INTERNATIONAL TOWING TANK CONFERENCE

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Updated by	Approved
Specialist Committee: Procedures for Resistance, Propulsion and Propeller Open Water Tests of 23rd ITTC 2002	23rd ITTC 2002
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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) and/or where high trim angles are expected or for dynamically supported vessels.

2 PARAMETERS

2.1 Data Reduction Equations

Total resistance Coefficient $C_{\mathrm{T}} = \dfrac{R_{\mathrm{T}}}{\frac{1}{2}\rho S V^2}$

Residual Resistance Coefficient

$$C_{\mathrm{R}} = C_{\mathrm{TM}} - C_{\mathrm{FM}} - C_{\mathrm{AAM}} - C_{\mathrm{AppM}}$$

Frictional Resistance Coefficient-
ITTC Model-Ship Correlation Line

$$C_F = \frac{0.075}{(\log_{10} Re - 2)}$$

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

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

Froude Number $Fr = \dfrac{V}{\sqrt{g L}}$

Depth Froude Number $Fr_h = \dfrac{V}{\sqrt{gh}}$

Reynolds number $Re = \dfrac{V L}{\nu}$

2.2 Definition of Variables

Total resistance	(N)	R_{T}
Appendage resistance	(N)	R_{App}
Speed	(m/s)	V
Air Speed	(m/s)	V_{A}
Running sinkage	(m)	z_V
Static trim	(m)	t_{S}
Running trim	(m)	t_V
Running (dynamic) trim angle	(°)	θ_V
Length on static waterline	(m)	L_{WL}
Mean wetted length, underway	(m)	L_{M}
Representative length [Normally L_{WL} for Fr and L_M for Re]	(m)	L
Tank water temperature	(^{0}C)	t
Depth of water	(m)	h
Wetted surface area (dynamic or static)	(m^2)	S

Air cushion pressure	(N/m^2)	Pc
Air cushion flow rate	(m^3/s)	Qc
Moulded displacement volume of the model	(m^3)	∇
Transverse section area (for air resistance)	(m^2)	A_V
Model-ship correlation allowance	(-)	C_A
Air drag coefficient	(-)	C_D
Scale ratio	(-)	λ
Form factor	(-)	$(1+k)$
Gravity constant	(m/s^2)	g
Mass density of water	(kg/m^3)	ρ
Mass density of air	(kg/m^3)	ρ_A
Kinematic viscosity	(m^2/s)	ν

Subscript M signifies model scale value
Subscript S signifies full scale ship 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 trim
- Scale effects on lifting surfaces and appendages can be a problem

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, although special problems with other types of HSMV are also considered.

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.

In these cases the model should generally be as large as possible for the size of the laboratory and the maximum speed of the towing carriage. 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 3.8.1). Adequate grid reference lines must be applied for estimating dynamic wetted area.

Boundary layer turbulence stimulation is recommended when the Reynolds number is less than $5x10^6$ based on hull length. For models tested solely at higher Reynolds numbers, turbulence stimulation might be omitted. Reynolds number should be based on mean or effective wetted length. For tests where Reynolds numbers below $5x10^6$ are unavoidable, a turbulent boundary layer should be stimulated. 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. 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 HSMV*s*. This question is discussed in more detail in section 3.8.2, 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 penetrating through the boundary layer of the model.

The size of HSMV appendages is often too small to obtain a Reynolds number of $5x10^6$. 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 in order 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.

The model should be attached to the measuring head of the resistance dynamometer by a connection which can transmit and measure only a horizontal 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 be such as to introduce the least possible friction forces. The model should be positioned such 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).

3.2 Measurement Systems

Fig 1 shows a typical measurement system:

