Evaluation of Surface-Ship Resistance and Propulsion Model-Scale Database for CFD Validation*

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An evaluation is performed of the surface-ship model-scale database for computational fluid dynamics validation with regard to current status and future uses and requirements. The specific emphasis is on data of relevance to resistance and propulsion and validation of Reynolds-averaged Navier-Stokes codes. The data is evaluated relative to criteria developed for geometry and flow, physics, computational fluid dynamics validation, and full scale as well as past uses. Conclusions are made with regard to the available data and past uses and recommendations are provided for future uses of the available data and future data procurement.

INTRODUCTION

Rapid advancements in the development of computational fluid dynamics (CFD) and experimental fluid dynamics (EFD) provide the necessary tools for realisation of simulation based design. However, validation and calibration are also required, which creates the need to maintain a current evaluation of databases for CFD validation with regard to status and future uses and requirements. This is the goal of the present study with specific focus on the surface-ship model-scale database and on data of relevance to resistance and propulsion and validation of Reynolds-averaged Navier-Stokes (RANS) codes. This is a continuing effort and updates (Longo and Stern, 1996; ITTC, 1996) in preparation for the 22nd International Towing Tank Conference (ITTC) and the Gothenburg 2000 CFD Workshop. The Gothenburg 2000 CFD Workshop will compare viscous CFD codes and data for cargo/container, combatant, and tanker hull forms with and without a free surface. A database evaluation was also done recently for aerospace applications (Marvin, 1995); however, the emphasis is more on building block experiments than practical geometries.

The previous evaluations (Longo and Stern, 1996; ITTC, 1996) are updated by down selection and inclusion of both unbeknownst and newly acquired data. The down selection is based on the recommendations of (ITTC, 1996) for cargo/container [Hamburg Test Case (HTC)], combatant [David Taylor Model Basin (DTMB) model 5415 (5415)], and tanker [Ryuko-Maru (RM)] geometries which required that full-scale data and/or ship existed along with the Series 60 C_B=.6 (S60) cargo/container and HSVA tanker geometries since the data and previous use are extensive. Unbeknownst data for a tanker (DAIOH) and newly acquired data for cargo/container (KCS) and tanker (KVLCC) geometries are also included since the data is extensive and holds promise for CFD validation. The data is organised in summary and detailed tables and evaluated using criteria developed for geometry and flow, physics, CFD validation, and full scale as well as past uses. Lastly, conclusions are made with

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regard to the available data and past uses and recommendations provided for future uses of the available data and future data procurement.

CRITERIA

In order to evaluate the data with regard to current status and future uses and requirements, criteria are developed for geometry and flow, physics, CFD validation, and full scale.

Geometry and flow

The geometry is restricted to practical surface-ship model-scale hull forms with or without appendages and/or propulsor. The facilities include towing tanks, circulating water channels, and wind tunnels.

The flow is restricted to conditions of interest to resistance and propulsion in distinction from seakeeping and manoeuvring. Many conditions are of interest, e.g., bare hull, appendages and/or propulsor, model size, hull-form variation, fixed or free model, tow point, turbulence stimulation, straight ahead calm water, ballast, restricted water, waves, yaw, double model, etc.

Physics

Many physics are of interest encompassing design variables for resistance and propulsion (forces and moments, sinkage and trim, wave profile, nominal wake, propulsion, etc.); geometry effects (model size, hull-form variation, flow control device, etc.); facility/experimental method effects (fixed or free model, tow point, turbulence stimulation, facility bias, etc.); and a myriad of flow phenomena, e.g., Re effects and scaling, boundary layer and wake, stern flow, turbulence, vortex flow and separation, Fr effects, wave breaking, bow flow, transom flow, propeller-hull interaction, wave-boundary layer and wake interaction, etc. The list of measured variables includes forces and moments, sinkage and trim, self propulsion, surface pressure and shear stress, wave profiles and elevations, mean velocity and pressure, and turbulence (i.e., Reynolds stresses). Physics is referred to as multi-issue, comprehensive, or limited.

CFD validation

The process of CFD validation is generally accepted as providing an assessment of the credibility of a CFD solution through comparisons with a benchmark usually provided by experimental data. Specific definition is lacking as is generally the case for the overall process of CFD uncertainty assessment, as discussed more later in conjunction with the evaluation of past uses. For the present, suffice to say that the documentation, quality, and quantity of the data should be sufficient for validation of RANS CFD codes.

Documentation. The documentation of the data is measured by the level of the detailed reporting of the geometry, conditions, and experimental methods; analysis of the data with regard to the physics of interest; and availability/usability. Although many of the studies are motivated both for explication of the flow physics and CFD validation, the documentation varies considerably. A consensus is needed for documentation, including archiving and dissemination. Documentation is referred to as detailed, partial, or limited.

Quality. The quality of data (i.e., uncertainty assessment) is measured through rigorous application of experimental uncertainty assessment methodologies. Unfortunately, reporting of experimental uncertainties continues to be a problem, including implementation procedures (e.g., simple repeat tests are often done in lieu of careful estimates for bias and precision limits) and documentation and presentation of results. This was one reason for the recent development of the AIAA Standard (AIAA Standard, 1995) for experimental uncertainty assessment methodology. The AIAA Standard (AIAA Standard, 1995) includes guidelines and examples for application of the experimental uncertainty assessment methodology for wind-tunnel tests. Similar guidelines and examples are needed for towing-tank tests. This will also provide values for expected uncertainties for towing-tank tests, which are also needed. The detailed tables include values for the reported uncertainties, which are useful in providing estimates for expected uncertainties for towing-tank tests. Quality is referred to as rigorous, partial, or none.

Quantity. The quantity of data is measured with regard to resolution of the flow physics. For this purpose, the data should be sufficiently dense for evaluation of the dominant terms in the RANS, continuity, and auxiliary (turbulence model, etc.) equations and other variables of interest (e.g., vorticity) and the dominant terms in their governing equations; however, equipment limitations and time and cost constraints are limiting factors such that this is practicably impossible. Quantity is referred to as large mapping and dense, large mapping and coarse, partial mapping and dense, or partial mapping and coarse.

Full scale

Validation and calibration ultimately must be done at full scale; however, full-scale testing is largely confined to speed trials and very much complicated by environmental conditions. Furthermore, relatively few CFD studies have included full-scale Re and/or environmental conditions. Thus, full-scale testing and CFD are beyond the scope of the present evaluation. Nonetheless, geometries are preferred for which full-scale data and/or ship exist. The existence of full-scale data and/or ship is indicated in discussions and the available full-scale data is included along with the available model-scale data in the detailed tables. The facility for full-scale data is referred to as the sea.

EVALUATION

Table 1 provides a summary of the database and is organised by hull form: cargo/container (S60, HTC, KCS); combatant (5415); and tanker (HSVA, RM, DAIOH, KVLCC). There are a total of 23 studies and 37 references: 6 studies for the S60 (ITTC, 1984; ITTC, 1987; ITTC, 1990; Fry and Kim, 1985; Ogiwara and Kajitani, 1994; Toda et al., 1990; Toda et al., 1992; Longo et al., 1993, Longo and Stern, 1996; Garofallidis, 1996; Suzuki et al., 1998a); 4 studies for the HTC (Lammers et al., 1989; Bertram et al., 1992; Bertram et al., 1994, Gietz and Kux, 1995; Suzuki et al., 1998b); 2 studies for the KCS (Van et al., 1997; Van et al., 1998b; Lee et al., 1998); 3 studies for 5415 (Fry and Kim, 1985; Ratcliffe, 1998; Longo and Stern, 1999; Avanzini et al., 1998; Olivieri and Penna, 1999; Olivieri et al., 1998); 4 studies for the HSVA (Hoffmann, 1976; Knaack, 1984; Knaack, 1990, Denker et al., 1992; Knaack, 1992; Lundgren and Ahman, 1994; Dyne, 1995); 2 studies for the RM (Suzuki et al., 1998b; Ogiwara, 1994, Suzuki et al., 1998c); 2 studies for the DAIOH (Tanaka et al., 1984; Kasahara, 1985); and 2 studies for the KVLCC (Van et al., 1998a; Van et al., 1998b). The facility, propulsor condition, and list of measured variables are indicated.

Tables 2-8 provide detailed tables for all the studies and data for S60, HTC, KCS and KVLCC, 5415, HSVA, RM, and DAIOH, respectively. Figures 1-8 provide body plans and bow and stern profiles and representative results for each hull form (in the same order as the summary table 1).

The database for each hull form and geometry is evaluated based on the criteria. Subsequently, past uses are discussed.

Criteria

Cargo/container. Data is available for 3 cargo/container geometries (S60, HTC, and KCS). There are 12 studies and 19 references.

For the S60, there are 6 studies and 11 references (table 2 and figure 1). The S60 geometry was conceived to provide systematic information on the design of lines for single-screw merchant ships ca. 1950 with clipper bow and cruiser stern. The parent form, C_B=0.6, was designed based on considerations of then successful ship designs. A full account of the original methodical series is provided by (Todd, 1963). Since conception, the S60 has been used for innumerable experimental studies and the data used extensively as a CFD benchmark. In particular, it was one of the four hull forms [along with Wigley hull (idealised), ATHENA (combatant), and HSVA] selected for the Cooperative Experimental Program (CEP) of the Resistance and Flow Committee of the 17, 18, and 19th ITTC (ITTC, 1984; ITTC, 1987; ITTC, 1990). Subsequent to the CEP, several extensive studies were performed. A wide range of conditions and physics have been investigated. The conditions include, bare hull with and without propeller, model size, fixed and free model, tow point (axial position and height), shallow water, yaw, turbulence stimulation, and double model. The physics are multi-issue and include, model size, fixed and free model, tow point, facility bias, turbulence stimulation, Re effects and scaling, Fr effects, bow flow, stern flow, propeller-hull interaction, wave-boundary layer and wake interaction, vortex flow and separation, wave breaking, and turbulence. All studies have detailed documentation, including availability. The quality of data is only partial, except for the two most recent studies, which are rigorous. However, most of the data is of relatively small uncertainties. The quantity of data for most studies is large mapping and dense, which is of relatively high density. No full-scale data and/or ship exist.

For the HTC, there are 4 studies and 5 references (table 3 and figure 2). The HTC was conceived to provide data for CFD validation for a relatively modern container ship ca. 1985 with a bulb bow and transom stern, including free-surface effects. Many conditions and physics have been investigated. The conditions include bare hull with and without propeller, fixed (velocities, pressure, wave elevation) and free (resistance and propulsion) model, and double model. The physics are comprehensive and include stern flow, Fr effects, propeller-hull interaction, and turbulence. The documentation is limited, although the data is available. The quality of data is partial, except the most recent study, which is rigorous. The uncertainties are close to the smallest. The quantity of data is partial mapping and coarse, which is of relatively coarse density. Full-scale data and ship exist.

For KCS, there are 2 studies and 3 references (table 4 and figure 3). The KCS was conceived to provide data both for explication of flow physics and CFD validation for a modern container ship ca. 1997 with bulb bow and stern. Some of the data is under procurement (as indicated in the tables). The conditions include bare hull and fixed model. The physics are limited and include stern flow and Fr effects. The documentation is partial, although the data is available. The quality is rigorous and the uncertainties are close to the smallest. The quantity is partial mapping and dense, which is of relatively high density. No full-scale data and/or ship exist.

Combatant. Data is available for 1 combatant geometry 5415 (table 5 and figure 4). There are 3 studies and 5 references, which are currently being conducted under an international collaborative study on EFD/CFD and uncertainty assessment between Iowa Institute of Hydraulic Research (IIHR), Istituto Nazionale per Studi ed Esperienze di Architettura Navale (INSEAN), and DTMB (Stern et al., 1998). 5415 was conceived as a preliminary design for a surface combatant ca. 1980 with a sonar dome bow and transom stern. About half the data is under procurement (as indicated in the tables), but should be available by early 1999. Many conditions and physics have been investigated. The conditions include bare hull with and without appendages and/or propulsor, fixed and free model, and model size. The physics are comprehensive and include model size, facility bias, Re effects, boundary layer and wake, stern flow, Fr effects, bow flow, transom flow, and wave breaking. All studies have detailed documentation, including availability. The quality of data is rigorous and of relatively small uncertainties. The quantity of data is large mapping and dense, which is of relatively high density. No full-scale data and/or ship exist.

Tanker. Data is available for 4 tanker geometries (HSVA, RM, DAIOH, KVLCC). There are a total of 9 studies and 14 references.

For HSVA, there are 4 studies and 7 references (table 6 and figure 5). The origins of the HSVA are not known. It represents a full-form tanker ca. 1970 with elliptical bow and cruiser stern. As noted earlier, it was one of the four hull forms selected for the CEP, although only very limited data was obtained under this program in comparison to the S60. Subsequent to the CEP, several extensive studies were performed. Many conditions and physics have been investigated. The conditions include bare hull with and without appendages and/or propulsor (for hull-form variation only), hull-form variation, and double model. The physics are comprehensive and include hull-form variation, Re effects, stern flow, turbulence, Fr effects, and propeller-hull interaction. The hull form variation (Dyne) has the same forebody lines as the HSVA, but more U-shaped stern sections in order to create stronger bilge vortices. The documentation is limited, except for the most recent study is detailed, although all the data is apparently available. The quality is partial and the uncertainties are close to the smallest. The quantity is partial mapping and dense, which is of relatively high density. No full-scale data and/or ship exist.

For RM, there are 2 studies and 3 references (table 7 and figure 6). The origins of the RM are not known. It represents a full-form tanker ca. 1970 with a bulb bow and cruiser stern. The conditions include double model. The physics include Re and scale effects, stern flow, and turbulence. The documentation is limited for the earlier study and detailed for the latter study, although all the data is apparently available. The quality is none for the earlier study and rigorous with relatively small uncertainties for the latter study. The quantity of data is partial mapping and coarse for the earlier study and partial mapping and dense for the latter study. Full- and intermediate-scale data are available. It is not known whether or not the full-scale ship remains in existence, but seems unlikely.

