The Specialist Committee on Scaling of Wake Field

Technical Committees and Group of the 26th ITTC
Members of the Specialist Committee

- **Thomas C. Fu (Chairman)**
  Naval Surface Warfare Center
  Carderock Division (NSWCCD)
  W. Bethesda, MD, U.S.A.

- **Ali Can Takinaci (Secretary)**
  Istanbul Technical University
  Faculty of Naval Architecture and Ocean Engineering
  Istanbul, Turkey

- **María J. Bobo**
  Canal de Experiencias Hidrodinámicas de El Pardo (CEHIPAR)
  Madrid, SPAIN

- **Wojciech Gorski**
  Ship Design and Research Center (CTO-SA)
  Gdansk, POLAND

- **Christian Johannsen**
  Hamburgische Schiffbau-Versuchsanstalt (HSVA)
  Hamburg, GERMANY

- **Hans-Jürgen Heinke**
  Schiffbau-Versuchsanstalt Potsdam (SVA Potsdam)
  Potsdam, GERMANY

- **Chiharu Kawakita**
  Mitsubishi Heavy Industries, Ltd (MHI)
  Nagasaki, JAPAN

- **Jin-Bao Wang**
  Marine Design & Research Institute of China (MARIC)
  Shanghai, CHINA
Past Committee Meetings

- Madrid, Spain, February 2009
  Canal de Experiencias Hidrodinámicas de El Pardo (CEHIPAR)

- Hamburg, Germany, October 2009
  Hamburgische Schiffbau-Versuchsanstalt (HSVA).

- Shanghai, China, June 2010
  Marine Design & Research Institute of China (MARIC).

- Istanbul, Turkey, February 2011
  Istanbul Technical University (ITU) Faculty of Naval Architecture and Ocean Engineering.
Tasks

1. Define the **physical nature** of wake.
2. Review the existing **scaling methods** and available full-scale data.
3. Review the applicability of **CFD methods** for the prediction of full-scale wake.
4. Address the available options for **simulating full-scale wake** both **numerically** and **experimentally** including the limitations of existing test procedures.
5. Write **guidelines** for methods of scaling of wake fields. Conduct a **survey of numerical methods** for prediction of wake-fields at model and full-scale.
Topics

1. Background
2. Survey Results
3. Review of Existing Wake Scaling Methods
4. Viscous Numerical Simulation of the Full-Scale Wake Field by RANS
5. Prediction of Ship Wake Pattern from Geosim Studies
6. Comparison of Methods
7. Experimental Methods for Full-Scale Wake Simulation
Background

• The Physical Nature of Wakes
• Wake Field Scaling
• Measurement of Full-Scale Wakes
Physical Nature of Wakes

- **Wake**: Disturbance flow field caused by the relative motion between a hull form and a uniform incident flow parallel to the hull longitudinal center plane

- **Nominal wake field**: Field measured at the propeller plane without the presence or influence of the propeller

\[
[w_n] = [w_p] + [w_v] + [w_w] + [\Delta w]
\]
Physical Nature of Wake

- **Effective** or **Total** Wake
  - Flow through the propeller for a given vessel related to the power transmitted by the propeller
  - If the interaction between the propeller and ship prevents flow separation, the normal relation between nominal and effective wakes will be influenced.
Wake Field Scaling

• For propeller design it is necessary to scale the wake measured from the model.
  – **Contraction methods**, which are the most popular methods, take a measured nominal wake as a starting point and then reduce, in different ways, the “width” of the wake.
  – Most scaling methods deal with the **axial velocities only**. In most design situations the usual practice is to scale the nominal wake field from model scale to ship scale and then find the effective wake field at ship scale from the derived effective wake model.
Measurement of Full-Scale Wakes

- Two Types of Total Wake Measurements
  - Utilizing probes in the flow
  - Optical Measuring Techniques (Laser Doppler Velocimetry)
- Possible Particle Image Velocimetry (PIV) use in the future

