ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

Sea trials for assessing the power saving from wind assisted propulsion

7.5	Process Control
7.5-04	Full Scale Measurements
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Disclaimer

Updated / Edited by	Approved by
Quality Systems Group of the 30th ITTC	Executive Committee of the 30th ITTC 2024
Date mm/yyyy	Date mm/yyyy

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Sea trials for assessing the power saving from wind assisted propulsion

1. INTRODUCTION

The purpose of this procedure is to provide a short-term method for verification of the power saving due to a Wind Propulsion Technology (WPT) installation.

The minimum test program can be conducted within one day and includes around 5 wind conditions. The scope can be extended to include a larger number of conditions, and be conducted over a longer period of time during operation.

The sea trial verifies the power saving at one ship's speed, one wind speed and a range of wind directions. To derive the total power saving potential for a given route or representative operational weather conditions, the sea trial needs to be combined with a performance prediction in the following manner:

1. The power saving is predicted according to ITTC 7.5-02-03-01.9 or for EEDI according to MEPC.1/Circ.896 sec 2.3 for all wind speeds, directions and relevant ship speeds.
2. The sea trial verifies the power saving for a limited number of wind conditions.
3. If the comparison between the predictions and the sea trial is satisfactory, the power saving for a given route or representative operational weather conditions can be calculated according to ITTC 7.5-02-03-01.9.
4. In case the comparison is not satisfactory, the provider of the prediction should give an updated prediction and a description of what has been modified. The changes should reflect all wind conditions in a reasonable way, not just the conditions tested in the sea trial.

The wind condition may not be suitable for sea trials for wind assisted ships at the time and location of delivery from a yard/retrofit site. In such case, it is suggested that the trial is conducted during service within an agreed period after delivery/installation.

The current procedure is based on a newly developed method and applied to a limited number of cases. It is expected that the procedure will be updated ones more experience is gained. The uncertainty of the sea trial procedures, as well as the uncertainty of the performance predictions are still not well established. At current stage it is recommended to not yet use sea trials to confirm performance guarantees in a contractual context. However, it is strongly recommended to conduct sea trial of each WPT installation to confirm the performance in a standardised manner.

2. DEFINITIONS

Symbols in this guideline refer to the ITTC Symbols and Terminology List. See also ITTC 7.5-02-03-01.9.

GNSS	Global navigation satellite system
Course	Direction of motion
GPS	Global positioning system
Heading	Direction in which the bow is pointing, relative north
RPM	Rotations per minutes
Trial team	Appointed persons responsible for the trial planning and execution,

	owner's representative, yard or WPT provider representative.
WPT	Wind Propulsion Technology

3. SHIP AND TRIAL BOUNDARY CONDITIONS

The ship can be in in-service condition. Draft and trim should be similar to the ones used in WPT performance prediction. Acceptable difference in draft and trim must be judged by the trial team. Trial boundary conditions should be as follows.

3.1 Location

The trial can be conducted during normal service on the voyage between the two normal port calls. The location will be selected in discussion with Ship master, aiming for:

- free space from other traffic and obstacles
- free wind away from land
- no shallow water

3.2 Wind

The minimum wind speed is such that the speed increase between two runs can be measured accurately. As a rule of thumb, this typically means more than 0.3 knots, or a difference in power corresponding to such speed difference. If that cannot be fulfilled, an average true wind speed of at least 8.0 m/s, should be satisfied. The upper limit for wind speed is such that the wind propulsion system is operating in normal mode.

3.3 Sea State

The limiting wave condition depends on the ship and the WPT and must be judged by the trial team for each individual trial. Large motions due to waves may affect the performance of the tested WPT. Moreover, higher sea state gives larger standard deviation in measured wind and ship speed, which reduce accuracy.

3.4 Water Depth

Water depth should be large enough for not causing speed reduction. (Refer to ITTC 7.5-04-01-01.1). If this is not possible in the trial area, care should be taken that the water depth is not changing during a run-pair.

4. TRIAL PROCEDURES

4.1 Data Acquisition

During the trial, two types of data acquisition should be used: automated by means of a data acquisition system, and manual recording by means of a log sheet. See further details in ITTC 7.5-04-01-01.1, section Data Acquisition.

Care should be taken that automatic acquisition system and manual recording are synchronised in time relative UTC.

4.2 Parameters to be Recorded

4.2.1 Primary parameters

The primary parameters to be measured during each run and the recommended measurement devices are given in Table 2.

