ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-07	Loads and Responses
7.5-02-07-02	Seakeeping
7.5-02-07-02.5	Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes

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Table of Contents

Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes

1. PURPOSE OF PROCEDURE

The purpose of this procedure is to provide guidelines on the verification and validation (V&V) of frequency- and time-domain seakeeping codes for the computation of the hydrodynamic coefficients, the wave-induced loads and motion responses of floating platforms in waves. The procedure is for V&V of linear and weakly nonlinear regimes, but could be extended to higher nonlinear phenomena in due course.

2. SCOPE

2.1 Introduction

Potential-flow based seakeeping codes play an important role in predicting hydrodynamic performance of ships and offshore structures in waves. Use of computational methods enhances the capabilities of ITTC organizations, which complements and changes the role of experiments.

Although currently the majority of seakeeping calculations are still based on potential flow theory, Computational Fluid Dynamics (RANS, LES, or DNS) are slowly being introduced in the seakeeping field. 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 (CAD) process.

The current procedure is focused on the verification and validation of linear and weakly nonlinear seakeeping computer codes based on potential flow theory. In the future a new procedure may be developed for CFD based methods.

The value of seakeeping 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.

The Panel on Validation Procedures of the 19th ITTC has given a first guideline for an inclusion of V&V procedures in the development process of seakeeping computer codes. 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 ensure that the simulation correctly represents the mathematical formulation. 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 processes 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 codes, the following aspects are of importance:

- Documentation, including any theoretical assumptions and model limitations;
- Verification activities;
- Validation activities.

These aspects are needed, as they influence the results of seakeeping codes. Furthermore, in the Annex, additional background information should be provided in terms of:

- Numerical aspects;
- Software engineering aspects.

In general, the results of frequency domain codes are evaluated by comparing the non-dimensional response amplitude operators (RAO) curves of the responses in the frequency band around the resonance frequency with available numerical benchmark data or experimental data that has been obtained by model tests in regular waves, irregular broadband spectra or transient wave packets. However, it is extremely difficult to express in terms of clear numbers the acceptable level of discrepancies for the outcome of the seakeeping codes. If no experimental data is available, the only guiding criterion that could be stated is that the discrepancy of the particular code compared to 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:

- Verification of predicted quantities with analytical results for special test cases involving simple geometries and limiting values of the parameters;
- Comparison with benchmark numerical results;
- Systematic numerical convergence test;
- Systematic numerical accuracy and stability analysis.

"Systematic numerical convergence test" indicates the dependency test on grid resolution and time step size (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. Numerical accuracy analysis means that numerical error sources are listed and the sensitivity of final results to each error source is identified. Numerical stability analysis is needed to show that round-off errors and small input perturbations will not be magnified and cause the numerical solution to diverge while the system is physically stable. Prior to performing numerical stability analysis, it is important to first determine the physical stability limits, and to check if the numerical code is able to predict the physical instability boundary.

2.3 Validation Activities

Validation of seakeeping codes requires that the predictions 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 to determine 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. Uncertainty assessment of experimental results should follow the ISO-GUM methodology (ISO/IEC 2008). A detailed approach to uncertainty analysis in experimental hydrodynamics can be found in ITTC procedure 7.5-02-01-01. More specifics on uncertainty assessment for seakeeping experiments can be found in ITTC procedure 75-02-07-02.1.

2.4 Linear seakeeping codes

The theoretical basis of a linear seakeeping codes for calculating wave-exciting loads and wave-induced motions on floating platforms in waves is:

- Potential flow seakeeping codes assume the flow to be incompressible, inviscid, and irrotational;
- Linear decomposition of the velocity potential into (assumed) 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.

2.5 Weakly Nonlinear Seakeeping Codes

The basis of weakly nonlinear computation is basically not much different from that of linear 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, and are explained later in this procedure. In general, computational effort for nonlinear codes are higher than linear codes, but nonlinear codes provide better representation of physics. Table 1 summarizes the typical numerical methods which are popular in seakeeping analysis.

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 ships get larger and the ocean environment gets harsher, the demand of nonlinear analysis gets higher.

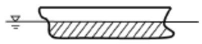
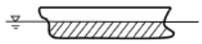
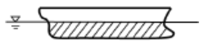
In the viewpoint of the level of nonlinearity, numerical methods for ship motion analysis can be divided into several categories. In general, these methods depend on two sources: body-geometry nonlinearity and free- surface nonlinearity. The former depends on the hull form and instantaneous wetted-surface profiles, while the latter is due to nonlinear characteristics of incident and disturbed waves.

