Remarks on Experimental Validation Procedures for Numerical Intact Stability Assessment with Latest Examples

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Abstract: For facilitating development of the guidelines of direct stability assessment as a part of the second generation intact stability criteria at the IMO (International Maritime Organization), this paper provides examples of comparison between model experiments and numerical simulations for stability under dead ship condition and for pure loss of stability in astern waves. As a result, some essential elements for reasonable validation were identified. For dead ship stability, adequate selection of representative wind velocity generated by wind fans is crucial. For pure loss of stability, accurate Fourier transformation and reverse transformation of incident irregular waves are important. These remarks should be reflected in the guidelines as appropriate.

Key words: second generation intact stability criteria, direct stability assessment, IMO, dead ship condition, pure loss of stability

1. Introduction

At the IMO, the second generation intact stability criteria, which consist of three level criteria, are now under development. Here its highest level means direct stability assessment using time-domain numerical simulation tools and the tools should be validated with physical model experiments. For this purpose, the IMO started to develop draft guidelines of direct stability assessment procedures under the initiative of the United States and Japan as SDC 1/INF. 8, annex 27 [1]. For finalizing the guidelines, particularly their quantitative acceptance criteria, it is indispensable to examine their feasibility by comparing model experiments with numerical simulations. Thus it is important to collect comparisons between model experiments and numerical simulations for the relevant stability failure modes.

The second generation intact stability criteria deal with five failure modes, i.e, parametric rolling, pure loss of stability in astern waves, broaching, stability under dead ship condition and excessive acceleration. Among them, relatively large number of validation reports for parametric rolling (e.g. Hashimoto et al., [2]) and broaching (e.g. Hashimoto et al., [3]) are available but only the limited number of reports for stability under dead ship condition [4] and pure loss of stability [5]. Since few published experimental data are available, even the experimental procedures for dead ship stability have not yet been established by the ITTC (International Towing Tank Conference) [6].

Therefore, this paper reports recent attempts to validate numerical simulation codes for dead ship stability in irregular beam wind and waves and for pure loss of stability in irregular astern waves. The authors presumes that these information could facilitate finalization of the IMO guidelines for direct stability assessment as well as the revision of the ITTC recommended procedure for intact stability model test.

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2. Current draft guidelines of direct stability assessment procedures

The current draft guidelines of direct stability assessment procedures drafted by the United States and Japan consist of requirements for numerical modelling, qualitative and quantitative validation of software and extrapolation procedures. For the quantitative validation, numerically simulated results are requested to be compared with the model experiments based on the ITTC recommended procedures [6]. Its acceptance criteria are shown in Table 1. In this table, it was widely accepted that all quantitative numbers appeared as the acceptance standards here should be considered as tentative unless the sufficient evidence of their feasibility is submitted to the IMO. It is noteworthy here that these requirements do not refer to irregular wind at all. This is because it is not so easy to find a literature describing ship model experiments with both artificial irregular wind and waves except for T. Kubo et al. [4]. It can be also remarked that no acceptance criteria for pure loss of stability in astern waves exists. This is because only recently mechanism of "pure loss of stability" was discussed as Umeda et al. [7] and H. Kubo et al. [5]. They experimentally and numerically confirmed that large roll triggered by loss of restoring moment due to longitudinal waves could usually induce lateral motions because of asymmetric underwater hull due to heel. Centrifugal force due to such lateral motions could induce further roll motion. Thus, the phenomenon known as "pure loss of stability" could be theoretically dealt with both restoring reduction and centrifugal force due to lateral motions. These raised points have already been adopted by the IMO for the vulnerability criteria as a part of the second generation intact stability criteria. Therefore, it is an urgent issue to provide examples of comparison in artificial irregular waves between model experiments and numerical simulation.