Table 1 Measurement devices for primary parameters

	Acceptable measurement devices
Track	GNSS
COG	GNSS
SOG	GNSS (see note below)
STW	Ship speed sensor, x-direction (see note on speed)
Shaft power	Torsion meter with calibrated permanent torque sensor or strain gauges (See note below)
Shaft RPM	Pick-up, optical sensor, ship revs counter
Propeller Pitch	Bridge replicator
Time	GPS Time, UTC and local
Water depth	Ship echo sounder + nautical charts
Ship heading	Gyro compass, or compass-GNSS
Relative speed and direction of wind	Ship anemometer
WPT power take in	• Electric motor power, or • Shaft generator PTO, or • Auxiliary generator (avoid other large consumers)
WPT setting	e.g. rotor RPM, wing rotation angle
Wave height and direction	Observation and metocean hindcast
Ship motions	If available, not required
Rudder angle	If available, not required
Heel angle	If available, not required

Note on Wind measurement

The anemometer is often disturbed by the ship's freeboard, superstructure and WPT. It is highly recommended if possible, to use a Lidar either to measure the wind at the trial, or to correct/calibrate the anemometer readings before the trial. CFD simulations can be used to find the most undisturbed position for the anemometer. Multiple anemometers at different positions can be used to find the most undisturbed.

Note on Ship's speed measurement

a) If the trial is conducted in a location which is known to be free of tidal current, or current that does not change in speed and direction during the course of the trial, then ship's speed shall be taken from GNSS.
b) If the trial is conducted in a location which is known to be affected by tidal current or in other way varying current, then the ship's speed shall be taken from the speed through water sensor. The reliability of the speed sensor must be checked before the trial.
c) If the speed log is unreliable, the trial should be conducted in a trial area with no tidal current.

Note on Shaft power measurement

Torsion meter with calibrated permanent torque sensor or strain gauges is preferred. If that is practically not possible then other options are:

- Fuel flow sensor. If fuel flow meter is used, the accuracy of the trial will be lower. Fixed power option should be used (see section 5.7). Make sure to note if whether the fuel flow includes WPT power consumption through auxiliary engines or shaft generator.
- Electric motor input in case of hybrid propulsion. If the power difference between runs is large, then electric motor input must be converted to mechanical energy output.

4.2.2 Secondary parameters

The secondary parameters listed in Table 3 shall be measured and recorded at the trial site at least once during the trial.

Table 2 Measurement devices for secondary parameters

	Recommended measurement devices
Air temperature	Thermometer
Air pressure	Barometer
Draughts, fore, amidships and aft at zero speed	Physical observation and/or calibrated draught gauges
Displacement	According to draught readings and water density

5. CONDUCT OF TRIAL

5.1 Initiation

When the ship has reached the trial area:

- In case the WPT power consumption will be measured indirectly via shaft generator: if possible, avoid other large consumers on this PTO.
- Make sure PTO from shaft generator do not disturb propeller shaft torque measurement.
- Register the true wind direction relative to north by reading wind instrument and if possible, by making a turn through the wind. When the relative wind angle is zero degrees then the true wind angle and apparent wind angle is the same. The true wind angle relative to north can then be determined based on the course.

5.2 5.2 Trial Trajectory

The runs are carried out in pairs, with and without the WPT applied. The arrangement and working condition of the WPT in "off" state shall be the same as in the conventional Speed/power Trial (ITTC 7.5-04-01-01.1).

The runs in a pair are done in a sequence with constant COG. An experienced helmsman or adaptive autopilot is required to maintain course during the runs.

In off state, the WPT should be tilted or retracted if possible. Non-tiltable devices should be de-activated by for example stop spinning rotors, stop suction fan in suction wings, or waning wing sails.

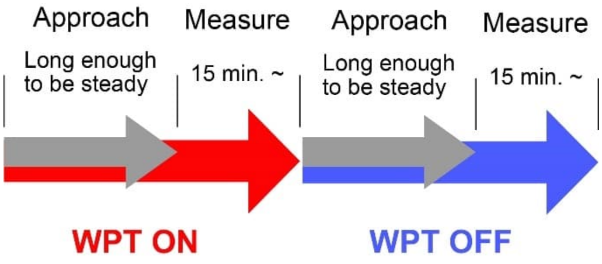

Figure 1 A run pair. (WPT is first activated and then deactivated.)

5.3 Run Duration

Measurements are done for at least 15 minutes for each run.

