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Validation of Sea Keeping Computer Codes in the Frequency Domain

1 PURPOSE OF PROCEDURE

The primary goal of member organizations in the Sea keeping and Ocean Engineering field is to be able to predict as accurately as possible, either by means of model tests or by using analytical techniques, the performance of a given floating structure geometry in waves. As shown in previous reports to the ITTC, there is considerable scatter among reported results from one organization to another, both experimentally and analytically.

Hydrodynamic coefficients at forward speed differ sometimes significantly from theoretical predictions, especially when non-linearities or viscous effects play a role. A typical example of these disagreements can be found for potential coefficients of Wigley hull forms.

Furthermore, in the case of regular wave transfer functions, there is sometimes a considerable bias between predictions and experiments. That is, the mean of the predictions differs from the mean of the measurements by an amount that is apparently greater than can be explained by the experimental scatter.

Obviously, this experimental scatter and bias between predictions and experiments will hold for the resulting motions too.

It is clear that there is considerable room for improvement in these areas, e.g. by carrying out uncertainty analysis as recommended by the ITTC.

The purpose of this procedure is to provide a preliminary guideline on the validation of 2D or 3D sea keeping computer codes for calculating the potential coefficients, wave exiting loads and motions of floating structures and displacement ships in regular waves in the frequency domain. Comments, based on experience with this first attempt to a guideline by member organizations, can lead to improvements of this procedure.

2 SCOPE

Computational fluid dynamics or sea keeping computer codes based on the potential theory play an increasingly important role in predicting hydrodynamic performance of ships and offshore structures. Use of computer skills enhances the capabilities of ITTC organizations, and complements and changes the role of experiments, rather than replacing model tests. The investigator’s insight into physical processes can be increased by means of computational fluid dynamics, because one can “step inside the flow” and study the flow in much greater detail than is usually possible through experiments. Further, it provides excellent possibilities for optimizing designs, particularly when it is integrated in a computer aided design process.

The value of sea keeping computer codes greatly depends on the level of confidence in the results. The level of confidence is determined by the accumulation of experience and experimental verifications carried out. The time span needed to reach a “mature capability" and the level of confidence, can both be influenced in a positive sense by a structured approach during the development.

The Panel on Validation Procedures of the 19th ITTC has given a first guideline for an inclusion of verification and validation procedures in the development process of sea keeping computer codes. In the flow diagram, as presented in Figure 1, the various steps that can be discerned in the development process of sea keeping computer codes were listed with the sources of error that could be associated with these steps.

A clear distinction has to be made between the **verification** and the **validation** of a sea keeping computer code:

- **Verification** of a computer code means to check that the code is actually a correct presentation of the mathematical model that forms the basis for it. It establishes that the code written echoes the intended operations and procedures necessary to fulfil or complete the required intended tasks. It means the code in itself is correct.
- **Validation** is the demonstration that the mathematical model of the verified computer code is an adequate representation of the physical reality. It establishes the applicability and integrity of the code developed.

Thus, validation is a much broader activity, which includes verification and comparison with benchmark experimental results. The validation process should provide estimates of suitable metrics, which are indicative of the

