ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Modelling the Behaviour of Cavitation in Waterjets

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Modelling the Behaviour of Cavitation in Waterjets

1. PURPOSE OF GUIDELINE

The purpose of this guideline is to ensure the best possible quality results in modelling the behaviour of cavitation in waterjets. This modelling - which encompasses both experimental and numerical modelling - must address key cavitation issues related to waterjet performance. This guideline focuses on the key issue of cavitation thrust breakdown, as well as cavitation erosion. In addition, this guideline addresses cavitation inception, which leads to performance issues of pressure fluctuations, vibration, fatigue, and noise. These latter performance issues are not addressed directly in this guideline. Finally, this guideline will briefly discuss the scaling of these cavitation phenomena.

For experimental modelling, this guideline can be applied in conjunction with the procedure recommended by the ITTC (2005a) - and discussed previously by the ITTC (1999) and the final report by the Specialist Committee on Cavitation for the 22nd ITTC - for waterjet propulsive performance. Where appropriate for specific issues, one can perform cavitation tests during the same experimental setups described by this previous procedure for predicting waterjet propulsive performance.

For additional information and background on waterjet cavitation, the reader can refer to the ITTC (2008) and the final report by the Specialist Committee on Cavitation for the 25th ITTC.

2. EXPERIMENTAL MODELING OF WATERJET CAVITATION

For the ITTC (1999), the Specialist Committee on Waterjets for the 22nd ITTC recommended three types of tests for determining the powering characteristics of waterjets: self-propulsion tests, waterjet system tests, and pump tests. Within a towing tank, the self-propulsion tests would provide the required flow rate, waterjet thrust, and effective waterjet system power - including waterjet/hull interaction factors. The waterjet system tests would then determine the system characteristics in terms of the flow rate, head, torque, and required power. Finally, the pump tests would determine the hydraulic characteristics of the pump without the flow distortion caused by the intake and hull boundary layer.

This guideline will describe how these three types of waterjet tests can address cavitation behaviour and the testing procedures that one should follow to ensure the best possible quality results.

2.1 Self-Propulsion Tests

Similar to self-propulsion tests for vessels powered by propellers, self-propulsion tests for vessels powered by waterjets involve models tested in a towing tank. To measure the model-scale resistance, waterjet testing requires that one conceals the inlets with an appropriately-contoured cover. For waterjet-powered tests, the ITTC (1999) has recommended many additional measurements than one would use for propeller-powered tests. Essentially, these measurements allow one to determine the momentum flux and energy flux at several key stations from upstream of the waterjet through the pump and into the downstream jet.

Self-propulsion tests are not appropriate for the evaluation of cavitation. Most facilities used for self-propulsion tests cannot be depressurized - so, one cannot achieve cavitation similarity. Even when it is possible to achieve cavitation similarity, cavitation viewing is difficult in the inlet region and almost impossible in the pump region. For well-designed inlets, cavitation should only be an issue at off-design values of the inlet velocity ratio,

$$\mathrm{IVR} = \frac{V_{\mathrm{pump}}}{V_\infty} \tag{2.1}$$

where V_∞ is the ship speed, and V_{pump} is the average axial velocity just upstream of the pump - or the volume flow rate divided by the cross sectional area at this location. Therefore, one would have to attempt to view the cavitation at the appropriate values of *IVR*.

Furthermore, operation at an appropriate Reynolds number is recommended for cavitation testing. For instance, characteristics of a cavitating flow field, such as flow separation, depend on the Reynolds number. The speed of the towing-tank carriage and the small dimensions of the waterjet model do not allow for testing at an appropriate Reynolds number. In most cases, the waterjet pump used for self-propulsion tests is not even a scaled model of the actual waterjet pump; it is simply a surrogate pump that ingests the appropriate mass flow rate.

2.2 Waterjet Systems Test

Waterjet system tests involve either closed-loop or open-loop experiments of an actual waterjet inlet and pump, without an actual model of the ship hull. In some cases, one may choose to simply perform an inlet duct test, with only an auxiliary pump used to ingest the proper flow rate. While some waterjet system tests involve a uniform inflow, more appropriate tests should incorporate incoming boundary layers - which are ingested through the inlet - that properly represent the scaled hull boundary layer. These tests can address cavitation observations of the inlet lip and ramp, as well as observations of pump cavitation.