For DAIOH, there are 1 study and 2 references (table 8 and figure 7). DAIOH was conceived as an experimental full form tanker ca. 1970 with a bulb bow and cruiser stern. The conditions include bare hull with and without propeller and model size. The physics include model size, Re and scale effect, stern flow, and propeller-hull interaction. The documentation is limited, although all the data is apparently available. The quality is none and the quantity is partial mapping and dense. Full-scale data are available for resistance, propulsion, and manoeuvring performance. It is not known whether or not the full-scale ship remains in existence, but seems unlikely.

For KVLCC, there are 2 studies and 2 references (table 4 and figure 8). The KVLCC was conceived to provide data both for explication of flow physics and CFD validation for a modern tanker ship ca. 1997 with bulb bow and stern. Some of the data is under procurement (as indicated in the tables). The conditions include bare hull, hull-form variation, and fixed model. The physics are limited and include hull-form variation, stern flow, and Fr effects. The hull-form variation (KVLCC2) has the same forebody lines, but fuller afterbody lines, which create stronger bilge vortices. The documentation is partial, although the data is available. The quality is rigorous and the uncertainties are close to the smallest. The quantity is partial mapping and dense, which is of relatively high density. No full-scale data and/or ship exist.

Past uses

Computational uncertainty assessment has been the subject of considerable recent discussion, e.g., (Coleman and Stern, 1997; Mehta, 1998); nonetheless, consensus is lacking such that currently there are no recommended practices for computational uncertainty assessment, much less standards and guidelines. Hopefully, methods such as (Coleman and Stern, 1997), which are pragmatic in obtaining quantitative estimates for many simulation uncertainties and include proper consideration to both the experimental and simulation uncertainties in performing validation, will help in establishment of recommended practices for computational uncertainty assessment.

The lack of recommended practices for computational uncertainty assessment makes evaluation of past uses difficult; since, most studies are either lacking or deficient in this regard. This in turn makes discrimination of results difficult and moreover is confounded by user variability, which is significantly larger than for experiments. Past uses include partial and complete uses through individual studies and national and international workshops.

The individual studies are too numerous for detailed review, but well represented by recent Proceedings of the Office of Naval Research Symposium on Naval Hydrodynamics (Rood, 1996) and the International Conference on Numerical Ship Hydrodynamics (Patel and Stern, 1993). Most studies are for S60 and HSVA (and Wigley hull), i.e., the eldest hull forms. Calculations have been performed for many of the conditions and physics. The conditions include bare hull with and without propulsor, model size, hull-form variation, fixed or free model, straight ahead calm water, waves, and yaw. The physics include design variables for resistance and propulsion (forces and moments, sinkage and trim, wave profile, nominal wake, and self propulsion), geometry effects (model size and hull-form variation), facility/experimental method effects (fixed or free model), and many flow phenomena, i.e., Re effects and scaling, boundary layer and wake, stern flow, turbulence, vortex flow and separation, Fr effects, bow flow, transom flow, propeller-hull interaction, and wave-boundary layer and wake interaction. Most studies make only partial vs. complete use of the data.

The national and international workshops include Ship Wave-Resistance Computations (Bai and McCarthy, 1979; Mori, 1980; Noblesse and McCarthy, 1973), Ship Viscous Flow (Larsson, 1981; Larsson and Ohlsson, 1985; Larsson et al., 1991), Comparative Accuracy of Numerical Kelvin Wake Code Predictions–"Wake-Off" (Lindenmuth et al., 1991), and CFD Workshop Tokyo 1994 (CFD Workshop Tokyo 1994, 1994). The workshops on Ship Wave-Resistance Computations compared inviscid CFD methods and data for the Wigley hull, Inui hull S-201 (idealised), S60, ATHENA, and HSVA hull forms. The comparisons included wave resistance and wave profile with focus on physics of Fr effects. The workshops on Ship Viscous Flow compared viscous CFD methods and data for the SSPA model 720 (cargo/container) and HSVA/Dyne hull forms. The comparisons included axial velocity contours and crossplane vectors for stations in the stern region with focus on physics of hull-form variation, stern flow, and turbulence. The workshop on Comparative Accuracy of Numerical Kelvin Wake Code Predictions–"Wake-Off" compared inviscid CFD methods and data for the QUAPAW (ocean tug) and 5415 hull forms. The comparisons included wave profiles and longitudinal elevations with focus on physics of Fr effects. The CFD Workshop Tokyo 1994 compared inviscid and viscous CFD methods and data for the S60 and HSVA/Dyne hull forms. The comparisons included wave profiles, wave contours, surface pressure and streamlines, and axial velocity contours and crossplane vectors for stations in the stern region with focus on physics of hull-form variation, Fr effects, stern flow, and turbulence.

Although most uses of the data have been selective (i.e., partial vs. complete use of the data), they have provided useful assessments of the state-of-the-art of CFD for resistance and propulsion. Complete use of the data enables a more thorough assessment. In general, the uncertainty assessments are deficient with regard to documentation of the iterative and grid convergence.

CONCLUSIONS

Considerable model-scale data for surface-ship resistance and propulsion has been procured for explication of flow physics and CFD validation as a continuing effort. The trend is towards more modern hull forms, but still the most extensive data is for the eldest hull forms.

Many conditions and physics have been investigated; nonetheless, there is a continuing need for additional model-scale data to facilitate CFD code development both for modelling (e.g., turbulence, separation and vortices, free-surface boundary conditions, wave breaking, etc.) and numerical methods (e.g., unsteady flow). Such developments should remove the necessity of distinguishing between the traditional ship hydrodynamics fields of study (i.e., resistance and propulsion, seakeeping, and manoeuvring) enabling extensions for motions, manoeuvring, and environmental conditions.

The documentation varies greatly and is often lacking both with regard to detailed reporting, analysis, and availability/usability. Recommended practices are needed for archiving and dissemination of data.

The quality of the data is difficult to judge; since, most studies have not rigorously followed experimental uncertainty assessment methodologies. There is a need to rigorously follow the current standard (AIAA Standard, 1995). Additionally, there is a need to establish guidelines, examples, and expected uncertainties for towing-tank tests.

The quantity of the data varies greatly, but is often of limited resolution (i.e., partial mapping and coarse and/or dense). There is a need for increased resolution, i.e., larger mappings and densities.

Very limited full-scale data for surface-ship resistance and propulsion has been procured. There is a need for full-scale data to facilitate CFD code development for Re effects and scaling and full-scale simulations.

There is no reporting of the use of CFD in the design of the benchmark experiments.

Most (if not all) of the data has been used for CFD validation either through individual studies or national and international workshops; however, the validations are incomplete since most studies are either lacking or deficient with regard to computational uncertainty assessment. Also, most studies make partial vs. complete use of the data. There is a continuing need to fully use the available data, including rigorous application of computational uncertainty assessment methodologies.

RECOMMENDATIONS

There are 8 general recommendations.

(1) Resources should be focused on extensive data procurement for modern hull forms.
(2) The conditions and physics should be extended to facilitate CFD code developments for unsteady flow, turbulence, wave breaking, and separation and vortices.
(3) Detailed documentation should always be provided, including detailed reporting of the geometry, conditions, and experimental methods; analysis of the data with regard to the physics of interest; and availability/usability.
(4) The quality of data should be reported through rigorous application of current standards for experimental uncertainty assessment methodology (AIAA Standard 1995).
(5) The quantity of data should be sufficient for resolution of the flow physics of interest.
(6) Full-scale tests should be planned and data procured to facilitate CFD code development for Re effects and scaling and full-scale simulations.
(7) CFD should be used complementarily in planning and guiding both model- and full-scale experiments.
(8) The available data should be fully used, including rigorous application of computational uncertainty assessment methodologies.

There are 6 recommendations for the ITTC.

(1) The current database (table 1) should be adopted by the ITTC as recommended benchmarks for CFD validation for Resistance and Propulsion.
(2) The Resistance Committee should provide recommended practices for archiving and dissemination of benchmark data.
(3) The Resistance Committee should provide guidelines for application of current standards for experimental uncertainty assessment methodology (AIAA Standard, 1995) for towing-tank tests, including examples and expected accuracies.
(4) The Resistance Committee should provide recommendations for full-scale experiments for CFD validation.
(5) The Resistance Committee should provide full-scale estimates and uncertainties for resistance and propulsion for the benchmarks selected for the Gothenburg 2000 Workshop to enable partial validation of full-scale simulations.
(6) The Resistance Committee should provide recommended practices for CFD uncertainty assessment.

There are 4 recommendations for the Gothenburg 2000 Workshop.

(1) The Gothenburg 2000 CFD Workshop should focus on validation of RANS codes for cargo/container, combatant, and tanker hull forms.
(2) The conditions and physics should focus on hull-form variation, boundary layer and wake, stern flow, turbulence, Fr effects, propeller-hull interaction, and full-scale simulations.
(3) Based on the currently available data, the HTC, 5415, and HSVA/Dyne are the recommended benchmarks. However, in the event that additional experiments are planned and data procured and be available by early 1999 for the KCS and/or KVLCC/KVLCC2 for turbulence and propeller-hull interaction, then the KCS and/or KVLCC/KVLCC2 are the recommended benchmarks, instead of HTC and HSVA/Dyne, respectively.
(4) The participants and workshop comparisons/validations should follow CFD uncertainty assessment methodologies as recommended by the ITTC.

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REFERENCES

AIAA Standard, 1995, “Assessment of Wind Tunnel Data Uncertainty,” AIAA S-071-1995, Washington D.C.

Avanzini, G., Benedetti, L., and Penna, R., 1998, “Experimental Evaluation of Ship Resistance for RANS Code Validation,” ISOPE '98, Montreal, Canada, Maggio.

Bai, K.J. and McCarthy, J.H., (editors), 1979, *Proceedings of the Workshop on Ship Wave-Resistance Computations*, Vol. 1 and 2, DTNSRDC.

Bertram, V., Chao, K.Y., Lammers, G., and Laudan J., 1994, “Experimental Validation Data of Free-Surface Flows for Cargo Vessels,” *Proceedings of CFD Workshop Tokyo 1994*, 1994, Vol. 1, pp. 311-320.

Bertram, V., Chao, K.Y., Lammers, G., and Laudan J., 1992, “Development and Verification of Numerical Methods for Power Prediction,” HSVA Rept. 1579 (in German).

CFD Workshop Tokyo 1994, 1994, Vol. 1 and 2, 1994, Ship Research Institute Ministry of Transport Ship & Ocean Foundation.

Coleman, H.W. and Stern, F., 1997, “Uncertainties and CFD Code Validation,” *Journal of Fluids Engineering*, Vol. 119, pp. 795-803.

Denker, J., Knaack, T., and Kux, J., 1992, “Experimental and Numerical Investigations of HSVA-Tanker 2 Flow Field,” Institute of Shipbuilding (IfS) Rept. 521, Uni. Hamburg.

Dyne, G., 1995, “An Experimental Investigation of the Tanker Model “Dyne” in a Towing Tank,” Chalmers University of Technology Rept. CHA/NAVR/-95/0036.

Fry, D.J. and Kim, Y.H., 1985, “Bow Flow Field of Surface Ships,” *Proceedings of the 15th ONR Symposium on Naval Hydrodynamics*, Hamburg, pp. 319-346.

Garofallidis, D. A., 1996, “ Experimental and Numerical Investigation of the Flow around a Ship Model At Various Froude Numbers Part II: Uncertainty Analysis for Measurements,” PhD Thesis, Dept. Of Naval Architecture and Marine Engineering, National Technical University of Athens.

Gietz, U. and Kux, J., 1995, “Flow Investigations on the Hamburg Test Case Model in the Wind Tunnel,” Institute of Shipbuilding (Ifs) Rept. 550, Uni. Hamburg (in German).

Hoffmann, H.P., 1976, “Investigation of 3-Dimensional Turbulent Boundary Layer on a Ship Double Model in Wind Tunnel,” Institute of Shipbuilding (IfS) Rept. 343, Uni. Hamburg (in German).

ITTC, 1984, “Report of the Resistance and Flow Committee,” *17th International Towing Tank Conference*, Goteborg, Sweden, pp. 75-138.

ITTC, 1987, “Report of the Resistance and Flow Committee,” *18th International Towing Tank Conference,* Kobe Japan, pp. 47-95.

ITTC, 1990, “Report of the Resistance and Flow Committee,” *19th International Towing Tank Conference*, Madrid, Spain, pp. 55-107.

ITTC, 1996 “Report of the Resistance and Flow Committee,” *21st International Towing Tank Conference*, Trondheim, Norway, pp. 439-514.

Kasahara, Y., 1985, “An Experimental Investigation of the Scale Effect on Nominal and Effective Wake Distribution Using Geosim Models of Two Different Ships,” *Proceedings 1st Osaka International Colloquium on Ship Viscous Flow*, Osaka, Japan, pp. 432-449.

Knaack, T., 1984, “Laser Doppler Velocimetry Measurements on a Ship Model in Wind Tunnel,” Institute of Shipbuilding (IfS) Rept. 439, Uni. Hamburg (in German).

Knaack, T., 1990, “LDV-Measurements of Reynolds-Stresses in Wake of a Ship Model in Wind Tunnel,” Institute of Shipbuilding (IfS) Rept. 499, Uni. Hamburg (in German).

Knaack, T., 1992, “Investigation of Structure of Reynolds Tensor Fields in a Three-Dimensional Flow,” Institute of Shipbuilding (IfS) Rept. 527, Uni. Hamburg (in German).

Lammers, G., Laudan, J., and Strohrmann, H., 1989, “Correlation of Wake and Cavitation and their Consequences,” HSVA Rept. 1565 (in German).

Larsson, L. and Ohlsson, C.S., (editors), 1985, *Proceedings Second International Symposium on Ship Viscous Resistance*, SSPA, Gothenburg, Sweden.

Larsson, L., (editor), 1981 *Proceedings SSPA-ITTC Workshop on Ship Boundary Layers 1980*, SSPA, No. 90, Gothenburg, Sweden.

Larsson, L., Patel, V.C., and Dyne, G., (editors), 1991, *Proceedings of 1990 SSPA-CHT-IIHR Workshop*, Flowtech International AB, Research Report No. 2, Gothenburg, Sweden.

