ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

High Speed Marine Vehicles Resistance Test

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Updated by	Approved
Resistance Committee of the 28th ITTC	28th ITTC 2017
Date 03/2017	Date 09/2017

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High Speed Marine Vehicle (HSMV) Resistance Test

1. PURPOSE OF PROCEDURE

The purpose of the procedure is to ensure consistency of methodology and the acquisition of correct results for the resistance tests of high-speed marine vehicles (HSMV). High speed marine vehicles are for this purpose defined to be vessels with a design speed corresponding to a Froude number above 0.45, and/or a speed above $3.7\nabla^{1/6}$ (m/s) (∇ in m^3) and/or where high trim angles are expected and/or for dynamically and/or aero-statically supported vessels.

There are many different types of HSMV, some of which require special test procedures. The primary focus of this procedure is on semi-displacement mono-hulls and catamarans as well as planing hulls. Where possible the procedure is kept general enough to suit a wider range of vessel types. Special problems with other types of HSMV are also considered.

2. PARAMETERS

2.1 Data Reduction Equations

Total resistance coefficient

$$C_{\mathrm{T}} = \frac{R_{\mathrm{T}}}{\frac{1}{2}\rho S_0 V^2}$$

Residuary resistance coefficient

$$C_{\mathrm{R}} = C_{\mathrm{TM}} - C_{\mathrm{FM}}\, S_{\mathrm{M}} / S_{0\mathrm{M}} - C_{\mathrm{AAM}} - C_{\mathrm{APPM}}$$

Frictional resistance coefficient – ITTC’57 model-ship correlation line

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

Air resistance coefficient

$$C_{\mathrm{AA}} = \frac{\rho_{\mathrm{A}} V_{\mathrm{A}}^2 A_{\mathrm{V}} C_{\mathrm{D}}}{\rho V^2 S}$$

Appendage resistance coefficient

$$C_{\mathrm{APP}} = \frac{R_{\mathrm{APP}}}{\frac{\rho}{2} S V^2}$$

Added resistance in waves (model scale)

$$R_{\mathrm{AWM}} = R_{\mathrm{TWM}} - R_{\mathrm{TM}}$$

Froude number

$$Fr = \frac{V}{\sqrt{g L}}$$

Depth Froude number

$$Fr_h = \frac{V}{\sqrt{gh}}$$

Reynolds number

$$Re = \frac{V L}{\nu}$$

2.2 Definition of Variables

A_{V}	Transverse section area (for air resistance) (m^2)
C_{A}	Model-ship correlation allowance
C_{AA}	Air drag coefficient
C_{APP}	Appendage resistance coefficient
$\mathrm{C_D}$	Drag coefficient
g	Gravity constant (m/s^2)
h	Depth of water (m)
k	Form factor

L	Representative length [normally L_{WL} for Fr and L_M for Re] (m)
L_M	Mean wetted length, underway (m)
L_{WL}	Length on static waterline (m)
p_{CU}	Air cushion pressure (N/m^2)
Q_{CU}	Air cushion flow rate (m^3/s)
R_T	Total resistance (horizontal force) (N)
R_F	Frictional resistance (N)
R_{AW}	Added resistance in waves (N)
R_{TW}	Total resistance in waves (N)
R_{App}	Appendage resistance (N)
S	Running wetted surface area (m^2)
S_0	Nominal wetted surface area (m^2)
S_{WW}	Average wetted surface area in waves (m^2)
t	Tank water temperature (^{0}C)
t_S	Static trim (m)
t_V	Running trim (m)
V	Speed (m/s)
V_A	Air speed (m/s)
z_V	Running sinkage (m)
θ_V	Running (dynamic) trim angle (degree)
λ	Scale ratio
∇	Moulded displacement volume of the model (m^3)
ν	Kinematic viscosity (m^2/s)
ρ	Mass density of water (kg/m^3)
ρ_A	Mass density of air (kg/m^3)

Subscript $_M$ signifies model scale value
Subscript $_S$ signifies full scale ship value
Subscript $_A$ signifies appendage value

3. DESCRIPTION OF PROCEDURE

The testing of resistance of HSMV is in many respects very similar to testing the resistance of conventional displacement ships. The main differences are related to:

- Dynamic lift and trim is more important
- Air resistance is more important and the effects of air resistance might influence the trim
- Scale effects on lifting surfaces and appendages can create problems

3.1 Model and Installation

3.1.1 Model

The model should be manufactured according to the ITTC Recommended Procedure 7.5-01-01-01 Ship Models, with particular attention being paid to model manufacturing tolerances, surface finish, appendage manufacture and the size and positioning of turbulence stimulation. It should be noted that compared with conventional displacement ship models, many HSMV*s* require special attention to minimising the model weight. This is especially the case for models that are going to be used for propulsion tests or for models to be fitted with appendages.

The model should generally be as large as possible for the size of the laboratory and the maximum speed of the towing carriage. Also the size of the propulsor(s) could determine the minimum size of a model. The geosim model tests reported in the 19th ITTC (1990) provide guidance on the likely practical limiting features of model size. In addition to what is stated in ITTC Recommended Procedure 7.5-01-01-01, Ship Models, it is recommended that the model be equipped with a superstructure with the same basic shape and main dimensions as that of the ship. The purpose and alternatives to the use of a superstructure are discussed in Section 4.1. Adequate grid reference lines must be applied to the model for estimating the dynamic wetted area.

