Abstract

Where in the past the operational cost of a ship was dominated by crew costs, this is now taken over by the bunker costs due to the ever increasing oil prices. To reduce operational costs, ships should be optimised in fuel efficiency considering environmental conditions and operational parameters. As a first step the speed-power relation should be established by means of speed trials upon delivery by the yard. A transparent and accurate industry standard for conducting and analysing speed trials is discussed. New methods to determine the added resistance of ships in waves are presented and a consistent practice for speed trials is proposed.

The second step in optimizing the vessel performance is to monitor the speed-power performance of the vessel in service. The vessel however is navigating under continuously changing loading and environmental conditions. By a proper analysis of the results and a display to the crew, the in service fuel consumption can be reduced by e.g. optimum trim of the vessel, engine settings or timely cleaning of the propeller.

Keywords
Performance, Speed Trials, Added Resistance in Waves, Fuel Consumption

1. Introduction

With increasing fuel costs and public attention to exhaust gasses, optimizing ship performance becomes a necessity to reduce operational costs and comply with emission restrictions. Obviously the design of the hull lines and propeller and the engineering of the propulsion plant are key elements in ship speed-power performance. To verify the actual performance against the contractual requirements a speed trial is conducted upon delivery by the yard.

To improve the transparency and reliability of speed trial results, MARIN in close cooperation with leading ship owners and major yards, cooperated in a Joint Industry Project regarding Sea Trials Analysis (STA-JIP).

This project resulted in 2006 in a “Recommended Practice for Speed Trials” and a “Recommended Analysis of Speed Trials” which are considered as industry standards.

ISO 19019 provides a standard method for performing speed trials. Previous so called standard analysis methods as proposed by ISO 15016 and the recommendations to the 22nd and 23rd ITTC by the Trials & Monitoring committee leave space for the engineer in charge of analysing speed trials to choose different types of correction methods. This makes it possible to make incorrect choices and thus come to a different contract speed than the actual speed of the ship. This difference can be as high as several tenths of a knot. In the STA recommended practice, no choices can be made for different methods which make the accuracy of the method more reliable. Correction methods for environmental conditions are based on verified procedures and data sets.

The goal of the STA-JIP was to come to a transparent and accurate way of performing and analysing speed trials. The aim was to determine the speed within 0.1 knots which means that the accuracy of the power measurement has to be within 2%. The scope of the project was to perform case studies of speed trials, develop a recommended practice and analysis for speed trials and program the recommended practice into software (QSTAP) which can be used by STA participants.

2. Recommended Practice of Speed Trials

In this section the recommended practice of how to perform a speed trial according to the STA-JIP is explained. To perform a high quality speed trial measurement, which is the basis of a contractual agreement of ship speed, the following should be taken in to consideration:

a  The trial parameters that should be logged
b  The trial conditions that should not be exceeded during the trial
c  The procedures that should be followed during the trial
d  The contents of the trial report
In the ITTC recommended procedures extensive procedures are given for the preparation of a speed trial and the execution thereof. The ISO procedure gives some guidelines for the boundary conditions that should apply during the speed trial. Furthermore, the existing procedures often give a good guideline, but are not specific.

The STA-JIP Practice combines the two latest standards and gives a transparent and practical overview of the minimum requirements that should be met in order to obtain reliable speed trial results.

