Validation Attempts on Draft New Generation Intact Stability Criteria

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ABSTRACT

For developing new generation intact stability criteria, the International Maritime Organization (IMO) requires validation and verification studies on draft criteria on stability under dead ship condition, pure loss of stability, broaching and parametric rolling. This paper summarises recent attempts at Osaka University on these failure modes except for parametric rolling. For stability under dead ship condition, an updated split time method for irregular beam wind and waves, which was originally proposed by Belenky (1993) and was proposed by Japan as a candidate for the new criteria, was well validated with the Monte Carlo numerical simulation in time domain (Kubo et al., 2010). As the next step, model experiment using the CEHIPAR 2792 ship in beam wind and waves was conducted for validating the numerical simulation model. The result demonstrates that numerical model is successfully validated with the model experiments. For pure loss of stability in following waves, a set of draft criteria on pure loss of stability proposed by Japan is based on a coupled surge-roll simulation model in irregular astern waves with restoring variation (Kubo and Umeda, 2010). Since the model has not yet been validated with experiment, model experiments using the high-speed RoRo ship were conducted for a comparison with the numerical simulation. The numerical simulation model shows fairly well agreement with the model experiment within the speed range relevant to this phenomenon. For broaching, a set of draft vulnerability criteria on broaching was jointly proposed by Japan and the United States (IMO SLF 53/3/8). In this study, firstly the applicability of the critical Froude number of 0.3 as the deterministic surf-riding threshold (MSC.1/Circ. 1228) is examined with captive model experiments in following waves. Secondly the theory for evaluating the probability of surf-riding situation (Umeda, 1990) is compared with a numerical simulation in irregular waves.

KEYWORDS

Second generation intact stability criteria; dead ship condition; pure loss of stability; surf-riding.

INTRODUCTION

Some of numerical codes in the time domain nowadays are able to evaluate intact stability failure probability at sea so that they could be utilised as direct stability assessment tools for the regulatory purpose at the IMO. It is important, however, to develop early design-stage stability criteria for the relevant stability failure modes and to minimise the use of the direct stability assessment. This is because most of ships are safely operated under the current prescriptive intact stability criteria. Thus it seems to be reasonable for us to concentrate our design efforts into only ships vulnerable to such intact stability failures, such as parametric rolling, pure loss of stability, broaching and harmonic resonance under dead ship condition. Therefore, designers are requested to initially check the vulnerability by the early-design stage criteria, which are much simpler than the direct time-domain simulation. If the ship is judged to be vulnerable for one of stability failure modes, the direct stability assessment should be used with considerable amount of computing efforts. This is the current framework agreed at the IMO for the second generation intact stability criteria.

For this purpose, several member states of the IMO (SLF 53/3/1) proposed draft vulnerability criteria, which consist of two levels, and draft direct stability assessment methods for parametric rolling, pure loss of stability, broaching and harmonic resonance under dead ship condition so far. As a next step, the IMO (SLF 53/WP.4) invites the member states to execute validation and verification studies on these draft vulnerability criteria and direct stability assessment methods and to report their outcomes to the IMO via the intersessional correspondence group coordinated by Japan. Responding to this situation, Osaka University executed some experiments and sample calculations for four major stability failure modes for this purpose. Since the effort on parametric rolling is reported in a separate paper (Hashimoto et al., 2011) at this workshop, this paper describes the work for harmonic resonance under dead ship condition, pure loss of stability and broaching.

For harmonic resonance under dead ship condition, Japan proposed a method for calculating stability failure probability of a ship in beam wind and waves using piece-wise linear restoring moment as a draft vulnerability level 2 criterion or a draft direct stability assessment method, based on a work by Belenky (1993). The formulae used here were upgraded for the simplified version by Belenky (2008) and for non-simplified version by Kubo et al. (2010). Then Kubo et al. (2010) successfully validated the new formulae with the Monte Carlo simulation in the time domain. Physical model experiment is expected as a next step of the validation study. Thus, model experiment of capsizing in beam wind and waves was executed and its result was compared in this paper with that of the Monte Carlo simulation used for validating the draft criteria.