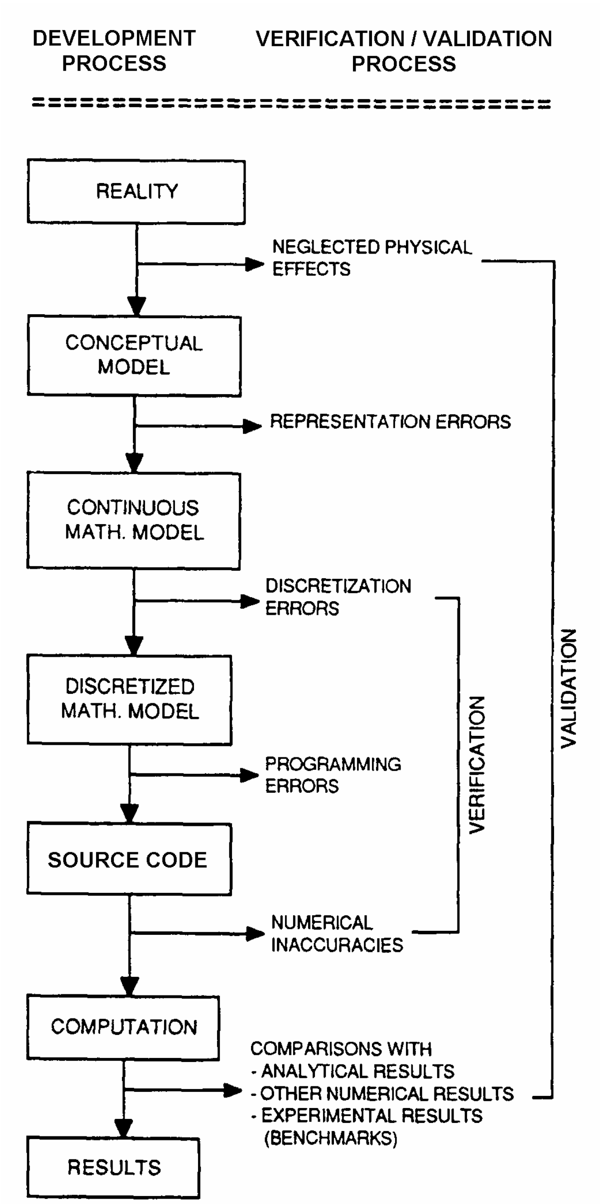

Figure 1: Development, Verification and Validation Process of a Sea keeping Computer Code

processes involved and lead to estimates that are compatible with other means of measuring the selected metrics.

In the development of sea keeping computer codes the following aspects are of importance:

- Present theoretical limitations;
- Numerical aspects;
- Software engineering aspects;
- Verification activities;
- Validation activities;
- Documentation.

These aspects are considered here as far as they influence the computational results of sea keeping computer codes.

2.1 Present Theoretical Limitations

Each sea keeping code is based on a mathematical model. It is important for users to be aware of the limitations inherent in the mathematical model underlying the code. Therefore, the basic simplifications must be clearly specified, such as:

- Slenderness of the body, if required;
- Linearity of output-input relations;
- Small amplitude assumptions;
- Displacement ship at forward speed and constant course;
- Hull form limitations, if required;
- Neglected effects of sinkage and trim at forward speed, viscosity, shallow water, walls or shores, appendices of the hull, propulsion and steering, dynamic positioning, mooring, etc.

In many cases, purely theoretical models are supplemented with empirical data (for instance data on viscous roll damping or mooring dynamics). But again, it is important to be aware whether or not empirical data is included, and if so the user should specify any empirical input.

2.2 Numerical Aspects

A mathematical model is translated into a numerical model, amendable to programming, through discretisation. In many cases the accuracy of the results of the numerical processes can be estimated.

Attention should be paid to:

- Modeling and discretisation of boundary conditions and limits of the fluid domain;
- 2D geometry effects, such as slenderness of the body and number and size of section or offset intervals;
- 3D grid effects, such as topography, number and size of panels or elements (resolution) and order of panels;
- Solution techniques, especially in case of high frequencies, sharp corners, skegs, and large matrices;
- Aspects of time and/or space integration, such as order of integration, stability, convergence, accuracy and initial conditions;
- Numerical summation or integration aspects of the panel length or the cross section interval length related to the shortest wavelength;
- Numerical accuracy of floating point operations, word length, and single or double precision definitions.

Convergence tests should not only include testing on the integrated quantities like hydrodynamic mass, damping, and exciting wave loads, but also tests on the local behavior. Especially, this is important when calculating local internal loads, such as sheer forces and bending moments. It is not sufficient merely to claim that results converge as the number of intervals increases, but it is also necessary to provide an evaluation that numerical modeling is consistent with what is wanted to be calculated.

The most important sources of possible numerical errors for sea keeping computer codes are:

- 2D conformal mapping: In case of N-parameter close-fit conformal mapping of the cross section to the unit circle, care should be taken for failures due to very low or very high sectional area coefficients. Differences between the re-transformed section and the actual section should be examined and, if necessary, warnings should be given. Re-entrant or asymmetrical re-transformed cross sections have to be avoided.
- 3D paneling of the body surface: The errors due to paneling can be investigated by assuming that the convergence or error ε_p convergence of the linear and drift forces due to paneling can be expressed as:

  $$\varepsilon_p = \frac{|f_N - f_\infty|}{|f_\infty|} = K\left(\frac{1}{N}\right)^\alpha$$

  where f_N is the computed value with N panels, and f_∞ is the value one would obtain if there were an infinite number of panels.

