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An Investigation into Capsizing Accident and Potential Technology for Vessel Stability Assessment

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Abstract : *In this paper, ship accidents are analyzed briefly and the main objective is to investigate a potential technological approach for risk assessment of vessel stability. Ship nonlinear motion equation and main parameters that induce ship capsizing in beam seas have analyzed, the survival probability of a ferry in random status have estimated and finally find out a risk assessment concept for ship's intact stability estimation by safe basin simulation method. Since a few main parameters are considered in the paper, it is expected to be more accurately for estimating ship survival probability when considering ship rolling initial condition and all other impact parameters in the future research.*

Key words : *ship rolling, stability, capsizing, safe basin, survival probability*

1. Introduction

As we are known that stability is the ability of a vessel to return to a previous position, which is of great importance for every ship. Positive stability would then be to return to upright and negative stability would be to overturn. On the other hand, instability(or capsizing) could be regarded as a statistically rare event concerned with extreme behavior of ships in waves, but the consequences of such event are fatal. Stability against capsizing in heavy sea as is one of the most fundamental requirements considered by naval architects when designing a ship(Walree et al., 2011). To assist in understanding what is a complex phenomenon, many efforts have been directed towards identifying modes of capsizing and their inter-relationships based on the results of model experiments and numerical simulations.

In the past years, *GZ* calculation method influence on parametric roll prediction is described by Vidic-Perunovic (2011). Mathematical modeling of sway, roll and yaw motions for determine the sensitivity of coupling on numerical simulation results have researched by Das, et al. (2010). Neves, et al. (2009) describes nonlinear coupling of unstable ship motions in head seas using bifurcation analysis and studying the erosion of the safe basin. Ahmed, et al. (2008) describes an investigation into parametric roll resonance in regular waves using a partly nonlinear numerical model.

In this paper, the maritime accidents because of ship capsizing reason and potential method for ship stability assessment have analyzed. A single degree of freedom (SDF) differential equation of ship rolling in harmonic beam seas is established considering nonlinear damping, nonlinear restoring moment and random beam seas excitation. The fourth-order Runge-Kutta algorithm to solve the SDF differential equation have applied and the capsizing process of the ship rolling is simulated. The purpose of studying capsizing and stability assessment is to establish an understanding of ship behavior in extreme seas and to relate this to the geometric and operational characteristics of the ship to achieve cost effective and safe operation. Mathematical and numerical models followed of increasing sophistication, capable of predicting with sufficient engineering accuracy the ability of the ship to resist capsize in a range of scenarios.

2. Noteworthy Capsizing Accidents Analysis

Comparisons of marine accidents record, the following accidents because of capsizing should noteworthy before discuss the necessity and potential method for ship stability assessment. The serious accidents such as 'Derbyshire'

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(1980) 'Herald of Free Enterprise' (1987),and 'Piper Alpha' (1988) tragedies and the environmental disasters such as the 'Amoco Cadiz' (1978) and 'Prestige' (2002) pollution incidents have focused world opinion on maritime safety in both design and operations(Wang, 2006).

On 27 March 1980, a semi-submersible accommodation platform 'Alexander Keilland' capsized in the Ekofisk field off Norway. The 'Alexander Keilland' was a semi-submersible rig comprising five large flotation pontoons. The whole structure was strengthened and stiffened by horizontal and diagonal bracing welded to each leg. The brace labeled D-6 was the trigger for the accident. Because of the capsizing accident, there are about 212 people on board 123 died(Strutt, 1992).

On 6 March 1987, the 'Herald of Free Enterprise' capsized about four minutes later after left its berth in Zeebrugge inner harbor. As a result of this capsizing, at least 150 passengers and 38 crew members lost their lives, which are shown in Fig. 1. Since the accident several improvements have been made. New International Maritime Organization (IMO) regulations are also in place that prohibit an open (undivided) deck of this length on a passenger RORO vessel.

