of speed, power and propeller revolutions under prescribed ship conditions, and thereby verifying the satisfactory attainment of the contractually stipulated ship's speed and power and to provide the ship's speed and power for the calculation of the Energy Efficiency Design Index (EEDI) as required by IMO.

The present Recommended Procedure concerns the preparation and execution of speed-power trials, as well as the method of analysing the results. It has been defined by the 27thand the 28thITTC Specialist Committee on the Performance of Ships in Service. In this work the Committee took into account:

- ITTC 7.5-04-01-01,2017,
- ISO 15016, 2015,
- Sea Trial Analysis JIP, 2006; (Boom, 2008).
- ISO 19019, 2002.

The descriptions for the calculation methods of the resistance increase due to wind and waves, as well as guidelines for analysis and speed corrections are based on relevant research results and modified from ITTC 7.5-04-01-01.2/2005to meet the IMO EEDI requirements.

The purpose of this document is to define and specify:

- the responsibility of each party involved,
- the trial preparations,
- the vessel's condition,
- the limiting weather and sea conditions,
- the trial procedure,
- the execution of the trial,
- the required measurements,
- the data acquisition and recording, and
- the processing of the results.

The contracted ship's speed and the speed for EEDI shall be determined for stipulated conditions which are defined at specific draughts (contract draught and EEDI draught) and usually for ideal environmental conditions i.e. no wind, no waves, no current, deep water.

Normally, such stipulated conditions are not experienced during the actual trials. In practice, certain corrections for the environmental conditions, such as water depth, wind, waves, current and deviating ship draught from specified draught have to be considered. For this purpose, not only the shaft power and ship's speed are measured, but also relevant ship data and environmental conditions shall be recorded during the speed-power trials.

In case it is physically impossible to meet the conditions in these Guidelines, a practical documented approach mutually agreed among Owner, Verifier and Shipbuilder can be allowed.

The applicability of these Guidelines is limited to commercial ships of the displacement type.

Special Propulsion Setups, CPPs, Power Sharing, Trial settings should be set to a configuration as close as possible to the model test.

All trial procedures and measurements shall be conducted in such a way that the speed at Contract power and the speed at EEDI Power are derived within 0.1 knots and the shaft power within 2%

2. DEFINITIONS

- **Brake power**: power delivered by the output coupling of the propulsion machinery before passing through any speed reducing and transmission devices.
- **Contract power**: shaft power that is stipulated in the newbuilding or conversion contract between Shipbuilder and Owner.
- **Docking report**: report that documents the condition of the ship hull and propulsors (available from the most recent dry-docking).
- **Double run**: two consecutive speed runs at the same power setting on reciprocal heading.
- **EEDI**: Energy Efficiency Design Index as formulated by IMO.
- **EEDI power**: shaft power that is stipulated by the EEDI regulations.
- **Ideal conditions**: ideal weather and sea condition; deep water of 15°C， no wind, no waves and no current.
- **Owner**: party that signed the newbuilding or conversion contract with the Shipbuilder.
- **Parties involved**: Shipbuilder, Ship Owner and EEDI Verifier.
- **Power setting**: setting of engine throttle and propeller shaft speed for fixed pitch propellers and setting of the pitch angle for controllable pitch propellers
- **Propeller pitch**: the design pitch, also for controllable pitch propellers.
- **Running pitch**: the operating pitch of a CPP.
- **Shaft power**: net power supplied by the propulsion machinery to the propulsion shafting after passing through all speed-reducing and other transmission devices and after power for all attached auxiliaries has been taken off.
- **Shipbuilder**: shipyard that signed the new building or conversion contract with the Owner.
- **Ship's speed**: speed that is realised under the stipulated conditions. "Contract Speed" refers to the contractual conditions agreed. "EEDI Speed" refers to the conditions specified by IMO. The ship's speed during a speed run is derived from the headway distance between start and end position and the elapsed time of the speed run.
- **Sister ships**: ships with identical main dimensions, body lines and propulsor system built in a series by the same Shipbuilder.
- **S/P trials**: speed-power trials to establish a speed-power relation of the vessel.
- **Speed run**: ship's track with specified heading, distance and duration over which ship's speed and shaft power are measured.
- **S/P trial agenda**: document outlining the scope of a particular S/P trial. This document contains the procedures on how to conduct the trial and table(s) portraying the runs to be conducted.
- **Trial baseline**: the track of the first S/P run.
- The **Trial Leader** is the duly authorised (Shipbuilder's representative) person responsible for the execution of all phases of the S/P trials including the pre-trial preparation.
- **Trial log**: for each speed run, the log contains the run number, the times when the speed run starts and stops, and the data as described in Section 9.2 and Appendix C of these Guidelines.
- The **Trial Team** consists of the Trial Leader, the Owner's representative, the appointed persons responsible for the S/P trial measurements and if required, the Verifier.
- **Verifier**: third authorized party responsible for verification of the EEDI.

3. RESPONSIBILITIES

3.1 Shipbuilders responsibilities

The Shipbuilder is responsible for planning, conducting and evaluating the S/P trials:

- The Shipbuilder is responsible for appointing an authorized Trial Leader.
- The Shipbuilder is responsible for that speed and shaft power measurements and analysis are conducted by persons acknowledged as competent to perform those tasks, as agreed between the Shipbuilder, the Owner and the Verifier.
- The Shipbuilder has to provide all permits and certificates needed to go to sea.
- The Shipbuilder is responsible for ensuring that all qualified personnel, needed for operating the ship, all engines, all systems and equipment during the sea trials are on board.
- The Shipbuilder is responsible for ensuring that all regulatory bodies, Classification Society, Owner, ship agents, suppliers, subcontractors, harbour facilities, departments organising the delivery of provisions, fuel, water, towing, etc., needed for conducting the sea trials, have been informed and are available and on board, when required.
- It is the Shipbuilder’s responsibility that all safety measures have been checked and that all fixed, portable and individual material (for crew, trial personnel and guests) is on board and operative.
- It is the Shipbuilder’s responsibility that dock trials of all systems have been executed and all alarms, warning and safety systems have been checked.
- It is the Shipbuilder’s responsibility that an inclining test has been performed and/or at least a preliminary stability booklet including S/P trials condition has been approved, in accordance with the SOLAS Convention.
- It is the Shipbuilders responsibility that all ship data relevant for the S/P trials preparation, conduct, analysis and reporting are made available to the Trial Team prior to the S/P trials. This data shall include the information requested in Appendix A as well as the results of the model tests for this ship at trial draught and trim, EEDI draught and trim and contract draught and trim.
- The Shipbuilder is responsible for the overall trial coordination between the ship's crew and Trial Team. A pre-trial meeting between the Trial Team and the ship’s crew shall be held to discuss the various trial events and to resolve any outstanding issues.
- The Shipbuilder has to arrange for divers to inspect the ship’s hull and propulsor if necessary.

The Trial Leader maintains contact with the Trial Team on the preparation, execution and results of the S/P trials.

3.2 The Trial Team’s responsibilities

The Trial Team is responsible for correct measurements and reporting of the S/P trials according to this document and for the analysis of the measured data to derive the ship’s speed and power at the stipulated conditions.

The Trial Team is responsible for the following:

- Conducting inspection of ship including hull and propeller condition.
- Providing, installing and operating all required trial instrumentation and temporary cabling.
- Providing the ship master and Owner’s representative with a preliminary data package and preliminary analysis before debarking.
- Providing a final report after completion of the trials in accordance with Chapter12.

4. TRIAL PREPARATIONS

The success of the S/P trials largely depends on the preparations. In this chapter, the most important steps are summarised.

4.1 Installation & Calibration

Assembling of all trials instrumentation in the configuration that will be used on the ship. Testing of the instrumentation system on malfunctioning or any other complications.

Apart from the obvious signals such as shaft torque, rpm and DGPS, it is important to check:

1. Gyrocompasses
2. Anemometer system
3. Speed log system
4. Propeller pitch (of each propeller)
5. Ship's draught measurement system (if available)
6. Water depth measuring system

Prior to the S/P trials all shipboard signals that will be recorded during the S/P trials shall be calibrated after the instrumentation has been installed. For this purpose, the sensors shall be cycled throughout the full operating range of the system.

This is accomplished by:

- Slewing the gyrocompasses
- Changing the propeller pitch

Prior to departure on S/P trials, the ship's draught measurement system (if available) needs to be verified by directly reading all draught marks, seawater temperature, specific density and the ship's draught measurement system at the same time. The shaft power will be derived from torque and rpm.

Shaft torque shall be measured by means of permanent torque sensor or strain gauges on the shaft. The measurement system shall be certified for power measurements on a test shaft with a bias error smaller than 1% so that an overall bias error smaller than 2% (on board of the actual ship) can be achieved.

Alternative shaft torque measurement devices with a certified accuracy equal to or better than the above figures are acceptable.

As part of the S/P trial preparation, the torsion meter's zero torque readings shall be determined since there is a residual torque in the shaft, which is resting on the line shaft bearings. The torsion meter zero setting is to be done according to its maker's instructions. If not specified otherwise, the zero torque value is determined with the ship at rest by turning the shaft ahead and astern and taking the mean of these two readings as the zero value.

The shaft material properties e.g. the *G*-Modulus shall be fully described and documented by the Shipbuilder. If no certificate based on an actual shaft torsional test is available, the *G*-Modulus of 82,400 N/mm^2 shall be used. The shaft diameter used in the power calculation shall be derived from the shaft circumference measured at the location of the torsion meter. In the case of controllable pitch propeller(s) the drilling diameter must to be taken into account (to be supplied by Shipbuilder).

When shaft torque measurement is not possible, an alternative power measurement method recommended by the engine manufacturer and approved by Owner and Verifier is acceptable.

As part of the pre-trial calibration for a ship equipped with controllable pitch propellers, the procedure shall be as follows:

7. Prior to dock-out the oil distribution mechanism showing the Propeller Pitch shall be checked for zero pitch;
8. Check zero pitch reading in the measurement system against the mechanical reading in the oil distribution box;
9. Determine the maximum ahead pitch, design pitch, and maximum astern pitch and then adjust the ship indicators to reflect the measurements. Determine the corrections to account for changes in pitch due to shaft compression as thrust increases and temperature effects on the Propeller Pitch control rod.
10. Verify the weight of the propulsor and hub from the manufacturer's specifications for making thrust measurement corrections.

An important deliverable of this stage is a document describing the test set-up including evidence of the calibrations that have been carried out.

It is important to note that there are two stages to consider in performing instrumentation checks, viz. the pre-trial check procedures and the post-trial check to verify the calibration results.

4.2 S/P trial agenda and pre-trial meeting

Before departure, a pre-trial meeting shall be held to fix the S/P trial agenda. During this meeting two items shall be addressed.

- Approval of the S/P trial agenda,
- Approval of the procedures and the consequential correction methods to be used to calculate the trial speed and to deliver the speed trial report i.e. this Recommended Procedure.

The S/P trial agenda is a document prepared by the Shipbuilder, outlining amongst others the scope of a particular Speed/Power trial. This document contains the procedures on how to conduct the trial and table(s) portraying the runs to be conducted. It outlines the particular responsibilities of the Trial Leader, Trial Team, ship's crew/ Shipbuilder, and the Owner's representative. The scope of the S/P trials shall be in line with this document.

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 and Verifier shall be obtained concerning the limits of wind forces, wave heights and water depths up to which the trials shall be performed. Agreement shall be obtained concerning the methods used to correct the trial data. The measured data, analysis process and the results shall be transparent and open to the Trial Team.

5. SHIP CONDITION

5.1 Displacement

The difference between the ship's actual displacement and the required displacement shall be less than 2% of the required displacement. If model test results are used for the analysis of the S/P trials, the deviation of the actual displacement during the S/P trials shall be within 2% of the displacement used during the model test.

The ship's draught at the perpendiculars, midship port and starboard, trim and displacement are obtained immediately prior to the S/P trial by averaging the ship draught mark readings. In the event that reading the draught marks is unsafe or provide an inaccurate result, displacement determination shall be conducted either by reading the internal draught measurement system or by evaluating all tank soundings.

Displacement shall be derived from the Bonjean data or using quadratic equations with hydrostatic data, taking into consideration the hog/sag using the draught data (forward, aft and at half length) and the density of the water.

The ship shall be brought into a loading condition that is as close as possible to contract condition and/or the condition at which model tests have been carried out. The loading condition shall be confirmed at zero ship's speed.

5.2 Trim

The trim shall be maintained within very narrow limits. For the even keel condition, the trim shall be less than 0.1% of the length between perpendiculars. For trimmed trial conditions, the forward draught shall be within ± 0.1 m of the ship condition for which model test results are available.

5.3 Hull &propeller

The ship shall have clean hull and propeller(s) for the sea trial. Hull roughness and marine growth can increase the resistance of the ship significantly but are not corrected for in S/P trials. Therefore, it is recommended that the hull and propeller(s) be carefully inspected before the sea trial, and cleaned as needed and as per coating manufacturer's recommendation. The dates of last docking and hull and propeller cleaning are to be recorded in the S/P trials report.

6. TRIAL BOUNDARY CONDITIONS

During the S/P trial, there are many conditions that deviate from the contract condition. The objective during the S/P trial is to minimize the number of influencing factors.

Although there are correction methods for certain deviations from the contract condition, these methods are only valid up to certain limits.

In order to arrive at reliable S/P trial results the boundary conditions shall not exceed the values given in this chapter.

6.1 Location

High wind and sea state in combination with a heading deviating from head waves and following waves, can require the use of excessive rudder deflections to maintain heading, and thus cause excessive fluctuations in propeller shaft torque, shaft speed and ship's speed.

The S/P trial shall be conducted in a location where the environmental conditions are expected to be constant and to have only the smallest possible impact on the vessel in order to avoid unexpected environmental effects in the S/P trial results.

This means that the speed trial range shall be located in a sheltered area (i.e. limited wind, waves and current). Furthermore, the area shall be free from hindrance by small boats and commercial traffic.

6.2 Wind

During the S/P trial the wind speeds shall not be higher than:

- Beaufort [1] number 6, for vessels with L_{PP}>100m or
- Beaufort number 5, for vessel with L_{PP}≤100m

where:

L_{PP} Length between perpendiculars [m].

6.3 Sea state

The total significant wave height $H_{W1/3}$, derived from the significant wave heights of local wind driven seas (wind waves) $H_{1/3W}$ and swells $H_{1/3S}$, by

$$H_{W1/3}=\sqrt{H_{1/3W}^2+H_{1/3S}^2} \tag{1}$$

shall satisfy the following criteria:

- $H_{W1/3} \leq 1.5x$ when the wave height is derived from visual observations,
- $H_{W1/3} \leq 2.25x$ when the wave spectrum encountered during the S/P trials is measured,

with $x = \sqrt{L_{PP}/100}$,

L_{PP} Length between perpendiculars [m]

See section 7.6.5 for definition of “observations” respectively “measurements” in this context.

The above limits are illustrated in Figure 1.

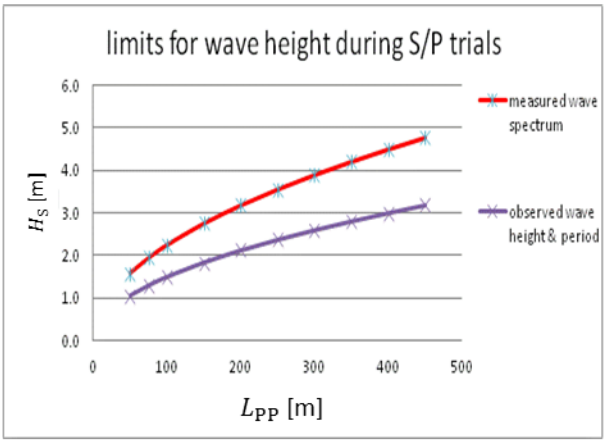


Figure 1. Limits for allowable wave height

6.4 Water depth

There are correction methods that compensate for shallow water (see 10.3.4). However, it is preferable to avoid the corrections by a suitable choice of the S/P trial location. The value of water depth to be used for correction shall not be less than larger value obtained from the following formulae:

$$h = 2.5T \qquad and \qquad h = 2.4\frac{V_S^2}{g} \tag{2}$$

where:

h	water depth [m],
B	ship’s breadth [m],
T_M	draught at midship [m],
V_S	ship’s speed [m/s],
g	acceleration of gravity [m/s²].

Furthermore, areas with significant variations in the bottom contours shall be avoided. The actual water depth during each speed run shall be read from the ship’s instruments and documented in the trial log.

---

[1] The Beaufort scale is given in Appendix B.

6.5 Current

Ideally S/P trials shall be conducted in a location where current speed and direction are essentially uniform throughout the trial area.

In cases of current time history deviating from the assumed parabolic / sinusoidal trend and the change of the current speed within the timespan of one double run is more than 0,5 knots/hour*timespan, neither of the correction methods in Appendix H are applicable. Areas where this may occur shall be avoided for S/P trials.

7. TRIAL PROCEDURES

7.1 Parameters that shall be recorded

In this chapter, an overview is given of the parameters that influence the trial speed. All these parameters shall be measured as accurately as possible and recorded.

For this purpose, a split has been made between primary and secondary parameters. For each of the parameters the preferable measurement methods are given.

7.2 Primary parameters

The primary parameters to be measured during each run and the accepted measurement devices are given in Table 1.

Table 1 Primary parameters

	Acceptable measurement devices	Unit
Ship Track	DGPS	[Latitude, Longitude] or [m]
Speed over Ground	DGPS	[Knots]
Shaft Torque or shaft power	Torsion meter with calibrated permanent torque sensor or strain gauges. Power calculated from torque and RPM	[kNm], [kW]
Shaft RPM	Pick-up, optical sensor, ship revs counter	[RPM]
Propeller Pitch	Bridge replicator	
Time	GPS Time	[hh:mm:ss]
Water depth	Ship echo sounder + nautical charts	[m]
Ship heading	Gyro compass, or compass- DGPS	[deg]
Relative wind, speed and direction	Ship anemometer, dedicated trial anemometer	[m/s], [knots], [deg]
Height, period and direction of wind waves and swell	Wave measuring device such as wave buoy, radar, or lidar. Observation by multiple Mariners.	[m], [sec], [deg]
Bow acceleration (for wave corr method G.1))	Calibrated acceleration gauges	[m/s^2]
Date		[YYYY-MM-DD]

It is recommended to record the wave height, wave direction and period, absolute wind speed and direction at station(s) in the vicinity of the S/P trial site.

7.3 Secondary parameters

The secondary parameters listed in Table 2 shall be measured and recorded at the trial site at least once during the S/P trial.

Table 2 Secondary parameters

	Acceptable measurement devices	Unit
Date		[YYYY-MM-DD]
Seawater density	Salinity sensor, Conductivity Density Temperature (CDT) sensor	[kg/m^3]
Seawater temperature	Thermometer, CDT sensor	[ºC]
Air temperature	Thermometer	[ºC]
Air pressure	Barometer	[hPa], [mBar]

Sea trial area	Geographical position by DGPS	[Latitude, Longitude]
Draughts, fore, amidships and aft at zero speed	Physical observation and / or calibrated draught gauges	[m]
Displacement	According to draught readings and water density	[metric tons]
Torsion meter zero setting	Torsion meter with calibrated torque sensor or strain gauges	kNm

7.4 General information

Prior to the trial, the data specified in Appendix A shall be recorded, based on measurements where applicable.

7.5 Model test information

The quality and accuracy of model tests play a large role in the outcome of full scale S/P trials. For some ship types, sea trials are normally carried out in ballast condition, whereas the contractual condition normally is defined in loaded design condition. For the conversion from ballast trial results to loaded condition, the difference between the ballast and loaded model test curves is used. Therefore, an accurate model test and validated consistent extrapolation method to full scale is required.

For the analysis of the S/P trials, i.e. to include the effect of the propeller loading in non-ideal conditions on the propulsion efficiency and rpm, it is required that the model tests data include the results of propeller load variation measurements as described in ITTC recommended procedures 7.5-02-03-01.4-(2017)]").

Based on ITTC recommendations, the model tests shall be conducted according to the following criteria:

Model tests shall be conducted at the contract draught and trim, the EEDI draught and trim as well as the trial draught and trim.

Model tests shall be conducted according to the ITTC Recommended Procedures for Resistance and Propulsion Model Tests (2017), including load variation tests.

For all draughts and trims, the same methods, procedures and empirical coefficients shall be used to extrapolate the model scale values to full scale. In case different empirical coefficients are used for the different draughts, these shall be documented in full detail and documentation must include justification by means of full scale S/P trial data for the specific ship type, size, loading condition, model test facility, and evaluation method. Refer to Guideline on the use and the determination of C_A- and C_P-correlation factors used in ITTC Recommended Procedures (2017).

The model test report shall be transparent and give sufficient information to enable the authorized party to check the model test results. This means that in the model test report, the measured data, the predicted full scale data and a detailed description of the extrapolation method and the coefficients used have to be given.

7.6 Scope and conduct of the measurements

7.6.1 Ship’s track and speed over ground

The ship’s position and speed shall be measured by a global positioning system such as DGPS. The DGPS system shall operate in the differential mode to ensure sufficient accuracy. Position and speed shall be monitored and stored continuously.

7.6.2 Torque

The calibration of the torque measurement shall not be altered during the S/P trials.

7.6.3 Wind

The wind measured on trials should be as close to a measurement of the undisturbed wind speed encountered by the vessel as possible. To this end it is encouraged to use technology capable of measuring wind speed outside the region where airflow is distorted by the vessel (e.g. LIDAR). If an anemometer is to be used for trials measurements, then it should be positioned so as to minimise the effect of airflow distortion on the measured wind speed. Computational fluid dynamics, or wind tunnel experiments, may be used to assist with such positioning. In general, the anemometer should be sited as close as possible to the upwind leading edge of superstructures and as high above them as possible. Directly above the leading edge is not recommended due to greater distortion effects at oblique wind angles. Any anemometer should be sited more than 3x mast diameter away from masts. Positioning on a foremast away from superstructures is preferable.

7.6.4 Water depth

Measuring the water depth can be done by using the ship echo sounder. It is important that the echo sounder is calibrated before the speed run in combination with the check of the water depth given on the charts and that the vessel's draught is taken into account. Continuous recording of water depth is recommended.

7.6.5 Waves

The wave spectrum and direction can be derived either by measurements or by observations.

Wave measurements

Preferably, the spectrum of waves induced by local wind and swell originating from remote wind, shall be measured during the S/P trials. The spectrum is derived from a spectral analysis of the measured wave elevation as a function of time. For this purpose, wave buoys in the speed trial area or ship born equipment such as wave radar or LIDAR can be used. The wave measurement equipment shall have been calibrated and the accuracy shall be validated and documented.

Measurement of directional wave spectrum is preferable.

Wave observations

In case the wave spectrum encountered during the S/P trials is not measured, the wave height, direction and period shall be derived from visual observations by multiple experienced mariners, including the Owner's representative and the Verifier. In addition to the wave observations, wave now- or hind- cast data provided by an experienced and independent weather office may be used. The wave spectrum is then obtained by entering the observed wave height, period and direction into the relevant equation (see section 10.3.2).

7.6.6 Density and temperature

The local seawater temperature and density at the trial site shall be recorded to enable the calculation of the ship's displacement and corrections with regard to viscosity. The water temperature shall be taken at sea water inlet level. Air temperature and pressure shall be measured at the trial location using a calibrated thermometer and barometer.

7.6.7 Current

Current speed in the direction of the ship's heading shall be derived as part of the evaluation of each run, either using the 'Mean of means' method (Appendix H-2) or the 'Iterative' method (Appendix H-1). See also section 10.2.4.

8. CONDUCT OF TRIAL

On the day of and during the S/P trial, a number of prerequisites shall be met in order to arrive at reliable trial results. In this chapter, an overview is given of the minimum requirements.

8.1 Initiation

Prior to the S/P trials, the weather forecast shall be studied.

Whenever possible, the runs at EEDI power shall be conducted in daylight to enable a clear visual observation of the wave conditions. For trials in which the encountered wave spectrum and the wave direction (both wind waves and swells) are derived by measurements, these runs may also be conducted without daylight.

It is important to check that the engine plant configuration during the S/P trial is consistent with normal ship operations.

Prior to the S/P trials, the following actions shall be taken at the vessel's zero speed through the water:

1. draught reading as described in section 5.1and calculation of displacement,
11. measurement of wind speed and direction,
12. zero setting of shaft torque meter,
13. measurement of water temperature and density.

8.2 Trial trajectory

The S/P trial runs need to be conducted over the same ground area. For each base course, each speed run will be commenced (COMEX) at the same place (within reason).

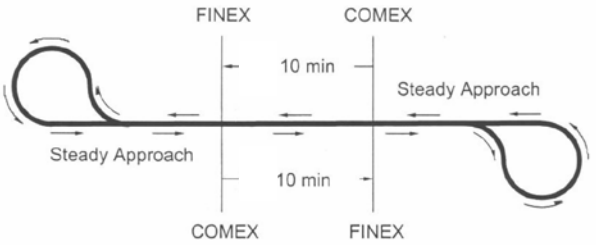


Figure 2Trial trajectory of one double run

Modified Williamson turns or similar types of manoeuvre will be executed between each run to return the ship to the reciprocal heading on, or parallel to, the trial baseline. Parallel means within one ship length of the trial baseline (see also 8.6). This procedure is used to avoid different sea states or different wind conditions. Engine throttles, rpm setting(s) or pitch setting(s)shall not be moved during this period. The rudder angle used in this manoeuvre shall be such that ship's speed loss and time loss are minimised.

8.3 Run duration and timing

The S/P trial duration shall be long enough to accommodate a speed/power measurement within the required accuracy. The run duration shall be the same for all speed runs with a minimum often (10) minutes. The speed runs for the same power setting shall be evenly distributed in time.

8.4 Trial direction

The speed runs shall preferably be carried out by heading into and following the dominant wave or wind direction, depending on which effects the ship's speed most.

Consequently, once the heading for the speed run and the reciprocal heading for the return run are fixed, the selected heading shall be maintained very precisely throughout the S/P trial. However, if the 'Mean of means' method is used for current correction, the trial direction can be changed between each power setting according to change of weather condition.

8.5 Steering

An experienced helmsman or adaptive autopilot will be required to maintain heading during each speed run. Minimum rudder angles are to be used while maintaining a steady heading.

During the speed run, the maximum single amplitude of rudder angles shall be not more than five (5) degrees.

8.6 Approach

The S/P trial approach shall be long enough to ensure a steady state ship's condition prior to commencement (COMEX) of each speed run. During the approach run, the ship shall be kept on course with minimum rudder angles.

