PREDICTION METHODS FOR BROACHING AND THEIR VALIDATION
- FINAL REPORT OF SCAPE COMMITTEE (PART 6) -

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ABSTRACT

Regarding broaching associated with surf-riding, this paper reports experimental, numerical and analytical studies conducted by the SCAPE (Strategic Research Committee on Estimation Methods of Capsizing Risk for the IMO New Generation Stability Criteria) committee, together with historical review of theoretical progress on this phenomenon. Here effect of higher-order terms in numerical modelling, extension to novel propulsion systems and application of global bifurcation theory, optimal control theory and random process theories are discussed. Experimental techniques are also investigated. Based on these outcomes, it also proposes draft stability criteria consisting of a vulnerability criterion and direct assessment as a candidate for the new generation criteria at the IMO (International Maritime Organization).

KEY WORDS: Broaching, surf-riding, IMO new generation intact stability criteria, global bifurcation, broaching probability.

INTRODUCTION

Broaching is one of the three major capsizing scenarios that the new performance-oriented stability criteria to be added to the Intact Stability Code at the IMO are requested to cover (Germany, 2005). This is a phenomenon that a ship cannot keep a constant course despite the maximum steering effort. If the ship speed is high enough, the centrifugal force due to this uncontrollable yaw motion could result in capsizing. This phenomenon often occurs when a ship runs in following and quartering seas with relatively high forward speed, especially when a ship is surf-ridden. Thus, this phenomenon is relevant to ships having their Froude number of 0.3 or above, such as destroyers, high-speed RoPax ferries, fishing vessels and so on. Broaching itself could occur also with slow speed (Oakley et al., 1974) but such broaching seems not to be a direct threat to ship stability. Thus, this paper focuses on broaching associated with surf-riding.

HISTORICAL REVIEW

A physical model experiment is definitely suitable for realising dangerous phenomena in ship stability because full scale measurement could be too risky. Du Cane (1957) executed model experiments of broaching in following waves at a towing tank. Here he added initial disturbance to a ship model running in the straight course and observed the ship response. Nicholson (1974) and Fuwa et al. (1982) conducted runs of manually-controlled models in stern quartering waves in seakeeping and manoeuvring basins, and identified broaching associated with surf-riding for a destroyer and a high-speed fishing craft, respectively. Kan et al. (1990) and Umeda et al. (1999A) executed free-running model experiments with auto pilots in stern quartering waves in seakeeping and manoeuvring basins, and recorded time histories of capsizing due to broaching for container ships and fishing vessels. In Umeda's experiment, it was confirmed that even a ship complying with the current IMO IS code can capsize as a result of broaching.

Davidson (1948) investigated directional stability in following waves by using a linear sway-yaw coupled model. Here he estimated wave-induced forces as the sum of the Froude-Krylov component and the hydrodynamic lift due to wave particle velocity. As a result, it was confirmed that even a directionally stable ship can be directionally unstable in a wave downslope. Wahab and Swaan (1964) pursued this approach further but with the Froude Krylov component on its own. Eda (1972) applied a coupled surge-sway-yaw model to this linear stability problem. Hamamoto (1973) and Renilson (1982) investigated the wave effect on linear manoeuvring coefficients theoretically and experimentally. Fujino et al. (1983) improved accuracy in prediction ability for manoeuvring coefficient in waves with free surface effects taken into account.

Motora et al. (1982) and Renilson (1982) numerically integrated nonlinear equation of surge-sway-yaw motion and concluded that necessary condition of broaching is that wave-induced yaw moment exceeds the maximum yaw moment due to rudder. Umeda and Renilson (1992 and 1994) developed a 4 DOF mathematical model based on a manoeuvring model with a linear wave forces. Assuming that wave steepness and manoeuvring motions are small, all higher-order terms, such as interactions due to manoeuvring and waves, are consistently ignored. Umeda and Hashimoto (2002) applied this model to explain the free-running model experiments (Umeda et al., 1999A) so that qualitative agreement was confirmed. The ITTC specialist committee on extreme motions and capsizing executed a benchmark testing study of numerical models with the free-running model test data by Umeda et al. (1999A), and concluded that some numerical codes can predict the occurrence of broaching qualitatively (Umeda and Renilson, 2001).

For realizing quantitative prediction, it is necessary to improve the mathematical model by adding higher order terms. Umeda et al. (2003) and Hashimoto et al. (2004A) developed a mathematical model with second-order terms taken into account, and reported that quantitative prediction is realized. Here hydrodynamic forces due to interaction between manoeuvring and waves, hydrodynamic forces due to large roll angle, nonlinear wave and manoeuvring forces and so on are estimated with potential theories or captive model experiments. Hashimoto et al. (2004B) utilised fully-captive model experiments in waves with a purpose-built apparatus.