For practical purposes, 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 the ship is slender.

2.6 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 assumptions/simplifications must be clearly specified, e.g.:

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
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

- Definition of earth-fixed and body-fixed coordinate systems and the solved degrees of motion;
- Fluid property: inviscid, incompressible, irrotational, and homogenous;
- Wave condition: incident wave generation, wave amplitude and/or slope;
- Linear codes: linear waves with small perturbations;
- Constant speed and heading;
- Hull form limitations if required;
- Neglected or included 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.

Confidence in the theory is based on accumulated knowledge and experience, which requires a complete and easily 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), boundary conditions and initial conditions (for time-domain codes) 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, etc.;
- Computational conditions and parameters: Grid resolution, time segment, empirical coefficients, computational domain, numerical beach domain, weight distributions, 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 well accepted computed or theoretical results;
- Standard outputs and checks: In order to minimize the possibility of unnoticed human errors, it is necessary to include several standard outputs and checks. Users should ensure that the domain size is sufficiently large to avoid unphysical reflections, and that the choice of time step size avoids the generation of spurious waves. For time domain codes, it is also necessary to check for temporal stability. Transient calculations need to be run long enough such that the solution reach steady-state for quasi-steady problems. The run time should also be long enough to obtain the necessary statistics. In addition, temporal stability should be observed in long-time simulations inphysically stable regimes.

3. PROCEDURE FOR LINEAR SEAKEEPING CODES

This section describes the minimal outputs to consider in V&V of linear seakeeping codes.

3.1 Geometry and Mass Property of Structure

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

- Panel discretization scheme and normal vector definition;
- Offsets of the wetted hull form: 2D or 3D plot of the hull form for visual control, which is a fast and effective way to determine human input errors. It is desirable to have a function for warnings of excessively twisted, over-lapping, high aspect ratio panels, presence of holes, or incorrect definition of normal vectors;
- Geometric properties: Check relevant geometric properties such as water plane area, volume of displacement, centre of buoyancy, centre of gravity, 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 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 centre of gravity, G. If the vertical position of the centre 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 an 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.

3.2 Wave Exciting Forces

Verification of seakeeping 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.

3.3 Radiation Forces

The accuracy of the numerical solution for the radiation problem can be estimated by observing the added mass and damping coefficients over a range of wave frequency. For the comparison with linear frequency-domain solution or experimental data, the body surface fixed at the same draft should be considered.

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

- Convergence check: Sensitivities of the coefficients to 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 comparing computed data with analytical results of added mass of simple bodies in a fluid domain without and 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: Check the stability of the impulse response functions to exclude irregular behaviour in the time domain. The form of the memory-effect function for $t \rightarrow \infty$ should be checked, as well as the behaviour at critical frequencies. One should be aware of 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, and dependence on free-surface panel distributions near the body.

Validation includes:

- 2D codes can be compared with experiments of simple geometries (circular, triangular and rectangular) for heave, sway and roll. 3D codes can be tested against cylindrical or spherical geometries 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.

3.4 Viscous Forces

V&V 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 and if the empirical corrections are valid for the geometry and operating condition of interest. Validation against model-scale 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.

Verification of computer code elements related to viscous effects include:

- 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 of computer code elements related to viscous effects include:

- 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.

3.5 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 at 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 prediction made with the same or similar theory;
- Transfer functions from irregular waves should be compared with the respective ones generated from regular waves to check if the linear superposition assumption is maintained;
- For predictions from irregular waves, the probability of exceeding fixed amplitudes should be determined and compared with appropriate probability distribution (e.g. 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.

3.6 Internal Tank Effects

Linear seakeeping codes based on potential theory are able to capture the primary coupling effects between wave-induced rigid body motions of a vessel and fluid motions in internal tanks. These can, for example, be partially filled LNG or LPG cargo tank or roll damping tanks. The computational domain consists of an external and a specified number of internal fluid domains, which constitute one global boundary surface, but the respective potentials are independent and do not influence each other.

The boundary value problems for the ship motion and sloshing can be solved using the same or different numerical methods, e.g. potential-based method for the ship motion and CFD-based method for the sloshing flow, and the two problems should be coupled.

