ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Waterjet Propulsive Performance Prediction – Propulsion Test and Extrapolation

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Waterjet Propulsive Performance Prediction – Propulsion Test and Extrapolation

1. PURPOSE OF PROCEDURE

The procedure is meant to give guidance in the prediction of powering performance of waterjet driven vehicles, using propulsion tests. It encompasses the self propulsion experiment and the extrapolation procedure from model to full scale.

The procedure is generally applicable for performance predictions for marine vehicles driven by waterjets with flush intakes. The procedure is kept as generic as is possible, so that only minor adaptations are necessary for other waterjet configurations.

The procedure will normally be applied in conjunction with other standard ITTC procedures, such as the procedure for:

- Resistance tests; proc. 7.5-02-02-01
- Testing and extrapolation methods High Speed Marine Vehicles – Resistance Test; proc. 7.5-02-05-01

The procedure is furthermore based on the ITTC procedure for propulsion tests (proc. 7.5-02-03-01.1). This procedure focuses on those parts of the procedure that deviate from the propeller propulsion test. The current propulsion test procedure is referred to as “Momentum Flux” method.

For an argumentation of the choices that needed to be made to arrive at the present procedure, the reader is referred to the 24th ITTC Report by the Specialist Committee on the Validation of Waterjet Test Procedures (24th ITTC, 2004).

2. DESCRIPTION OF PROCEDURE

2.1 Model and installation

2.1.1 Resistance test model

The model will have closed intake(s) and nozzle(s) during the resistance test. The waterjet(s) can be filled with water but also the water in the duct can be accounted for with a compensation ballast weight. In this way, the displacement weight and centre of gravity of the resistance and the propulsion model are identical.

2.1.2 Propulsion test model

The intake and nozzle geometry will have to be scaled geometrically, in order to ensure similar flow conditions about the intake and the nozzle as would occur on the full scale ship.

A pump of convenience may be used to deliver the required flow rate. The position of the pump need not be identical to that of the prototype waterjet system, as long as kinematic similarity of the flow in the intake region (station 1 to 2) and in the nozzle region (station 6 to 7) is ensured.

2.2 Measurements

The following quantities need to be measured directly or determined indirectly:

- Volume flow rate Q_J

- Static pressure at the capture area (at least at one position on the hull, preferably at the centreline of the capture area)
- Sinkage of the nozzle

The following quantities need to be measured or derived from CFD

- Velocity distribution in the capture area

The following quantities are measured in addition, which is similar for a propulsion test with a propeller propelled vehicle:

- Model speed
- Resistance / External tow force
- Impeller torque (optional)
- Impeller rate of revolution (optional)
- Water temperature (for calculation of viscosity)
- Sinkage fore and aft (or running trim and sinkage)

2.3 Instrumentation and calibration

2.3.1 Flow rate

The most important and difficult measurement to be made for the "momentum flux approach" is the flow rate. The uncertainty of the overall powering prediction is very sensitive to errors in flow rate, as is clearly demonstrated in the example of the uncertainty analysis provided in the Report to the 24th ITTC.

A selection of potentially accurate and reliable flow rate measurements is listed below. Special attention is needed however as bias errors for this type of measurement are easily introduced.

- Differential Pressure Transducers (DPTs) through nozzle, e.g. an averaging static Pitot tube through nozzle
- LDV measurement of velocities in cross sectional plane and integration of velocities

A discussion on alternative flow rate measurement procedures can be found in the proceedings of the 23rd ITTC (2002).

When Differential Pressure Transducers (DPTs) are used, the pressure signal needs to be calibrated with the flow rate in situ. One should be aware that an externally imposed pressure gradient, which varies with speed (such as due to a changing nozzle immersion), may affect the pressure difference and therefore contribute to a bias error in the flow rate signal.

2.4 Test procedure and data acquisition

The method recommended for Self Propulsion Tests with Waterjets is referred to as the "momentum flux" method. For this method, any pump of convenience can be used to provide the required flow rate, as long as the flow at the interface of waterjet internal flow and external flow is scaled properly. Proper scaling of the flow at these interfaces is required to correctly model the hull-waterjet interaction effects.