  K and α depend on the frequency, wave heading, response variable, shape of the body, and specific choice of panels.
- 3D Green's function calculation: One important numerical source of error in 3D calculations, due to the Green's function evaluation, is associated with the specific manner by which the Rankine part (*1/R*) is integrated analytically over a panel. Another example of a numerical source of error is the calculation of tangential velocity at an element. Using Green's second identity to represent the velocity potential, approximating the body surface by plane quadrilateral elements (panels), and assuming constant variation of the velocity potential over each element, the tangential velocity will always be in error at the element. The reason for this is the assumption that a constant variation of the velocity potential over a panel is inconsistent with finding the tangential velocity (i.e. tangential derivative of the velocity potential) at the element.
- Discretisation of the body surface: The magnitude of these errors depends on the frequency, wave heading, response variable, shape of the body, and specific choice of cross sections and offsets. Large errors may occur if the size of the panels is not small enough to account for the local variations in the flow. This is, in general, important near the edges and corners, and, in particular, near the free surface for the drift forces. Similarly, the panel size should be small compared to the wavelength. In some special cases, the results may converge to wrong values. An example is the flow prediction near a sharp corner when not accounting for the singular behavior in the solution procedure.
- Solution techniques: Errors due to a solution of the linear equation system are believed to be insignificant, except in the vicinity of irregular frequencies. If one assumes a constant, a linear or other type of

polynomial variation of source density or velocity potential over elements or panels adjacent to a sharp corner, the solution will always be in error at these panels. However, correctly converging results will be obtained if the singular behavior of the velocity at the sharp corner is accounted for in the solution procedure.

- Irregular frequencies: When the computer code has no method to cure irregular frequencies problems (such as closing the inner side of the body in the water plane), calculations can fail for frequencies in its vicinity. Often, it can be assumed that irregular frequencies are higher than the wave frequency domain. However, in case of the calculation of local internal loads, errors associated with irregular frequencies should be evaluated.

2.3 Software Engineering Aspects

Investment in software engineering can enhance the performance of sea keeping codes significantly, not only in terms of quality, but also with respect to costs and turnaround. Often, man-hours needed for input preparation are a major part of the total costs. These can be reduced by proper pre- and post-processing routines.

Of importance are:

- Pre-processing: grid generation for different loading conditions;
- Post-processing: data reduction and graphic representation of complex data;
- Communication with other programs and data bases;
- User interfaces;
- User guidance systems and expert systems (in this respect it is of importance to state the level of experience that is required for use of a specific program);
- Software quality assurance.

2.4 Verification Activities

The verification process includes:

- Comparison with analytical results for special test cases involving simple geometries and limiting values of the parameters;
- Comparison with benchmarks of numerical results;
- Verifications of analytical relations between computed quantities;
- Verifications by use of relations based on conservation principles involving mass, momentum, and/or energy;
- Systematic accuracy analysis.

Systematic accuracy analysis means that numerical error sources are listed and the sensitivity of final results to each error source is identified. The accuracy analysis should be done by convergence tests where, for instance, grid size or final steps are systematically varied. It is realized that convergence tests are not always possible to do, sometimes because of limitations in computer storage and speed. One should state what tests are necessary, including specification of structure types, parameter variations and response variables.

2.5 Validation Activities

Validation of sea keeping codes requires that the results be compared with results of trustworthy model tests or full-scale observations. With respect to the development of the theory, trustworthy model experiments are extremely important. In this respect, the following fundamental types of experiment can be discerned:

- Experiments designed to understand the flow physics;
- Experiments designed to validate computer codes, aiming as determining the accuracy and limitations of such codes.

Validation experiments should be carefully designed to provide data in the form and detail required for comparison with numerical results. Also, the accuracy and limitation of the experimental data must be known. Validation should be performed for a range of specified parameters and cases. If possible, the degree of agreement should be specified in quantitative terms.

2.6 Documentation

Confidence in the theory is based on accumulated knowledge and experience, which requires a complete and accessible documentation covering the following aspects:

- Object of computation: A differentiation should be made in the level of confidence for the various quantities that can be obtained by the program.
- Equations and computational conditions: The governing equation(s), auxiliary equation(s) for modelling or closure, and approximations employed should be described together with the boundary conditions.
- Discretizations and grid/panel generation: The employed method to discretise the governing equations should be described together with its limitations. Examples of the grid scheme or panel arrangements must be illustrated together with a description of the minimum grid/panel size.
- Systematic accuracy analyses: The results of the systematic accuracy analyses must be stated, when the dependency of grid or panel size or computing domain, convergence, etc. is discussed. Examples for less complicated special cases can be a part of the systematic accuracy analyses when they are compared with the well accepted computed results or theoretical results.
- Standard printouts and checks: In order to minimize the possibility of unnoticed human errors, it is necessary to include several standard printouts and checks.