No fixed approach distance can be given. In order to verify that the vessel reached the steady ship's condition the measured values of shaft rotation rate, shaft torque (if available) and ship's speed at the control position shall be monitored. When all three values are stable the ship's condition shall be deemed "steady".

8.7 Power settings

A minimum of three (3) different power settings are required. These shall be adequately distributed within the power range of 65% MCR and 100% MCR.

8.8 Number of speed runs

All S/P trials shall be carried out using double runs, i.e. each run shall be followed by a return run in the exact opposite direction performed with the same engine settings.

8.8.1 'Iterative' method

When the current correction is carried out using the 'Iterative' method (Appendix H.1), the runs shall comprise at least:

- One (1) double run below EEDI / Contract power,
- Two (2) double runs (at the same power setting) around EEDI / Contract power,
- One (1) double run above EEDI / Contract power.

The EEDI / Contract power runs shall be conducted not as the first or the last power setting in the trial sequence.

8.8.2 'Mean of means' method

When the current correction is carried out using the 'Mean of means' method (Appendix H.2), the runs shall comprise at least:

- Two (2) double runs (at the same power setting) below the EEDI/Contract power,
- Two (2) double runs (at the same power setting) around the EEDI/Contract power,
- Two (2) double runs (at the same power setting) above the EEDI/Contract power.

Two (2) double runs compensate for the effect of current and second order current variations. In order to obtain sufficient accuracy, the time intervals between each run at the same power setting shall be more or less the same (time interval deviation of 25% between single runs is acceptable).

8.8.3 Sister ships

If the results of the S/P trials of the first ship of a series are acceptable, sister ships may be subjected to a reduced speed trial program. The runs shall comprise at least:

- One (1) double run below EEDI / Contract power,
- One (1) double run around EEDI / Contract power,
- One (1) double run above EEDI / Contract power.

Additional runs– sister ships

For 'Mean of means' method, if after evaluation the vessel speed deviates more than 0.3 knots, compared to the first ship, then the same procedure as the first ship should be followed.

8.8.4 Additional runs due to limiting wave height

For the first of a series or a sister ship at any power setting, when the wave height is around the limiting conditions and significant wave-induced ship motions are observed then one (1) additional double run at that power setting shall be conducted.

8.9 Test sequence

1. Fixing of speed run heading (see section 8.4);
14. Navigating through the approach distance on direct course;
15. Prepare all measurements to start;
16. Start speed run. Control levers shall remain unchanged, maximum rudder angle shall not be more than 5 deg. port and starboard. After agreed duration (minimum of 10 minutes) stop speed run. Determine the achieved speed and power;
17. During S/P trial run make environmental observations;
18. Turn ship with small rudder angles to navigate the counter run covering the same geographical track as the first run;
19. Repeat steps 2 to 6.

9. DATA ACQUISITION

During the speed/power trial, accurate recording of the speed and power relationship is of great importance.

Apart from this, an accurate quantification of the boundary conditions is necessary since the ship's speed and powering characteristics are extremely sensitive to conditions such as hull and propeller condition, ship displacement, shallow water effects, sea state and wind velocity. Consequently, these factors shall be monitored and documented to the greatest possible extent.

During the S/P trials, two types of data acquisition shall be used: Automated acquisition by means of a data acquisition system (measurement computer), and manual recording of information by means of a log sheet. The objective shall always be to record as many parameters as possible by means of the measurement computer in order to increase the level of accuracy of the S/P trials.

9.1 Acquisition system

The acquisition system shall record time histories of the measurements described in chapter 7.2 to assure quality control and to provide information that will allow for the development of uncertainty analysis.

9.1.1 System requirements

The data acquisition system shall:

- Record all available parameters simultaneously.
- Perform a time trace recording with a sampling rate of at least 1 Hz.
- Display time traces of the trial parameters specified in section 7.2.

- Calculate statistics (mean min, max, standard deviation).

At the end of each run, the data acquisition system shall be able to present all recorded time histories to evaluate the quality and consistency of the acquired trial data and be stored for subsequent graphical presentation.

Furthermore, the acquisition system shall present the following values for each of the measured data:

1. Trial start time
2. Number of samples taken
3. Maximum value
4. Minimum value
5. Average value
6. Standard deviation
7. Trial end time

Filtering of the run data is recommended to avoid “spikes” in the recorded time histories. Chauvent’s criterion that provides a ratio of maximum acceptable deviation to precision index as a function of the number of readings, (N) is to be used. Readings are automatically rejected from use in the data analysis when they fall outside of the selected mean value bandwidth.

9.1.2 Location

The data acquisition system shall be located on the bridge.

9.2 Manual data collection

For those parameters that cannot be measured and recorded automatically by means of the data acquisition system, manual data collection is required using a log sheet (see Appendix C).

The log sheet is important for two aspects:

1. To complete the dataset.
2. To provide a backup for the automated measurements and give a written overview of the measurements.

It is important that the parameters that are varying in time are recorded every few minutes so that the average can be determined over the run period.

9.3 Sign convention

The sign conventions to be used for wave and wind direction are presented in Figure 3, Figure 4 and Figure 5.

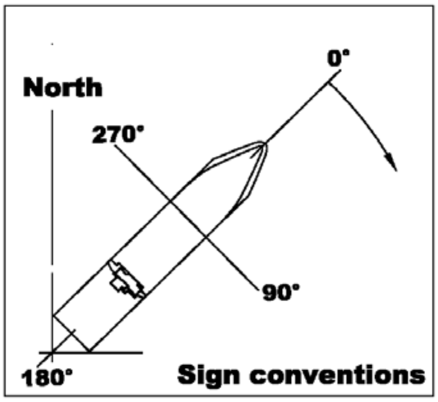


Figure 3. Sign conventions

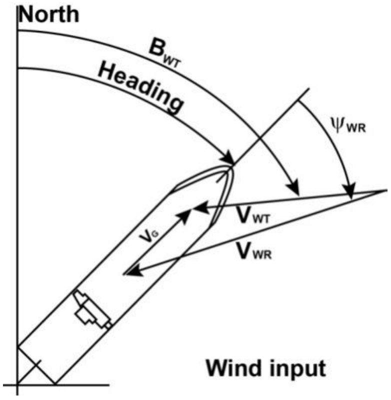


Figure 4. Sign convention for wind directions

The wind direction is defined as the direction from which the wind is coming. Zero (0) degrees on the bow and positive to starboard (clockwise).

Input parameters:

ψ: Heading of the ship [deg]
V_{WR}: Relative wind speed [m/s]
ψ_{WR}: Relative wind direction relative to the bow, ship fixed; 0 means head winds [deg]
V_{G}: Measured ship's speed over ground [knots]

Computed parameters:

B_{WT}: True wind angle in earth system [deg]
V_{WT}: True wind speed [m/s]

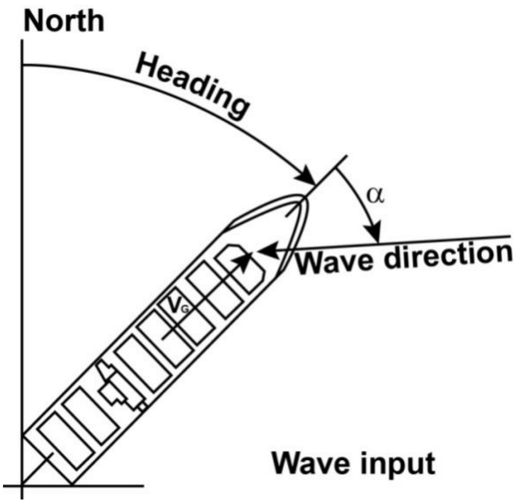


Figure 5. Sign convention for wave directions

The wave direction is defined as the direction relative to the ship's heading from which the wave fronts are approaching.

Input parameters:
ψ: Heading of the ship [deg]
$H_{1/3\mathrm{W}}$: Significant wave height (wind waves) [m]
$H_{1/3\mathrm{S}}$: Significant wave height (swell) [m]
α: Angle between ship heading and wave direction relative to the bow; 0 means head waves [deg]
V_{G}: Measured ship's speed over ground [knots]

10. ANALYSIS PROCEDURE

10.1 General Remarks

This section describes the methods to analyse the results of speed/power trials as conducted according to the previous sections. The method to be used depending on situation and available data is given in Table 3.

10.2 Description of the Analysis Procedure

The analysis of speed/power trials shall consist of

- evaluation of the acquired data
- correction to ship power for resistance increase due to wind, waves, water temperature and salt content
- correction to ship's speed at each run for the effect of current
- correction to ship's speed or power for the effect of shallow water
- correction to ship power for displacement
- presentation of the trial results

Details of the methods are given in the following chapters. 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 analysis and correction method to be followed is prescribed below and summarized in Table 3.

Evaluation

For the evaluation the Direct Power Method in combination with the propulsive efficiency correction based on load variation tests (refer to ITTC 7.5-02-03-01 (2017)) shall be used.

Table 3. Evaluation method to be followed. The numbers identify the method by the chapters or Appendix in which the methods are described.

Condition				Evaluation / Correction Method							
				Evaluation	Waves	Wind	Current	Air Resistance	Temp. & Density	Water Depth	Displ. & Trim
Heading changed between power settings	Yes						H.2	Included in method	10.3.3	10.3.4	10.3.5
	no						H.1 or H.2				
Load Variation Test available	Yes			D							
	No			D							
Ship geometry available to Verifier	No	heave and pitch	No		G.1-G.3						
			Yes		G.2-G.3						
	Yes				G.1-G..4						
	Full Seakeeping Model Tests available				G.5						
Dataset of wind resistance coefficients Available	Wind Tunnel Tests /CFD					E.1/E.2					
	Data set					E.3					
	No					E.4					

Wind Correction

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

If **wind tunnel measurements are available**:

- Wind resistance coefficients from model test are used (Appendix F.1).

If **CFD simulations are available**:

- Wind resistance coefficients from simulations are used (Appendix F.2).

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

- Wind resistance coefficients from standard data sets (Appendix F.3)

or

- Regression formula by Fujiwara et al. (Appendix F.4).

are(is) used.

Wave correction

In calculating resistance increase due to waves, the following procedure shall be used:

If s**hip's geometry cannot be made available** to Verifier:

- Under the condition that heave and pitch motions are small, the direct correction wave method based on wave reflection prescribed in Appendix G.1 or G.2, G.3 shall be used.
- In case significant heave and pitch is observed during the trials, the empirical formulation of the response function prescribed in Appendix G.2 if the wave direction is within 45° from the heading, or G.3 shall be used for the analysis. These empirical transfer functions cover both the mean resistance increase due to wave reflection and the motion induced added resistance.

Provided that the **ship geometry is available** to Verifier

- The theoretical method with tank test in short waves or empirical formulae as prescribed in Appendix G.4, or G.1-G.3 shall be used according to ship motion and wave direction.
- In the case, transfer functions of added resistance in waves derived from seakeeping tank tests are available for the specific vessel at the relevant draught, trim, speed range and relative wave direction; these shall be used in combination with the wave spectrum (Appendix G.5).

The wave spectrum applied for calculations of added resistance shall be reported.

Shallow water

To correct for shallow water effect, the method specified in Appendix K shall be applied.

10.2.1 Resistance data derived from the acquired data

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

$$\Delta R = R_{\mathrm{AA}} + R_{\mathrm{AW}} + R_{\mathrm{AS}} \tag{3}$$

with

R_{AA}: resistance increase due to relative wind (see Appendix E and F),
R_{AS}: resistance increase due to deviation of water temperature and water density (see section 10.3.3),
R_{AW}: resistance increase due to waves (see Appendix G).

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

10.2.3 Evaluation based on Direct Power Method

To derive the speed/power performance of the vessel from the measured speed over ground, power and rpm, the Direct Power Method is to be used. In this method the measured power is directly corrected by the power increase due to added resistance in the trial conditions. The analysis is based on the delivered power.

More details are given in Appendix D.

The delivered power in the trial condition is derived by:

$$P_{\mathrm{Dms}} = P_{\mathrm{Sms}} \eta_{\mathrm{S}} \tag{4}$$

when the measured power is shaft power

$$P_{\mathrm{Dms}} = P_{\mathrm{Bms}} \eta_{\mathrm{M}} \tag{4}$$

when the measured power is brake power

with

P_{Sms}: shaft power measured for each run
η_{S}: shaft efficiency (0.99 for conventional shaft)
P_{Bms}: brake power measured for each run
η_{M}: transmission efficiency

The corrected delivered power P_{Did} is obtained as follows (under condition $P_{\mathrm{Dms}} - \frac{\Delta R V_{\mathrm{S}}}{\eta_{\mathrm{Did}}} > 0$):

$$P_{\mathrm{Did}} = \frac{1}{2}\left\{P_{\mathrm{Dms}} - \frac{\Delta R V_{\mathrm{S}}}{\eta_{\mathrm{Did}}} + \sqrt{\left(P_{\mathrm{Dms}} - \frac{\Delta R V_{\mathrm{S}}}{\eta_{\mathrm{Did}}}\right)^2 + 4 P_{\mathrm{Dms}} \frac{\Delta R V_{\mathrm{S}}}{\eta_{\mathrm{Did}}} \xi_{\mathrm{P}}}\right\} \tag{5}$$

V_{S}: ship's speed through water [m/s], see 10.2.4
η_{Did}: propulsion efficiency coefficient in ideal condition, from model test.
ξ_{P}: overload factor derived from load variation model test.
ΔR: resistance increase due to wind, waves and temperature deviations [N] (eq.3).

P_{Did} is the power in ideal conditions, i.e. no wind, waves or other disturbances. For shallow water a power correction is applied according to 10.3.4. It is noted that due to variations in shallow water of wake fraction, propulsive efficiency changes slightly, which could be ignored. Deviations in displacement are corrected for according to 10.3.5.

The correction of the propeller frequency of revolution is also carried out considering load variation effects (Appendix D). The corrected shaft rate n_{id} is

$$n_{\mathrm{id}} = \frac{n_{\mathrm{ms}}}{\xi_n \cdot \frac{P_{\mathrm{Dms}} - P_{\mathrm{Did}}}{P_{\mathrm{Did}}} + 1} \tag{6}$$

with

n_{ms}: measured propeller frequency of revolution [1/s]
V_{S}: ship's speed through water [m/s], see 10.2.4
ξ_n: overload factors derived from load variation model test

The extended analysis in Appendix J, which is included informatively, is useful for model test correlation purposes since it involves the full-scale wake fraction. It shall not be used for official evaluations of S/P trials.

10.2.4 Correction of the measured ship's speed due to the effect of current

The ship's speed through water (V_{S}) is the measured speed over the ground (V_{G}) corrected for the current speed (V_{C}) at each run, V_{S}=V_{G}-V_{C}.

The current correction can be achieved by two (2) different methods: *either* the 'Iterative' method or the 'Mean of means' method. The details are given in Annex H.

'Iterative 'method

Based on the assumption that the current speed varies with a semi-diurnal period, a current curve as a function of time is created. In the same process a regression curve representing the relationship between the ship's speed through the water and corrected power is determined. The current curve and the regression curve are created in one process. The regression curve has no relation with the speed/power curve from the tank tests.

The analysis of the direct power method as described in Appendix D shall be repeated after the value of V_S has been derived by the current correction analysis.

'Mean of means' method

Based on the assumption that for a given power setting, the current speed varies parabolically, the influence of current is accounted for by applying the 'Mean of means' method for each set of runs with the same power setting (Principles of Naval Architecture, 1988).

'Mean of means' method gives one corrected ship's speed for each power setting as described in Appendix H.2. Therefore, for each power setting, the values of corrected power and corrected propeller rate of revolutions shall be combined and averaged to derive the final results.

10.2.5 Prediction of power curve from trial condition to other loading condition

For dry cargo vessels it is difficult to conduct speed trials at full load condition. For such ships speed trials are performed at ballast condition 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 tank test results shall be provided by the Shipbuilder. These tank test results shall be obtained in full compliance with the requirements given in Section 7.5.

The conversion method to be followed to convert the trial results for trial condition to results for the contractual or stipulated condition is given in Appendix I.

10.3 Calculation methods for resistance increase and other corrections

10.3.1 Resistance increase due to the effects of wind

The resistance increase due to relative wind is calculated by:

$$R_{AA}=\frac{1}{2}\rho_A C_{DA}(\psi_{WRref})A_{XV}{V_{WRref}}^2-\frac{1}{2}\rho_A C_{DA}(0)A_{XV}{V_G}^2 \tag{7}$$

with

A_{XV}: area of maximum transverse section exposed to the wind [m^2],
C_{DA}: wind resistance coefficient
Note: C_{DA} = -C_X for method F.3 and cannot be replaced by C_{AA}
V_G: measured ship's speed over ground [m/s],
V_{WRref}: relative wind speed[m/s] at reference height,
ρ_A: mass density of air [kg/m^3],
ψ_{WRref}: relative wind direction at reference height; 0 means heading wind.

By nature, the 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 run. The average speed and direction during the 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 at vertical position of anemometer is found. The wind speed as measured by the anemometer shall be corrected for the wind speed profile taking into account the vertical position of the anemometer and the reference height for the wind resistance coefficients (normally 10 m) according to Appendix E.2. 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 E.1.

In case the average true wind speed from two subsequent runs is within 5% or 0.5m/s whichever is larger, averaging of wind speeds is not required and averaged single run wind speed can be used. Alternatively, in case the undisturbed (not affected by any part of the ship) wind speed encountered by the vessel is measured remotely by a certified instrument accurately, the averaged single run wind speed may be used.

The wind resistance coefficient shall be based on the method according to Appendix F.

10.3.2 Resistance increase due to the effects of waves

The most reliable way to determine the decrease of ship’s increase of resistance in waves is to carry out sea keeping tests in regular waves of constant wave height or steepness, at different wave lengths and directions and at various speeds, and according to ITTC 7.5-02-07-02.2.

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}.

$$R_{\mathrm{AW}} = 2\int_0^{2\pi}\int_0^{\infty}\frac{R_{\mathrm{wave}}(\omega,\alpha;V_{\mathrm{S}})}{\zeta_{\mathrm{A}}{}^2}E(\omega,\alpha)d\omega d\alpha \quad (8)$$

with

R_{AW}: mean resistance increase in short crested irregular waves,
R_{wave}: transfer function of mean resistance increase in regular waves,
ζ_{A}: wave amplitude,
ω: circular frequency of regular waves,
α: angle between ship heading and component waves; 0 means heading waves,
V_{S}: ship’s speed through the water,
E: directional spectrum.

If the directional spectrum is measured at sea trials by a sensor and the accuracy is confirmed, the directional spectrum is available. If the directional spectrum is not measured it is calculated by the following relation:

$$E = S_{\eta}(\omega)G(\alpha) \quad (9)$$

with

G: angular distribution function.
S_{η}: frequency spectrum.

The standard form of the frequency spectrum and the angular distribution function are assumed for the calculation.

For ocean waves the modified Pierson-Moskowitz spectrum of ITTC 1978 is used:

$$S_\eta(\omega) = \frac{A_{\mathrm{fw}}}{\omega^5} \exp\left(-\frac{B_{\mathrm{fw}}}{\omega^4}\right) \qquad (10)$$

with

$$A_{\mathrm{fw}} = 173 \frac{{H_{\mathrm{W}1/3}}^2}{{T_{01}}^4} \qquad (11)$$

$$B_{\mathrm{fw}} = \frac{691}{{T_{01}}^4} \qquad (12)$$

Other spectra can be used if appropriate for the specific location and environment, given that it can be supported by public references.

For the angular distribution function the cosine-power type shown in formula (14) is generally applied; e.g. $s = 1$ for wind waves and $s = 75$ for swells are used in practice.

$$G(\alpha) = \frac{2^{2s}}{\pi} \frac{\Gamma^2(s+1)}{\Gamma(2s+1)} cos^{2s}(\alpha - \theta_m)$$

$$\text{for } -\frac{\pi}{2} \le \alpha - \theta_m \le \frac{\pi}{2} \qquad (13)$$

where

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

For wind waves and swells, R_{AW} is calculated for each run with the relevant wave height, period and direction.

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

10.3.3 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, speed trials are corrected to a sea water temperature of 15°C and a density of 1026kg/m³. The effects of water temperature and density that differ from these values are calculated as follows:

$$R_{\mathrm{AS}} = R_{\mathrm{T0}}\left(\frac{\rho_{\mathrm{S}}}{\rho_0} - 1\right) - R_F\left(\frac{C_{\mathrm{F0}}+\Delta C_{\mathrm{F0}}}{C_{\mathrm{F}}+\Delta C_{\mathrm{F}}} - 1\right) \qquad (14)$$

with

$$R_{\mathrm{F}} = \frac{1}{2}\rho_{\mathrm{S}} S {V_{\mathrm{S}}}^2 (C_{\mathrm{F}} + \Delta C_{\mathrm{F}}) \qquad (15)$$

$$R_{\mathrm{F0}} = \frac{1}{2}\rho_0 S {V_{\mathrm{S}}}^2 (C_{\mathrm{F0}} + \Delta C_{\mathrm{F0}}) \qquad (16)$$

$$R_{\mathrm{T0}} = \frac{1}{2}\rho_0 S {V_{\mathrm{S}}}^2 C_{\mathrm{T0}} \qquad (17)$$

where

C_{F}: frictional resistance coefficient for actual water temperature and salinity,
C_{F0}: frictional resistance coefficient for reference water temperature and salinity,
ΔC_{F}: roughness allowance associated with Reynolds number for actual water temperature and salinity,
ΔC_{F0}: roughness allowance associated with Reynolds number for reference water temperature and salinity,
C_{T0}: total resistance coefficient for reference water temperature and salinity,
R_{AS}: resistance increase due to deviation of water temperature and water density [N],
R_{F}: frictional resistance for actual water temperature and salt content[N],
R_{F0}: frictional resistance for reference water temperature and salt content[N],
R_{T0}: total resistance for reference water temperature and salt content[N],
S: wetted surface area[m^2],
V_{S}: ship's speed through the water [m/s],

ρ_S: water density for actual water temperature and salt content [kg/m^3],
ρ_0: water density for reference water temperature and salt content.

C_F, C_{F0}, ΔC_F and ΔC_{F0} are derived according to ITTC Recommended Procedures 7.5-02-03-01.4, latest version, using the same roughness k_S for ideal and actual condition.

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

Within the restrictions on water depth stipulated in section 6.4, the results of S/P trials in restricted water depth may be corrected according to the Raven Shallow Water Correction Method (2016) for which the calculation procedure is specified in Appendix K.1.

The Raven method is based on CFD and validated with sea trials at several water depths and varying speeds for four commercial vessels: 600 ton, 3000 ton,10000 ton and 80000m^3 LPGC. However, the LPGC vessel trials, from deep to shallow water conditions, were not made according to standards but only by the single run.

If agreed between builder, owner and verifier, the corrections for power due to shallow water may be derived from propulsion model tests for the specific vessel on deep and shallow water corresponding with the water depth during the speed/power trials. Such model tests have to be conducted in a towing tank with sufficient width for which results have been validated with full scale trials on shallow water. The recommended basin width is:

- blockage (midship sectional area / tank cross section) < 2.0%,
- 2.0 model lengths for $Fr_H <= 0.5$
- 2.7 model lengths for $0.5 < Fr_H < 0.7$

Extrapolation of the model test results to full scale shall be done using the ITTC Recommended Procedure 7.5-02-03-01.4 including the form factor, with the form factor determined for the water depth considered. For deep and shallow water, the same methods, procedures and empirical coefficients shall be used to extrapolate the model scale values to full scale (Raven 2012).

10.3.5 Correction of the ship's performance due to the effects of displacement

If the displacement of the vessel at the speed/power trial differs from the specified displacement within the limits mentioned in section 5.1, the following equation, based on the Admiralty formula, shall be applied to the power values:

$$P_2 = P_1 \left(\frac{\nabla_2}{\nabla_1}\right)^{2/3} \tag{18}$$

where

P_1: power corresponding to displacement volume ∇_1,
P_2: power corresponding to displacement volume ∇_2,
∇_1: displacement volume during the speed/power trial,
∇_2: displacement volume used in the tank test.

11. PROCESSING OF THE RESULTS

After completion of the S/P trials the measured data shall be processed in the following sequence, also illustrated in Figure 6:

1. Derive the average values of each measured parameter for each speed run. The average speed component in the heading direction is found from the DGPS recorded start and

end positions in the heading direction of each speed run and the elapsed time;

2. Correct ship's speed for current by 'Mean of means' method in case of two double runs (Appendix H) or mean speed in case of one double run. (If 'Iterative' method is used, this is the initial speed.);
3. Derive the true wind speed and direction for each double run by the method described in Appendix E;
4. Derive the resistance increase due to wind (Appendix F);
5. Derive the resistance increase due to waves (Appendix G);
6. Derive the resistance increase due to effect of water temperature and salinity (10.3.3);
7. Correct power using the Direct Power Method (Appendix D);
8. Correct ship speed for current if 'Iterative' method is used.
9. If 'Iterative' method is used, repeat item 7;
10. Correction of power for the effect of shallow water (10.3.4) (Appendix K);
11. Correction of power for the difference of displacement from the stipulated conditions (10.3.5);
12. Correction of propeller revolution;
13. Use the speed/power curve from the model tests for the specific ship design at the trial draught. Shift this curve along the power axis to find the best fit with all corrected speed/power points according to the least squares method. When more than three(3) power settings, all above 50% MCR, are measured, it is acceptable to use a polynomial curve of degree one less than the number of power settings, fitted to the corrected points using least squares method.
14. Intersect the curve at the specified power to derive the ship's speed at trial draught in ideal conditions;
15. Apply the conversion from the trial condition to other stipulated load conditions according to 10.2.5 and Appendix I;
16. Apply corrections for the contractual weather conditions if these deviate from ideal conditions.

