Theoretical Prediction of Broaching Probability for a Ship in Irregular Astern Seas

Naoya Umeda, Masakazu Shuto and Atsuo Maki,

Osaka University, JAPAN

ABSTRACT

For developing the performance-based intact stability criterion focusing on broaching, the authors firstly extended their numerical simulation model on broaching in regular waves to irregular waves, and validated it with the existing full scale data in irregular waves. Secondly, we numerically evaluated the probability of broaching by using the extended model together with a judging criterion of broaching. Thirdly, an analytical method for calculating broaching probability was formulated with given deterministic thresholds of broaching in regular waves. Finally we confirmed that the theoretically predicted values of broaching probability well agree with those from the numerical simulation. Therefore, the authors believe the newly proposed theoretical procedure can be used for the performance-based intact stability criteria at the IMO.

KEYWORDS

Broaching, Surf-riding, Astern Seas, Narrow-Band Spectrum, Probability, Performance-Based Intact Stability Criteria

INTRODUCTION

At the International Maritime Organization (IMO) revision of the Intact Stability Code started in 2002 and, other than its prescriptive rules, performance-based criteria are requested to be developed by 2010. This new criteria should cover three major capsizing scenarios: restoring variation problems such as parametric rolling, stability under dead ship condition and manoeuvring-related problems such as broaching. It was expected to be a probabilistic stability assessment based on physics by utilising first principle tools. Regarding broaching among the three scenarios, quantitative prediction of broaching in regular waves was realised with a numerical simulation model in time domain if data from limited numbers of captive model tests are available. (Umeda and Hashimoto, 2006) Moreover, a deterministic threshold of its occurrence can be directly estimated by applying a heteroclinic bifurcation analysis so that tedious repeat of numerical simulation can be avoided. (Umeda, Hori et al., 2006) However, for realising probabilistic stability assessment required at the IMO, numerical modelling of broaching in irregular waves and estimation of broaching probability in irregular waves are indispensable.

Unfortunately, no remarkable progress on the probabilistic approach on broaching has been reported so far. Although broaching in regular waves was discussed as a kind of transition from periodic states to non-periodic states, ship motion in irregular waves is almost always not periodic. It is difficult even to define the wave phase velocity in irregular waves while surf-riding, which is a prerequisite for broaching, is defined as a phenomenon that a ship runs with the wave phase velocity. On the other hand, ocean waves are not completely random. Since it has a narrow-banded spectrum, a phenomenon similar to that in regular waves can be realised even in ocean waves. This can be justified that several reports of broaching exists from mariners without a record of time series (Du Cane and Goodrich, 1962) but few model experiment on broaching in irregular waves with statistical accuracy seems to be available in existing literatures (e.g. Rutgersson and Ottosson, 1987). This might be because existing seakeeping and manoeuvring basins are too small to obtain broaching records for a ship model running with high speed in irregular waves. A possible exception can be found in a full-scale measurement with a pleasure fishing craft at Japanese coastal area by Motora et al. (1982).

Based on the above situation, the authors attempted to extend their numerical model for regular waves, which had been validated with the free-running model experiments in regular waves, to that for irregular waves and to validate it with Motora's full scale data at sea. Then we identified samples of broaching records from the time series obtained by numerical simulation in time domain. Finally, based on a theoretical work on surf-riding in irregular waves by Umeda (1990), we developed a theory for calculating broaching probability in irregular waves with the deterministic threshold of broaching in regular waves and then compared the theoretical result with numerical experiments.