The verification process for the numerical approach to model internal tank effects on seakeeping characteristics should be conducted for simple cases, e.g.:

- Clean solitary cuboid tank (no internal structures such as damping grids). The internal geometry should be accurately represented in the discretized numerical model. A study to quantify the influence of the grid resolution of the tank model on the results should be performed;
- Filling height h_f to achieve deep liquid conditions ($h_f/B_T > 1.0$ for transverse liquid motions, where B_T is the tank breadth and $h_f/L_T > 1.0$ for longitudinal liquid motions, where L_T is the tank length) at a level to avoid roof impacts or the tank bottom falling dry.

When there are damping grids or other internal structures present, the modelling of the correct implementation of the damping effect should be verified by additional tests on a motion rig including internal structures or a CFD-based computation including viscous effects.

The verification of coupling effects (vessel with internal tanks) should generally follow the recommended procedure for the verification of wave-induced motions, assuming that the absolute values and phases of the transfer functions for the 6-DOF vessel motions have been calculated.

The validation procedure should follow the recommendation for the validation of wave-induced motions. In addition to the rigid body motions of the vessel, transfer functions of internal fluid motions at different positions inside the internal tank should be compared against available benchmark (model test) data. Special attention should be payed to the location of the sloshing-induced peaks in the transfer function of the roll motion. Due to coupling effects of the added masses in sway, roll and yaw, the peak in the motion transfer function is shifted from the natural period of the tank. The location of the internal tanks in the vessel coordinate system has to agree with the location of the tank for the benchmark data set.

The characteristics of the coupling effects between rigid body motions and internal fluid motions are dependent on the density of the liquid inside the internal tank. For practical reason, V&V activities are conducted with fresh water, while for the actual calculations, the real fluid density (e.g. for liquefied gas) should be used.

3.7 Global Loads

Verification of linear seakeeping codes related to global load predictions is similar to that applied to frequency domain methods. The assumption is that these verification activities are undertaken with the wetted body remaining constant, and this or other assumptions should be clearly stated in the documentation and results. The verification includes:

- Check whether the location of the centre of gravity of the vessel in a longitudinal (or off chance transverse) direction coincides with that location of the centre 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 accounted 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;
- Check numerical stability of the method, and perform systematic convergence studies.

Validation includes a check of the transfer functions of the shear forces, bending and torsion moments, against benchmark data of ships at different speeds and headings. Validation studies should include checks on natural frequencies and damping coefficients for dynamic simulations, as well as quantification of modelling uncertainties.

4. PROCEDURE FOR WEAKLY NONLINEAR SEAKEEPING CODES

4.1 Added Input & Output Requirements

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 following parameters are mandatory in the documentation and the presentation of results for weakly nonlinear seakeeping codes **in addition to** the list given in Section 3 for the recommended procedure for linear seakeeping codes:

1) Formulation and input data

- Nonlinearities to be considered: treatment of Froude-Krylov force, restoring force, hydrodynamic force, free-surface boundary condition;
- Body geometry: include the hull form above the still water level.

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 amplitude. 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.

The appearance of nonlinear effects (e.g. nonlinear effects due to wave slope, body-surface geometry, body motion etc.) should be documented.

V&V of computer codes for nonlinear problems are basically not much different from the procedure for linear computations, but the following points 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;
- Comparison with other nonlinear results: The validation can be carried out by comparison with benchmark results of nonlinear computation and/or experiment. The comparison of the time-histories of motion responses and/or pressure is strongly recommended.

5. PROCEDURE FOR HYDROELASTIC SEAKEEPING CODES

This section provides preliminary guidelines on the verification of hydroelastic seakeeping codes for the computation of the hydrodynamic coefficients, the wave-induced loads, motion responses and global load effects of floating structures and ships in waves.

The hull hydro-elasticity computation requires estimation of springing and whipping, wave-induced vibration, combined with wave-induced motions and loads. In order to predict a hydro elastic response, it is essential to solve a fluid-structure interaction (FSI) problem. It can be solved by either monolithic or partitioned method. The current procedure deals with the latter.

5.1 Documentation

In addition to the documentation requirements listed in Section 2.6 for hydrodynamic simulations, the following is also needed in the Theory Manual for hydro elastic seakeeping codes:

- To what extent FSI is taken into account. In hydro elastic seakeeping codes, it is common practice to include the structural deformation response only when calculating the radiation potentials; i.e. the body is assumed rigid when the diffraction potential and the Froude-Krylov pressure is calculated;
- The approach used for modelling the FSI. In most hydro elastic seakeeping codes, a modal approach is used, where global deformation modes are included in addition to the rigid body modes. The global modes are usually the global eigenmodes of the structure when vibrating in vacuum ("dry modes") or, less commonly, in water ("wet modes"). However, other modes shapes may also be used;
- Structural damping model. These are generally empirical models. Often modal damping or Rayleigh damping models are used, but more refined models may also be applied.

