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Waterjet Propulsive Performance Prediction – Waterjet Inlet Duct, Pump Loop and Waterjet System Tests and Extrapolation

1. PURPOSE OF PROCEDURE

The purpose of the procedure is to ensure consistency of methodology and acquisition of correct results from Waterjet Inlet Tests, Waterjet Pump Loop Tests and Waterjet System Tests.

The procedure is meant to give guidance in the prediction of waterjet system performance. It encompasses tests of the waterjet system or inlet duct in water tunnels as well as pump tests in pump loop circuits. Extrapolation issues are addressed.

The procedure will normally be applied in conjunction with the ITTC procedure 7.5-02-05-03.1: Waterjet Propulsive Performance Prediction. It aims at defining the data exchange between propulsion test data and waterjet system data that is necessary to arrive at a full scale powering performance prediction for a waterjet driven craft.

The procedure is mainly applicable for waterjets with flush-type inlet, but can with minor adaptations also be used for other waterjet configurations.

For additional information and background to the present procedure the reader is referred to 24th ITTC Report by the Specialist Committee on the Validation of Waterjet test procedures (24th ITTC, 2005).

2. DESCRIPTION OF PROCEDURE

The use of a pump of convenience in the propulsion test requires other tests or analysis to be performed with the design pump geometry in order to derive the shaft power and speed (rpm).

Flow rate and duct inflow conditions are the main inputs from the propulsion test. Shaft power and speed are the main outputs from the tests or the analysis of the waterjet system.

A traditional pump loop test, with a uniform inflow to the pump, gives the pump characteristics in the same way as the open water test does for a propeller. Note however that waterjets rarely operate under such ideal conditions.

In an inlet duct test, the duct losses can be measured to obtain the duct efficiency, which combined with the pump efficiency, obtained from a pump loop test, gives a first approximation of the waterjet system performance.

A waterjet system test can either replace the inlet duct and pump tests or contribute to improve the performance prediction mainly by allowing the interaction effect between inlet duct and pump to be studied. This will determine the installation efficiency, defined as the influence of the non-uniform inflow to the pump on the pump performance characteristics. The pump might also have an effect on the duct losses.

Tests can be supplemented or replaced by CFD calculations of the inlet duct, pump unit or waterjet system. CFD can also provide additional scaling information.

In conclusion, required shaft power and speed for given flow rate and inflow conditions can be obtained directly from a system test or indirectly from different combinations of tests and calculations.

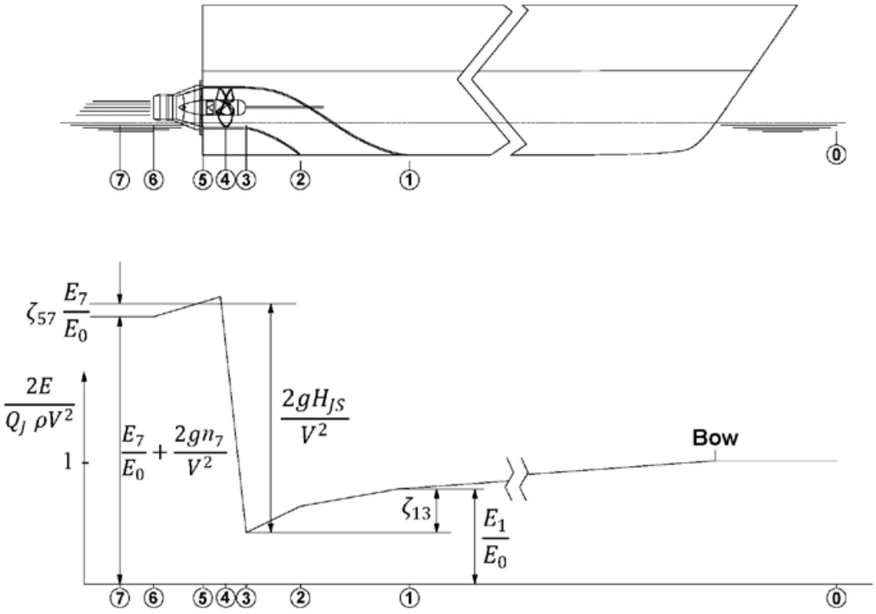

Figure 1. Definition of station numbers and normalized energy flux.