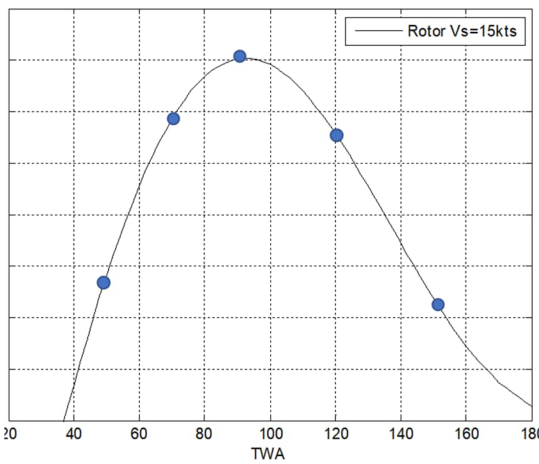

Figure 2 Example generic WPT force at ship speed 15 knots.

5.4 Wind Angles

The trial should include at least 5 pairs of runs distributed over the range of wind angles where the WPT is expected to generate thrust.

The difference between the wind angles should be more than 10 degrees. The wind angles should be distributed such that the thrust peak as well as the slopes towards the zero thrust angles are captured. If the WPT is expected to give significantly different power saving at starboard and port tacks, it should be considered to cover both tacks with 5 wind angles.

5.5 Ship's Speed

The runs with WPT should be done at approximately around the reference speed V_{ref} which will be used for the normalised result. V_{ref} is the speed that the ship owner and yard or provider agreed that the WPT should be verified at. It is not necessarily the same as the EEDI speed.

5.6 Approach and Time Between Runs

To avoid that the weather conditions change between the ON and OFF runs, they should be done just after each other. However, the approach and time between the runs shall be long enough to ensure a steady state ship's condition prior to commencement of each speed run. During the approach run, the ship shall be kept on course with minimum changes of rudder angles.

No fixed approach distance can be given, as it is case dependent. 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", i.e. the running average is not monotonically increasing or decreasing, the ship's condition shall be deemed "steady". This will be monitored and judged by the Trial Executer. If, in the post-processing phase, the measured values are found not to be stable, the run shall be omitted.

If the wind speed or direction change during the run pair, the run shall be cancelled and re-run. This will be monitored and judged by the Trial Executer.

5.7 Power Setting

A wind assistance trial can be conducted either with constant propulsion setting between the run pairs, or with constant speed between the two runs.

(1) Constant propulsion setting

The propulsion setting is kept untouched between the two runs in a run-pair. Propulsion setting means either a set point on power using a power control if that is available or setting of engine throttle and propeller shaft speed for fixed pitch propellers or setting of the shaft speed and pitch angle for controllable pitch propellers.

This option is preferable if there is no accurate power meter, and the power is estimated using fuel flow.

Ships with substantial wind propulsion, expecting large speed increase should use constant speed setting instead.

(2) Constant speed setting

The speed of the second run in a pair is aimed to be the same as that of the first run by adjusting engine power setting.

This option reduces the need for correction (see section 7). It can therefore be advantageous if the speed-power curve is uncertain. It is difficult to reach the same average speed by instant visual reading of speed log, and therefore some corrections will be required anyway. However, the use of a speed-power prediction before the trial will give a good indication of the expected setting.

The disadvantage is that the trial may take longer time, since it takes longer time to adjust and reach a new stable condition, if there is no accurate prediction of power difference available.

Constant speed setting may not be possible for very powerful WPT, if the speed from the ON-run cannot be reach within the engine limit during the OFF-run. In such case, the ship's speed in the ON run must be reduced.

5.8 Test Sequence

For option (1) Constant propulsion setting:

1. Start with WPT activated, with its automatic control system on.
2. Run with constant COG at one of the target wind angles.
3. Adjust propulsion setting such that ship speed is around the reference speed V_{ref}, ± 0.5 knots.
4. Wait for stable speed to be reached.
5. Run for 15 minutes.
6. Deactivate WPT. Do not touch propulsion setting.
7. Wait for stable speed is reached.
8. Keep same COG, run for 15 minutes.
9. Repeat for the other wind directions.

For option (2) Constant speed setting:

1. Start with WPT activated, with its automatic control system on.
2. Run with constant COG at one of the target wind angles.
3. . Adjust power setting such that ship speed is around the reference speed $V_{ref,}$ ± 0.5 knots.
4. Wait for stable speed to be reached.
5. Run for 15 minutes.
6. Deactivate WPT. Adjust the engine power to keep the speed constant.
7. Wait for stable speed and stable power re reached.
8. Keep same COG, run for 15 minutes.
9. Repeat for the other wind directions.