The application of a boundary layer turbulence stimulation is recommended when the Reynolds number is less than 5×10^6 based on mean or effective wetted length. For models tested solely at higher Reynolds numbers, turbulence stimulation might be omitted. Refer to ITTC Recommended Procedure 7.5-01-01-01 Ship Models for a description of alternative means of turbulence stimulation. The use of trip wires is not recommended on high speed models due to the risk of air suction. Sand strips are the preferred method of turbulence stimulation for long slender hulls, such as high speed catamarans. For vessels with significant change in running attitude with speed, great care must be taken in the placement of the turbulence stimulation. Test runs must be carried out if there are doubts about the placement.

The resistance of appendages is often an important and difficult question for HSMVs. This question is discussed in more detail in Section 4.2, but the following basic approximate rule is offered: Appendages not used for producing lift or altering the trim could be left off the model and the computed resistance of these appendages added in the extrapolation to full scale. Appendages required for the propulsion test (if such a test is to be carried out) must be present. For small models it is advisable to leave out appendages following the above rule in order to avoid problems with laminar separation. For large models it can be beneficial to include appendages, at least the ones located in the wake affected area in the aft part of the model. Turbulence stimulation is recommended for appendages protruding out of the boundary layer of the model.

The size of HSMV appendages is often too small to obtain a Reynolds number of 5×10^6. In such cases, turbulence stimulation on the appendages might be a reasonable solution.

3.1.2 Installation

The application of the tow force should be such that it resembles the direction of the propulsion force as closely as possible. This is to avoid artificial trim effects due to the tow force. The preferred way of doing this is to tow in the elongation and the direction of the propeller shaft. If this cannot be accomplished, then the artificial trim moments introduced by the towing should be corrected for by an appropriate shift in the LCG. An alternative is to test the model fixed to the carriage in a range of different heave and trim values, as described in more detail in Section 4.6.

The resistance is taken as the horizontal component of the applied tow force.

Guides may be fitted to prevent the model from yawing or swaying: these should not restrain the model in any other direction of movement, nor be able to impose any force or moment on the model which would cause it to roll or heel. The arrangement of any such guides that include sliding or rolling contacts should introduce the least possible friction forces. The model should be positioned in a way that it is in the centreline of the tank and parallel to the tank walls.

If any instruments carried in the model are linked to the carriage by flexible cables, great care should be taken to ensure that the cables do not impose any force on the model in the running condition; in practice the cables should therefore hang vertically from the carriage. Care should also be taken to balance any instruments that must have attachments to both the model and the carriage (e.g. mechanical trim recorders).

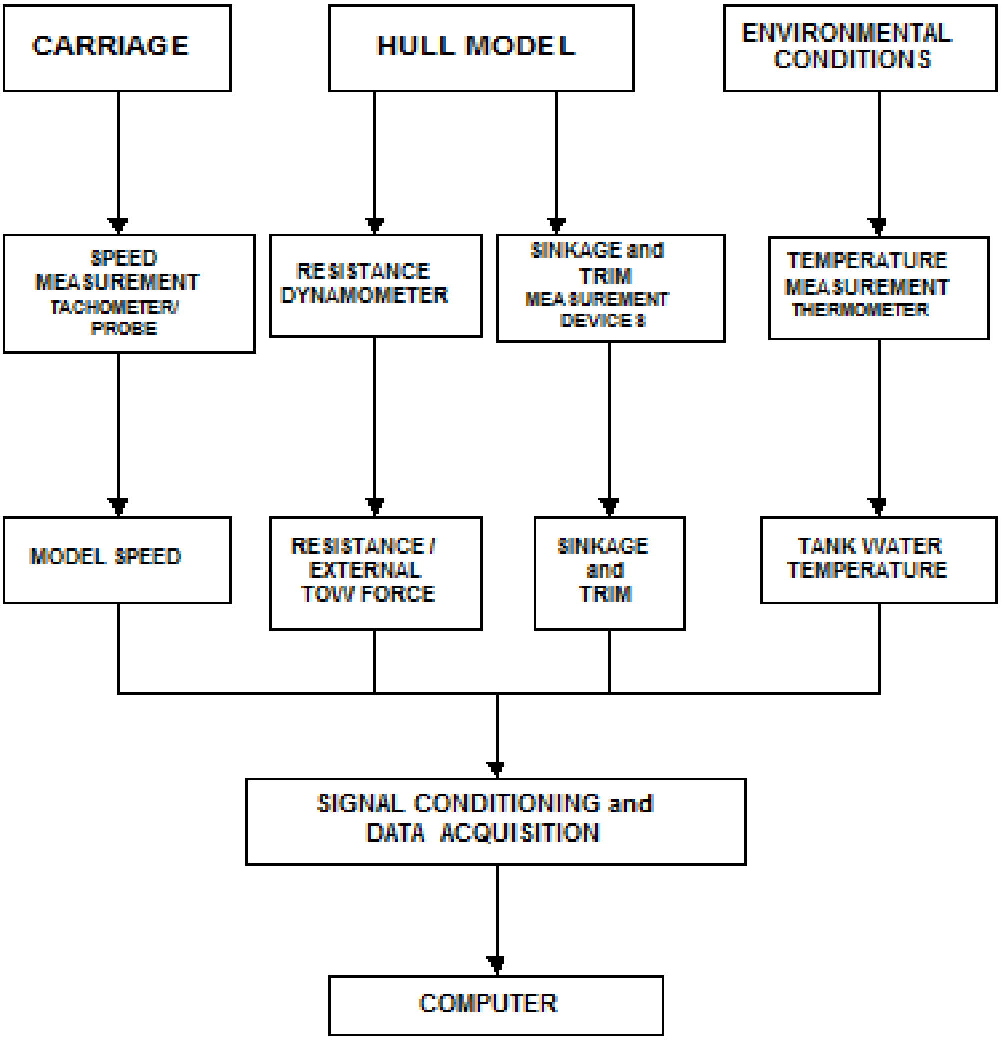

Figure 1 Typical measurement system

3.2 Measurement Systems

Figure 1 shows a typical measurement system. The following quantities are measured:

- Model speed
- Total resistance
- Sinkage fore and aft (or running trim and sinkage)
- Water temperature (for calculation of viscosity)
- Dynamic wetted surface area (for models with significant change in wetted area)
- Air cushion pressure (for models with air cushion)
- Air flow rate (for models with air cushion)

3.3 Instrumentation

The quoted bias accuracies are for indicative purposes only. Uncertainty analysis should be used to derive actual requirements. Dynamic wetted surface area estimation is covered in Section 4.1.

3.3.1 Resistance

The resistance dynamometer should measure the horizontal tow force to within 0.2% of its maximum load or 0.05 N, whichever is the larger. This does not necessarily imply that the resistance itself is measured within the same tolerance of its true value.

3.3.2 Speed

Ideally the speed of the model through the water should be measured directly throughout the measuring run. Since this is in general impractical, one of the following two methods may be employed:

I. the speed of the towing carriage relative to the ground should be measured. This may be measured using a trailing wheel with encoder or similar, direct from the carriage drive, using optical/proximity sensors with a counter/timer, or by another appropriate method.
II. the speed of the towing carriage relative to the water should be measured by a flowmeter far in front of the model. In this case the flowmeter wake and waves should be minimised.

The speed of the model should be measured to within 0.1% of the maximum speed or within 3 mm/sec, whichever is the larger.

3.3.3 Sinkage and trim

Sinkage fore and aft may be measured with mechanical guides, potentiometers, encoders, LDVTs or with remote (laser or ultrasonic) distance meters; the running trim is then calculated from the measured running sinkage fore and aft. Alternatively, the running trim may be measured directly using an angular measuring device with the measurement of the sinkage at one point.

The sinkage should be measured to within 1.0 mm. If the trim is measured directly, rather than deduced from a measurement of sinkage fore and aft, it should be measured to an accuracy of 0.1 deg.

3.3.4 Temperature

The water temperature should be measured at a depth near half of the model draught using a thermometer.

3.3.5 Air cushion pressure

The air cushion pressure (if measured) should be measured with an accuracy of 1% of the average (designed) air cushion pressure.

3.3.6 Air cushion flow rate

The air cushion flow rate should be detectable to within 10% of the mean (design) air flow rate. The air cushion flow rate is often determined by the use of a calibration diagram on the measured pressure and fan speed.

3.4 Calibration

3.4.1 General remarks

All devices used for data acquisition should be calibrated regularly. For calibration, the measured quantities should be either substituted by calibrated weights and pulses or checked by already calibrated other measuring devices. The range of the calibration should include at least the range of values to be measured in the experiment. Calibration diagrams, where the measured quantities (output values) are plotted versus the calibration units (input units), may be useful to check the calibration itself as well as the linearity of the instruments. Calibration should generally be in accordance with ITTC Recommended Procedure 7.6-01-01.

The calibrations of the resistance dynamometer and the sinkage and/or trim sensors should be checked immediately prior to the testing. The calibrations should preferably include as much of the measurement chain as possible (e.g. amplifier, filter, A/D converter). If the check indicates that the required accuracies cannot be met, the calibration should be renewed or the instrument replaced and the check repeated. Daily checking of a pulse counter type speed measurement device is usually not required. Instead, the check on this device is covered by calibrations carried out at regular intervals.

Where the gravitational constant *g* is used in calculations, the value chosen should be appropriate to the location of the tank.

3.4.2 Resistance dynamometer

The calibration of the resistance dynamometer should be carried out by the use of calibrated weights as an input to the instrument.

3.4.3 Sinkage and trim transducers

The calibration of linear measuring devices should be performed with a calibrated ruler or other appropriately calibrated device such as a length bar or Vernier height gauge. Angular measuring devices should be calibrated against an accurate angular scale.

3.4.4 Air cushion pressure

The air pressure sensor should be calibrated against a well-known pressure, either by use of another pressure sensor that is already calibrated, or against a known height of water column (a mercury column can be used, but it is then harder to obtain an accurate reading).

3.4.5 Air cushion flow rate

If the air flow rate in the experiment is going to be found from measurement of cushion pressure and fan rotational speed, then calibration curves for the fan(s) must be determined as part of the calibration. A calibrated flow rate meter is needed, or a Venturi meter or orifice type instrument must be constructed. The fan is then run at different rotational speeds and the delivered pressure must be varied using a variable aperture or some other method. The delivered flow rate is measured for each combination of backpressure and fan rate of revolutions. Two-variable calibration curves may then be constructed. The rotational speed sensor on the fan should be calibrated, for instance using a pulse counter with verified accuracy.

