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Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes

1. PURPOSE OF PROCEDURE

The primary goal of member organisations in the fields of seakeeping and ocean engineering is to be able to predict as accurately as possible the performance of a given floating structure in waves. This can be done either by means of model tests or by using analytical techniques.

The purpose of this procedure is to provide preliminary guidelines on the verification and validation of frequency- and time-domain seakeeping computer codes for the computation of the hydrodynamic coefficients, the wave-induced loads and motion responses of floating structures and ships in waves. The procedure aims at the validation in the linear and weakly nonlinear regime but should be extended to higher nonlinear phenomena in due course.

2. SCOPE

2.1 Introduction

Computational Fluid Dynamics or seakeeping computer codes based on 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, which complements and changes the role of experiments. 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 (CAD).

The value of seakeeping 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 validations 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 seakeeping computer codes. This process is executed in two subsequent steps, the formulation of the mathematical model on the basis of the physical one and its solution by model discretization and implementing numerical methods. Validation is necessary to ensure that the formulated problem doesn't deviate significantly from reality. Furthermore, the derivation of the solution of the mathematical model should be verified to control the errors associated both with the discretization of the model and the accuracy and robustness of the numerical methods applied in the derivation of the solution.

Thus, a clear distinction has to be made between the **verification** and the **validation** of a seakeeping computer code:

- **Verification** of a computer code is the proof of its implementation. To verify a computer code one has to check that the simulation code is actually a correct representation of the mathematical model that forms the basis for it. One, thus, establishes that the code written echoes the intended operations and procedures necessary to fulfill or complete the required intended tasks. Its successful accomplishment means that the way the code emulates the theory in itself is correct.

- **Validation** of a computer code is the proof of its applicability. To validate a computer code one has to demonstrate that the mathematical model of the verified computer code is an adequate representation of the physical reality.

The verification and validation process should provide estimates of suitable metrics, which are indicative of the processes involved and lead to estimates that are compatible with other means of measuring the selected metrics. In the development of seakeeping computer codes the following aspects are of importance:

- Documentation including any theoretical limitations;
- Verification activities;
- Validation activities;

These aspects are considered here as far as they influence the computational results of seakeeping computer codes. Furthermore, in the Annex additional background information is provided in terms of:

- Numerical aspects;
- Software engineering aspects;

In general, the results of frequency domain codes are evaluated by comparing the non-dimensional RAO curves of the responses in the frequency band around the resonance frequency with available benchmark data. However, it is extremely difficult to express in terms of clear numbers the acceptable level of discrepancies for the outcome of the seakeeping codes. The only guiding criterion that could be stated is that the discrepancy of the code under consideration over some benchmark data should not exceed the combined uncertainty of that code and the one used to produce the benchmark data.

2.2 Verification Activities

The verification process of seakeeping codes 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 convergence test;
- Systematic accuracy and/or stability analysis.

“Systematic convergence test” indicates the dependency test on grid resolution and time step (in time-domain codes). In a time-domain computation, the accuracy of the numerical solution depends on the discrete spatial representation and the temporal scheme. Sometimes such tests are difficult due to the limitation of computer resources, but systematic tests are necessary for the variations of temporal and spatial parameters. Systematic accuracy analysis means that numerical error sources are listed and the sensitivity of final results to each error source is identified. Stability analysis provides very useful information about the consistency between solutions in discrete computational domain and continuous physical domain. Moreover, criteria of spatial and temporal stability can be found by carrying out systematic and/or stability analysis.

2.3 Validation Activities

Validation of seakeeping codes requires that the results should 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 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.

3. PROCEDURE FOR LINEAR COMPUTATION

The theoretical basis of a linear seakeeping computer program for calculating wave-exciting loads and wave-induced motions on floating structures or displacement ships in regular waves is:

- An incompressible and (basically) inviscid fluid;
- An irrotational flow, which justifies the use of a potential theory;
- Linear decomposition of the velocity potential into several independent components, i.e. the incident-wave, the diffraction and the radiation potentials;
- Linearized free surface and body boundary conditions;
- Linearized pressure and force expressions;
- Linearized equations of motions;
- Harmonic motions and loads.

The following sections describe the standard steps for the validation and verification of linear ship motion computer codes.