Surf-riding is regarded as a prerequisite of broaching. Thus it is very important to estimate the surf-riding threshold. Grim (1951) explained that surf-riding boundary coincides with the case that a trajectory from an unstable equilibrium of an uncoupled surge model on a wave is connected to another unstable equilibrium. This is a heteroclinic bifurcation in nonlinear dynamical system theory. Makov (1969) demonstrated the validity of Grim's statement by using a phase plane analysis. Ananiev (1966) obtained an analytically approximated solution by applying a perturbation technique. Umeda and Renilson (1992) extended the nonlinear dynamical system approach from an uncoupled surge model to a coupled surge-sway-yaw model. Spyrou (1995, 1996, 1997) and Umeda (1999) numerically obtained the heteroclinic bifurcation for an uncoupled surge model and the coupled surge-sway-yaw-roll model with a PD autopilot, respectively. Umeda and Vassalos (1996) obtained the region of unstable periodic motion in stern quartering waves by applying an averaging method. Spyrou (2001) presented an exact analytical solution of heteroclinic bifurcation of uncoupled surge model.

The above researches deal with broaching in regular waves only. Although Rutgerssen and Ottosson (1987) and Motora et al. (1982) executed model experiments in irregular waves in a seakeeping and manoeuvring basin and full scale measurement at actual sea, respectively, no probabilistic study on broaching had been reported. Umeda (1990), however, proposed a theoretical method for calculating the surf-riding probability in irregular waves. Here the surf-riding probability is calculated with the deterministic surf-riding threshold and the joint probability of local wave height and wave period.

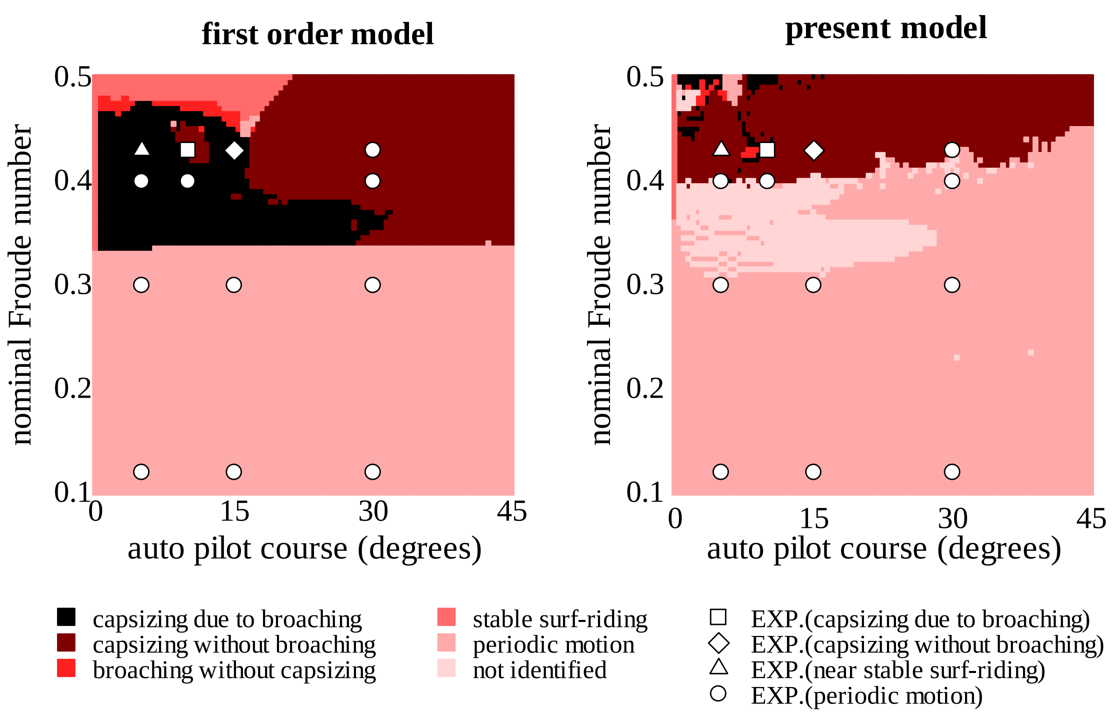

Figure 1 Comparison between the experimental results and numerical results (first order model and present model) for the ITTC Ship A-2 with wave steepness of 0.1 and wavelength to ship length ratio of 1.637 (Umeda and Hashimoto, 2006C).