2.1 Trial Parameters

The accuracy of the each measured parameter is the basis of the accuracy of the final trial speed. All the parameters should be recorded as accurately as possible. The primary measured parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship Track,Speed over ground</td>
<td>DGPS</td>
</tr>
<tr>
<td>Shaft Torque</td>
<td>Torque sensor</td>
</tr>
<tr>
<td>Shaft RPM</td>
<td>RPM sensor</td>
</tr>
<tr>
<td>Propeller pitch</td>
<td>Bridge replicator</td>
</tr>
<tr>
<td>Time</td>
<td>GPS Time, Stopwatch</td>
</tr>
<tr>
<td>Water depth</td>
<td>Ship echo sounder + nautical charts</td>
</tr>
<tr>
<td>Ship heading</td>
<td>Gyro compass, or twin DGPS</td>
</tr>
<tr>
<td>Relative wind</td>
<td>Ship anemometer, external anemometer</td>
</tr>
<tr>
<td>Wave height &amp; direction</td>
<td>Wave measuring device (i.e. radar, scanner. etc), Wave buoy, Hind cast, observation by multiple observers</td>
</tr>
<tr>
<td>Draughts</td>
<td>Physical observation and / or calibrated draught gauges</td>
</tr>
</tbody>
</table>

The speed is to be measured by a global positioning system such as GPS. The GPS system should operate in the Differential mode to ensure sufficient accuracy; i.e. the speed should be measured within 0.05 knots. The position and speed should be monitored and stored continuously. The ocean current is determined and corrected for by performing forward and counter runs at equal power settings.

Shaft torque should be measured by means of strain gauges on the shaft for which the zero offset is determined just prior to the trial. The measurement system should be certified for measurements on a test shaft with a bias error smaller than 1% so that an overall bias error of smaller than 2% (on board of the actual ship) can be achieved.

The ship’s own sensor or an external wind meter can be used. The wind meter must be as clear as possible from the superstructure. In the analyses of the measurements the wind data from two consecutive runs at the same power level are combined to eliminate effects due to the ships superstructure. Continuous recording of the wind during each run is recommended.

Preferably the wave height, wave period and direction of waves due to wind and swell should be determined using instruments. Use can be made of wave buoys or instruments onboard the ships such as a wave radar and wave scanner. Although less accurate, wave observations may also be determined from observations by multiple observers, including an experienced captain, supported by hind casting if the expected effect of the seaway is significant.

Both hull and propeller are expected to be clean during the speed trial. It is the responsibility and benefit of the ship yard to make sure both are clean and smooth.

2.2 Trial Conditions

During the trial there are many conditions that deviate from the contract condition. The objective during the trial is to keep the number of influencing factors as limited as possible. Correction methods to compensate for certain deviations from the contract condition are only valid up to certain limits. In order to arrive at reliable speed trial results the boundary conditions should not exceed.

The ship’s displacement should be within 2% difference of the actual required displacement. If model test results are used for the analysis of the speed trials, the displacement of the vessel during the trials should be within 2% of the displacement used in the model tests for the trial draught.

Trim shall be maintained within very narrow limits. For the even keel condition the trim shall be less than 1.0% of the mid-ships draught. For the trimmed trial condition, the trim shall be within 3% of the trim tested at model scale and the immergence of the bulbous bow should be equal to the model test condition.

During the trial wind speeds should not be higher than:
- Beaufort 6, for vessels with a Lpp \( \geq 100 \text{ m} \), or
- Beaufort 5, for vessels with a Lpp < 100 m

The total wave height, \( H \), which is the sum of significant wave heights of sea \( H_{\text{1/3}} \) and swell \( H_{\text{s/1/3}} \), shall satisfy the following:

\[
L_{\text{pp}} > 100 \text{ m}: \text{the lower value of } H \leq 0.015 L_{\text{pp}} \text{ or maximum } 4 \text{ m.} \\
L_{\text{pp}} \leq 100 \text{ m}: H \leq 1.5 \text{ m}
\]
Where: \( H = \sqrt{H_1^{2/3} + H_2^{2/3}} \)

In addition to the above limitations, it is required that when the significant wave height \( H \) exceeds 3.0 m (for vessels with \( L_{pp} > 200 \) m), the actual wave spectrum encountered during the trial should be measured accurately i.e. the significant wave height should be known within 5%.