*LDV system for full-scale wake measurements*
Survey Results

• Wake Scaling
• Experimental Testing
• Wake Simulation
• Numerical Wake Predictions
Wake Scaling

• The purpose of this scaling was mainly propeller design and cavitation investigation.
• Secondary purposes were input wake simulation and acoustic testing, as well as CFD validation.
• Effective wake and average values were of secondary importance.
Experimental Testing

- The experimental testing facilities are mainly Close Type Cavitation Tunnel and Towing Tank. Other types of facilities are in the minority.
Wake Simulation

• Testing facilities commonly use wire screens, dummy hull models, and full hull models for wake simulation.

• Additional wire screens are not used in facilities using full hull models; however, additional wire screens are used in facilities using dummy models.

• Scale effect correction is not generally used in the facilities using dummy model or wire screen to produce simulated wake based on wake survey data from towing tanks.
Numerical Wake Predictions

• The **majority** of institutions use **CFD wake results**.

• The purposes of the CFD results are mainly hull quality assessment, hull optimization and propeller design input. Most of the CFD predictions are **performed at full-scale**.

• Most of the CFD simulations are used without the contribution of the free surface, but with propeller modelling usually by body forces.
Review of Existing Wake Scaling Methods

• Wake Scaling Using Simple Methods
• Wake Scaling Using CFD Methods
• Correction of a Measured Wake Field with CFD Results
• Boundary Layer Derived Wake Scaling Methods
  – Method from Sasajima
  – Method from Dyne
  – Method from Hoekstra
  – Method from Tanaka
  – Method from Garcia
  – Method from Mehlhom
  – Method from Nagamatsu
  – Method from Tanaka Ichiro
Review of Existing Wake Scaling Methods

• This section provides details for the numerical wake scaling in connection with propeller calculations and cavitation tests in model basins.

• It deals with considerations regarding computational fluid dynamics (CFD) methods to predict a full-scale wake field on the basis of RANS calculations as well as on the use of measured model-scale wake fields and application of scaling procedures.
Review of Existing Wake Scaling Methods

• The comparison of calculated wake fields for model and full-scale shows in general, that the **thickness of the boundary layer** at the ship is **relatively smaller** than on a model (Figures 3 and 4). The result is a **smaller wake peak** and a **larger wake gradient**.

Figure 3: Calculated Wake Fields - Tanker “Ryuko Maru”

Figure 4: Calculated Wake Fields – Container Ship “Ville de Mercure”
Wake Scaling Using Simple Methods

- **Simple method** refers to the use of **one scaling factor** for whole wake field
  - e.g. ITTC recommended formula:

  \[
  w_{TS} = (t + 0.04) + (w_{TM} - t - 0.04) \frac{(1 + k)C_{FS} + \Delta C_F}{(1 + k)C_{FM}}
  \]

- Other scaling factors are imaginable.
Wake Scaling Using CFD Methods

• There are existing methods which are based on available model data and use CFD to compute the full-scale effect (meaning the difference in field distribution in model and full-scale) in order to extrapolate the model measured wake values to full-scale.
Boundary Layer Derived Wake Scaling Methods

- The following wake scaling methods are based on the proportionality between boundary layer thickness and the coefficient of the friction resistance of the ship.
- The characteristic of the nominal wake field will be mostly similar in model and full-scale.
- This is why the contraction of the model wake field is the simplest way to predict a full-scale wake field. The contraction of the boundary layer is the basis of a number of different methods.
Boundary Layer Derived Wake Scaling Methods

Method from Sasajima

- This method (1966) is based on the determination of the total wake and potential wake, towing the model astern.
- The values used for the extrapolation are taken, on the potential and total wake charts, at the propeller plane in several horizontal sections parallel to the water plane.