NUMERICAL MODELLING OF BROACHING IN IRREGULAR WAVES

As an extension of the model for regular waves proposed by the authors (Umeda and Hashimoto, 2002), a surge-sway-yaw-roll mathematical model in irregular stern quartering waves is proposed here, based on the coordinate system shown in Fig. 1. A long-crested irregular wave train is assumed to propagate in the direction of ξ of the space-fixed coordinate system O-ξ, η, ζ and a ship is assumed to be situated with the heading angle, χ, from the wave direction. The ship fixed horizontal coordinate system G-x, y, z with the origin at the centre of ship gravity, G, has the x-axis pointing towards the bow, the y axis to starboard and the z-axis downwards. In calm water, the positive rudder angle normally induces the positive yaw rate. When the surge and sway velocities described with u and v, the position of the ship centre of gravity, (ξ_G, η_G), are calculated as follows:

$$\xi_G = \int_0^t (u\cos\chi - v\sin\chi)d\tau \qquad (1)$$

$$\eta_G = \int_0^t (u\sin\chi + v\cos\chi)d\tau \qquad (2)$$

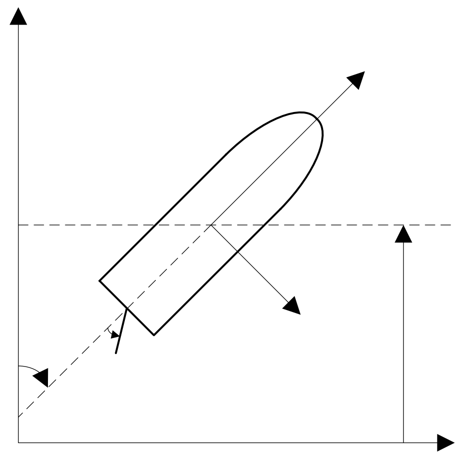

Fig. 1: co-ordinate systems

If we assume that ocean waves can be modelled with the ITTC spectrum, S(ω, α), the ocean wave elevation, ζ_w, can be calculated as follows:

$$\zeta_w(\xi_G,\eta_G,t) = \int_0^\infty \int_{-\pi/2}^{\pi/2} \sqrt{2S(\omega,\alpha)d\omega d\alpha}\cdot\cos(\omega t - k\xi_G\cos\alpha - k\eta_G\sin\alpha + \delta_b) \qquad (3)$$

Here δ_b is a random number ranging from 0 to 2π.

Assuming that the wave elevation and ship motion due to waves are small and ignoring their higher order terms, the following mathematical model in irregular waves can be obtained:

$$(m+m_x)\dot{u} = \{T_P(u;n) - R(u) + X_W(\xi_G,\eta_G,t,\chi)\}$$

$$(m+m_y)\dot{v} = \{-(m+m_x)ur + Y_v(u;n)v + Y_r(u;n)r + Y_\phi(u)\phi$$

$$+Y_{\delta}(u;n)\delta + \underline{Y_w(\xi_G,\eta_G,t,u,\chi;n)} \; \}$$

$$(I_{ZZ} + J_{ZZ})\dot{r} = \{ N_v(u;n)v + N_r(u;n)r + N_{\phi}(u)\phi + N_{\delta}(u;n)\delta$$

$$+\underline{N_w(\xi_G,\eta_G,t,u,\chi;n)} \; \}$$

$$(I_{xx} + J_{xx})\dot{p} = \{ m_x z_H ur + K_v(u;n)v + K_r(u;n)r + K_P(u)p + K_{\phi}(u)\phi$$

$$+K_{\delta}(u;n)\delta + \underline{K_w(\xi_G,\eta_G,t,u,\chi;n)} - mgGZ(\phi) \; \} \qquad (4)$$

The symbols used here are defined in the nomenclature.