3. Stability failure in irregular beam wind and waves

3.1 experimental procedures

For examining the validation procedures for dead ship stability, experiments using a 1/70 scaled model of the 205.7m-long CEHIPAR2792 vessel were conducted at a seakeeping and manoeuvring basin of National Research Institute of Fisheries Engineering. The ship model has a flat plate on the upper deck for realising the windage area and its area centre height of the super structure but without additional buoyancy. It was not equipped with bilge keels, propellers, shaft brackets and rudders. An optical fibre gyroscope inside the model is used for detecting the roll, pitch and yaw angles. For sway and heave motions, the total station system, which will be described in Chapter 3, was used.

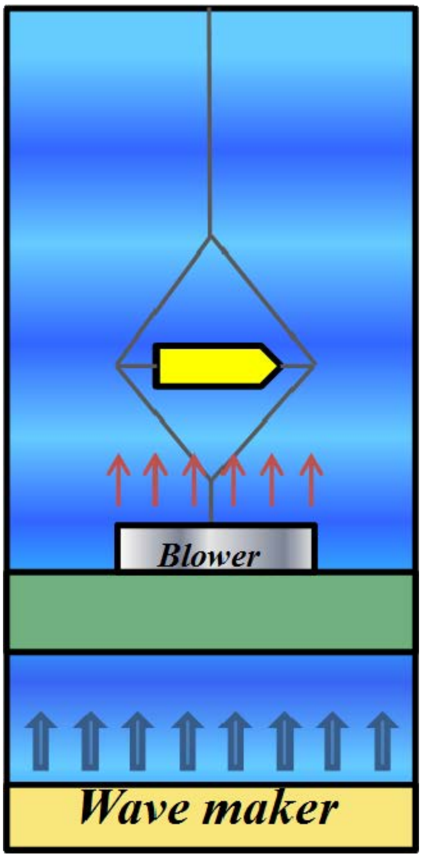

Fig. 1 – Overviews of experimental set-up

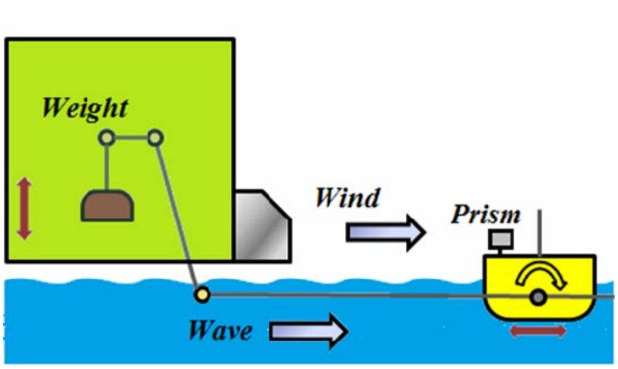

Fig. 2 – Lateral views of experimental set-up

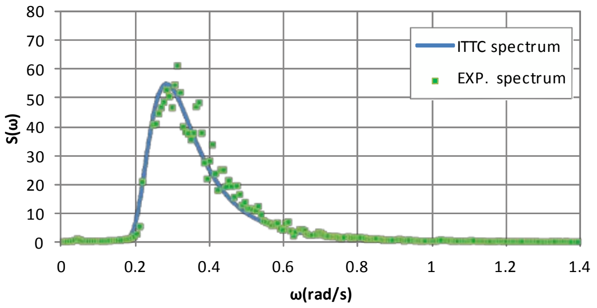

Fig. 3– Comparison of wave spectra

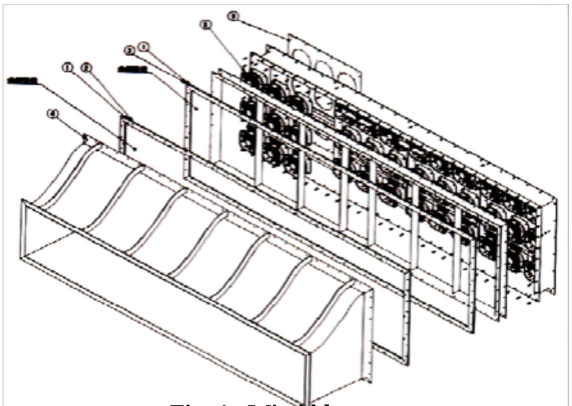

Fig. 4 - Wind blower

The model was kept to be orthogonal to the wind and wave direction by a wire system, which softly restrains drift and yaw, as shown in Figs. 1-2. Here the wire system was connected to the ship model at bow and stern where the height was set to be equal to calm water surface based on measured hydrodynamic reaction force and moment in a captive model test of the subject ship. The mean of fluid dynamic force in the sway direction was cancelled out by a counter weight.

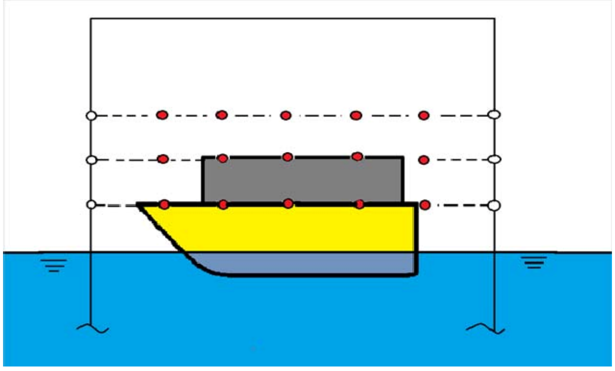

Fig. 5 – Measurement points for wind velocity

Irregular water waves were generated by plunger-type wave makers with the ITTC spectrum. As shown in Fig. 3 the specified spectrum was satisfactorily realized. Fluctuating wind was generated by a wind blower in the wave direction. The wind blower, as shown in Fig. 4 consists of 36 axial flow fans and is controlled by invertors with a v/f control law.