One can quantify or categorize cavitation performance using the cavitation number (or cavitation index),

$$\sigma = \frac{p_{\mathrm{ref}} - p_{\mathrm{V}}}{\frac{1}{2}\rho V_\infty^2} = \frac{p_{\mathrm{atm}} - \rho g h - p_{\mathrm{V}}}{\frac{1}{2}\rho V_\infty^2} \tag{2.2}$$

In this equation, p_{ref} is a reference static pressure defined as the atmospheric pressure, p_{atm}, minus the local elevation head, $\rho g h$. In addition, ρ is the fluid density, g is the acceleration of gravity, h is the local elevation, p_V is the vapour pressure (usually at the bulk temperature of the fluid), and V_∞ is the freestream velocity (which is usually the ship speed).

2.2.1 Model Accuracy.

One should inspect the model geometry prior to testing. This inspection should include visual observation of any nicks or locally-damaged regions, which should subsequently be repaired. Using more sophisticated means - such as gauges, coordinate measuring machines, or laser systems - one should verify whether the manufacturing accuracy is within prescribed tolerances.

Waterjet geometry - especially the pump - should follow similar recommendations used for propeller cavitation testing, where the ITTC (2002b) recommended a blade-surface global tolerance of ±0.05 mm for a typical 250-mm-diameter propeller. Leading and trailing edges require a higher level of accuracy, which can be very difficult to manufacture and inspect. The correct modelling of the gap between the rotor and the housing is important and requires much care.

2.2.2 Water Quality.

As discussed by the ITTC (2002a), cavitation inception measurements require knowledge of the water quality of the test facility - including some knowledge of the nuclei size distribution and liquid tension, as well as the dissolved gas content. While water-quality measurements are challenging, the ITTC (2002a) provided information on what needs to be measured and how to make the measurements. Water with too many nuclei bubbles, for instance, can lead to gaseous cavitation - or pseudo cavitation - instead of the desired vaporous cavitation. On the other hand, water with too few nuclei may delay cavitation inception as it is known from conventional cavitation testing.

2.2.3 Water Temperature.

Cavitation testing requires a measurement of the water temperature using a resistance temperature device or some other means - primarily to determine the water density, viscosity, and vapour pressure. For waterjet tests, the ITTC (2005a) recommended that one should measure the water temperature within accuracy of ±0.1°C. Continuous measurements during the test are recommended to keep track of eventual water heating, especially in smaller testing loops.

2.2.4 Visual Cavitation Inception.

Visual observation of cavitation inception and developed cavitation is necessary within the waterjet inlet. At high values of *IVR*, the flow accelerates into the inlet, relative to the flow at the design *IVR*. For a flush inlet, the resulting incidence angle can lead to cavitation on the upper side of the lip or cutwater - while for a pod inlet, cavitation can occur just inside of the inlet lip. At low values of *IVR*, the flow decelerates in the inlet, relative to the flow at the design *IVR*. The resulting incidence angle for a flush inlet can lead to cavitation on the underside of the lip or cutwater. In addition, this deceleration within the inlet can result in a significant adverse pressure gradient along the roof of the inlet, leading to possible cavitation in this region as well. Finally, for a pod inlet, the resulting incidence angle at a low value of *IVR* can lead to cavitation just outside of the inlet lip.

Waterjet system tests may also allow for visual observation of cavitation inception and developed cavitation on the rotor blades of the pump. Forms of cavitation that may lead to inception can include cavitation in the tip leakage vortex, cavitation within the tip gap, or blade surface cavitation. Hub vortex cavitation downstream of the pump stator blades may be of interest as well.

Windows within the test facility must allow visual observation in these critical regions of the waterjet inlet. Sufficient lighting must be supplied to allow for the best possible observations and records using sketches, photographs, or video. Possible back lighting may improve the illumination of cavitation inception. Records should include the type and location of cavitation at inception. For cavitation inception on the pump rotor blades, visual observation on all blades would be preferable - but at a minimum, one should record observations on both the best blade and the worst blade. Stroboscopic lighting is needed to capture and freeze images of chosen blades at positions throughout the cavitating region of the disk. Additional video cameras may be necessary within the hull or on pods.

The ITTC (2002b) provided related procedures for cavitation inception tests on propellers.