Figure 5: Typical propeller plane wake chart
Boundary Layer Derived Wake Scaling Methods

Method from Sasajima

• The width of wake is in proportion to the momentum thickness and not to the scale of model and ship.
• Velocity distribution in wake varies downstream as a function of non-dimensional distance divided by momentum thickness.
• The value of the wake peak is affected significantly by the difference of the velocity profile at the stern frame between model and ship.
Boundary Layer Derived Wake Scaling Methods

Method from Dyne

- Dyne’s method (1974) to determine the scale effect on the nominal wake, consists of carrying out wake measurements on a geosim series of models covering a large range of Reynolds numbers and studying the variation of the wake with $C_F$. 
Boundary Layer Derived Wake Scaling Methods

Method from Hoekstra

- Hoekstra’s method (1975) is based on the assumption that the wake components, $w_f$, $w_p$ and $w_w$, are not independent of each other.
- The wake contraction between ship and model affects the total wake and not only the frictional part of it.
- The total contraction of the nominal wake is threefold, namely contraction to the center plane, contraction to the hull above the propeller and a concentric contraction around the propeller axis.
Boundary Layer Derived Wake Scaling Methods

Method from Tanaka

- The main idea of Tanaka’s method (1979) is to consider the near-wake on the propeller plane as the result of the interpolation between the characteristics of the boundary layer at the stern and those of the far-wake downstream.

- The wave component of the wake is ignored and the ship is considered to lie between a two-dimensional body and a body of revolution.
Boundary Layer Derived Wake Scaling Methods

Method from García

- To avoid or at least mitigate the dependency of the wake extrapolation on the model scale and obtain a unique ship prediction no matter which model is used, García (1989) has developed a new method, based in Tanaka’s but introducing the dependency of the form factor on the model scale and its repercussion on the friction wake component.
Boundary Layer Derived Wake Scaling Methods

Method from Mehlhorn

• The method from Mehlhorn (1983) is based on the main assumptions from Hoekstra.
• The method for shifting of the coordinates in the propeller disc with help of the contraction parts for the determination of the ship wake had been modified.
Boundary Layer Derived Wake Scaling Methods

Method from Nagamatsu

• Nagamatsu presented a method (1979) to predict ship wake from measured model wake by applying the theory of two-dimensional turbulent wake.

• From basic investigations of a two-dimensional wing, the following physical properties of a turbulent wake were made clear with respect to the scale effect on viscous wake.
Boundary Layer Derived Wake Scaling Methods

Updated method from Tanaka

• The scale effects of the boundary layer and wake distribution of ships with bilge vortices are investigated as an extension of the author's previous paper on the same problem without bilge vortices (1983).

• It is assumed that the flow consists of the ordinary wake portion without bilge vortices and the vortex wake.

• The characteristics of the latter are discussed firstly with the main purpose of investigating the Reynolds number effects on the location of the vortex center, circulation, velocity and vortices distributions.
Viscous Numerical Simulation of the Full-Scale Wake Field by RANS

- From Model-Scale Simulation to Full-Scale Nominal Wake Simulation
- Twin-Screw Ship Arrangements
- Ships with Wake Influencing Devices
- From Full-Scale Total Wake Simulation to Full-Scale Nominal Wake
- Suggestions for Full-Scale Nominal Wake Simulation
Viscous Numerical Simulation of the Full-Scale Wake Field by RANS

• Advances in CFD software and hardware make it possible to numerically simulate full-scale wakes

• Two possible approaches
  1. Grid generation and calculation method to validate model-scale nominal wake simulations
  2. Validate the method for full-scale total wake simulation
Figure 10: Calculated wake fields – HTC ship (left)

Figure 11: Calculated wake fields – KCS ship (left)

Figure 12: Calculated wake fields - ITU ship (above)

At model scale, the CFD and experimental results agree with each other very well and the results for full-scale were also encouraging (Figure 10-12).
Twin-Screw Ship Arrangements

• Wake results from ship hull and the appendages such as shaft tube, propeller shaft, shaft brackets etc