3 PROCEDURE

The theoretical basis of a conventional sea keeping computer program for calculating the wave exciting loads and motions on floating structures or displacement ships in regular waves is:

- An incompressible and (basically) inviscid fluid;
- An irrotational flow, which requirement follows from using a potential theory;
- Linearised free surface and body boundary conditions;
- Linearised pressure and force expressions;
- Harmonic motions and loads.

The 3D diffraction/radiation programs are (in general still) valid for zero forward speed.

The 2D strip theory is not limited to zero speed. This means that the boundary conditions are different. In addition a slender body assumption is made. There exist different strip theories, all valid for displacement ships only. The theoretical basis of each strip method is the mathematical model of that specified strip theory. It specifies the boundary value problems to be solved, and how the solutions from the boundary value problems should be combined to obtain the added mass, damping and wave excitation loads.

The following sections describe the minimal required steps for the verification and validation of frequency domain ship motion computer codes.

3.1 Geometry of Structure

Verification and validation of computer code elements, related to the underwater geometry of the floating structure or sailing vessel, are closely connected; they include:

- Panel size or section and offset interval length: These dimensions should be small enough that one can expect only minor influences on computed data.
- Offsets of the under water hull form: Present a 2D or 3D screen plot of the hull form input data for visual control, which is a very fast and effective way to determine human input errors.
- Geometric properties: Check relevant geometric properties such as: water plane area, volume of displacement, location of centre of buoyancy, initial stability, etc.

  Check for presence of computing errors by:
  - Comparing calculated geometrical data with manual results of simple bodies, like (hemi)spheres and combinations of cylinders with rectangular, triangular and circular cross sections;
  - Comparing calculated geometrical data of actual hull forms with results of other computer codes, such as stability programs;
  - Checking whether the program takes tunnels, tumble homes, bulbous forms, etc. correctly into account.
- Origin of axis system: Loads and motions for 6 degrees-of-freedom are generally defined at and about the center of gravity, G of the ship's solid mass. If the vertical position of the center of gravity, $\overline{KG}$, follows from an input of the metacentric height, $\overline{GM}$, and the properties determined from the under water geometry of the vessel, care should be taken that this metacentric height does not include a reduction, $\overline{GG'}$, due to free surfaces of liquids in tanks.
- Metacentric height: Check for a positive computed $\overline{GM}$ when $\overline{KG}$ is input.

3.2 Potential Coefficients

Verification of computer code elements related to the potential coefficients (added mass and damping) includes:

- Symmetry of coupling coefficients: Check symmetry of coupled added mass and damping coefficients at zero speed.
- Conservation of energy: Check for negative damping values and for the relations between damping coefficients and radiated wave amplitudes according to conservation of energy.
- Analytical results: Check for program

errors by a comparing computed data with 2D or 3D analytical results of added mass of bodies of certain geometries in a fluid domain without a free surface and bodies such as a circle or a hemisphere in a fluid domain with a free surface.

- Irregular frequencies: Check for the presence of irregular frequencies; at least a warning should be given for this. However, this problem can be avoided into a large extend by closing the inner side of the body in the water plane.
- Extreme aspect ratios: Check 2D coefficients of sections that are high and thin, as well as wide shallow-draft sections.
- Check for program errors by a comparison with asymptotic values in very long and in very short wavelengths relative to the structure's dimensions.

Validation includes:

- Comparisons with 2D experiments (e.g. simple circular, triangular and rectangular shapes) for heave, sway and roll. 3D codes can be tested against cylinder or sphere shapes.
- Check coefficients against benchmark data of ships at different speeds. Special attention should be made to cross-coupling coefficients e.g. between heave and pitch as well as between sway and roll and between roll and sway.

3.3 Viscous Effects

Verification and validation of correction methods for viscous effects in a potential theory code is perhaps the most difficult task to generalize. Viscous effects are not a part of the potential theory, and they are usually treated by empirical or semi-empirical approaches. Thus, verification of these codes depends to a high degree on how the empirical terms are treated in the theory in question. Also, the validation against model tests may sometimes be questioned, as one may expect scale effects on some viscous phenomena. Some examples of how viscous effects may be treated are:

- Surge motions: speed derivative of still water resistance curve.
- Roll motions: semi-empirical method of Ikeda, Himeno and Tanaka (1978)

However, some general features that may be checked are suggested below.