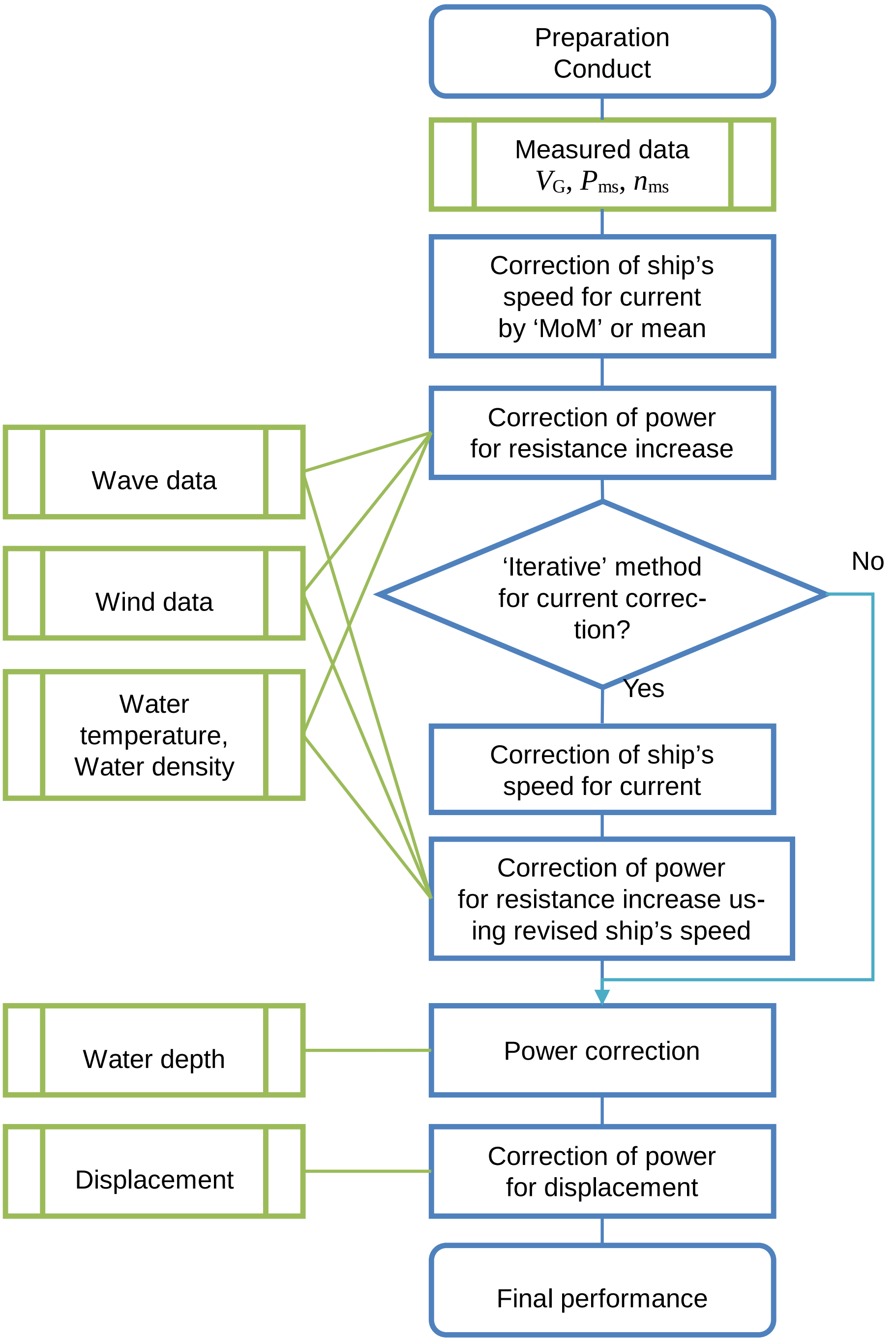


Figure 6.Flowchart of speed/power trial analysis

12. REPORTING

In the trial report, an overview of the trial conditions and all corrections that have been applied to arrive at the contract speed and the EEDI speed shall be given.

The trial report shall contain all relevant information to carry out the data analysis. It shall be presented in such a way that all results can be reprocessed.

The trial report shall contain the following sections:

Trial Report Summary comprising details of

A) Ship particulars (including trial draughts and displacement)
Propeller details
Engine data
Details of hull appendages and rudder

Contract conditions including contract speed, power, and displacement.

EEDI conditions including EEDI speed, power and displacement.

Description of Instrumentation describing the instrument set-up, calibration procedure, data acquisition interfacing details, location of sensors (e.g. strain gauges on shaft, anemometer etc.), etc.

Description of Trial Site. This will give information on geography, distance from land, water depth etc.

Environment Parameters. This shall list the measured/observed environmental conditions at the site during S/P trials such as wave height, wave period, wave direction, air pressure, wind direction, wind velocity, air temperature, water temperature, water density etc.

S/P trial agenda. This shall give a complete and chronological order of the trial programme (both planned and actual) with specification of the duties of the different recording/monitoring stations on board.

Trial Results of each speed run

- Date and Time at start of speed run
- Run number
- Ship’s position
- Ship’s heading
- Run duration
- Mean values of measured ship's speed
- Mean value and standard deviation of torque (per shaft)
- Mean value and standard deviation of shaft rpm (per shaft)
- Mean value and standard deviation of shaft power (per shaft)
- Relative wind speed and direction
- Significant wave height, mean period and direction
- Mean water depth

Analysis and Correction methods. The analysis and correction of the measured trial data shall be conducted in compliance with the present procedure.

Conclusions. Speeds and powers on the contractually specified point and in the EEDI condition, derived from the S/P trial analysis, have to be reported.

13. REFERENCESAND BIBLIOGRAPHY

Boom et al., "Speed/Power Performance during Trials and In-Service" Proceedings SNAME, Athens, September 2008.

Boom, H.van den, Huisman, H. and Mennen, F.:"New Guidelines for Speed/Power Trials" SWZ/Maritime, Jan./Feb.2013;

BSRA,"BSRA standard method of Speed Trial Analysis", Report NS 466, 1978.

Deng Rui, Li Chao, Dong Guoxiang, etc. "Optimization of the superstructure and forecastle fairing of a multi-purpose ship" OMAE 2017-61256.

Fujiwara, T., Ueno, M. and Ikeda, Y.: "A New Estimation Method of Wind Forces and Moments acting on Ships on the basis of Physical Component Models", J. JASNAOE, Vol.2, 2005.

Hansa Int. Maritime Journal 150th Year, No. 4, April 2013, Hansa-online.de/STA-JIP.pdf.

ISO 15016;"Guidelines for the assessment of speed and power performance by analysis of speed trial data", 2002.

ISO 19019; "Guide for Planning, Carrying out and Reporting Sea Trials", 2002.

ITTC Performance Committee, "ITTC guide for measured-mile trials", Report of the ITTC Performance Committee, Appendix I, 12th ITTC, 1969.

ITTC Performance Committee, "Hull Roughness", Report of the ITTC Performance Committee, 19th ITTC, 1990.

ITTC Powering Performance Committee, "An Updated Guide For Speed/Powering Trials", Report of the ITTC Powering Performance Committee, Appendix I, 21st ITTC, 1996.

ITTC 7.5-04-01-01.2;"Recommended Procedures and Guidelines for Speed/Power Trials", 23rd ITTC 2002.

ITTC "Recommendations and Guidelines for Resistance & Propulsion Model Tests", 23rd ITTC, 2002.

Japan Ship Research Association, "SR208: New Speed Trial Analysis Method", Report of the SR208 Committee, 1993.

JTTC, "A proposal for a standard method of speed trial analysis", Bull. SNAJ, No.262, 1944.

JTTC, "A tentative guide for the operation of speed trials with large vessels", Bull. SNAJ, No. 442, 1966.

Kaiser, M., Ph.D. (2016), Results of aerodynamic model tests for Handy Size Bulk Carrier, Technical Report No. RH-2016/T-104E, CTO.S.A.

Maruo H., "On the increase of the resistance of a ship in rough seas (2nd report)", J. SNAJ, Vol. 108, 1960.

Ministry of Transport, "Guaranteed speed specifications and the analysis procedure", Notification No. 174, Japan, 1955.

Principles of Naval Architecture, Volume II, Section II, Ship Standardization Trials; published by SNAME 1988.

Raven, H.C.: "A Computational Study of Shallow-Water Effects on Ship Viscous Resistance”, 29th Symposium on Naval Hydrodynamics, Gothenburg, Sweden, August 2012.

Raven, H.C.: “A New Correction Procedure for Shallow-Water Effects in Ship Speed Trials”, Proceedings of PRADS2016, Copenhagen, 2016.

Sea Trial Analysis JIP; “Recommended Practice for Speed Trials”, 2006, Public document from www.marin.nl.

The Ship Testing and Trial Trip Committee of the Association of Ship Technical Societies in Norway, "Standardization code for trials and testing of new ships", , 2nd Edition, 1971.

SNAME, "Code for Sea Trials", 1989.

SRAJ, "A Study of ship speed trials", No. 2 Standardization Panel, , Res. Rep. No. 12R, 1972.

Taniguchi, K. & Tamura, K., "On a new method of correction for wind resistance relating to the analysis of speed trial results", 11th ITTC, 1966.

Tsujimoto, M, Kuroda, M. and Sogihara, N., “Development of a calculation method for fuel consumption of ships in actual seas with performance evaluation”, Proceedings of OMAE 2013, OMAE2013-11297, 2013.

World Meteorological Organization: Manual on Codes, International Codes, Volume I.1, Part A-Alphanumeric Codes, WMO-No. 306 (1995 edition).

Appendix A. GENERAL SHIP AND TRIAL DATA

Hull condition	
Last date of cleaning hull	
Hull appendages and Rudder	
Geometry	
Type	
Rate of Movement during speed trials	
Wind fetch	
Height of anemometer above waterline	
Transverse Projected area above the waterline including superstructures at trial draught	
Lateral projected area above the waterline including superstructures at trial draught	If F.3 method is used
Propeller(s)	
Type (FPP/CPP)	
Pitch (FPP)	
Direction of rotation	
Number of blades	
Shaft(s)	
G modulus Diameter (inside) Diameter (outside)	

Appendix B. BEAUFORT SCALE OF WIND

Beafort number	Descriptive term	Velocity equivalent at a standard height of 10 metres above open flat ground				Specifications				
		Mean velocity in knots	m s-1	km h-1	m.p.h.	Land	Sea	Coast	Probable wave height* in metres	Probable wave height* in feet
0	Calm	<1	0-0.2	<1	<1	Calm; smoke rises vertically	Sea like a mirror	Calm	-	-
1	Light air	1-3	0.3-1.5	1-5	1-3	Direction of wind shown by smoke drift but not by wind vanes	Ripples with the appearance of scales are formed, but without foam crests	Fishing smack just has steerage way	0.1 (0.1)	¼ (¼)
2	Light breeze	4-6	1.6-3.3	6-11	4-7	Wind felt on face; leaves rustle; ordinary vanes moved by wind	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break	of smacks which then travel at about1–2 knots	0.2 (0.3)	½ (1)
3	Gentle breeze	7-10	3.4-5.4	12-19	8-12	Leaves and small twigs in constant motion; wind extends light flag	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses	Smacks begin to careen and travel about 3–4 knots	0.6 (1)	2 (3)
4	Moderate breeze	11-16	5.5-7.9	20-28	13-18	Raises dust and loose paper; small branches are moved	Small waves, becoming longer; fairly frequent white horses	Good working breeze, smacks carry all canvas with good list	1 (1.5)	3½ (5)
5	Fresh breeze	17-21	8.0-10.7	29-38	19-24	Small trees in leaf begin to sway; crested wavelets form on inland waters	Moderate waves, taking a more pronounced long form; many white horses are formed(chance of some spray)	Smacks shorten sail	2 (2.5)	6 (8½)
6	Strong breeze	22-27	10.8-13.8	39-49	25-31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray)	Smacks have double reef in mainsail; care required when fishing	3 (4)	9½ (13)
7	Near gale	28-33	13.9-17.1	50-61	32-38	Whole trees in motion; inconvenience felt when walking against wind	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind	Smacks remain in harbour and those at sea lie to	4 (5.5)	13½ (19)
8	Gale	34-40	17.2-20.7	62-74	39-46	Breaks twigs off trees; generally impedes progress	Moderately high waves of greater length; edges of crests begin to break into the spindrift; the foam is blown in well-marked streaks along the direction of the wind	All smacks make for harbour, if near	5.5 (7.5)	18 (25)
9	Strong gale	41-47	20.8-24.4	75-88	47-54	Slight structural damage occurs (chimney pots and slates removed)	High waves; dense streaks of foam along the direction of the wind; crests of waves begin to topple ,tumble and rollover; spray may affect visibility	-	7 (10)	23 (32)
10	Storm	48-55	24.5-28.4	89-102	55-63	Seldom experienced inland; trees uprooted; considerable structural damage occurs	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of the sea takes on a white appearance; the tumbling of the sea becomes heavy and shock- like; visibility affected	-	9 (12.5)	29 (41)
11	Violent storm	55-63	28.5-32.6	103-117	64-72	Very rarely experienced; accompanied by widespread damage	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the waves); the sea is completely covered with long white patches of foam lying along the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility affected	-	11.5 (16)	37 (52)
12	Hurricane	64 and over	32.7 and over	118 and over	73 and over	-	The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected	-	14 (-)	45 (-)

* This table is only intended as a guide to show roughly what may be expected in the open sea, remote from land. It shall never be used in the reverse way; i.e., for logging or reporting the state of the sea. In enclosed waters, or when near land, with an off-shore wind, wave heights will be smaller and the waves steeper. Figures in brackets indicate the probable maximum height of waves. (ref. World Meteorological Organization, 1995)

State of the sea

Code figure	Descriptive terms	Height* in metres
0	Calm (glassy)	0
1	Calm(rippled)	0 – 0.1
2	Smooth(wavelets)	0.1 – 0.5
3	Slight	0.5 – 1.25
4	Moderate	1.25 – 2.5
5	Rough	2.5 – 4
6	Very rough	4 – 6
7	High	6 – 9
8	Very high	9 – 14
9	Phenomenal	Over 14

Notes:

(1)*These values refer to well-developed wind waves of the open sea. While priority shall be given to the descriptive terms, these height values may be used for guidance by the observer when reporting the total state of agitation of these resulting from various factors such as wind, swell, currents, angle between swell and wind, etc.

(2) The exact bounding height shall be assigned for the lower code figure; e.g. a height to figure 5 is 2.5≤h<4.0m.

Appendix C. FORMAT S/P TRIAL LOG SHEET

Speed - Power Trials Log Form

Ship name:			Date:			

Ship				**Environment**		
T_{fwd}		m		T_{air}		°C
T_{aft}		m		T_{water}		°C
Displacement		tons		ρ_{water}		kg/m^3
Height of anemometer above water line:						m

Propeller shaft		
outer dia D1		mm
inner dia D2		mm
steel type		N/mm^2

Measurement location:	
Lat	
Lon	
Description	

						Relative wind		Wind driven waves			Swell			Propeller PS			Propeller SB		
Run No.	Time	Forward / Return	Heading	Speed (SOG)	UKC	Speed	Direction	Height	Direction	Period	Height	Direction	Period	Torque	Power	Revs	Torque	Power	Revs
[-]	[-]	[F / R]	[deg]	[kn]	[m]	[kn] [m/s]	[deg]	[m]	[deg]	[s]	[m]	[deg]	[s]	[kNm]	[kW]	[RPM]	[kNm]	[kW]	[RPM]

Appendix D. PROPULSIVE EFFICIENCY CORRECTION BASED ON LOAD VARIATION TESTS

D.1. Propulsive efficiency correction

The ship's propulsive efficiency is affected by the added resistance. This has to be taken into account when correcting the power.

The delivered power corrected to ideal condition is derived by

$$P_{\text{Did}} = P_{\text{Dms}} - \Delta P \tag{D-1}$$

with

ΔP: correction of delivered power due to the increased resistance and the changed propulsive efficiency

ΔP can be written as:

$$\Delta P = \frac{\Delta R V_{\text{S}}}{\eta_{\text{Did}}} + P_{\text{Dms}}\left(1 - \frac{\eta_{\text{Dms}}}{\eta_{\text{Did}}}\right) \tag{D-2}$$

with

P_{Dms}: delivered power derived from shaft power or break power measured on board for each single run [W],
V_{S}: ship's speed through the water [m/s], which can be obtained by the 'Iterative' method or the 'Mean of means' method,
ΔR: resistance increase from relative wind, waves and deviation of water temperature and water density for each run. The value is computed according to section 10.3 in these Guidelines, [N],
η_{Did}: propulsive efficiency coefficient in ideal condition obtained from standard towing tank test and interpolated to the speed V_{S},
η_{Dms}: propulsive efficiency coefficient during sea trial.

The propulsive efficiency is assumed to vary linearly with the added resistance according to:

$$\frac{\eta_{Dms}}{\eta_{Did}} = \xi_P \frac{\Delta R}{R_{id}} + 1 \tag{D-3}$$

where

ξ_P: overload factor derived from load variation model test, according to ITTC Recommended Procedure 7.5-02-03-01.4（2017）
R_{id}: resistance in ideal condition

This leads to the expression for the corrected delivered power:

$$P_{\text{Did}} = P_{\text{Dms}} - \frac{\Delta R V_{\text{S}}}{\eta_{\text{Did}}}\left(1 - \frac{P_{\text{Dms}}}{P_{\text{Did}}}\xi_{\text{P}}\right) \tag{D-4}$$

This is expressed explicitly as:

$$P_{\text{Did}} = \frac{1}{2}\left\{P_{\text{Dms}} - \frac{\Delta R V_{\text{S}}}{\eta_{\text{Did}}} + \sqrt{\left(P_{\text{Dms}} - \frac{\Delta R V_{\text{S}}}{\eta_{\text{Did}}}\right)^2 + 4P_{\text{Dms}}\frac{\Delta R V_{\text{S}}}{\eta_{\text{Did}}}\xi_P}\right\} \tag{D-5}$$

D.2. Correction of shaft rotation rate – effect of added resistance and of shallow water

With the P_{Did} found as described above the correction on shaft rate is:

$$\frac{\Delta n}{n_{\text{id}}} = \xi_n \frac{P_{\text{Dms}} - P_{\text{Did}}}{P_{\text{Did}}} \tag{D-6}$$

Where

$$\Delta n = n_{\text{ms}} - n_{\text{id}} \tag{D-7}$$

with

n_{m}: measured shaft rate [1/s],
n_{id}: corrected shaft rate [1/s],
ξ_{n}: overload factor derived from load variation model test,

From this follows that the corrected shaft rate n_{id} is:

$$n_{\mathrm{id}} = \frac{n_{\mathrm{ms}}}{\xi_n \frac{P_{\mathrm{Dms}} - P_{\mathrm{Did}}}{P_{\mathrm{Did}}} + 1} \qquad \text{(D-8)}$$

Appendix E. EVALUATION OF WIND DATA

E.1. Averaging process for the true wind vectors

The true wind vectors in each run are found from the ship's speed over ground and heading and the measured relative 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 runs-set averaged true wind vector shall be used to recalculate the relative wind vector for each run of the set.

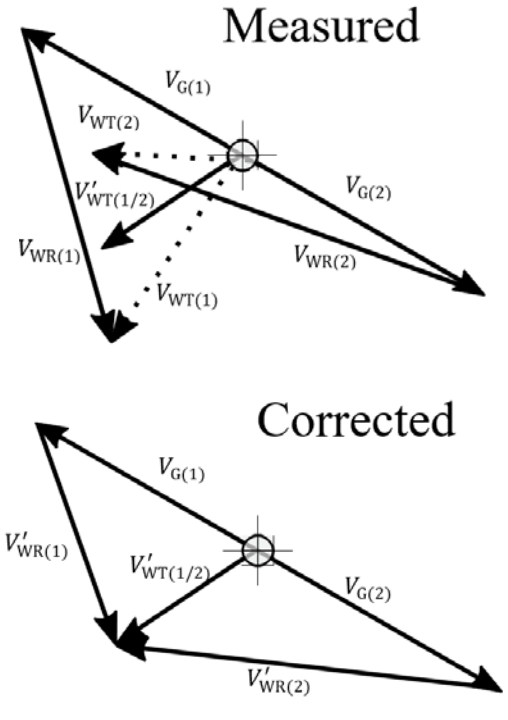


Figure E-1 True wind vectors and relative wind vectors.

The true wind velocity and direction at the vertical position of the anemometer are calculated by:

$$V_{\mathrm{WT}} = \sqrt{V_{\mathrm{WR}}^2 + V_{\mathrm{G}}^2 - 2V_{\mathrm{WR}}V_{\mathrm{G}}\cos\psi_{\mathrm{WR}}} \qquad \text{(E-2)}$$

$$\psi_{\mathrm{WT}} = \tan^{-1}\left\langle\frac{V_{\mathrm{WR}}\sin(\psi_{\mathrm{WR}}+\psi)-V_{\mathrm{G}}\sin(\psi)}{V_{\mathrm{WR}}\cos(\psi_{\mathrm{WR}}+\psi)-V_{\mathrm{G}}\cos(\psi)}\right\rangle \qquad \text{(E-3a)}$$

for $V_{\mathrm{WR}}\cos(\psi_{\mathrm{WR}}+\psi) - V_{\mathrm{G}}\cos(\psi) \geq 0$

$$\psi_{\mathrm{WT}} = \tan^{-1}\left\langle\frac{V_{\mathrm{WR}}\sin(\psi_{\mathrm{WR}}+\psi)-V_{\mathrm{G}}\sin(\psi)}{V_{\mathrm{WR}}\cos(\psi_{\mathrm{WR}}+\psi)-V_{\mathrm{G}}\cos(\psi)}\right\rangle + 180 \qquad \text{(E-3b)}$$

for $V_{\mathrm{WR}}\cos(\psi_{\mathrm{WR}}+\psi) - V_{\mathrm{G}}\cos(\psi) < 0$

where:

V_{G}: measured ship's speed over ground [m/s];
V_{WR}: mean value of the measured relative wind velocity at the vertical position of the anemometer in[m/s];
V_{WT}: true wind velocity at the vertical position of the anemometer in [m/s];
ψ: ship's heading in [degrees];
ψ_{WR}: mean value of the measured relative wind direction at the vertical position of the anemometer[degrees];
ψ_{WT}: true wind direction at the vertical position of the anemometer [degrees].

The true wind velocity and direction are corrected by an averaging process over both runs of the double run.

$$V'_{\mathrm{WT(i/i+1)}} = \sqrt{\left(\frac{V_{\mathrm{WT(i)}}\cos\psi_{\mathrm{WT(i)}}+V_{\mathrm{WT(i+1)}}\cos\psi_{\mathrm{WT(i+1)}}}{2}\right)^2 + \left(\frac{V_{\mathrm{WT(i)}}\sin\psi_{\mathrm{WT(i)}}+V_{\mathrm{WT(i+1)}}\sin\psi_{WT(i+1)}}{2}\right)^2} \qquad \text{(E-4)}$$

$$\psi'_{\mathrm{WT(i/i+1)}} = \tan^{-1}\left\langle\frac{V_{\mathrm{WT(i)}}\sin\psi_{\mathrm{WT(i)}}+V_{\mathrm{WT(i+1)}}\sin\psi_{\mathrm{WT(i+1)}}}{V_{\mathrm{WT(i)}}\cos\psi_{\mathrm{WT(i)}}+V_{\mathrm{WT(i+1)}}\cos\psi_{\mathrm{WT(i+1)}}}\right\rangle \qquad \text{(E-5a)}$$

for $V_{\mathrm{WT(i)}}\cos\psi_{\mathrm{WT(i)}} + V_{\mathrm{WT(i+1)}}\cos\psi_{\mathrm{WT(i+1)}} \geq 0$

$$\psi'_{\mathrm{WT(i/i+1)}} = \tan^{-1}\left\langle\frac{V_{\mathrm{WT(i)}}\ \sin\psi_{\mathrm{WT(i)}}+V_{\mathrm{WT(i+1)}}\sin\psi_{\mathrm{WT(i+1)}}}{V_{\mathrm{WT(i)}}\cos\psi_{\mathrm{WT(i)}}+V_{\mathrm{WT(i+1)}}\cos\psi_{\mathrm{WT(i+1)}}}\right\rangle + 180 \qquad \text{(E-5b)}$$

for $V_{\mathrm{WT(i)}}\cos\psi_{\mathrm{WT(i)}} + V_{\mathrm{WT(i+1)}}\cos\psi_{\mathrm{WT(i+1)}} < 0$

$$V'_{\mathrm{WR(i)}} = \sqrt{V'^2_{\mathrm{WT(i)}} + V^2_{\mathrm{G(i)}} + 2V'_{\mathrm{WT(i)}}V_{\mathrm{G(i)}}\cos\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right)} \qquad \text{(E-6)}$$

$$\psi'_{\mathrm{WR(i)}} = \tan^{-1}\left\langle\frac{V'_{\mathrm{WT(i)}}\sin\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right)}{V_{\mathrm{G(i)}} + V'_{\mathrm{WT(i)}}\cos\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right)}\right\rangle \qquad \text{(E-7a)}$$

for $V_{\mathrm{G(i)}} + V'_{\mathrm{WT(i)}}\cos\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right) \geq 0$

$$\psi'_{\mathrm{WR(i)}} = \tan^{-1}\left\langle\frac{V'_{\mathrm{WT(i)}}\sin\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right)}{V_{\mathrm{G(i)}} + V'_{\mathrm{WT(i)}}\cos\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right)}\right\rangle + 180 \qquad \text{(E-7b)}$$

for $V_{\mathrm{G(i)}} + V'_{\mathrm{WT(i)}}\cos\left(\psi'_{\mathrm{WT(i)}} - \psi_{\mathrm{(i)}}\right) < 0$

where:

V'_{WT}: averaged true wind velocity at the vertical position of the anemometer [m/s];
V'_{WR}: corrected relative wind velocity at the vertical position of the anemometer [m/s];
ψ'_{WT}: averaged true wind direction at the vertical position of the anemometer [degrees];
ψ'_{WR}: corrected relative wind direction at the vertical position of the anemometer [degrees];
(i) run number.

The true wind velocity $V_{\mathrm{WT(i)}}$, true wind direction $\psi_{\mathrm{WT(i)}}$, relative wind velocity $V_{\mathrm{WR(i)}}$ and relative wind direction $\psi_{\mathrm{WR(i)}}$ can then be replaced by $V'_{\mathrm{WT(i)}}$, $\psi'_{\mathrm{WT(i)}}$, $V'_{\mathrm{WR(i)}}$and $\psi'_{\mathrm{WR(i)}}$.

E.2. Correction for the vertical position of the anemometer

The difference between the vertical position of the anemometer and the reference height is to be corrected by means of the wind speed profile given by formula (E-8).

$$V_{\mathrm{WTref}} = V_{\mathrm{WT}}\left(\frac{Z_{\mathrm{ref}}}{Z_{\mathrm{a}}}\right)^{\frac{1}{9}} \qquad \text{(E-8)}$$

where

V_{WTref}: true wind velocity at the reference height [m/s];
V_{WT}:: true wind velocity at the vertical position of the anemometer in [m/s];
Z_{ref}: reference height for the wind resistance coefficients in [m];
Z_{a} vertical position of the anemometer in [m].

The reference height for the wind resistance coefficients, $Z_{\mathrm{ref}}$is selected as the corresponding height for the wind resistance coefficient from wind tunnel tests (normally 10m).