3.1 Documentation

Each seakeeping 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, in the accompanying Theory Manual the basic simplifications must be clearly specified, such as:

- Fluid property: inviscid, incompressible, and homogenous
- Flow property: irrotational
- Linear potential flow problem with small perturbation.

- Linear waves with small disturbance
- Constant speed and heading
- Hull form limitations if required.
- Neglected or inclusion of effects due to sinkage and trim at forward speed, dynamic positioning, mooring, etc.

In many cases, purely theoretical models are supplemented with empirical data (for instance data on viscous roll damping, course keeping, or mooring dynamics). However, again, it is important to be aware whether or not empirical data are included and whether those empirical data are pertinent for the design task being undertaken.

The present procedure concentrates on the computation particularly based on the following assumptions:

- Adoption of velocity potential
- Linear free surface and body boundary conditions
- Linear pressure expressions
- Linear boundary value problem - The principle of superposition is valid.
- Linear equations of motion.

Confidence in the theory is based on accumulated knowledge and experience, which re-quires a complete and accessible documentation presented in the User Manual and 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.
- Mathematical formulation and equations: Basic assumption, the governing equation(s), and boundary conditions for numerical modeling.
- Numerical Scheme; Method of solution with the associated limitation of application, time-marching scheme, discretization and the order of basis function, e.g. constant or higher-order panel, course-keeping algorithm, radiation condition..
- Computational conditions and parameters: Grid resolution, time segment, empirical coefficients computational domain, weight distribution, wave conditions.
- Systematic convergence and accuracy analyses: The results of the systematic convergence and accuracy analyses must be stated, when the dependency of panel resolution, temporal discretization, domain size, 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.

The following sections describe the minimal required quantities to be printed out and checked for the verification and validation of time domain ship motion computer codes.

3.2 Geometry and Mass Property of Structure

Verification and validation of computer code elements, related to the wetted geometry of ships or floating structures are closely connected, they include:

- Panel size or section and offset interval length: These dimensions should be uniformly distributed and small enough that one can expect only minor influences on computed data.
- Offsets of the wetted 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. It is desirable to have a function for warnings of excessively twisted, overlapping, high aspect ratio or inward-pointing panels.

- Geometric properties: Check relevant geometric properties such as: water plane area, volume of displacement, location of center of buoyancy, initial stability, etc.
- Check for presence of computing errors by:
  - Comparing well-known geometrical data with manual results of simple bodies, like cylinders or barge;
  - 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 (but not limited) at and about the center of ship mass, G. 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 underwater geometry of the vessel, care should be taken that this metacentric height does not include a free surface reduction due to liquids in tanks.
- Metacentric height: Check for a positive computed $\overline{GM}$ when $\overline{KG}$ is input.
- Check that $\overline{KM}+\overline{BM}$ (determined from the offsets) is equal to $\overline{KG}+\overline{GM}$ (provided as input)
- Check the consistency of point or continuous mass distribution and corresponding radii of gyration (given for the computation of global structural loads) with the mass matrix elements for ship motion.
- Axis or location of point for structural load computation: Neutral axis for torsion, shear centre, vertical location of bending moment to be considered

3.3 Wave Exciting Forces

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

- Haskind relations: If applicable, compare diffraction forces and moments obtained by pressure integration with those by 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, if needed), relative to the dimensions of the structure.
- Steady state wave resistance, sinkage force and trim moment can be verified from the steady state limit following an impulsive acceleration force.

Validation includes:

- Comparisons with 2D and 3D experiments (e.g. simple circular, triangular and rectangular shapes) for heave, sway and roll. 3D codes can be tested against wave loads on well-known hull forms, like Series 60 and S-175 hulls or other benchmark data.
- Comparisons with data given forces in calm water (resistance, sinkage force and trim moment)
- Check transfer functions of wave loads against benchmark data of ships at different speeds and headings in regular waves.

3.4 Reaction Forces

The accuracy of the numerical solution for the radiation problem can be estimated by observing the added mass and damping coefficients in a range of wave frequency. Harmonic or irregular forced body motion can be imposed in time, and the time signals of hydrodynamic force should be transformed to frequency do-main. For the comparison with linear frequency-domain solution or experimental data, the body surface fixed at the same draft should be considered. The issue relating to verification is similar to a frequency domain code.