The Trial Executor will perform an initial check of the results regarding stable speed/power and wind conditions. If needed, some angles may need to be re-run.

5.9 Speed-power Curve

The shape of the speed-power curve will be used for post-processing the trial results. The speed-power curve can be taken from either a Speed/Power trial from yard delivery, or model test of the actual ship.

If there is no speed-power curve available for the ship covering the trial speed and loading condition, then additional speed variation tests should be included in the program. Since it is just the shape of the curve and not the absolute level that will be used, this test can be done with single runs based on STW.

The speed variation test consists of four single runs of 10 min each, covering the speed range of the WPT trial ±1 knots. No corrections needs to be done.

6. EVALUATION OF ACQUIRED DATA

The measured data from the data acquisition system will be filtered (depending on the frequency of the data) and averaged over the run time. The time trace will be plotted over time to ensure that steady condition was reached.

7. CORRECTIONS

7.1 Current

In standard speed trial analysis, the ship's SOG is measured with the GPS and corrected to STW using the double runs (ITTC 7.5-04-01-01.1). The GPS is generally regarded as far more accurate than the speed log. This procedure is not possible to follow in a sea trial for wind assisted ships, due to the presence of wind propulsion. Therefore, no current correction is done. See section 4.2.1 on measurement of ship's speed.

7.2 Drift and Rudder Angles

No correction is made for drift and rudder angles.

7.3 Correction for Superstructure Resistance

If the wind varies between the two runs in a run pair, the superstructure air resistance will be different between the runs and that will affect the comparison. Therefore, the power is corrected for superstructure resistance of the run without WPT, to the apparent wind of the run with WPT. This is done using the latest version of ITTC 7.5-04-01-01.1.

If the WPT is not tiltable or retractable in off-state, or there are larger structures like WPT fundaments, their resistance should be subtracted from the total air resistance for the runs when WPT is off. Their resistance coefficient can be taken from empirical relation, CFD or wind tunnel coefficient.

The correction of propulsive efficiency due to the added resistance corrections and idling WPT resistance is derived using the Direct Power Method according to ITTC 7.5-04-01-01.1using the assumed load variation factor stated in the ship specific document.

8. POWER SAVING FOR REFERENCE SPEED

After the Evaluation and Correction described above, the sea trial measurements consist of a list of speeds and corrected powers at various wind angles and wind speeds. To be useful, the data must be post-processed in a series of steps, which will be explained below. Step 4 is optional, depending on how the results is to be presented and used.

Post-processing steps:

1. Derive power difference from the WPT at the sea trial condition (speed and apparent wind)
2. Compare the sea trial results to the predicted power difference for exactly those conditions. This verifies the computational model used to drive the performance expectation based on ITTC 7.5-02-03-01.9, or the EEDI force matrix according to IMO (2021) .
3. Optional: Normalize the power difference to a reference condition close to the sea trial condition. Present the result as a curve versus TWA.
4. Optional: Derive power difference for all weather conditions and perform a voyage simulation to extract the average power saving potential on a route.

The steps will be explained in detail in the following sections.

8.1 Step 1: Power Difference at Sea Trial Conditions

Firstly, the measured and corrected speed and power are converted to a power difference.

To illustrate the process, consider two runs, with and without WPT (Figure 3). The measured ship's speed and delivered power are denoted V_0 and P_0 for the run without WPT and V_1 and P_1 for the run with WPT. In this example, Constant power setting was used, i.e constant shaft rate (see section 5.7). Note that the *power* decrease somewhat, due to increased propeller efficiency when the propeller is unloaded.

If Constant speed approach is used (see section 5.7), the correction still needs to be done, since it is in practice not possible to match exactly the same speed in the two runs.

1) Fit a polynomial $P=f(V)$ to the baseline speed-power curve without WPT, or part of the baseline curve that covers the range of speeds measured in the trial. Normally a 3rd order works well. Extract the polynomial coefficients.

2) The power difference ΔP at V_1 is derived as Equation (1).

$$\Delta P = -[f(V_1) - f(V_0) + P_0 - P_1] \quad (1)$$

Note that ΔP at is only valid at V_1 and at the sea trial wind condition. (ΔP is negative for a power reduction.)

The Baseline curve can either be taken from the conventional speed trial performed earlier, model test results, or a speed variation test carried out in conjunction with the wind assistance sea trial.