3.4.6 Speed

The calibration of the carriage speed will depend mainly on how the carriage speed is measured. The carriage speed should be checked regularly and respective records should be stored.

Where possible the carriage speed measured with the primary speed measurement system should be checked with an alternative measurement system.

3.4.7 Thermometer

Thermometers should be calibrated according to common standards and/or following the advice of the manufacturer and should be accurate to within 0.1° C.

3.4.8 Signal conditioning and data acquisition system

The various components of the signal conditioning and data acquisition system (e.g.

amplifies, filters, A/D converters) should be checked and calibrated according to the manufacturers recommended schedule. Key features of the system, such as cut-off frequencies of filters employed, and resolution and sampling rate of A/D converters should be recorded.

3.5 Test Procedure & Data Acquisition

3.5.1 Method

Before each run begins zero readings of all instruments must be taken, over a period long enough to give a representative mean value.

The model is towed at speeds giving the same Froude numbers as for the full scale ship.

The model speed is selected and the model accelerated to that speed.

It is important to minimise “overshoot” of speed, since this will result in waves overtaking the model.

If the model has been held during initial acceleration, it is released as soon as the selected speed has been reached.

It is recommended that the data acquisition may either begin after a steady speed has been reached; or, alternatively, data acquisition may take place continuously from the time at which the zero readings are logged (in order to allow the entire speed profile to be determined).

The mean values are derived afterwards from a section of the time series during which the speed was steady. In some cases unsteady oscillations (related to unsteady wave resistance effects) may be observed in the measurements even when the model speed is constant. Where these oscillations have a significant magnitude, it is important to calculate the mean values of parameters of interest over an integer number of oscillation cycles; where possible, it is desirable to use at least five oscillations to find the mean. Note that the frequency of these oscillations in an unbounded fluid may be estimated as:

$$f = 8\pi V / g\left(Hz\right)$$

Maximum and minimum values together with mean and standard deviations should be stored for each run.

This process is repeated at other selected speeds covering the required speed range, avoiding continuous progression from one limit to the other. For example, runs at alternate speeds from the lowest speed to the highest followed by the highest speed to the lowest filling in the gaps.

There should be sufficient waiting time between consecutive runs to achieve similar conditions for each of the runs and to obtain consistency in results. This waiting time will depend on the size and type of model, model speed and test facility. The waiting time should be recorded.

In some cases it may be necessary to shift the LCG of the model to correct for artificial trim effects from resistance components that influence the trim but do not follow Froude’s scaling laws. Examples of such resistance are air resistance, appendage resistance and viscous resistance, when the propulsion force is applied far from the centre of viscous resistance, such as for a vessel to be propelled by air propellers. When the tow-point is not in the extension of the propulsor line of thrust, it is then also necessary to shift the LCG for the trim effect of the total model resistance.

An alternative approach to correct for artificial trim effects would be to apply the towing force in such a way that its lever also produces the correct longitudinal trimming moment.

3.5.2 Range and interval

The speed range should extend from at least 5% below the lowest speed at which reliable data is required to at least 5% above the highest speed required. This range should be covered by a suitable number of speeds. Care should be taken to ensure that there is sufficient number of speeds to define humps or hollows and other rapidly changing features of the curve.

3.5.3 Speed

The following aspects should be noted when measuring speed:

- Attention should be paid to residual currents in the towing tank near the surface, which are caused by previous tests. It is not unusual to exclude the first run of the day if no active artificial circulating device is available. This has however not always shown to be necessary and can be investigated with an uncertainty analysis. For more information see General Guidelines for Uncertainty Analysis in Resistance Tests, provided in QM 7.5-02-02-02.
- It is essential that the speed of the model through the water should be constant throughout, and for a significant distance before, that part of the time series used for the calculation of the mean values of the parameters of interest.
- Steadiness of the carriage speed is an essential element in achieving a steady model speed, but it is not necessarily sufficient since the rate of change of the initial acceleration and the moment and manner of release of the model may interact with the model-dynamometer system and cause it to oscillate.
- During the measuring run, the carriage speed should normally not vary by more than 0.1% of the mean speed or 3 mm/s, whichever is the larger. The cyclic characteristics of the carriage speed control system should be such as not to synchronise with the natural frequency of the model dynamometer system.

3.5.4 Measured quantities

During each run, the measured values of speed, resistance, sinkage and trim should be recorded continuously. Quantities used to establish wetted surface should be established as an average for the run.

The sampling rate shall be selected following Nyquist requirements and taking into account low pass filtering to minimize the effects of aliasing.

Water temperature should be measured at a depth near half of the model draught. If there is a non-homogeneous temperature in the tank it should be recorded. Temperature measurements should be recorded at the beginning and end of each test sequence or at least on a daily basis.

3.6 Data Reduction and Analysis

The speed, resistance, sinkage and trim and any other continuously recorded quantities of the test should be presented as mean values derived from an integration of the instantaneous measured values over the same measuring interval (chosen according to the guidelines in Sections 3.5.1 and 3.5.2), with the appropriately averaged zero measurements subtracted from the average values.

Running wetted surface is normally derived from underwater or above-water photographs, video recordings, paint smear techniques or from visual observations during the test runs as described in Section 4.3.

Total resistance and residual resistance coefficients, together with Froude number, are calculated for each speed using the data reduction equations given in Section 2.1.