Alternative methods are addressed in the Report to the 24th ITTC.

The description of the different stations of the waterjet stream tube is presented in Fig 1, and is based on the proposal by the 21st ITTC.

2.4.1 Tow force

A skin friction correction force (F_D), applied as an external tow force, is to achieve the theoretically correct waterjet loads during the self propulsion test. Its magnitude is discussed in the Report to the 24th ITTC.

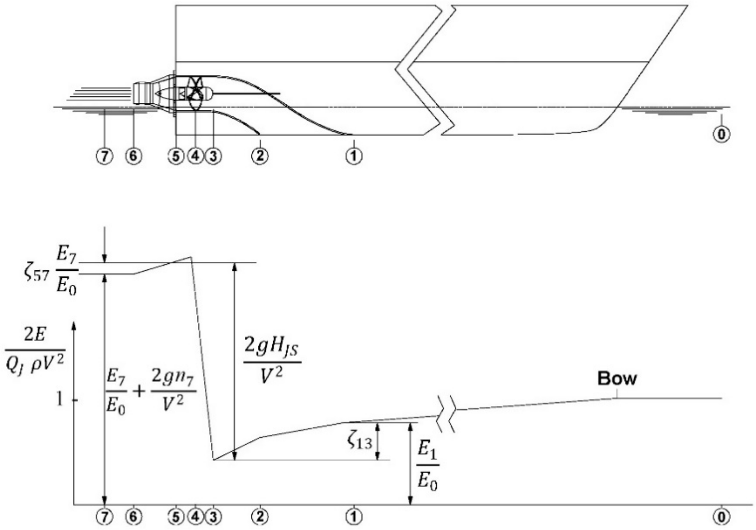

Figure 1 Definition of station numbers and normalized energy flux

2.4.2 Measured or calculated quantities

- model speed V_M
- flow rate (measured) Q_J
- torque Q and impeller rpm n (reference signals – optional)
- external tow force F_D
- velocity distribution in the capture area (measured or calculated) $u_{1x}(y, z)$
- static pressure at capture area (station 1A) (measured or calculated) p_{1A}
- sinkage fore and aft z_{VF}, z_{VA}

2.4.3 Corrections to measured forces and moments

The forces and other quantities measured during the test run may require corrections for shaft losses, speed errors etc. See also ITTC recommended procedure 7.5-02-03-01.1.

