Some Issues on Broaching Phenomenon in Following and Quartering Seas

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ABSTRACT

This paper summarises recent research outcomes of the authors on broaching of a ship in following and quartering seas. First, the definition of broaching is revisited using an optimal control theory. Second, an example parametric instability in yaw motion is shown from their numerical simulation for a trimaran. Third, the probability of capsizing due to broaching is presented for a ship in irregular seas. The authors hope these could facilitate fruitful discussion at the workshop.

KEYWORDS

Broaching; Following sea; Quartering sea; Optimal control; Parametric instability; Cumulative broaching; Period doubling bifurcation; Chaos; capsizing probability.

INTRODUCTION

The 2008 IS Code of the IMO explicitly states that broaching is one of three dangerous modes to be assessed with a dynamics-based approach. Although the dynamic research on broaching has long history probably since Davidson (1948), there is an urgent need to discuss broaching for developing a basis of dynamics-based criteria. (Umeda et al., 2008A)

On this opportunity, the authors table their recent research outcomes on broaching from some different aspects. They wish it could facilitate fruitful discussion on broaching and criteria against broaching.

BROACHING AND OPTIMAL CONTRCL

Based on the published experience of mariners and model experiments (e.g. Motora et al., 1982), the first author (Umeda, 1996) attempted to define the broaching as follows: the broaching is a phenomenon that a ship cannot maintain her constant course in spite of the maximum steering effort and then suffer a violent yaw motion. It is important here that the definition should be qualitative so that it cannot be defined with the quantitative threshold in the course deviation from the desired course. And the definition should include a steering control element. On the other hand, it is desirable to provide a judging criterion of broaching from time series from physical or numerical simulation. Thus, based on the discussion in Umeda and Renilson (1992), Umeda et al. (1999) proposed the following criterion.

$$\delta = \delta_{\max}, r < 0, \dot{r} < 0$$

or (1)

$$\delta = -\delta_{\max}, r > 0, \dot{r} > 0$$

Here δ is the rudder angle and applying the maximum rudder deflection, δ_{max}. is regarded as the maximum steering effort. If the ship yaw angular velocity, r, increases in the opposite direction, this seems to be regarded as broaching with the definition proposed by Umeda (1996). This judging criterion was applied to many model experiments and numerical simulations, and provides reasonable judgments of broaching. A typical example (Umeda and Hashimoto, 2002) can be shown in Fig. 1. In this case, a ship model is captured in a wave down slope and then deviated from her desired course. Despite the maximum opposite rudder angle, the yaw angular velocity increases for a while. Finally a ship capsized in the direction of the centrifugal force due to this violent yaw motion.

It is noteworthy here that usually an auto pilot is used in these model experiments and numerical simulation. Its control law is based on PD or PID one. However, a PID control is not so suitable to express the maximum steering effort. It is desirable to use an optimal control in place of a PID control. If a ship cannot maintain her constant course even with an optimal control, it can be regarded as broaching.

Therefore, Maki and Umeda (2008) attempted to apply an optimal control theory for a course keeping problem in heavy astern waves. Here a surge-sway-yaw-roll model (Umeda and Hashimoto, 2002) is used as the state equation and the judging index, J, for the optimal control is set as follows

$$J = \int_0^{t_f} (\chi - \chi_c)^2 dt \tag{2}$$

where χ: yaw angle, χ_c: desired yaw angle and t_f: time duration. In addition, a constraint is given as follows:

$$-\delta_{\max} < \delta < \delta_{\max} \tag{3}$$

By requesting the judging index is the minimum with Lagrange's multiplier, the above mathematical problem was solved by the Sequential Conjugate Gradient Restoration Algorithm. Its numerical example is shown in Fig. 2. While a proportional auto pilot fails to keep the desired course, the optimal control obtained here successfully keeps the desired course with a Bang-Bang control. If wave steepness further increases, even this optimal control could face a difficulty to keep the specified course and then broaching could be more rigorously identified.

PARAMETRIC YAW INSTABILITY AND CHAOS

The broaching shown in Fig. 1 is associated with surf-riding. A different type of possible broaching has been found in the literature; it occurs in the region where the ship speed is much slower than the wave celerity. Some researcher named it as cumulative broaching. This phenomenon was explained by Spyrou (1997) as a parametric instability. By eliminating the sway velocity from a coupled sway-yaw equation set with wave exciting forces and a PD auto pilot, the Mathieu equation is obtained. As a result, parametric yaw motion could emerge. Here the restoring term due to the auto pilot could vary in time.