2.2.1 Acoustic Cavitation Inception.

Cavitation inception can occur before visual observation is possible, and acoustic measurements often give a cavitation number higher than the one observed visually where cavitation incepts. Using a hydrophone, one can determine acoustic cavitation inception - or sub-visual cavitation inception - by measuring the sound pressure level (SPL) produced by the device under test conditions of constant velocity and at a series of tunnel pressures. Acoustic cavitation inception occurs when the level and/or frequency content of the measured SPL increases. Figure 2.1 shows an example of such a measurement of SPL with cavitation events present. The advantages of acoustic cavitation detection are the quantitative nature, the consistency, and the earlier detection over visual methods. The disadvantages include the difficulty of setting up the test, the inability to discriminate extraneous cavitation noise sources, and the potential masking by other noise sources. Furthermore, acoustic cavitation detection does not allow for the classification of the type of cavitation.

2.2.2 Velocity Measurements.

While experimental modelling of cavitation inception does not necessarily require flow-field velocity measurements, one may choose to acquire velocity data to quantify the waterjet inflow boundary layer, the flow through the inlet (upstream of the pump), to compare with the inlet design intent, and to compare with numerical modelling.

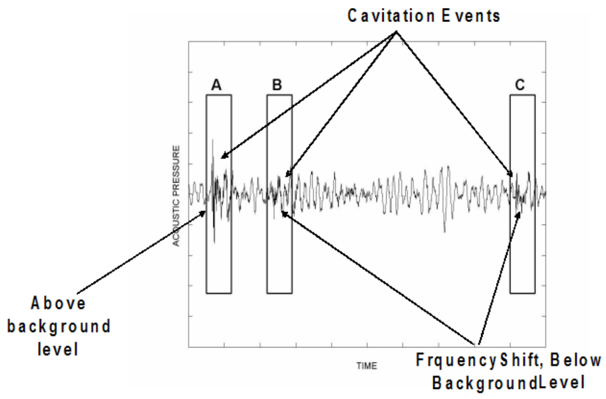

Figure 21. Measured SPL to determine acoustic cavitation inception

A laser Doppler velocimeter (LDV) provides the best direct measurements of flow-field velocities and turbulence intensities, but one can infer the velocities (less accurately) from total- and static-pressure measurements.

2.2.3 Operating Conditions.

The waterjet operating conditions have to be defined by the customer in accordance with the self-propulsion tests - including the ship speed, whether constant or accelerating, and the ship loading. During the cavitation test, one needs to test with different values of IVR and varying cavitation parameters - and possibly with different incoming boundary layers. All of these parameters must be measured and recorded.

2.2.4 Cavitation Inception Test Procedure.

Two procedures exist to experimentally determine cavitation inception. Using the first procedure, known as incipient cavitation, one holds the velocity constant - eliminating all cavitation - and then decreases the tunnel pressure until cavitation appears at the inception pressure. Using the second procedure, known as desinent cavitation, one holds the velocity constant - establishing a cavitating flow - and then increases the pressure until cavitation disappears at the desinence pressure. Hysteresis can occur in the cavitation cycle, giving a desinence pressure that can be larger than the inception value. Thus, desinent cavitation is a more conservative value in determining cavitation performance.

During a waterjet system test, one may also want to determine cavitation thrust breakdown and cavitation erosion. These types of cavitation tests are described in the next two sections of this guideline.

2.3 Pump Tests

If one does not have an appropriate setup to conduct a waterjet system test, then historically waterjet designers have relied on tests within a pump loop. One valuable characteristic of pump-loop testing is the ability to change the resistance of the pump loop and operate the pump at a large range of flow coefficients, allowing the designer to evaluate the off-design characteristics of the pump - from stall at low flow coefficients through the design flow coefficient through high flow coefficients, where lower values of static pressure could enhance issues related to cavitation. Fortunately, most waterjets tend to operate at a nearly constant flow coefficient. However, if this operational flow coefficient differs significantly from the design flow coefficient, this off-design testing can prove very useful.