Figure 13: Calculated wake fields of a navy ship for model and full-scale

Differences between the wake field of the model and the ship has a high influence on the accuracy of the predicted cavitation and acoustic behaviour of the ship.
Ships with Wake Influencing Devices

- Cavitation at the propeller
- Wake equalizing ducts (WED)
  - Change velocity field in the range of the wake peak making a more uniform propeller inflow

Vortex generators depend on the thickness of the local boundary layer. Produce a distinctly reduction of the wake peak

Figure 14: Calculated wake fields ship with Wake Equalizing ducts (above)

Figure 15: Calculated wake fields- ship with vortex generators fins (right)
From Full-Scale Total Wake Simulation to Full-Scale Nominal Wake

- Other method of simulating nominal wakes is to adopt full-scale total wake simulation

- EFFORT-project
  - Seven different hull forms studied showing that accurate viscous-flow computations are possible at full-scale

- Ability to apply full-scale total wake simulation methods to a full-scale nominal wake would be a convincing CFD calculation; however, difficult to achieve
Suggestions for Full-Scale Nominal Wake Simulation

Factors that influence the simulation of nominal wakes most

- Free Surface and Trim
- Turbulence Model
- Boundary Layer
- Grid Type and Quality
- Computation Factors
Free Surface and Trim

- Necessary to minimize the model errors for single phase wake calculations in order to calculate the wake field with required accuracy.
- Slow ship – unnecessary to consider the free surface as well as trim and sinkage.
- Moderate to high speed vessel follow this approach:
  - Essential to incorporate the stern wave in the calculations, due to the circumstance that the area in the propeller plane above the propeller may change considerably, which has a major impact on the wake peak.
  - The dynamic sinkage and trim has also to be taken into account. Particularly the outer radii of the propeller plane are influenced.
Boundary Layer

- Treatment of the boundary layer has a large effect on the wake field
- Thickness of the wall closest grid chosen carefully
- This condition, in general, implies the use of wall functions. Flow separation, due to an increasing pressure gradient, is considered as an issue with less importance at full-scale
Turbulence Modeling

- Two-equation turbulence models standard
- Shear-Stress-Transport (SST)
- Seven-equation Reynolds-Stress Transport (RSM) performs best among all the models
- Large eddy simulations demand more resources
- Two-equation models SST $k\omega$, with a low Reynolds-number formulation are considered still to be the choice for wake field calculations for production work
Grid Type and Quality

- Structured grids are better in predicting wake fields than unstructured ones
  1. Aspect ratios of numerical cells should be smaller than 100 in the undisturbed flow. For wall bounded flows in no-slip conditions much higher ratios are acceptable.
  2. The angle between cell’s faces has to be higher than 15°.
  3. Volume change between neighboring grid cells are not allowed to exceed the value of 20.
Computation Factors

- The computations have to be carried out in double precision mode.
- A second order discretization scheme is required for all items.
- If a RSM model is used, it’s advisable to perform kε model first to provide a good base for the RSM model regarding relaxation.
- Relaxation factors should be adjusted according to the used solver, in general higher values decrease the computational time however may impose problem with convergence. In such cases lower values down to 0.15 shall be used.
- A SIMPLE method is recommended to couple velocity and pressure equations.
The wake scaling methods proposed by Sasajima, Hoekstra, Tanaka, and Garcia have been applied to the geosim models of one cargo ship in order to obtain the configuration of the ship wake,

The prediction of the nominal wake configuration of the biggest model (scale 25) has been made from the results of the other two models (scales 34.4 and 60) applying the different extrapolation methods,

Sasajima, Tanaka and Garcia extrapolation methods give a good approximation to the experimental results while the Hoekstra extrapolations are not so close to the test results of the largest model. The same apply to other studies made with different series of geosim models.
Comparison of Methods

• Assessment of the Scaling Methods Based HTC, KCS, and ITU Ships
  – Methodology of Assessment
  – Results
  – Analyses

• Guidance for Wake Scaling
Assessment of the Scaling Methods Based HTC, KCS, and ITU Ships

• Review of the results of questionnaires submitted to the committee revealed that several different methods are in use for the purpose of wake scaling.