The authors (Umeda et al., 2008B) recently investigated dynamic behaviour of a trimaran in following and quartering waves by using a surge-sway-yaw-roll coupled model with a PD auto pilot. They identified harmonic motion, stable surf-riding and broaching but some numerical runs cannot categorised by these modes. Such numerical runs exist in the region where the nominal Froude number is much smaller than the surf-riding threshold. They applied a Poincare mapping technique to such region and then identified parametric yaw motion, where the yaw period is twice the encounter frequency, as shown in Fig.3. When the nominal Froude number increases further, period doubling and chaos appear. It is interesting the region of chaos is relatively wide but the region of this instability is limited in the nominal Froude number. In these yaw motion region the rudder angle occasionally reaches its limit and the yaw amplitude is about 30 degrees. However, these runs do not satisfy the judging criterion indicated by Eq. (1). It was confirmed that this instability in yaw can be easily prevented by increasing the differential gain of the auto pilot. Therefore, we can say the maximum steering effort can prevent this instability in yaw. Further researches are required to examine whether even optimal steering can prevent this kind of instability in yaw or not.

PROBABILITY OF SURF-RIDING, BROACHING AND CAPSIZING

For regulatory purpose, it is essential to evaluate probability of dangerous events in irregular seas. Umeda (1990) proposed a methodology for calculating probability of surf-riding per encounter wave cycle. Here it is calculated by integrating the joint probability of local wave height and period within the deterministic surf-riding region which can be calculated by a global bifurcation analysis. This methodology is extended to probability of broaching by Umeda et al. (2007) and it was successfully validated with the Monte Carlo simulation. The authors further extend this methodology to probability of capsizing due to broaching. Here it is calculated by integrating the joint probability density of local wave height and period within the deterministic region of capsizing due to broaching which is estimated by numerical simulation in regular waves.

The numerical examples of probability of surf-riding and that of capsizing due to broaching for the ITTC Ship A-2 as functions of the Beaufort wind scale are shown in Figs. 4-5, respectively. The probability of capsizing due to broaching is much smaller than that of surf-riding. While the probability of surf-riding ranges from 0.1 to 0.01, that of capsizing due to broaching does from 0.001 to 0.00001. This suggests that a ship master should reduce the ship speed if surf-riding occurs even once. It also shows difficulty to estimate the probability of capsizing due to broaching using simple Monte Carlo simulation because of very small probability. Therefore, this methodology is expected to be a key for the direct stability assessment as a part of performance-based criteria at the IMO.

CONCLUDING REMARKS

The main remarks from this work are summarized as follows:

(1) Final judgement of broaching is desirable to be made with an application of optimal control.
(2) Parametric yaw motion in slower speed region could exist for a certain ship with a PD auto pilot but further research is required to conclude that it could be a kind of broaching.
(3) The methodology for calculating probability of surf-riding, broaching and capsizing by using the deterministic thresholds is promising for the direct stability assessment as a part of the IMO performance-based criteria.

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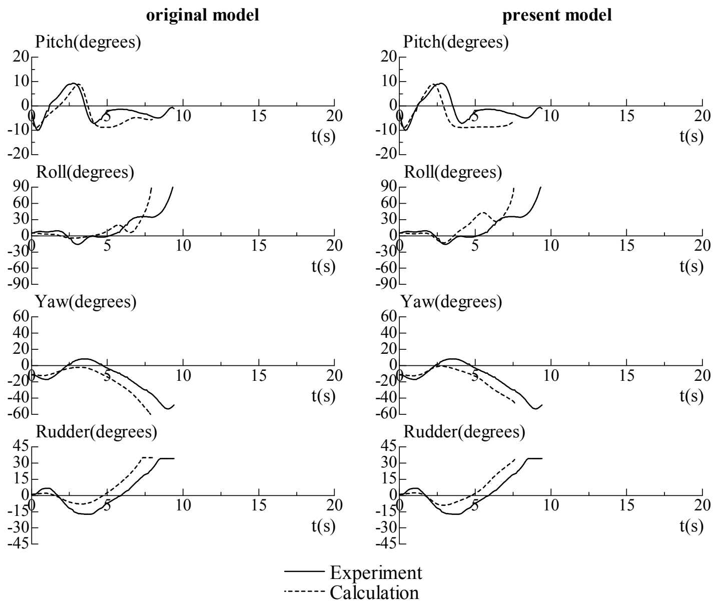