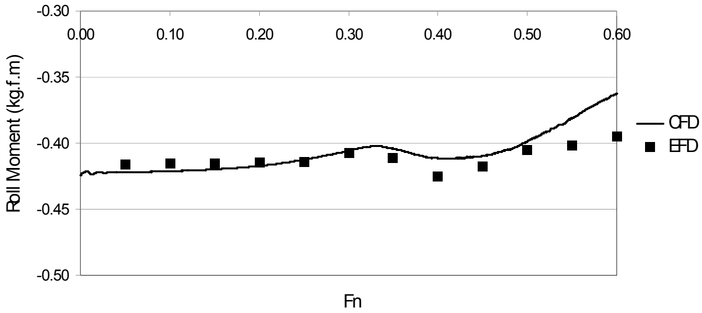

Figure 2 Comparison between the physical model experiment (EFD) and the RANS solution (CFD) in roll moment acting on the ONR tumblehome model running in still water with the heel angle of 10 degrees (Hashimoto and Stern, 2007).

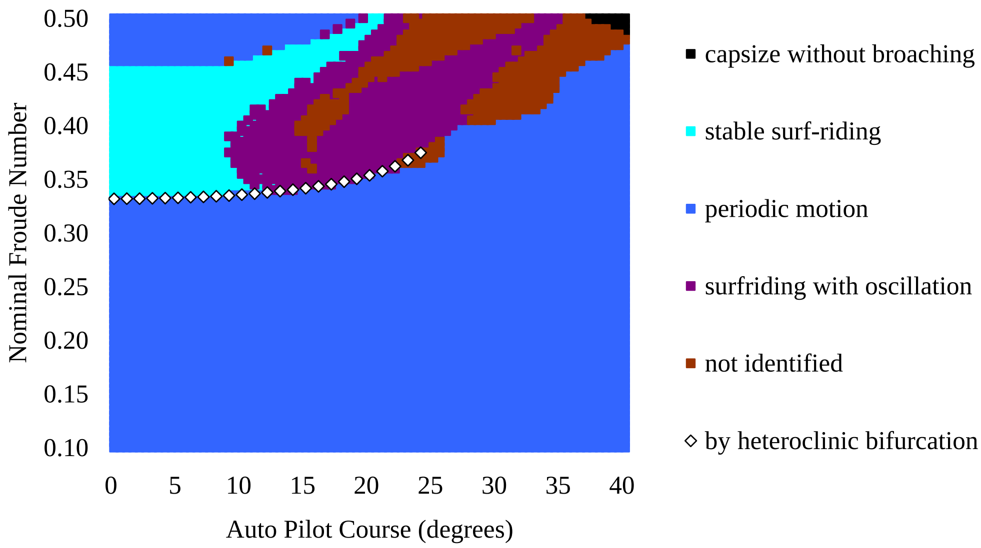

Figure 3 Comparison in motions of the ITTC Ship A-2 running in following waves between numerical simulation results and the heteroclinic bifurcation (Umeda et al., 2006A).

To avoid broaching, it is effective to increase ship drag by some means. Renilson (1986) investigated the Sea Brake, which is a kind of sea anchor to add drag to ship resistance. Umeda et al. (1999B) invented the Anti-Broaching Steering System (ABSS), in which the rudder deflection limit is allowed to be a large angle, such as 70 degrees, so that the rudder drag can deteriorate surf-riding equilibrium under the yaw deviation from the desired course, and successfully validated it with free-running model experiments. Further, Umeda et al. (2002) optimised the design of the ABSS by using numerical simulations.

OUTCOMES FROM SCAPE ACTIVITIES

The two-year activities of the SCAPE committee output the following fruits for broaching.

Nonlinear modelling

Although Hashimoto et al. (2004A) realised quantitative prediction by adding many higher-order terms, it is important to provide guidelines for simpler but accurate enough modelling. For this purpose Hashimoto and Umeda (2005), Umeda and Hashimoto (2006C) recommended to add the following three terms to their first-order model as a result of systematically degrading study.

- nonlinearity of wave-induced surge force,
- nonlinearity of sway-roll coupling,
- nonlinearity of roll-induced moment in calm water.

Here captive tests in a towing tank are required but not in a seakeeping and manoeuvring basin. Agreement between the recommended mathematical model and the free-running model experiment by Umeda et al. (1999A) is satisfactory as shown in Figure 1

The above mathematical modelling is developed for single-screw and single-rudder ships, while other ships are also susceptible for broaching. They include twin-screw and twin-rudder ships as shown in model experiments and water-jet propelled craft. For twin-screw and twin-rudder ships Umeda et al. (2006B) proposed a mathematical model as an extension of the above model and then validated with Lloyd’s experiment (Renilson, 1982). Furthermore, for a craft propelled by water-jet Umeda et al. (2005A) provides a mathematical model.