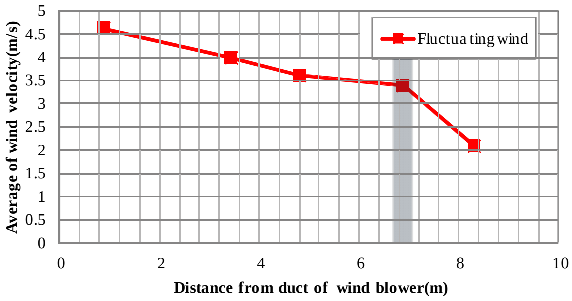

Fig. 6 – Measured wind velocity as a function of the distance from the blower. Here the shaded zone indicates ship position during the experiments in wind and waves.

Although in our previous experiment [4] the relationship between the drive frequency for this control and the wind velocity was adjusted by measuring steady heel angle of the ship model under non-fluctuating wind, the wind velocity was directly measured with a hot wire anemometer in this experiment. This wind measurement was executed without the ship model and 15 measured points we used as shown in Fig. 5. Further, the distance between the wind blower and the ship position were changed with the shift of the position of the blower. These measured data as shown in Fig. 6, the wind velocity gradually decreases with the distance from the blower. In this study the data where the ship model position measured during the experiment is used so that the mean wind velocity used here is about 28 metres per second in full scale. The wind velocity has some spatial non-uniformness as shown in Fig. 7 because the ratio of blower breadth to ship length of 1.327 is not so sufficiently small. The use of wider blower or smaller ship model is preferable. The wind velocity spectrum is designed with the Davenport one without the transfer function between the drive frequency and the wind velocity. The measured spectrum was slightly larger than the specified one, as shown in Fig.8. In our previous experiment [4] better agreement between the two but with its mean wind velocity of 22.5 metres per second was obtained. In case of high wind velocity it seems to be appropriate to take account of the transfer function.