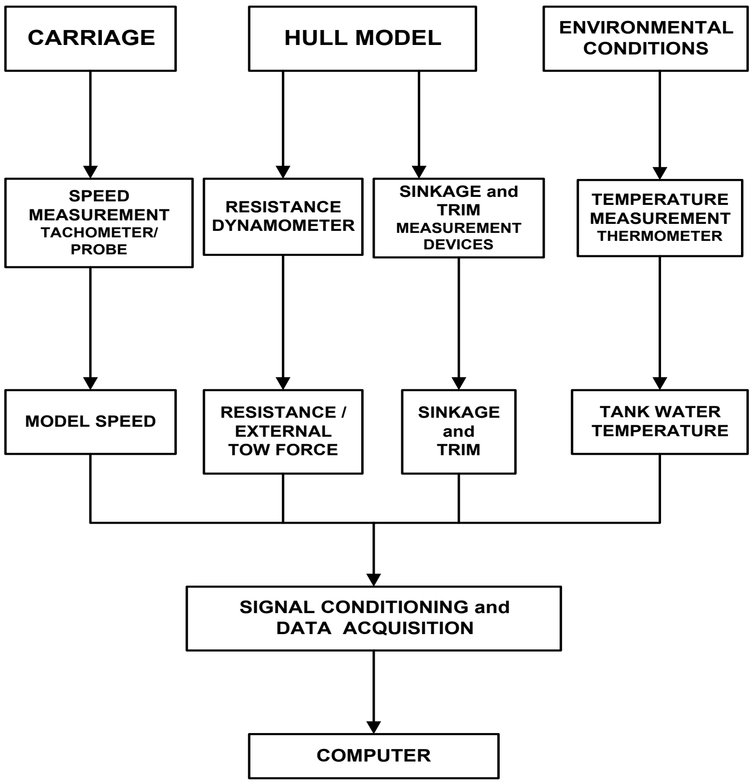

Figure 1 Typical measurement system

The following quantities are measured:

- Model speed
- Total resistance
- Sinkage fore and aft (or running trim and sinkage)
- 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)
- Water temperature (for calculation of viscosity)

3.3 Instrumentation

The quoted bias accuracies are for indicative purposes only. Uncertainty analysis should be used to derive actual requirements.

3.3.1 Resistance

The resistance dynamometer should measure the horizontal tow force to within 0.2% of maximum resistance 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.

(ii) the speed of the towing carriage relative to the water should be measured by a current meter far in front of the model. In this case the current meter wake and waves should be minimised.

The speed of the model should be measured to within 0.1% of the maximum speed or to 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.

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 detected through the use of a calibration diagram from the measured pressure and fan speed.

3.4 Calibrations

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 Quality Manual Standard 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.

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. 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.

3.4.7 Thermometer

Thermometers should be calibrated according to common standards and/or following the advice of the manufacturer.

3.5 Test Procedure and Data Acquisition

3.5.1 Method

Before the test begins, zero readings of all instruments are taken. Zeros should be checked between runs to ensure no drift has occurred. 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. If the model has been held during initial acceleration, it should be released smoothly as soon as the selected speed has been reached. It is recommended that the data acquisition should begin not later than after releasing the model or a steady speed has been reached. The mean values are derived afterwards from the time series, selecting a time window with the criterion that, after the mean measurement values have stabilised, a period of at least five oscillations should be used for the average that is entered into the result. 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 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 is necessary to modify the LCG to correct for artificial trim effects from resistance components that influence the trim but do not follow the Froude 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 modify the LCG for the trim effect of the total model resistance.

An alternative approach to correcting 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 tested with uncertainty analysis. For more information see Uncertainty Analysis, Example for Resistance test, provided in QM 7.5-02-02-02.

- It is essential that the speed of the model through the water should be constant throughout that part of the test run during which resistance is measured, and for a significant distance before measuring begins. Steadiness of carriage speed is an essential element in achieving steady model speed, but 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.

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

3.6 Data Reduction and Analysis

The speed, resistance, sinkage, trim, pressure and other continuously recorded quantities of the test should be the mean value derived from an integration of the instantaneously measured values over the same measuring interval, with the zero measurement being subtracted from the averaged values.

Running wetted surface must normally be derived manually from underwater or above-water photographs, video recordings, paint smear techniques or from visual observations during the test runs as described in Section 3.8.3.

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

$$C_{TM} = \frac{R_{TM}}{\frac{1}{2}\rho_M S_M V_M^2}$$

It should be noted that the observed running wetted surface area will normally be used for HSMV*s*, see Section 3.8.3. The speed should, if necessary, be corrected for blockage by methods such as those described in Section 3.8.5. Values of water density and viscosity should be determined according to ITTC Standard Procedure 7.5-02-01-03.

The residual resistance coefficient C_R is calculated without the use of a form factor (1+*k*):

$$C_R = C_{TM} - C_{FM} - C_{AAM} - C_{AppM}$$

where C_{FM} is derived from the ITTC –1957 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 total resistance coefficient of a HSMV without bilge keels is

$$C_{TS} = C_R + C_{FS} + C_{AAS} + C_{AppS} + C_A$$

where

C_{FS} is the frictional coefficient of the ship according to the ITTC-1957 model-ship correlation line

C_R is the residual resistance calculated from the total and frictional coefficients of the model in the resistance tests.

C_{AA}, is the air resistance

$$C_{AA} = \frac{\rho_A V_A^2 A_V C_D}{\rho V^2 S}$$

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 from calculations, using the same method as for finding C_{AppM} but at full scale *Re*. If C_{AppM} is found from testing with and without appendages, then C_{AppS} should be found 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

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

where S is equivalent to the observed model wetted surface area.

The following specific considerations can be made for SWATH, Hydrofoils, SES, and ACV.