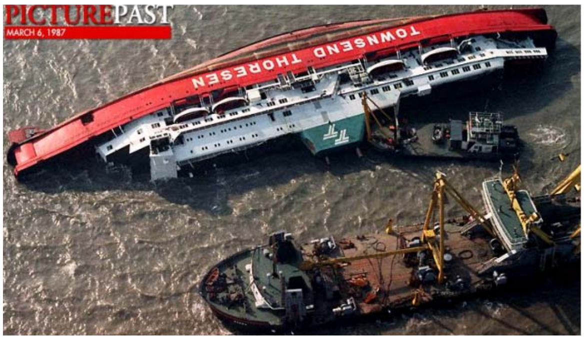


Fig. 1 Capsize accident of the Herald of Free Enterprise

The accidents described above may justify the need for the maritime industry to improve its safety culture and so move towards a risk-based regime in both design and operations. From the Marine Accident Investigation Branch reports, it is evident that the majority of capsizing incidents occurred during the fishing and recovery of gear operations. This shows that for the vessels that do capsize, there is a negative factor of safety in the present stability criteria(Wang, 2005). From the above maritime disaster results, we have found that the stability of ship is very important due to the high frequency and high cost loss in accidents. So risk assessment of ship stability will be focused on the following research.

3. Theoretical Formulation of Ship Rolling

Usually, the typical single degree of freedom (SDF) differential equation of intact ship rolling in beam seas can be written as follows (Wright et al., 1980 ; Lee et al., 2005):

$$(I_{44}+A_{44})\ddot{\theta}+B_{44}(\dot{\theta},\theta)+C_{44}(\theta)=M(t) \tag{1}$$

where

I_{44}: ship mass moment of inertia about the roll axis

A_{44}: added mass moment of inertia

B_{44}: hydrodynamic damping moment

C_{44}: hydrostatic restoring moment of the ship

$M(t)$: excitation moment (including wave and wind excitation)

θ: ship rolling angle

The natural frequency is given by the equation: $\omega_o{}'=(\omega_o-\nu)^{1/2}$,where $\omega_o^2=K_1/(I_{44}+A_{44})$, $K_1=\Delta g \cdot GM$ is the coefficient of stiffness (the product of the buoyancy force Δg and the initial metacentric height GM). As ν is small, $\omega_o{}'\approx\omega_o$. Hence,$I_{44}+A_{44}=K_1\omega_o{}'^2$,where $\omega_o{}'=2\pi/T$ is the circular frequency of free roll.

The added mass moment of inertia and damping moment are constant only in harmonic roll, and their values depend on circular frequency of the roll w. In the case of the non-linear roll, even if the excitation moment is harmonic, the response is non-harmonic and the two coefficients, strictly speaking, vary with time.

Nonetheless, for the sake of simplicity it is assumed that A_{44} and B_{44} are constant, and such as during the free decay roll in calm water with the natural frequency. Furthermore, the nonlinear damping term is normally approximated by an odd quadratic polynomial of the form:

$$B_{44}(\dot{\theta},\theta)=B_1\dot{\theta}+B_2\dot{\theta}|\dot{\theta}| \tag{2}$$

where B_1 and B_2 are constants. The type of approximation can be seen as a non-analytic because the first derivative with respect to the speed of roll does not exist at $\dot{\theta}=0$. Damping term is an odd function of the speed of roll $\dot{\theta}$. It seems natural to use odd polynomials for approximating odd functions. In this case, it is sufficient to use a cubic polynomial:

$$B_{44}(\dot{\theta},\theta)=D_1\dot{\theta}+D_3\dot{\theta}^3 \tag{3}$$

The constant B_1 and B_3 are then supposed to be independent of the amplitude of roll. The same rule applies to other odd functions e.g. the *GZ*-curve, which is an odd function of the angle of heel (roll) and hence it is rightly approximated here by an odd polynomial of the angle.

The restoring moment is hydrostatic and given by an odd function of the roll angle. It can be represent here by a seventh-order polynomial as follows:

$$C_{44}(\theta) = K_1\theta + K_3\theta^3 + K_5\theta^5 + K_7\theta^7 \quad (4)$$

The restoring moment $C_{44}(\theta)$ simply equals the righting moment in calm water: $C_{44}(\theta) = \Delta g \cdot GZ$, where Δg is the buoyancy force, and GZ is the righting arm as a function of the roll angle θ. If GZ is approximated by an odd polynomial, then the first term $K_1 = \Delta g \cdot GM$ is nothing other than the coefficient of stiffness. According to Wang(2005), there is a sufficiently good approximation of the *GZ*-curve by odd polynomials of the 7th degree. The approximations of the *GZ*-curve for a general cargo ship of length $L_{PP} = 150\,m$ is shown in Fig. 2 and the 7th degree polynomial almost coincides with the curve generally.