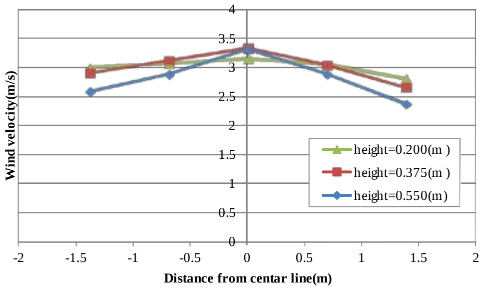

Fig. 7 – Mean wind velocities measured at different positions

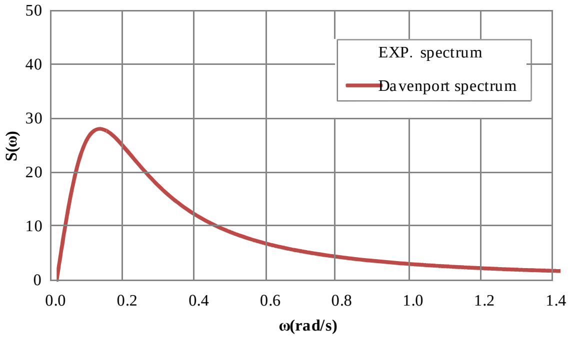

Fig. 8 – Comparison of wind spectra

3.2 numerical modelling

For a comparison with the model experiment, uncoupled roll model [7] was used in this study. As usual, the nonlinear roll damping coefficients in calm water and the effective wave slope coefficient were estimated with roll decay model tests and the roll response model tests in beam regular waves, respectively. The wind-induced moment was estimated with measured wind drag and heel angle only with constant beam wind velocities. As shown in Figs. 9-10, the estimated wind drag and heel angle reasonably agrees with the measured data so that the estimation of wind velocity from these ship data, which was used in our previous work [4], can be judged as reliable.

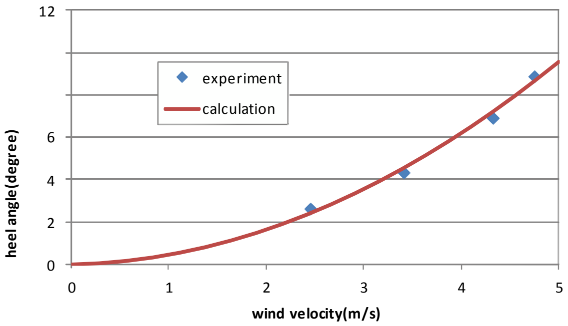

Fig. 9 – Steady heel angle with constant wind velocity

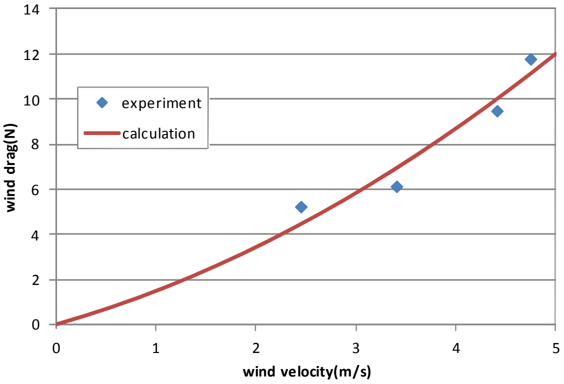

Fig. 10 – Wind drag with constant wind velocity

3.3 Comparison of experiment and simulation

Following the current draft guidelines, the ensemble average of variance of roll angle obtained by the model experiment was compared with that by the numerical simulation with 5 % confidential intervals using *t* distribution as shown in Fig. 11. Here 20 realizations were used for both model experiment and numerical simulation and the duration is 3600 seconds in full scale. The initial heel angle due to cargo shift was 6 degrees towards leeside. In the numerical simulation, the mean wind velocity was set to that from the central points for wind velocity measurement except highest one. Since the two confidential intervals are overlapped, we could conclude that the numerical model was validated with the model experiment.