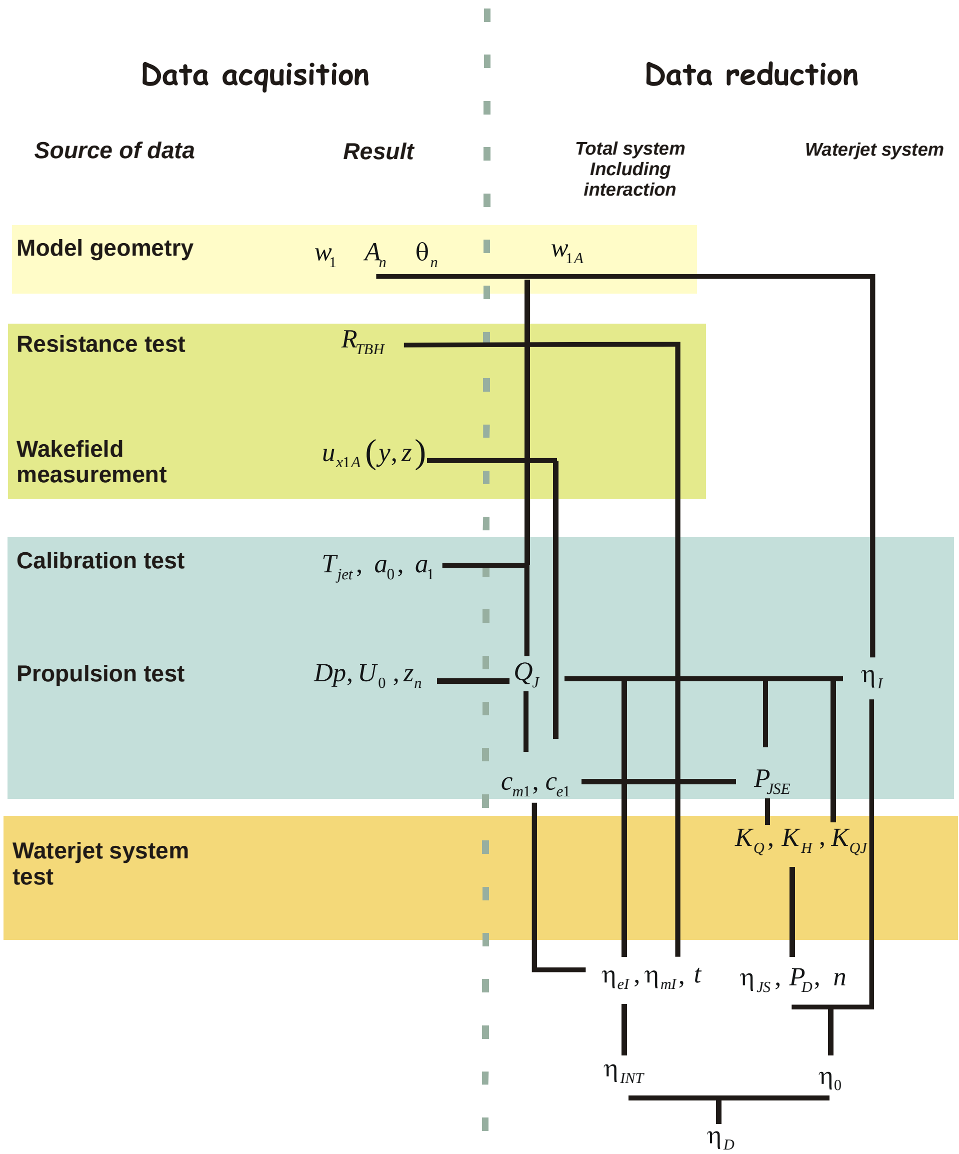

Figure 1 Dataflow in analysis of propulsion test results

2.5 Data reduction and analysis

Figure 2 shows the data flow in the analysis of the propulsion test. The input data consists of geometrical data for the intake and nozzle. Prior to the propulsion test, a calibration of the flow rate transducer needs to be made in situ, so that the flow rate data is available during the propulsion test. The propulsion test subsequently yields flow rate and nozzle sinkage

The velocity profile at the capture area is measured with closed intakes (resistance test model), in order to ensure that no intake induced velocities are included. If the velocity profile is measured with an active waterjet, care should be taken that the intake induced velocities are subtracted using a CFD analysis.

2.5.1 Bare hull resistance and change in Momentum flux

The thrust exerted by the jet on the hull is coupled to the resistance of the hull through the following relation:

$$\Delta\overline{M}_x = \frac{R_{\mathrm{TBH}}}{(1-t)} \tag{1}$$

For the operating conditions where the nozzle is either completely ventilated or completely immersed, the change in momentum flux is equal to the net thrust exerted by the jet on the hull (ITTC [2005]):

$$\Delta\overline{M}_x = T_{\mathrm{net}} \tag{2}$$

The change in momentum in *x*-direction is determined over the system boundaries defined by the stations 1 and 7. In case of a parallel nozzle outflow, the assumption is justifiable that the vena contracta has the same diameter as the nozzle discharge, and hence the change in momentum flux can be determined from station 6:

$$\Delta\overline{M}_x = \overline{M}_{x6} - \overline{M}_{x1} \tag{3}$$

The momentum flux from the nozzle can be obtained directly from the flow rate sensor that is calibrated with the jet thrust $T_{\mathrm{J}x}$:

$$\overline{M}_{x6} = T_{\mathrm{J}x} \tag{4}$$

For the determination of the ingested momentum flux through station 1, the assumption is made, that the capture area is located at right angles with the flow in *x*-direction. The momentum flux in *x*-direction through the capture area A_1, is then defined by:

$$\overline{M}_{x1} = \iint_{A_1} \rho u_x^2 dA \tag{5}$$

This momentum flux can be determined from the flow rate Q_{J} and the ship velocity V_0 as:

$$\overline{M}_{x1} = \rho Q_{\mathrm{J}} c_{\mathrm{m1}} V_0 \tag{6}$$

where the flow rate Q_{J} is preferably obtained from:

$$Q_{\mathrm{J}} = \frac{1}{c_{\mathrm{m6}}}\sqrt{\frac{T_{\mathrm{J}x}A_n}{\rho\cos\theta_n}} \tag{7}$$

and the momentum velocity coefficient c_{m1} by definition from velocity measurements at station 1:

$$c_{\mathrm{m1}} = \frac{1}{\sqrt{(1-C_p^2)Q_{\mathrm{J}}V_0}}\int_{A_1} u_x^2 dA \tag{8}$$

2.5.2 Delivered power and change in energy flux

The effective jet system power P_{JSE} is one of the most important signals derived from propulsion tests. This hydraulic power is by definition the power required to deliver a pressure head for a given flow rate. It should be noted that the kinetic energy is taken in the local axial direction. This direction is denoted as ξ. The effective jet system power is thus equal to the net rate of change of the energy flux:

$$P_{\mathrm{JSE}} = E_{7\xi} - E_{1\xi} \tag{9}$$

In case of a parallel nozzle outflow, the assumption is justifiable that the vena contracta has the same diameter as the nozzle discharge, and hence the jet system power can be determined from station 6:

$$P_{\mathrm{JSE}} = E_{6\xi} - E_{1\xi} \tag{10}$$

The total axial (in ξ direction) energy flux through a cross sectional area A_s at station s is defined as:

$$E_{s\xi} = \int_{A_s} \rho \left(\frac{1}{2}u_\xi^2 + \frac{p}{\rho} - gz_s\right)\left(u_\xi n_\xi\right) dA \quad (11)$$

It is often convenient to express the axial kinetic energy in terms of an average energy velocity $\overline{u}_{e\xi s}$:

$$\overline{u}_{e\xi s}^2 = c_{es}^2 \frac{Q_J^2}{A_s^2} \quad (12)$$

where

$$c_{es}^2 = \frac{A_s^2}{Q_J^3}\int_{A_s} u_\xi^3 dA \quad (13)$$

Once the flow rate Q_J and the cross sectional area A_s are known and a velocity distribution is measured or assumed, the total energy fluxes through the stations 6 and 1 can be computed. A remaining problem is then the determination of the geometry and area of the capture area A_1. Guidance for the determination of the capture area is given in the Report to the 24th ITTC (2005).

To arrive at a practical expression for the effective Jet System Power P_{JSE}, it is assumed that for operational conditions the nozzle is completely effective in converting the pressure energy into kinetic energy, so that the pressure outside the nozzle is equal to the ambient pressure p_0. Assuming a thin boundary layer, applying Bernoulli's theorem and taking into account that the nozzle centre is situated on the free water surface in free stream conditions, the following expression for P_{JSE} is found:

$$P_{JSE} = P_{JSE0} + +\rho Q_J \left[\frac{1}{2}(1 - c_{e1}^2)(1 - C_{p1})V_0 - gz_6\right] \quad (14)$$

where the effective power in free stream conditions P_{JSE0} can be reduced to (ITTC (2005)):

$$P_{JSE} \quad (15)$$

The static pressure coefficient at station s c_{ps}, is defined as:

$$c_{ps} = \frac{p_s - p_0}{\frac{1}{2}\rho V_0^2} \quad (16)$$

2.5.3 Waterjet-hull interaction summary

The interaction between the waterjet and the hull can be expressed in non-dimensional coefficients. A complete set of coefficients describing the full interaction effect is for instance given by Van Terwisga (1996):

$$\frac{1}{\eta_{mI}} = 1 + \frac{1 - c_m}{NVR - 1} \quad (17)$$

$$\frac{1}{\eta_{eI}} = 1 - \frac{gz_n}{\frac{1}{2}U_0^2(NVR^2 - 1)} - + \frac{(c_e^2 - 1)(1 - C_{p1})}{(NVR^2 - 1)} \quad (18)$$

This set is completed with the thrust deduction factor $(1 - t)$, defined by eq. (1).