The relative wind velocity at the reference height is calculated by:

$$V_{\mathrm{WRref}} = \sqrt{V^2_{\mathrm{WTref}} + V^2_{\mathrm{G}} + 2V_{\mathrm{WTref}}V_{\mathrm{G}}\cos(\psi_{\mathrm{WT}} - \psi)} \qquad \text{(E-9)}$$

The relative wind direction at the reference height is calculated by:

$$\psi_{\mathrm{WRref}} = \tan^{-1}\left\langle\frac{V_{\mathrm{WTref}}\sin(\psi_{\mathrm{WT}} - \psi)}{V_{\mathrm{G}} + V_{\mathrm{WTref}}\cos(\psi_{\mathrm{WT}} - \psi)}\right\rangle \qquad \text{(E-10a)}$$

for $V_{\mathrm{G}} + V_{\mathrm{WTref}}\cos(\psi_{\mathrm{WT}} - \psi) \geq 0$

$$\psi_{\mathrm{WRref}} = \tan^{-1}\left\langle\frac{V_{\mathrm{WTref}}\sin(\psi_{\mathrm{WT}} - \psi)}{V_{\mathrm{G}} + V_{\mathrm{WTref}}\cos(\psi_{\mathrm{WT}} - \psi)}\right\rangle + 180 \qquad \text{(E-10b)}$$

for $V_{\mathrm{G}} + V_{\mathrm{WTref}}\cos(\psi_{\mathrm{WT}} - \psi) < 0$

where:

V_{WRref}: relative wind velocity at the reference height [m/s];

V_{WTref} true wind velocity at the reference height in [m/s];

ψ_{WRref} relative wind direction at the reference height [degrees];

Appendix F. CORRECTION METHODS FOR RESISTANCE INCREASE DUE TO WIND

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

F.1. Wind resistance coefficients by wind tunnel test

If wind resistance tests for the specific, or similar, vessel have been performed in a qualified wind tunnel, the wind resistance coefficients derived by these measurements shall be used to compute the wind resistance of the vessel in the trial condition. The coefficients should be derived based on projected frontal area.

F.2. Wind resistance coefficients by CFD

Wind resistance coefficients derived from a CFD viscous flow solver is acceptable provided that the CFD code and the user have demonstrated verification and validation against qualified wind tunnel results for similar ships using ITTC Recommended Procedures 7.5-03-01-01 and with a required uncertainty of the derived R_{AA} corresponding to 2% on the total power. The simulation corresponding to the actual speed trial case has to use the same grid structure, grid density, degree of geometrical resolution and modelling (e.g. turbulence models and boundary conditions) as used for the validation demonstration.

F.3. Data sets of wind resistance coefficients

Data sets of the wind resistance coefficient C_X are available for certain ship types shown in Table F-1. These are based on projected frontal area and wind speed at 10 m reference height except the Cape Size Bulk Carrier where a height average wind velocity is applied.

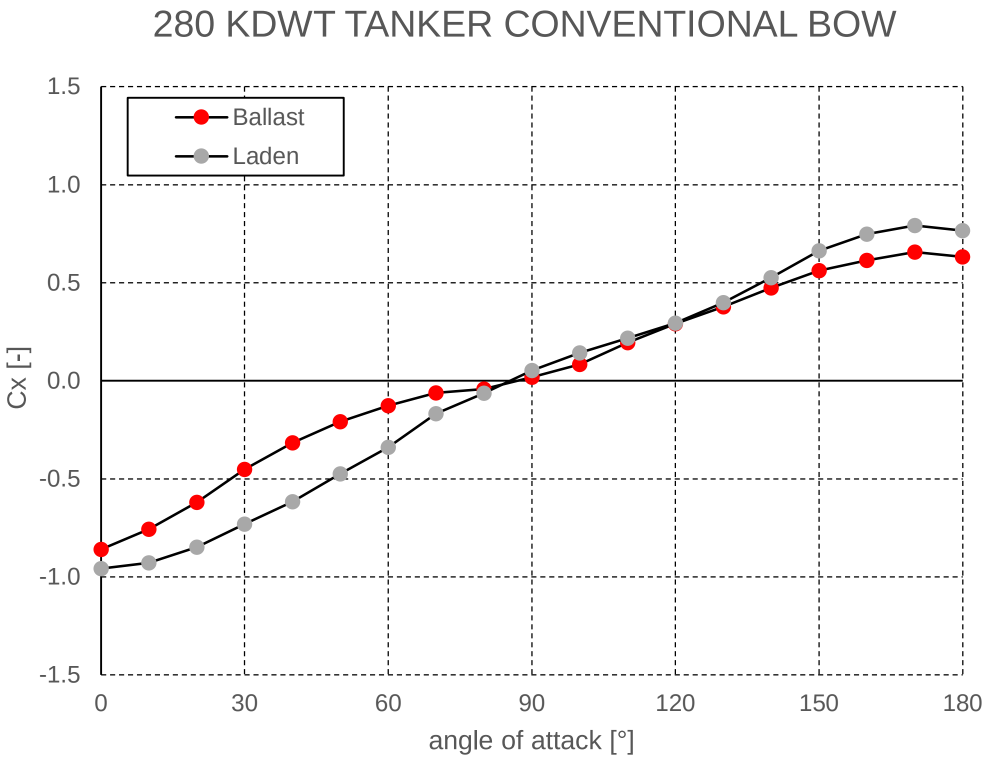
For the use of these coefficients the vessel type, shape and outfitting shall be carefully evaluated and compared with the geometry of the vessel from the data set. The data provided are limited to the present-day common ship types. For special vessels such as tugs, supply ships, fishery vessels and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

Table F-1 Ship type for the wind resistance data set

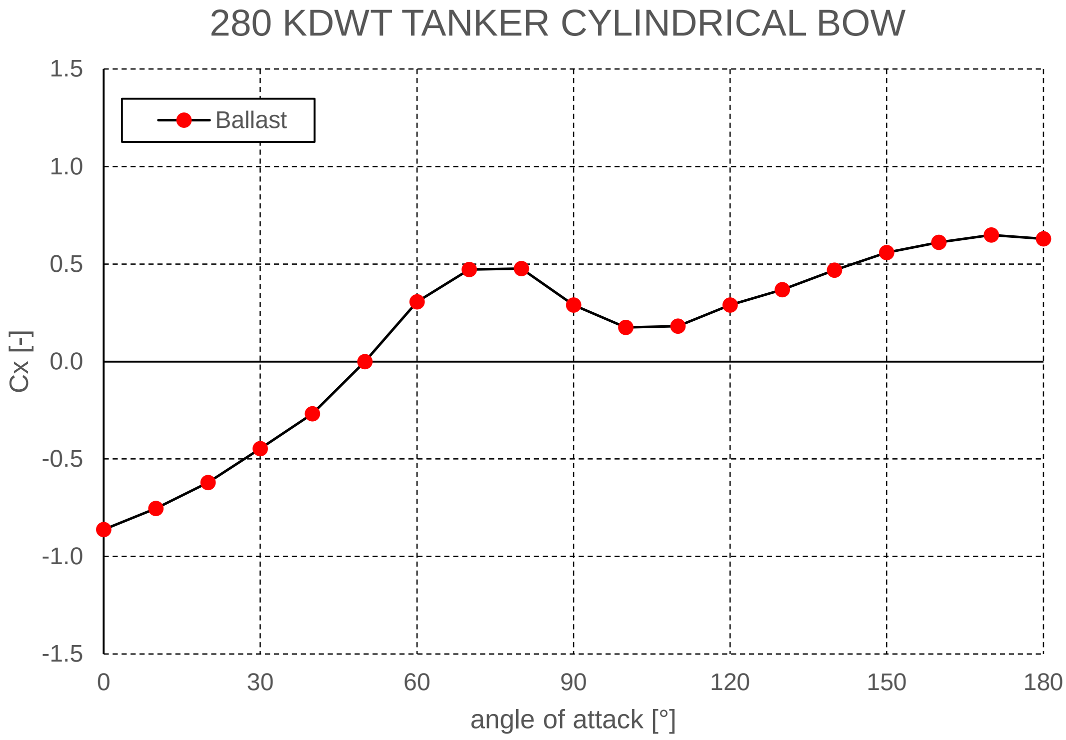
Ship type	LC	Superstructure	Vessel	Reference
Tanker conventional bow	L	normal	280kDWT	WT (Boom 2013)
Tanker conventional bow	B	normal	280kDWT	WT (Boom 2013)
Tanker cylindrical bow	B	normal	280kDWT	WT (Boom 2013)
LNG carrier	A	prismatic integrated	125k-m^3	CFD (Boom 2013)
LNG carrier	A	prismatic extended deck	138k-m^3	CFD (Boom 2013)
LNG carrier	A	spherical	125k-m^3	CFD (Boom 2013)
Container ship	L	with containers	6800TEU	WT (Boom 2013)
Container ship	L	without containers, with lashing bridges	6800TEU	WT (Boom 2013)
Container ship	B	with lashing bridges	6800TEU	WT (Boom 2013)
Container ship	B	without lashing bridges	6800 TEU	WT (Boom 2013)
Car Carrier	A	normal	Autosky	CFD (Boom 2013)
Ferry/Cruise ship	A	normal		WT (Boom 2013)
General Cargo ship	A	normal		WT (Boom 2013)
Handy size bulk carrier	B	Cranes		WT (Kaiser 2016)
Handy size bulk carrier	B	No cranes		WT (Kaiser 2016)
Multi-purpose carrier	L	With containers	19000DWT carrier	WT (Deng,2017)
Multi-purpose carrier	B	With partly containers	19000DWT carrier	WT (Deng,2017)
Cape Size Bulk Carrier	L	No cranes		WT (Kume, 2019

LC = Loading Condition
L = Laden
B = Ballast
A = Average

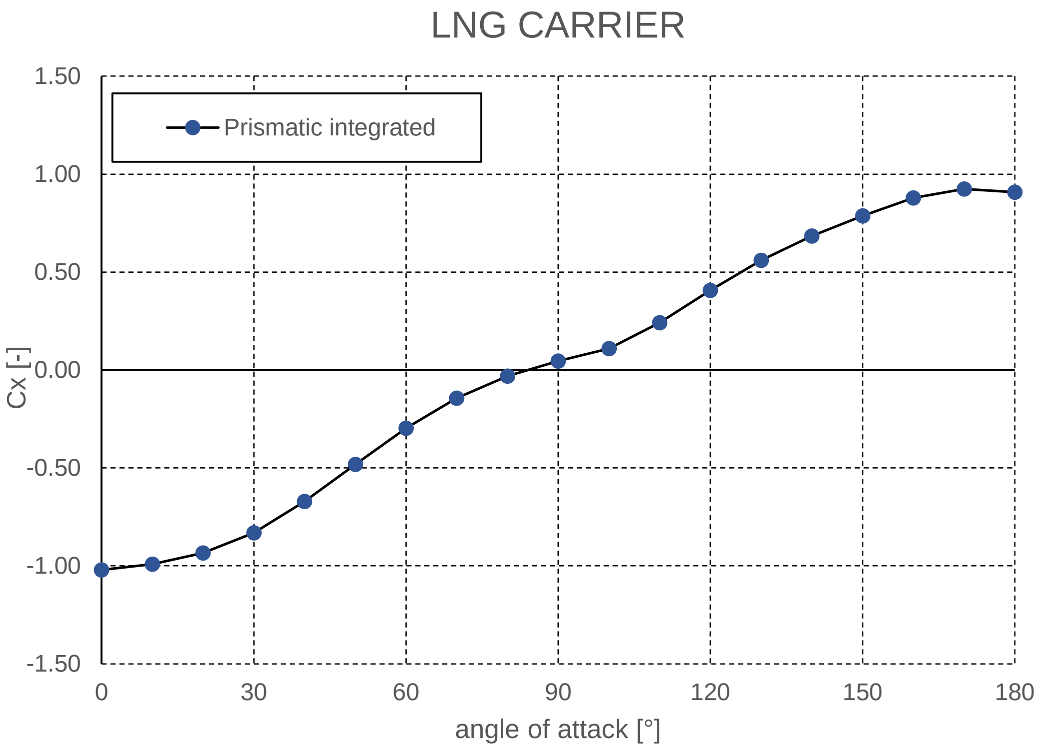
WT = Wind tunnel
CFD = CFD computations



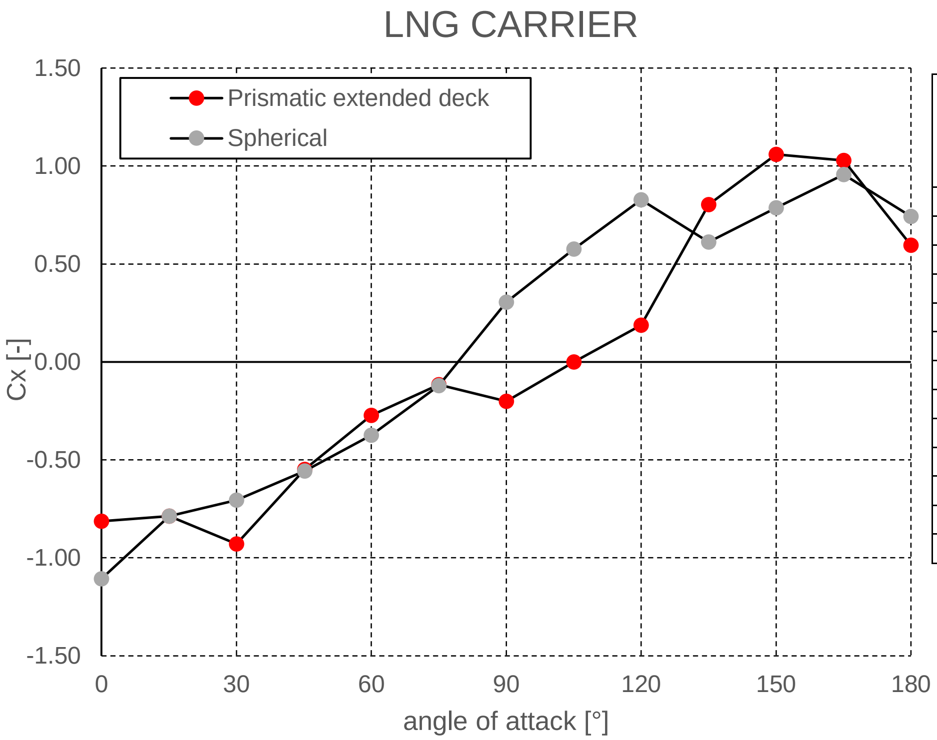
Angle of attack[°]	C_x [-]	
	Ballast	Laden
0	-0.86	-0.96
10	-0.76	-0.93
20	-0.62	-0.85
30	-0.45	-0.73
40	-0.32	-0.62
50	-0.21	-0.47
60	-0.13	-0.34
70	-0.06	-0.17
80	-0.04	-0.06
90	0.02	0.05
100	0.08	0.14
110	0.19	0.22
120	0.29	0.29
130	0.38	0.40
140	0.47	0.53
150	0.56	0.66
160	0.61	0.75
170	0.66	0.79
180	0.63	0.77



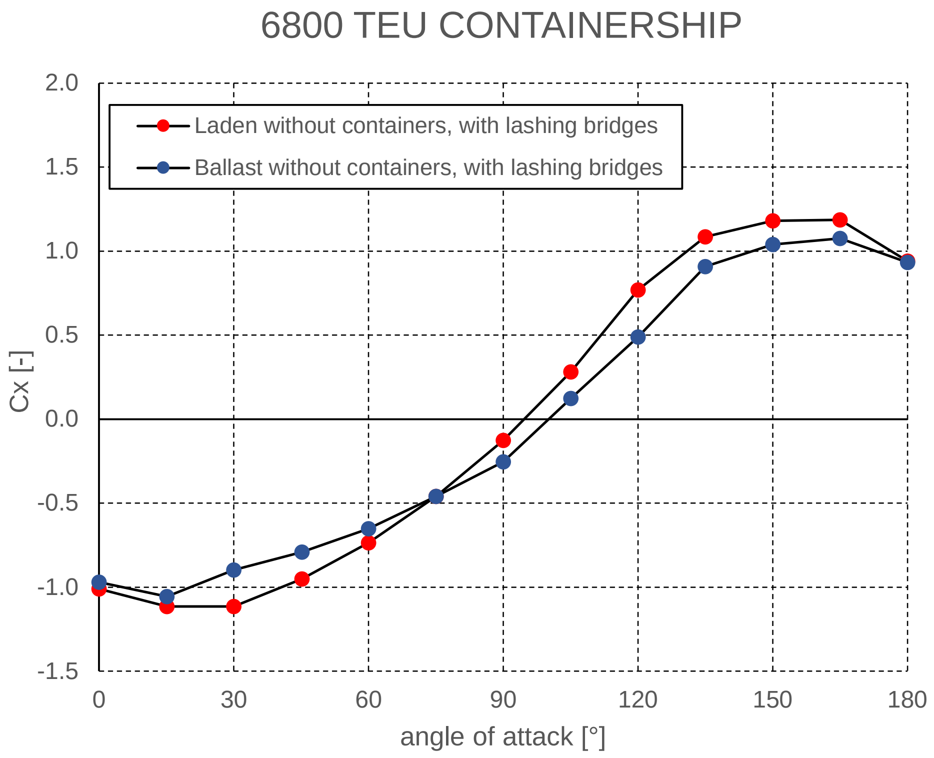
Angle of attack[°]	C_x [-]
	Ballast
0	-0.86
10	-0.75
20	-0.62
30	-0.45
40	-0.27
50	0.00
60	0.31
70	0.47
80	0.48
90	0.29
100	0.18
110	0.18
120	0.29
130	0.37
140	0.47
150	0.56
160	0.61
170	0.65
180	0.63



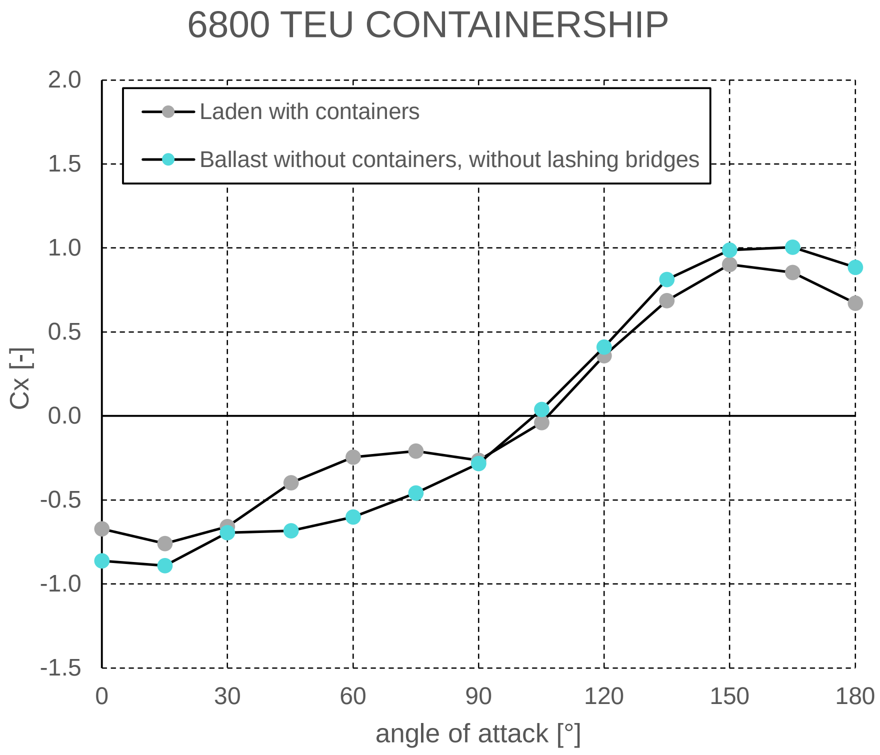
	C_x [-]
Angle of attack[°]	Prismatic integrated
0	-1.02
10	-0.99
20	-0.93
30	-0.83
40	-0.67
50	-0.48
60	-0.30
70	-0.14
80	-0.03
90	0.05
100	0.11
110	0.24
120	0.41
130	0.56
140	0.68
150	0.79
160	0.88
170	0.92
180	0.91



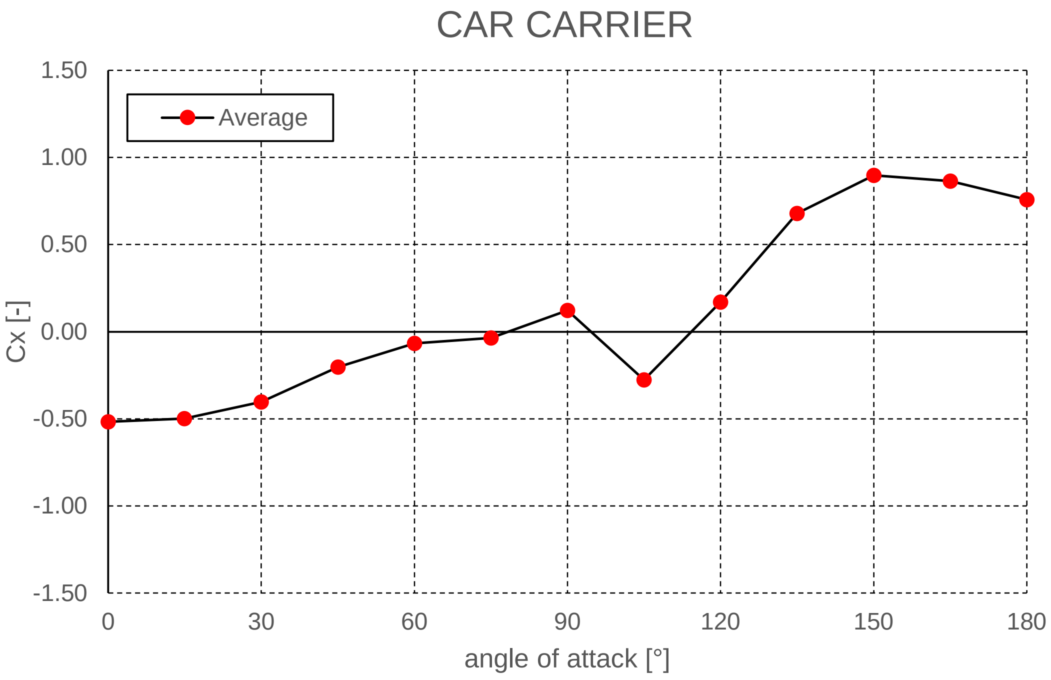
	C_x [-]	
Angle of attack[°]	Prismatic extended deck	Spherical
0	-0.81	-1.11
15	-0.79	-0.79
30	-0.93	-0.70
45	-0.55	-0.56
60	-0.27	-0.37
75	-0.12	-0.12
90	-0.20	0.30
105	0.00	0.58
120	0.19	0.83
135	0.80	0.61
150	1.06	0.79
165	1.03	0.96
180	0.60	0.74



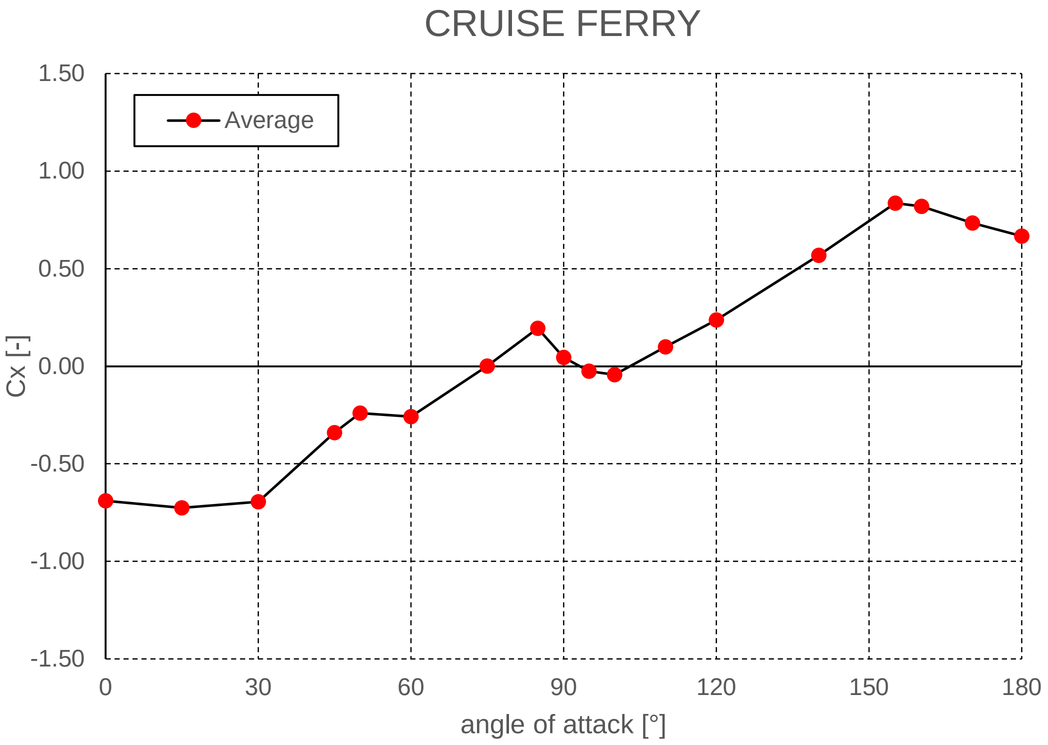
Angle of attack[°]	C_x [-]	
	Without containers with lashing bridges	
	Laden	Ballast
0	-1.01	-0.97
15	-1.11	-1.06
30	-1.11	-0.90
45	-0.95	-0.79
60	-0.74	-0.65
75	-0.46	-0.46
90	-0.13	-0.25
105	0.28	0.12
120	0.77	0.49
135	1.09	0.91
150	1.18	1.04
165	1.19	1.08
180	0.94	0.93