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 partitioned method coupling linear seakeeping codes (where the assumptions are listed in Section 3) with structural calculations. It should be cautioned that FSI approaches using the "dry" modes only, where the influence of fluid added mass are placed on the right-hand-side of the equation of motion may be subject to the "virtual added mass instability," which can cause numerical solutions to diverge, even with decreasing time-step size.

In addition to the documentation requirements listed in Section 2.6, the following aspects also needed to be defined in the User Manual for hydro elastic computations:

- Structural model: Timoshenko beam, Vlasov beam, 3D FEM, etc. Structural discretization and structural damping model;
- Slamming model: von Karman model, generalized Wagner model (GWM), modified Logvinovich model (MLM), CFD, or etc.;
- Frequency-domain approach or time-domain approach;
- FSI coupling method: 1-way coupling or 2-way coupling;
- Dynamic analysis method: modal superposition or direct integrationNonlinearities to be considered for slamming and/or green water;
- Capability: global structural response (bending and uniform/non-uniform torsion) and local structural response (nominal/hot-spot stress);
- Systematic numerical convergence and accuracy analyses for both the fluid and structural models, and the iteration parameters between the fluid and structural computations.

The procedures listed in Sections 3 and 4 for linear and weakly nonlinear computations can be applied to the ship motion solver of hull hydro-elasticity computation. However, the boundary condition on the hull surface should be correctly modified to include the flexible motion of hull surface. A precise definition of the boundary conditions and the fluid-structure interface handling scheme should be documented.

5.2 Structural Model

The required hull geometry and mass property for the flow solver is given in Section 6.1. In addition, a structural model is needed to calculate the eigenvectors and eigenvalues of the "dry modes" of the structure, and to calculate the load effects of interest.

Due to the orthogonality properties of the eigenvectors, the off-diagonal terms in the generalized structural mass- and stiffness matrices are zero, and it is common to normalize the eigenmodes so that the diagonal mass-terms become unity and the associated diagonal stiffness terms equal the eigenvalues. This reduces the set of data to be transferred from the structural (eigenvalue) analysis to the hydro elastic (seakeeping) analysis to eigenvectors and eigenvalues only. The relevant load-effects for each mode are used during post processing (modal superposition) of the results from the hydro elastic analysis.

For ships, the most relevant load effects are hull girder moments and shear forces and a relatively coarse structural model can then be used. Beam element models are typically used for monohulls, while 3D shell element models may be used for multihulls or other floating structures.

It is assumed here that the program used for the eigenvalue analysis has been verified and validated. Verification of the structural model includes:

- Comparison of eigenmodes and frequencies with analytical results for uniform beams, and with results from established finite element codes for other structures;
- Convergence studies with increasing number of structural elements.

Verification will then primarily be concerned with the FSI coupling:

- Ensure that the eigenvectors are normalized in a manner that is consistent with the formulation in the hydroelastic code;
- Ensure that the load-effects are scaled consistently;
- Inconsistencies in the hydro-structural coupling are normally discovered by analysing cases where the load-effects (e.g. vertical bending moment) are known from measurements or alternative calculation methods;
- Ensure that the mode shapes are correct;
- Convergence checks with increasing number of eigenmodes. Convergence checks should be carried out at different longitudinal locations and for all responses of interest (e.g. vertical shear forces and bending moments).

5.3 Calm Water Responses

Some analyses in calm water may be useful in the verification of hydroelastic codes:

- Analysis of deformation and load-effects of a beam of uniform shape afloat in calm water; subjected to gravity and hydrostatic pressure only. The analysis may be repeated with point-masses added at different positions of the beam;
- Eigenvalue analysis of a uniform beam floating in calm water;
- Trim, sinkage and deformation/load-effects of the beam moving at different forward speeds.

5.4 Wave Exciting Forces

In hydroelastic seakeeping codes that are based on a modal approach, there will be modal external forces. Hence, in addition to the modal external forces in the 6 rigid body modes, there will be modal forces in the eigenmodes. The transfer functions of the wave exciting forces should be studied for each mode; including the 5-10 first eigenmodes. The values for very short and very long waves should be observed and compared with known results, where applicable. Different wave headings should be investigated.