Pump tests can address how cavitation affects waterjet performance, particularly in evaluating cavitation thrust breakdown. Control of the static pressure within the pump loop allows for testing at different cavitation numbers. The cavitation number corresponding to a 3% decrease in total-head rise across the pump is commonly used to identify the point of cavitation breakdown. In most pump tests, the pump inflow comes from flow through a pipe or through a bell mouth nozzle (which does not represent the inflow that the actual waterjet pump would experience). One could attempt to better model the correct inflow by using a properly-designed honeycomb, screens, fins, and/or a pipe elbow. In any event, the testing should include a measurement of the pump inflow.

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 with an upstream bell mouth - as illustrated in Figure 2.2 - and connecting the discharge to a pipe or hose that takes the water to a flow meter and returns it to the tunnel. However, a separate specially-designed pump-loop circuit can offer advantages like better inflow conditions and easier access to the pump for measurements or observations.

The model accuracy should follow the recommendation described in Section 2.2.1.

2.3.1 Shaft Rate of Revolutions.

Pump tests require the measurement of the shaft rate, usually measured in revolutions per minute (rpm). For waterjet testing, the ITTC (2005a) recommended that one measures the shaft rate with an encoder within an accuracy of ±0.05% of its true value.

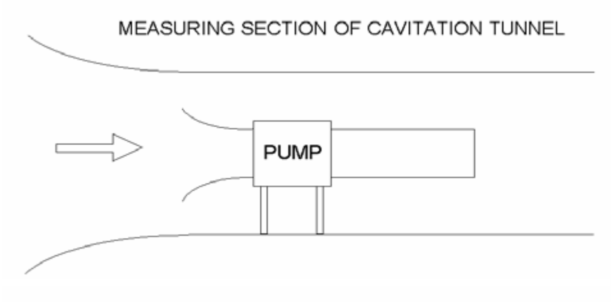

Figure 2.2 Installation of a pump model and bell mouth inlet within a cavitation tunnel

2.3.2 Volumetric Flow Rate.

The evaluation of cavitation thrust breakdown requires the measurement of the volumetric flow rate through the pump. For a pump-loop circuit arranged within a cavitation tunnel, one can install an upstream bell mouth and use it as a flow meter, using a differential pressure transducer that measures the static-pressure drop from the upstream tunnel to a pressure tap located in the throat of the bell mouth. One can calibrate this bell mouth flow meter be measuring the axial velocity in the straight portion of the duct downstream of the bell mouth, using a measurement technique such as LDV.

For a specially-designed pump loop, one can use a commercial flow meter. ASME (1989) provided standards for measuring the volumetric flow rate with flow meters that use orifice plates, nozzles, and Venturi tubes, as well as for estimating the measurement uncertainty. For waterjet tests, the ITTC (2005a) recommended that one should measure the volume flow rate within an accuracy of ±0.5% of its true value.

2.3.3 Static-Pressure Measurements.

Pump tests should include static-pressure measurements upstream and downstream of the pump, using pressure taps along the wall. These measurements allow a mapping of the pump characteristics of static-pressure rise versus volumetric flow rate. Thus, the operating point of the pump will be known for the cavitation thrust breakdown testing. Also, the static pressure upstream of the pump may be required to compute the net positive suction head (NPSH), which is an important parameter for cavitation breakdown. Extreme care should be taken when machining static-pressure taps that are flush to the wall, with no jagged edges. Various types of pressure transducers are available for measuring the static pressure. For waterjet tests, the ITTC (2005a) recommended that one should measure the static pressure within an accuracy of ±0.5% of its true value.

2.3.4 Total-Pressure Measurements.

Pump tests should include total-pressure probes, such as Kiel probes. The inlet total pressure is required to compute the NPSH. Alternatively, one could acquire LDV velocity measurements in the same axial plane as the static-pressure tap located upstream of the pump (and then infer the value of total pressure). These measurements provide the total head available to the pump blade rows, or NPSH,

$$NPSH = \left(h_s + \frac{V_s^2}{2g} \pm \Delta z \right) - \frac{p_V}{g\rho} \tag{2.3}$$

where h_s is the static head equal to the static pressure divided by the weight per unit volume of the fluid ($g\rho$), V_s is the fluid velocity at the place where h_s is measured, and Δz is the difference in elevation between the point where h_s is measured and the point of cavitation.

In addition, the measurement of the total pressure downstream of the pump is necessary to determine the total-head rise across the pump. For waterjet tests, the ITTC (2005a) recommended that one should measure the total head within an accuracy of ±1.0% of its true value.