SUBJECT SHIP AND CONDITIONS

In this paper, the pleasure fishing craft used by Motora et al. (1982) was selected for enabling us to utilise their data. Its length between perpendiculars is 7.14 m, its breadth is 1.87m, its depth is 0.63 m, its draught is 0.3835m and its GM is 0.715 m. The resistance, propulsion and manoeuvring coefficients in calm water were based on captive model tests by Motora et al. (1982) and Fuwa et al. (1983) Wave-induced forces were estimated with a linear slender body theory (Umeda and Renilson, 1992a). The numerical model for regular waves had been compared with the free-running model tests with the subject ship by Fuwa et al. (1983) and good agreements in the occurrence of broaching in regular waves between the simulation and experiment had been reported. (Umeda and Renilson, 1992b)

In the full scale tests by Motora et al. (1982) the ship ran with about 8.5 knot in following wind waves or stern quartering wind waves whose heading angle is about 30 degrees from the wave direction. The wave height visually estimated ranged from 1.0 m to 1.5 m and the wave length did from 10m to 15m. For comparison sake, numerical calculations in this paper were carried out under the following condition. The ship runs with the constant propeller revolution that is capable to propel the ship with 8.5 knot in calm water and with the auto pilot courses of 5 degrees and 30 degrees from the direction of long-crested irregular waves. The significant wave height, $H_{1/3}$, is 1.25 m, the mean wave period, T_{01}, is 2.392 seconds. Here the auto pilot has a proportional control law with 1.0 of the rudder gain. The initial condition is that the ship speed is 8.5 knot in the direction of the auto pilot course. The rudder angle limit is 30 degrees both in the full scale test and the numerical calculation.

COMPARISON WITH FULL SCALE TEST

The numerical calculation was conducted under the condition of Motora's full scale tests with the auto pilot course of 5 degrees with many different realisations and the authors attempted to find calculated results similar to the published time series of the full scale tests shown in Figs. 2-3. In this case, while the rudder angle saturates in the negative direction, the yaw angular velocity has a peak of 0.2 radians per second in the positive direction. Then, after one cycle of yaw angular velocity, the rudder angle gradually increases from its minimum limit. The calculated result having the similar qualitative nature was successfully selected as shown in Figs. 4-5. This means that a typical broaching in irregular waves recorded in the full scale test can be reproduced by the numerical calculation for the same ship, operational and wave conditions. It should be noted here that time series of incident waves, other than the representative wave properties, are different between the two and manual steering was used in the full scale tests while the auto pilot was used in the calculation. Nevertheless, the success of qualitative reproduction of broaching time series suggests that the proposed numerical model can be useful for investigating broaching behaviours in irregular waves.

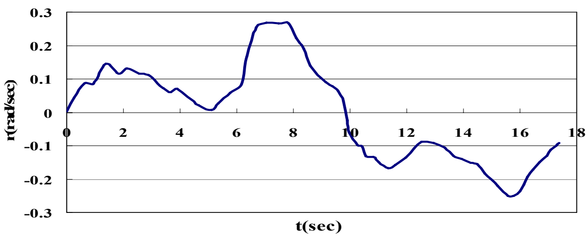

Fig. 2: yaw angular velocity measured in the physical experiment (Motora et al., 1982)

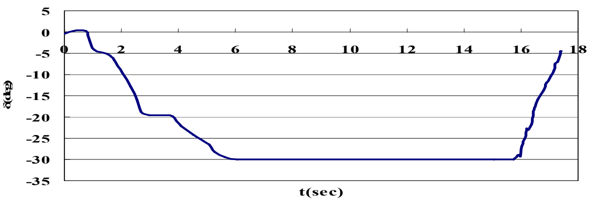

Fig. 3: rudder angle measured in the physical experiment (Motora et al., 1982)