For making captive tests easier to obtain some higher order terms, Matsuda et al. (2007) developed a new captive testing technique, which allows heave and pitch motions. To replace such model experiment with numerical calculation, Hashimoto and Stern (2007) applied a RANS-based CFD code to heel-induced hydrodynamic forces and showed a good agreement with the model experiment, as shown in Figure 2.

Bifurcation analysis

It was already established that the critical condition for surf-riding in regular following and quartering waves is a heteroclinic (or homoclinic) bifurcation. Next step is to directly evaluate such bifurcation point from mathematical models, especially a 4 DOF model. Hori and Umeda. (2005) and Umeda et al. (2006A) proposed a theoretical formulation of this bifurcation problem with the coupled surge-sway-yaw-roll mathematical model and well validated with the direct initial-value simulation as shown in Figure 3. Here the critical Froude number for surf-riding is determined for requesting the unstable invariant manifold from a saddle to reach another saddle within the framework of the Newton method. Thus the repetition of numerical simulation for many different initial and control values can be avoided. Above this surf-riding threshold, capsizing due to broaching occurs if wave steepness is very high. Maki et al. (2007) further improved this methodology, focusing to an uncoupled surge model in regular following waves, from theoretical and numerical viewpoints so that deterministic surf-riding threshold hyperplane could be efficiently estimated.

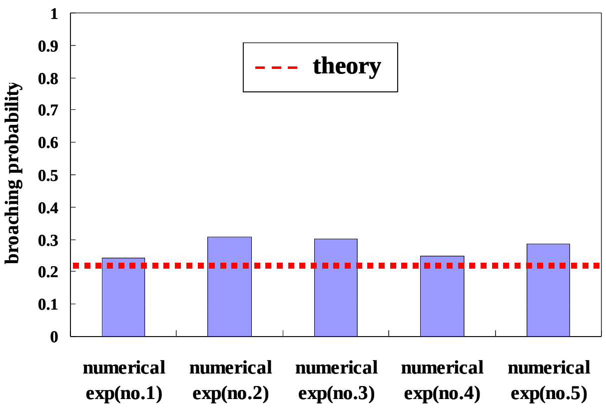

Figure 4 Comparison in broaching probability between numerical experiments and theory for a high-speed fishing craft in irregular stern quartering waves (Umeda et al., 2007).

Probabilistic assessment

To evaluate danger of broaching in actual seaways, it is essential to evaluate broaching probability or probability of capsizing due to broaching in irregular waves. Umeda et al. (2007) proposed a theoretical calculation method for broaching probability as an extension of Umeda's theory for surf-riding probability (Umeda, 1990). Here the broaching probability is calculated by integrating the joint probability density of local wave height and wave period, which was proposed by Longuet-Higgins (1983), within the deterministic broaching region. The present theory was well validated with the Monte Carlo simulation as shown in Figure 4.

Optimal control theory

In the above theoretical and experimental studies, steering is modelled as a PD auto pilot. The maximum steering effort, however, could be different from a PD auto pilot. Therefore, Maki and Umeda (2006) proposed the application of optimal control theory. When it is applied, a kind of the bang-bang control could be obtained as maximum steering effort to prevent broaching.

Prevention device

Other than the Sea brake and the ABSS, a new device for preventing broaching was proposed by Hashimoto et al. (2007B). It is a pair of wings attached to bow above a still water plane. Once broaching is initiated, a ship deviated from the desired course. This turning results in outward roll. The wing in the side of roll will be submerged so that yaw moment towards desired course and the roll moment towards upright position can be generated. As a result, broaching can be avoided. The effectiveness of this device was validated with a free-running model experiment.

RECOMMENDATION FOR IMO NEW GENERATION CRITERIA

The IMO requests both the vulnerability criteria and the direct assessment for broaching, following the framework proposed by Japan, the Netherlands and the United States (2007). Responding to this requirement, the SCAPE committee recommends the following draft criteria.