2.1 Model and installation

2.1.1 Pump and inlet duct models

The basic requirement is that the models should be geometrically similar to the full-scale. The quoted tolerances are for indicative purpose only.

Model waterjet inlet duct

Manufacturing tolerances (for waterjet inlet or system tests):

It is considered good practice to have the inside of the inlets numerically milled. Special attention should be paid to the shaping accuracy of the inlet lip region and the sides of the inlet opening.

The surface finish should be smooth and equivalent to that achieved with a 320 to 400 grit wet and dry paper.

Model waterjet pump:

Manufacturing tolerances (for waterjet pump loop and system tests):

Impellers and stators having diameter (*D*) typically from 150mm to 300mm should be finished to the following tolerances:

Diameter (*D*)	±0.05 mm
Blade thickness (*t*)	±0.10 mm
Cord length (*c*)	±0.10 mm
Tip clearance	±0.05 mm
Mean pitch at each radius (*P/D*)	±0.5 deg.

Special attention should be paid to the shaping accuracy near the leading and trailing edges of the blade section and to thickness distributions. The impeller will normally be completed to a polished finish.

The bearing arrangement should be such that it ensures the tip clearance tolerance.

2.1.2 Waterjet system test installation

The waterjet system test is commonly carried out in a cavitation tunnel. The use of other facilities is not discussed further in this document.

In a conventional cavitation tunnel, the hull bottom may be simulated by any of the walls of the measuring section, unless a dummy hull is used for a more correct representation of the geometry around the inlet duct. The discharge normally has to be arranged by connecting a pipe or hose that returns the water to the tunnel. Accurate flow rate measurement and adjustment can easily be arranged.

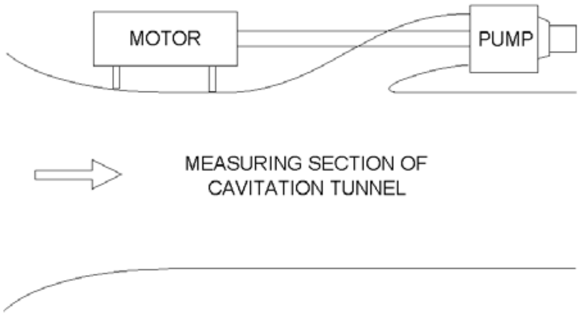

Figure 2. Installation of waterjet system in cavitation tunnel

In a free-surface cavitation tunnel, both inlet and discharge can be arranged in a realistic way. Direct thrust measurement is made possible while flow rate measurement may become more complex. The model is usually also less accessible for observations and measurements than in a conventional cavitation tunnel.

2.1.3 Pump loop test installation

A pump loop circuit can quite easily be arranged in a cavitation tunnel by installing the pump unit in the middle of the measuring section and connecting the discharge to a pipe or hose that takes the water to a flow meter and returns it to the tunnel.

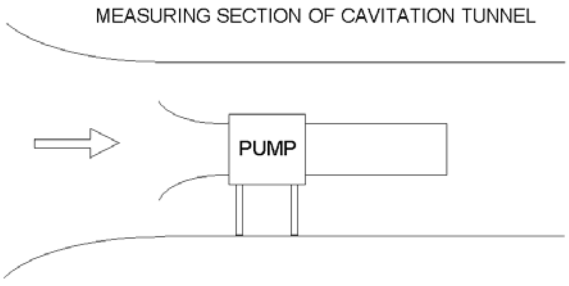

Figure 3. Installation of model pump in cavitation tunnel

A separate specially designed pump loop circuit is however likely to offer some advantages, like better inflow conditions and easier access to the pump for measurements or observations.