Verification of computer code elements related to viscous effects:

- Analytical results: If the terms can be expressed analytically for simple geometries, the code should be tested against these (analytical) values.
- If the theory includes different components such as viscous roll damping which may be expressed in terms of lift damping, eddy damping, friction damping, bilge keel damping etc., each of the terms should be tested separately against analytical values.
- Unphysical data: Check for negative damping values.
- Check against other computer codes implementing the same theory.

Validation includes:

- Comparison with decay tests with different initial values.
- 2D sections: Comparisons with benchmark data for simple 2D geometries (cylinders).
- Forward speed effects: The integrated results should be checked against benchmark data with decay tests at various forward speeds (including zero speed).

- Check for unphysical values e.g. negative damping.
- A suitable range of hull forms should be tested to establish the valid range of hull forms for the computer code.

3.4 Wave Exciting Loads

Verification of computer code elements related to the wave exciting loads includes:

- Haskind relations: If applicable, check wave loads by applying the Haskind relations.
- Asymptotic values: Check for program errors by a comparison with asymptotic values for very long and very short wavelengths (taking the water depth into account too), relative to the dimensions of the structure.

Validation includes:

- Comparisons with 2D experiments (e.g. simple circular, triangular and rectangular shapes) for heave, sway and roll. 3D codes can be tested against wave loads on cylinder shapes.
- Check, in case of determining an average depth for obtaining the equivalent water particle accelerations and velocities for calculating 2D diffraction wave loads the value of this depth in relation to the sectional draft. In particular, this could be important for bulbous sections.
- Check transfer functions of wave loads against benchmark data of ships at different speeds and headings in regular waves.

3.5 Transfer Functions of Motions

Verification of computer code elements related to the transfer functions includes:

- Asymptotic values: Check for program errors for the transfer functions of the motions of the center of gravity by a comparison with asymptotic values in very long and in very short wavelengths (accounting for the water depth), relative to the structure’s dimensions.
- Superposition of motions: Check whether the program calculates the transfer functions of the (vertical relative) motions in any arbitrary point on the vessel correctly from the transfer functions of the basic motions of the center of gravity.
- Accelerations: Define well in the documentation whether the horizontal accelerations have been calculated in an earth-bound or a ship-bound axes system.

Validation includes a check of the transfer functions of motions (or accelerations) against benchmark data of ships at different speeds and headings.

3.6 Transfer Functions of Added Resistance

None.

3.7 Transfer Functions of Bending and Torsion Moments

Verification of computer code elements related to bending moments includes:

- Check whether the integrated solid mass of the vessel coincides with the mass of the volume of displacement.

- Check whether the location of the center of gravity of the vessel in a longitudinal (or off chance transverse) direction coincides with that location of the center of buoyancy.
- Check bending moment calculations by carrying out an integration of the horizontal and vertical sheer forces (caused by mutually independent hydromechanic loads, wave loads and “solid mass times acceleration” loads) over the total ship length. This check should result in fair close to zero bending moments. A similar check should be carried out for the calculated torsion moment.

Validation includes a check of the transfer functions of the sheer forces and bending and torsion moments against benchmark data of ships at different speeds and headings.

3.8 Computations for Irregular Waves

None.

4 BENCHMARK DATA

Reports on sea keeping experiments that have been collected by ITTC are listed below.

In order to be included in an ITTC benchmark database, a report on loads and responses experiments should satisfy several conditions. Among others, all experimental and measuring conditions should be documented in detail and a detailed uncertainty analysis should be carried out.

As benchmark data for sea keeping tests, the 1978 15th ITTC Quality Manual on Loads and Responses Sea keeping Experiments (Procedure 7.5-02-07-02.1) refers to:

1) Seagoing Quality of Ships
   (7th ITTC, 1955, pp. 247-293)
   Model of the Todd-Forest Series 60 with $C_b = 0.60$; 7 tanks used 5 ft. models, 2 tanks used 10 ft. models and 1 tank used a 16 ft. model.
   Froude numbers: 0.00, 0.18, 0.21, 0.24, 0.27 and 0.30.
   Wave heights: $L/48$, $L/60$ and $L/72$.
   Wave lengths: $0.75L$, $1.00L$, $1.25L$ and $1.50L$.

2) Comparative Tests in Waves at Three Experimental Establishments Using the Same Model
   (11th ITTC, 1966, pp. 332-342)
   British Towing Tank Panel: 10 ft. fibre-glass model of S.S. Cairndhu.
   A series of experiments on a ship model in regular waves using different test techniques.
   Data obtained in irregular and transient waves and some results predicted by the theory (based on Korvin Kroukovsky’s work and employing the added mass and damping coefficients calculated by Grim)

3) Full Scale Destroyer Motion Measurements
   (11th ITTC, 1966, pp. 342-350)
   Full scale and model (1:40) motion tests in head seas of destroyer H.M. "Groningen” of the Royal Netherlands Navy.