Lee, J., Lee, S.J., and Van, S.H., 1998, "Wind Tunnel Test on a Double Deck Shaped Ship Model," *3rd International Conference on Hydrodynamics*, Seoul, Korea.

Lindenmuth, W.T., Ratcliffe, T.J., and Reed, A.M., 1991, "Comparative Accuracy of Numerical Kelvin Wake Code Prediction - Wake-Off," DTMB Rept. DTRC-91/004, David Taylor Research Center, Bethesda, MD.

Longo, J., Stern, F., and Toda, Y., 1993, "Mean-Flow Measurements in the Boundary Layer and Wake and Wave Field of a Series 60 C_B=0.60 Ship Model - Part 2: Scale Effects on Near-Field Wave Patterns and Comparisons with Inviscid Theory," *Journal of Ship Research*, Vol. 37, No. 1, pp. 16-24.

Longo, J. and Stern, F., 1996a, "Technical Note: Evaluation of Surface-Ship Resistance and Propulsion Model-Scale Database for CFD Validation," *Journal of Ship Research*, Vol. 40, No. 2, pp. 112-116.

Longo, J. and F. Stern, 1996b, "Yaw effects on model-scale ship flows," *Proceedings of the 21st ONR Symposium on Naval Hydrodynamics*, Trondheim, Norway, pp. 312-327.

Longo, J. and Stern, F., 1999, "Resistance, Sinkage and Trim, Wave Profile, and Nominal Wake and Uncertainty Assessment for DTMB Model 5512," *Proceedings 25th ATTC*, Iowa City, IA.

Lundgren, H. and Ahman, M., G., 1994, "Experimentell och numerisk bestamning av vagmotstand for ett tankfartyg (Dyne tankern)," Chalmers University of Technology Rept. X-94/58 (in Swedish).

Marvin, J.G., 1995, "Dryden Lectureship in Research: Perspectives on Computational Fluid Dynamics Validation," AIAA Journal, Vol. 33, No. 10, pp. 1778-1787.

Mehta, U.B., 1998, "Credible Computational Fluid Dynamics Simulations," *AIAA Journal*, Vol. 36, No. 5, pp. 665-667.

Mori, K., (editor), 1980, *Proceedings of the Continued Workshop on Ship Wave-Resistance Computations*, Faculty of Engineering Hiroshima University.

Noblesse, F. and McCarthy, J.H., (editors), 1973, *Proceedings of the Second DTNSRDC Workshop on Ship Wave-Resistance Computations*, Vol. 1 and 2, DTMB.

Ogiwara, S., 1994, "Stern Flow Measurements for the Tanker 'Ryuko-Maru' in Model Scale, Intermediate Scale, and Full Scale Ships," *Proceedings of CFD Workshop Tokyo 1994*, Vol. 1, pp. 341-349.

Ogiwara, S. and Kajitani, H., 1994, "Pressure Distribution on the Hull Surface of Series 60 (C_B=0.60) Model," *Proceedings of CFD Workshop Tokyo*, Vol. 1, pp. 350-358.

Olivieri, A. M. Penna, R., 1999, "Suncertainty Assessment in Wave Elevation Measurements," ISOPE '99, Brest, France, (to be presented).

Patel, V.C. and Stern, F., 1993, *Proceedings 6th International Conference on Numerical Ship Hydrodynamics*, National Academy Press, Washington D.C., Iowa City, Iowa.

Ratcliffe, T., 1998, http://www50.dt.navy.mil/5415/.

Rood, E. P. (editor), 1996, *Proceedings 21st Symposium on Naval Hydrodynamics*, National Academy Press, Washington D.C., Trondheim, Norway.

Stern, F., Longo, J., Penna, R., Avanzini, G., Benedetti, L., Olivieri, A., T. Ratcliffe, and H. Coleman 1998, "International Collaboration on Steady-Flow Tests and Uncertainty Assessment for Ship Models DTMB 5415 and 5512 and INSEAN 2340," IIHR Rept. (in preparation).

Suzuki, H., Miyazaki, S., Suzuki, T., and Matsumura, K., 1998a, "Turbulence Measurements in Stern Flow Field of Two Ship Models," *Proceedings 3rd Osaka Colloquium on Advanced CFD Applications to Ship Flow and Hull Form Design*, Osaka, Japan.

Suzuki, H., Suzuki, T., and Miyazaki, S., 1998b, "Turbulence Measurements in Stern Flow Field of a Ship Model–Series 60, C_B=0.60–," *Journal of Kansai Society of Naval Architects*, No. 227, pp. 29-40 (in Japanese).

Suzuki, H., Suzuki, T., Miyazaki, S. and Matsumura, K., 1998c, "Turbulence Measurements in Stern Flow Field of Two Ship Models–Ryuko-Maru and Hamburg Test Case–," *Proceedings of the Kansai Society of Naval Architects*, No. 10, pp. 1-4.

Tanaka, I., Suzuki, T., Himeno, Y., Takahei, T., Tsuda, T., Sakao, M., Yamazaki, Y., Kasahara, Y., and Takagi, M., 1984, "Investigation of Scale Effects on Wake Distribution Using Geosim Models," *J. Kansai Soc. N.A.*, Japan, No. 192, pp. 103-120.

Toda, Y., Stern, F., Tanaka, I., and Patel, V.C., 1990, "Mean-Flow Measurements in the Boundary Layer and Wake of a Series 60 C_B=0.60 Model Ship With and Without Propeller," *Journal of Ship Research*, Vol. 34, No. 4, pp. 225-252.

Toda, Y., Stern, F., and Longo, J., 1992, "Mean-Flow Measurements in the Boundary Layer and Wake and Wave Field of a Series 60 C_B=0.60 Ship Model - Part 1: Froude Numbers 0.16 and 0.316," *Journal of Ship Research*, Vol. 36, No. 4, pp. 360-377.

Todd, F.H., 1963, "Series 60 Methodical Experiments with Models of Single-Screw Merchant Ships," David Taylor Model Basin Report 1712,.

Van, S.H., Yim, G.T., Kim, W.J., Kim, D.H., Yoon, H.S., and Eom, J.Y., 1997, "Measurement of Flows Around a 3600TEU Container Ship Model," *Proceedings of the Annual Autumn Meeting*, SNAK, Seoul, pp. 300-304 (in Korean).

Van, S.H., Kim W.J., Kim, D.H., Yim, G.T., Lee, C.J., and Eom, J.Y., 1998a, "Flow Measurement Around a 300K VLCC Model," *Proceedings of the Annual Spring Meeting*, SNAK, Ulsan, pp. 185-188.

Van, S.H., Kim, W.J., Yim, G.T., Kim, D.H., and Lee, C.J., 1998b, "Experimental Investigation of the Flow Characteristics Around Practical Hull Forms," *Proceedings 3rd Osaka Colloquium on Advanced CFD Applications to Ship Flow and Hull Form Design*, Osaka, Japan.

Table 1. Benchmark database for CFD validation for resistance and propulsion.

Facility, propulsor, and data → ↓ **Database entry** ↓	**Facility**	**Propulsor**	**F/M**	**Self propulsion**	**Sinkage and trim**	**Surface pressure**	**Wave profile**	**Wave elevation (l)**	**Wave elevation (t)**	**Mean velocity**	**Mean pressure**	**Turbulence**
Cargo-container												
Series 60 C_B=0.600 (S60) Full-scale ship does not exist												
1.1 Cooperative Experimental Program												
ITTC (1984, 1987, 1990)	tt, wc	wo	√		√	√	√	√				
Fry and Kim (1985)	tt	wo						√	√	√		
Ogiwara and Kajitani (1994)	tt	wo	√		√	√	√					
1.2 Osaka University & Iowa Institute of Hydraulic Research Toda et al. (1990)	tt	w, wo	√	√		√	√			√	√	
1.3 Iowa Institute of Hydraulic Research Toda et al. (1992); Longo et al. (1993)	tt	wo	√				√	√	√	√	√	
1.4 Iowa Institute of Hydraulic Research Longo and Stern (1996)	tt	wo	√		√		√	√	√	√	√	
1.5 National Technical University of Athens Garofallidis (1996)	tt	wo	√			√	√	√	√	√	√	
1.6 Osaka University Suzuki et al. (1998a)	wt	wo								√		√
Hamburg Test Case C_B=0.645 (HTC) Full-scale ship exists												
2.1 HSVA Lammers et al. (1989)	s	w								√		
2.2 HSVA Bertram et al. (1992) Bertram et al. (1994)	tt	w, wo	√	√	√	√	√	√	√	√		√
2.3 University of Hamburg Gietz and Kux (1995)	wt	wo								√		√
2.4 Osaka University Suzuki et al. (1998b)	wt	wo								√		√
KRISO 3600 TEU C_B=0.651 (KCS) Full-scale ship does not exist												
3.1 Korean Research Institute of Ships & Ocean Engineering Van et al. (1997) Van et al. (1998b)	tt	w, wo	√	√	√	<u>√</u>	√	√	√	√	√	
3.2 Pohang University of Science and Technology Lee et al. (1998)	wt	wo								√		√
Combatant												
DTMB model 5415 C_B=0.506 (5415) Full-scale ship does not exist												
4.1 David Taylor Model Basin Fry and Kim (1985) Ratcliffe (1998)	tt	<u>w</u>, wo	√	√	√	√	√	√	√	√	√	
4.2 Iowa Institute of Hydraulic Research Longo and Stern (1999)	tt	wo	√		√		√			√	√	
4.3 INSEAN Avanzini et al. (1998) Olivieri and Penna (1999)	tt	wo	√		√	√	√	√	√	<u>√</u>	<u>√</u>	

Facility, propulsor, and data → **↓ Database entry ↓**	**Facility**	**Propulsor**	**F/M**	**Self propulsion**	**Sinkage and trim**	**Surface pressure**	**Wave profile**	**Wave elevation (l)**	**Wave elevation (t)**	**Mean velocity**	**Mean pressure**	**Turbulence**
Tanker												
HSVA C_B=0.850 (HSVA) Full-scale ship does not exist												
5.1 University of Hamburg Hoffmann (1976)	wt	wo								√	√	
5.2 University of Hamburg Knaack (1984) Knaack (1990)	wt	wo								√		√
Hull-form variation *Dyne tanker C_B=0.850 (Dyne)*												
5.3 University of Hamburg Denker et al. (1992) Knaack (1992)	wt	wo								√		√
5.4 Chalmers University of Technology Lundgren and Åhman (1994)	tt	wo										
Dyne (1995)	tt	w, wo	√	√				√		√	√	
Ryuko-Maru C_B=0.830 (RM) Full-scale ship does not exist												
6.1 Ishikawajima-Harima Heavy Industries Co., Ltd. Ogiwara (1994)	s, tt	w, wo	√							√	√	
6.2 Osaka University Suzuki et al. (1998b) Suzuki et al. (1998c)	wt	wo								√		√
DAIOH C_B=0.837 (DAIOH) Full-scale ship does not exist												
7.1 Osaka University, Akashi Ship Model Basin, and Nippon Kokan K. K. Tanaka et al. (1984) Kasahara (1985)	s, tt	w, wo	√	√		√				√	√	
KRISO 300K VLCC C_B=0.810 (KVLCC) Full-scale ship does not exist												
8.1 Korea Research Institute of Ships & Ocean Engineering Van et al. (1998a) Van et al. (1998b)	tt	w, wo	√	√	√	$\underline{\surd}$	√	√	√	√	√	
Hull-form variation *VLCC2 C_B=0.810 (KVLCC2)*												
8.2 Korea Research Institute of Ships & Ocean Engineering No reference available	tt	w, wo	√	√	√	$\underline{\surd}$	√	√	√	√	√	

tt, wt, wc, s	:	Towing tank, wind tunnel, water channel, and sea, respectively
w, wo	:	With and without, respectively
√	:	Data available
$\underline{\surd}$	:	Data under procurement
NA	:	Data not available
%	:	Percentage range of variable

Table 2a. Series 60 C_B=0.60/cargo-container.

Study/institution(s)		Study 1.1: Multiple (ITTC)		Study 1.1: DTMB		Study 1.1: UT, IHI, NKK		Study 1.2: OU, IIHR	
Facility		Towing tank		Towing tank		Towing tank		Towing tank	
Model length(s)		L=1.8-10.0 m		L= 6.1 m		L= 2.5, 4.0, 10.0 m		L=4.0 m	
Cond.	Study 1.1: Multiple (ITTC)	Bare hull; model size; fixed and free model; tow point (axial and vertical position); shallow water							
	Study 1.1: DTMB	Bare hull							
	Study 1.1: UT, IHI, NKK	Bare hull; fixed and free model; model size							
	Study 1.2: OU, IIHR	Bare hull; fixed (except resistance and self-propulsion tests); with and without propeller							
Physics	Study 1.1: Multiple (ITTC)	Model size; fixed and free model; tow point; facility bias; Re effects; Fr effects							
	Study 1.1: DTMB	Bow flow							
	Study 1.1: UT, IHI, NKK	Bare hull; model size; fixed and free model; Fr effects; Re effects							
	Study 1.2: OU, IIHR	Stern flow; propeller-hull interaction							
Equip.	Study 1.1: Multiple (ITTC)	Dynamometer; pressure transducers; 35-mm photography							
	Study 1.1: DTMB	Cameras; ultrasonic probes and point gages; 3D LDV system							
	Study 1.1: UT, IHI, NKK	NA; NA; pressure transducers; NA							
	Study 1.2: OU, IIHR	Dynamometer; pressure transducers; camera/video camera; 5-hole pitot probes/pressure transducers							
Fr and Re		**Fr**	**Re×10⁶**	**Fr**	**Re×10⁶**	**Fr**	**Re×10⁶**	**Fr**	**Re×10⁶**
Data	F/M	0.10-0.43	0.75-20.7			0.05-0.35	0.46-35.0	0.08-0.27	1.6-5.4
	Self propulsion							0.11-0.19	2.8-4.8
	Sinkage and trim	0.10-0.43	0.75-20.7			0.05-0.35	0.46-35.0		
	Surface pressure	0.18-0.32	1.9-14.7			0.18-0.34	2.4-30.0	***0.16***	***3.08***
	Wave profile	0.22-0.35	2.7-16.4			0.3	2.9-30.0	0.3,0.25,***0.16***	6.0, 5.0, ***3.2***
	Wave elevation (l)			0.32	15.1				
	Wave elevation (t)			0.32	15.1				
	Mean velocity			0.32	15.1			***0.16***	***3.2***
	Mean pressure							***0.16***	***3.2***
	Turbulence								
Quality (uncertainty)	F/M	***NA***				NA		0.5-5.0%	
	Self propulsion							NA	
	Sinkage and trim	***NA***				NA			
	Surface pressure	***NA***				NA		0.01	
	Wave profile	***NA***				NA		NA	
	Wave elevation (l)			±2.5 mm					
	Wave elevation (t)			±2.0 mm					
	Mean velocity			(<0.5, 1.5, 1.5)%				(1.5, 1.5, 1.5)%	
	Mean pressure							0.05	
	Turbulence								
Quantity	F/M					32 pts/free and fixed		22 pts	
	Self propulsion							Yes	
	Sinkage and trim					~36 pts/model			
	Surface pressure†	100/study				(6, 15, 7, -) 200 pts/Fr		(0, 0, 9, -) 376 pts/Fr	
	Wave profile†	(5, 11, 5, -) 21/study				(8, 20, 15, -) 43 pts/Fr		(8, 9, 8, -) 25 pts/Fr	
	W. elevation (l)†			6 m x 15 m					
	W. elevation (t)†			(16, 0, 0, 0) 20 pts/st					
	Mean velocity†			(17, 0, 0, 0) 200 pts/st				(0, 2, 8, 3) 400-700 pts/st	
	Mean pressure†							(0, 2, 8, 3) 400-700 pts/st	
	Turbulence								

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 2b. Series 60 C_B=0.60/cargo-container.