There are correction methods that compensate for shallow water; however it is better to avoid the corrections by the choice of the trial location. An acceptable minimum water depth for the trials where data do not need to be corrected for shallow water can be calculated using the larger of the two values obtained from these two equations.

\[ h > 3\sqrt{B \cdot T} \quad \text{and} \quad h = 2.75 \frac{V^2}{g} \]

Furthermore significant variations in the bottom contours should be avoided.

### 2.3 Trial Procedures

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

![Fig. 1: Path of the ship during trial manoeuvre](image)

Modified Williamson turns will be executed between each run to return the ship to the reciprocal baseline and to the same ground area, in which the previous run was conducted. This procedure is used to avoid the possibility of coming across different magnitudes of seawater or wind due to large changes in the geographical position of the ship. Engine throttles should not be moved during this evolution so that the ship’s machinery plant will steady out sooner. The rudder angle used in this manoeuvre should be such that ship speed and time loss will be minimized. A typical path of the ship during a trial is shown in Fig. 1.

The trial duration should be between at least 10 minutes in order to accommodate a speed/power measurement within the required accuracy. The following minimum run lengths should be observed:

- \( V_S \geq 18 \) knots \( \rightarrow \) min. trial length is 3 nm
- \( V_S < 18 \) knots \( \rightarrow \) min. trial length is 2 nm

All speed trials shall be carried out using double runs, i.e. each run should be followed by a return run in the exact opposite direction performed with the same power settings. To determine the speed-power curve for the first of a series ship, a minimum number of 4 double runs at 3 different power settings are required. These runs comprise:

- Two double runs at the same power setting near the contract power;
- Double runs at two other power settings between 65% and 100% MCR.

Double runs are performed to correct for ocean current, the average speed of a forward and return run is used as speed for the power setting. The set of two double runs is used to determine the effect of changes in tidal currents.

It is strongly recommended to carry out the speed runs with and against the dominant wave direction. Good correction methods exist for wind from different angles but not for waves. Once the heading for the trial is fixed, and the reciprocal heading for the return run, the selected tracks should be maintained very precisely throughout the trial.

### 3. Speed Trial Analysis

This section discusses two main factors in the analysis of ship speed trials, added resistance in waves and wind resistance of the ship. Also the correction for current and other correction factors will be discussed.

#### 3.1 Added Resistance in Waves

The added resistance of a ship in waves consists of two parts, motion induced resistance and reflection induced resistance, this is shown in Fig. 2. From this it can be seen that the motion induced added resistance in waves is a function of the wave length while the reflection induced added resistance in a nearly constant factor for a \( \lambda/L_{pp} \) smaller than approximately 1/2.

![Fig. 2: Added resistance in waves](image)
In the STA-JIP existing methods for calculating the added resistance in waves and widely used for wave corrections in speed trial analysis have been evaluated. For various modern ship types the added resistance computed by methods published by Fuji (1975), Nakamura (1977), Townsin (1993) and Jinkine (1974) have been compared with the results from model tests in both regular and irregular waves.

Fig. 3 and Fig. 4 respectively show this comparison for a cruise vessel and a ferry. Based on the results form this systematic comparison it was concluded that the existing methods show large discrepancies and can not be considered as reliable.

This can partly be explained by differences in hull shapes between the regarded vessels and the vessels in the database on which these calculation methods were based. It should also be noted that the ferry is just on the edge of the domain of applicability of the Townsin (1993) method. This shows the importance of being well within the limits of the Trial Conditions discussed in a previous section.

Based on model tests at MARIN’s Seakeeping and Manoeuvring Basin, two new methods have been developed to correct for added resistance in waves. One method is only based on the added resistance due to reflection and the other method is based on both the reflection part as the motion induced part of the added resistance.