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

- Convergence check: Check sensitivities of coefficients panel distribution (i.e. resolution and domain size), time segment, time window for the Fourier transform. Fourier-transform scheme.
- 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.
- Symmetry of coupling coefficients: Check symmetry of coupled added mass and damping coefficients at zero speed.
- 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 encountered wavelengths relative to the structure’s dimensions.
- For impulse-response function method: The stability of the impulse response functions to ensure no irregular behavior in the time domain. The form of the memory-effect function as $\to\infty$ and to check for any irregular behavior at the critical frequencies. The sensitivity of impulse response function or retardation function to the number of frequency components
- For Rankine panel method: Observe the effects of domain size, numerical method for radiation condition, free-surface panels near body.

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 or well-known ships, like Series 60 (block coefficient 0.7), S175 hull or other benchmark data.
- Check coefficients against benchmark data of ships at different speeds. Cross-coupling coefficients as well as diagonal coefficients should be carefully observed.

3.5 Viscous Forces

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 motion: speed derivative of still water resistance curve

- Sway and yaw motions: empirical sectional drag coefficients or total drag coefficient combined with soft spring or auto-pilot
- Roll motion: semi-empirical method of Ikeda, Himeno and Tanaka (1978), or pure linear damping based on equivalent energy-loss concept.
- The implementation of viscous effects into a time-domain potential flow code is similar with implementing into the frequency domain potential flow codes, but the application of pure linear damping is getting popular in the time-domain computation. On the assumption that for the purpose of verification the wetted hull form is fixed, 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 from the hull and appendages, eddy damping, friction damping, bilge keel damping and appendage drag. Each of the terms should be tested separately against available analytical values.
- Unphysical data: Check for negative damping values.
- Check against other computer codes implementing the same theory.

Validation includes:

- Comparison of decay coefficients determined from decay tests with different initial values.
- Comparison of roll RAOs in beam sea in a frequency range that includes at least the roll natural frequency.
- 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.

3.6 Wave-Induced Motions

The basic approach to V&V of the motion predictions is based upon post-processing the predicted time histories into amplitude and phase transfer function to aid in understanding the terms and comparing against valid experimental (benchmark) data.

In the first instance, the code developer should have a validated method of extracting the amplitude and phase from both regular and irregular time histories. The V&V process should be undertaken for both regular and irregular waves to investigate the linear superposition aspect.

Once the transfer functions have been extracted from the time domain simulation, verification of computer code elements 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 total motions (combinations of rigid body motion) at any arbitrary point on the vessel correctly from the transfer functions of the basic motions at the center of gravity.

- Verification that the movement of the control surfaces (fins and rudders), if applicable, are implemented correctly and reflect the control laws driving them.
- Check against computer prediction made with the same or similar theory.
- Accelerations: Define well in the documentation whether the horizontal accelerations have been calculated in an earth-bound or a ship-bound axes system.
- Transfer functions from irregular waves should be compared with the respective ones generated from regular waves to check the linear superposition assumption is maintained
- For predictions from irregular waves, the probability of exceeding fixed amplitudes should be determined and compared with a standard Rayleigh distribution.

Validation includes a check of the following against benchmark data for ships at different speeds:

- Transfer functions from regular wave tests: motion responses, relative motions at specified location, pressures at specified location, etc.
- RMS motions and motion spectra from irregular wave tests
- Probability distributions of motion amplitudes
- Phase relationships between motions.

Surge, sway, and yaw motions have no restoring forces and moments in potential theory. In reality, these motions are controlled by course-keeping control mechanism, mooring or dynamic positioning system. In addition viscous effect exists. Recent time-domain programs apply the course-keeping algorithm, e.g. PID control, or soft-spring mechanism. To account for these effects, a few empirical coefficients must be tuned by comparing with benchmark data.

3.7 Shear Forces, Bending and Torsional Moments

Verification of computer code elements related to bending moments is similar to that applied to frequency domain methods. The assumption is that these verification activities are undertaken with the wetted body remaining constant. The verification includes:

- 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. This can be done for both zero speed and with forward speed in calm water, if the effects of sinkage and trim are ac-counted for.
- Check bending moment calculations by carrying out an integration of the horizontal and vertical shear forces (caused by mutually independent hydrodynamic loads, wave loads and “solid mass times acceleration” loads) over the total ship length. This check should result in 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 shear forces and bending and torsion moments against benchmark data of ships at different speeds and headings.