Fig. 2 Approximations of the *GZ*-curves

The wave excitation moment for a regular wave in beam seas is calculated according to the linear theory when the ship is in an upright position and can be approximated as follows(Senjanovic et al., 2000):

$$M(t) = \kappa K\zeta_0 [(K_1 - \omega^2 A_{44})\cos\omega t + \omega B_{44}\sin\omega t] \quad (5)$$

which is equivalent to

$$M(t) = \kappa K\zeta_0 [(K_1 - \omega^2 A_{44}) + (\omega B_{44})^2]^{1/2}\cos\omega t \quad (6)$$

where k is the reduction coefficient for the effective wave slope, $K = 2\pi/\lambda_w$ is the wave number, and $\zeta_w = (1/2)h_w$ is the wave amplitude. Assuming that ωB_{44} is negligible in relation to $K_1 - \omega^2 A_{44}$, the above Eq.(6) takes the form:

$$\begin{aligned} M(t) &= \kappa K\zeta_0 (K_1 - \omega^2 A_{44})\cos\omega t \\ &= \kappa\pi(h_w/\lambda_w)(K_1 - \omega^2 A_{44})\cos\omega t\,(\omega B_{44})^2]^{1/2}\cos\omega t \\ &= \kappa\pi(h_w/\lambda_w)|\omega_o^2(I_{44} + A_{44}) - \omega^2 A_{44}|\cos\omega t \end{aligned} \quad (7)$$

Substituting the above Eq.(3), (4) and (5) into (1), and dividing the result by the virtual mass moment of inertia, the final form of the differential equation of roll motion is obtained as follows

$$\ddot{\theta} + 2\nu\dot{\theta} + k_1\theta + k_3\theta^3 + k_5\theta^5 + k_7\theta^7 = m(t) \quad (8)$$

where

$$2\nu = B_{44}/(I_{44} + A_{44})$$
$$k_i = K_i/(I_{44} + A_{44})\; i = 1,3,5,7$$
$$m(t) = M(t)/(I_{44} + A_{44})$$

In the above Eq.(8), ν is the nondimensional logarithmic decrement coefficient of damping. The ratio of $A_{44}/(I_{44}A_{44})$ is around a value 1/6. Substituting for the wave length $\lambda_w = 2\pi g/\omega^2$, we get:

$$m(t) = (1/2)\kappa(h_w/g)\omega^2|\omega_o^2 - (1/6)\omega^2|\cos\omega t \quad (9)$$

The Eq.(9) is reasonable as long as the roll angle θ does not exceed the angle of deck edge immersion or the angle at which the bilge comes out from water whichever is smaller.

4. Stability and Capsizing Probabilistic Prediction

Ship rolling and survival analysis are illustrated in the case of ferry with the following particulars. As an accidental coincidence of the 3rd and higher degree polynomials to the nondimensional restoring, so the 5th polynomials here are used instead of the 7th polynomials(Long et al., 2009).

For the calculation of rolling and capsizing of the intact ship in harmonic excitations Eq.(9), the equation of rolling in called so called Duffing form is used(linear damping, nonlinear restoring moment):

$$\ddot{\theta} + d_1\dot{\theta} + k_1\theta + k_3\theta^3 + k_5\theta^5 = Fcos(\omega t) \quad (10)$$

where

$$F = (1/2)\kappa(h_w/g)\omega^2 \left|\omega_o^2 - (1/6)\omega^2\right|$$

Differential Eq.(10) is a typical nonlinear dynamical system. Although the ship is subjected to harmonic excitation, its response is non-harmonic, indeed chaotic due to the non-linear relationship. Whether the ship capsizes or not depends on the initial conditions and the amplitude of excitation and indirectly on the wave height. The probability for excitation moment is assigned as uniform distribution for simplicity sake, while wave elevation follows Gaussian distribution. Eq.(10) finds a maximum wave height which a given ship is capable to withstand without capsize allows for.