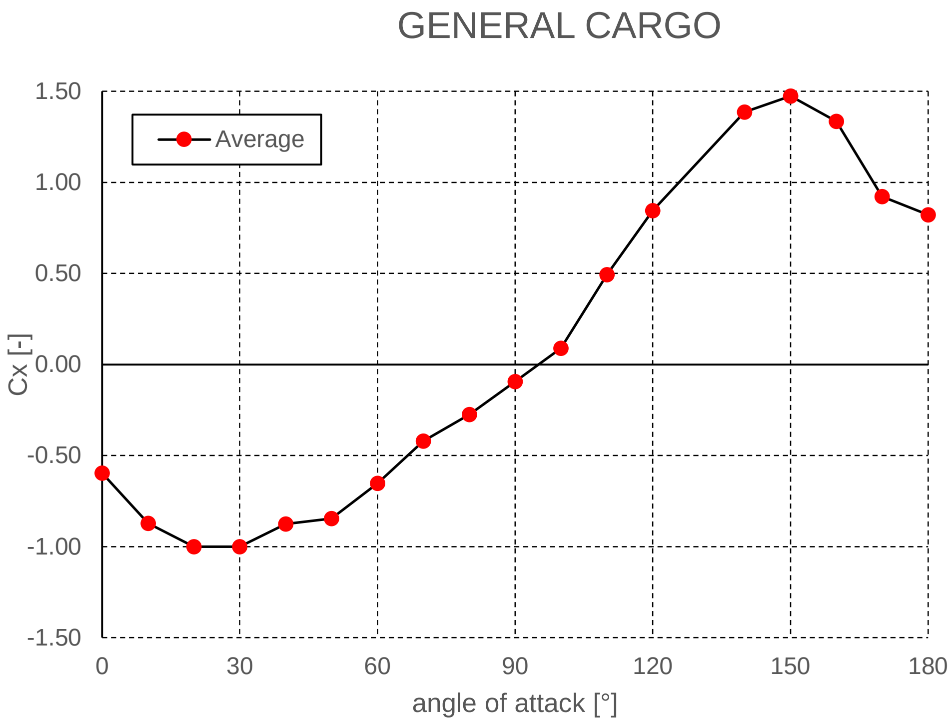
Angle of attack[°]	C_x [-]	
	Ballast without containers	Laden with containers
0	-0.86	-0.67
15	-0.89	-0.76
30	-0.69	-0.66
45	-0.68	-0.40
60	-0.60	-0.25
75	-0.46	-0.21
90	-0.28	-0.26
105	0.04	-0.04
120	0.41	0.36
135	0.81	0.69
150	0.99	0.90
165	1.00	0.85
180	0.89	0.67



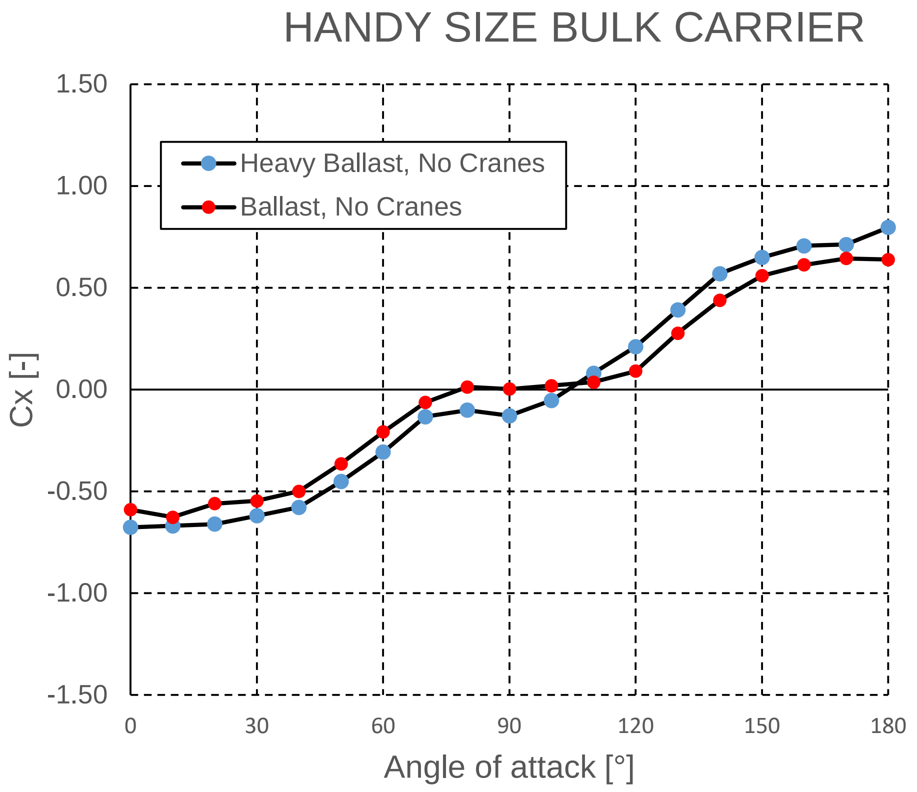
Angle of attack[°]	C_x [-] Average
0	-0.52
15	-0.50
30	-0.40
45	-0.20
60	-0.07
75	-0.04
90	0.12
105	-0.28
120	0.17
135	0.68
150	0.90
165	0.86
180	0.76



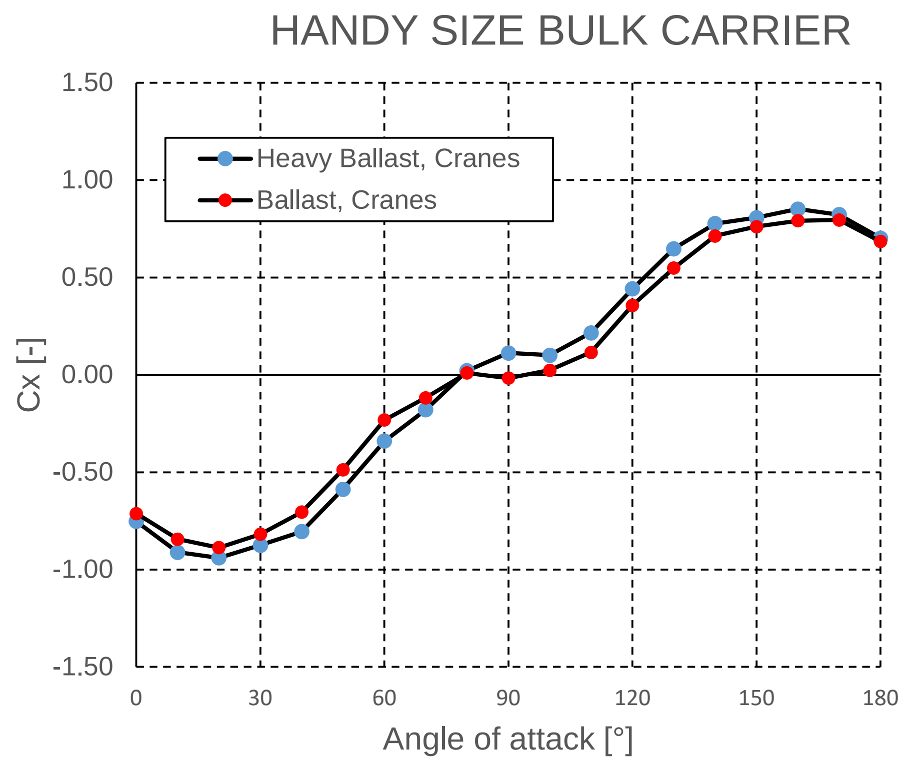
Angle of attack[°]	C_x [-] Average
0	-0.69
15	-0.73
30	-0.69
45	-0.34
50	-0.24
60	-0.26
75	0.00
85	0.19
90	0.04
95	-0.03
100	-0.04
110	0.10
120	0.24
140	0.57
155	0.84
160	0.82
170	0.73
180	0.67



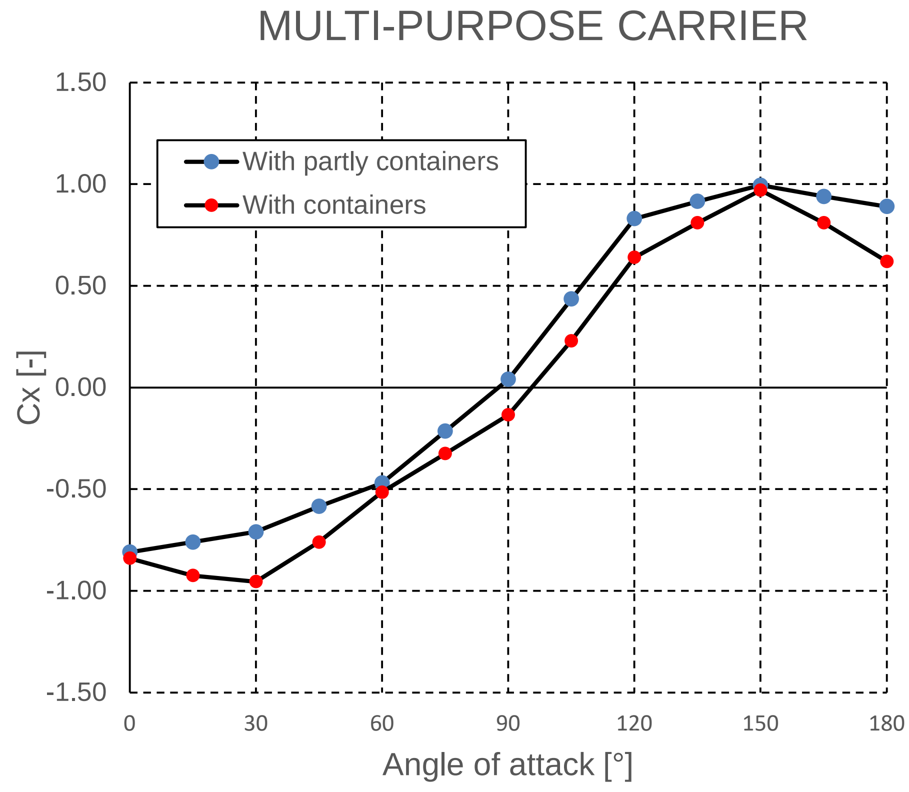
Angle of attack[°]	C_x [-] Average
0	-0.60
10	-0.87
20	-1.00
30	-1.00
40	-0.88
50	-0.85
60	-0.65
70	-0.42
80	-0.27
90	-0.09
100	0.09
110	0.49
120	0.84
140	1.39
150	1.47
160	1.34
170	0.92
180	0.82



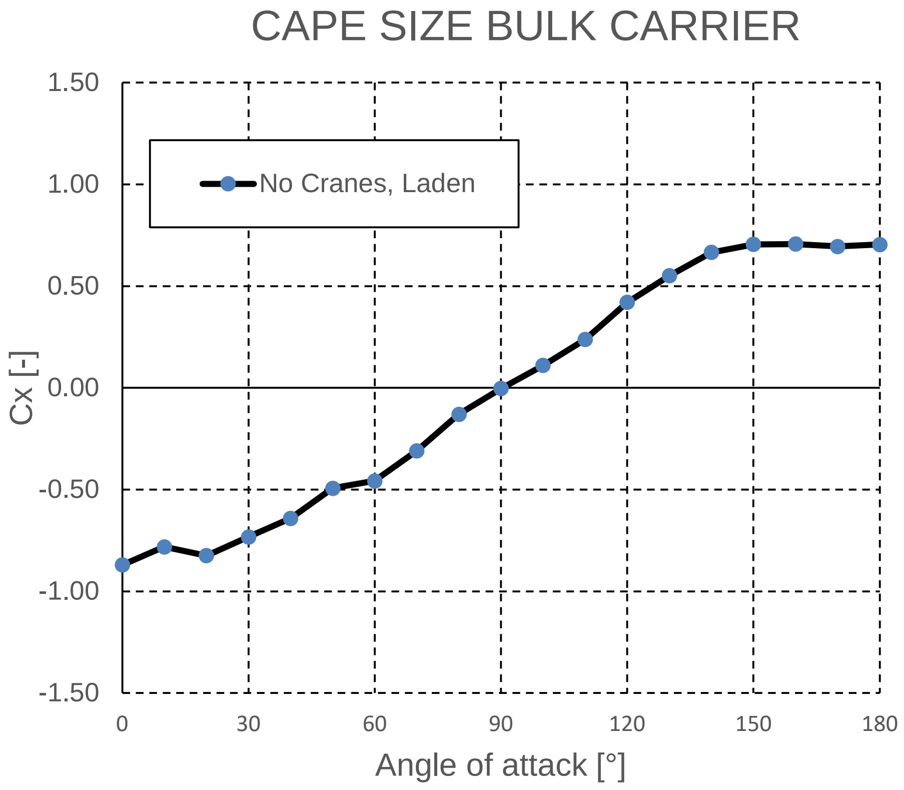
Angle of attack[°]	C_x [-]	
	Heavy Ballast, No Cranes	Ballast, No Cranes
0	-0.68	-0.59
10	-0.67	-0.63
20	-0.66	-0.56
30	-0.62	-0.55
40	-0.58	-0.50
50	-0.45	-0.36
60	-0.31	-0.21
70	-0.13	-0.06
80	-0.10	0.01
90	-0.13	0.00
100	-0.05	0.02
110	0.08	0.04
120	0.21	0.09
130	0.39	0.28
140	0.57	0.44
150	0.65	0.56
160	0.71	0.61
170	0.71	0.64
180	0.80	0.64



Angle of attack[°]	C_x [-]	
	Heavy Ballast, Cranes	Ballast, Cranes
0	-0.75	-0.71
10	-0.91	-0.84
20	-0.94	-0.89
30	-0.87	-0.82
40	-0.80	-0.70
50	-0.59	-0.49
60	-0.34	-0.23
70	-0.18	-0.12
80	0.02	0.01
90	0.11	-0.02
100	0.10	0.02
110	0.22	0.12
120	0.44	0.36
130	0.65	0.55
140	0.78	0.71
150	0.81	0.76
160	0.85	0.79
170	0.82	0.80
180	0.70	0.68



Angle of attack[°]	C_x [-]	
	With partly containers	With containers
0	-0.81	-0.84
15	-0.76	-0.93
30	-0.71	-0.96
45	-0.59	-0.76
60	-0.47	-0.52
75	-0.22	-0.33
90	0.04	-0.14
105	0.44	0.23
120	0.83	0.64
135	0.92	0.81
150	1.00	0.97
165	0.94	0.81
180	0.89	0.62



Angle of attack[°]	C_x [-]
	Laden
0	-0.871
10	-0.782
20	-0.825
30	-0.733
40	-0.641
50	-0.493
60	-0.457
70	-0.309
80	-0.130
90	-0.003
100	0.110
110	0.238
120	0.420
130	0.551
140	0.666
150	0.705
160	0.706
170	0.695
180	0.705

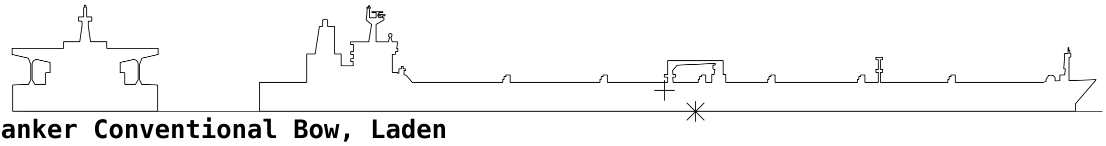
NOTE:

C_X of Cape Size Bulk Carrier is non-dimensionalized by "height average wind velocity V_{A1}", not by wind velocity at 10 m reference height. V_{A1} is determined by following formula:

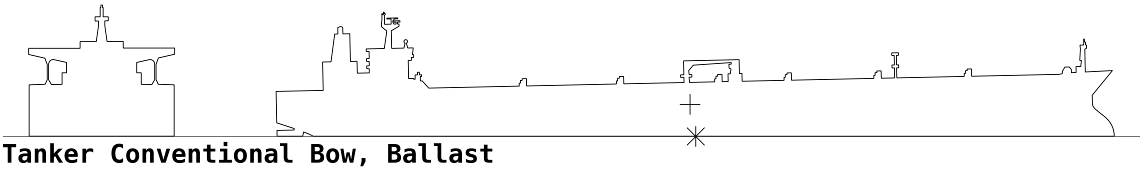
$$V_{A1}{}^2 = \frac{1}{H_{\mathrm{BR}}} \int_0^{H_{\mathrm{BR}}} V(z)^2 dz$$

H_{BR} is the height between top of the navigation bridge and sea surface.

$V(z)$ means a vertical distribution of the wind velocity above sea surface.

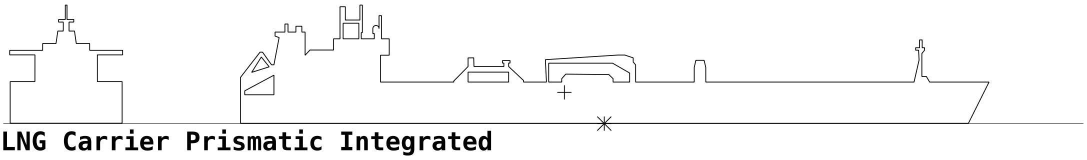


Tanker Conventional Bow, Laden

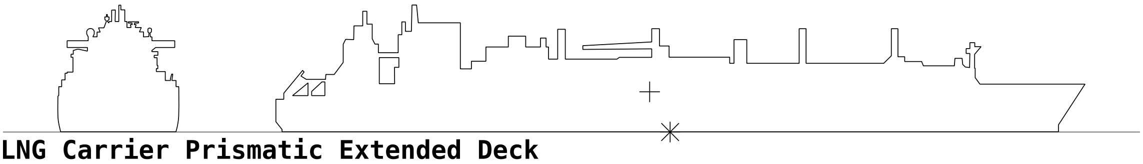


Tanker Conventional Bow, Ballast

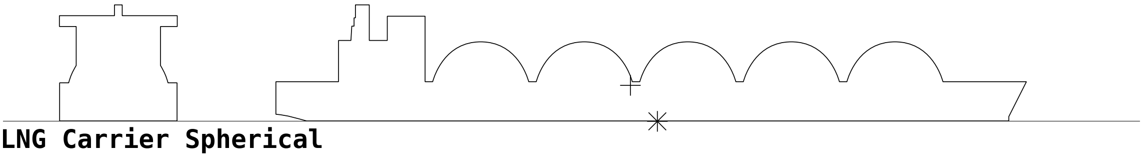
Tanker Cylindrical Bow, Ballast



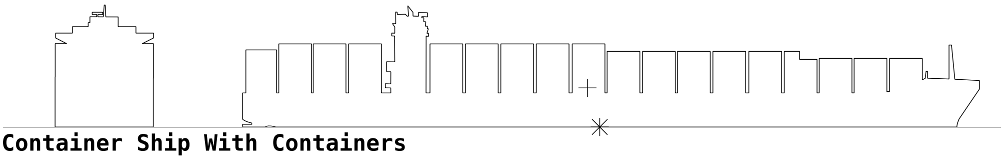
LNG Carrier Prismatic Integrated



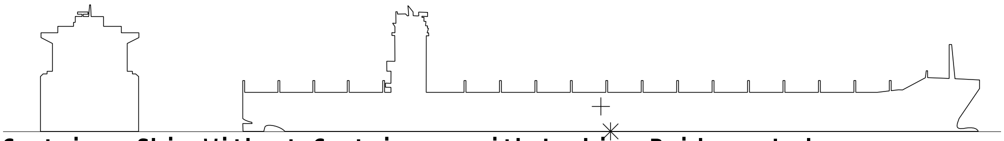
LNG Carrier Prismatic Extended Deck



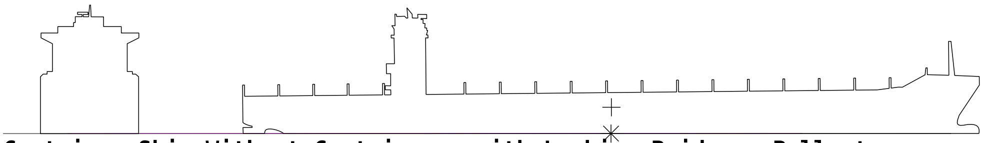
LNG Carrier Spherical



Container Ship With Containers

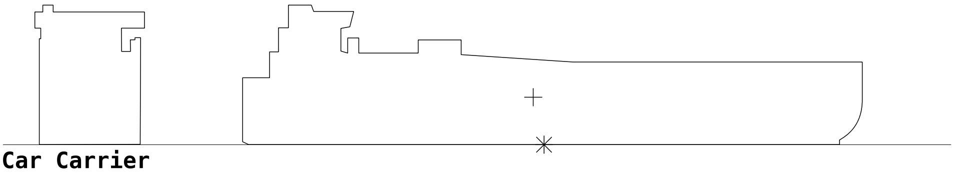


Container Ship Without Containers, with Lashing Bridges, Laden

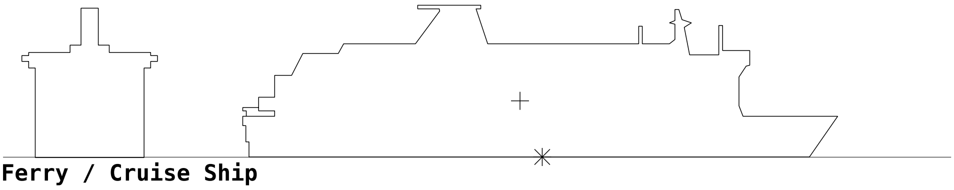


Container Ship Without Containers, with Lashing Bridges, Ballast

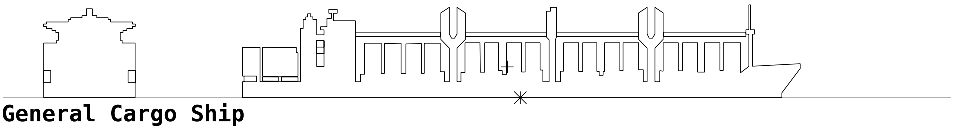
Container Ship Without Containers



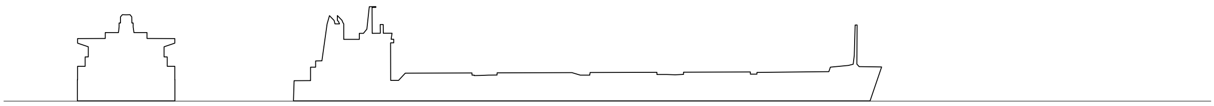
Car Carrier



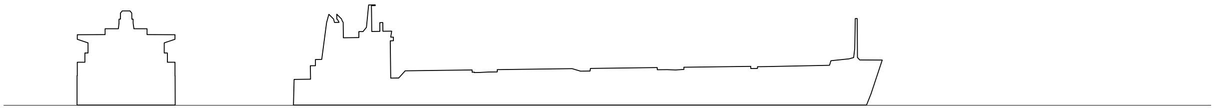
Ferry / Cruise Ship



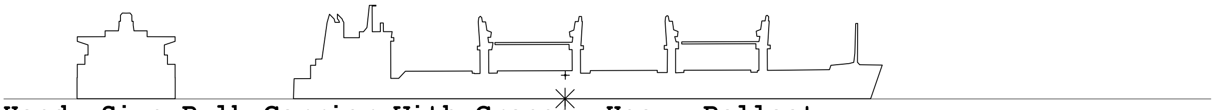
General Cargo Ship



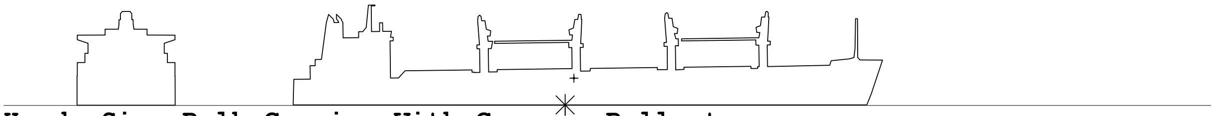
Handy Size Bulk Carrier Without Cranes, Heavy Ballast



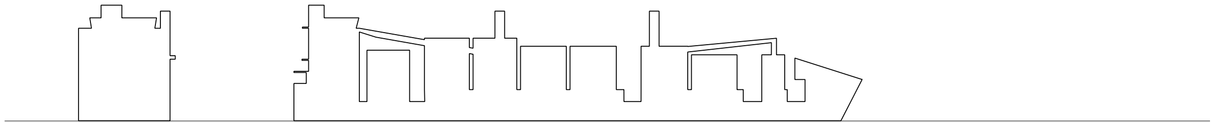
Handy Size Bulk Carrier Without Cranes, Ballast



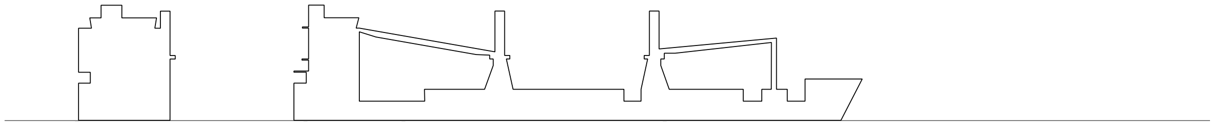
Handy Size Bulk Carrier With Cranes, Heavy Ballast



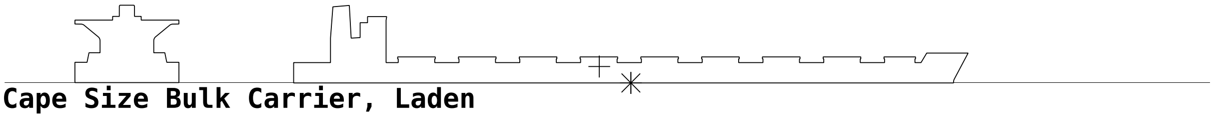
Handy Size Bulk Carrier With Cranes, Ballast



Multi-purpose Carrier, With Containers



Multi-purpose Carrier, With Partly Containers



Cape Size Bulk Carrier, Laden

Figure F-2 Ship types

F.4. Regression formula by Fujiwara et al.

A general regression formula based on model tests in wind tunnels for various ships has been developed by Fujiwara et al (2005).

$$C_{\mathrm{DA}} = C_{\mathrm{LF}} \cos\psi_{\mathrm{WR}} + C_{\mathrm{XLI}} \left(\sin\psi_{\mathrm{WR}} - \frac{1}{2} \sin\psi_{\mathrm{WR}} \cos^2\psi_{\mathrm{WR}} \right) \sin\psi_{\mathrm{WR}} \cos\psi_{\mathrm{WR}} + C_{\mathrm{ALF}} \sin\psi_{\mathrm{WR}} \cos^3\psi_{\mathrm{WR}} \qquad \text{(F-1)}$$

with

for $0 \leq \psi_{\mathrm{WR}} < 90(\mathrm{deg.})$

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

$$C_{\mathrm{XLI}} = \delta_{10} + \delta_{11} \frac{A_{\mathrm{YV}}}{L_{\mathrm{OA}} h_{\mathrm{BR}}} + \delta_{12} \frac{A_{\mathrm{XV}}}{B h_{\mathrm{BR}}} \qquad \text{(F-3)}$$

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

for $90 < \psi_{\mathrm{WR}} \leq 180(\mathrm{deg.})$

$$C_{\mathrm{XLI}} = \delta_{20} + \delta_{21} \frac{A_{\mathrm{YV}}}{L_{\mathrm{OA}} h_{\mathrm{BR}}} + \delta_{22} \frac{A_{\mathrm{XV}}}{A_{\mathrm{YV}}} + \delta_{23} \frac{B}{L_{\mathrm{OA}}} + \delta_{24} \frac{A_{\mathrm{XV}}}{B h_{\mathrm{BR}}} \qquad \text{(F-5)}$$

$$C_{\mathrm{LF}} = \beta_{20} + \beta_{21} \frac{B}{L_{\mathrm{OA}}} + \beta_{22} \frac{h_{\mathrm{C}}}{L_{\mathrm{OA}}} + \beta_{23} \frac{A_{\mathrm{OD}}}{{L_{\mathrm{OA}}}^2} + \beta_{24} \frac{A_{\mathrm{XV}}}{B^2} \qquad \text{(F-6)}$$

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

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

$$C_{\mathrm{DA}}|_{\psi_{\mathrm{WR}}=90(\mathrm{deg.})} = \frac{1}{2} \left(C_{\mathrm{DA}}|_{\psi_{\mathrm{WR}}=90(\mathrm{deg.})-\mu} + C_{\mathrm{DA}}|_{\psi_{\mathrm{WR}}=90(\mathrm{deg.})+\mu} \right)$$

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_{DA}: 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 F-2.