If applicable, alternative ways of calculating the forces should be compared. Two commonly used methods in linear codes are:

Calculate the force by integration of the pressure around the wetted part of the body;
Calculate the force directly from the velocity potential using integral theorems.

5.5 Hydrodynamic Coefficients

In hydro elastic seakeeping codes that are based on a modal approach, the added mass and damping matrices will be extended from size 6x6 to (6+m) x (6+m), where m is the number of eigenmodes. The behavior of the coefficients for the entire range of oscillation frequencies should be studied. The study should include the first few (5-10) eigenmodes. As with the wave exciting forces, the behavior at very high and very low frequencies is of particular interest. In addition, one should ensure that the variation of the coefficients with vessel forward speed is reasonable. Results should be compared with measurements and/or alternative calculation methods. As for conventional seakeeping codes, convergence checks with respect to body (and free surface) discretization (and, for time-domain codes, temporal discretization) should be performed. In addition, convergence with number of iterations between hydrodynamic and structural calculations within each step should be examined.

5.6 Wave-Induced Motions and Load Effects

Verification of wave-induced motions follows the same lines as for ordinary seakeeping codes. When verifying the load-effects, one should study the response in each eigenmode as well as the total load-effect obtained after superposition of the modal responses. Resonance (springing) peaks in the modal responses and in the total load-effects (e.g. vertical shear forces and bending moments) should be studied, and the shape and location of these peaks along the frequency axis for different structural damping and stiffness levels should be observed. The behavior for very high and very low frequencies should be checked.

For the total load effects, convergence studies with respect to the number of modes should be performed for all responses of interest at different longitudinal locations.

The load effects calculated by hydro elastic codes should not deviate from those calculated by conventional seakeeping codes in the frequency region where hydro elastic effect is insignificant.

As for conventional seakeeping codes, convergence checks with respect to body (and free surface) discretization (and, for time-domain codes, temporal discretization) should be performed.

If applicable, one should also study horizontal shear forces and bending moments as well as torsional moments.

Comparisons of load-effects should be made with alternative calculation methods and can also be made with global loads obtained with ordinary seakeeping codes. In the latter case, good agreement for frequencies below the springing-regime should be expected.

5.7 V&V of Each Part of FSI Analysis

In prior to hull hydro-elasticity computation, each part of fluid model, structural model, and slamming model must be separately verified and validated. V&V process of linear or weakly nonlinear seakeeping codes should be referred to Sections 3 and 4, respectively.

Verification of structural model includes:

- For beam model: Check if important sectional properties such as bending rigidity, Saint-Venant torsional constant and warping torsional constant. Check if the number and positions of beam elements are adequate. Check if an effect of discontinuous structure such as stool and bulkhead on torsion is considered;
- For 3D FE model: Check cargo modeling and inertial property. Reinforce local structures if the result of eigenvalue analysis is polluted by locally deformed modes. Check the mesh size for nominal/hot-spot stress estimation;
- Natural frequency in air (dry mode): Natural frequencies of important natural modes, 2-

node vertical bending and 1-node torsion, should be within a predictable range.

Verification of slamming model includes:

- Geometry of slamming section: Check if dead-rise angle is larger than 0 degree and smaller than 90 degrees because when a potential-based method is used. Sharp edge should be smoothed for numerical stability;
- Grid and time segment: Convergence test is needed to determine the maximum sizes of grid and time segment. Generally, slamming model requires smaller time segment compared to fluid and structural models;
- Comparison with well-known results for 2D circular and wedges: Verify the result by comparing with analytic, numerical, or experimental result. Compare the maximum pressure and pressure distribution of water entry event with constant velocity.

Validation of slamming model includes:

- Comparison with 2D or 3D experimental results for ship-section: Compare the time history of pressure, local force, or sectional force. Check if the modification of geometry is reasonable.

5.8 V&V of Coupled FSI Response

After the above V&V of each part, those of coupled response must be done in certain order. First, a coupled response in calm water should be verified and validated. It includes:

- Grid and time segment: Convergence test should be performed to determine the grid and time step sizes of fluid and slamming models;
- Natural frequency and total damping ratio in water (wetted mode): Check natural frequencies and damping ratios of 2-node vertical bending and 1-node torsion. Those should be acceptable in view of experience, model test, and analytical prediction. Structural damping should be adjusted according to the total damping ratios.