The safe basins of Eq.(10) can be defined using a bounded green area in the phase space trajectories (Long et al., 2010). The trajectory start from the safe basins will remain in the green area when the time t tends to infinity. Otherwise, the trajectory start beyond the safe basins will escape this green area; such a trajectory is unstable and may destroy or collapse the system. The green area shape of the safe basins will change when the parameter of the system changes. A possible approach, not applied here, could be assume that the excitation moment is applied to the upright stationary ship, which have zero initial conditions at instant of time $t = t_0$, sampled randomly from the interval $(0, T)$, with a homogeneous probability distribution. Instead, it is assumed that the ship is exposed to a group of regular waves over $2000s$, of given amplitude, frequency and amplitude of excitation. Until the group occurs the ship performs linear roll in irregular beam seas of known wave spectrum.

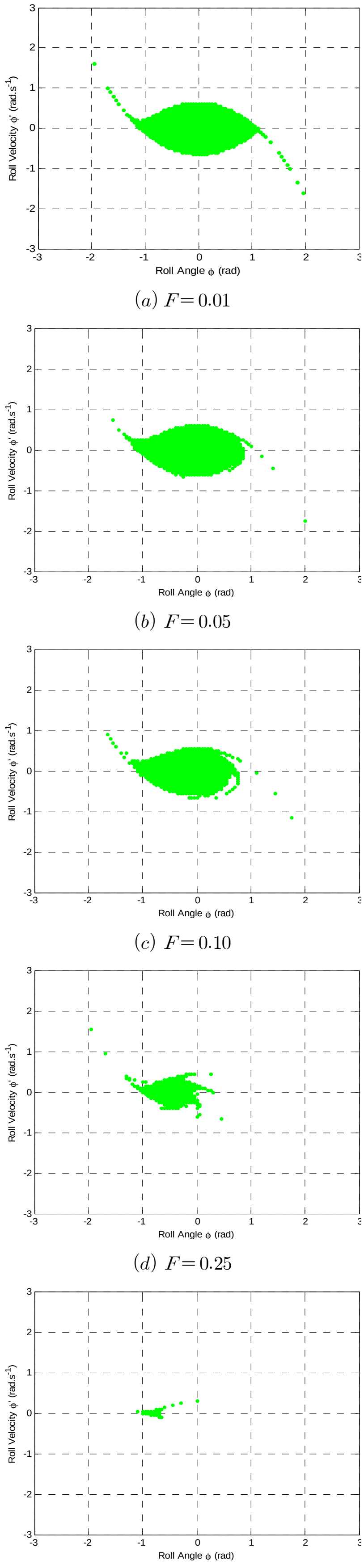
3.1 Safe basin erosion with wave excitations

Firstly, the variation of the safe basins is studied for Eq.(10) by changing the value of the excitation parameter F and other variables are chosen from the above discussed. The bounded area A is defined as follows:

$$A = \{(x,y) : -2 \le x \le 2, -2 \le y \le 2,\ y = \dot{x}\}\pi r^2$$

where A is divided into 80×80 points, and the lattice points are taken as the initial values for the solutions of Eq.(10).

If the solution of Eq.(10) remains in the area A for a enough time up to $t = 2000s$, then the solution can be taken as a safe solution approximately, and the corresponding



(a) $F = 0.01$

(b) $F = 0.05$

(c) $F = 0.10$

(d) $F = 0.25$

(e) $F = 0.50$

Fig. 3 Erosion of safe basins in different forces ($T = 1$)

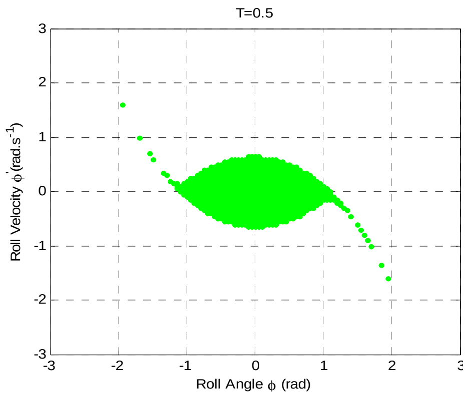
lattice can also be taken as part of the safe basins; if the solution of Eq.(10) escapes the area A, such a solution is taken as an unsafe solution, and the corresponding lattice is certainly out of the safe basin area. At first, assuming the initial probability density function obeys the Gaussian distributing here. The stochastic differential Eq.(10) is solved within the domain of $x \in [-2,2]$ and $y \in [-2,2]$. The Eq.(10) is numerically integrated by the fourth-order Runge - Kutta algorithm and the final numerical results are shown in Fig. 3(a) - (e). The green region denotes the safe basins while the blank region represents the unsafe area.