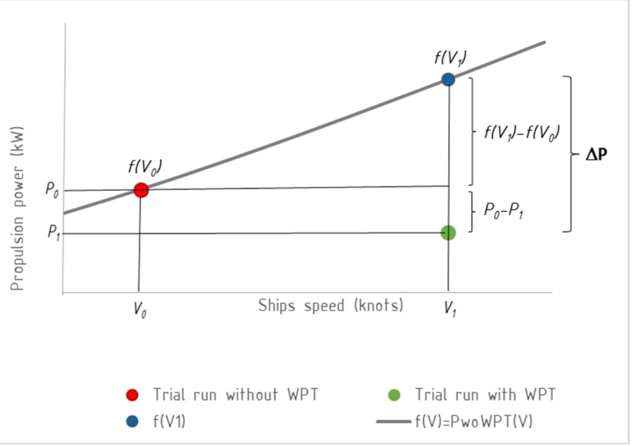

Figure 3 Extracting sea trial power difference due to WPT using the ship's speed-power curve without WPT $f(V)$.

8.2 Step 2: Compare sea trial result and prediction at sea trial run conditions

If the numerical model used to predict the performance of the WPT or EEDI force matrix is available, a comparison can be made by running the model at the same conditions as was measured during the sea trial runs. Examples are given in Figures 4 and 5. Note that the wind must be corrected to the same reference height, using the atmospheric boundary layer profile with exponent 1/9. (See ITTC 7.5-04-01-01.1).

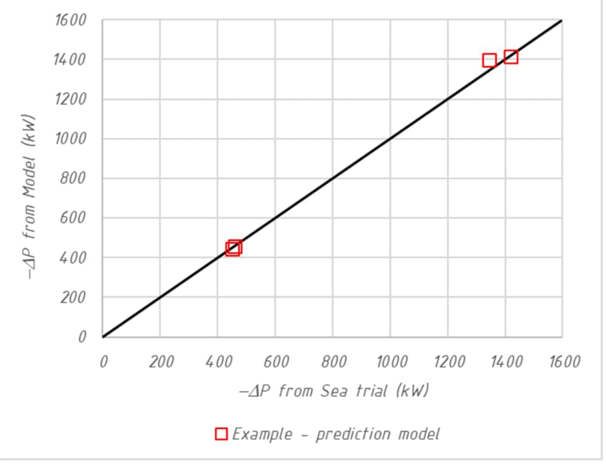

Figure 4 Demonstration of model fit compared to sea trial runs with respect to ΔP.

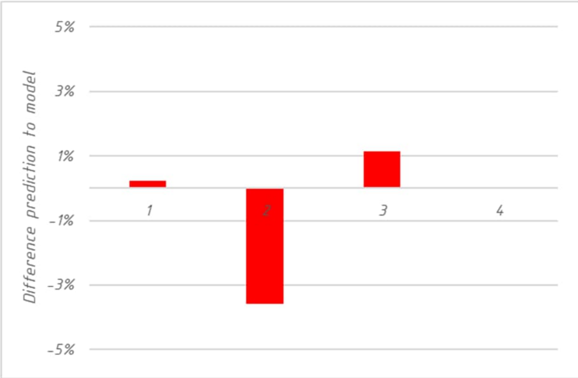

Figure 5 Difference of model fit and sea trial runs.

8.3 Step 3: Normalisation to reference condition

Small variations of wind angle, wind speed and ship speed are expected from the sea trial measurements. To be able to present the analysed result as a curve versus wind angle (as the example in Fig 7), the numbers from previous step must be translate to a reference condition. The reference condition is supposed to be given as a ship speed V_{ref} and a true wind at 10m height over water $TWS_{ref,10}$.

The apparent wind measured at the anemometer is translated to the corresponding height of the mid-point of the WPT using the 1/9 power law ($\rightarrow AWS_a$, AWA_a). (See ITTC 7.5-04-01-01.1)

The apparent wind corresponding to the reference condition is computed for the true wind angles at the sea trial, and at a height at the midpoint of the WPT ($\rightarrow AWS_{ref,m}$, $AWA_{ref,m}$).

From Equation (1), we have ΔP_1 valid at ship speed V_1 and apparent wind $AWS_{1,m}$, $AWA_{1,m}$.