Fig.1 Typical time series of broaching for the ITTC Ship A-2 with the wave steepness of 1/10, the wave length to ship length ratio of 1.637, the nominal Froude number of 0.43 and the desire course from the wave 10 degrees. (Umeda and Hashimoto, 2006)

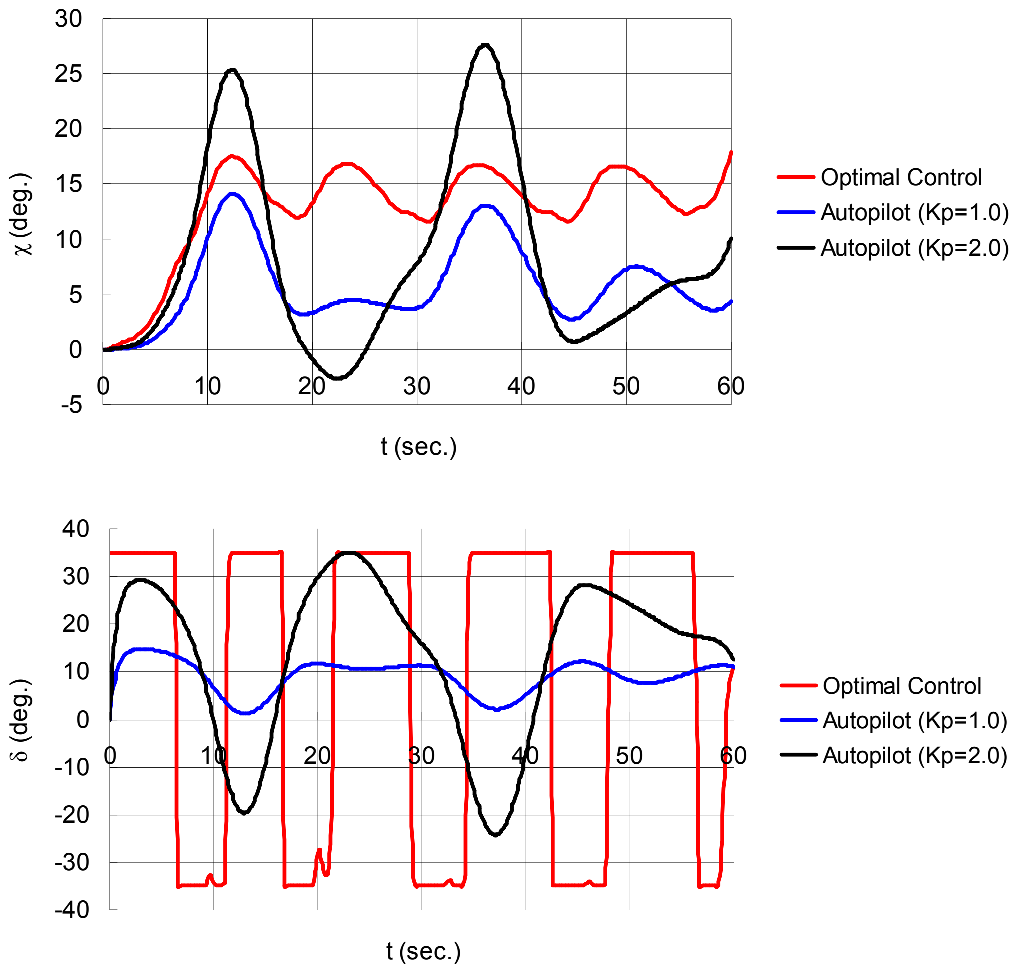

Fig. 2 : An example of optimal control applied to course keeping for the ITTC Ship A-2 in stern quartering waves with the wave steepness of 0.1, the wave length to ship length ratio of 1.637, the nominal Froude number of 0.3 and the desired course of 15 degrees from the wave direction. (Maki and Umeda, 2008)