2.3.5 Shaft Torque and Thrust.

One can determine cavitation breakdown from the measurement of some powering parameter as a function of NPSH - or some other parameter that characterizes the cavitation condition, such as the cavitation number, Thoma’s cavitation factor, or the suction specific speed. The powering parameter can be the total-head rise across the pump, the shaft torque, or the shaft thrust.

One can measure the shaft torque using a dynamometer, or torque cell with strain gauges, in the shaft line. It is essential to keep the shaft friction losses as low as possible, and these losses should, if possible, be recorded separately during the test, for instance by running the pump in air or by removing the pump impeller. Alternatively, one could integrate a dynamometer into the hub in order to avoid friction losses. The ITTC (2005a) recommended that one should measure the shaft torque within an accuracy of ±0.5% of its true value.

One can measure the shaft thrust using a force transducer, or load cell with strain gauges, in the shaft line. This floating force transducer is separated from its environment by a small gap, which requires special attention to avoid large forces in the thrust direction. The ITTC (1999) recommended that one should measure thrust within an accuracy of ±2.0% of its true value.

2.3.6 Velocity Measurements.

As with cavitation inception, experimental modelling of cavitation thrust breakdown does not necessarily require flow-field velocity measurements. However, one again may choose to acquire velocity data to quantify the pump inflow, to compare with the pump design intent, and to compare with numerical modelling. LDV provides the best direct measurements of flow-field velocities and turbulence intensities, but one can infer the velocities (less accurately) from total- and static-pressure measurements.

2.3.7 Cavitation Breakdown Test Procedure.

For a given operating point of flow rate and total-head rise for the pump, one can measure the cavitation breakdown by reducing the tunnel pressure at a constant tunnel velocity and impeller rpm. Using the measurement of the tunnel pressure, one can quantify or characterize the cavitation by calculating the NPSH, the cavitation number, Thoma’s cavitation factor, or the suction specific speed.

Starting at a high tunnel pressure with no cavitation, the initial reduction in tunnel pressure will not affect powering parameters such as the total-head rise, the shaft torque, or the shaft thrust. Adequate visual access will allow one to document the tunnel pressure where visual cavitation inception will occur, as well as the type and location of the cavitation inception. Further reduction in tunnel pressure will eventually lead to a major deterioration in the powering performance of the pump. The critical NPSH or cavitation number for this breakdown in performance is typically defined as a 3% loss in thrust, torque, or total-head rise across the pump (although values of 2% and 5% have also been used).

For axial-flow pumps, a cavity will form on the suction surface of the rotor blades, which can initially increase the blade camber - and, thus, the flow turning and blade lift - and cause a small increase in the powering parameters. However, as the static pressure further decreases towards the breakdown NPSH or cavitation number, the cavity will enlarge and decrease the flow turning, causing a significant reduction in the powering parameters. For radial-flow (or centrifugal) pumps - which are rarely used within modern waterjets—the cavity may need to grow to the point where it blocks a significant portion of the impeller channel before finally resulting in performance breakdown.

2.4 Cavitation Erosion Tests

Cavitation erosion testing for waterjet impellers can follow the procedure recommended by the ITTC (2005b) for soft-paint experiments on model-scale propellers and rudders.

3. NUMERICAL MODELING OF WATERJET CAVITATION

While numerical modelling of cavitation phenomena has existed for many years, the complexity of both the physics of the flow fields and the geometry of the applications can lead to a lack of confidence in computational simulations of cavitating flows. However, with the high cost and time required for experimental modelling of cavitation behaviour in waterjets, many organizations have relied more and more on numerical modelling. Thus, improving the confidence in these numerical models is at the very heart of predicting waterjet cavitation behaviour.

For numerical modelling of the behaviour of cavitation in waterjets, this guideline provides information on the current status of numerical modelling for the cavitation phenomena that occur in waterjets.

3.1 Cavitation Inception

For cavitation inception, where the volume of the cavitation is a very small percentage of the flow field, one can suitably assume that the existence of the cavitation will have a negligible impact on the flow. Therefore, one can numerically model the bulk flow field and then use that simulation as input to numerically model the bubble dynamics, if desired. The simulation of the bubble dynamics will not influence the simulation of the bulk flow field.