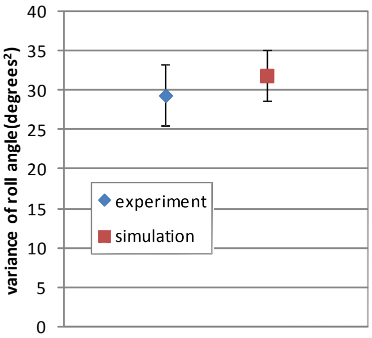

Fig. 11 – Comparison of variance of roll angle between experiment and simulation

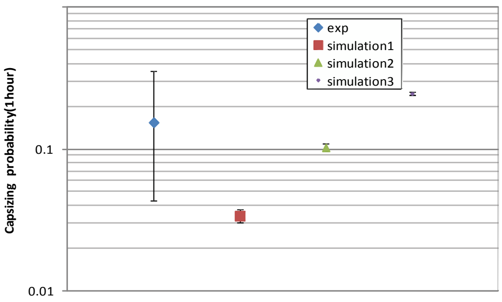

Fig. 12 – Comparison of capsizing probability of experiment and simulation

As a next step, the comparison of capsizing probability between the model experiment and numerical simulations is shown in Fig. 12 with 5% confidence intervals using binomial distribution. Here three different ways for determining the mean wind velocity are used. The "simulation 2" indicates the way that used in the comparison of variance of roll angles. The "simulations 1 and 2" use the mean of three central points and that of the central point at the middle height, respectively. The results indicate that both the "simulation 2 and 3" shows acceptable agreement and the "simulation 1" provides too low probability. Thus, appropriate selection of measured points for wind velocity is crucial for validation of numerical models.

4. Stability failure due to pure loss of stability

For validating a numerical model for pure loss of stability in irregular astern waves, experiments using a 1/48.8 scaled model of the 154m-long ONR flare topside vessel were executed at the seakeeping and manoeuvring basin of National Research Institute of Fisheries Engineering, based on the ITTC recommended procedure on intact stability model test [6]. The position of the ship model was observed by a total station system, which consists of the theodolite, an optical distance and direction measuring device and the prism which reflects light rays from the theodolite is on the ship model, as shown in Fig. 13. By synchronizing data of the total station system and gyroscope which is on the vessel, the ship position in inertia coordinate system was obtained. Ship velocity was calculated by differentiating the position of centre of gravity of the ship.

For precise comparison in time series between the experiment and the simulation, estimation of wave height at each ship position is indispensable. The wave elevation was measured by a servo-needle-type wave height metre near the wave maker. The Fourier spectrum from these measured wave data was converted with the ship position data and then it was inversely transformed so that the wave elevation at the ship position was obtained. This converted Fourier spectrum was also used for numerical simulation as its input.

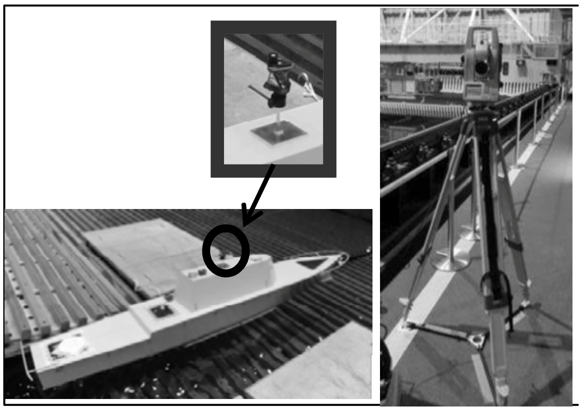

Fig.13 - Total station system (left; prism right; theodolite) used in the model experiment

The wave elevation at the ship centre was calculated by the above procedure and is shown in Fig. 14 with measured roll and pitch data. This result indicates that roll angle becomes large whenever the ship meets a wave crest, which is defined as minima of the wave elevation. Here the significant wave height is 0.2066m, the mean wave period is 1.627 s, the rudder gain is 1.0, the Froude number is 0.25 and the autopilot course from the wave direction is -15 degrees. Earlier and similar procedures and results were published in [8].