Regarding pure loss of stability, Japan proposed a set of three level criteria. Its draft level 1 criterion utilises a metacentric height estimation using transverse moment of inertia of flat waterplane at the worst water level and the draft level 2 criterion does the maximum righting arm hydrostatically calculated with the worst sinusoidal wavy surface. The draft third level method is a direct use of surge-roll coupled simulation in the time domain for evaluating the probability of the event in which roll angle in the North Atlantic exceeds the critical one (Kubo and Umeda, 2010). The order of conservativeness among the three levels was verified. These assessment, however, has not yet been validated with a physical experiment. Therefore, we conducted physical model experiments in following waves for comparing their results with the numerical simulation used in the level 3 method.

For broaching, the United States and Japan (IMO SLF 53/3/8) jointly proposed a set of three level criteria. Its draft level 1 criterion requests that the nominal Froude number of a ship with its length is 200 metres or less is smaller than 0.3 and the level 2 criterion utilises the probability of surf-riding situation in the North Atlantic using deterministic bifurcation analysis. The draft third level method requests calculations of probability of stability failure due to broaching associated with surf-riding in the North Atlantic. While the validation study of the draft third level method was reported (Umeda et al., 2007b), the draft first and second level criteria have not yet been sufficiently established. Thus, the authors attempt to examine these criteria by using captive model experiments and numerical simulation in the time domain.

HARMONIC ROLL RESONANCE UNDER DEAD SHIP CONDITION

The worst case of harmonic roll under dead ship condition can be regarded as a situation of a ship in irregular beam wind and waves without forward velocity (Umeda et al., 2007a). Thus for validating a simulation model used in the draft criteria, capsizing experiments of a ship model in beam wind and waves were conducted in a seakeeping and maneuvering basin of National Research Institute of Fisheries Engineering (NRIFE). Here irregular water waves were generated by a plunger-type wave maker with the ITTC spectrum and wind having a constant velocity was realized with a wind blower in the wave direction. The use of fluctuating wind remains as a future task. The subject ship is a hypothetical ship known as CEHIPAR2792. Its principal particulars is shown in Table 1. Its 1/70 scaled model has a flat plate on the upper deck for realizing the windage area and its area centre height of the super structure but without additional buoyancy. The ship model was not equipped with bilge keels, propellers, shaft brackets and rudders. An optical fiber gyroscope inside the model was used for detecting the roll, pitch and yaw angles. The model was kept to be orthogonal to the wind and wave direction by a wire system, which softly restrains drift and yaw. Here the wire system was connected to the ship model at bow and stern where the height was set to be equal to water surface, based on the heel angle data of free drifting test in beam wind.

Table1: Principal particulars of the CEHIPAR2792 ship

Displacement	24585.7	Ton
Length between perpendicular	205.7	m
Breadth	32	m
Draught	6.6	m
Metacentric height: GM	2	m
Natural roll period	18.36	s

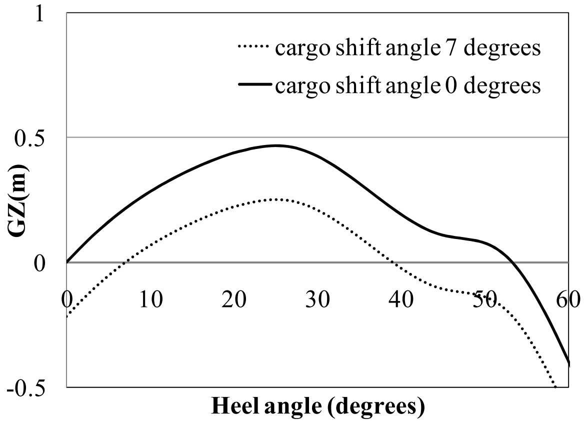

Fig. 1: GZ curves of the CEHIPAR2792 ship

The experimental condition in full scale was specified as the wind velocity of 30 metres per second, the significant wave height of 11.04 metres, the mean wave period of 16.48 seconds and the duration of 1 hour. Furthermore, for simulating cargo shifts, four different constant heel angles, i.e. seven, eight, ten and eleven degrees, were added due to lateral shift of weight on board. The wave elevation was measured by a capacitance-type wave probe and the wind velocity was measured by a hot wire sensor.

Many realisations were repeated and then capsizing probability was estimated as the ratio of the number of capsizing to that of realizations. The confidence interval was estimated based on the procedure recommended by the ITTC (2008).