Study/institution(s)	Study 1.3: IIHR	Study 1.4: IIHR	Study 1.5: NTUA	Study 1.6: OU
Facility	Towing tank	Towing tank	Towing tank	Wind tunnel
Model length(s)	L=3.048 m	L=3.048 m	L=3.048 m	L=3.0 m

Cond.	Study 1.3: IIHR	Bare hull; fixed (except resistance tests)
	Study 1.4: IIHR	Bare hull; fixed (except forces, moment, sinkage, trim, and heel angle tests); yaw
	Study 1.5: NTUA	Bare hull; turbulence stimulation
	Study 1.6: OU	Double model
Physics	Study 1.3: IIHR	Boundary layer and wake; Fr effects; wave-boundary layer and wake interaction
	Study 1.4: IIHR	Boundary layer and wake; Fr effects; vortex flow and separation; wave breaking
	Study 1.5: NTUA	Boundary layer and wake; Fr effects; turbulence stimulation
	Study 1.6: OU	Stern flow; turbulence
Equip.	Study 1.3: IIHR	Load cell; 35-mm camera; capacitance-wire probe; servo probe; 5-hole pitot probe/pressure transducers
	Study 1.4: IIHR	Load cell; grid/marker; capacitance-wire probe; point gage; 5-hole pitot probes/pressure transducers
	Study 1.5: NTUA	Dynamometer; potentiometers; photograph/paper rulers; manual gages; E/M probes; five-hole probes/trans.
	Study 1.6: OU	Triple-sensor hot wire system

Fr and Re		**Fr**	**Re×10⁶**	**Fr**	**Re×10⁶**	**Fr**	**Re×10⁶**	**Fr**	**Re×10⁶**
Data	F/M	0.10-0.36	1.67-6.0	0.10-0.35	1.67-6	0.05-0.38	0.732-5.56		
	Self propulsion								
	Sinkage and trim			0.10-0.35	1.67-6.0				
	Surface pressure					0.25-0.35	3.66-5.12		
	Wave profile	0.316, 0.3, 0.25	5.27, 5.0, 4.17	0.316, 0.16	5.27, 2.67	0.12-0.35	1.76-5.12		
	Wave elevation (l)	0.316, 0.3, 0.25	5.27, 5.0, 4.17	0.316, 0.16	5.27, 2.67	0.12-0.35	1.76-5.12		
	Wave elevation (t)	0.316, 0.3, 0.25	5.27, 5.0, 4.17	0.316, 0.16	5.27, 2.67	0.25-0.35	3.66-5.12		
	Mean velocity	0.316, 0.16	5.27, 2.67	0.316, 0.16	5.27, 2.67	0.12-0.35	1.76-5.12		3.7
	Mean pressure	0.316, 0.16	5.27, 2.67	0.316, 0.16	5.27, 2.67	0.12-0.35	1.76-5.12		
	Turbulence								3.7

		Study 1.3: IIHR	Study 1.4: IIHR	Study 1.5: NTUA	Study 1.6: OU
Quality (uncertainty)	F/M	0.5-5.0%	0.6-6.0%	0.2%	
	Self propulsion				
	Sinkage and trim		0.3-1.8%	1-6%	
	Surface pressure			17.6%	
	Wave profile	±0.5 mm	1.3-2.6%	5.6-22.0%	
	Wave elevation (l)	±0.5 mm	1.1-2.2%	±2.5 mm	
	Wave elevation (t)	±0.5 mm	1.3-5.0%	4.0%	
	Mean velocity	(1.5, 1.5, 1.5)% U_C	(1.5, 1.5, 1.5)%	19%	(4, 4, 6)%
	Mean pressure	0.05	0.05	38.4%	
	Turbulence				8%
Quantity	F/M	34 pts	35 pts	>50	
	Self propulsion				
	Sinkage and trim		35 pts		
	Surface pressure			(6, 5, 14, -) 406 pts/Fr	
	Wave profile†	(5, 5, 5, -) 15 pts/Fr	(10, 9, 10, -) 29 pts/Fr	(8, 9, 12, -) 29 pts/Fr	
	W. elevation (l)†	3 m x 5 m 18 st/Fr	3 m x 5 m 850 pts/m^2	160 cuts	
	W. elevation (t)†	(9, 0, 11, 0) 20 pts/st	(15, 10, 15, 5) 20 pts/st	(30, 0, 6, 5) 27 pts/st	
	Mean velocity†	(3, 2, 3, 2) 400-700 pts/st	(3, 2, 3, 2) 1400 pts/st	(3, 0, 5, 3) 110-230 pts/st	(0, 0, 6, 0) 150 pts
	Mean pressure†	(3, 2, 3, 2) 400-700 pts/st	(3, 2, 3, 2) 1400 pts/st	(3, 0, 5, 3) 110-230 pts/st	
	Turbulence†				(0, 0, 6, 0) 150 pts

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 3. Hamburg Test Case/cargo-container.

Study/institution(s)		Study 2.1: HSVA		Study 2.2: HSVA		Study 2.3: IfS		Study 2.4: OU	
Facility		Sea		Towing tank		Wind tunnel		Wind tunnel	
Model length(s)		L=157.7 m		L=6.404 m		L=2.69 m		L=3.0 m	
Cond.	Study 2.1: HSVA	Full scale							
	Study 2.2: HSVA	Bare hull with and without propeller; fixed and free model							
	Study 2.3: IfS	Double model							
	Study 2.4: OU	Double model							
Physics	Study 2.1: HSVA	Stern flow; Re effects and scaling							
	Study 2.2: HSVA	Stern flow; Fr effects; propeller-hull interaction; C_{th}=0.617 and 1.248 for Fr=0.238 and 0.31, respectively							
	Study 2.3: IfS	Stern flow; turbulence							
	Study 2.4: OU	Stern flow; turbulence							
Equip.	Study 2.1: HSVA	NA							
	Study 2.2: HSVA	Load cell; manometer; 35-mm camera; resistance probes; 3D LDV system							
	Study 2.3: IfS	NA							
	Study 2.4: OU	Triple-sensor hot wire system							
Fr and Re		**Fr**	**Re$\times10^6$**	**Fr**	**Re$\times10^6$**	**Fr**	**Re$\times10^6$**	**Fr**	**Re$\times10^6$**
Data	F/M			0.024-0.275	1.18-13.6				
	Self propulsion			0.1-0.3	4.52-13.5				
	Sinkage and trim			0.0989-0.31	4.47-14.0				
	Surface pressure			0.207, ***0.238, 0.31***	9.35, ***10.7***, ***14.0***		5.0		
	Wave profile			0.2492	11.3				
	Wave elevation (l)			0.185, 0.207, ***0.238***, 0.28, 0.31	8.35, 9.35, ***10.7***, 12.6, 14.0				
	Wave elevation (t)								
	Mean velocity	***0.2354***	***1635.41***	***0.238, 0.308***	***10.7, 13.9***		5.0		3.7
	Mean pressure								
	Turbulence						5.0		3.7
Quality (uncertainty)	F/M			NA					
	Self propulsion			NA					
	Sinkage and trim			NA					
	Surface pressure			NA		NA			
	Wave profile			±2.5 mm					
	Wave elevation (l)			±0.2 mm					
	Wave elevation (t)								
	Mean velocity	(5, -, -)%		(2, 2, 2)%		(1, 1, 1)%		(4, 4, 6)%	
	Mean pressure								
	Turbulence					NA		8%	
Quantity	F/M			17 pts					
	Self propulsion			8 pts					
	Sinkage and trim			12 pts					
	Surface pressure†			(4, 10, 4, -) 216 pts		NA			
	Wave profile†			(10, 21, 10, -) 41 pts					
	W. elevation (l)†			2 m x 45 m 130 pts/m^2					
	W. elevation (t)								
	Mean velocity†	(0, 0, 1, 0) 80 pts		(0, 0, 5/***6***, 0) 200-300 pts/st (0, 0, ***1***, 0) 200-300 pts/st		(0, 1, 5, 1) 120 pts/st		(0, 0, 6, 0) 150 pts/st	
	Mean pressure								
	Turbulence†					(0, 1, 5, 1) 120 pts/st		(0, 0, 6, 0) 150 pts/st	

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 4. KCS/cargo-container and KVLCC(2)/tanker.

Study/institution(s)		Study 3.1: KRISO		Study 3.2: KRISO		Study 8.1: KRISO		Study 8.2: KRISO	
Facility		Towing tank		Wind tunnel		Towing tank		Towing tank	
Model length(s)		L=7.279 m		L=2.0 m		L=5.5172 m		L=5.5172 m	
Cond.	Study 3.1: KRISO	Bare hull; fixed except for resistance and self-propulsion tests							
	Study 3.2: KRISO	Double model							
	Study 8.1: KRISO	Bare hull; fixed except for resistance and self-propulsion tests							
	Study 8.2: KRISO	Bare hull; hull variation; fixed except for resistance and self-propulsion tests							
Physics	Study 3.1: KRISO	Stern flow; Fr effects							
	Study 3.2: KRISO	Turbulence							
	Study 8.1: KRISO	Stern flow; Fr effects							
	Study 8.2: KRISO	Stern flow; Fr effects; hull variation							
Equip.	Study 3.1: KRISO	Load cell; telescope/digital video recorder/camera; servo-needle probe; 5-hole pitot probe rake/press. tran.s							
	Study 3.2: KRISO	Five-hole pitot probe/pressure transducers; x-type hot-wire probes							
	Study 8.1: KRISO	Load cell; telescope/digital video recorder/camera; servo-needle probe; 5-hole pitot probe rake/press. trans.							
	Study 8.2: KRISO	Load cell; telescope/digital video recorder/camera; servo-needle probe; 5-hole pitot probe rake/press. trans.							
Fr and Re		**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**
Data	F/M	0.10-0.30	5.4-16.0			0.1-0.16	3.2-5.2	0.1-0.16	3.2-5.2
	Self propulsion	0.10-0.30	5.4-16.0			0.1-0.16	3.2-5.2	0.1-0.16	3.2-5.2
	Sinkage and trim	0.10-0.30	5.4-16.0			0.1-0.16	3.2-5.2	0.1-0.16	3.2-5.2
	Surface pressure								
	Wave profile	0.26	14.0			0.142	4.6	0.142	4.6
	Wave elevation (l)	0.26	14.0			0.142	4.6	0.142	4.6
	Wave elevation (t)	0.26	14.0			0.142	4.6	0.142	4.6
	Mean velocity	0.26	14.0		6.41	0.142	4.6	0.142	4.6
	Mean pressure								
	Turbulence				6.41				
Quality (uncertainty)	F/M	1.0%				1.0%		1.0%	
	Self propulsion	NA				NA		NA	
	Sinkage and trim	NA				NA		NA	
	Surface pressure								
	Wave profile	±1 mm				±1 mm		±1 mm	
	Wave elevation (l)	±0.5 mm				±0.5 mm		±0.5 mm	
	Wave elevation (t)	±0.5 mm				±0.5 mm		±0.5 mm	
	Mean velocity	(0.8, 0.8, 0.8) %		(1.0, 1.0, 1.0) %		(0.8, 0.8, 0.8) %		(0.8, 0.8, 0.8) %	
	Mean pressure	NA				NA		NA	
	Turbulence			(10-15) %					
Quantity	F/M	15 pts				8 pts		8 pts	
	Self propulsion	NA				NA		NA	
	Sinkage and trim								
	Surface pressure								
	Wave profile†	(8, 7, 7, -) 22 pts				(7, 7, 8, -) 22 pts		(7, 7, 8, -) 22 pts	
	W. elevation (l)†	6m x 30m 36 cuts				6m x 20m 25 cuts		6m x 20m 25 cuts	
	W. elevation (t)†	(13, 0, 0, 10) 20-36 pts/st				(14, 0, 0, 16) 13-20 pts/st		(14, 0, 0, 16) 13-20 pts/st	
	Mean velocity†	(0, 0, 3, 2) 760-1030 pts/st		NA		(0, 0, 4, 2) 500-970 pts/st		(0, 0, 4, 2) 500-970 pts/st	
	Mean pressure								
	Turbulence			NA					

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 5. 5415/combatant.