4. PROCEDURE FOR WEAKLY NONLINEAR COMPUTATION

The basis of weakly nonlinear computation is basically not much different from that of nonlinear computation. Therefore the scope and procedure for the weakly nonlinear computation are similar to those for linear computation. However, since the weakly nonlinear computation requires more effort and data to be handled, the scope and procedure should cover more details about the numerical methodology, input data, and output results. In general, the latter is physically more profound and difficult to analyze relatively than the former. Whatever the nonlinearity is concerned, computational effort can be significantly increased, compared with the analysis of linear problems. Table 1 summarizes the typical numerical methods which are popular in seakeeping analysis.

4.1 Nonlinear Formulations and Scope

The demand of nonlinear seakeeping analysis is rapidly increasing for more accurate prediction of motion responses in large amplitude ocean waves. As the size of modern ships is getting larger and ocean environment is getting harsher, the demand of nonlinear analysis is higher.

In the viewpoint of nonlinearity level, the numerical methods for ship motion analysis can be divided into several categories. In general, these methods are dependent on the considering two sources: body-geometry nonlinearity and free- surface nonlinearity.

Table 1. Categorization of nonlinear methods

Nonlinearity	Incident Wave	Disturbance Hydrodynamics	Froude-Krylov & Restoring Forces	Numerical Methods
Linear	Linear	Linear	Linear	Strip, Wave Green Function, Rankine Panel, CFD
Weakly Nonlinear	Linear	Linear	Nonlinear	Strip, Impulse-Response-Function, Green Function, Rankine Panel
Weak Scatterer	Linear or Nonlinear	Linear w.r.t. incident wave (Nonlinear in conventional method)	Nonlinear	Rankine Panel
Fully Nonlinear	Nonlinear	Nonlinear	Nonlinear	CFD

The former depends on the hull form and instantaneous wetted-surface profiles, while the latter is due to nonlinear characteristics of incident and disturbed waves.

Today, for practical purpose, the weakly nonlinear method is the most popular nowadays. The weakly nonlinear method has been considered to predict the primary nonlinear effects due to incident wave and instant restoring variation due to nonlinear body motion. This method is effective and efficient, particularly when ship is slender.

This procedure considers a short procedure for nonlinear computation, particularly focusing on weakly or weak-scatterer-based nonlinear analysis and the time-domain approach. There are some frequency-domain methods, e.g. quadratic strip method, but the majority of nonlinear methods have been applied the time-domain analysis during last two decades

4.2 Verification and Validation

V&V of computer code for nonlinear problem are basically not much different from the linear computation, but the followings should be carefully checked:

- Reproduction of linear solutions:
  When the body motion amplitude or incident wave amplitude is small, the nonlinear results should show consistency with linear solution if the amplitude of the body motion is small for the radiation problem, and if the amplitude of incident wave is very small for diffraction and free motion analysis. The added mass, damping, wave excitation RAO, motion RAO should converge to the values of linear solution. The time-domain solution should be converted to the frequency-domain solution by a proper Fourier transformation scheme.
- Convergence test for computational parameters:
  Check the results for various spatial and temporal discretizations. The domain size is another important computational parameter if Rankine panel method or CFD computation is considered. The convergent solutions should be obtained, and further computation should be carried out by using a set of computational parameters which provide convergent nonlinear solution.
- Temporal stability:
  The solution should be temporally stable. The transient solution should be decayed enough time if quasi-steady solution is concerned. The temporal stability should be observed in long-time simulations.
- Comparison with other nonlinear results:
  The validation can be carried out by comparison with the benchmark results of nonlinear computation and/or experiment. The comparison of the time-histories of motion responses and/or pressure is strongly recommended.

4.3 Documentation and Representation of Results

Since the nonlinear solution depends on the formulation of nonlinear components, incident wave amplitude, and body geometry above the still water level, those should be specified with the presentation of nonlinear solutions. The followings are mandatory parameters in the documentation and the representation of computational results:

1) Formulation and input data

- Nonlinearities to be considered: treatment of Froude-Krylov force, restoring force, hydrodynamic force, free-surface boundary condition
- Numerical methodology: numerical method, e.g. strip method with incident nonlinearity, transient wave Green function, Rankine panel method, or CFD, viscosity models

- Body geometry: include the hull form above the still water level
- Discretization: spatial and/or free-surface discretizations, computational domain, time segment
- Wave condition: incident wave generation, wave amplitude and/or slope,