3.6.1 Analysis of model scale results

Resistance R_{TM} measured in the resistance tests is expressed in the non-dimensional form

$$C_{\mathrm{TM}} = \frac{R_{\mathrm{TM}}}{\frac{1}{2}\rho_{\mathrm{M}} S_{0\mathrm{M}} V_{\mathrm{M}}^2}$$

It should be noted that the observed running wetted surface area will normally be used for HSMVs, see Section 4.3. It is however practical to use a constant value of wetted surface for non-dimensionalisation, so in the formula above, S_0 is a nominal wetted surface, for instance the value for zero speed, while S is used as symbol for the running wetted surface. The speed should, if necessary, be corrected for blockage by methods such as those described in Section 4.5. Values of water density and viscosity should be determined according to ITTC Recommended Procedure 7.5-02-01-03.

The residuary resistance coefficient C_{R} is calculated without the use of a form factor k (see Section 3.6.3):

$$C_{\mathrm{R}} = C_{\mathrm{TM}} - C_{\mathrm{FM}}\, S_{\mathrm{M}} / S_{0\mathrm{M}} - C_{\mathrm{AAM}} - C_{\mathrm{APPM}}$$

where C_{FM} is derived from the ITTC1957 correlation line for the model, C_{AAM} is the model wind resistance coefficient, and C_{APPM} is the model appendage resistance coefficient (if appendages are present and their resistance scaled separately). C_{APPM} can be found by calculation or from the difference in resistance by testing with and without appendages.

The C_{R} or C_{T} curve is the best basis for judging if a sufficient number of test points have been obtained in order to define humps and hollows. The model resistance curve should be faired in order to facilitate reliable interpolation to obtain the resistance at the required speeds. The smoothing should be carried out with care in order not to remove humps and hollows. An acceptance criterion for the test might be derived based on the scatter in the C_{R} or C_{T} curve.

3.6.2 Extrapolation to full scale

The proposed extrapolation method requires an established model - ship correlation for each type of HSMV. It is not possible to give general guidance to what this correlation factor should be, but is left instead to each facility to establish its own correlation factor. The extrapolation method adopted should be documented clearly in the test report.

The total resistance coefficient of a HSMV is

$$C_{\mathrm{TS}} = C_{\mathrm{R}} + C_{\mathrm{FS}}\, S_{\mathrm{S}} / S_{0\mathrm{S}} + C_{\mathrm{AAS}} + C_{\mathrm{APPS}} + C_{\mathrm{A}}$$

where

- C_{FS} is the frictional resistance coefficient of the ship according to the ITTC-1957 model-ship correlation line.
- C_{R} is the residual resistance coefficient obtained by the analysis of the model test results.
- C_{AA}, is the air resistance coefficient

$$C_{\mathrm{AA}} = \frac{\rho_{\mathrm{A}} V_{\mathrm{A}}^2 A_{\mathrm{V}} C_{\mathrm{D}}}{\rho V^2 S_0}$$

The equation for air resistance coefficient C_{AA} is used for both model (C_{AAM}) and full scale (C_{AAS}). For model scale the wind velocity V_{A}

might be different from the through water velocity V due to carriage displacement effects. In addition, the wind area A_V and the drag coefficient C_D might be different in model and full scale. However, if $V_A=V$, and A_V and C_D are considered to be equal in model and full scale, then the wind resistance might be left out of the extrapolation process.

- C_{APPS} is the appendage resistance coefficient of the ship. It can be found by calculations, using the same method as for finding C_{APPM} but at full scale *Re*. If C_{APPM} is determined by testing with and without appendages, then C_{APPS} should be obtained from extrapolation of C_{APPM} using an acceptable friction line.
- C_A is the model-ship correlation allowance.

The full scale ship resistance is then

$$R_{TS} = \tfrac{1}{2}\,\rho_S V_S^2\, S_{0S}\; C_{TS}$$

Further details on the extrapolation process from model to full scale can be found in Recommended Procedure 7.5-02-03-01.4 1978 ITTC Performance Prediction Method.

The following specific considerations can be made for small waterplane area twin hulled craft (SWATH), hydrofoils, surface effect ships (SES), and air cushion vehicles (ACV).

Small Waterplane Area Twin Hull (SWATH) – Separate friction coefficients are determined for the struts and submerged hulls based on the Reynolds number of each component. Depending on the hull shape, it might be appropriate to use individual form factor values for the struts and submerged hulls when extrapolating resistance to full scale. Form factors for cylindrical hulls, struts and control surfaces have been derived using theoretical and experimental methods (Granville, 1976) which may be used if no other source is available. Correlation allowances for SWATHs have been proposed over a wide range from 0.0000 to 0.0005.

Hydrofoils – For hydrofoils, the hull resistance should be analysed like the resistance of an ordinary HSMV without foils. The foil system resistance should be computed for full scale Reynolds number, or extrapolated from tests at a Reynolds number high enough to ensure fully turbulent flow. It is strongly advised that the foil system resistance be measured during the towing tests, as the uncertainty regarding the extent of turbulent flow on the foils in model scale will make it difficult to calculate the drag in model scale. If the hull is of a type for which a correlation is available, the hull resistance can be corrected with the applicable correlation coefficient, while the foil system drag should be added without a correction for correlation.

For high speed cavitating hydrofoils moving under free water surface the cavitation number is expressed in terms of Froude number, the submergence depth of the hydrofoil from free surface and the dynamic pressure. The cavitation number is therefore not a new parameter that affects the performance of cavitating hydrofoil as given by Bal (2007).