Study/institution(s)		Study 4.1: DTMB		Study 4.2: IIHR		Study 4.3: INSEAN	
Facility		Towing tank		Towing tank		Towing tank	
Model length(s)		L=5.72 m		L=3.048 m		L=5.72 m	
Cond.	Study 4.1: DTMB	Bare hull with and without appendages and propulsor; fixed and free model					
	Study 4.2: IIHR	Bare hull; fixed (except for resistance test)					
	Study 4.3: INSEAN	Bare hull; fixed and free model					
Physics	Study 4.1: DTMB	Fr effects; bow flow; stern flow; transom flow; wave breaking					
	Study 4.2: IIHR	Model size					
	Study 4.3: INSEAN	Boundary layer and wake; Fr effects; wave breaking					
Equip.	Study 4.1: DTMB	Load cell; string pots; press. trans.; marker/grid; servo probe; 5-hole pitot probe/press. trans. and LDV					
	Study 4.2: IIHR	Load cell; linear potentiometers; adhesive marker/grid; 5-hole pitot probe/pressure transducers					
	Study 4.3: INSEAN	Load cell; linear potentiometers; camera; capacitance-wire probes; 5-hole pitot probes/press. trans.					
Fr and Re		**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**
Data	F/M	0.05-0.44	1.88-16.91	0.05-0.45	0.93-8.36	0.05-0.45	1.88-16.91
	Self propulsion						
	Sinkage and trim	0.05-0.44	1.88-16.91	0.05-0.45	0.93-8.36	0.05-0.45	1.88-16.91
	Surface pressure	0.28, 0.41	10.52, 15.40				
	Wave profile	0.28, 0.41	10.52, 15.40	0.28, 0.41	5.30, 7.80	0.28, 0.41	10.52, 15.40
	Wave elevation (l)	0.28, 0.41	10.52, 15.40			0.28, 0.41	10.52, 15.40
	Wave elevation (t)	***0.28, 0.41***	***10.52, 15.40***			0.28, 0.41	10.52, 15.40
	Mean velocity	0.28, ***0.41***	10.52, ***15.40***	0.28, 0.41	5.30, 7.80	0.28, 0.41	10.52, 15.40
	Mean pressure	0.28, 0.41	10.52, 15.40	0.28, 0.41	5.30, 7.80	0.28, 0.41	10.52, 15.40
	Turbulence						
Quality (uncertainty)	F/M	1.5-0.76%		5.12-0.67%		2.7-0.60%	
	Self propulsion						
	Sinkage and trim	NA		NA		NA	
	Surface pressure	NA					
	Wave profile	3.37%, 1.75%		±1 mm		±2 mm	
	Wave elevation (l)	±2.5%				±7.5%	
	Wave elevation (t)	±2.0 mm				NA	
	Mean velocity	(2.0, 2.0, 2.0)%		(1.5, 1.5, 1.5)%		NA	
	Mean pressure	±1.5%		±0.05		NA	
	Turbulence						
Quantity	F/M	24 pts		41 pts		43 pts	
	Self propulsion						
	Sinkage and trim						
	Surface pressure†	(7, 0, 0, -) 60 pts/Fr					
	Wave profile	23 pts		44 pts		42	
	W. elevation (l)†	1 cut (y/L=0.324) ~266, 177 pts/L				136 cuts (0.36x2.75 L)	
	W. elevation (t)†	(21, 0, 0, ~12) ~400 pts/cut				NA	
	Mean velocity†	(0, 0, 1, 0) 500 pts/Fr		(0, 0, 1, 0) 900 pts/Fr		(3, 2, 3, 2) 500-700 pts/Fr	
	Mean pressure†	(0, 0, 1, 0) 500 pts/Fr		(0, 0, 1, 0) 900 pts/Fr		(3, 2, 3, 2) 500-700 pts/Fr	
	Turbulence						

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 6. HSVA and Dyne/tanker.

Study/institution(s)		Study 5.1: IfS		Study 5.2: IfS		Study 5.3: IfS		Study 5.4: CUT and SSPA	
Facility		Wind tunnel		Wind tunnel		Wind tunnel		Towing tank	
Model length(s)		L=2.663 m		L=2.663 m		L=2.663 m		L=7.028 m	
Cond.	Study 5.1: IfS	Double model							
	Study 5.2: IfS	Double model							
	Study 5.3: IfS	Double model; hull variation							
	Study 5.4: CUT and SSPA	Bare hull; with and without appendages and propulsor							
Physics	Study 5.1: IfS	Stern flow; Re effects							
	Study 5.2: IfS	Stern flow; turbulence							
	Study 5.3: IfS	Stern flow; turbulence; hull variation							
	Study 5.4: CUT and SSPA	Stern flow; propeller-hull interaction							
Equip.	Study 5.1: IfS	NA							
	Study 5.2: IfS	LDV							
	Study 5.3: IfS	NA							
	Study 5.4: CUT and SSPA	Force balances; pressure transducers; servo-needle wave gauge; prandtl probes; 5-hole pitot							
Fr and Re		**Fr**	**Re×10^6**	**Fr**	**Re×10^6**	**Fr**	**Re×10^6**	**Fr**	**Re×10^6**
Data	F/M							0.108-0.217	5.1-10.375
	Self propulsion							0.108-0.217	5.1-10.375
	Sinkage and trim								
	Surface pressure		2.8, 4.8, 6.8				5.00	***0.108-0.206***	***5.1-9.85***
	Wave profile								
	Wave elevation (l)							0.165	9.63
	Wave elevation (t)								
	Mean velocity		2.8, 4.8, 6.8		5.0		5.00	***0.173***	***8.3***
	Mean pressure		2.8, 4.8, 6.8					***0.173***	***8.3***
	Turbulence				5.0		5.00		
Quality (uncertainty)	F/M							0.7%	
	Self propulsion							0.7% (Thrust and torque)	
	Sinkage and trim								
	Surface pressure	0.10% C_p				0.10% C_p		0.7%	
	Wave profile								
	Wave elevation (l)							5%	
	Wave elevation (t)								
	Mean velocity	(3, 3, 5)%		(1, 4, 1.2)%		(1.00, 1.00, 1.00)%		(2.5, 2.5, 2.5)%	
	Mean pressure	0.10% C_p						0.01 C_p	
	Turbulence			5.00%		5.00%			
Quantity	F/M							11 pts	
	Self propulsion							11 pts	
	Sinkage and trim								
	Surface pressure†	(13, 5, 11, -) 239 pts				(0, 1, 5, -) 45 pts		(-, -, 3, 0) 4 pts/st	
	Wave profile								
	Wave elevation (l)							7 cut	
	Wave elevation (t)								
	Mean velocity†	(0, 0, 6, 4) 600-1300 pts/st		(0, 0, 27, 0) 2319 pts/st		(0, 1, 5, 1) 415-1380 pts/st		(-, -, -, 1) 240 pts	
	Mean pressure†	(0, 0, 6, 4) 600-1300 pts/st						(-, -, -, 1) 240 pts	
	Turbulence†			(0, 0, 27, 0) 2319 pts/st		(0, 1, 5, 1) 415-1380 pts/st			

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 7. Ryuko-Maru/tanker.

Study/institution(s)		Study 6.1: IHI		Study 6.1: IHI		Study 6.1: IHI		Study 6.2: OU	
Facility		Sea		Sea		Towing tank		Wind tunnel	
Model length(s)		L=300.0 m		L=30.0 m		L=7.0 m		L=3.0 m	
Cond.	Study 6.1: IHI	Full scale							
	Study 6.1: IHI	Intermediate scale							
	Study 6.1: IHI	Model scale							
	Study 6.2: OU	Double model							
Physics	Study 6.1: IHI	Stern flow; Re effects							
	Study 6.1: IHI	Stern flow; Re effects							
	Study 6.1: IHI	Stern flow; Re effects							
	Study 6.2: OU	Stern flow; turbulence							
Equip.	Study 6.1: IHI	5-hole pitot probes/pressure transducers							
	Study 6.1: IHI	5-hole pitot probes/pressure transducers							
	Study 6.1: IHI	Load cell; 5-hole pitot probes/pressure transducers							
	Study 6.2: OU	Triple-sensor hot wire system							
Fr and Re		**Fr**	**Re×10^6**	**Fr**	**Re×10^6**	**Fr**	**Re×10^6**	**Fr**	**Re×10^6**
Data	F/M					0.025-0.20	1.4-11.5		
	Self propulsion								
	Sinkage and trim								
	Surface pressure								
	Wave profile								
	Wave elevation (l)								
	Wave elevation (t)								
	Mean velocity	***0.153***	***2430***	***0.153***	***65.6***	***0.153***	***7.4***		3.6
	Mean pressure								
	Turbulence								3.6
Quality (uncertainty)	F/M					NA			
	Self propulsion								
	Sinkage and trim								
	Surface pressure								
	Wave profile								
	Wave elevation (l)								
	Wave elevation (t)								
	Mean velocity	(3, 5, 5)%		(3, 5, 5)%		(2, 3, 3)%		(4, 4, 6)%	
	Mean pressure								
	Turbulence							8%	
Quantity	F/M					12 pts			
	Self propulsion								
	Sinkage and trim								
	Surface pressure								
	Wave profile								
	Wave elevation (l)								
	Wave elevation (t)								
	Mean velocity†	(0, 0, 1, 0) 30 pts/st		(0, 0, 1, 0) 60 pts/st		(0, 6, 5, 0) 60 pts/st		(0, 0, 6, 0) 200-400 pts/st	
	Mean pressure								
	Turbulence†							(0, 0, 6, 0) 200-400 pts/st	

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

Table 7. Ryuko-Maru/tanker.

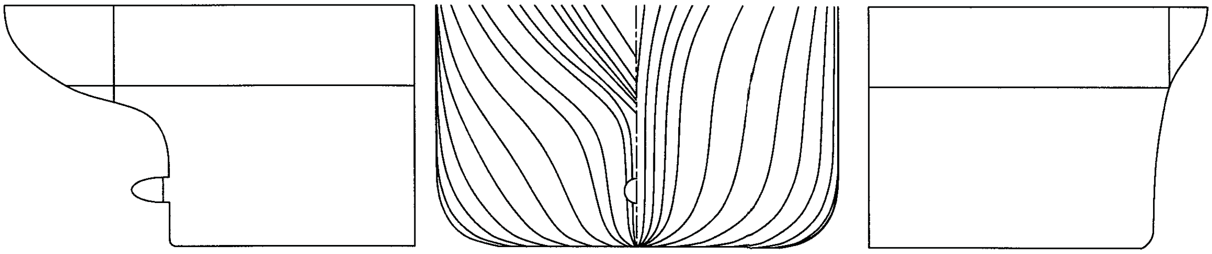
Study/institution(s)		Study 6.1: IHI		Study 6.1: IHI		Study 6.1: IHI		Study 6.2: OU	
Facility		Sea		Sea		Towing tank		Wind tunnel	
Model length(s)		L=300.0 m		L=30.0 m		L=7.0 m		L=3.0 m	
Cond.	Study 6.1: IHI	Full scale							
	Study 6.1: IHI	Intermediate scale							
	Study 6.1: IHI	Model scale							
	Study 6.2: OU	Double model							
Physics	Study 6.1: IHI	Stern flow; Re effects							
	Study 6.1: IHI	Stern flow; Re effects							
	Study 6.1: IHI	Stern flow; Re effects							
	Study 6.2: OU	Stern flow; turbulence							
Equip.	Study 6.1: IHI	5-hole pitot probes/pressure transducers							
	Study 6.1: IHI	5-hole pitot probes/pressure transducers							
	Study 6.1: IHI	Load cell; 5-hole pitot probes/pressure transducers							
	Study 6.2: OU	Triple-sensor hot wire system							
Fr and Re		**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**	**Fr**	**Re$\times 10^6$**
Data	F/M					0.025-0.20	1.4-11.5		
	Self propulsion								
	Sinkage and trim								
	Surface pressure								
	Wave profile								
	Wave elevation (l)								
	Wave elevation (t)								
	Mean velocity	***0.153***	***2430***	***0.153***	***65.6***	***0.153***	***7.4***		3.6
	Mean pressure								
	Turbulence								3.6
Quality (uncertainty)	F/M					NA			
	Self propulsion								
	Sinkage and trim								
	Surface pressure								
	Wave profile								
	Wave elevation (l)								
	Wave elevation (t)								
	Mean velocity	(3, 5, 5)%		(3, 5, 5)%		(2, 3, 3)%		(4, 4, 6)%	
	Mean pressure								
	Turbulence							8%	
Quantity	F/M					12 pts			
	Self propulsion								
	Sinkage and trim								
	Surface pressure								
	Wave profile								
	Wave elevation (l)								
	Wave elevation (t)								
	Mean velocity†	(0, 0, 1, 0) 30 pts/st		(0, 0, 1, 0) 60 pts/st		(0, 6, 5, 0) 60 pts/st		(0, 0, 6, 0) 200-400 pts/st	
	Mean pressure								
	Turbulence†							(0, 0, 6, 0) 200-400 pts/st	

Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable

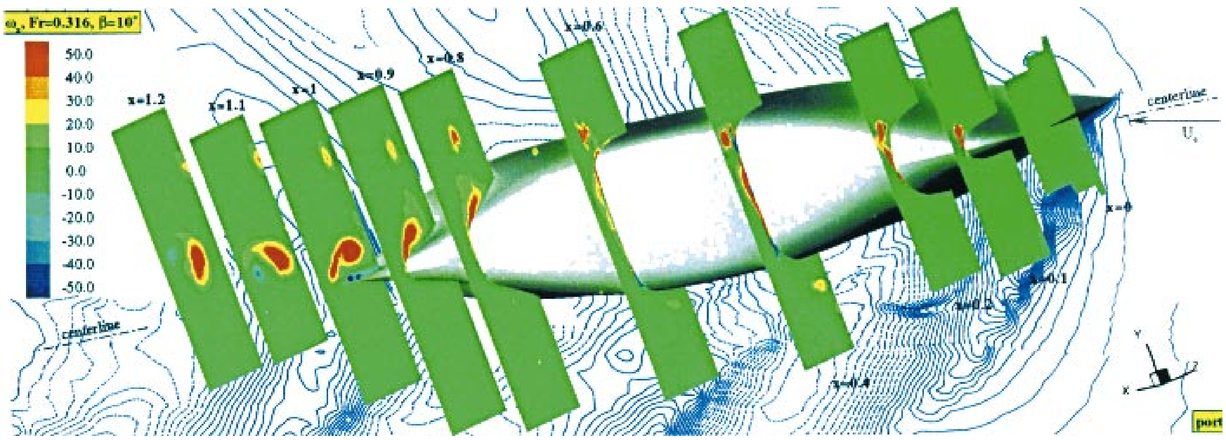
Table 8. DAIOH/tanker.