2.1.4 Inlet duct test installation

The installation in a conventional cavitation tunnel can be done in the same way as for the waterjet system test. Auxiliary pumps are needed to vary the flow rate.

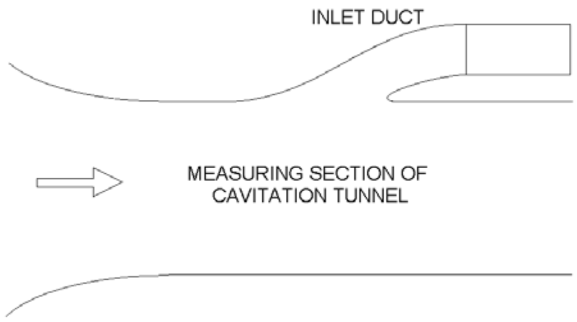

Figure 4. Installation of inlet duct in cavitation tunnel

2.2 Measurements

The following quantities need to be measured directly or determined indirectly during the inlet test (I), pump loop test (P) and waterjet system test (S).

- Tunnel bypass velocity V_t (I, S)
- Tunnel static pressure p_t (I, P, S)
- Impeller shaft speed n (P, S)
- Impeller torque Q (P, S)
- Head rise across the pump H_{JS} (P, S)
- Inlet duct loss coefficient ζ_{13} (I, S)
- Volume flow rate Q_J (I, P, S)
- Water temperature t_W (for calculation of viscosity and vapour pressure) (I, P, S)
- Waterjet net thrust T_{net} (optional) (S)

2.3 Instrumentation

The quoted bias accuracies in this section are for indicative purpose only. Uncertainty analysis should be used to derive the actual requirements.

2.3.1 Tunnel bypass velocity

Tunnel bypass velocity should be measured upstream of the inlet duct opening in order not to be affected by the flow though the waterjet.

Velocity should be measured to within an accuracy of ±0.2% of its true value.

2.3.2 Tunnel static pressure

Tunnel static pressure should be measured well upstream of the inlet duct opening in order not to be affected by the flow though the waterjet.

Pressure should be measured to within an accuracy of ±0.5% of its true value.

2.3.3 Impeller shaft speed

It is essential to keep the shaft speed constant during the test.

Impeller shaft speed should be measured to within an accuracy of ±0.05% of its true value.

2.3.4 Impeller torque

Impeller torque is measured using a dynamometer in the shaft line. It is essential to keep the shaft friction losses as low as possible, and these should, if possible, be recorded separately during the test, for instance by running the pump in air or disconnecting/removing the impeller. An alternative is to have a dynamometer integrated into the hub, by which means friction losses can be avoided.

Torque should be measured to within an accuracy of ±0.5% of its true value.

2.3.5 Head rise across the pump

Head rise is the mean increase of total local head over stations 3 and 5. The minimum is to measure the mean static pressures in four points in the wall at the two stations. In addition, flow rate and sectional areas are required to calculate the head rise.

Good accuracy in head rise may require velocity and pressure distributions at stations 3 and 5 to be measured. An alternative approach is to combine results from CFD analysis with model test results.

Head rise should be derived from measurements to within an accuracy of ±1.0% of its true value.

2.3.6 Inlet duct loss

Inlet duct loss is the mean reduction of total local head over stations 1 and 3. The minimum requirement is to measure the boundary layer at station 1 and the mean static pressures at four points on the wall at the station 3. In addition, capture area, flow rate and duct exit area are required to calculate the inlet duct loss.

Good accuracy in inlet duct loss may require velocity and pressure distributions at station 3 to be measured. Strong secondary flow may require 3-axis velocity measurements. An alternative approach is to combine results from CFD analysis with model test results.