• Taking into account the observed differences between the towing tank wake measurements and model scale CFD results, it was decided for the purpose of consistency to use the CFD results for the model scale data as well.
Assessment of the Scaling Methods Based HTC, KCS, and ITU Ships

Methodology of Assessment

• The assessment was performed in two steps.
  1) The general agreement between the CFD derived full-scale wake and the full-scale wake obtained from a particular method was evaluated.
     • This assessment was done based on the visual analysis of the wake patterns (contour maps of the axial velocity, Figures 19-21).
  2) The method was evaluated using the standard wake assessment procedure proposed by Odabasi and Fitzsimmons (1978) and widely used by many organizations.
     • The aim at this point was to determine the propeller operational conditions imposed by the resulting full-scale wake with reference to the cavitation and pressure pulses.
Figure 19: Comparison of different scaling methods – HTC ship
Figure 20: Comparison of different scaling methods – KCS ship
Figure 21: Comparison of different scaling methods – ITU ship
Assessment of the Scaling Methods Based HTC, KCS, and ITU Ships Analyses

- None of the analyzed methods give perfect agreement with the full-scale CFD results.
  - Some of the methods (Mehlhorn, Hoekstra) gave somewhat strange results which in general did not agree with the full-scale reference results, exhibiting for some cases unrealistic wake pattern (e.g. negative values of the wake fraction).
  - Other methods tend to underestimate the wake deficit (Garcia-Gomez, Tanaka) thus leading to reducing the safety margin in terms of propeller cavitation.
  - The most applicable although still not ideal was the Sasajima method which performed relatively well especially in the upper part of the wake field.
Guidance for Wake Scaling

• It is believed that, to date, the best approximation of the full-scale nominal wake can be obtained using high resolution CFD calculations. Therefore it is suggested to use this technique whenever applicable and feasible.

• The Sasajima method of wake scaling is not only the most commonly used but also provides the results with lowest discrepancy from the full-scale CFD wake prediction.
Experimental Methods for Full-Scale Wake Simulation

- Direct Simulation of a Target Wake Field
- Model Wake Field from a Complete Model
  - Scaling by Water Speed Increase
  - Scaling by Flow Guiding
  - Scaling by Model Shortening
  - Scaling by Adjustment of a Local Significant Advance Coefficient
  - Scaling by Hull Surface Treatment
- Model Wake Field from a Dummy Model
- New Concept of using ‘Smart Dummy’ Models
Experimental Methods for Full-Scale Wake Simulation

• The **goal** in general of full-scale wake simulation for experiments is to generate a wake field for a **cavitation test**, which **represents, as well as possible, the propeller inflow** as it is expected to be in reality.

• The methods described focus on considerations regarding experimental methods to tune a model scale wake field in a cavitation tunnel towards a target wake field.
Model Wake Field from a Complete Model
Scaling by Water Speed Increase

- Cavitation tests in a large cavitation tunnel without free surface are normally conducted at much higher speed than would result from Froude's scaling law.
- This speed increase results in a higher Reynolds number generating a more full-scale-like wake field.
- Since principally propeller load and cavitation number can be adjusted at any tunnel water speed in a cavitation tunnel, this freedom gives the opportunity to tune the wake field towards the full-scale wake.
- A high tunnel water speed can therefore be regarded as one efficient mean for wake scaling.
Model Wake Field from a Complete Model
Scaling by Flow Guiding

- The tunnel walls of a cavitation tunnel force the water particles to go straight along the tunnel wall.

- To avoid this wake deformation, one can install **so-called flow liners**, which can be used to tune the flow not only towards the unrestricted (tank) situation, but even towards the high Reynolds number full-scale situation.