These experimental results were compared with the results from the time domain simulation model used in the validation study of the theoretical method based on piece-wise linear approach (Kubo et al., 2010). This simulation model utilises an uncoupled roll equation. Here the nonlinear GZ curve is hydrostatically calculated, the linear and quadratic roll damping estimated by roll decay model tests, the effective wave slope coefficient estimated by a strip theory as a function of frequency and the wind heeling moment estimated with lateral projection area and height of its centre and aerodynamic drag coefficient as functions of roll angle. The aerodynamic drag coefficient is calculated with a momentum theorem.

The results of comparison between the experiment and the calculation with these confidence intervals are shown in Fig. 2. Except for the heel angle due to cargo shift of 8 degrees, both confidence intervals are overlapped. Thus, it can be concluded that agreement between the experiment and calculation is fairly good and the simulation slightly overestimates the experiment. This means the simulation model used here, as well as the piece-wise linear method for stability failure probability, provides a conservative prediction at least for this subject ship and the tested environmental condition.

PURE LOSS OF STABILITY

For validating the set of draft criteria on pure loss of stability, model experiment was conducted at the towing tank of Osaka University. The subject ship is a high-speed RoRo ship and its principal particulars and body plans are shown in Table 2 and Fig. 3, respectively. Its 1/60 scaled model was towed by two ropes at the bow point in long-crested irregular following waves. The surge, sway and yaw motions were softly restrained and the roll, pitch and yaw motions were measured by a gyroscope. The waves were realised with ten different realisations using the ITTC spectrum. The restoring arm curves in longitudinal waves were calculated for the RoRo ship with its designed metacentric height of 1 metre using the Froude-Krylov assumption with static heave and pitch as shown in Fig. 4. Here the wavelength is equal to the ship length and the wave steepness ranges from -0.1 to 0.1. The positive and negative wave steepnesses here indicate wave crest amidship and wave trough amidship, respectively. This shows that the restoring reduction at wave crest amidship for this RoRo ship is not so large even the wave steepness of 1/10 that the draft level 2 criterion shows that this RoRo ship with the design metacentric height is not vulnerable to danger due to pure loss of stability (IMO SLF 53/INF.10). Only for a validation purpose, the metacentric height of 0.5 metres was used in the model experiment. Furthermore, the heel angle due to cargo shift is added due to lateral shift of weight. This is because asymmetry is required to induce roll motion due to pure loss of stability in exact following waves.

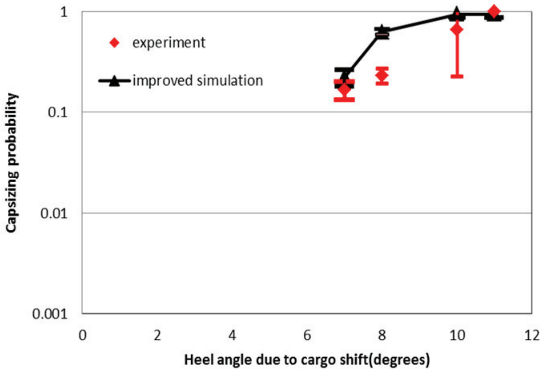

Fig. 2: Capsizing probabilities for the CEHIPAR2792 ship, estimated by model experiment and numerical simulation.

Table2: Principal particulars of the high-speed RoRo ship

Length between perpendiculars	187.7	m
Breadth	24.5	m
Depth	21.32	m
Mean draught	6.9	m

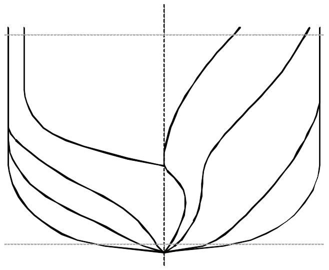

Fig. 3: Body plan of the high-speed RoRo ship.

The simulation model used here is a coupled surge-roll model in irregular stern quartering wind and waves (Umeda and Yamakoshi, 1994). Nonlinear roll restoring variation due to irregular waves is estimated with the Froude-Krylov assumption and Grim’s effective wave concept (Grim, 1961). Linear wave exciting surge force and roll moment are calculated and ship resistance and propeller thrust in calm water as well as roll damping are obtained from conventional model tests.