Study/institution(s)		Study 7.1: OU, ASMB, NKK	
Facility		Towing tank	
Model length(s)		L=3.5, 4.7 (OU); L=3.5, 7.0 (ASMB); L=4.7, 7.0, 12.0 (NKK)	
Cond.	Study 7.1: OU, ASMB, NKK	Bare hull; fixed (at running trim) and free models	
Physics	Study 7.1: OU, ASMB, NKK	Stern flow; Re effects on wake distribution	
Equip.	Study 7.1: OU, ASMB, NKK	5-hole pitot probes/pressure transducers	
Fr and Re		**Fr**	**Re×10[6]**
Data	F/M	NA	NA
	Self propulsion	NA	NA
	Sinkage and trim		
	Surface pressure	NA	NA
	Wave profile		
	Wave elevation (l)		
	Wave elevation (t)		
	Mean velocity	***0.12, 0.14; 0.12, 0.12; 0.14, 0.132, 0.14***	***2.5, 4.2; 2.5, 6.5; 4.0, 6-7.5, 16.0***
	Mean pressure	***0.12, 0.14; 0.12, 0.12; 0.14, 0.132, 0.14***	***2.5, 4.2; 2.5, 6.5; 4.0, 6-7.5, 16.0***
	Turbulence		
Quality (uncertainty)	F/M	NA	
	Self propulsion	NA	
	Sinkage and trim		
	Surface pressure	NA	
	Wave profile		
	Wave elevation (l)		
	Wave elevation (t)		
	Mean velocity	NA	
	Mean pressure	NA	
	Turbulence		
Quantity	F/M	NA	
	Self propulsion	NA	
	Sinkage and trim		
	Surface pressure†	(0, 0, 0,2) 160-350 pts/Fr	
	Wave profile		
	Wave elevation (l)		
	Wave elevation (t)		
	Mean velocity	NA	
	Mean pressure	NA	
	Turbulence		

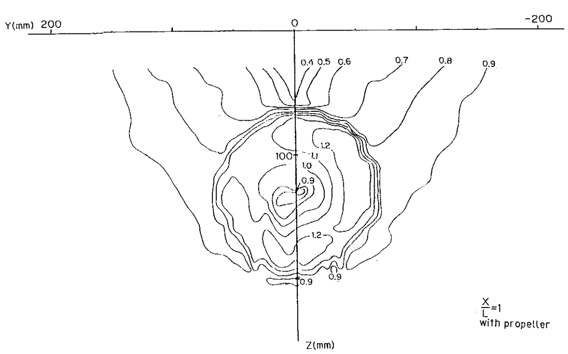
Bold Italic : Data for with and without-propulsor condition
† : (b, m, s, w)…Data locations corresponding to bow, midship, stern, and wake regions, respectively, and number of points
NA : Data not available
% : Percentage range of variable



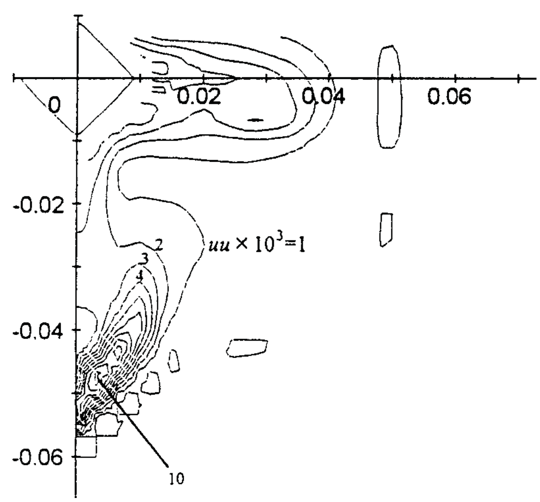
(a) Body plan



(b) Axial vorticity contours and free surface elevations for yaw angle =10^o and Fr=0.316 (Study 1.4)

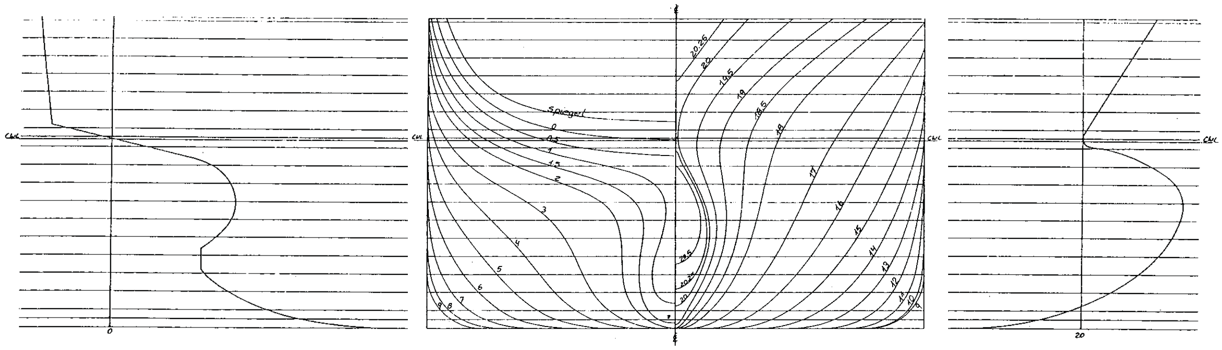


(c) Axial velocity contours with propeller at x=1.0, Fr=0.16 (Study 1.2)

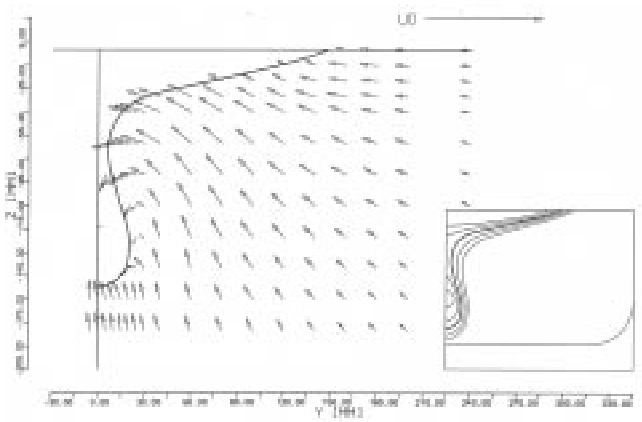


(d) $\overline{u'u'}$ contours at x=0.9944 (Study 1.6)

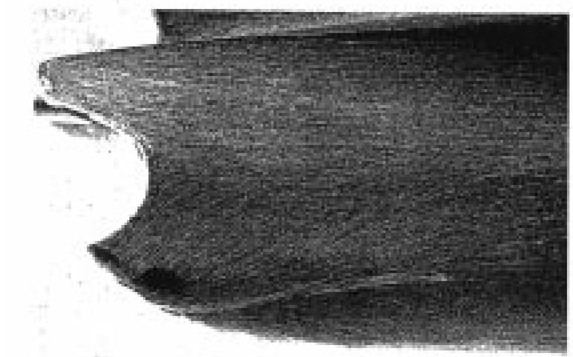
Figure 1. Representative results for Series 60 C_B=0.60.



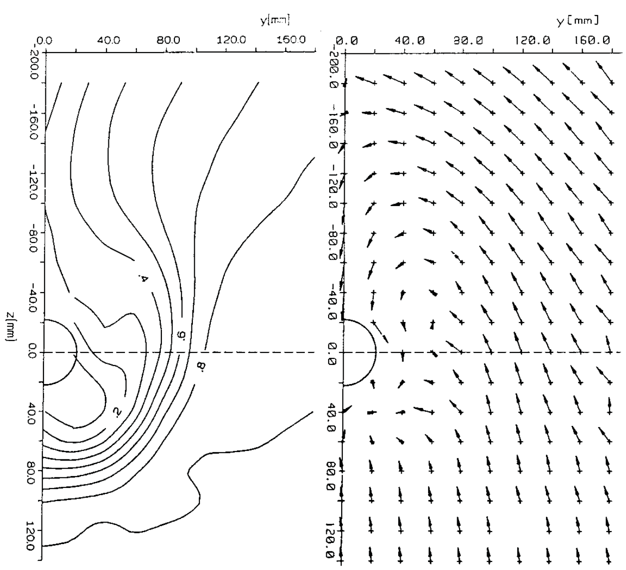
(a) Body plan



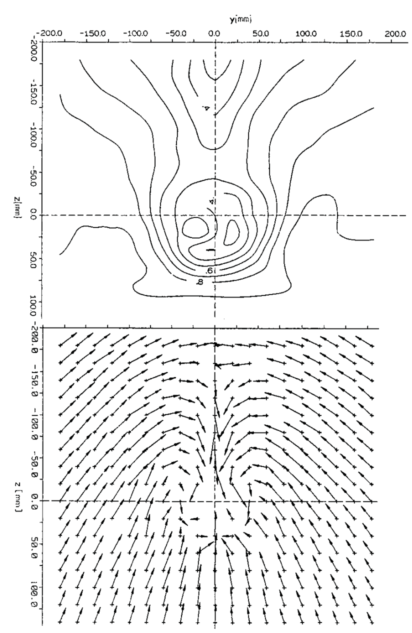
(b) Cross-flow vectors at x=0.9525 (Study 2.3)



(c) Visualization of shear directions (Study 2.3)

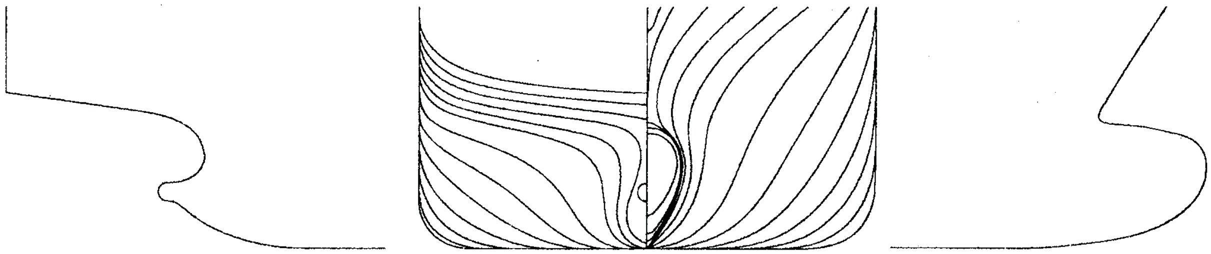


(d) Axial velocity contours and vectors for Fr=0.238 and x=0.03373 without propeller (Study 2.2)

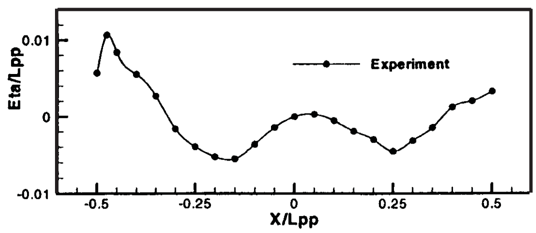


(e) Axial velocity contours and vectors for Fr=0.238 and x=0.03373 with propeller (Study 2.2)

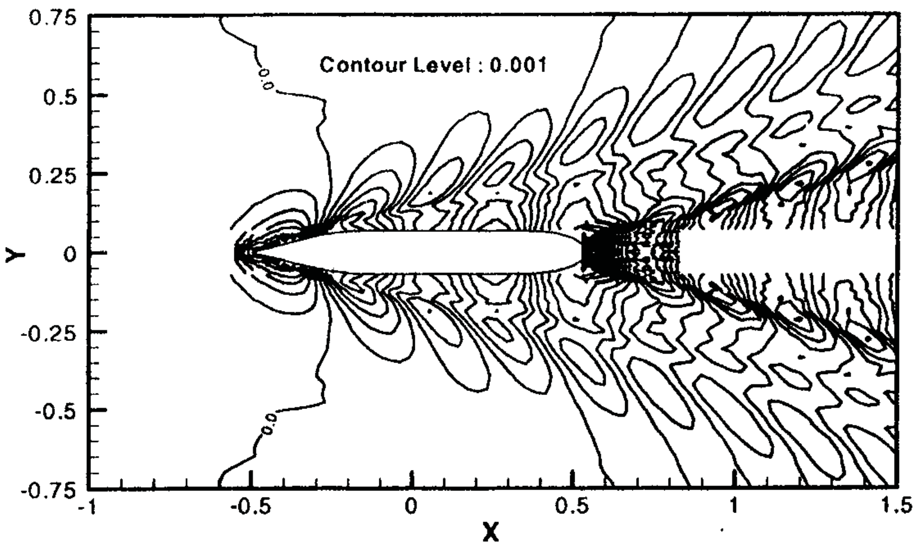
Figure 2. Representative results for HTC.