The STAWAVE1 method was developed for trial conditions meaning mild waves for large ships with a high forward speed. For these conditions, the wave added resistance is dominated by wave reflection. STAWAVE1 therefore only takes into account the reflection part of the added resistance in waves. This has based on the length of the bow section of the ship and the wave height and direction. The STAWAVE2 method was developed for swell conditions and conditions where the waves are relatively long. STAWAVE2 therefore also has a wave motion induced added resistance part together with the wave reflection added resistance. For this method the input should be the wave period, height and direction as well as some ship geometry.

Fig. 3 and Fig. 4 show that the results of both new methods provide a better agreement with the model test results than the conventional methods.

Fig. 5 shows the consistency of both STAWAVE methods for different loading conditions and different speeds. Again the computational results are compared with the results from model tests in irregular waves (blue bars). This shows the STAWAVE2 method is favourable for lower speeds, where the waves become relatively longer, thus the motion induced resistance becomes a larger part. It is recommended to use the STAWAVE1 in conditions where the vessel is not heaving and pitching and STAWAVE2 in other cases.

3.2 Wind Resistance

In correcting for wind resistance there are three important aspects which have to be accounted for. First of all it is important to measure the wind correctly, thus taking account for effects of the superstructure such as shielding or over-speed. During a speed trial, the relative wind for each run is measured. Using the ship speed, the absolute wind speed and direction can be determined. If this is done for the forward and counter run, two different wind speeds and directions are determined. If these two wind vectors are then averaged as indicated in Fig. 6, the absolute wind is found.
The second issue in wind corrections is to correct for the height of the anemometer. As shown in Fig. 7, the wind speed varies significantly over the height above the water. The reference height for most wind resistance tables is 10 meters. In Fig. 7, the wind speed at 10 meters height is 16 m/s. At a height of 50 meters, this already is 20.1 m/s. Since the wind speed is to the second power in the wind added resistance, a significant error is made when no correction is done for the height of the anemometer. The correction for the height of the anemometer can be done using:

\[ V_{\text{wind}}(z) = V_{\text{wind}}(z_{\text{ref}}) \left( \frac{z_{\text{ref}}}{z} \right)^{1/7} \]  

(1)

In which \( z \) is the height of the anemometer above the water and \( z_{\text{ref}} \) is the reference height used in the wind resistance table.

3.3 Loading condition

If the loading condition during the speed trial deviates (more than 5% in displacement) from the contractual loading condition, results of the speed trial have to be converted to the contractual draft.

For this purpose use is made of model tests results for the trial draft and the contractual draft. The model tests should be conducted according to the Propulsion test Procedure recommended by the 23rd ITTC in 2002.

For both the trial draft and the contract draft the same extrapolation procedures and coefficients should be used. In case different procedures or coefficients are used these should be fully documented and justified with full scale speed-power data.

The factor of the speed trial results i.e. the power measured during the trials corrected for environmental conditions, over the power obtained from the model tests for the trial loading conditions is determined. The reference speed-power curve from the model tests at contract loading condition is then multiplied with the same factor to come to the speed trial results for contract condition.

3.4 Further Corrections

Other conditions for which corrections can be applied are:

- Small Displacement deviations
- Water depth
- Salinity of the water
- Propeller rotation rate

These corrections are relatively small compared to wind and wave corrections. Especially if the recommended practice is followed, the corrections for water depth, displacement and trim should be zero. The correction methods used will briefly be discussed.

For small deviations in the displacement the following equation can be used to correct for the measured power:

\[ \Delta P_{\text{Disp}} = \left( \frac{\sqrt[3]{z_{\text{ref}}}}{\sqrt[3]{z}} \right)^{5/3} \left( \frac{\Delta z}{\Delta z_{\text{max}}} \right)^{1/5} P_{\text{measured}} \]  

(2)

This is only valid for a maximum deviation in displacement of not more than 5% and the deviation in displacement does not lead to a different immersgence of transom or bulbous bow.