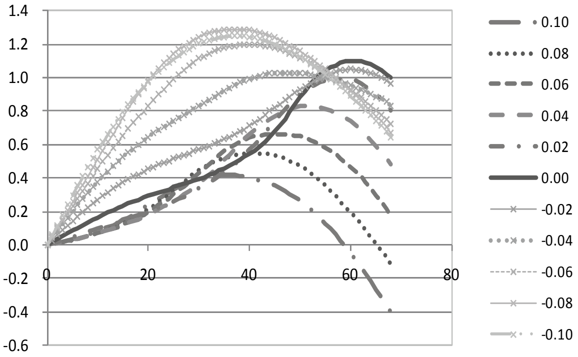

Fig. 4: Righting arms of the RORO ship for wave steepness from -0.1 to 0.1.

An example of comparisons between the experiment and the simulation is shown in Figs. 5 and 6. Reasonably good agreement is shown in ensemble average of ten realizations. In detail, the simulation slightly underestimates the experiment. This could be because a small lateral motion exists in the model experiment but not in the simulation. Thus the simulation model is expected to take account of the heel-induced hydrodynamic sway force and yaw moment in future.

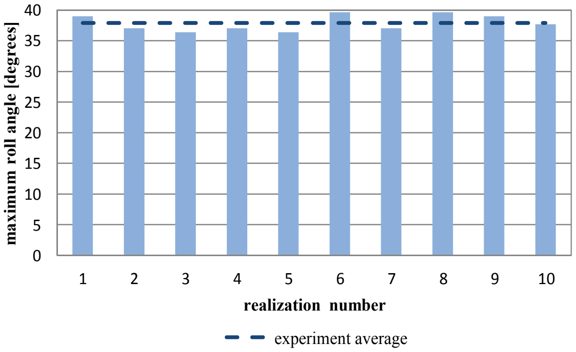

Fig. 5: Measured maximum roll amplitude of the RoRo ship in following waves with the metacentric height of 0.5 m, the Froude number of 0.3 and the heel angle due to cargo shift of 15 deg.

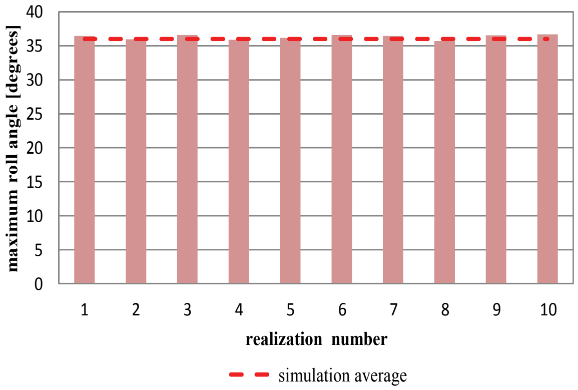

Fig. 6: Calculated maximum roll amplitude of the RoRo ship in following waves with the metacentric height of 0.5 m, the Froude number of 0.3 and the heel angle due to cargo shift of 15 deg.

BROACHING

A set of draft vulnerability criteria on broaching was jointly proposed by Japan and the United States (IMO SLF 53/3/8). As the level 1 vulnerability criterion, critical Froude number of 0.3 as the deterministic surf-riding threshold is used. This critical value was adopted in MSC/Circ. 707, which was superseded by MSC.1/Circ. 1228, based on the results of phase plane analyses of an uncoupled surge model for several ships under the wave steepness of 1/10 (IMO SLF 36/INF.4). Recently, however, simulation results for fine ships sometimes show that this critical Froude number could be smaller than 0.3. These simulations normally utilize the Froude-Krylov assumption for calculating the wave-induced surge force, X_w. Thus it is necessary to carefully examine the applicability of this assumption.

For this purpose, we conducted captive model experiments for the high-speed RoRo ship at the towing tank of Osaka University. Here the scaled model was connected to a towing carriage by means of a dynamometer and then was towed with a constant velocity in regular following waves. Measured surge force is compared with linearly calculated value with the Froude-Krylov assumption. The comparison between the two is shown in Fig. 7 where the wave exciting force is normalised with the wave steepness. It shows the experimental results also have almost a linear relationship with the wave steepness and the experiment shows good agreements in phase lag of the force to waves between the experiment and the calculation.