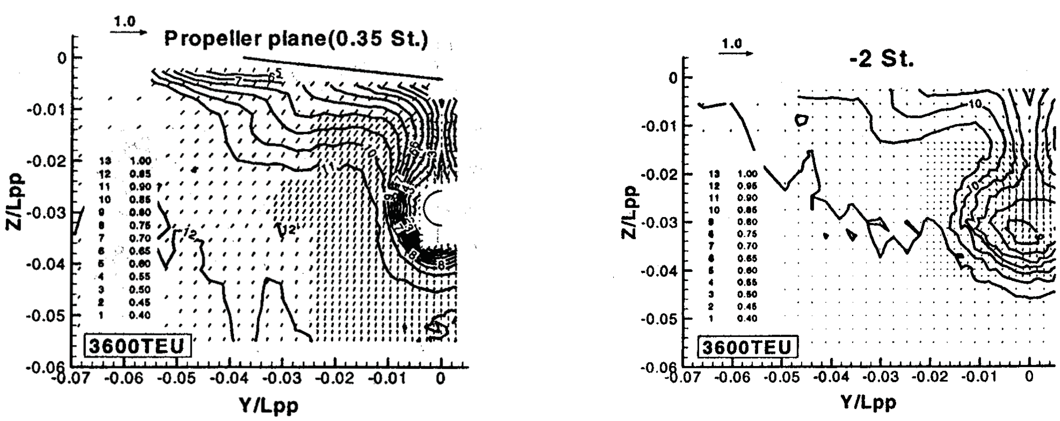
(a) Body plan



(b) Wave profile on the hull surface at Fr=0.26 (Study 3.1)

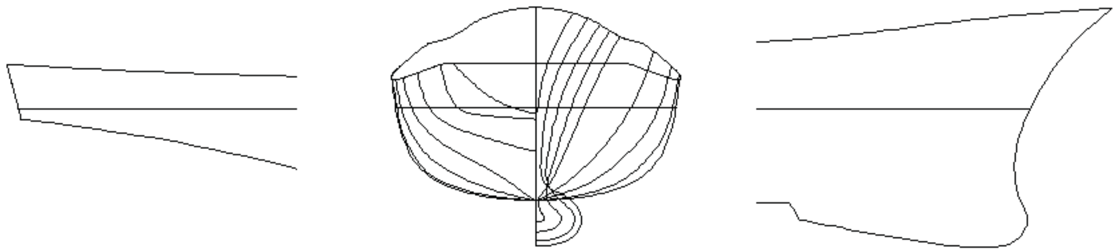


(c) Wave elevations at Fr=0.26 (Study 3.1)

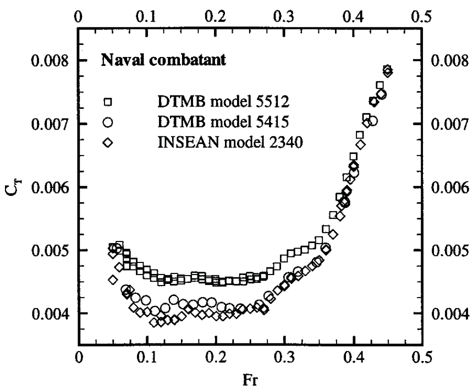


(d) Axial velocity contours and velocity vectors at two stern stations for Fr=0.26 (Study 3.1)

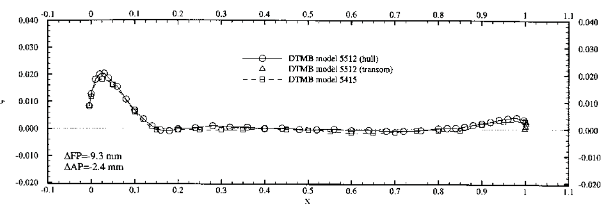
Figure 3. Representative results for KCS.



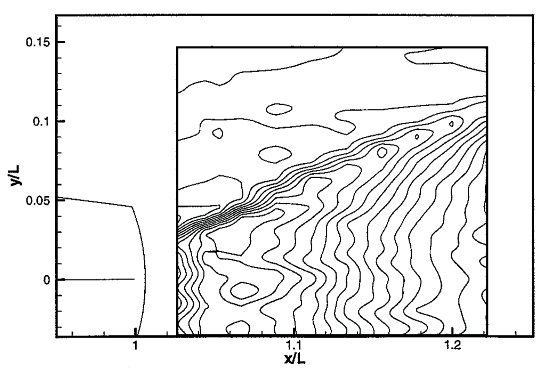
(a) Body plan



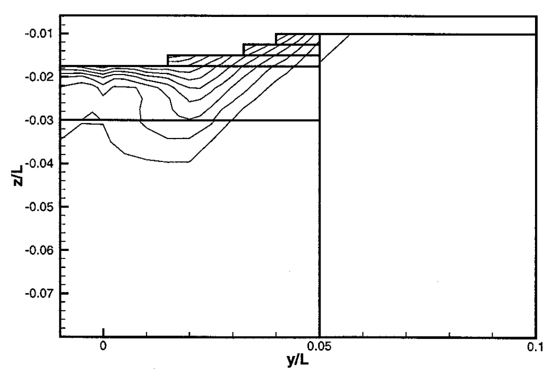
(b) Resistance measurements for two scales and three facilities (Study 4.1-4.3)



(c) Wave profiles at Fr=0.28 and L=3.048 and 5.72 m (Study 4.1-4.3)

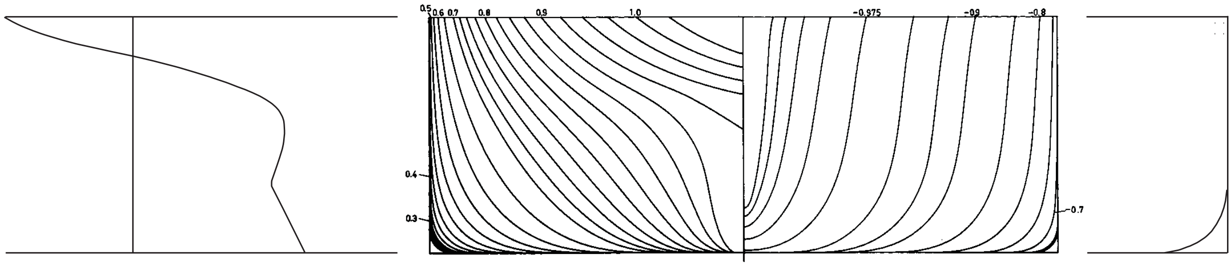


(d) Wave elevations in the near wake at Fr=0.41 (Study 4.1)

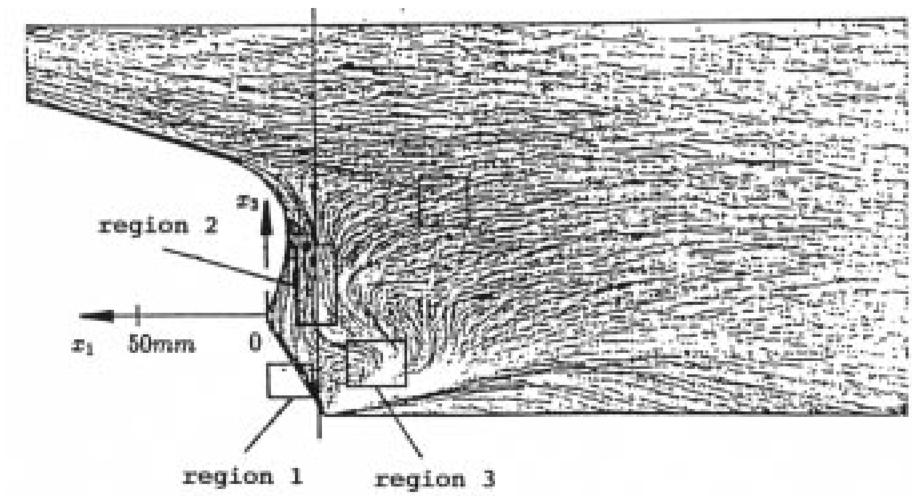


(e) Nominal wake measurements for Fr=0.28 (L=3.048 m) (Study 4.1)

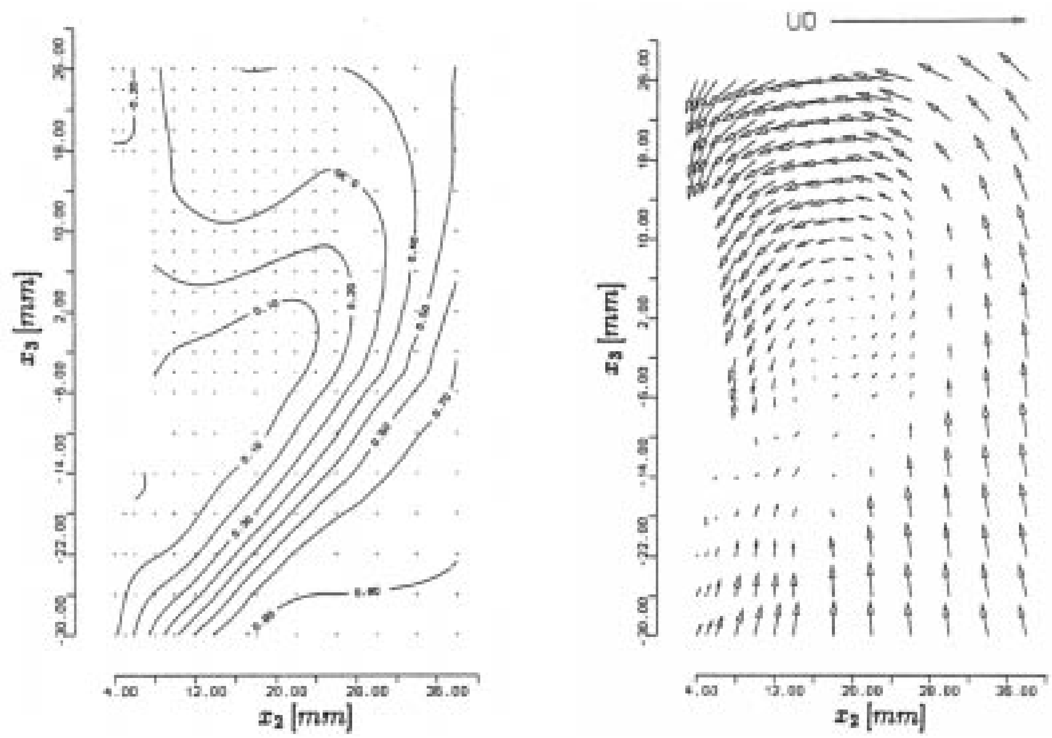
Figure 4. Representative results for 5415.



(a) Body plan

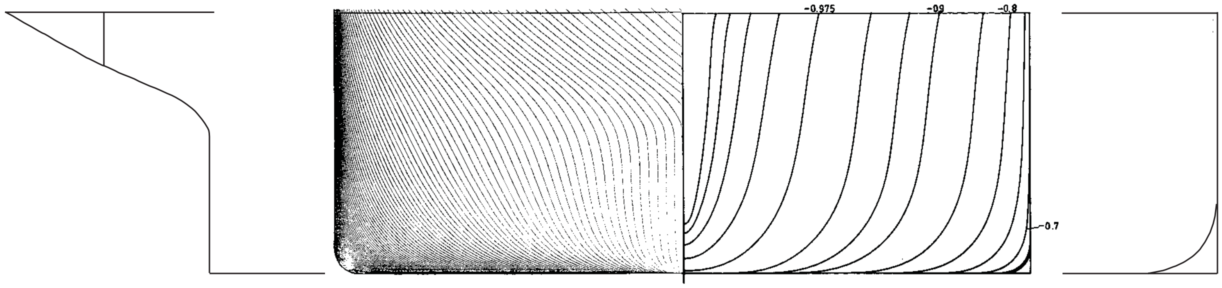


(b) Wall shear-stress fields and measurement regions (Study 5.3)

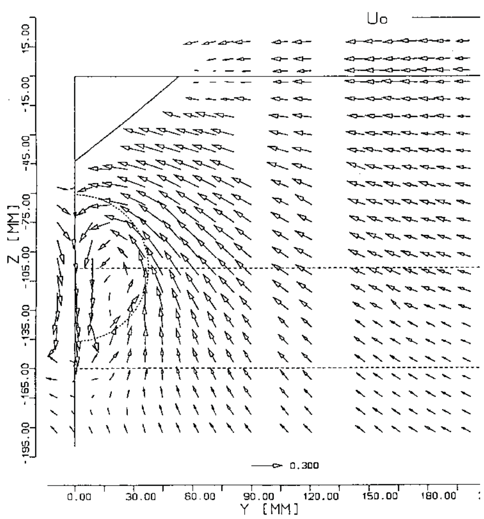


(c) Axial velocity contours and transverse vectors in region 2 at Re=5.0e06 (Study 5.3)

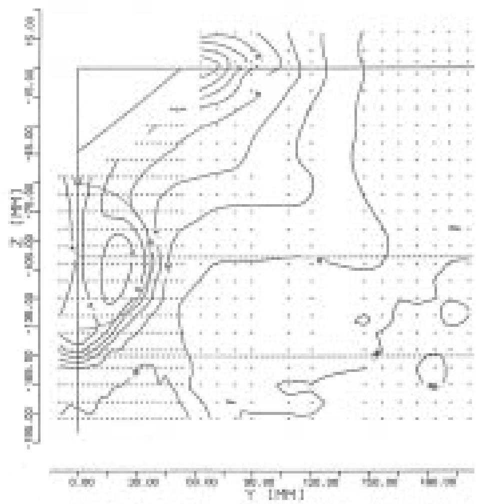
Figure 5a. Representative results for HSVA.