Numerical analysts have had success in modelling surface (sheet) cavitation inception by solving the Reynolds-averaged Navier-Stokes (RANS) equations. Following the proper use of the RANS solver, such as using adequate grid quality, the minimum static-pressure region near a solid surface will correspond closely with the region of surface cavitation inception. While unsteady flow phenomena can alter this result, these types of simulations have matched well with experimental results for visual observation of inception.

While RANS simulations have proven successful in determining the minimum static-pressure region near a surface, they have not been very successful in determining the minimum static-pressure region within a vortex core. Obtaining adequate grid resolution within the vortex core is certainly one problem, but the effects of unsteady flow phenomena are an even greater problem, including unsteadiness due to turbulent-flow structures. Traditional turbulence modelling within a RANS solver *averages out* the unsteadiness of these turbulent-flow structures. Therefore, numerical modelling of vortex cavitation inception requires a direct simulation of the larger, energy-containing turbulent scales. Large-eddy simulation (LES) has become a more mature method to model these important turbulent scales, but the computational costs remain prohibitively large. However, methods like detached-eddy simulation (DES) allow one to compute these important turbulent scales only in the areas of interest, reverting to a RANS simulation elsewhere. These types of methods are beginning to make the numerical modelling of vortex cavitation inception possible, but they still remain primarily a research topic.

3.2 Cavitation Performance Breakdown

The most detrimental effect of cavitation within a waterjet involves the breakdown of pump performance parameters such as thrust, torque, and total-head rise. Recent investigations have led to the development of multiphase flow models using three-dimensional RANS solvers that have shown some promising numerical simulations of cavitation breakdown for pumps and propellers. Multiphase flow modelling is further advanced for cavitation breakdown, since it is a more global cavitation event, not a local event such as cavitation erosion. These methods should be utilized in future modelling of cavitation breakdown in waterjet pumps.

3.3 Cavitation Erosion

The prediction of erosion due to cavitation is very difficult because micro-scale bubble dynamics play an important role. Therefore, numerically modelling the behaviour of cavitation erosion is a research topic in its infancy. Researchers have pursued two approaches to this multiphase flow modelling problem. The first approach uses a cavitation model that includes modelling of the micro-scale bubble dynamics, which estimates the impulsive pressure directly. The second approach models the relationship between the fluctuation of the void fraction and the occurrence of erosion. To date, both approaches have predicted erosion areas that qualitatively agree with experimental data, but much further research is required to achieve quantitative predictions, especially for the complex geometry and flow fields found in a waterjet pump.

4. SCALING OF WATERJET CAVITATION

As discussed previously, one attempts to quantify or categorize cavitation performance using the cavitation number (or some related parameter). When using experimental modelling to determine the behaviour of cavitation in a waterjet, test facilities usually dictate the use of model-scale hardware. Unfortunately, the cavitation number that characterizes a cavitation phenomenon at model scale may differ for the full-scale prototype hardware. These differences result from cavitation-scale effects. This guideline has already discussed two of these effects, namely the method of cavitation detection (visual or acoustic) and water quality. The ITTC (2002a) provided in-depth discussion of the effects of water quality.

Other cavitation-scale effects can include Reynolds-number effects, geometry effects (such as surface roughness or manufacturing tolerances), turbulence, and the residence time that nucleation sources spend within low-pressure regions of the flow.

The scaling of cavitation inception depends strongly on whether one is concerned with surface (sheet) cavitation inception or vortex cavitation inception. For experimental models with geometric similarity, one is usually not able to run the model-scale test at the full-scale Reynolds number. However, for surface (sheet) cavitation inception, after one accounts for water-quality effects, Reynolds-number effects may be small and are usually neglected. The exception can be for the Reynolds-number effects on flow separation, which can influence cavitation on a waterjet inlet. However, for a waterjet inlet, dynamic similitude of the incoming boundary layer is probably more important than Reynolds-number effects. The biggest problem is that modelling the highly unsteady, three-dimensional boundary layer that a full-scale waterjet ingests at sea is probably impossible in a model-scale test facility. For the waterjet pump, cavitation inception probably occurs in the tip-leakage vortex rather than on the rotor-blade surface, so the Reynolds-number effects on surface cavitation may not be of primary importance anyway.