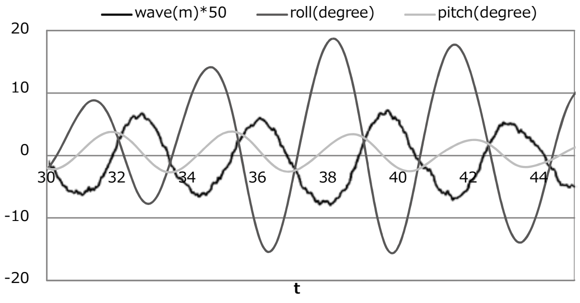

Fig. 14 - Wave height at the ship position and measured roll and pitch angle in irregular waves

The numerical model proposed by H. Kubo et al. [5] is based on nonlinear manoeuvring model with linear wave forces and nonlinear restoring variation. The manoeuvring, roll damping and propulsion coefficients were obtained by conventional model tests such as CMT. The linear wave forces were estimated with a slender body theory with very low encounter frequency and nonlinear restoring variation was predicted with Grim's effective concept and the Froude-Krylov assumption.

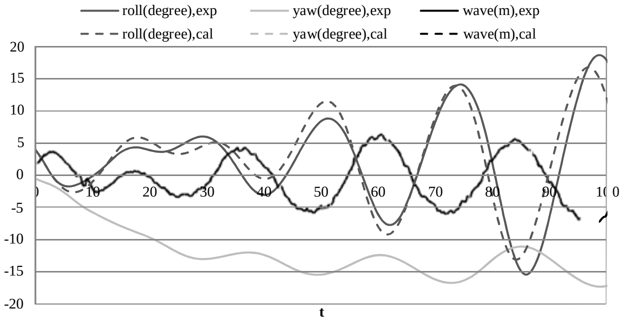

Fig. 15 - Comparison in time series between experiment and calculation in irregular waves

As shown in Fig. 15, this numerical model was well validated with the present model experiment in irregular waves. This validation procedure could be useful for developing standard guidelines of validation of direct stability assessment at the IMO.

5. Concluding remarks

The main remarks from this work are summarized as follows:

(1) For dead ship stability, adequate selection of representative wind velocity generated by wind fans is crucial.

(2) For pure loss of stability, accurate Fourier transformation and reverse transformation of incident irregular waves are important.