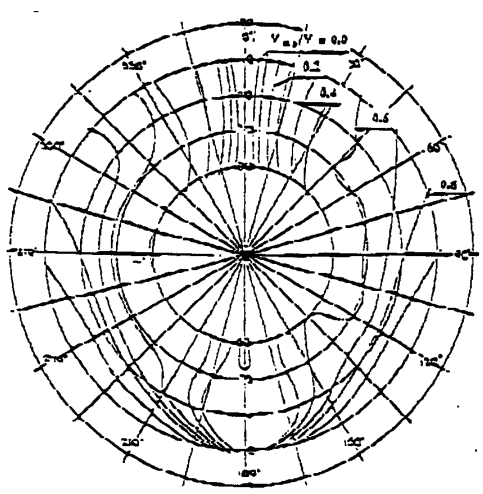
(a) Body plan



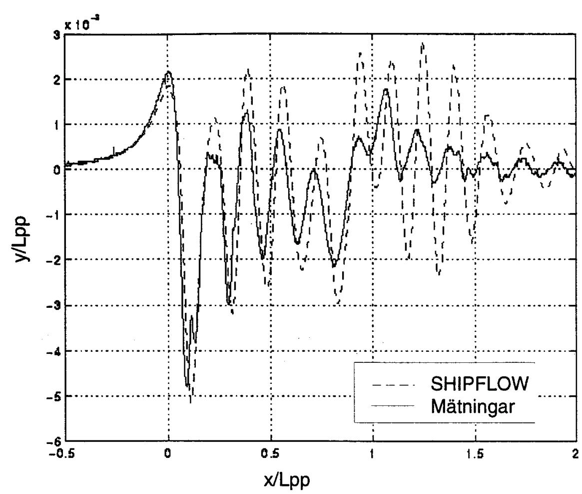
(b) Cross-flow vectors at x=0.989 (Study 5.3)



(c) Axial-velocity contours at x=0.989 (Study 5.3)

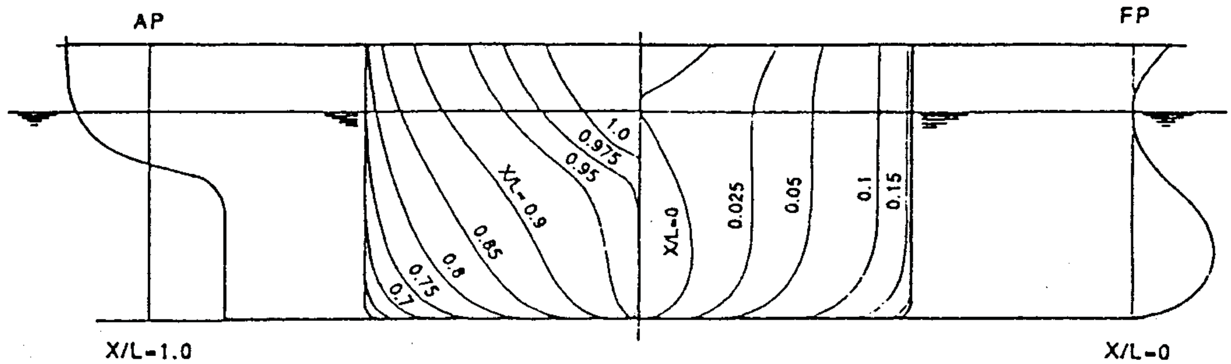


(d) Axial-velocity contours at x=0.979 with propeller (Study 5.4)

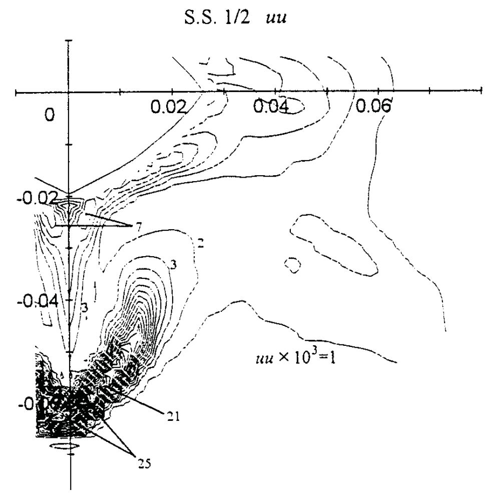


(e) Longitudinal wave cut at y=0.1943 and Fr=0.165 (Study 5.4)

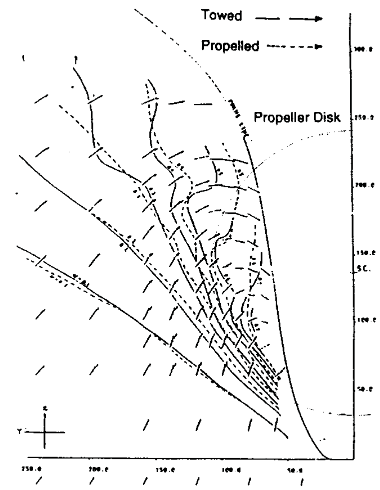
Figure 5b. Representative results for Dyne.



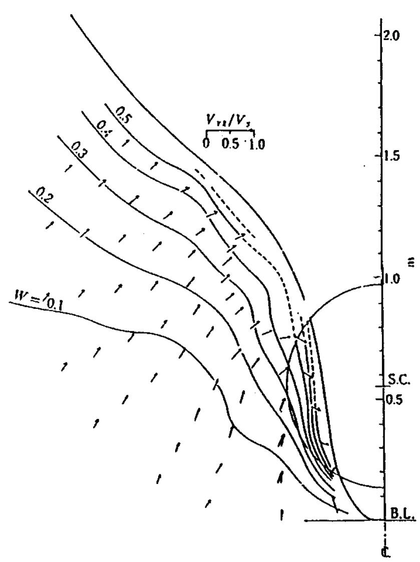
(a) Body plan



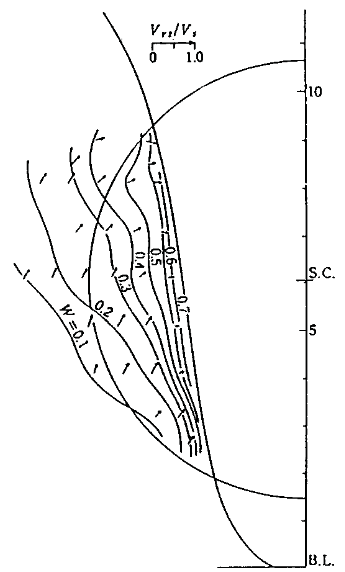
(b) $\overline{u'u'}$ contours in the propeller plane at Re=3.55e06 (Study 6.2)



(c) Axial velocity contours and vectors for Fr=0.153 and x=0.925 (7.0 m model) (Study 6.1)

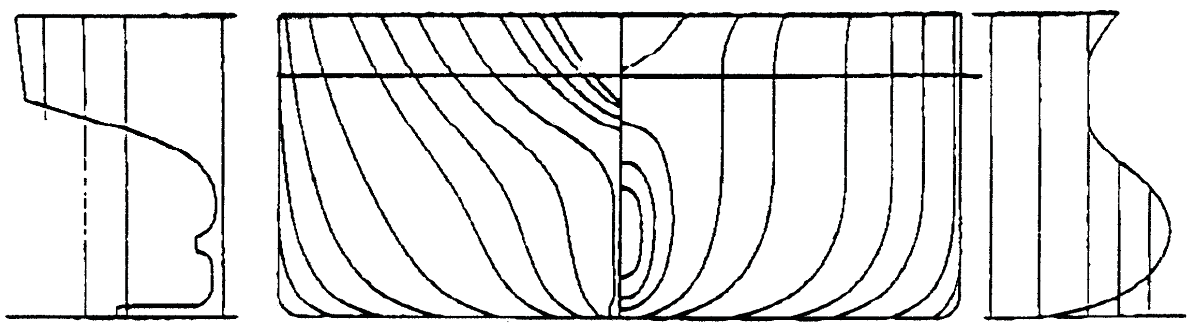


(d) Axial velocity contours and vectors for Fr=0.153 and x=0.925 (30.0 m model) (Study 6.1)

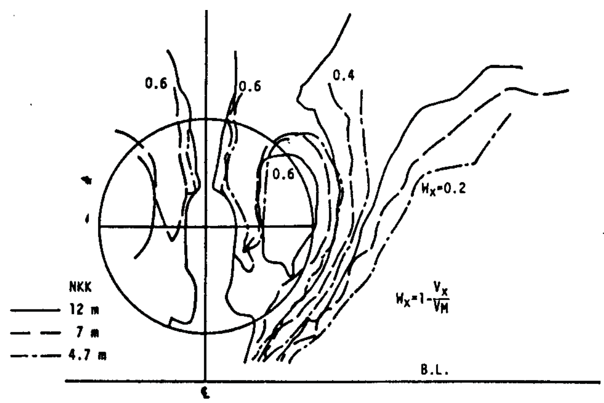


(e) Axial velocity contours and vectors for Fr=0.153 and x=0.925 (full scale) (Study 6.1)

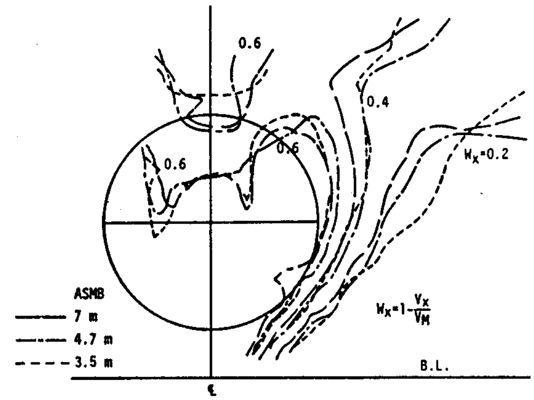
Figure 6. Representative results for Ryuko-Maru.



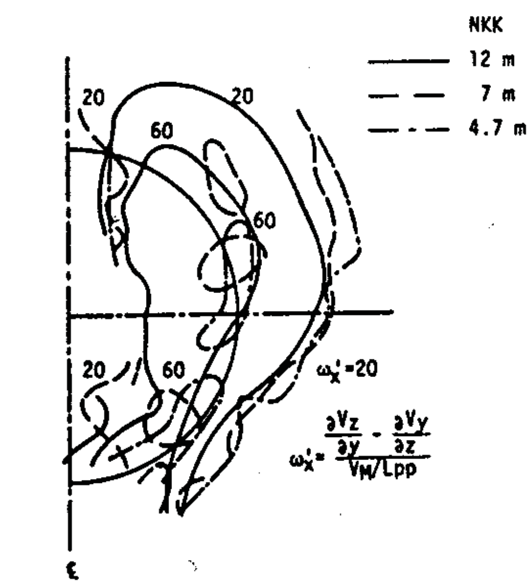
(a) Body plan



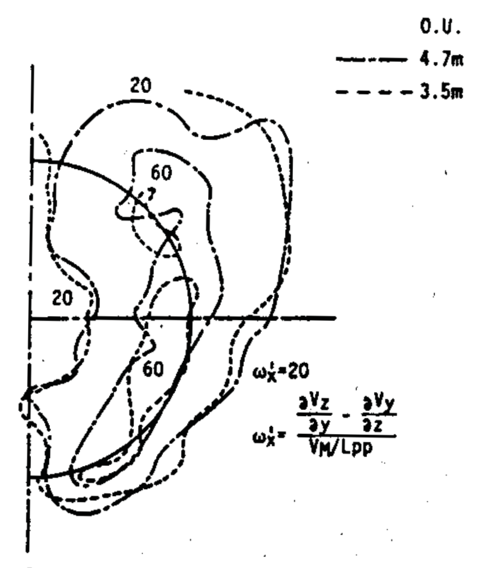
(b) Comparison of measured wake distributions at the propeller plane (NKK) (Study 7.1)



(c) Comparison of measured wake distributions at the propeller plane (ASMB) (Study 7.1)

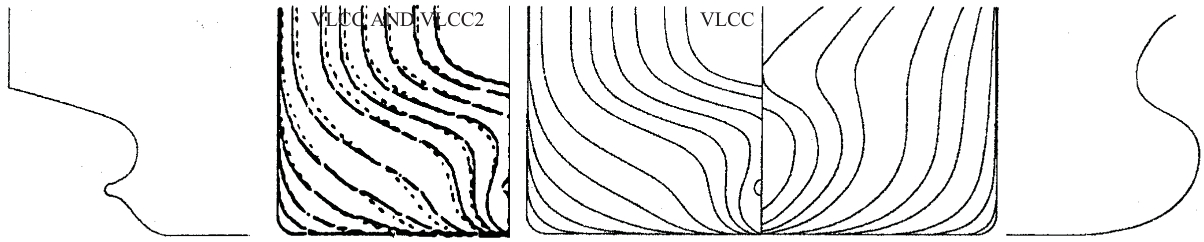


(d) Comparison of measured vorticity distributions at the propeller plane (NKK) (Study 7.1)

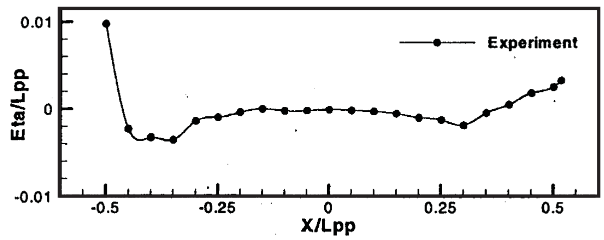


(e) Comparison of measured vorticity distributions at the propeller plane (OU) (Study 7.1)

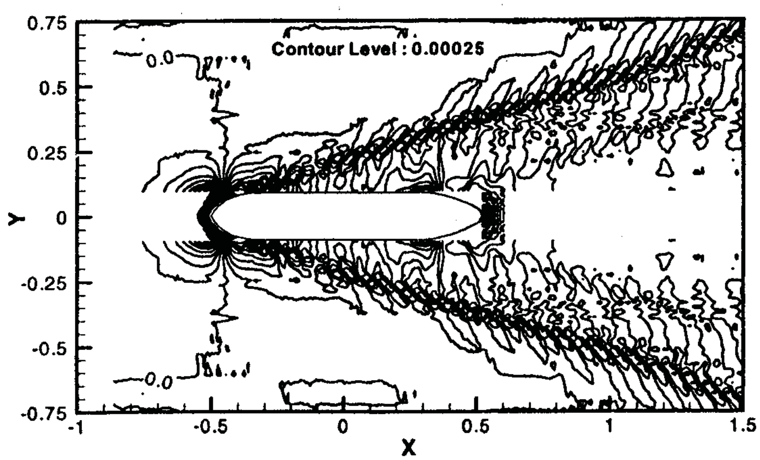
Figure 7. Representative results for DAIOH.



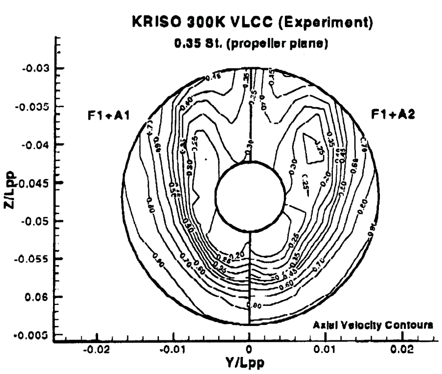
(a) Body plan



(b) Wave profile on the hull surface at Fr=0.26 (VLCC) (Study 8.1)



(c) Wave elevations at Fr=0.26 (VLCC) (Study 8.1)



(d) Comparison of axial velocity contours in the propeller plane for VLCC and VLCC2 (Study 8.1-8.2)

Figure 8. Representative results for VLCC and VLCC2.