SWATH – Separate friction coefficients are determined for the struts and submerged hulls based on the Reynolds number of each component. 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 expanded from tests at a Reynolds number high enough to ensure fully turbulent flow. In case the foil system was present during the towing tests, the drag of the model foil system must then be subtracted from the total resistance to get the bare hull resistance. In this case it is strongly advised that the foil system resistance be measured during the towing tests, as uncertainty regarding the extent of turbulent flow on the foils in model scale will make it difficult to calculate the drag in model scale. Due to lack of correlation data, it is recommended that a correlation coefficient of zero be used. Alternatively, if the hull is of a type for which 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 due to correlation.

Surface Effect Ships (SES) – For SES craft, it is common practice to estimate resistance components due to hull friction and aerodynamic forces and then deduce the residual resistance, which includes the friction and induced drag of the seals. Froude scaling of speed is based on the cushion length. For calculating friction resistance it is recommended that a Reynolds number based on the length of the wetted sidewall is used. Underwater photography is recommended for estimating wetted surface area of the inner sidewalls. Aerodynamic resistance is best estimated from wind tunnel tests. If that is not a possibility, aerodynamic resistance can be approximated using a drag coefficient of approximately 0.5 applied to the entire frontal area of the vehicle. 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 Cushion Vehicles (ACV) – It is common practice to Froude scale 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.

3.6.2.1 Form factor

The use of the 1978 powering performance procedure implies the use of a form factor $(1+k)$. Particular problems arise with estimates of $(1+k)$ for HSMVs in that 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 continue to be assumed $(1+k)=1.0$.

3.6.2.2 Model-Ship Correlation

The proposed extrapolation method requires an established model-ship correlation, partly because the form factor is set to zero. 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.

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 Standard Procedure 7.5-01-01 Ship Models)
- Particulars of the towing tank including length, breadth and water depth, together with the method of towing the model including 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)
  - Correlation factor (even if a correlation factor is not applied, this should be stated)
  - Air resistance coefficients for model and full scale
- For each speed, the following data should be given as a minimum:
  - 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)

3.8 Special Considerations

3.8.1 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 single 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 above the model as the carriage travels down the tank.

The speed at which air resistance becomes significant varies with the facility, towing arrangement and 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 since the model can be tested at or close to the correct Reynolds number. However, for most test programmes, the expense of wind tunnel tests can be cost prohibitive. A practical alternative is to tow the model, fitted with a superstructure, above the water surface. Corrections can then be made to account for Reynolds number effects based on the wind speed measured under the towing carriage and resistance contributed by the normally-submerged portion of the hull. Since ship superstructures are in general relatively bluff, the Reynolds number effects on drag are often moderate. This would confirm that the most straightforward way of minimising the errors introduced by air resistance is to fit the model with a modelled superstructure during the tests.

Before making air resistance corrections 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 us 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 by a modelled superstructure 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.

3.8.2 Appendage Effects

It is important to make adequate corrections for appendage effects on HSMV model test results. Two 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

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

Testing both with and without appendages has the advantage of providing more information for expanding 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 & 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 appendage so that the lift characteristics of the model appendage 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.

Also, for lift-producing appendages, there is the choice of either to test with the appendage, correcting for scale effects on lift and drag, or to test without the appendage and correct for the computed (or separately tested) lift and drag of the appendage. 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).

3.8.3 Wetted Area Estimation

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

- visual observations from outside model
- visual observations from inside 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 with the use of larger models, higher speeds, and the fitting of model spray rails which correctly simulate full scale rails and which can aid 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 better 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.

3.8.4 Spray Resistance

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

3.8.5 Blockage

For all types of HSMV it is important to avoid the situation in which the hump speed of the model approaches or coincides with the critical depth speed of the tank, i.e. $Fr_h = 1.0$. Blockage was addressed for different types of HSMVs by Savitsky, Müller-Graf and others, and these are summarised as follows:

For planing hulls, Savitsky 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 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, van Oossanen stated that blockage corrections 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 (1961) have been found useful for this purpose.

3.8.6 Captive Resistance Tests

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

3.8.6.1 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 ordinary towed models. The problem of the scale effect on running attitude can be avoided. The effect of appendages can be obtained as a result of the simulation by adding hydrodynamic forces acting on them into 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, 1993), Yokomizo (1992), and Katayama & Ikeda (1993, 1995, 1996) for planing craft and by Minsaas (1993) for fully submerged hydrofoils.

3.8.6.2 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.-

3.8.6.3 Automatic Attitude Control Method

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 VALIDATION

4.1 Uncertainty Analysis

Uncertainty analysis should be performed in accordance with 'Uncertainty Analysis in EFD, Uncertainty Assessment Methodology' as described in QM 4.9-03-01-01 and 'Uncertainty Analysis in EFD, Guidelines for Uncertainty Assessment' as described in QM 4.9-03-01-02. In addition to the above an example 'Uncertainty Analysis, Example for Resistance Test' is provided in QM 7.5-02-02-02.

4.2 Benchmark Tests

Benchmark data are collected and described in 'Benchmark Database for CFD, Validation for Resistance and Propulsion', QM 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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