The water depth is corrected for using the method of
Lackenby (1963). This is a generally used method for the effect of shallow water on the ship speed. This is given by:

\[
\frac{\Delta V}{V_s} = 0.1242 \left( \frac{\Delta u}{h^2} - 0.05 \right) + 1 - \sqrt{\tanh \left( \frac{gh}{V_s} \right)}
\]

(3)

It is recommended however to do the speed trials at sufficient water depth to avoid the above correction.

The salinity of the water can be corrected for by the ratio of the water density of the trial and the reference condition:

\[
\Delta \rho_{\text{dens}} = \left( \frac{\rho_{\text{ref}}}{\rho_{\text{trial}}} - 1 \right) \rho_{\text{measured}}
\]

(4)

The propeller rotation rate has to be corrected for. The relation between power and rotation rate has to be the same. The formulation below corrects for this:

\[
\Delta N = \left( 0.1 \frac{\alpha \Delta P}{P_{\text{measured}}} + 0.03 \frac{\beta \Delta V}{V_{\text{measured}}} \right) N_{\text{measured}}
\]

(5)

In this \(\Delta P\) and \(\Delta V\) are the total corrections for power and speed due to all conditions mentioned above.

3.5 QSTAP Software

All above discussed corrections are programmed in the analysis software QSTAP developed within the STA-JIP. This program makes use of an input sheet which can be prepared in Excel. The measured values can be put into the sheet during the speed trial, together with the contractual conditions and some ship dimensions. After the speed trial is complete QSTAP, which produces a standard speed trial report, can be run.

In QSTAP only one choice for analysis method has to be made, this is between STAWAVE 1 or 2. STAWAVE 1 is used when no heave and pitch of the vessel are observed. STAWAVE 2 is used in the other cases. Reducing the number of choices that can be made improves the transparency of the method and the accuracy of the result.

4. In-Service Performance

From fleet comparisons it is known that the fuel consumption of sister ships on the same trade may vary up to 10%. Optimum trim, routing, speed control, autopilot and propeller pitch setting and propeller cleaning can reduce fuel bills by more than 5%. Together with leading ship owners, yards, class societies and suppliers of ship equipment, MARIN has accepted this challenge in the Service Performance Analysis JIP (SPA-JIP). In this project, the focus is on the hydromechanical side of ship performance, engine optimisations and fuel characteristics are not taken into account.

The missing link in the hydromechanical service performance monitoring of ships is the analysis, as shown in Fig. 8. Use can be made of existing control systems, sensors, display and data logging devices. A reliable performance analyses however is not available. The main goal of the SPA-JIP is to develop this analysis tool.

Fig. 8: Schedule of ship performance monitoring

Objectives of the SPA-JIP are:

- Develop a method for speed-power performance analysis for service conditions;
- Base input on available data and sensors (VDR, ER CM);
- Specify standard for performance monitoring;
- Reduce data and present meaningful results to crew in order to assist them in fuel reduction;
- Connect to existing ship-shore communication to relay data to ship owner offices for fleet comparison.

With the SPA results, participating companies will obtain a software tool for continuous performance monitoring on board their ships. The tool can be used to optimize the ship’s operation, to improve ship systems and to plan maintenance on the hull, propeller and engine room. Moreover, participating companies will derive valuable feedback for future ship and propulsion design, the so called ‘design for service’ of new ships.

Reducing the fuel consumption is reached by displaying the ship’s performance to the crew so that they can optimise the setting of the engine or the autopilot or change the trim within available limits.
5. Conclusions

From the above the following conclusions can be drawn:

- An industry standard for performing and analysing of ship speed trials is available through the results of the STA-JIP:
  - The Recommended Practice for speed trials is public and can be requested by the authors.
  - The Recommended Analysis for speed trials and analysis software QSTAP are available for STA members.
- The STAWAVE1 and STAWAVE2 method for correcting speed trials for added resistance in waves show great improvement compared to existing methods.
- Ship Performance can be improved by real time monitoring, analysing and displaying of the ship in-service performance.

6. Acknowledgements

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References


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