Acknowledgements

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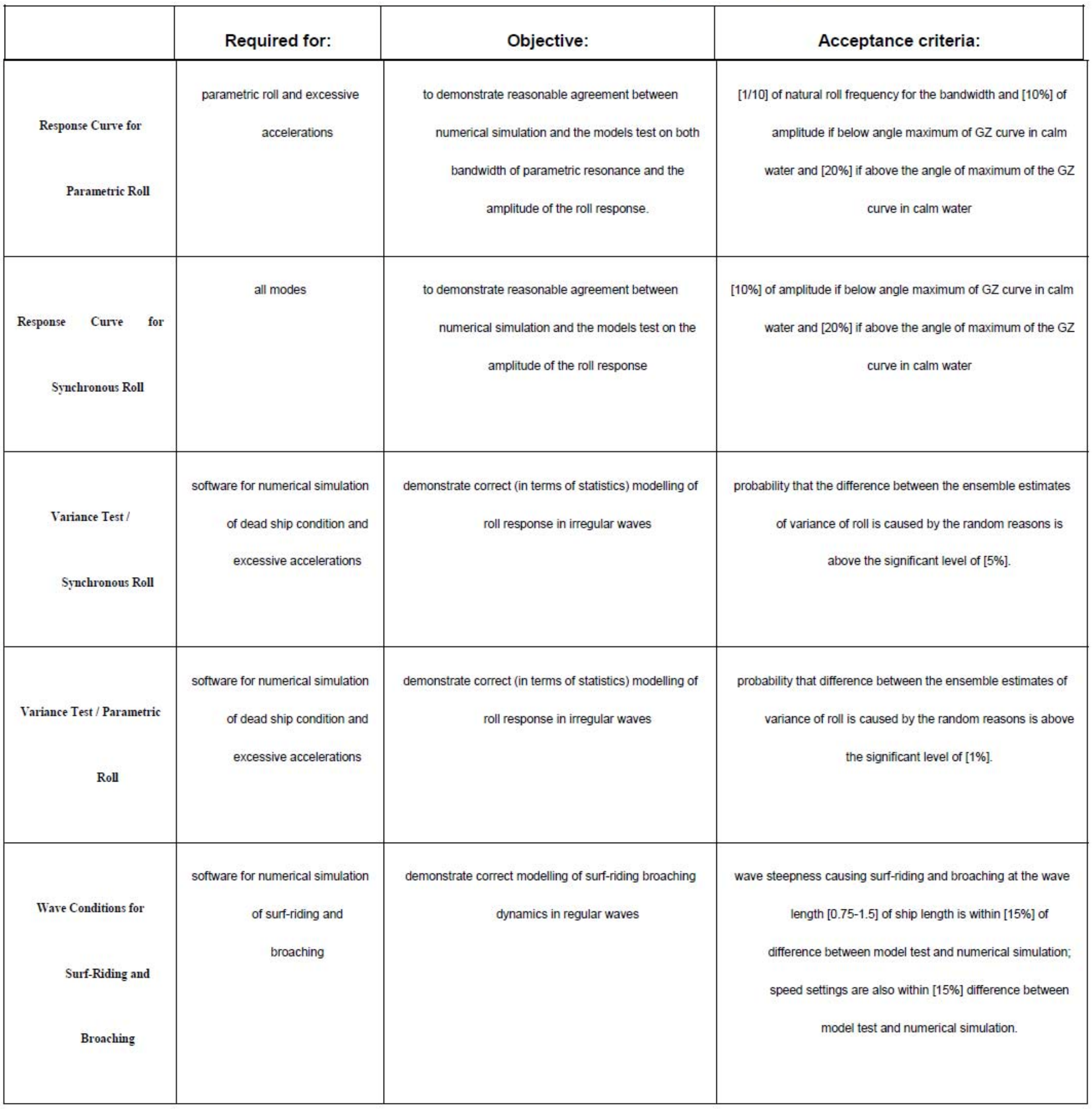
Table 1 Quantitative validation requirements [1]



	Required for:	Objective:	Acceptance criteria:
Response Curve for Parametric Roll	parametric roll and excessive accelerations	to demonstrate reasonable agreement between numerical simulation and the models test on both bandwidth of parametric resonance and the amplitude of the roll response.	[1/10] of natural roll frequency for the bandwidth and [10%] of amplitude if below angle maximum of GZ curve in calm water and [20%] if above the angle of maximum of the GZ curve in calm water
Response Curve for Synchronous Roll	all modes	to demonstrate reasonable agreement between numerical simulation and the models test on the amplitude of the roll response	[10%] of amplitude if below angle maximum of GZ curve in calm water and [20%] if above the angle of maximum of the GZ curve in calm water
Variance Test / Synchronous Roll	software for numerical simulation of dead ship condition and excessive accelerations	demonstrate correct (in terms of statistics) modelling of roll response in irregular waves	probability that the difference between the ensemble estimates of variance of roll is caused by the random reasons is above the significant level of [5%].
Variance Test / Parametric Roll	software for numerical simulation of dead ship condition and excessive accelerations	demonstrate correct (in terms of statistics) modelling of roll response in irregular waves	probability that difference between the ensemble estimates of variance of roll is caused by the random reasons is above the significant level of [1%].
Wave Conditions for Surf-Riding and Broaching	software for numerical simulation of surf-riding and broaching	demonstrate correct modelling of surf-riding broaching dynamics in regular waves	wave steepness causing surf-riding and broaching at the wave length [0.75-1.5] of ship length is within [15%] of difference between model test and numerical simulation; speed settings are also within [15%] difference between model test and numerical simulation.