Next, validation of linear hydroelastic response includes the following after the above V&V process:

- Comparison with experimental results: Check motion and load transfer functions. However, it is hard to evaluate the peak of linear springing component because uncertainty of linear springing is high in the experimental result.

Once linear motions and loads are validated, nonlinear hydroelastic responses can be validated. The first step in validation of nonlinear response is to validate super harmonic springing in regular waves includes:

- Comparison with experimental results: Check super harmonic springing responses by comparing high frequency components of sectional forces. Super harmonic springing is induced by geometry nonlinearity of instantaneously wetted body surface. Check validity of incomplete nonlinear methods such as weakly nonlinear approach and weak scatterer method.

Super harmonic springing should be validated in advance of validation of slamming-whipping in regular waves, which includes:

- Comparison with experimental results: Check high-frequency component of sectional forces and local pressure. Categorize wave conditions into bow flare slamming, stern slamming, and combined slamming.

The final step is to validate nonlinear response in irregular waves, which includes:

- Comparison with experimental results: Compare time-series of motions and loads if the same incident wave is generated. Compared the wave-frequency and high-frequency components using FFT which include linear and nonlinear springing components;
- Computation of statistics of the body response and loads.

6. PROCEDURE FOR RARELY OCCURRING EVENTS

While the previous sections contain recommendations for V&V procedures for linear and weakly non-linear seakeeping computer codes and non-rare events, this section focusses on V&V for seakeeping codes that compute occurrences of rare events such as deck wetness, slamming and propeller emergence in the time or frequency domain. Recommendations how to perform benchmark model tests for validation are given in **7.5-02-07-02.3**.

<u>Deck Wetness:</u>

V&V of deck wetness events can be divided into two types of studies:

1. Statistical studies of deck wetness events:

For a given allowed probability of occurrence for green water on deck events or a limiting number of events per defined time window, the limiting significant wave height can be predicted based on linear seakeeping computations in the frequency or time domain. This is based on the probability of exceedance of freeboard height by relative vertical motions at the location of interest.

The V&V procedure for this type of deck wetness study should firstly follow the recommendations for the V&V procedure for wave-induced motions. The correct computation of relative vertical motions at the location of interest is critical. For a selected number of locations, these properties should be compared to available trustworthy model test data for a ship running in head seas at different forward speeds according to **7.5-02-07-02.3.**

2. Studies of local green water impacts:

When local water levels, fluid velocities or impact pressures are of interest, non-linear time domain methods should be used. It is important that the geometry in the numerical calculations is complete up to the uppermost weather deck, including forecastle and bulwarks. Deck fittings, deck houses and freeing ports may also be necessary.

The V&V procedure for this type of deck wetness study should firstly follow the recommendations for the V&V procedure for wave-induced motions and non-linear seakeeping codes. The correct computation of relative vertical motions at the location of interest as well as the accurate capturing of the local wave contour is critical. When local impact pressures due to green water on deck are of interest, the typical rise of pressure associated with an impact occurs within a time frame of 0..-0.35 s (full scale), the time step of the numerical solver has to be small enough to capture the impact. When comparing local pressure magnitudes with model test data, it is important to consider the area and the location of the pressure cell used in the experiments. For validation of the local pressure prediction model, wedge drop tests in controlled calm water conditions can be used. For validation of the local wave contour and the fluid velocity on deck, model test data in either deterministic irregular sea states or transient wave packets can be used.

Slamming:

V&V of slamming events can be divided into two types of studies:

1. Statistical studies of slamming events:

For a given allowed probability of occurrence for slamming events or a limiting number of slamming events per defined time window, the limiting significant wave height can be predicted based on linear seakeeping computations in the frequency or time domain. This is based on the joint probability of air exposure and an exceedance of a critical re-entry velocity. The critical re-entry velocity can for example be based on Ochi's criterion, or on a critical pressure at the location of interest.

The V&V procedure for this type of slamming study should firstly follow the recommendations for the V&V procedure for wave-induced motions. The correct computation of relative vertical motions and velocities at the location of interest is critical. For a selected number of locations that are prone to slamming, these properties should be compared to available trustworthy model test data for a ship running in head (bow slamming) or following seas (stern slamming) at different forward speeds according to **7.5-02-07-02.3.** The validity of the threshold for the re-entry velocity should be checked by model tests in a reproducible irregular sea of defined phase distribution, where slamming events are registered.