Surface Effect Ships (SES) – For SES craft, it is common practice to estimate the resistance components caused by hull friction and aerodynamic forces and then deduce the residual resistance, which includes the friction and induced drag of the seals. For calculating the friction resistance it is recommended that a Reynolds number based on the length of the wetted sidewall is used. Underwater or inside cushion photography is recommended for estimating the wetted surface area of the inner sidewalls. The aerodynamic resistance is best estimated from wind tunnel tests. Alternatively, the air resistance can be determined by towing the model slightly above the water surface. The air drag coefficients are taken to be the same in model and full scale. Testing with a superstructure covering the entire model is recommended in order to model the important trim effect of the air lift and drag. Air momentum drag, from the air supply to the cushion, should also be considered.

Air Cushion Vehicles (ACV) – It is common practice to apply Froude scaling laws for all of the resistance measured on an ACV model except for that of fully wetted appendages. Stevens and Prokhorov (Savitsky et al., 1981) defended this approach with the premise that the unrealistically high friction resistance of the model's wetted skirt would be partially offset by lower spray resistance of the model. It is recommended that fully wetted appendages should be treated the same as for other HSMVs.

3.6.3 Form factor

The use of the 1978 powering performance procedure implies the use of a form factor *k*. Particular problems arise with estimates of (1+*k*) for HSMVs as low speed tests are not normally reliable or sufficient. Many HSMVs employ transom sterns, leading to a confused flow aft of the transom at low speeds and wetted surface area generally changes with speed, resulting in a change in true (1+*k*) with speed. For this reason it is currently recommended that, for consistency and for the time being, form factors for HSMVs with transom sterns continue to be assumed (1+*k*) = 1.0. Exceptions can be made for SWATHs, which are often not considered high speed ships and do not have transom sterns, thus form factors can be calculated using the accepted method.

3.7 Documentation

The results from the test should be collated in a report which should contain at least the following information:

- Model specification:
    - Identification (model number or similar)
    - Loading condition
    - Turbulence stimulation method
    - Model scale
    - Main dimensions and hydrostatics, included static wetted surface area (see recommendations of ITTC Recommended Procedure 7.5-01-01-01 Ship Models)
- Particulars of the towing tank including length, breadth and water depth, together with the method of towing the model, position and angle of towing force.
- Test date
- Parametric data for the test:
    - Water temperature
    - Water density
    - Kinematic viscosity of the water
    - Form factor (even if (1+k)=1.0 is applied, this should be stated)
    - Friction correlation line
    - Model-ship correlation allowance
    - Air resistance coefficients for model and full scale
- For each speed, as a minimum, the following data should be given:
    - Resistance of the model
    - Sinkage fore and aft, or sinkage and trim
    - Dynamic wetted surface area (if considered)
    - Air cushion pressure (if applicable)
    - Air cushion flow rate (if applicable)

4. SPECIAL CONSIDERATIONS

4.1 Air Resistance

This is an important area to address for the testing of HSMVs. However, given the differences in physical characteristics of each facility it is not possible to propose a particular testing method that will provide identical results in each facility. Factors such as the size of the carriage and permeability of its structure are difficult to quantify but can significantly affect the flow of air around the model as the carriage travels down the tank.

The speed at which air resistance becomes significant varies with the vehicle type. If it is decided that air resistance is insignificant for a particular HSMV model test, the justification for that decision should be documented in the test report.

When air resistance is considered to be significant, wind tunnel tests provide the best source of information for the superstructure since the model can be tested at higher Reynolds numbers.

Before making air resistance corrections for the model hull it is important to measure the actual airspeed beneath the carriage in the area the model will be tested. These measurements can be made without the model in place if the model cross section is small compared with the cross section of the air space housing the tank. Air speed measurements should be made over the speed range of interest with the carriage configured as it will be when tests are conducted. The air speed measurements and physical features of the above-water portion of the model should be well documented in the test report so that users of the test data can make their own estimates of air effects if they wish. When estimates of air resistance are made by staff members at the test facility, the method used, including details such as frontal cross section area and drag coefficient should be documented in the test report. Drag coefficients typically range from 0.3 - 1.0. Since HSMVs such as planing boats are extremely sensitive to trim, estimates of the effects of aerodynamic forces on trim should be made and documented in the same manner as for air resistance.

The recommended method of accounting for aerodynamic effects on trim, which are not properly taken into account on the model, is to calculate the difference in bow-up or bow-down moment between the model and full-scale vehicle by assuming centres of aerodynamic pressure and hydrodynamic pressure. These forces are then balanced against the towing force and the resulting moment converted to an effective shift in longitudinal centre of gravity.

4.2 Appendage Effects

It is important to make adequate corrections for appendage effects on HSMV model test results. The following methods are commonly used to account for appendage effects:

i. Testing the bare hull and then separately accounting for the lift and drag of individual components using analytical methods. This method doesn’t account for hull-appendage interaction effects, and should only be used in cases where only a very small model can be tested.

ii. Testing the hull with and without appendages and extrapolating the values based on the local Reynolds number of each component.

iii. A less time-consuming, but also less accurate method is to test the hull with appendages only, and then to calculate the scale effect of the appendages (C_{AppM} - C_{AppS}) by considering the local *Re* of each appendage.