For vortex cavitation inception, one traditionally scales the inception cavitation number using some form of the equation presented by McCormick (1962),

$$\left(\frac{\sigma_{\mathrm{i,fullscale}}}{\sigma_{\mathrm{i,modelscale}}}\right)=\left(\frac{\mathrm{Re}_{\mathrm{fullscale}}}{\mathrm{Re}_{\mathrm{modelscale}}}\right)^{\mathrm{m}} \tag{4.1}$$

Using this equation as a basis, the ITTC (1996) presented an empirical equation for scaling rotor-blade-tip cavitation inception,

$$\sigma = const\left(C_L\right)^a\left(\frac{\overline{W}_{\mathrm{tip}}}{V_{\mathrm{ref}}}\right)^2 Re^m \tag{4.2}$$

where C_L is the average of the lift coefficients over some finite span of the rotor-blade tip, $\overline{W}_{\mathrm{tip}}$ is the mean relative velocity at the rotor-blade tip, V_{ref} is a reference velocity (such as ship speed), and Re is the Reynolds number based on $\overline{W}_{\mathrm{tip}}$ and the chord length of the rotor-blade tip. The ITTC (1996) gives a theoretical value of

2 for the exponent a. Many researchers have suggested empirical values for the proportionality *constant* and the exponent m. Again, one must also take water-quality effects into account. Each organization has to determine their own empirical exponents and proportionality *constant* using their own comparisons between model- and full-scale results.

The ITTC (2005c) presented an extensive overview of scaling effects for cavitation erosion. Most efforts to determine this type of scaling concentrate on pitting damage rate and the volume damage rate of controlled samples, with most researchers using the incubation period of material to analyze the flow and study the scaling effects.

Very little information is available for the Reynolds-number scaling effects for cavitation performance breakdown. Since cavitation breakdown is most often related to surface (sheet) cavitation, Reynolds-number scaling effects for cavitation breakdown are normally neglected.

Finally, numerical modelling of the behaviour of waterjet cavitation should theoretically allow for at least the Reynolds-number scaling effects, since one can use these models to simulate flows at both model-scale and full-scale Reynolds numbers. However, this guideline has already discussed the issues regarding numerical modelling of waterjet cavitation. While practitioners will continue, and should continue, to employ numerical models to determine the behaviour of cavitation in waterjets, they need to be aware of the issues in using these models.

5. REFERENCES

ASME (American Society of Mechanical Engineers), 1989, "Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi," ASME MFC-3M-1989.

ITTC (International Towing Tank Conference), 1996, "Report of Cavitation Committee," 221st ITTC, Trondheim, Norway, pp. 63-126.

ITTC (International Towing Tank Conference), 1999, "Report of the Specialist Committee on Waterjets," 22nd ITTC, Seoul, South Korea and Shanghai, China, pp. 587-613.

ITTC (International Towing Tank Conference), 2002a, "Report of the Specialist Committee on Water Quality and Cavitation," 23rd ITTC, Venice, Italy, pp. 459-491.

ITTC (International Towing Tank Conference), 2002b, "Model-Scale Cavitation Test," ITTC Recommended Procedures and Guidelines: Testing and Extrapolation Methods for Propulsion and Cavitation.

ITTC (International Towing Tank Conference), 2005a, "Waterjet Propulsive Performance Prediction - Waterjet Inlet Duct, Pump Loop, and Waterjet System Tests and Extrapolation," ITTC Recommended Procedures and Guidelines: Testing and Extrapolation Methods for High Speed Marine Vehicles and Waterjets.

ITTC (International Towing Tank Conference), 2005b, "Cavitation Induced Erosion Damages Soft Paint Model Scale Experiments," ITTC Recommended Procdures and Guidelines: Propulsion and Cavitation.

ITTC (International Towing Tank Conference), 2005c, "Report of the Specialist Committee on Cavitation Erosion on Propellers and Appendages on High Powered/High Speed Ships," 24th ITTC, Edinburgh, United Kingdom, pp. 509-542.

ITTC (International Towing Tank Conference), 2008, “Report of the Specialist Committee on Cavitation,” 25th ITTC, Fukuoka, Japan.

McCormick, B. W., 1962, “On Cavitation Produced by a Vortex Trailing from a Lifting Surface,” Journal of Basic Engineering, Transactions of the American Society of Mechanical Engineers (ASME), pp. 369-379.