Figure 25: Flow liners in a cavitation tunnel using a complete ship model for wake simulation.
Model Wake Field from a Complete Model

Scaling by Model Shortening

- Shortening the ship model is a well known technique to **reduce the boundary layer thickness**, making the frictional model wake more similar to full-scale.

\[ l_{\text{shortened model}} = l_{\text{ship}} \left( \frac{V_{\text{tunnel water}}}{V_{\text{ship}}} \right)^{0.111} \cdot \lambda^{-1.111} \]

An easy relation to estimate the required shortening can be derived from simple flat plate boundary layer considerations according to Johannsen (1992)

Figure 26: Shortening of a container vessel model.
Model Wake Field from a Complete Model

Scaling by Adjustment of a Local Significant Advance Coefficient

- Normally, the tunnel water speed is adjusted to meet a certain $K_T$-value for the model propeller (thrust identity).
- This $K_T$, however, is an integral value, and for wake scaling purposes it can be worthwhile to deviate from the resulting speed to achieve full-scale identity of a local advance coefficient $J$ instead.
- If so, $J$-identity should be achieved in the same region as described above with respect to the cavitation number, i.e. in the region of maximum wake.
- Due to scale effects the 12 o'clock wake peak behind the ship model is generally deeper than at full-scale and compensation of this scale effect will require a higher tunnel water speed than obtained from $K_T$-identity.
Model Wake Field from a Complete Model
Scaling by Hull Surface Treatment

• Due to the low Reynolds number at model scale, flow separation may occur earlier on the hull than on the real ship.

• It is possible to reduce this scale effect to some extent by surface treatment of the model hull. Sand roughening or wire screens along the surface are in use for this purpose.

• This technique, however, should be handled with care since the unrealistic surface roughening might also stimulate unrealistic cavitation.
Model Wake Field from a Dummy Model

• A dummy model should be used in medium sized cavitation tunnels for cavitation tests and pressure fluctuation measurements.

• The wake field of the dummy model at a given inflow speed should be measured to get the necessary information regarding the wake field simulation.

• Typically, the wake of a small dummy model results in a wake peak that is even less pronounced than in full-scale; wire mesh screens can therefore be mounted perpendicular to the hull to simulate the predicted full-scale propeller inflow.
New Concept of Using ‘Smart Dummy’ Models

- The Smart Dummy is a geometrically non-similar ship model with full-scale wake field resemblance; this concept is to simulate the wake scale effect in cavitation tests.

Figure 27: View from behind the Smart Dummy design (left), and the original geosim hull (right).

Figure 28: Axial wake velocities of the Smart Dummy design (left) compared to those at ship scale (right).
Limitations

• In cases where no experimental wake scaling can be used in a cavitation experiment, one should at least be aware of the effects that this deficiency may cause:
  – over prediction of suction side cavitation extent
  – inception of suction side cavitation at lower cavitation numbers already
  – under prediction of pressure side cavitation extent
  – over prediction of safety margin against face cavitation inception
  – over prediction of first harmonic hull pressure pulses
  – influence on higher harmonic pressure pulses in either direction
Recommendations

• Acceptance of the one new procedure “Experimental Scaling of a Model Wake to a Target Wake”

• Adoption of the changes to the four existing procedures to reference the new guidelines:
  • 7.5-02-03-03.1: Model-Scale Cavitation Test
  • 7.5-02-03-03.3: Cavitation Induced Pressure Fluctuations Model Scale Experiments
  • 7.5-02-03-03.5 Cavitation Induced Erosion on Propellers, Rudders and Appendages
  • 7.5-02-03-03.6: Podded Propulsor Model-Scale Cavitation Test
Recommendations

- That the Specialist Committee on CFD develops procedures for Simulating Model Scale and Full-Scale Nominal Wakes,
  - and specifically focus on the use and validation of CFD methods for full-scale wake prediction,
  - and explores other techniques for direct numerical simulation of wakes (LES, DNS, SPH, etc).

- That the Propulsion Committee examines and monitors other methods of target wake simulation, e.g. the “smart” dummy approach.
Thank-you
Any questions?