Testing both with and without appendages has the advantage of providing more information for extrapolating the test data using different methods. Trim moments caused by appendage forces not correctly represented in the experiment should be accounted for using equivalent shifts in centre of gravity location and displacement. If these corrections are made after the tests are completed, the results can be obtained by interpolating between results from tests with different centre of gravity locations. A method for setting up test programmes with the intent of making corrections at a later time was proposed by Hoyt and Dipper (1989).

HSMVs with lift-producing appendages have the added complication of Reynolds number effects on lift. One approach for addressing scale effects of lift-producing appendages is to modify the section shape or angle of attack of the model appendages so that the lift characteristics of the model appendages better represent those of the full-scale vehicle. Another way of dealing with the problem is to adjust the amount of ballast in the model to account for the scale effect on lift, but then one must remember also to correct for error introduced to the induced drag.

Further, for lift-producing appendages, there is the choice of either testing with the appendages, correcting for scale effects on lift and drag, or testing without appendages and to correct for the computed (or separately tested) lift and drag of the appendages. When a hydrofoil vessel is tested without the main hydrofoil system it will usually be most practical to test the hull fixed in heave and pitch at a range of draughts and trims, measuring the forces in the vertical plane in addition to the resistance. When calculating the combined resistance of hull and foils it is then required to interpolate the results to get the hull resistance at the draught and trim that matches the computed (or tested) lift and drag of the foil system. A more thorough discussion of this is given in the report of the Committee for Testing of HSMV of the 22nd ITTC (1999).

4.3 Wetted Area Estimation

In cases where the wetted surface area varies significantly with speed, which is quite frequent with HSMVs, the running wetted surface area (WSA) should be estimated for each different speed. Possible methods include:

- visual observations from outside the model
- visual observations from inside the model
- above water photography or video
- underwater photography or video
- insoluble paint techniques
- water soluble paint techniques
- electrical wetting probes

Surface tension may have an effect on WSA, as discussed in some detail in the proceedings of the 18th ITTC (1987). Surface tension leads to a different form of spray between model and full scale, the model spray appearing like a sheet of water rather than droplets as at full scale. For this reason, separation of the spray sheet at model scale is delayed and the WSA tends to become relatively larger with decreasing model size and model speed. Minimisation of scale effects due to surface tension can be achieved by using larger models, higher speeds, and the fitting of model spray rails which correctly simulate full scale rails and which can aid to the correct determination of WSA.

When making estimates of WSA and wetted length, a distinction is made between the area covered by spray and that covered by solid water. It is common practice to disregard the viscous drag of spray-covered areas and to account for only the viscous drag of the area wetted by solid flow. This practice is questionable but the flow in the spray region is extremely complex and no alternative practices are known.

For SWATHs it is standard practice to measure wetted area separately for the hulls and struts. The appropriate Reynolds number is later used to analyse the viscous resistance of each component separately. This procedure is also used for trimarans, where the length of the side hulls is different from that of the main hull.

Based on the need for higher accuracy and representation of the correct physics, it is recommended that running WSA should be used for HSMVs instead of static WSA. Any one of the measurement methods listed may give good results depending on the vehicle type and test facility characteristics, but the method of measurement and likely level of accuracy should be described and defined in test reports.

4.4 Spray Resistance

At present there is no accepted method available to account for scale effects in resistance attributable to spray.

4.5 Blockage

Blockage was addressed for different types of HSMVs by Savitsky et al., Müller-Graf and others, and these are summarised as follows:

For planing hulls, Savitsky et al. (1981) stated that wall effects are believed to be minimal if the tank width is at least seven times the model beam. For semi-displacement hulls and hydrofoils, Müller-Graf (1987) stated that tank depth should be greater than 0.8 times the model length and the tank width should be greater than two times the model length.

For SWATHs, the blockage correction for conventional ships can be used at Froude numbers below 0.35. At higher speeds, blockage effects can be estimated using three dimensional wave resistance calculations for the situation with the model in a tank.

For SES and ACVs blockage effects might be calculated using simple numerical methods like those summarised by Doctors (1992).

For displacement and semi-displacement ships, two-dimensional wave resistance calculations might be applied. Relatively simple computer programs for blockage and shallow water corrections based on thin-ship theory by Lunde (1951) have been found useful for this purpose.

For high speed cavitating submerged or surface piercing hydrofoils the blockage effects can be calculated using iterative panel methods as given by Bal (2008, 2011).

4.6 Captive Resistance Tests

In some cases the standard way of connecting the model to the carriage is not the best for HSMV. Some alternative test set-ups are described below.

4.6.1 Fully captured force measurements and simulation

The method is made up of force measurements on a fully or partly captured model and a computer simulation using the database of the measured hydrodynamic forces. In this method, any additional forces acting on appendages and scale effects can be taken into account. Hydrodynamic forces (drag, lift, and trim moment) acting on a fully captured model, are measured by systematically changing trim, sinkage (negative), and speed. By solving the equilibrium equation of forces using the measured data, running attitudes and resistance of a craft can be obtained. Multi-component load cells are used to measure the forces.

Extrapolation to full scale is carried out in the same way as for ordinarily towed models. The effect of appendages can be obtained by a summation of hydrodynamic forces in the equilibrium equation. This method can easily cope with design changes, such as the location of the centre of gravity, appendages and thrust force direction. The disadvantage of the method is that the hydrodynamic force measurements are time-consuming compared with a conventional resistance test. Also, investigations of porpoising and chine walking are precluded.