Table F-2 Non-dimensional parameters

	i	*j*				
		0	1	2	3	4
βij	1	0.922	-0.507	-1.162	-	-
	2	-0.018	5.091	-10.367	3.011	0.341
δij	1	-0.458	-3.245	2.313	-	-
	2	1.901	-12.727	-24.407	40.310	5.481
εij	1	0.585	0.906	-3.239	-	-
	2	0.314	1.117	-	-	-

The system of co-ordinates and the sign conventions and explanation of the input parameters are shown in Fig F.2

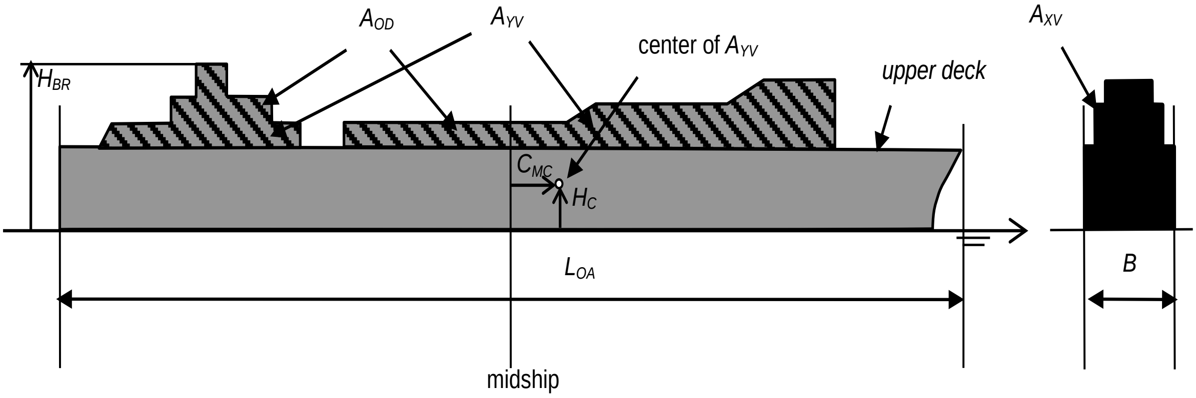


Figure F.2 Input parameters for regression formula by Fujiwara

Appendix G. CORRECTION METHODS FOR RESISTANCE INCREASE DUE TO WAVES

All method mention below shall satisfy the significant wave height criterion stated in Section 6.3.

G.1. Simplified correction method for ships with limited heave and pitch during the speed runs (STAWAVE-1)

Specifically, for speed trial conditions with present day ships a dedicated and practical method has been developed by STA-JIP (Boom, 2013) 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 short 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 of the vessel 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 (Figure G-1).

Formula G-1 estimates the resistance increase in head waves provided that heave and pitch motions are small. The application is restricted to waves in the bow sector, within +/-45 deg. off the bow. For wave directions outside this sector no wave correction is applied.

$$R_{AWL}=\frac{1}{16}\rho_s g H_{1/3W}^{2} B\sqrt{\frac{B}{L_{BWL}}} \qquad \text{(G-1)}$$

where

B: beam of the ship [m]
$H_{1/3W}$: significant wave height of wind waves [m],
L_{BWL}: length of the bow on the water line to 95% of maximum beams shown in Figure G-1 [m],
ρ_s: water density for actual water temperature and salt content [kg/m3],
g: acceleration of gravity [m/s²].

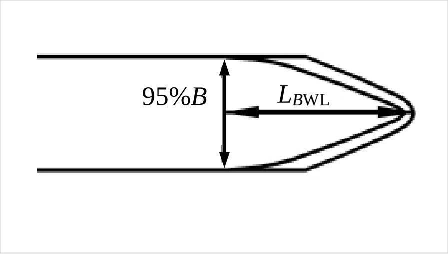


Figure G-1 Definition of L_{BWL}

STAWAVE-1 has been extensively validated for the following conditions:

1. Heave and pitch during speed/power trial are small (vertical acceleration at bow <0.05g).
2. Head waves. Wave directions within 0 to ±45 degrees from bow are corrected as head waves.

G.2. Empirical correction method with frequency response function for ships with heave and pitch during the speed runs (STAWAVE-2)

The empirical method STAWAVE-2 (Boom, 2013) has been developed by STA-JIP 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 Figure G-2. For this purpose, an extensive database of sea keeping model test results for a large population of ships has been used to derive parametric transformation functions.

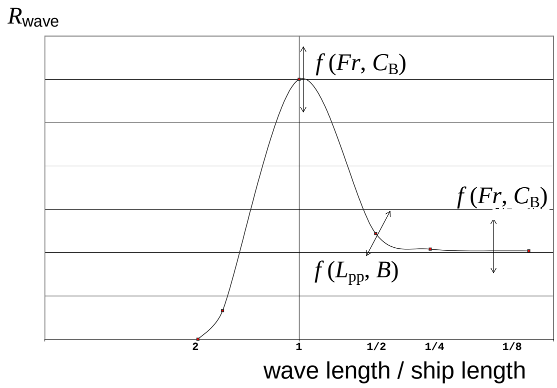


Figure G-2 Parametric transfer function of mean resistance increase in regular waves.

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

$$R_{\mathrm{wave}} = R_{\mathrm{AWRL}} + R_{\mathrm{AWML}} \qquad \text{(G-2)}$$

where,

$$R_{\mathrm{AWML}} = 4\rho_S g {\zeta_A}^2 B^2 / L_{\mathrm{PP}} \overline{r_{aw}}(\omega) \qquad \text{(G-3)}$$

with

$$\overline{r_{aw}}(\omega) = \overline{\omega}^{b_1} \exp\left\{\frac{b_1}{d_1}\left(1-\overline{\omega}^{d_1}\right)\right\} a_1 Fr^{1.50} \exp(-3.50Fr) \qquad \text{(G-4)}$$

$$\overline{\omega} = \frac{\sqrt{\frac{L_{\mathrm{PP}}}{g}}\sqrt[3]{k_{yy}}}{1.17Fr^{-0.143}}\,\omega \qquad \text{(G-5)}$$

$$a_1 = 60.3{C_B}^{1.34} \qquad \text{(G-6)}$$

$$b_1 = \begin{cases} 11.0 & \text{for } \overline{\omega} < 1 \\ -8.50 & \text{elsewhere} \end{cases} \qquad \text{(G-7)}$$

$$d_1 = \begin{cases} 14.0 & \text{for } \overline{\omega} < 1 \\ -566\left(\frac{L_{\mathrm{PP}}}{B}\right)^{-2.66} & \text{elsewhere} \end{cases} \qquad \text{(G-8)}$$

(G-8)

and

$$R_{\mathrm{AWRL}} = \frac{1}{2}\rho_S g {\zeta_A}^2 B \alpha_1(\omega) \qquad \text{(G-9)}$$

$$\alpha_1(\omega) = \frac{\pi^2 {I_1}^2(1.5kT_M)}{\pi^2 I_1^2(1.5kT_M) + K_1^2(1.5kT_M)} f_1 \qquad \text{(G-10)}$$

$$f_1 = 0.692\left(\frac{V_S}{\sqrt{T_M g}}\right)^{0.769} + 1.81{C_B}^{6.95} \qquad \text{(G-11)}$$

where:

C_B: block coefficient,
V_S: ship's speed in m/s
k_{yy}: non-dimensional radius of gyration in lateral direction,
L_{PP}: ship length between perpendiculars,
T_M: draught at midship,
I_1: modified Bessel function of the first kind of order 1,
K_1: modified Bessel function of the second kind of order 1,

with the following restrictions:

1. $50\mathrm{m} \leq L_{\mathrm{PP}} \leq 400m$,
2. $4.0 < \frac{L_{\mathrm{PP}}}{B} < 9.0$,
3. $2.2 < \frac{B}{T_M} < 9.0$,
4. $0.10 < Fr < 0.30$,
5. $0.39 < C_B < 0.90$ and
6. wave direction within 0 to ±45deg. from bow.

The method is applicable to the mean resistance increase in long crested irregular head waves R_{AWL}, formula (G-12). The wave corrections are thus restricted to wave directions in the bow sector to ±45(deg.) off bow. Waves within this sector are corrected as head waves. Waves outside the ±45 (deg.) sector are not corrected for.

$$R_{\mathrm{AWL}} = 2\int_0^{\infty} \frac{R_{\mathrm{wave}}(\omega; V_S)}{{\zeta_A}^2} S_\eta(\omega)\, d\omega \qquad \text{(G-12)}$$

G.3. Semi-empirical method for predicting the added resistance of a ship advancing in waves of arbitrary directions

The Semi-empirical SNNM method has been developed to approximate the transfer function of the mean resistance increase in waves of arbitrary headings based on regular waves. The method has been validated against the experimental results of a large number of vessels that well represent the current world fleet and these investigations are documented in a series of academic publications (Liu & Papanikolaou, 2015~2020).

The mean added resistance in regular waves R_{wave} is calculated as the sum of the motion induced component R_{AWM} and the wave reflection induced component R_{AWR}.

$$R_{\mathrm{wave}}(\omega,\alpha;V_{\mathrm{S}}) = R_{\mathrm{AWM}} + R_{\mathrm{AWR}} \tag{G-13}$$

The expression of R_{AWM} is given by

$$\mathrm{R}_{\mathrm{AWM}} = 3859.2\rho_s g\zeta_{\mathrm{A}}{}^2\frac{\mathrm{B}^2}{\mathrm{L}_{\mathrm{PP}}}\mathrm{C}_{\mathrm{B}}^{1.34}\mathrm{k}_{\mathrm{yy}}{}^2 \cdot a_1 a_2 a_3 \overline{\omega}^{b_1} e^{\frac{b_1}{d_1}\left(1-\overline{\omega}^{d_1}\right)} \tag{G-14}$$

where

$$\overline{\omega} = 2.142\sqrt[3]{k_{yy}}\sqrt{\frac{L_{\mathrm{pp}}}{\lambda}}\left(\frac{C_{\mathrm{B}}}{0.65}\right)^{0.17} \cdot \left[1 - \frac{0.111}{C_{\mathrm{B}}}\left(\ln\frac{B}{T_{\mathrm{deep}}} - \ln 2.75\right)\right] \cdot \left[\left(-1.377Fr^2 + 1.157Fr\right)|\cos\alpha| + \frac{0.618(13+\cos 2\alpha)}{14}\right] \tag{G-15}$$

$$a_1\left(0 \le \alpha \le \frac{\pi}{2}\right) = \left(\frac{0.87}{C_{\mathrm{B}}}\right)^{(1+Fr)\cos\alpha}\left(\ln\frac{B}{T_{\mathrm{deep}}}\right)^{-1}\frac{(1+2\cos\alpha)}{3} \tag{G-16}$$

$$a_1(\alpha = \pi) = \begin{cases} \left(\frac{0.87}{C_{\mathrm{B}}}\right)^{1+Fr}\left(\ln\frac{B}{T_{\mathrm{deep}}}\right)^{-1} & V_S > \frac{V_g}{2}\ and\ Fr_{\mathrm{rel}} \ge 0.12 \\ \left(\frac{0.87}{C_{\mathrm{B}}}\right)\left(\ln\frac{B}{T_{\mathrm{deep}}}\right)^{-1} & \text{elsewhere} \end{cases} \tag{G-17}$$

$$a_2\left(0 \le \alpha \le \frac{\pi}{2}\right) = \begin{cases} 0.0072 + 0.1676Fr & \text{for } Fr<0.12 \\ Fr^{1.5}e^{-3.5Fr} & \text{for } Fr\ge 0.12 \end{cases} \tag{G-18}$$

$$a_2(\alpha = \pi) = \begin{cases} 0.0072\left(4V_{\mathrm{S}}/V_{\mathrm{g}} - 1\right) & \text{for } V_{\mathrm{S}} \le \frac{V_{\mathrm{g}}}{2} \\ 0.0072 + 0.1676\mathrm{Fr}_{\mathrm{rel}} & \text{for } V_{\mathrm{S}} > \frac{V_g}{2} \text{ and } \mathrm{Fr}_{\mathrm{rel}} < 0.12 \\ \mathrm{Fr}_{\mathrm{rel}}{}^{1.5}e^{-3.5\mathrm{Fr}_{\mathrm{rel}}} & \text{for } V_S > \frac{V_g}{2} \text{ and } \mathrm{Fr}_{\mathrm{rel}} \ge 0.12 \end{cases} \tag{G-19}$$

The a_1 and a_2 values in stern oblique waves, i.e. for $\frac{\pi}{2} \le \alpha \le \pi$, are found by linear interpolation of the values in beam and following waves.

$$a_3 = 1.0 + 28.7\mathrm{atan}\frac{|T_{\mathrm{A}}-T_{\mathrm{F}}|}{L_{\mathrm{PP}}} \tag{G-20}$$

$$b_1 = \begin{cases} 11.0 & \text{for } \bar{\omega} < 1 \\ -8.5 & \text{elsewhere} \end{cases} \tag{G-21}$$

$$d_1 = \begin{cases} 566\left(\frac{L_{\mathrm{PP}}C_{\mathrm{B}}}{B}\right)^{-2.66} & \text{for } \bar{\omega} < 1 \\ -566\left(\frac{L_{\mathrm{PP}}}{B}\right)^{-2.66}\left(4 - 125atan\frac{|T_{\mathrm{A}}-T_{\mathrm{F}}|}{L_{\mathrm{PP}}}\right) & \text{elsewhere} \end{cases} \tag{G-22}$$

where

L_{PP}: ship length between perpendiculars (m);
B: Beam (m);
T: Draught at midship (m);
T_{F}: Draught at F.P. (m);
T_{A}: Draught at A.P. (m);

T_{deep} = max (T_F, T_A);
L_E: Length of entrance of the waterline (m);
L_R: Length of run of the waterline (m);
C_B: block coefficient;
k_{yy}: non-dimensional radius of gyration of pitch, % L_{PP};
Fr: Froude number, $\mathrm{Fr} = V_S/\sqrt{gL_{PP}}$;
$Fr_{\mathrm{rel}} = \left(V_{\mathrm{S}} - V_{\mathrm{g}}/2\right)/\sqrt{gL_{\mathrm{PP}}}$;
V_{g} is the group velocity of the incident wave, $V_{\mathrm{g}} = \frac{g}{2\omega}$;
V_S is a ship's speed through the water;
λ is the wavelength.

The expression of the added resistance due to reflection effect, R_{AWR}, takes the following form:

$$R_{\mathrm{AWR}} = \sum_{\mathrm{i}=1}^{4} R_{\mathrm{AWR,i}} \qquad \text{(G-23)}$$

where

$$\mathrm{R}_{\mathrm{AWR,1}} = \frac{2.25}{4}\rho_s g B {\zeta_{\mathrm{A}}}^2 \alpha_{T^*} \left\{\sin^2(E_1+\alpha) + \frac{2\omega V_{\mathrm{S}}}{g}[\cos\alpha - \cos\mathrm{E}_1\cos(E_1+\alpha)]\right\}\left(\frac{0.87}{C_{\mathrm{B}}}\right)^{(1+4\sqrt{Fr})f(\alpha)} \qquad \text{(G-24)}$$

for $0 \le \alpha \le \pi - E_1$

$$R_{\mathrm{AWR,2}} = \frac{2.25}{4}\rho_s g B {\zeta_{\mathrm{A}}}^2 \alpha_{T^*} \left\{\sin^2(E_1-\alpha) + \frac{2\omega V_{\mathrm{S}}}{g}[\cos\alpha - \cos E_1\cos(E_1-\alpha)]\right\}\left(\frac{0.87}{C_{\mathrm{B}}}\right)^{(1+4\sqrt{Fr})f(\alpha)} \qquad \text{(G-25)}$$

for $0 \le \alpha \le E_1$

$$R_{\mathrm{AWR,3}} = -\frac{2.25}{4}\rho_s g B {\zeta_{\mathrm{A}}}^2 \alpha_{T^*} \left\{\sin^2(E_2-\alpha) + \frac{2\omega V_{\mathrm{S}}}{g}[\cos\alpha - \cos E_2\cos(E_2-\alpha)]\right\} \qquad \text{(G-26)}$$

for $E_2 \le \alpha \le \pi$

$$R_{\mathrm{AWR,4}} = -\frac{2.25}{4}\rho_s g B {\zeta_{\mathrm{A}}}^2 \alpha_{T^*} \left\{\sin^2(E_2+\alpha) + \frac{2\omega V_{\mathrm{S}}}{g}[\cos\alpha - \cos E_2\cos(E_2+\alpha)]\right\} \qquad \text{(G-27)}$$

for $\pi - E_2 \le \alpha \le \pi$

where E_1 and E_2 are angles defined on the concerned waterline, as shown in Figure G-3.

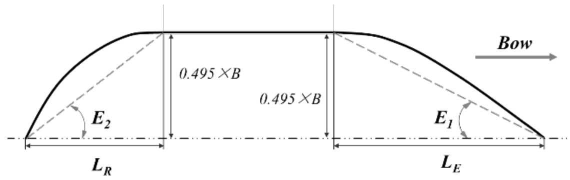


Figure G-3. Sketch of the half waterline of a ship and related definitions

$$f(\alpha) = \begin{cases}\cos\alpha & 0 \le \alpha \le E_1 \\ 0 & \alpha > E_1\end{cases} \qquad \text{(G-28)}$$

α_{T^*} is the draft coefficient, calculated as:

$$\alpha_{T^*} = \begin{cases} 1 - e^{-4\pi\left(\frac{T^*}{\lambda} - \frac{T^*}{2.5L_{\mathrm{pp}}}\right)} & \frac{\lambda}{L_{\mathrm{pp}}} \le 2.5 \\ 0 & \frac{\lambda}{L_{\mathrm{pp}}} > 2.5 \end{cases} \qquad \text{(G-29)}$$

where for $R_{\mathrm{AWR,1}}$ and $R_{\mathrm{AWR,2}}$

$$T^* = T_{\mathrm{deep}} \qquad \text{(G-30)}$$

and for $R_{\mathrm{AWR,3}}$ and $R_{\mathrm{AWR,4}}$

$$T^* = \begin{cases} T_{\mathrm{deep}}\left(4 + \sqrt{|\cos\alpha|}\right)/5 & C_{\mathrm{B}} \le 0.75 \\ T_{\mathrm{deep}}\left(2 + \sqrt{|\cos\alpha|}\right)/3 & C_{\mathrm{B}} > 0.75 \end{cases} \qquad \text{(G-31)}$$

The SNNM formula has the following limitations:

1. 75 m ≤ L_{PP} ≤400 m;
2. 5.0 ≤ L_{PP}/B ≤ 8.0;
3. 2.0 ≤ B/T ≤ 8.0;

4. $0.52 \leq C_{\mathrm{B}} \leq 0.88$;
5. $0.09 \leq Fr \leq 0.30$.

G.4. Theoretical method with simplified tank tests in short waves or empirical formula

Applying the theoretical method, 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}.

$$R_{\mathrm{wave}} = R_{\mathrm{AWM}} + R_{\mathrm{AWR}} \tag{G-32}$$

where

R_{AWM}: mean resistance increase in regular waves based on Maruo's theory (Maruo, 1960), 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 high accuracy because the mean resistance increase in short waves is predominant one.

This theoretical method is valid for all ship types with the following restrictions:

1. $50\mathrm{m} \leq L_{\mathrm{PP}}$,
17. $4.0 < \frac{L_{\mathrm{pp}}}{B} < 9.0$,
18. $2.2 < \frac{B}{T_{\mathrm{M}}} < 9.0$,
19. $0.39 < C_{\mathrm{B}} < 0.90$

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

$$R_{\mathrm{AWM}} = 4\pi\rho_S \left(-\int_{-\infty}^{m_3} + \int_{m_4}^{\infty}\right) |H_1(m)|^2 \frac{(m+k_0\tau)^2(m+k\cos\alpha)}{\sqrt{(m+k_0\tau)^4 - m^2{k_0}^2}} dm$$

$$\text{for } \tau \geq \frac{1}{4} \tag{G-33}$$

$$R_{\mathrm{AWM}} = 4\pi\rho_S \left(-\int_{-\infty}^{m_3} + \int_{m_4}^{m_2} + \int_{m_1}^{\infty}\right) |H_1(m)|^2 \frac{(m+k_0\tau)^2(m+k\cos\alpha)}{\sqrt{(m+k_0\tau)^4 - m^2{k_0}^2}} dm$$

$$\text{for } \tau < \frac{1}{4} \tag{G-34}$$

with

$$\tau = \frac{\omega_{\mathrm{E}} V_{\mathrm{S}}}{g} \tag{G-35}$$

$$k = \frac{\omega^2}{g} \tag{G-36}$$

$$k_0 = \frac{g}{{V_{\mathrm{S}}}^2} \tag{G-37}$$

$$\omega_{\mathrm{E}} = \omega + kV_{\mathrm{S}}\cos\alpha \tag{G-38}$$

$$m_1 = \frac{k_0\left(1-2\tau+\sqrt{1-4\tau}\right)}{2} \tag{G-39}$$

$$m_2 = \frac{k_0\left(1-2\tau-\sqrt{1-4\tau}\right)}{2} \tag{G-40}$$

$$m_3 = -\frac{k_0\left(1+2\tau+\sqrt{1+4\tau}\right)}{2} \tag{G-41}$$

$$m_4 = -\frac{k_0\left(1+2\tau-\sqrt{1+4\tau}\right)}{2} \tag{G-42}$$

$$H_1(m) = \int_L \sigma(x) \mathrm{e}^{imx} dx \tag{G-43}$$

where

g: gravitational acceleration,

$H_1(m)$: function to be determined by the distribution of singularities which represents periodical disturbance by the ship,
V_S: ship's speed through the water,
α: encounter angle of incident waves (0 deg. means head waves),
ρ_S: 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. (2013). 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.

$$R_{\mathrm{AWR}} = \frac{1}{2}\rho_{\mathrm{S}} g {\zeta_{\mathrm{A}}}^2 B B_{\mathrm{f}} \alpha_T (1 + C_U Fr) \tag{G-44}$$

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

$$\alpha_T = \frac{\pi^2 {I_1}^2(k_e T_{deep})}{\pi^2 I_1^2(k_e T_{deep}) + K_1^2(k_e T_{deep})} \tag{G-45}$$

$$k_e = k(1 + \Omega cos\alpha)^2 \tag{G-46}$$

$$\Omega = \frac{\omega V_{\mathrm{S}}}{g} \tag{G-47}$$

$$B_{\mathrm{f}} = \frac{1}{B}\left\{\int_I \sin^2(\alpha + \beta_{\mathrm{w}}) \sin\beta_{\mathrm{w}} dl + \int_{II} \sin^2(\alpha - \beta_{\mathrm{w}}) \sin\beta_{\mathrm{w}} dl\right\} \tag{G-48}$$

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_{deep}: draught; for a trim condition T_{deep} 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 Figure G-4.

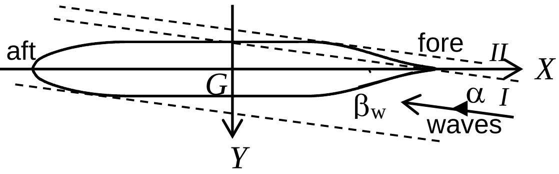


Figure G-4 Coordinate system for wave reflection.

The coefficient of the advance speed in oblique waves $C_U(\alpha)$ is calculated on the basis of the empirical relation line shown in Figure G-5[2], which has been obtained by tank tests of

---

[2] The empirical relation line in Figure G-5 was obtained as follows. C_U is derived from the result of tank tests and R_{AWM}, as formula (G-49).

$$C_{\mathrm{U}} = \frac{1}{Fr}\left\{\frac{R_{\mathrm{wave}}^{\mathrm{EXP}}(Fr) - R_{\mathrm{AWM}}(Fr)}{\frac{1}{2}\rho_{\mathrm{S}} g \zeta_{\mathrm{A}}^2 B B_{\mathrm{f}} a_{\mathrm{T}}} - 1\right\} \tag{G-49}$$

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 (G-50)and the singularity is concentrated at depth of $C_{VP}T_M$.

$$\sigma = -\frac{1}{4\pi}\left(i\omega_{\mathrm{E}} - V_{\mathrm{S}}\frac{\partial}{\partial x}\right)\{Z_{\mathrm{f}}(x)B(x)\} \tag{G-50}$$

with

$B(x)$: sectional breadth,
C_{VP}: vertical prismatic coefficient,
t : time,
T_M: draught at midship,
x: longitudinal coordinate,

various ship types following to the procedures in the next paragraph.

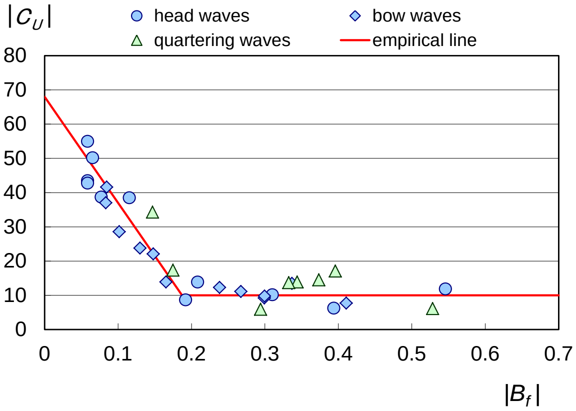


Figure G-5 Relation between the coefficient of advance speed on added resistance due to wave reflection and the bluntness coefficient for conventional hull form above water.

When $C_U(\alpha=0)$ is obtained by tank tests the relation used in oblique waves is shifted parallel to the empirical relation line. This is illustrated in Figure G-6 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 affected by short waves. The length of short waves should be $0.5L_{PP}$ or less. The coefficient of advance speed C_U is determined by the least square method through the origin against *Fr*; see Figure G-7.