A pseudo WPT thrust coefficient is computed as Equation (2).

$$\tilde{C}_{x1} = \frac{-\Delta P_1 \cdot \eta_D}{V_1} \cdot \frac{1}{0.5 \cdot \rho_{Ast} \cdot A_{\mathrm{WPT}} \cdot {AWS_{1,m}}^2} \qquad (2)$$

The thrust coefficients vary with AWA according to Equation (3).

$$\tilde{C}_{x1} = C_L \sin(AWA_m) - C_D \cos(AWA_m) \qquad (3)$$

$\tilde{C}_{x1}$ can be corrected to the reference AWA using the first term in the Taylor expansion of Equation (3), which is shown in Equation (4).

$$\tilde{C}_{x1\,ref} = \tilde{C}_{x1} + \left[C_L \cos(AWA_{1,m}) + C_D \sin(AWA_{1,m})\right] \cdot \left(AWA_{ref,m} - AWA_{1,m}\right) \qquad (4)$$

The power difference at the reference condition and at $TWA_{1,m}$ is then estimated as Equation (5).

$$\Delta P_{1,ref} = -\frac{\tilde{C}_{x1\,ref} \cdot V_{ref}}{\eta_D} \cdot 0.5 \cdot \rho_{Aref} \cdot A_{\mathrm{WPT}} \cdot {AWS_{ref,m}}^2 \qquad (5)$$

Note that $\tilde{C}_{x1}$ is a pseudo coefficient and its magnitude cannot be compared with theoretical performance of the WPT.

C_L, C_D and η_D are assumed values for the specific case. η_D shall be set to 0.7, if no other value is specified.

The method should only be used to normalise the sea trial result to a reference condition close to the sea trial condition. That means in practice that the reference condition will be selected after the trial, to be the average true wind speed during the sea trial, rounded to closest full or half whole number, and similar for the ship speed (e.g. 10.5 knots).

The normalised power saving is only valid for the loading condition at the trial.

8.3.1 Presentation of results

The normalised result is presented as shown in the example in Figure 7.

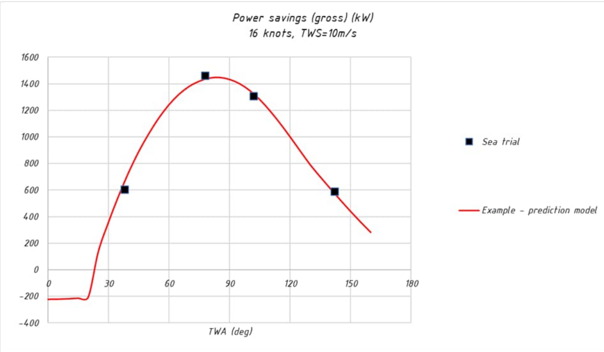

Figure 7 Presentation of results (an example). Power saving compared to prediction model.

8.4 Step 4: Net Power Saving for All Weather Conditions and Voyage Simulation

If a power saving matrix has been derived according to ITTC 7.5-02-03-01.9 and the comparison with sea trial (Step 2) was satisfactory, the average power saving potential for a given route can be calculated according to ITTC 7.5-02-03-01.9.

In case the comparison was not satisfactory, the provider of the prediction should provide an updated power saving matrix and a description of what has been modified. The changes should reflect the complete matrix in a reasonable way, not just the conditions tested in the sea trial.

The power consumption of the WPT (PTI) (e.g. for rotors and suction wings) should be included in the average power saving calculation. The power consumption stated by the provider should be verified against the measured PTI during the trial.

9. REPORTING

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

- Ship particulars
- Wind Propulsion System main dimensions, including vertical position over water line.
- Propeller details
- Details of hull appendages and rudder
- Measured data
- Test program and log
- Procedures
- The values and origins of all input parameters that are not measures.
- Results

Description of Instrumentation describing the instrument set-up, calibration procedure, data acquisition interfacing details, location of sensors, etc.

Description of Trial Site. Geography, distance from land, water depts etc.

Environment Parameters. This shall list the measured/observed wave condition, wind, air temperature.

Sea trial agenda. This shall give a complete and chronological order of the trial program (both planned and actual).

Trial results of each run

- Data and time of start and stop of run
- Run number
- Position
- Heading
- Run duration

- Mean values and standard deviation of measured values
- Time trace of measured values

Analysed results

The result should be presented as a list of power savings for the reference ship speed, reference true wind speed and wind angles as measured during the trial, corrected to 10m above water.

The reference ship speed and wind speed must be close to what was measured at the trial, for example the average between the measured runs, rounded to closest full or half whole number.