In the above figures, the safe basin shown in Fig. 3(a) is completely while the safe basins shown in Fig. 3(b) - (e) display clear erosions. Calculation results show that in the case when $F \leq F_1$, where $F_1 = 0.01$ is the minimum excitation moment, the boundaries of the safe basins of Eq.(10) are smooth without any erosion as shown in Fig. 3(a); in the case when $F > F_1$, the boundaries of the safe basins are eroded more and more with an increase of f as shown in Fig. 3(b) - (e); and the safe basins disappear completely in the case of $F \geq F_2$, where $F_2 = 0.60$ is the maximum excitation moment. Accordingly, the values of F_1 and F_2 are two significant critical points for the evolution of erosion.

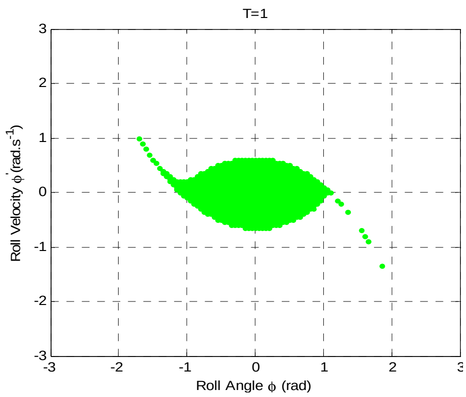
3.2 Safe basin erosion of different wave frequency

After calculating the effect of excitation forces, we consider the effects of different rotating wave frequency on the safe basins as following. In order to make the problem more clear, the amplitude of the random excitation caused by the forces of sea are set as $F = 0.02$. Herein, the excitation forces maintain as a constant 0.02 and alter the wave period T from $0.5s$ to $2s$ as shown in Fig.4(a) - (d). It shows the variation of the safe basins in different wave frequency. The safe basins area become larger as the wave frequency increased, with the wave period decrease. But when the wave frequency is higher than 1.0 such as Fig.4(a) and (b), there are not obviously changes in the safe basins, which mean that it is safe for the high frequency waves.

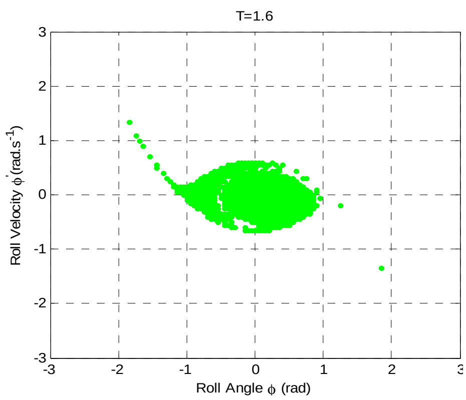
The following Fig. 5(a) - (d) gives the calculation results of safe basins in different wave frequency considering the changes of the excitation forces F base on the variations of the wave frequency. The relationship between the excitation forces F and the wave frequency ω in the beam seas have discussed in the above Eq.(9). Obviously, even though the wave frequency changes eight times than the initial