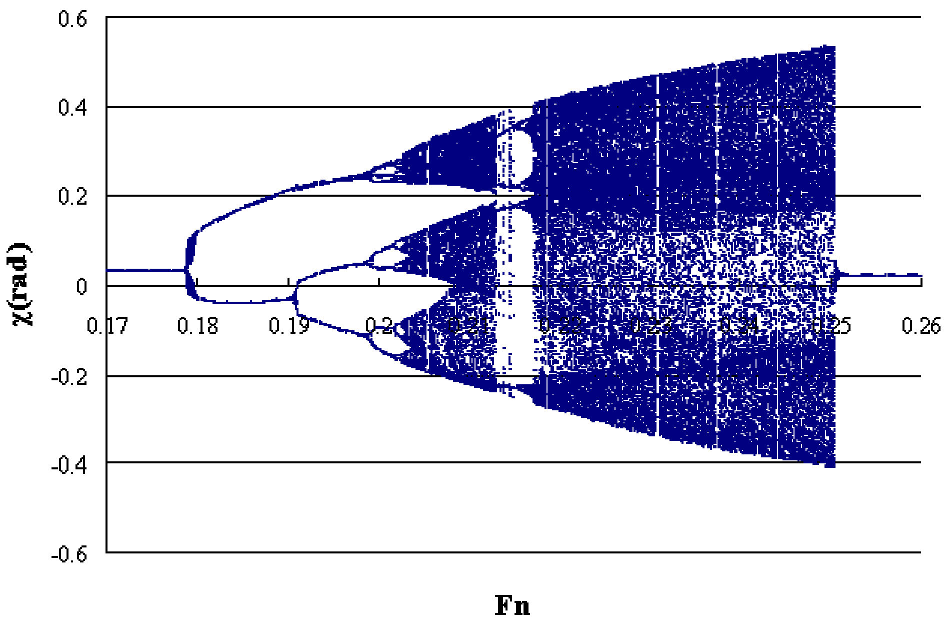

Fig. 3 : Bifurcation diagram of parametric yaw instability, period doubling and chaos in the numerical simulation of a trimaran in astern waves. The wave steepness of 0.07, the wave length to ship length ratio of 1.2, the nominal Froude number of 0.23, the desired course of 3.5 degrees from the wave direction and the rudder gain of 1.0. (Umeda et al., 2008B)

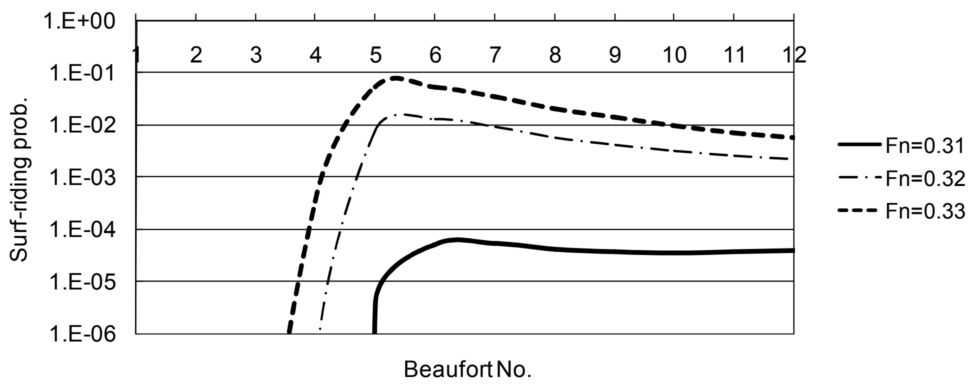

Fig. 4 Probabillity of surf-riding per encounter wave cycle for the ITTC Ship A-2 in pure following waves.

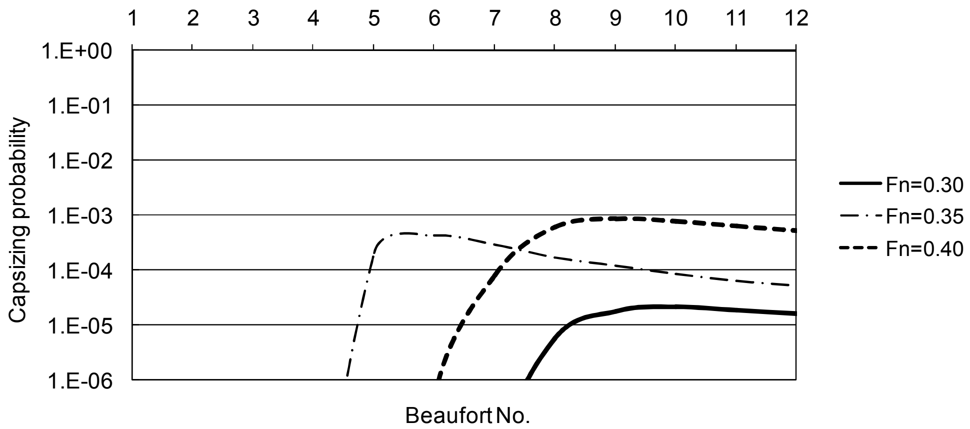

Fig. 5 Probabillity of capsizing due to broaching per encounter wave cycle for the ITTC Ship A-2 in stern quartering waves with the desired course of 5 degrees from the wave direction.