3 SYMBOLS

ρ_{Aref} Air density at reference condition, 1.225 (kg/m^3)
ρ_{Ast} Air density at sea trial condition (kg/m^3)
φ Heel angle (deg)
η_D Total efficiency of main propulsion (-)
ψ: Heading relative earth (deg)
A_T Transversal projected area above waterline incl. superstructure, excl. wind propulsion unit (m^2)
AWA β_{WA} Apparent wind angle (deg in graphs, rad in equations)
AWS V_{WR} Apparent wind speed (m/s)
AWA_a *AWA* at anemometer(deg in graphs, rad in equations)
AWS_a *AWS* at anemometer (m/s)
$AWS_{ref,m}$ *AWS* at a height at the midpoint of the WPT translated using the 1/9 power law (see ITTC 7.5-04-01-01.1) (m/s)
$AWA_{ref,m}$ *AWA* at a height at the midpoint of the WPT (deg in graphs, rad in equations)
A_{WPT} Representative projected area of WPT (m^2)
B Beam of hull (m)
C_D Drag coefficient of complete WPT installation (1)
C_L Lift coefficient of complete WPT installation (1)
C_X Force coefficient in the ships longitudinal direction of complete WPT installation (1)
COG Course over ground relative earth (deg)
P Delivered power (W)
PTO Power of shaft generator (W)
SOG Speed over ground (knots)
STW *V* Speed through water in heading direction (knots)
TWA True wind angle relative ship's course (deg in graphs, rad in equations)
TWD β_{WT} True wind angle relative to north deg)
TWS V_{VT} True wind speed (m/s)
$TWS_{ref,10}$ *TWS* at 10m height over water (m/s)
V_{ref} Reference ship speed (knots)

(Note: without current and drift, *TWS* is equal to V_{WTref} and *TWD* is equal to ψ_{WT} defined in the speed-power trial ITTC 7.5-04-01-01.1. Since the wind speed and direction is crucial in the present procedure, the influence of current on drift on the wind is included. Hence, the different definitions.)

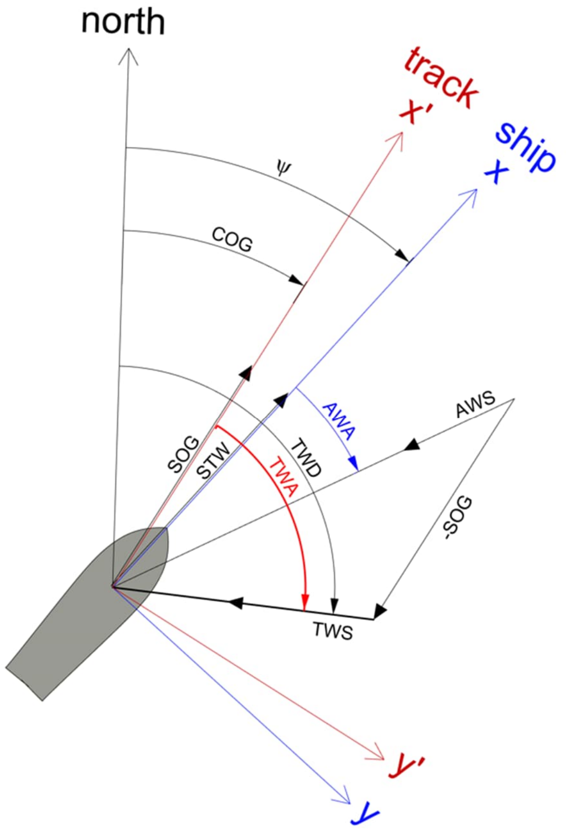

Figure 8 Definitions

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APPENDIX A. EVALUATION OF WIND DATA

Wind speed and angle on board are expected to be measured as "Apparent Wind", also called "relative wind" in other ITTC documents. This apparent wind includes the effects of ship speed, heel, leeway and current and is measured at the height of the anemometer and thus the reading will generally not be the same as the common reference at 10m from sea level. The apparent wind angle is assumed to be measured relative to ship centre line. The anemometer measurement may also be influenced by disturbance of the ship superstructure and wind propulsion units in the vicinity. However, a correction for this last effect is not yet specified here.

The measured apparent wind is to be translated to "True Wind". "True Wind is defined relative to the track over ground of the vessel, at a level of 10m above sea level. See Figure A-1 for an overview.