Vulnerability criterion

It is important that a vulnerability criterion can be easily used, can guarantee conservative safety level and should be based on non-empirical approach. The surf-riding threshold in regular following waves can be substituted to that of capsizing due to broaching because surf-riding is a prerequisite to broaching and following waves are most dangerous for surf-riding. To determine the surf-riding threshold in regular following waves, an analytical solution is obviously most suitable because it is easily evaluated but is still based on theoretical background. Spyrou (2001) proposed an analytical solution by assuming the balance of resistance and propeller thrust to be proportional to square of ship velocity. Maki and Umeda (2008) utilised a piece-wise linear approximation of wave-induced surge force and then different analytical formula for surf-riding threshold in regular following waves was obtained. Here the balance of resistance and thrust is approximated to have a linear relationship with ship velocity. In this procedure, ship resistance in calm water, propeller thrust and distribution of sectional hull area are required. They executed comparisons among the two analytical formulae, numerically-obtained bifurcation points and a free-running model experiment so that they concluded that Maki and Umeda's analytical solution is more accurate than Spyrou's and almost identical to the numerically-obtained bifurcation points and the experiment, as shown in Figure 5.

Direct assessment

If a ship design fails to comply with the vulnerability criterion, it is expected to apply direct stability assessment to the subject ship design. It is preferably to evaluate risk level of the ship design. For this purpose, it is necessary to evaluate probability of capsizing due to broaching. The SCAPE committee already developed a theoretical procedure for broaching probability in irregular stern quartering waves (Umeda et al., 2007) and an extension of this method to probability due to broaching is straight-forward. First, we should identify deterministic thresholds for capsizing due to broaching as a function of wave height and period by heteroclinic bifurcation analysis of the coupled surge-sway-yaw-roll model with an auto pilot or the repetition of numerical simulation with the same model. Second, the probability of capsizing due to broaching is calculated by integrating the joint probability density of local wave height and wave period, which was proposed by Longuet-Higgins (1983), within the deterministic capsizing region mentioned before. In this procedure, ship resistance in calm water, propeller thrust, hull form offset, calm-water manoeuvring coefficients, roll damping coefficient and restoring moment are required at least.

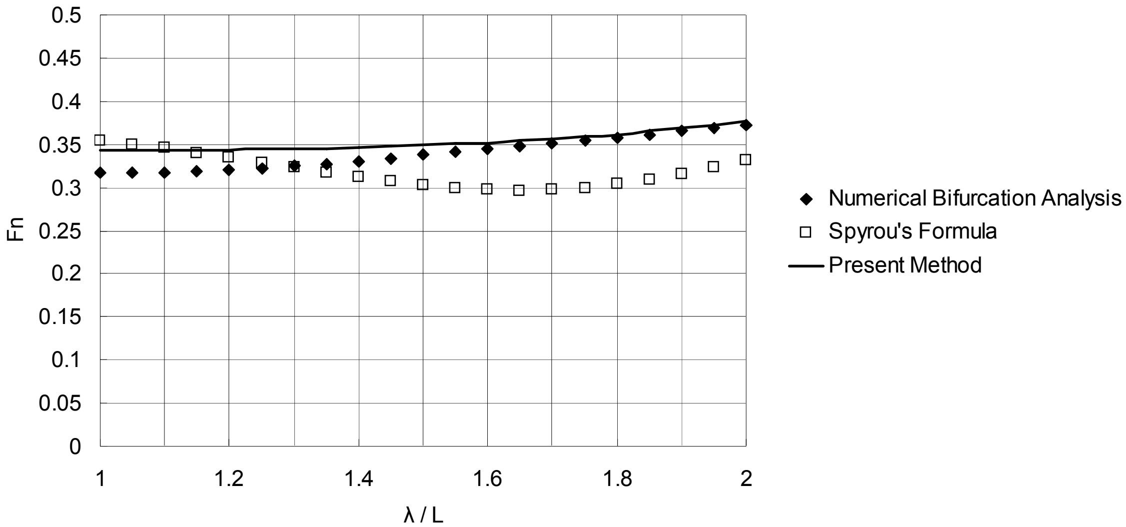

Figure 5 The surf-riding thresholds in following waves obtained by model experiments, numerical bifurcation analysis and analytical bifurcation analysis for the ITTC Ship A-2 with the wave steepness of 0.08 (Maki and Umeda, 2008).

CONCLUDING REMARKS

The activity of the SCAPE committee for broaching provides the following concluding remarks:

1. For quantitative prediction in regular waves, an enhanced system-based model is proposed and validated with the free-running model experiments.
2. For estimating the deterministic threshold of surf-riding in stern quartering waves as a heteroclinic bifurcation, an equation set was theoretically formulated and was validated with the direct numerical simulation.
3. For calculating broaching probability in irregular waves, a theory was formulated and was validated with the Monte Carlo simulation.
4. A device for preventing broaching was proposed and was validated with model experiments.

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