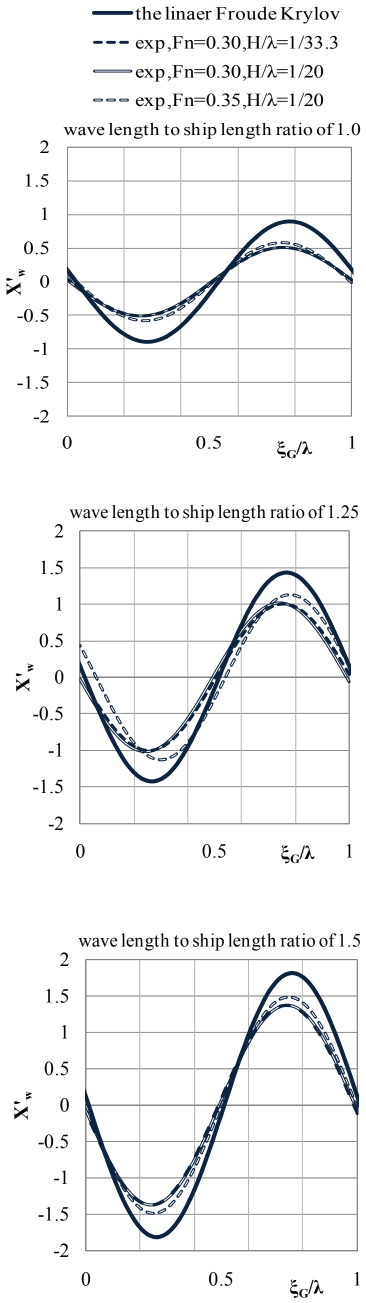

Fig. 7: Comparisons between the captive model experiment and linear Froude-Krylov calculation in wave exciting surge forces for the RoRo ship with three different wavelength.

On the other hand, the calculation significantly overestimates the experiment. This could be a possible reason why the critical Froude number with the Froude-Krylov assumption could be smaller than 0.3. Thus, the authors recalculate the surf-riding threshold by applying their numerical bifurcation analysis tool (Umeda et al., 2007c) to the uncoupled surge model with measured wave exciting force. The results shown in Fig. 8 indicate that the critical Froude number with the measured wave exciting force is larger than 0.3.

Similar procedure is applied also to other finer ships using the published captive test data of the ONR tumblehome topside vessel (Umeda et al., 2008) and the ITTC A2 fishing vessel (Hashimoto et al., 2004). As a result, the result justifying the critical Froude number of 0.3 as the current proposal is obtained in Fig. 9. It is noteworthy here that more captive test data of fine ships should be collected and the level 2 criterion should utilise captive test data for the wave force as well.

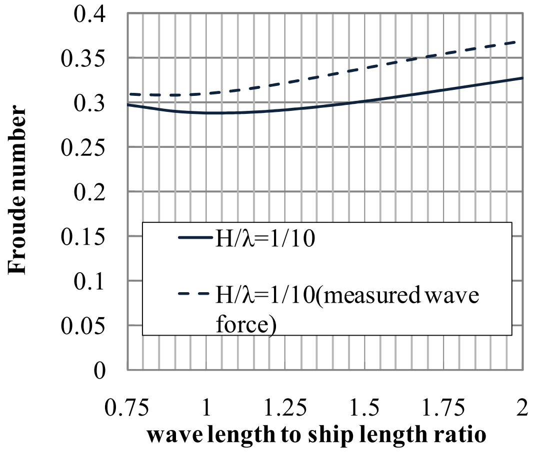

Fig. 8 Surf-riding threshold in regular waves for the RoRo ship with the wave steepness (H/λ) of 1/10.

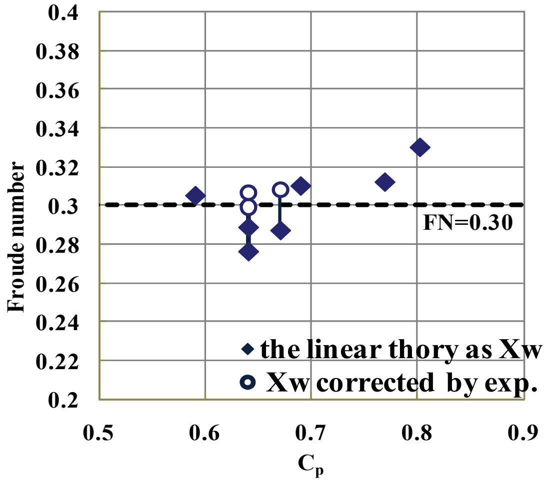

Fig. 9: Surf-riding threshold for seven sample ships in regular following waves with the wave steepness of 1/10. Here C_p indicates the prismatic coefficient.