First, the wind is decomposed into longitudinal and transverse velocities in the ship reference frame (x-axis along ship centre line, y-axis to starboard). The heeled condition of the anemometer is corrected for. If heel is known to be below 5 degrees it may be neglected (put to zero). Compass heading is to be corrected for deviation and variation.

The apparent wind decomposed into the ship x and y axis:

$$AW_x = AWS \cdot \cos(AWA) \quad \text{(A-1)}$$

$$AW_y = AWS \cdot \frac{\sin(AWA)}{\cos(\varphi)} \quad \text{(A-2)}$$

where

AWS: Apparent Wind Speed as measured [m/s]
AWA: Apparent Wind Angle as measured [deg]
φ Heel angle (positive starboard down) [deg]
SOG: Ship's speed over ground (GNSS) [m/s]

The difference between the heading and course is a combination of drift due to the wind and due to current, is here denoted λ:

$$\lambda = COG - \psi \quad \text{(A-3)}$$

where

COG: Course over ground (GNSS) [deg]
ψ: Heading (corrected, from compass) [deg]

Define a second co-ordinate system with its x-axis x' along the ship track over ground. The angle between the x and x' axis is λ. The apparent wind transposed to the x' system is obtained by the equations for rotating coordinate system:

$$AW_{x'} = AW_x \cos(\lambda) + AW_y \sin(\lambda) \quad \text{(A-4)}$$

$$AW_{y'} = -AW_x \sin(\lambda) + AW_y \cos(\lambda) \quad \text{(A-5)}$$

Then the true wind, decomposed in the x'-y' system is:

$$TW_{x'} = AW_{x'} - SOG \quad \text{(A-6)}$$

$$TW_{y'} = AW_{y'} \quad \text{(A-7)}$$

The true wind speed and angle can be derived at 10 m height from sea level. As standard a Helmann exponent of 1/9 is used for the power law describing the atmospheric boundary layer.

$$TWS_a = \sqrt{TW_{x'}^2 + TW_{y'}^2} \quad \text{(A-8)}$$

$$TWS = TWS_a \left(\frac{10}{z_a}\right)^{1/9} \quad \text{(A-9)}$$

$$TWA = atan2\left(TW_{x'}, TW_{y'}\right) \qquad \text{(A-10)}$$

where

z_a: Height of anemometer from sea [m]
TWS: True Wind Speed at 10m height [m/s]
TWA: True Wind Angle at 10m height [deg]

Finally, the true wind direction relative to north can be computed as

$$TWD = COG + TWA \qquad \text{(A-11)}$$

TWD can be compared with external hindcast weather data for a sanity check.

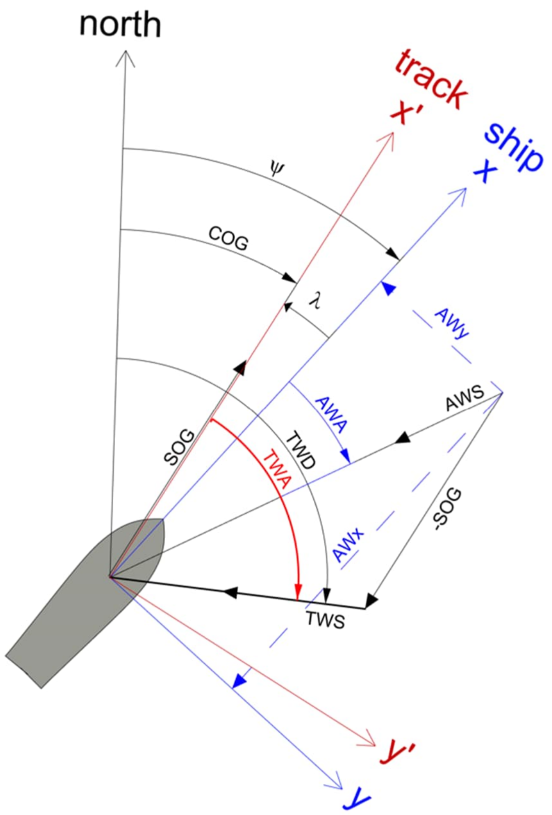

Figure A-1 Definitions

The analysis accounts for the combined effect of current and leeway partially as both true heading and course over ground are used. However, the procedure described does not use longitudinal (and possibly transverse) velocity measured with a speed log as it was not ascertained that this is generally sufficiently reliable.

With the core set of signals, current cannot be separated from leeway. The procedure effectively assumes that trials are done with very little current such that it can be neglected. However, if possible, it is recommended to collect additional information as available to judge the quality of the trial.