4) Comparison of the Computer Calculations of Ship Motions

(11th ITTC, 1966, pp. 350-355)
Ship response functions for the Series 60, C_b = 0.70 parent form.

5) Computer Program Results for Ship Behaviour in Regular Oblique Waves
(11th ITTC, 1966, pp. 408-411)
Series 60, C_b = 0.60 and 0.70 parent form, DTMB model 4210W and 4212W.

6) Experiments in Head Seas:

6-1) Comparative Tests of a Series 60 Ship Model in Regular Waves
(11th ITTC, 1966, pp. 411-415)
Series 60, C_b = 0.60.

6-2) Experiments on Heaving and Pitching Motions of a Ship Model in Regular Longitudinal Waves
(11th ITTC, 1966, pp. 415-418)
Series 60, C_b = 0.60.

6-3) Experiments on the Series 60, C_b = 0.60 and 0.70 Ship Models in Regular Head Waves
(11th ITTC, 1966, pp. 418-420)
Series 60, C_b = 0.60 and 0.70.

6-4) Comparison of Measured Ship Motions and Thrust Increase of Series 60 Ship Models in Regular Head Waves
(11th ITTC, 1966, pp. 420-426)
Series 60, C_b = 0.60 and 0.70.

6-5) Estimation of Ship Behaviour at Sea from Limited Observation
(11th ITTC, 1966, pp. 426-428)

7) Computer Results, Head Seas:

7-1) Theoretical Calculations of Ship Motions and Vertical Wave Bending Moments in Regular Head Seas
(11th ITTC, 1966, pp. 428-430)
Series 60, C_b = 0.70.

7-2) Comparison of Computer Program Results and Experiments for Ship Behaviour in Regular Head Seas
(11th ITTC, 1966, pp. 430-432)
Series 60, C_b = 0.60 and 0.70.

7-3) Computer Program Results for Ship Behaviour in Regular Head Waves
(11th ITTC, 1966, pp. 433-436)
Series 60, C_b = 0.60 and 0.70 parent form, DTMB model 4210W and 4212W.

7-4) Comparison of Calculated and Measured Heaving and Pitching Motions of a Series 60, C_b = 0.70, Ship Model in Regular Longitudinal Waves
(11th ITTC, 1966, pp. 436-442)
Series 60, C_b = 0.70.

7-5) Computer Calculations of Ship Motions
(11th ITTC, 1966, pp. 442)

7-6) Comparison of the Computer Calculations of Ship Motions and Vertical Wave Bending Moment
(11th ITTC, 1966, pp. 442-445)
Series 60, C_b = 0.60 and 0.70.

8) Comparison of the Computer Calculations for Ship Motions and Sea keeping Qualities by Strip Theory

(14th ITTC, 1975, pp. 341-350)
Large sized ore-carrier.

9) Comparison on Results Obtained with Computer Programs to Predict Ship Motions in Six Degrees of Freedom
(15th ITTC, 1978, pp. 79-90)
S-175, $C_b = 0.572$.

10) Comparison of Results Obtained with Compute Programs to Predict Ship Motions in Six-Degrees-of-Freedom and Associated Responses
(16th ITTC, 1981, pp. 217-224)
To identify the differences in the various strip-theories and computation procedures utilised by the various computer programs and provide guidance for improvement, if necessary.
S-175 container ship for $Fn = 0.275$.

11) Analysis of the S-175 Comparative Study
(17th ITTC, 1984, pp. 503-511)

12) S-175 Comparative Model Experiments
(18th ITTC, 1987, pp. 415-427)

13) Rare Events
(19th ITTC, 1990, pp. 434-442)
Sea keeping.

14) Validation, Standards of Reporting and Uncertainty Analysis Strip Theory Predictions
(19th ITTC, 1990, pp. 460-464)

15) ITTC Database of Sea keeping Experiments
(20th ITTC, 1993, pp. 449-451)
Two-dimensional model, Wigley hull form and S-175.

16) Validation of Sea keeping Calculations
(21st ITTC, 1996, pp. 41-43)
Basic theoretical limitations and numerical software engineering aspects.

ITTC Database of Sea keeping Experiments
(21st ITTC, 1996, pp. 43)
S-175 and a HSMV.