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*.

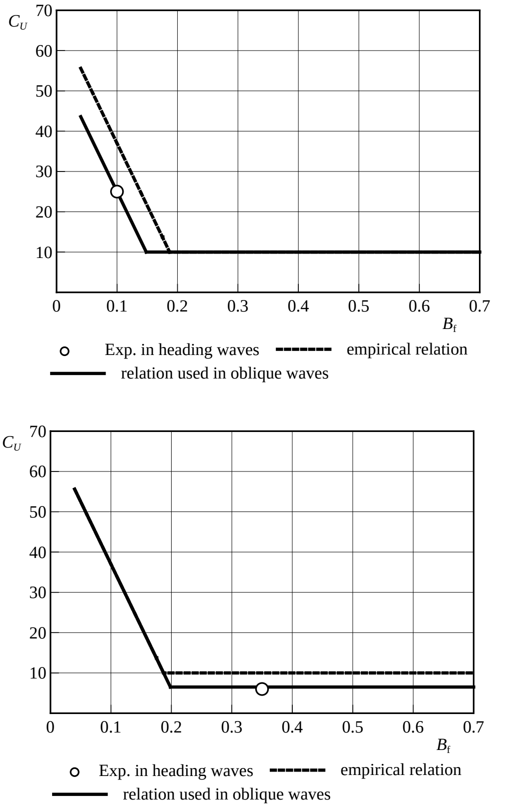


Figure G-6 Shift of the empirical relation in oblique waves (upper; for fine ship $B_\mathrm{f} < 58/310$, lower; for blunt ship $B_\mathrm{f} \geq 58/310$).

When tank tests are not carried out, the coefficient of advance speed in head waves $C_U(\alpha=0)$ is calculated by the following empirical relations, formulae (G-51), shown in Figure G-5. The formulae are suitable for all ships.

$$C_U(\alpha) = \mathrm{sgn}(B_f(\alpha)) \cdot {C_U}^+(|B_f(\alpha)|) \qquad \text{(G-51)}$$

with

$${C_U}^+(B_f(\alpha)) = \mathrm{Max}[F_C, F_S] \qquad \text{(G-52)}$$

(i) $B_f(\alpha = 0) < B_{fc}$ or $B_f(\alpha = 0) < B_{fs}$

Z_r: vertical displacement relative to waves in steady motion.

$$F_S = C_U(\alpha = 0) - 310\{B_f(\alpha) - B_f(\alpha = 0)\} \quad \text{(G-53)}$$

$$F_C = \mathrm{Min}[C_U(\alpha = 0),\ 10] \quad \text{(G-54)}$$

(ii) $B_f(\alpha = 0) \geq B_{fc}$ and $B_f(\alpha = 0) \geq B_{fs}$

$$F_S = 68 - 310B_f(\alpha) \quad \text{(G-55)}$$

$$F_C = C_U(\alpha = 0) \quad \text{(G-56)}$$

where $B_{fc} = \frac{58}{310}$ and $B_{fs} = \frac{68 - C_U(\alpha=0)}{310}$.

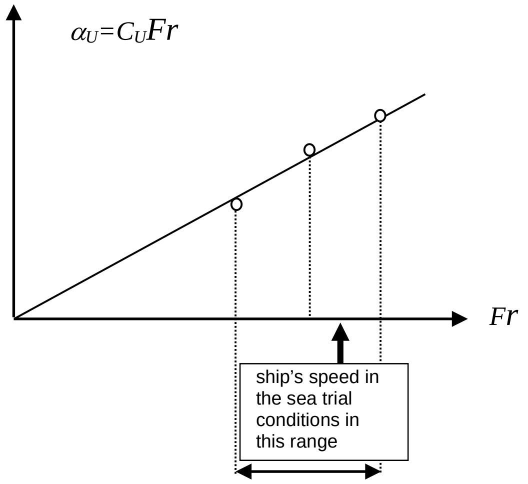


Figure G-7 Relation between effect of advance speed (α_U=C_UFr) and Froude number Fr.

G.5. Seakeeping model tests

Transfer functions of the resistance increase in waves (R_{wave}) may be derived from the tank tests in regular waves. The tank tests have to be conducted for the specific vessel geometry at the trial draughts and trim, and at contractual draughts if required. A minimum of two different ship's speeds V_S covering the speed range tested in the speed/power trials have to be tank tested.

As trials are not always conducted in head seas and following seas, the tank tests should not only comprise head and following waves but also the relevant oblique wave conditions. A maximum interval of incident wave angle shall be 30° for head to beam seas (0°-90°) but may be larger for beam to following seas (90°-180°).

These tests shall be performed for a combination of circular frequency of regular waves (ω), angle between ship heading and incident regular waves (α) and ship's speed through the water (V_S) based on the following: A minimum of 5 wave lengths in the range of $0.3L_{PP}$ or less to $2.0L_{PP}$. The test set-up and procedure shall follow ITTC 7.5-02- 07-02.2.

Appendix H. EFFECT OF CURRENT

Considering the nature of currents, the current speed shall be estimated from the measured ship's speed at each run.

There are two methods to account for the effect of current:

- • The 'Iterative' method, where the current speed is assumed as a semi durational phenomenon.
- • The 'Mean of means' method, where the current speed is assumed to vary parabolically within a given power setting.

H.1. 'Iterative' method

In the 'Iterative' method, the current speed is assumed to vary with, inter alia, the semidiurnal period. A current curve is determined as a function of time as follows:

$$V_\mathrm{C} = V_\mathrm{C,C}\cos\left(\frac{2\pi}{T_\mathrm{C}}t\right) + V_\mathrm{C,S}\sin\left(\frac{2\pi}{T_\mathrm{C}}t\right) + V_\mathrm{C,T}t + V_\mathrm{C,0} \qquad \text{(H-1)}$$

where:

V_C: is the current speed in knots,
T_C: is the period of variation of current speed,
t: is the time for each run.
$V_\mathrm{C,C}$, $V_\mathrm{C,S}$, $V_\mathrm{C,T}$,$V_\mathrm{C,0}$: unknown factors

The most dominant period is the lunar semidiurnal period of 0,517 53 day (12 hours, 25 minutes and 12 seconds).

The ship's speed through the water V_S is derived from a regression curve (H-2) which represents the relationship between the ship's speed through the water and its power corrected in accordance with clause 10.2.3and is defined as follows:

Stage 1: first approximation of ship's speed through the water

$$P(V_\mathrm{S}) = a + bV_\mathrm{S}^q \qquad \text{(H-2)}$$

Therefore:

$$V_\mathrm{S} = \sqrt[q]{\frac{P(V_\mathrm{S})-a}{b}} \qquad \text{(H-3)}$$

where:

$P(V_\mathrm{S})$: is the regression curve,
V_S: is the ship's speed through the water in knots.

and unknown factors a, b and q.

The initial value of V_S shall be taken as the mean of the measured ship's speeds V'_G of a double run. As a first approximation of the regression curve representing the relationship between ship's speed and power, a mean curve is derived by determining the unknown factors, a, b and q of formula (H-2) by fitting the formula (H-2) to combinations of the initial value of V_S and averaged corrected power P'_id by the 'least squares' method.
The ship's speed on the mean curve at the corrected power for each run is calculated as the updated ship's speed through the water V_S from the formula (H-3) applying the coefficients obtained as described above.

Stage 2: calculation of current velocity

Current speed at the time for each run V'_C is calculated by subtracting the updated ship's speed through the water V_S from the measured ship's speed over the ground V_G.

$$V'_\mathrm{C} = V_\mathrm{G} - V_\mathrm{S} \qquad \text{(H-4)}$$

A current speed curve is obtained by determining the unknown factors $V_\mathrm{C,C}$, $V_\mathrm{C,S}$, $V_\mathrm{C,T}$ and $V_\mathrm{C,0}$ of formula (H-1) by fitting the formula (H-

1) to the combinations of time and current speed obtained from formula (H-4) by the 'least squares' method.

The current speed on the current curve at the time for each run V_C is calculated as the updated current speed from the formula (H-1) and applying the coefficients obtained as described above.

Stage 3: calculation of ship's speed through the water

The ship's speed, corrected for current V'_S,V'_S is calculated by subtracting the updated current speed $V_C$$V_C$ from the measured ship's speed over the ground V_G.

$$V'_S = V_G - V_C \tag{H-5}$$

The updated regression curve representing the relationship between ship's speed and power is obtained by determining new factors of formula (H-2) by fitting the formula (H-2) to the combination of ship's speed obtained from formula (H-5) and corrected power by the 'least squares' method again.

The ship's speed through the water at the corrected power for each run V_S is recalculated as the updated one from the formula (H-3), and the processes of Stage 2 and Stage 3 are then repeated until $\sum(P(V'_S)_i - P_{\mathrm{id}i})^2$ is minimized.

H.2. 'Mean of means' method

If the 'Mean of means' method is used, two double runs shall be performed at each power setting.

This method assumes that the current speed varies parabolically over the time, and the following formula is used to account for the current effect:

$$V_S = \frac{V_{G1}+3V_{G2}+3V_{G3}+V_{G4}}{8} \qquad V_S = \frac{V_{G1}+3V_{G2}+3V_{G3}+V_{G4}}{8} \tag{H-6}$$

where:

V_S: is the ship's speed through the water in knots,
V_{G1}: is the measured ship's speed over the ground on the first of four runs in knots,
V_{G2}: is the measured ship's speed over the ground on the second of four runs in knots,
V_{G3}: is the measured ship's speed over the ground on the third of four runs in knots,
V_{G4}: is the measured ship's speed over the ground on the fourth of four runs in knots.

Assuming that the current speed varies parabolically, a current curve is defined as a quadratic function of time.

$$V_C = V_{C,2}t^2 - V_{C,1}t + V_{C,0} \tag{H-7}$$

where:

$V_{C,0}$, $V_{C,1}$and $V_{C,2}$are unknown factors.

If two double runs, i.e. four runs, are conducted, the following relationship is derived for each run from formula (H-7).

$$V_{G1} = V_S + \{V_{C,2}(t+3\Delta t)^2 - V_{C,1}(t+3\Delta t) + V_{C,0}\} \tag{H-8}$$

$$V_{G2} = V_S - \{V_{C,2}(t+\Delta t)^2 - V_{C,1}(t+\Delta t) + V_{C,0}\} \tag{H-9}$$

$$V_{G3} = V_S + \{V_{C,2}(t-\Delta t)^2 - V_{C,1}(t-\Delta t) + V_{C,0}\} \tag{H-10}$$

$$V_{G4} = V_S - \{V_{C,2}(t-3\Delta t)^2 - V_{C,1}(t-3\Delta t) + V_{C,0}\} \tag{H-11}$$

where:

V_S: is the ship's speed through the water in knots,
V_{G1}: is the measured ship's speed over the ground on the first of four runs in knots,
V_{G2}: is the measured ship's speed over the ground on the second of four runs in knots,
V_{G3}: is the measured ship's speed over the ground on the third of four runs in knots,
V_{G4}: is the measured ship's speed over the ground on the fourth of four runs in knots,
t: is the start time of the first speed run of a power setting,
Δt: is half of the elapsed time between two successive runs.

The current speed is accounted for by substituting the above four formulae from (H-8) to (H-11) for the formula (H-6). The ship's speed through the water is the 'Mean of means' of the two double runs.

The propeller shaft speed and power shall be averaged over the two runs of each double run and then over the other double runs for the same power setting.

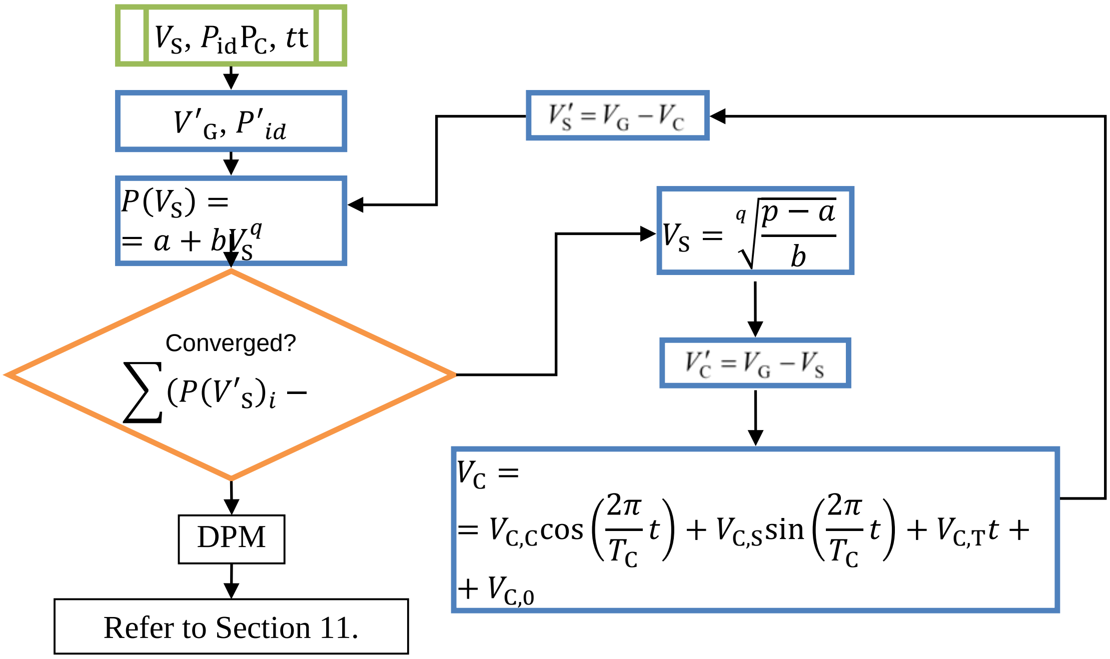


Figure H-1 Flow chart of the 'Iterative' method

Appendix I. CONVERSION FROM TRIAL 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 model tank test results.

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

Using the speed/power curve obtained by the speed trials at trial condition as described in chapter 10 and 11, the conversion on ship's speed from trial condition to the other stipulated condition to be carried out by the power ratio α_P defined in formula (I-1). The adjusted power at the stipulated condition ($P_{\mathrm{Full,S}}$) shall be calculated by formula (I-2).

$$\alpha_{\mathrm{Pi}} = \frac{P_{\mathrm{Trial,Pi}}}{P_{\mathrm{Trial,Si}}} \tag{I-1}$$

$$P_{\mathrm{Full,Si}} = \frac{P_{\mathrm{Full,Pi}}}{\alpha_{\mathrm{Pi}}} \tag{I-2}$$

where

$P_{\mathrm{Trial,P}}$: predicted power at trial condition by tank tests,
$P_{\mathrm{Trial,S}}$: power at trial condition obtained by the speed trials,
$P_{\mathrm{Full,P}}$: predicted power at stipulated condition by tank tests,
$P_{\mathrm{Full,S}}$: power at stipulated condition,
α_{P}: power ratio.
i: index of each power setting.

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

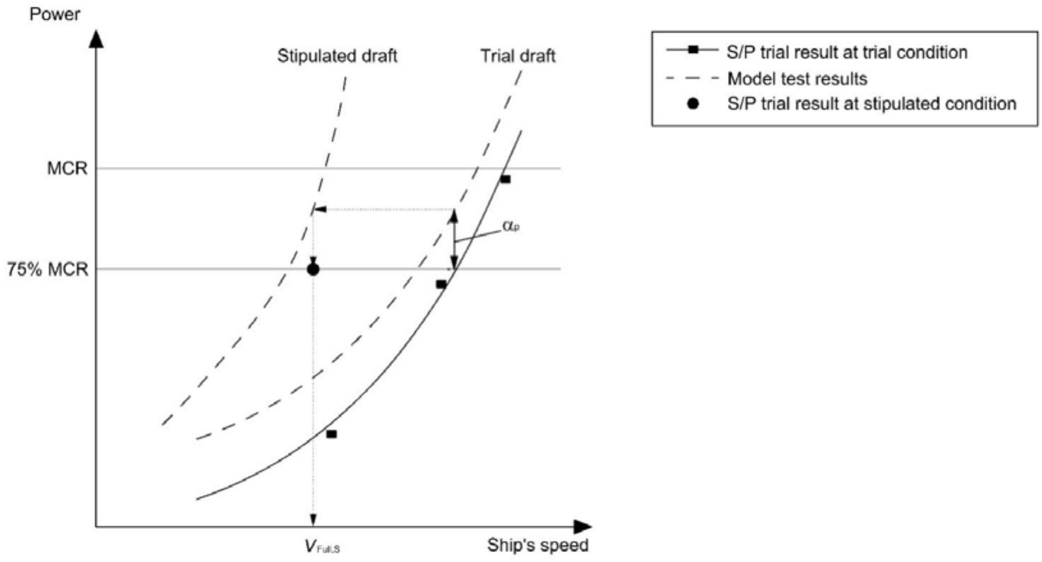


Figure I-1 Example of conversion from trial condition to other stipulated load condition at 75% MCR

Appendix J. EXTENDED ANALYSIS OF DIRECT POWER METHOD (*INFORMATIVE*)

This method is useful for model test correlation purposes since it involves the full-scale wake fraction. It shall not be used for official evaluations of S/P trials.

The delivered power corrected to ideal condition, P_{Did}, is derived by

$$P_{\mathrm{Did}} = P_{\mathrm{Dms}} - \Delta P \tag{J-1}$$

with

P_{Dms}: delivered power derived from shaft power or brake power measured on board for each single run [W],
ΔP: correction of delivered power due to the increased resistance and the changed propulsive efficiency [W].

The correction of delivered power, ΔP, can be written as:

$$\Delta P = \frac{\Delta R V_{\mathrm{S}}}{\eta_{\mathrm{Did}}} + P_{\mathrm{Dms}}\left(1 - \frac{\eta_{\mathrm{Dms}}}{\eta_{\mathrm{Did}}}\right) \tag{J-2}$$

with

ΔR: Resistance increase [N], which is derived from the data measured during sea trial,
V_{S}: ship's speed through the water [m/s], which can be obtained by the 'Iterative' method or the 'Mean of means' method,
η_{Did}: propulsive efficiency coefficient, η_{D} , in ideal condition,
η_{Dms}: propulsive efficiency coefficient, η_{D}, during sea trial.

The propulsive efficiency coefficients, η_{Did} and η_{Dms} obtained as outlined in the following sections.

J.1. Propulsive efficiency correction

The ship's propulsive efficiency is affected by the added resistance. This has to be taken into account when correcting the power.

The propulsive efficiency coefficient, η_{D}, is calculated as follows:

$$\eta_{\mathrm{D}} = \eta_{\mathrm{O}}\eta_{\mathrm{R}}\frac{1-t}{1-w_{\mathrm{S}}} \quad \text{(J-3}$$

where:

η_{O}: propeller open water efficiency, which is derived from propeller open water characteristics of the actual propeller, considering the propeller load,
η_{R}: relative rotative efficiency,
t: thrust deduction factor,
w_{S}: full-scale wake fraction.

The self-propulsion factors relative rotative efficiency, η_{R}, thrust deduction factor, t, and model wake fraction, w_{M}, are obtained from model self-propulsion tests. Between full-scale wake fraction, w_{S}, and model wake fraction, w_{M}, it is generally assumed that there is the following relationship:

$$1 - w_{\mathrm{S}} = (1 - w_{\mathrm{M}})e_i \tag{J-4}$$

with:

e_{i}: scale correlation factor of the wake fraction.

Calculation of η_{Dms}

The propulsive efficiency coefficient in the trial condition, η_{Dms}, is obtained as follows, by rewriting the formula (J-3):

$$\eta_{\mathrm{Dms}} = \eta_{\mathrm{Oms}}\eta_{\mathrm{Rms}}\frac{1-t_{\mathrm{ms}}}{1-w_{\mathrm{Sms}}} \tag{J-5}$$

η_{Oms}: propeller open water efficiency in the trial condition,
η_{Rms}: relative rotative efficiency in the trial condition,

t_{ms}: thrust deduction factor in the trial condition,
w_{Sms}: full-scale wake fraction in the trial condition.

Each self-propulsion factor in the trial condition, η_{Rms}, t_{ms} and w_{Mms}, is obtained by adding the deviation of each factor between the trial and the ideal condition, $\Delta\eta_{\mathrm{R}}$, Δt and Δw_{M}, to each factor for the ideal condition, η_{Rid}, t_{id} and w_{Mid}, respectively, as follows:

$$\eta_{\mathrm{Rms}} = \eta_{\mathrm{Rid}} + \Delta\eta_{\mathrm{R}}(\Delta R/R_{\mathrm{id}}) \qquad \text{(J-6)}$$

$$t_{\mathrm{ms}} = t_{\mathrm{id}} + \Delta t(\Delta R/R_{\mathrm{id}}) \qquad \text{(J-7)}$$

$$w_{\mathrm{Mms}} = w_{\mathrm{Mid}} + \Delta w_{\mathrm{M}}(\Delta R/R_{\mathrm{id}}) \qquad \text{(J-8)}$$

where:

η_{Rms}: relative rotative efficiency in the trial condition,
t_{ms}: thrust deduction factor in the trial condition,
w_{Mms}: model wake fraction in the trial condition,
η_{Rid}: relative rotative efficiency in the ideal condition,
t_{id}: thrust deduction factor in the ideal condition,
w_{Mid}: model wake fraction in the ideal condition,
$\Delta\eta_{\mathrm{R}}(\Delta R/R_{\mathrm{id}})$: deviation of relative rotative efficiency corresponding to $\Delta R/R_{\mathrm{id}}$,
$\Delta t(\Delta R/R_{\mathrm{id}})$: deviation of thrust deduction factor corresponding to $\Delta R/R_{\mathrm{id}}$,
$\Delta w_{\mathrm{M}}(\Delta R/R_{\mathrm{id}})$: deviation of wake fraction corresponding to $\Delta R/R_{\mathrm{id}}$,
ΔR: resistance increase [N], which is derived from the data measured during sea trial,
R_{id}: resistance in the ideal condition [N], which also can be derived from the measured data during sea trial.

The self-propulsion factors in the ideal condition, η_{Rid}, t_{id} and w_{Mid}, are obtained from standard self-propulsion test and interpolated to the speed, V_{S}.

The deviations of the self-propulsion factors $\Delta\eta_{\mathrm{R}}$, Δt and Δw_{M} are considered as the functions of $\Delta R/R_{\mathrm{id}}$. The details of the functions are described in Appendix J.2.

It is acceptable that $\Delta\eta_{\mathrm{R}}$, Δt and Δw_{M} are set to zero, because these values are negligibly small in comparison with the deviation of η_{O} due to the load variation effect.

Propeller efficiency η_{O} and full-scale wake fraction w_{S} are determined using propeller open water characteristics for the ship's fitted propeller, i.e. curves of thrust coefficient, torque coefficient and load factor, according to the following procedure.

Thrust coefficient, torque coefficient and load factor can be written as follows:

$$K_T = a_T J^2 + b_T J + c_T \qquad \text{(J-9)}$$

$$K_Q = a_Q J^2 + b_Q J + c_Q \qquad \text{(J-10)}$$

$$\tau_{\mathrm{P}} = a_T + b_T/J + c_T/J^2 \qquad \text{(J-11)}$$

where:

K_T: thrust coefficient,
K_Q: torque coefficient,
τ_{P}: load factor equal to K_T/J^2,
J: propeller advance coefficient,
a_T, b_T, c_T: factors for the thrust coefficient curve,
a_Q, b_Q, c_Q: factors for the torque coefficient curve.

These factors, a_T, b_T, c_T and a_Q, b_Q, c_Q are obtained by fitting the formula (J-9) and (J-10) to the propeller open characteristics data for the ship’s fitted propeller with the least square method.

The torque coefficient in the trial condition, $K_{Q\text{ms}}$, is calculated by the following formula:

$$K_{Q\text{ms}} = \frac{P_{\text{Dms}}}{2\pi\rho_{\text{S}} n_{\text{ms}}^3 D^5} \times \eta_{\text{Rms}} \tag{J-12}$$

where:

P_{Dms}: delivered power in the trial condition [W],
ρ_{S}: water density [kg/m^3],
n_{ms}: measured propeller shaft speed [rev./s],
D: propeller diameter [m],
η_{Rms}: relative rotative efficiency in the trial condition.

The propeller advance coefficient, J_{ms}, is determined with the following formula derived from the formula (J-10):

$$J_{\text{ms}} = \frac{-b_Q - \sqrt{b_Q^2 - 4a_Q(c_Q - K_{Q\text{ms}})}}{2a_Q} \tag{J-13}$$

where:

$K_{Q\text{ms}}$: torque coefficient in the trial condition.

The thrust coefficient in the trial condition, $K_{T\text{ms}}$, is obtained as follows, by rewriting the formula (J-9):

$$K_{T\text{ms}} = a_T J_{\text{ms}}^2 + b_T J_{\text{ms}} + c_T \tag{J-14}$$

where:

J_{ms}: propeller advance coefficient in the trial condition,

Therefore, the propeller efficiency in the trial condition, η_{Oms}, is:

$$\eta_{\text{Oms}} = \frac{J_{\text{ms}}}{2\pi} \frac{K_{T\text{ms}}}{K_{Q\text{ms}}} \tag{J-15}$$

where:

J_{ms}: propeller advance coefficient in the trial condition,
$K_{T\text{ms}}$: thrust coefficient in the trial condition,
$K_{Q\text{ms}}$: torque coefficient in the trial condition.

The speed of flow into propeller, V_{A}, is:

$$V_{\text{A}} = J_{\text{ms}} n_{\text{ms}} D \tag{J-16}$$

where:

J_{ms}: propeller advance coefficient in the trial condition,
n_{ms}: measured propeller shaft speed [rev./s],
D: propeller diameter [m].

and the full-scale wake fraction in trial condition, w_{Sms}, is:

$$1 - w_{\text{Sms}} = \frac{V_{\text{A}}}{V_{\text{S}}} \tag{J-17}$$

where:

V_{A}: speed of flow into propeller [m/s],
V_{S}: ship's speed through the water [m/s].

In addition, the total resistance in the trial condition, R_{ms}, is also estimated using the load factor in the trial condition, τ_{Pms}.

The load factor in the trial condition, τ_{Pms}, is:

$$\tau_{\text{Pms}} = \frac{K_{T\text{ms}}}{J_{ms}^2} \tag{J-18}$$

where:

J_{ms}: propeller advance coefficient in the trial condition,
$K_{T\text{ms}}$: thrust coefficient in the trial condition.