2.6 Extrapolation

2.6.1 Scale effects

Scale effects occur in the following quantities:

- Determination of the "Self Propulsion Point Ship". This point is defined in terms of the towing force. A discussion on the procedure is given by 24th ITTC (2005).
- Ingested boundary layer flow. For full scale, the boundary layer will be relatively thinner than on model scale. This requires a correction for the ingested momentum

and energy fluxes. These corrections are most conveniently accounted for in the momentum and energy velocity coefficients c_m and c_e.
- The transom stern flow before full ventilation of the transom is subject to strong viscosity dominated processes. Scale effects can occur here, although it is expected that these are generally small. The biggest effects on overall powering may occur at the speed where the nozzle is about to be fully ventilated.

2.6.2 Conversion of model jet to prototype characteristics

The overall performance of the hull-waterjet system can be expressed as a non-dimensional effective output, usually referred to as the overall efficiency η_{OA}. The overall efficiency can be broken down into a so called "free stream efficiency" η_0 and an interaction efficiency η_{INT}:

$$\eta_{OA} = \eta_0 \eta_{INT} \tag{19}$$

The interaction efficiency is determined from the results of the propulsion test:

$$\eta_{INT} = (1-t)\frac{\eta_{eI}}{\eta_{mI}} \tag{20}$$

The free stream efficiency η_0 is defined by:

$$\eta_0 = \eta_I \eta_P \eta_{duct} \tag{21}$$

This free stream efficiency determines the performance of the waterjet system in an undisturbed environment. Pump efficiency and ducting efficiency can be determined from waterjet system or pump loop tests, as is discussed in ITTC test procedure 7.5-02-05-03.2. The values for these efficiencies follow from the jet system characteristics after the required Head over the system H_{JS} and the flow rate through the system are known from the propulsion tests, where the system head can be determined from:

$$H_{JS} = \frac{P_{JSE}}{Q_J} \tag{22}$$

The ideal efficiency is uniquely dependent on the nozzle velocity ratio *NVR*, which value also results from the propulsion test:

$$\eta_I = \frac{2}{1+NVR} \tag{23}$$

2.7 Documentation

The results from the propulsion test should be collated in a report which should contain the information specified in ITTC recommended procedure 7.5-02-03-01.1 (Propulsion Test):

For each speed, the following data should be given as a minimum:

- Flow rate Q_J
- Net thrust T_{net} required by hull-waterjet system
- Effective Jet System Power P_{JSE}
- Total interaction efficiency η_{INT} and components η_{mI}, η_{eI} ,(1-t)
- Nozzle Velocity Ratio *NVR*
- Ideal efficiency η_I

If possible, estimates for the internal jet system performance and impeller rotation rate should be given. The availability of these data is dependent on the availability of the jet system characteristics

3. VALIDATION

3.1 Uncertainty analysis

Uncertainty analysis should be performed in accordance with ‘Uncertainty Analysis in EFD, Uncertainty Assessment Methodology’, as described in QM 7.5-02-01-01 and ‘Uncertainty Analysis in EFD, Guidelines for Uncertainty Assessment’ as described in QM 7.5-02-01-02. In addition to the above, an example ‘Uncertainty Analysis, Example for Waterjet Propulsion Test’ is provided in QM 7.5-02-05-03.3

3.2 Benchmark tests

See Report of 24th ITTC (2005).

4. REFERENCES

ITTC, 2005, "Report of Specialist Committee on Validation of Waterjet Test Procedures", ITTC Proc. of 24th ITTC

Van Terwisga, T.J.C., 1996, “Waterjet-Hull Interaction”, PhD Thesis, Delft University of Technology, April 1996, ISBN90-75757-01-8.