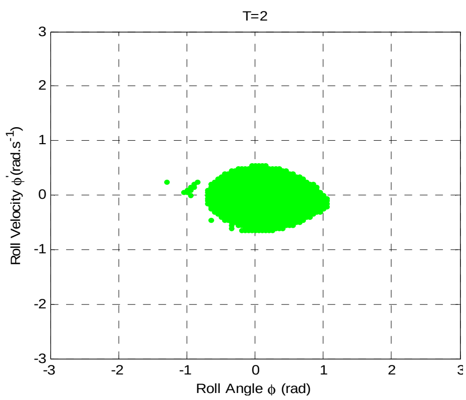
(a) $T = 0.5s$



(b) $T = 1.0s$

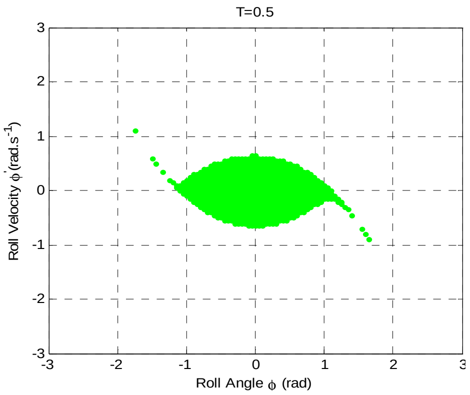


(c) $T = 1.6s$

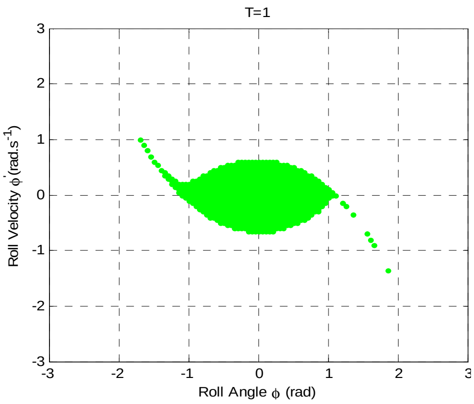


(d) $T = 2.0s$

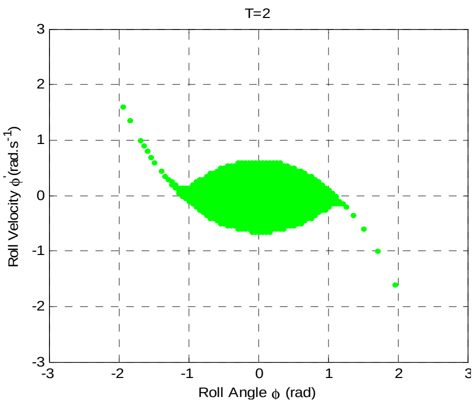
Fig. 4 Safe basins erosion of in different wave periods ($F = 0.02$)



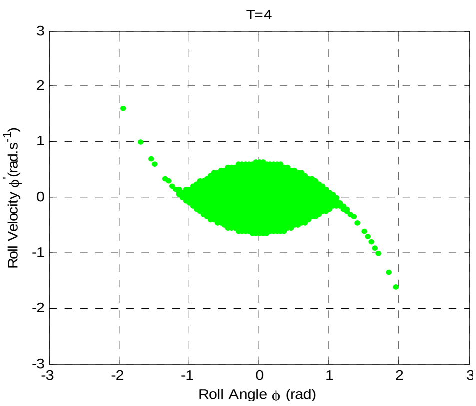
(a) $T=0.5s$



(b) $T=1.0s$



(c) $T=2.0s$



(d) $T=4.0s$

Fig. 5 Safe basins erosion in F varies with T

simulation status, the safe basins shown in Fig.5 have no significant alteration.

4. Summary and conclusions

Vessel stability assessment is very important in operational procedures and management as it reveals weak points of ships. This paper concludes with a discussion of the capsizing accidences and probability assessment of ship capsizing in regular waves combined with statistical and nonlinear safe basin method. The excitations are expressed based on the hazard scenarios of the sea status and the following conclusions can be drawn from the present study.

1) Several noteworthy capsizing accidents have analyzed briefly. The potential method for ship stability assessment is necessary for reducing marine accidents and improving vessel operation and human safety.

2) Base on the ship hazards from the beam seas, a preliminary stability assessment approach is proposed in this article. One advantage of using this method is to predict the probability assessment for ship stability quantitatively.

3) As the simulation results shown that survival probability of ship capsizing has been adopted in time domain. Safe basin erosion is very sensitive to the alteration of the excitation forces by waves. In the next research, the probability distribution of intial condition of rolling, i.e. roll angle and rolling velocity, shall be focused. The knowledge for distribution of severe nonlinear rolling by the combination of wave and wind forces are also important. Impact of further range of parameters, such as the random properties of wave, the navigation speeds, heading angles etc., should all be considered in the next research. After all of the above impact factors have been investigated accurately, it is expected that this method shall be more effective for analysis vessel capsizing probability when ship navigates in random waves and excited by the forces of the sea.

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