Inlet duct loss should be measured to within an accuracy of ±3.0% of its true value.

2.3.7 Volume flow rate

Accurate flow meters of different type can easily be arranged in the pipe connected to the discharge of the pump or inlet duct.

Volume flow rate should be measured to within an accuracy of ±0.5% of its true value.

2.3.8 Water temperature

Water temperature should be measured to within an accuracy of ±0.1°C.

2.3.9 Waterjet thrust

Waterjet thrust is an optional reading in waterjet system tests.

Waterjet thrust can be directly measured with a force transducer if the complete system is “floating” or separated from its environment by a small gap. It needs to be supported sideways and in the vertical direction in a way that does not affect the thrust measurement. The gap design also requires special attention to avoid large forces in the thrust direction.

Thrust should be measured to within an accuracy of ±2.0% of its true value.

2.4 Calibrations

Recommendations in this section consider only the test specific measuring equipment, not the stationary equipment of the cavitation tunnel.

2.4.1 Impeller torque and waterjet thrust

Torque and thrust dynamometer calibration should be carried out using traceable loads and performed within an established time period prior to the test and preferably also checked after the test.

2.4.2 Head rise and inlet duct loss

Pressure transducer and velocity probe calibrations should be carried out using traceable pressure loads and velocities performed within an established time period prior to the test and preferably also checked after the test.

2.5 Test procedure and data acquisition

The conditions in the cavitation tunnel need to be stable in case all recordings cannot be done simultaneously. This applies especially when pressure and velocity surveys are carried out.

Prior to pump loop and system tests, runs should be made to determine the friction torque, unless the dynamometer is integrated into the hub to avoid friction.

A blockage coefficient, based on the largest section of dummy hull or full hull, of less than 10% is recommended for the system test.

It is important to pay attention to the water quality, especially in case cavitation has a significant effect on the measurements.

Measurements should be conducted at more than one Reynolds number to get an appreciation of the Reynolds number dependency.

Inlet duct test

The range of inlet velocity ratios should cover the range from bollard pull to full speed ahead.

Inflow conditions to the inlet duct, largely governed by the boundary layer, may need to be simulated in order to reduce scaling errors.

Flow separation in the duct may occur at some conditions. Even symmetric ducts may cause strong asymmetric flow separation that distorts the flow at the duct exit. Observations of the flow prior to the measurements are recommended, for instance by inserting air bubbles.

Measurements can normally be carried out at atmospheric pressure. Note however that losses may be higher if cavitation is present at the full-scale condition. It is therefore recommended that the most extreme working point be checked on cavitation.

Pump loop test

The range of flow rate coefficients should cover off-design conditions on both sides of the pump optimum to the extent expected on the vessel during normal operation.

Measurements of head rise and power versus flow rate can in most cases be carried out at atmospheric pressure. Waterjet pumps are however normally designed and sized in a way that they operate with a certain amount of cavitation. It is therefore recommended that cavitation limits and effects for the pump be explored during the test.

Waterjet system test

The range of simulated ship speeds and shaft speeds should cover all corresponding full-scale operating conditions.

The test procedure depends on the purpose of the system test. It can be regarded as a simultaneous inlet duct and pump test,- following the recommendations above for these tests -, with the aim to obtain the effect of interaction between inlet duct and pump, or the purpose can be to directly measure the required power and shaft speed for given flow rate and inflow conditions.

A ship reference velocity and pressure measurement from the propulsion test may be used in the waterjet system test, to set the self-propulsion condition more accurately, in case tunnel bypass velocity and static pressure do not determine the ship speed.

The self-propulsion test condition is obtained in the waterjet system test by adjusting rpm to achieve the same *NVR* as in the propulsion test.