2. Prediction of slamming impact pressures and maximum stresses on structural elements:

When the local impact pressure is of interest, non-linear methods in the time domain should be applied. An accurate representation of the geometry of the underwater hull form is important. If flare slamming is of interest, then the geometry must be modelled up to the upper most weather deck.

The V&V procedure for this type of slamming study should firstly follow the recommendations for the V&V procedure for wave-induced motions and non-linear seakeeping codes. The correct computation of relative vertical motions and velocities at the location of interest as well as the accurate capturing of the local wave contour is critical. Since the typical rise of pressure associated with a slamming event occurs within a time frame of 10-20 μs, the time step of the numerical solver has to be small enough. When comparing local pressure magnitudes with model test data, it is important to consider the area and the location of the pressure cell used in the experiments. For validation of the local pressure prediction model, wedge drop tests in controlled calm water conditions can be used.

Propeller, tunnel thruster, rudder, or ride control fin emergence

Emergence events for propellers or tunnel thrusters or rudder or ride control fins can be computed on different levels of complexity. V&V of slamming events therefore can be divided into two types of studies:

1. Statistical studies of emergence events:

For a given allowed probability of occurrence for emergence events or a limiting number of events per defined time window, the limiting significant wave height can be predicted based on linear seakeeping computations in the frequency or time domain. This is based on the probability of exceedance of submergence depth by relative vertical motions at the location of interest.

The V&V procedure for this type of emergence study should firstly follow the recommendations for the V&V procedure for wave-induced motions. The correct computation of relative vertical motions at the location of interest is critical. For a selected number of locations, these properties should be compared to available trustworthy model test data for a ship running in head seas at different forward speeds according to **7.5-02-07-02.3.**

2. Studies of local emergence impacts:

When the local submergence event of a running propeller or tunnel thruster is of interest, non-linear methods in the time domain should be applied. An accurate representation of the geometry of the underwater hull form, especially the aft ship including propeller geometry and rudder as well as the thruster tunnel is important.

The V&V procedure for this type of emergence study should firstly follow the recommendations for the V&V procedure for wave-induced motions and non-linear seakeeping codes. The correct computation of relative vertical motions at the location of interest is critical. In addition, the propeller should operate under the same conditions as in the benchmark model test. If the numerical model can capture ventilation losses that degrade the performance of the propulsor or control surface, the time series of the hydrodynamic loads should be compared to model test data in regular head wave conditions that cause larger relative vertical motions at the propeller.

7. 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 C_B = 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, C_B= 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:

A) Comparative Tests of a Series 60 Ship Model in Regular Waves (11th ITTC, 1966, pp. 411-415) Series 60, CB= 0.60
B) Experiments on Heaving and Pitching Motions of a Ship Model in Regular Longitudinal Waves (11th ITTC, 1966, pp. 415-418) Series 60, CB= 0.60.
C) Experiments on the Series 60, CB = 0.60 and 0.70 Ship Models in Regular Head Waves (11th ITTC, 1966, pp. 418-420) Series 60, CB = 0.60 and 0.70.
D) 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, CB = 0.60 and 0.70.
E) Estimation of Ship Behavior at Sea from Limited Observation (11th ITTC, 1966, pp. 426-428).

7. Computer Results, Head Seas:

A) Theoretical Calculations of Ship Motions and Vertical Wave Bending Moments in Regular Head Seas (11^{th} ITTC, 1966, pp. 428-430) Series 60, *C*B =0.70.
B) Comparison of Computer Program Results and Experiments for Ship Behavior in Regular Head Seas (11^{th} ITTC, l966, pp. 430-432) Series 60, *C*B = 0.60 and 0.70.
C) Computer Program Results for Ship Behavior in Regular Head Waves (11^{th} ITTC, 1966, pp. 433-436) Series 60, *C*B = 0.60 and 0.70 parent form, DTMB model 4210W and 4212W.
D) Comparison of Calculated and Measured Heaving and Pitching Motions of a Series 60, *C*B = 0.70, Ship Model in Regular Longitudinal Waves (11^{th} ITTC, l966, pp. 436-442) Series 60, *C*B = 0.70.
E) Computer Calculations of Ship Motions (11^{th} ITTC, 1966, pp. 442)
F) Comparison of the Computer Calculations of Ship Motions and Vertical Wave Bending Moment (11^{th} 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) - 175, CB =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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Appendix A. 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 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.