2) Output

- V&V results: consistency with linear solution at small incident waves, comparison with other nonlinear results
- Nonlinear Motion: nonlinear solution for specified wave amplitude, the RAOs can be represented as a function of wave frequency and wave amplitude
- Nonlinear structural loads: nonlinear solution for specified wave amplitude, the RAOs can be represented as a function of wave frequency and wave. Particular interest should be given to difference between hog and sag moments. The set-up or set-down of mean value is recommended to be observed and specified with hog and sag moments.
- Higher-order components: The double, triple, and higher-order components can be obtained by Fourier transform. Those values represent the amount of nonlinearity.
- Appearance of nonlinear effects: general findings such as body-geometry effects, effects of wave slope, change of wave profile, so on.

5. BENCHMARK DATA

Reports on seakeeping 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 seakeeping tests, the 1978 15th ITTC Quality Manual on Loads and Responses Seakeeping 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 CB = 0.60; 7 test 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: and $L/48$, $L/60$ 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. fiberglass model of S.S. Cairndhu.

3) Full Scale Destroyer Motion Measurements
(11th ITTC, l966, 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, l966, pp. 350-355)
Ship response functions for the Series 60, CB= 0.70 parent form

5) Computer Program Results for Ship Behavior in Regular Oblique Waves (11th

ITTC, l966, 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 Behavior in Regular Head Seas
(11th ITTC, l966, pp. 430-432)
Series 60, *C*B = 0.60 and 0.70.

7-3) Computer Program Results for Ship Behavior 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, l966, 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 Seakeeping 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 Seakeeping.
(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 utilized by the various computer programs and provide guidance for improvement, if necessary.
S-175 container ship for *Fr*= 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) Seakeeping

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

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

16) Validation of Seakeeping Calculations (21st ITTC, 1996, pp. 41-43)
Basic theoretical limitations and numerical software engineering aspects
ITTC Database of Seakeeping Experiments (21st ITTC, 1996, pp. 43)
S-175 and a HSMV.

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ANNEX: RECOMMENDATIONS

In this Annex recommendations regarding the numerical and the software engineering aspects of the linear seakeeping codes are presented and discussed.

A 1. Numerical Aspects

A mathematical model is translated into a numerical model, amenable to programming, through discretization. In many cases the accuracy of the results of the numerical processes can be estimated. Attention should be paid to:

- Formulation and linearisation of (initial) boundary value problem and equations of motion
- Discretisation of the body surface into panels or patches
- Modeling and discretization of boundary conditions and limits of the fluid domain
- Method of time integration and time marching for free surface evolution in the time-domain computation
- Spatial and/or temporal integration of the radiation and diffraction quantities
- 2D geometry effects, such as slenderness of the body and number and size of section or offset intervals in 2D (section-based) method.
- Grid dependency such as resolution, the order of panel topology and physical-quantity representation.
- Spatial and/or temporal stability related to consistency with continuous problem in the time-domain computation.
- Asymptotic behavior of the solution in the low and high frequency ranges.
- Treatment of sharp corners, skegs, appendages, and large matrices.
- Numerical accuracy of floating point operations, word length, and single or double precision definitions.
- Numerical treatment of artificial restoring or control mechanism for non-restoring motions, i.e. sway, surge, and yaw.

Convergence tests should include not only include testing on the integrated quantities like hydrodynamic mass, damping, and exciting wave loads, but also tests on the local behavior, e.g. hydrodynamic pressure and sectional loads. Especially, this is important when calculating local internal loads, such as shear 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 the aim of the calculation.

A 2. Software Engineering Aspects

Investment in software engineering can enhance the performance of computer 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.

In the following software engineering aspects of importance to computer codes and specifically in seakeeping codes are listed:

- Pre-processing: proper grid generation for different loading conditions

- Post-processing: data reduction and graphic representation of complex data in the frequency and time-domain, e.g. conversion to Fourier-domain quantities, graphic representation, e.g. animation;
- Communication with other programs and data bases for pre- and post-processing;
- User interfaces;
- User guidance systems;
- Software quality assurance.

In addition, the compiler, its level of optimization and/or the platform (e.g. Windows or UNIX) of implementation of the developed computer codes may affect the accuracy of the numerical results, although this kind has been observed in rare occasions. Test runs with alternative compilers and platforms should be undertaken to ensure that the code is compiler and platform independent.