2.6 Data reduction and analysis

The overall performance of the hull-waterjet system can be expressed by the overall efficiency η_{OA}:

$$\eta_{OA} = \eta_0 \eta_{INT} \qquad (1)$$

The free stream efficiency η_0, defined by eq. (2), determines the performance of the waterjet system in an undisturbed environment. The interaction efficiency η_{INT},is determined from the results of the propulsion test.

$$\eta_0 = \eta_I \eta_P \eta_{duct} \qquad (2)$$

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

$$\eta_I = \frac{2}{1+NVR} \qquad (3)$$

Pump efficiency η_P, and ducting efficiency η_{duct}, are determined in the tests described in this procedure and defined by:

$$\eta_P = \frac{P_{PE}}{P_D} \qquad (4)$$

$$\eta_{duct} = \frac{P_{JSE}}{P_{PE}} \qquad (5)$$

The effective jet system power P_{JSE} is defined by:

$$P_{JSE} = E_7 - E_1 \qquad (6)$$

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: $P_{JSE} = E_6 - E_1$.

The effective pump power P_{PE} is defined by:

$$P_{PE} = P_{JSE} + \zeta_{13} E_0 + \zeta_{57} E_7 \qquad (7)$$

or

$$P_{PE} = \rho g Q_J H_{JS} \qquad (8)$$

Inlet duct test

The inlet duct loss coefficient ζ_{13}, defined by eq. (9) and measured in an inlet duct test, determines the ducting efficiency.

$$\zeta_{13} = \frac{E_1 - E_3}{E_0} \qquad (9)$$

The energy flux E_j is obtained by integrating the local energy velocity $V_{\mathrm{E}j}$ at Station j, as follows:

$$E_{\mathrm{s}} = \tfrac{1}{2}\rho \int_{Q_{\mathrm{J}}} V_{E_j}^2 \, dQ_{\mathrm{J}} \qquad (10)$$

The outlet nozzle loss coefficient ζ_{57} is not obtained in an inlet duct test. CFD or a waterjet system test is needed.

Pump loop test

The pump efficiency η_{P}, defined in eq. (4), is composed of free stream pump efficiency η_{P0}, as measured in a pump loop test and corresponding to the open water efficiency of a propeller and the installation efficiency η_{inst} as follows:

$$\eta_{\mathrm{P}} = \eta_{\mathrm{P0}}\eta_{\mathrm{inst}} \qquad (11)$$

where

$$\eta_{\mathrm{P0}} = \frac{\rho g Q_{\mathrm{J}} H_{JS}}{P_{\mathrm{D}}} \qquad (12)$$

The installation efficiency is not obtained in the pump loop test. A waterjet system test is needed.

Waterjet system test

As discussed before in this procedure, the waterjet system test may be done with the objective to obtain the missing pieces from the inlet test and the pump loop test, which are the nozzle loss coefficient ζ_{57} and the installation efficiency η_{inst}.

The other approach would be to use the measured shaft power and speed directly for extrapolation to full-scale.

2.7 Extrapolation

2.7.1 Scale effects

Scale effects occur in the following quantities:

- Ingested boundary layer flow. Model scale propulsion tests give relatively thicker boundary layer than full scale, while inlet duct and waterjet system tests normally give thinner boundary layer.
- Ducting losses and pump characteristics.

2.7.2 Conversion of model data to full scale

Regarding inlet duct performance, it is recommended to study the influence of boundary layer thickness and Reynolds number on the inlet duct losses by using CFD.

Scaling of the pump performance, mainly the pump efficiency, the cavitation limits and the power to rpm relation, can either be based on empirical or computational methods.

2.8 Documentation

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

- Model specification, e.g. identification numbers, model scale and material.
- Particulars of the test facilities e.g. test section dimensions.
- Test date
- Parametric data for the test, e.g. water temperature, air content, density and viscosity.

For each operating point, measured and calculated data should be given, e.g. flow rate, head rise, pump efficiency and ducting losses.

3. VALIDATION

3.1 Benchmark tests

See Report of 24th ITTC.

3.2 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.

4. REFERENCES

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