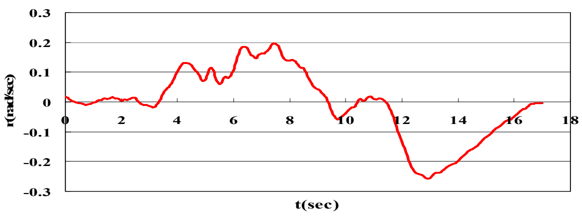

Fig. 4: yaw angular velocity calculated in the numerical experiment

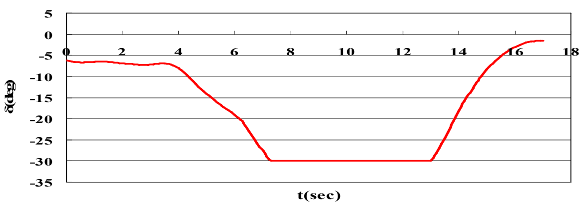

Fig. 5: rudder angle calculated in the numerical experiment

ROUGH ESTIMATE OF BROACHING PROBABILITY BY NUMERICAL EXPERIMENT

As a next step, the authors conducted numerical experiments by utilising the validated numerical model under the same condition but with the auto pilot course of 30 degrees for the duration of 2000 seconds per realisation. Here five different realisations for irregular waves were used. An example is shown in Figs. 6-8. Although the auto pilot course is set to be 30 degrees from the wave direction, the calculated course scatters between 5 degrees and 90 degrees and the rudder angle often reaches its limit in the negative direction. This means that the ship faces a significant difficulty to keep her straight course.

Then the following judging criterion for broaching (Umeda et al., 1999) was applied to the calculated time series and the occurrence of broaching was identified.

$$\delta = \delta_{MAX}, r < 0, \dot{r} < 0 \quad \text{or} \quad \delta = -\delta_{MAX}, r > 0, \dot{r} > 0 \qquad (5)$$

The broaching probability can be roughly estimated as the ratio of the number of the events satisfying the above judging criterion to the number of zero-crossing wave cycle at the centre of gravity. If zero crossing wave cycle involves two events or more, it was regarded as one event per wave cycle. The calculated results are shown in Fig. 9. Since broaching is a nonlinear phenomenon, the broaching probabilities estimated from different realisations scatter to some extent. The ensemble average of them is about 0.28. This means that broaching can occur once every three wave encounters. The confidence interval of this estimate can be evaluated with the formula of binomial distribution (Paroka and Umeda, 2006) and its evaluation will be our future task. The confidence interval, however, is obviously small because the number of the wave cycle is very large and the estimated probability is sufficiently high.

THEORY FOR ESTIMATING BROACHING PROBABILITY

It is desirable to estimate the broaching probability in irregular waves with a given deterministic threshold of broaching in regular waves, which can be calculated by numerical simulations in time domain or a global bifurcation theory. This, considering that broaching occurs within one or two waves, the authors attempted to develop a theory for estimating broaching probability. First, the deterministic threshold of broaching in regular waves, *S*, are estimated as a function of wave height, *H*, and the wave period, *T*. Then, based on Longuet-Higgins's theory (Longuest-Higgins, 1983) under the assumption of narrow-banded wave, a joint probability of local wave height and local wave period can be calculated as follows:

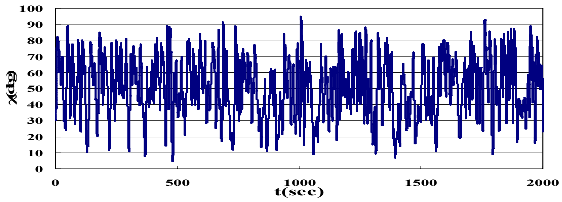

Fig. 6: heading angle from wave direction in a numerical experiment

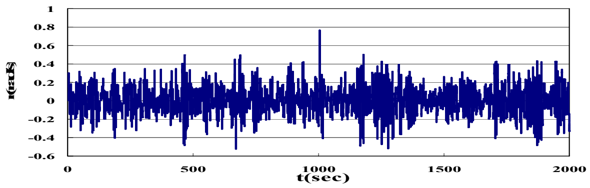

Fig. 7: yaw angular velocity in a numerical experiment

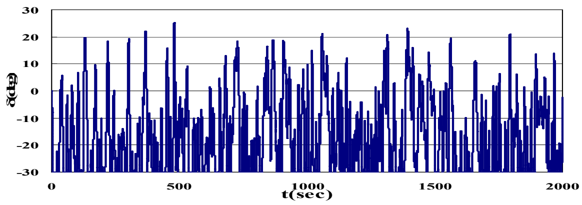

Fig: 8 rudder angle in a numerical experiment

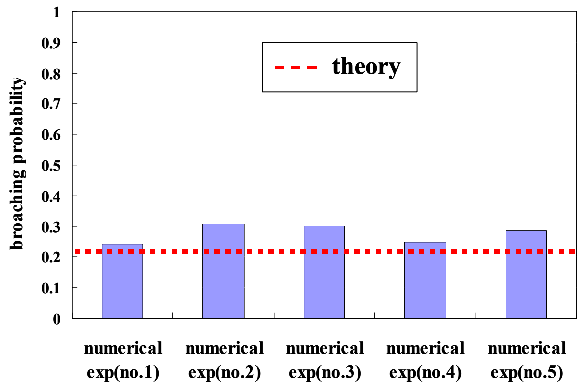

Fig.: 9 comparison in broaching probability between numerical experiments and theory with $H_{1/3}$=1.25 m and T_{01}=2.392s

$$p(H,T)=\frac{2\times(1.414)^3(H/H_{1/3})^2}{\sqrt{\pi}\nu}\exp\left\{-1.414^2\left(\frac{H}{H_{1/3}}\right)^2\left[1+\frac{(T/T_{01}-1)^2}{\nu^2}\right]\right\} \quad (6)$$

Here ν is a parameter for band width and ν is 0.4256 for the Pierson-Moskowitz type wave spectrum such as the ITTC one. Finally, if we assume that the occurrence of broaching does not depend on an initial condition, the broaching probability per wave encounter, P, can be calculated as follows:

$$P=\iint_{S(H,T)} p(H,T)\frac{1}{H_{1/3}T_{01}}dHdT \quad (7)$$

If we take the effect of initial condition on the occurrence of broaching, we may follow the methodology used by Umeda (1990) for surf-riding.

The numerical results using Eq. (7) were 0.211 under the condition used for the numerical experiment. This theoretical value is slightly below the values from the numerical experiments, as shown in Fig. 8. Since this theory efficiently estimates broaching probability, it is useful for discussing the relationship among broaching, wave condition, rudder area and so on. This theory is also promising as a tool for providing design and operational criteria as a part of new performance-based criteria for broaching.

CONCLUSIONS

The following conclusions were drawn based on this work.

1) The authors firstly extended their numerical simulation model for regular waves to irregular waves, and validated it with the existing full scale data in irregular waves.
2) We numerically evaluated the probability of broaching by using the extended model together with a judging criterion of broaching.
3) A theory for calculating broaching probability was developed with given deterministic thresholds of broaching in regular waves. And it was confirmed that the theoretically predicted values of broaching probability well agree with those from the numerical simulation.

4) The methodology proposed here is expected to be utilised for the performance-based intact stability criteria discussed at the IMO.

ACKNOWLEDMENTS

This research was supported by a Grant-in Aid for Scientific Research of the Japan Society for promotion of Science (No. 18360415). It was partly carried out as a research activity of SPL project of Japan Ship Technology Research Association in the fiscal year of 2006, funded by the Nippon Foundation. The authors express their sincere gratitude to the above organizations.

REFERENCES

Du Cane, P. and G.J. Goodrich, The following Sea, Broaching and Surging, Transaction of the Royal Institution of Naval Architects, vol. 104, pp. 109-140, 1962.

Fuwa, T., Sugai K., Yoshino, T. Yamamoto, T.: An Experimental Study on Broaching of a Small High Speed Craft, Papers of Ship Research Institute, No. 66, pp. 1-40, 1982.

Longuet-Higgins, M.S.: On the Joint Distribution of Wave Periods and Amplitudes in a Random Wave Field, Proceedings of the Royal Society of London, Series A, 389, pp. 241-258, 1983.