Then, the total resistance in the trial condition, R_{ms}, is:

$$R_{\text{ms}} = \tau_{\text{Pms}}(1 - t_{\text{ms}})(1 - w_{\text{Sms}})^2 \cdot \rho_{\text{S}} V_{\text{S}}^2 D^2 \tag{J-19}$$

where:

τ_{Pms}: load factor in the trial condition,
t_{ms}: thrust deduction factor in the trial condition,
w_{Sms}: full-scale wake fraction in the trial condition,

ρ_S: water density in kilograms per cubic metre,
V_S: ship's speed through the water in metres per second,
D: propeller diameter in metres.

The total resistance in the ideal condition, R_{id}, is obtained by subtracting the resistance increase, ΔR, from the total resistance in the trial condition, R_{ms}:

$$R_{\mathrm{id}} = R_{\mathrm{ms}} - \Delta R \qquad \text{(J-22)}$$

where:

ΔR: resistance increase [N], which is derived from the data measured during sea trial.

The total resistance in the ideal condition, R_{id}, is also used when the self-propulsion factor in the trial condition are calculated with the formulae (J-6) to (J-8).

Calculation of ηDid

The propulsive efficiency coefficient in the ideal condition, η_{Did}, is obtained as follows, by rewriting the formula (J-3):

$$\eta_{\mathrm{Did}} = \eta_{\mathrm{Oid}}\eta_{\mathrm{Rid}}\frac{1-t_{\mathrm{id}}}{1-w_{\mathrm{Sid}}} \qquad \text{(J-23)}$$

η_{Oid}: propeller open water efficiency in the ideal condition,
η_{Rid}: relative rotative efficiency in the ideal condition,
t_{id}: thrust deduction factor in the ideal condition,
w_{Sid}: full-scale wake fraction in the ideal condition.

The self-propulsion factors in the ideal condition, η_{Rid}, t_{id} and w_{Mid}, are obtained from standard self-propulsion test and interpolated to the speed, V_S.

The full-scale wake fraction in the ideal condition, w_{Sid}, is calculated by the following formula obtained by rewriting the formula (J-4):

$$1 - w_{\mathrm{Sid}} = (1 - w_{\mathrm{Mid}})e_i \qquad \text{(J-24)}$$

The scale correlation factor of wake fraction, e_i, included in the above formula is obtained using the full-scale and model wake fractions in the trial conditions:

$$e_i = \frac{1-w_{\mathrm{Sms}}}{1-w_{\mathrm{Mms}}} \qquad \text{(J-25)}$$

where:

w_{Mid}: model wake fraction in the ideal condition,
w_{Sms}: full-scale wake fraction in the trial condition derived from the formula (J-17),
w_{Mms}: model wake fraction in the trial condition derived from the formula (J-8).

The load factor in the ideal condition, τ_{Pid}, is calculated by the following formula:

$$\tau_{\mathrm{Pid}} = \frac{R_{\mathrm{id}}}{(1-t_{\mathrm{id}})(1-w_{\mathrm{Sid}})^2 \rho_S V_S^2 D^2} \qquad \text{(J-26)}$$

where:

R_{id}: resistance in the ideal condition [N],
t_{id}: thrust deduction factor in the ideal condition,
w_{Sid}: full-scale wake fraction in the ideal condition,
ρ_S: water density [kg/m^3],
V_S: ship's speed through the water [m/s],
D: propeller diameter [m].

The propeller advance coefficient, J_{id}, is determined as follows:

$$J_{id} = \frac{-b_T - \sqrt{b_T^2 - 4(a_T - \tau_{\mathrm{Pid}})c_T}}{2(a_T - \tau_{\mathrm{Pid}})} \qquad \text{(J-27)}$$

where:

τ_{Pid}: load factor in the ideal condition,

Once J_{id} can be obtained, the thrust coefficient in the ideal condition, K_{Tid}, and the torque coefficient in ideal condition, $K_{Q\mathrm{id}}$, are also obtained as follows, by rewriting the formula (J-9) and (J-10):

$$K_{T\mathrm{id}} = a_T J_{\mathrm{id}}^2 + b_T J_{\mathrm{id}} + c_T \tag{J-28}$$

$$K_{Q\mathrm{id}} = a_Q J_{\mathrm{id}}^2 + b_Q J_{\mathrm{id}} + c_Q \tag{J-29}$$

Therefore, the propeller efficiency in the ideal condition, η_{Oid}, is:

$$\eta_{\mathrm{Oid}} = \frac{J_{\mathrm{id}}}{2\pi} \frac{K_{T\mathrm{id}}}{K_{Q\mathrm{id}}} \tag{J-30}$$

where:

J_{id}: propeller advance coefficient in the ideal condition,
K_{Tid}: thrust coefficient in the ideal condition,
K_{Qid}: torque coefficient in the ideal condition.

The correction for the propeller shaft speed

Finally, the corrected propeller shaft speed, n_{id}, is derived as follows:

$$n_{\mathrm{id}} = \frac{V_{\mathrm{S}}(1 - w_{\mathrm{Sid}})}{J_{\mathrm{id}} D} \tag{J-31}$$

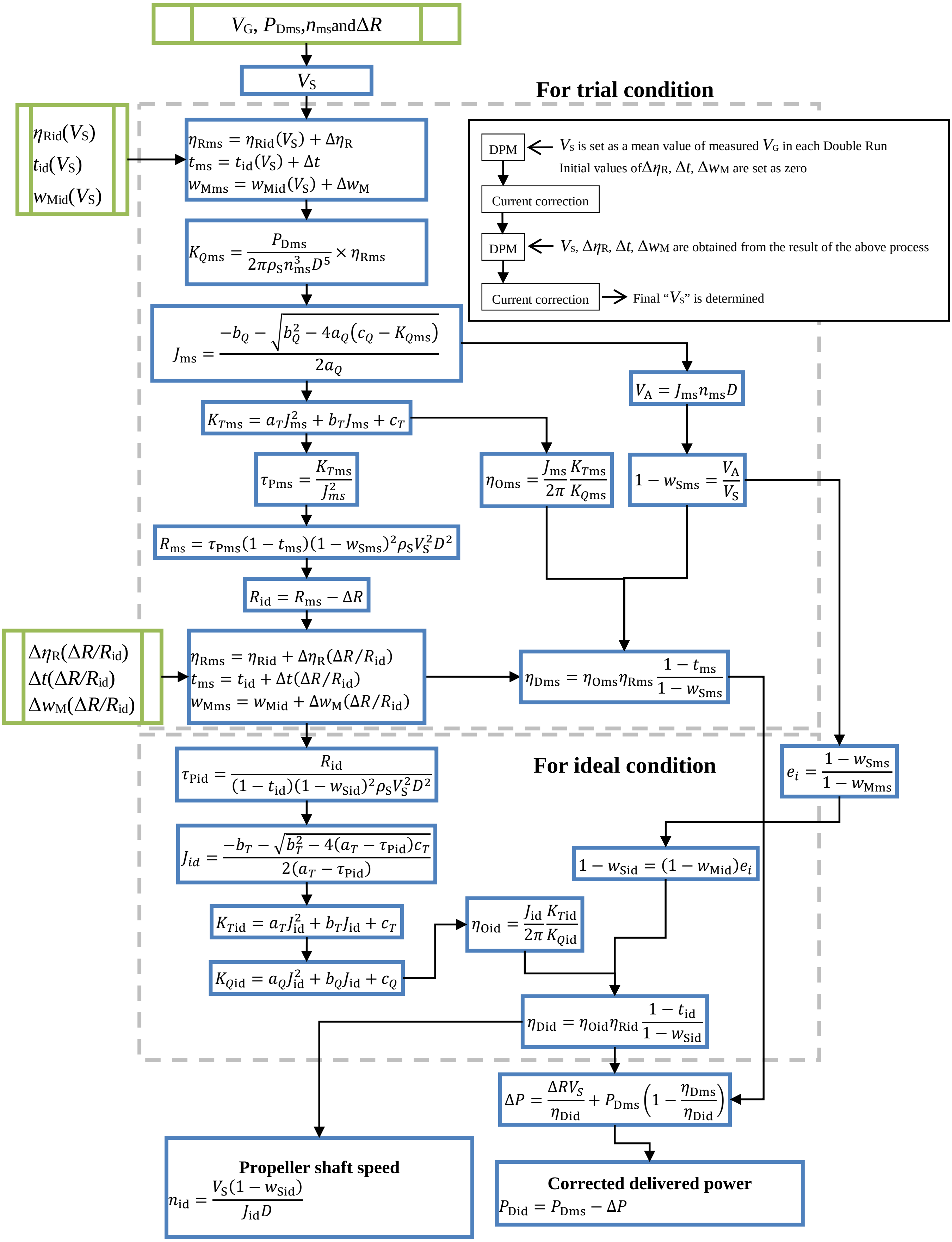
where:

V_{S}: ship's speed through the water [m/s],
w_{Sid}: full-scale wake fraction in the ideal condition,
J_{id}: propeller advance coefficient in the ideal condition,
D: propeller diameter [m].

Applying the analysis process in Figure J.1, the value of V_{S}, and thus the values of η_{Rid}, t_{id} and w_{Mid} are known after the analysis of the current velocity.

Additionally, the value of $\Delta R/R_{\mathrm{id}}$, and thus the values of $\Delta\eta_{\mathrm{R}}$, Δt and Δw_{M} are known after the extended analysis. Therefore, this analysis shall be repeated after the value of V_{S} is obtained by the current analysis.

For the evaluation described above, the mean value of V_{G} for double run or 'Mean of means' value of V_{G} for two double runs shall be used as the initial value, and the values of $\Delta\eta_{\mathrm{R}}$, Δt and Δw_{M} are set to zero.


V_G, P_{Dms}, n_{ms} and ΔR
V_S
For trial condition
$\eta_{Rid}(V_S)$
$t_{id}(V_S)$
$w_{Mid}(V_S)$
$\eta_{Rms} = \eta_{Rid}(V_S) + \Delta\eta_R$
$t_{ms} = t_{id}(V_S) + \Delta t$
$w_{Mms} = w_{Mid}(V_S) + \Delta w_M$
DPM
V_S is set as a mean value of measured V_G in each Double Run
Initial values of $\Delta\eta_R$, Δt, Δw_M are set as zero
Current correction
DPM
V_S, $\Delta\eta_R$, Δt, Δw_M are obtained from the result of the above process
Current correction
Final "V_S" is determined
$K_{Qms} = \frac{P_{Dms}}{2\pi\rho_S n_{ms}^3 D^5} \times \eta_{Rms}$
$J_{ms} = \frac{-b_Q - \sqrt{b_Q^2 - 4a_Q(c_Q - K_{Qms})}}{2a_Q}$
$V_A = J_{ms} n_{ms} D$
$K_{Tms} = a_T J_{ms}^2 + b_T J_{ms} + c_T$
$\tau_{Pms} = \frac{K_{Tms}}{J_{ms}^2}$
$\eta_{Oms} = \frac{J_{ms}}{2\pi}\frac{K_{Tms}}{K_{Qms}}$
$1 - w_{Sms} = \frac{V_A}{V_S}$
$R_{ms} = \tau_{Pms}(1-t_{ms})(1-w_{Sms})^2 \rho_S V_S^2 D^2$
$R_{id} = R_{ms} - \Delta R$
$\Delta\eta_R(\Delta R/R_{id})$
$\Delta t(\Delta R/R_{id})$
$\Delta w_M(\Delta R/R_{id})$
$\eta_{Rms} = \eta_{Rid} + \Delta\eta_R(\Delta R/R_{id})$
$t_{ms} = t_{id} + \Delta t(\Delta R/R_{id})$
$w_{Mms} = w_{Mid} + \Delta w_M(\Delta R/R_{id})$
$\eta_{Dms} = \eta_{Oms}\eta_{Rms}\frac{1-t_{ms}}{1-w_{Sms}}$
For ideal condition
$e_i = \frac{1-w_{Sms}}{1-w_{Mms}}$
$\tau_{Pid} = \frac{R_{id}}{(1-t_{id})(1-w_{Sid})^2 \rho_S V_S^2 D^2}$
$1 - w_{Sid} = (1 - w_{Mid})e_i$
$J_{id} = \frac{-b_T - \sqrt{b_T^2 - 4(a_T - \tau_{Pid})c_T}}{2(a_T - \tau_{Pid})}$
$K_{Tid} = a_T J_{id}^2 + b_T J_{id} + c_T$
$\eta_{Oid} = \frac{J_{id}}{2\pi}\frac{K_{Tid}}{K_{Qid}}$
$K_{Qid} = a_Q J_{id}^2 + b_Q J_{id} + c_Q$
$\eta_{Did} = \eta_{Oid}\eta_{Rid}\frac{1-t_{id}}{1-w_{Sid}}$
$\Delta P = \frac{\Delta R V_S}{\eta_{Did}} + P_{Dms}\left(1 - \frac{\eta_{Dms}}{\eta_{Did}}\right)$
Propeller shaft speed
$n_{id} = \frac{V_S(1-w_{Sid})}{J_{id} D}$
Corrected delivered power
$P_{Did} = P_{Dms} - \Delta P$

J.2. Application of load variation test results

In order to determine each component of propulsive efficiency coefficient η_D, propeller open water tests, resistance and self-propulsion tests are carried out at trial draught and evaluated according to the tank's normal procedures. In addition, a self-propulsion test with load variation effect may be carried out at the trial draught and, as a minimum, one speed close to the predicted EEDI speed (75% MCR). This speed shall be one of the speeds tested in the normal self-propulsion test.

The self-propulsion test with load variation effect includes at least 4 self-propulsion test runs, each one at a different propeller shaft speed while keeping the model's speed constant. The propeller shaft speed is to be selected such that:

$$\frac{\Delta R}{R_0} \approx [-0.1, 0{,}0.1{,}0.2] \qquad \text{(J-32)}$$

where:

$$\Delta R = (F_D - F_M)\lambda^3 \frac{\rho_S}{\rho_M} \qquad \text{(J-33)}$$

ΔR: resistance increase [N],
R_{id}: full scale resistance at the actual speed from resistance test [N],
F_X: external tow force measured during load variation test [N],
F_D: skin friction correction force, same as in the normal self-propulsion tests [N],
λ: scale factor,
ρ_S: water density in full scale [kg/m^3],
ρ_M: water density in the model test [kg/m^3].

Each self-propulsion factor obtained from the procedure mentioned above shall be expressed as a function of $\Delta R/R_{id}$ as follows:

$$\Delta\eta_R = \xi_R \left(\frac{\Delta R}{R_{id}}\right)^2 + \zeta_R \frac{\Delta R}{R_{id}} \qquad \text{(J-34)}$$

$$\Delta t = \xi_t \left(\frac{\Delta R}{R_{id}}\right)^2 + \zeta_t \frac{\Delta R}{R_{id}} \qquad \text{(J-35)}$$

$$\Delta w = \xi_w \left(\frac{\Delta R}{R_{id}}\right)^2 + \zeta_w \frac{\Delta R}{R_{id}} \qquad \text{(J-36)}$$

where:

$\Delta\eta_R$: deviation of the relative rotative efficiency,
Δt: deviation of the thrust deduction factor,
Δw_M: deviation of the wake fraction,
ΔR: resistance increase in Newton,
R_{id}: resistance in the ideal condition in Newton,

and ξ_R, ξ_t, ξ_w, ζ_R, ζ_t and ζ_w are unknown factors and determined by fitting the formulae (J.34), (J.35) or (J.36) to the results of the load variation tests with the 'least squares' method.

Appendix K. SHALLOW-WATER CORRECTION-RAVEN METHOD

Shallow water correction can be done with the method described in K.1.

K.1. Raven shallow-water correction

The computation of the power correction for trials conducted in shallow-water consists of two parts:

1. The first is a correction for the increase of the viscous resistance in shallow water. This requires to estimate the magnitude of the viscous resistance in deep water at equal speed. Its increase in shallow water is found from the formula given in Raven 2016.
2. The second is a correction for the resistance increase caused by the additional dynamic sinkage in shallow water. This correction is based on a constant Admiralty coefficient.

The inputs required to the computation are:

L_{PP}: length between perpendiculars [m]
B: breadth [m]
T_{M}: draught at midship[m]
C_{B}: block coefficient [-]
A_{W}: water plane area [m^2]
S: wetted surface hull (at the zero speed trials condition) [m^2]
h: water depth [m]
η_{Did}: propulsion efficiency coefficient in ideal condition, from model test [-]
V_{S}: ship's speed through water as derived from the previous steps in the trial evaluation process [m/s]
P_{Dshallow}: trial power corrected and averaged through the previous steps in the trial evaluation process but not corrected for shallow water [W]

The power correction is computed according to the following steps:

K.1.1. Calculation of viscous resistance

A) The flat plate friction coefficient is found from the ITTC 57correlation line:

$$C_{\mathrm{F}} = \frac{0.075}{(\log_{10} Re - 2)^2} \tag{K-1}$$

$$Re = \frac{V_{\mathrm{S}} \cdot L_{\mathrm{PP}}}{\nu} \tag{K-2}$$

where

Re: Reynolds number
ν: kinematic viscosity for sea water at the temperature measured [m^2/s].

The form factor 1 + *k* is found from the expression by Gross & Watanabe:

$$1 + k = 1.017 + 20 C_{\mathrm{B}} (B/L_{PP})^2 (T_M/B)^{1/2} \tag{K-3}$$

The roughness resistance is found from the Townsin's formula:

$$\Delta C_{\mathrm{F}} = 0.044 \left[\left(\frac{k_{\mathrm{s}}}{L_{\mathrm{WL}}} \right)^{\frac{1}{3}} - 10 Re^{-\frac{1}{3}} \right] + 0.000125 \tag{K-4}$$

with a minimum of 0.0.

L_{WL} can in this case be approximated as L_{PP}.

Here k_{s} is the 'Average Hull Roughness' or Mean Apparent Amplitude. The value to be used for delivery trials and EEDI trials is 0.00015 m.

The viscous resistance coefficient thus becomes:

$$C_{\mathrm{V}}' = 1.06 C_{\mathrm{F}} (1 + k) + \Delta C_{\mathrm{F}} \tag{K-5}$$

The viscous resistance in deep water is:

$$R_{\mathrm{Vdeep}} = C_{\mathrm{V}}' \, \frac{1}{2} \rho_{\mathrm{S}} {V_{\mathrm{S}}}^2 S \tag{K-6}$$

with

ρ_s: density of the sea water, for actual temperature & salt content [kg/m³]

It is noted that the viscous resistance coefficient is multiplied by a factor 1.06, to incorporate the relevant part of the correlation allowance.

K.1.2. Shallow-water correction of viscous resistance

The viscous resistance is corrected according to

$$\Delta R_\mathrm{V} = R_\mathrm{Vdeep} 0.57 \left({}^{T_\mathrm{M}}/_{h}\right)^{1.79} \tag{K-7}$$

K.1.3. Estimate of additional sinkage

The increase of the dynamic sinkage due to shallow water is found from the formula given in Raven 2016:

$$d(sinkage) = 1.46 \frac{\nabla}{{L_\mathrm{PP}}^2} \left[\frac{{Fr_\mathrm{h}}^2}{\sqrt{1-{Fr_\mathrm{h}}^2}} - \frac{{Fr_\mathrm{hd}}^2}{\sqrt{1-{Fr_\mathrm{hd}}^2}} \right] \tag{K-8}$$

with a minimum of 0.0 and with

$$Fr_\mathrm{hd} = \frac{V_\mathrm{S}}{\sqrt{0.3 g L_\mathrm{PP}}}$$

$$Fr_\mathrm{h} = \frac{V_\mathrm{S}}{\sqrt{gh}}$$

and

$$\nabla = L_\mathrm{PP} \cdot B \cdot T_\mathrm{M} \cdot C_\mathrm{B}$$

K.1.4. Estimate of the resulting additional displacement

The additional displacement due to sinkage is computed as:

$$\delta\nabla = d(sinkage) \cdot A_\mathrm{W} / \nabla$$

with the restriction

$$\delta\nabla \leq 0.05 \tag{K-9}$$

I.e. the displacement increase due to additional sinkage is limited to 5% of the displacement. For larger sinkages the correction is based on the limited increase of 5% of the displacement.

K.1.5. K.1.5 Estimate of resistance increase caused by additional sinkage in shallow water

Assuming a constant Admiralty coefficient, the resistance increase caused by additional sinkage is estimated as:

$$rsink = (1 + \delta\nabla)^{2/3} \tag{K-10}$$

K.1.6. Correction of the measured power

The power corrected for the sinkage effect and for the shallow-water effect on viscous resistance is:

$$P_\mathrm{Ddeep} = \frac{P_\mathrm{Dshallow}}{rsink} - \frac{\Delta R_\mathrm{V} \cdot V_\mathrm{S}}{\eta_\mathrm{Did}} \tag{K-11}$$

K.1.7. Check of the validity of the calculated viscous resistance

Finally, it is checked whether the calculated deep-water viscous resistance from step K.1.1, is less than the total resistance deduced from the deep-water power as found in step K.1.6:

$$R_\mathrm{Vdeep} \leq \frac{P_\mathrm{Ddeep} \cdot \eta_\mathrm{Did}}{V_\mathrm{S}} \tag{K-12}$$

If this constraint is not satisfied, R_{Vdeep} is reduced to this upper limit, and the procedure is redone starting with step K.1.2.

K.1.8. Limits of applicability:

Water depth and ship's speed as stipulated in section 6.4.

Appendix L. NOMENCLATURE

A_E/A_O	blade area ratio [-]
A_X	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_W	water plane area [m^2]
A_{XV}	area of maximum transverse section exposed to the wind[m^2]
B	ship breadth [m]
B_f	bluntness coefficient [-]
b_R	rudder span[m]
C	coefficient for starboard and port rudder [-]
C_{AA}	air resistance coefficient
C_{DAjj}	measured wind resistance coefficient at wind tunnel [-]
$\hat{C}_{DAjj}$	estimated wind resistance coefficient [-]
$C_{DA}(\psi_{WR})$:	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_V	viscous resistance coefficient [-]
C_{VP}	vertical prismatic coefficient [-]
C_{WA}	water plane area coefficient of aft part (from midship to A.P.) [-]
C_{WL}	prismatic waterline coefficient [-]
C_X	Wind resistance coefficient
D	diameter of the actual full scale propeller [m]
D	depth, moulded, of a ship hull [m]
$d(sinkage)$	increase of the dynamic sinkage due to shallow water [m]
E:	directional sea spectrum [m^{2}s]
Fr	Froude number [-]
Fr_h	Depth Froude number [-]
Fr_{hd}	Depth Froude number deep water [-]
G	angular distribution function [-]
g	gravitational acceleration [m/s^2]
h	water depth[m]
h_{ANEMO}	height anemometer above water [m]
h_R	rudder height[m]
$H_{W1/3}$	sum of significant wave height of swell and wind waves[m]
$H_{1/3S}$	significant wave height of swell [m]
$H_{1/3W}$	significant wave height of wind waves [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	circular wave number[rad/s]
k	form factor
k_S	hull roughness
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]
$P_{Dshallow}$	trial power averaged and corrected for all effects but for shallow water [W]
P_{Ddeep}	trial power averaged and corrected for shallow water [W]
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_{AWL}	mean resistance increase in long crested irregular waves [N]
R_{AWM}	mean resistance increase in regular waves due to motion[N]
R_{AWR}	mean resistance increase due to wave reflection [N]
Re	Reynolds number [-]
R_T	total resistance in still water [N]
R_{T0}	resistance for reference water temperature and salt content[N]
R_{Vdeep}	viscous resistance in deep water
R_{wave}	mean resistance increase in regular waves [N]
r_{sink}	factor for increase of power due to sinkage [-]
S	wetted surface hull [m^2]
S_η	frequency spectrum for ocean waves [m^{2}s]
S_{APP}	wetted surface appendages [m^2]
T_A	draught at aft perpendicular [m]
T_{deep}	for a trim condition, the deepest draught [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's speed over the ground at (i+1)th run [m/s]
V_G	ship's speed over ground [m/s]
V_{KN}	ship's speed over ground [knot]
V_S	ship's speed (VS) [knot]
$V_{SC.}$	corrected ship's speed (VSC) [knot]
V_{WR}	apparent wind speed, relative wind velocity [m/s]
V_{WRref}	relative wind velocity at the reference height[m/s]
V'_{WR}	corrected relative wind velocity at the vertical position of the anemometer [m/s]
V_{WT}	true wind velocity [m/s]
V'_{WT}	averaged true wind velocity at the vertical position of the anemometer [m/s]
V_{WTref}	true wind velocity at the reference height[m/s]
w	wake fraction [-]
w_m	mean wake fraction
Z	number of propeller blades [-]
Z_a	vertical position of the anemometer in [m]
Z_{ref}	reference height for the wind resistance coefficients in [m]
α	wave direction relative to bow, angle between ship heading [deg] and incident regular waves; 0 means head waves.
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]
ΔC_F	roughness allowance associated with Reynolds number for actual water temperature and salinity [-]
ΔR	resistance increase [N]
ΔR_V	viscous resistance increase due to shallow water [N]
Δ_{ref}	reference displacement[m^3]
ΔV_S	decrease of ship's speed due to shallow water [knot]
$\Delta\tau$	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	power correction factor for temperature (DPTEM) [kW]
$\delta \mathrm{P}\rho$	power correction factor for density (DPDEN) [kW]
$\delta \mathrm{P}\Delta$	power correction factor for displacement (DPDIS) [kW]
δV_H	speed correction factor for depth (DVDEP) [knot]
$\delta \nabla$	additional displacement due to sinkage [-]
ζ_A	wave amplitude [m]
η_R	relative rotative efficiency by use of the thrust identity [-]
η_S	mechanical efficiency in shafting(s) and gear box(es) [-]
η_Did	propulsion efficiency coefficient in ideal condition, from model test [-]
ν	kinematic viscosity for sea water at the temperature measured [m^2/s]
ρ_s	density of the sea water, for actual temperature & salt content [$\mathrm{kg/m}^3$]
ρ_A	mass density of air [$\mathrm{kg/m}^3$]
ρ_WSref	sea water density according to contract [$\mathrm{kg/m}^3$]
ρ_WS	sea water density [$\mathrm{kg/m}^3$]
ρ_0	water density for reference water temperature and salt content[$\mathrm{kg/m}^3$]
ψ	heading of ship; compass course [deg]
ψ_WR	relative wind direction [deg]
ψ'_WR	corrected relative wind direction at the vertical position of the anemometer [deg]
ψ_WRref	relative wind direction at the reference height[deg]
ψ_WT	true wind direction the vertical position of the anemometer [deg]
ψ'_WT	averaged true wind direction the vertical position of the anemometer [deg]
$\xi_\mathrm{p}, \xi_\mathrm{n}$	overload factor derived from load variation model test [-]
ω	circular frequency of incident regular waves [rad/s]