The draft level 2 vulnerability criteria utilise the calculation of the index representing surf-riding probability in irregular waves. The method is based on the work by Umeda (1990) using a combination of deterministic analyses and probabilistic wave theory but no validation was reported even with a direct numerical simulation so far. Thus, it is desirable to compare the theoretical results with the numerical simulation. Thus, the authors executed the numerical simulation of the uncoupled surge model with static heave and pitch in the time domain for the high-speed RoRo ship. Noting the definition of surf-riding in irregular waves in the time domain is not so clear, occurrence of surf-riding is judged when the zero-crossing pitch period is longer than a threshold. The threshold here is tentatively selected as the largest encounter wave period with the specified and constant Froude number in regular waves with the wavelength to ship length ratios ranging from 1 to 2, which are relevant to broaching. An example of probability density function of simulated pitch period is shown in Fig. 10 with the mean wave period is 11.5 seconds and the specified Froude number of 0.35. When the significant wave height increases, the density of longer pitch period increases. This is due to an effect of nonlinearity of surging. Then, integrating the probability density above the threshold, probability of surf-riding related events can be obtained as shown in Fig. 11. The results show that qualitative agreement between the probabilistic theory and direct numerical simulation exists and the theory overestimates the simulation. Thus it can be stated that the probabilistic theory used in the draft level 2 criterion could provide a conservative prediction for probability of surf-riding related events.

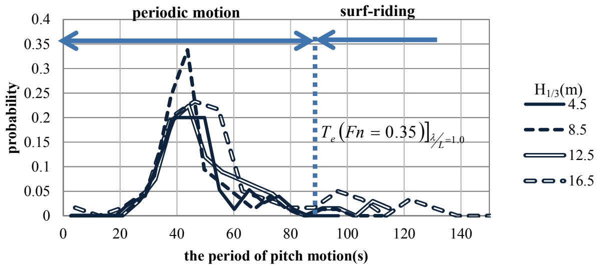

Fig. 10: Probability density of pitch period for the RoRo ship with the nominal Froude number of 0.35 and the mean wave period of 11.5 seconds.

CONCLUSIONS

Validation attempts described in this paper are concluded as follows:

- Numerical simulation model for estimating capsizing probability in beam wind and waves shows fairly good agreement with model experiments for the CEHIPAR2792 ship. This simulation model already showed good agreement with the draft criterion for harmonic resonance under dead ship condition by the delegation of Japan.

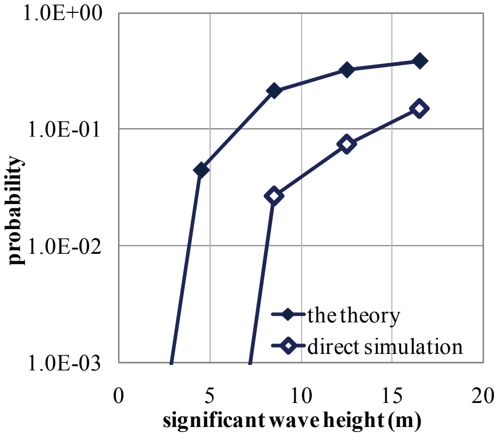

Fig. 11: Probability of occurrence of surf-riding related events for the RoRo ship in irregular following waves with the nominal Froude number of 0.35 and the mean wave period of 11.5 seconds.

- Numerical simulation model for estimating stability failure probability in following waves shows fairly good agreement with model experiments for the RoRo ship. This simulation model was used for a base of a set of draft criteria for pure loss of stability by the delegation of Japan.
- The critical Froude number of 0.3 used for the draft level 1 criterion for broaching by the delegation of the United States and Japan is reasonable within the seven sample ships if the captive test data for wave exciting surge force are taken into account.
- The theoretical methodology used in the draft level 2 criterion by the delegations of the United States and Japan, to some extent, overestimates the frequency of surf-riding related events appeared in the simulated time records of behaviours of the RoRo ship in irregular waves.

ACKNOWLEDMENTS

This work was supported by a Grant-in Aid for Scientific Research of the Japan Society for Promotion of Science (No. 21360427). It was partly carried out as a research activity of Stability Project of Japan Ship Technology Research Association in the fiscal year of 2010, funded by the Nippon Foundation.

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