It is noted that any standing waves in the towing tank should be reduced as much as possible since they affect the lift force directly. It is also more important to have well-aligned rails and a smooth running carriage for this method than for towing a model free to heave and trim. Typical practical methods together with results are described by Ikeda (1992), Ikeda et al. (1993), Yokomizo and Ikeda (1992), and Katayama and Ikeda (1995, 1996) for planing craft and by Minsaas (1993) for fully submerged hydrofoils.

4.6.2 Partially captured force measurements

To avoid the effect of water surface fluctuation on lift force, hydrodynamic force measurements in the free-to-heave condition have been developed. Using the measured drag and moment, an equilibrium equation of two forces is solved to provide the running attitude and resistance of a fast craft. A variation of this method, which is used in cases where the trim of the ship is going to be controlled, for instance by a forward lifting foil system, the model is fixed in the required trim without the need for any iterations. The required control system force is then easily determined from the trim moment measurement.

4.6.3 Automatic attitude control

A more sophisticated experimental method has been developed on the basis of the same philosophies. The experimental apparatus is composed of a force measurement system, a system for solving the equilibrium equation of the forces by a computer in real time and a system for continuously changing the running attitude of the model, for instance by stepping motors. Forces acting on a model craft are measured and its attitude changed using these values to satisfy the equilibrium of forces. Additional forces acting on appendages and any predictable scale effects can be taken into account in the calculation.

4.7 Added Resistance in Waves

4.7.1 Speed & connection to carriage

To measure the added resistance in waves, it is important that the application point and direction of the tow force resemble the propulsor thrust as closely as possible, so that artificial pitching moments are not introduced. The resistance is taken as the horizontal component of the towing force, as in calm water.

An important point to consider is whether to keep the model speed constant (by having a fairly inelastic towing connection to the carriage), or to allow for surge motions relative to the carriage. Alternatives to constant speed are constant force (speed will be the result, and added resistance found from interpolation of the calm water resistance curve), or “semi-constant” force. The simplest way of getting a “semi-constant” force is to use a fairly soft spring in the towing connection. Spring stiffness must be selected to avoid resonance in surge, and to avoid overloading of the spring. A more advanced way is to use a computer controlled winch (or servo), or a feedback control of the carriage speed, to get a specified relation between towing force (resembling propeller thrust) and speed. Constant force can be obtained by using a weight, string and pulley system, although the inertia of the weight is a source of error.

What towing method to choose depends on the purpose of measuring the added resistance, as well as the type of ship, and sea state.

4.7.2 Waves

By testing in regular waves of different length, one might calculate the full scale added power or speed loss using for instance the method outlined in ITTC Recommended Procedure 7.5-02-03-01.5.

By testing in irregular waves, the added resistance in that particular sea state is found directly. Added power is then found by use of a propulsive efficiency. For small and moderate sea states, the propulsive efficiency might be taken as the value found in calm water. For higher sea states, propulsive efficiency had better be determined by self-propulsion tests in waves.

4.7.3 Calculating the added resistance

The added resistance in model scale is calculated as:

$$R_{\mathrm{AWM}} = R_{\mathrm{TWM}} - R_{\mathrm{TM}}$$

where R_{TMW} is the total resistance measured in waves. Note that the calm water resistance of the model R_{TM} should be measured with exactly the same set-up and connections as for the tests in waves.

Usually, the added resistance is scaled according to Froudes similarity law:

$$R_{\mathrm{AWS}} = R_{\mathrm{AWM}}\ \lambda^3\ \rho_{\mathrm{S}} / \rho_{\mathrm{M}}$$

For this to be strictly valid, there shall be no increase in frictional resistance due to waves. There is usually a change in wetted surface when running in waves, but this change is very time-consuming to determine with accuracy. However, if the wetted surface in waves can be determined, a better scaling relation for added resistance in waves is:

$$R_{\mathrm{AWS}} = \left(R_{\mathrm{TWM}} - R_{\mathrm{TM}} - R_{\mathrm{FM}}\left(\mathrm{S}_{\mathrm{WWM}} / S_{\mathrm{M}} - 1\right)\right)\lambda^3$$
$$\rho_{\mathrm{S}} / \rho_{\mathrm{M}} + R_{\mathrm{FS}}\left(S_{\mathrm{WWM}} / S_{\mathrm{M}} - 1\right)$$

where R_{F} is the frictional resistance and S_{WW} is the wetted surface in waves. Froude scaling the added resistance will over predict the full scale added resistance.

5. VALIDATION

5.1 Uncertainty Analysis

Uncertainty analysis should be performed in accordance with the ‘Guide to the Expression of Uncertainty Analysis in Experimental Hydrodynamics’ 7.5-02-01-01 and ‘General Guidelines for Uncertainty Analysis in Resistance Tests’ 7.5-02-02-02.

5.2 Benchmark Tests

Benchmark data are collected and described in ‘Benchmark Database for CFD, Validation for Resistance and Propulsion’, 7.5-03-02-02.

See also the following reference: Summary and Conclusions of Co-operative Model Resistance Experiments (19th ITTC 1990 pp. 329-332), (1) Hard Chine BTTP Model, (2) Semi-Displacement Geosim Models in Japanese Towing Tanks (11-1) Resistance Tests (19th ITTC 1990 pp.360-365).

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