Motora, S., Fujino, M., Fuwa, T.: On the Mechanism of Broaching-to Phenomena, Proceedings of the 2nd International Conference on Stability of Ships and Ocean Vehicles, Society of Naval Architects of Japan (Tokyo), pp. 535- 550, 1982.

Paroka, D. and N. Umeda: Capsizing Probability Prediction for a Large Passenger Ship in Irregular Beam Wind and Waves: Comparison of Analytical and Numerical Methods, Journal of Ship Research, 50, pp. 371-377, 2006.

Rutgersson, O. and Ottosson, P., Model Tests and Computer Simulations – An Effective Combination for Investigation of Broaching Phenomena, Transaction of the Society of Naval Architects and Marine Engineers, Vol. 95, pp. 263-281 1987.

Umeda, N.: Probabilistic Study on Surf-riding of a Ship in Irregular Following Seas, Proceedings of the 4th International Conference on Stability of Ships and Ocean Vehicle, Naples, Sept., pp.336-343, 1990.

Umeda, N. and M.R. Renilson : Wave Forces on a Ship Running in Quartering Seas - A Simplified Calculation Method -, Proceedings of the 11th Australian Fluid Mechanics Conference, Hobar, pp.363-366t, 1992a.

Umeda, N. and M.R. Renilson : Broaching - A Dynamic Analysis of Yaw Behaviour of a Vessel in a Following Sea, in Manoeuvring and Control of Marine Craft (Wilson,P.A. eds.), Computational Mechanics Publications (Southampton), pp.533-543, 1992b.

Umeda, N., A. Matsuda and M. Takagi: Model Experiment on Anti-Broaching Steering System, Journal of the Society of Naval Architects of Japan, 185, May, pp.41-48, 1999.

Umeda, N. and Hashimoto, H.: Recent Developments of Capsizing Prediction Techniques of Intact Ships Running in Waves, Proceedings of the 26th Symposium on Naval Hydrodynamics, Rome, 2006.

Umeda, N., Hori, M., Hashimoto, H.: Theoretical Prediction of Broaching in the Light of Local and Global Bifurcation Analysis, Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, 2006.

NOMENCLATURE

g	gravitational acceleration
GZ	righting arm
H	local wave height
I_{xx}	moment of inertia around the x-axis
I_{zz}	moment of inertia around the z-axis
J_{xx}	added moment of inertia around the x-axis
J_{zz}	added moment of inertia around the x-axis
k	wave number
K_p	derivative of roll moment with respect to roll rate
K_r	derivative of roll moment with respect to yaw rate
K_v	derivative of roll moment with respect to sway velocity
K_w	wave-induced roll moment
K_ϕ	derivative of roll moment with respect to heel angle
K_δ	derivative of roll moment with respect to rudder angle
m	ship mass
m_x	added mass in the x direction
m_y	added mass in the y direction
n	propeller revolution number
N_v	derivative of yaw moment with respect to sway velocity
N_r	derivative of yaw moment with respect to yaw rate
N_w	wave-induced yaw moment
N_ϕ	derivative of yaw moment with respect to heel angle
N_δ	derivative of yaw moment with respect to rudder angle
p	roll angular velocity
r	yaw angular velocity
R	ship resistance
T	wave period
T_P	propeller thrust
u	ship speed in the x direction
v	ship speed in the y direction
X_w	wave-induced surge force
Yr	derivative of sway force with respect to yaw rate
Y_v	derivative of sway force with respect to sway velocity
Y_δ	derivative of sway force with respect to rudder angle
Y_ϕ	derivative of yaw moment with respect to heel angle
Y_w	wave-induced sway force
z_H	height of centre of sway force due to lateral motions
α	propagation angle of element wave
δ	rudder angle
δ_{max}	limit of rudder angle
ρ	water density
ϕ	roll angle
χ	heading angle from the wave direction
ω	frequency of element wave