Journal of Navigation and Port Research International Edition
Vol.33, No.4 pp. 255~261, 2009 (ISSN-1598-5725)

Probabilistic Prediction of Stability of Ship by Risk Based Approach

Zhan-Jun Long† · *Seung-Keon Lee** · *Sung-Jong Lee*** · *Jae-Hun Jeong****

**Professor, Dept. of Naval Architecture and Ocean Engineering, Pusan National University, Pusan 609-735, Korea*
†,**,*** *Dept. of Naval Architecture and Ocean Engineering, Pusan National University, Pusan 609-735, Korea*

Abstract : *Prediction of the stability for ships is very complex in reality. In this paper, risk based approach is applied to predict the probability of capsize for a certified ship, which is effected by the forces of sea especially the wave loading. Safety assessment and risk analysis process are also applied for the probabilistic prediction of stability for ships. The probability of shipsencountering different waves at sea is calculated by the existed statistics data and risk based models. Finally, ship capsizing probability is calculated according to single degree of freedom(SDF) rolling differential equation and basin erosion theory of nonlinear dynamics. Calculation results show that the survival probabilities of ship excited by the forces of the seas, especially in the beam seas status, can be predicted by the risk based method.*

Key words : *risk analysis, ship stability, capsizing, safe basin, survival probability, nonlinear dynamics*

1. Introduction

Recently there has been a great deal of interest on the study of ship's stability by method various methods. Stability of ships is of very important because the safety of life at sea is strong concerned with it in recent years. Instability or capsizing would be regarded as a rare event concerned with extreme behavior of ships at sea, but the final results of the event are fatal. Stability against capsizing in heavy sea is one of the most fundamental requirements considered by naval architects when designing a ship (McTaggart, 1992; Taylan, 2003; Konovessis and Vassalos, 2007; Mamontov and Naess, 2009; Neves and Rodriuez, 2009). The purpose of study capsizing 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. The revision of the Intact Stability Code was started in 2001 and the first step, consisting in an important structural reorganization and in the development of an alternative way on experimental basis to fulfill the requirements of weather criterion for ships having parameters outside the original range, which was completed in 2006(Francescutto, 2007) and will become compulsory under the provisions of the SOLAS convention in 2009.

2. Risk Based Approach for Safety of Vessels

Ship stability system is rather complicated. Analysis of LOSA(loss of stability accident) casualties reveals that the causes of casualty may be attributed to functional, operational aspects, external causes resulting or cargo related aspect (Kobylinski, 2008).

2.1 Stability Criteria for the Forces of Seas

Hazards posed by the forces of sea are of the most serious hazards to the LOSA and the safety of capsizing. The present set of stability criteria that are inherent part of the IS Code includes consideration of the forces of the sea in the form of "weather criterion", which was originally adopted by Resolution A.562(IMO, 1987). The ability of a ship to withstand the combined effects of beam wind and rolling should be demonstrated for each standard condition of loading, with reference to the figure as follows:

1) The ship is subjected to a steady wind pressure acting perpendicular to the ship's centerline which results in a steady wind heeling lever H_{w1}.

2) The ship is rolling in waves around the heeling angle ϕ_0 due to steady wind. Amplitude of rolling is equal ϕ_1 to windward side. Angle of heel due to steady wind should not be larger than 16°or 80% of an angle of deck immersion, whichever is smaller.

3) In this situation the ship is subjected to dynamical

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† Corresponding author: Zhan-Jun Long, Long@pusan.ac.kr051)510-2755
* leesk@pusan.ac.kr 051)510-2411
** kafa789@daum.net 051)510-2755
*** wave0120@pusan.ac.kr 051)510-2755

wind heeling moment H_{w2}.

4) The area A_2 should be equal or greater from area A_1 in Fig. 1(IMO, 1987).

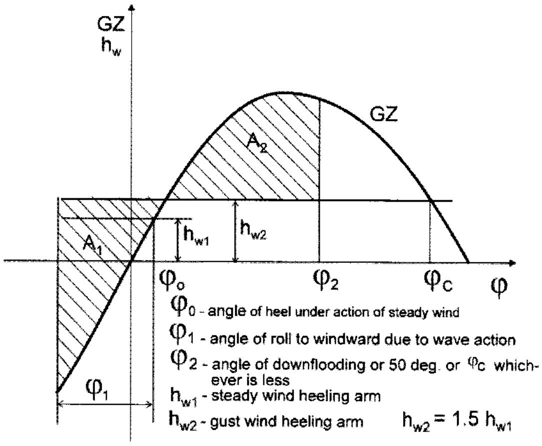


Fig. 1 Weather criterion as in the IS Code

The IMO Intact Stability Code including weather criterion is a simple criterion based on the experience with ships of older construction and hull parameters, which were different from modern design. So application of risk analysis may be possibility for the development of improved criteria.

2.2 Hazard Identification and Capsizing Scenarios

Hazard identification and ranking procedure is the first step for a risk analysis proceeding. With respect to stability, hazard identification could be achieved using standard methods involving evaluation of available data in the context of functions and systems relevant to the type of ship and mode of its operation. And the hazard identification was based on analysis of historical data on capsizing accidents, statistical analyses of cause of accidents available in various sources, detailed description of capsizing accidents, analysis of the few accidents using other methodology or analysis by the group of experts etc. As the potential factors for ship stability system are so large and not possible to considerate all of them. The expert groups just consider the first level of the following hazards and capsizing scenarios by the force of seas(Kobylinski, 2008). Ships are inclined by various external forces: wave action; wind; collision; grounding; shifting of onboard weights; and addition or removal of weight etc. But according to the forces of the sea, the main capsizing scenarios are list as following: following seas, head seas, beam seas, ballast, freak waves and special circumstances(Kobylinski, 2007).

2.3 Assessment of Capsizing Probability

Because the term "risk" is defined as a composite of the probability (likelihood) of any accident or damage, which will lead to loss of property, and the consequence(Ben Webster and Sampson, 2006; Paik and Thayamballi, 2007; Iqbal and Bulian, 2008). After the most important scenario hazards identified in the previous step, the probabilities and consequences of every hazard are being investigated. And the total risk index can be established by adding the probability and consequence indices.

$$R_i = P_i \times C_i \tag{1}$$

Where P_i is the probability (frequency) index of occurrence a given hazard; C_i is the consequences index following the occurrence of data hazard and scenario development, in terms of fatalities, injuries, property losses and damage to the environment.

Once the probability of capsize for seaway duration has been computed , the associated annual probability of capsize can be computed and the similar approach can be used to determine capsize probability during the life of the ship.

3. Theoretical Equations of Rolling Motion

The first-order couplings from surge, heave and pitch to roll are zero and the couplings from sway and yaw to roll are not because of the port-starboard symmetry of ship. The typical single-degree-of-freedom roll differential equation of ships in beam seas is generally as follows(Wright and Marshfield, 1980; Lee and Surendran, 2005):

$$(I_{44} + A_{44})\ddot{\theta} + B_{44}(\dot{\theta}, \theta) + C_{44}(\theta) = M(t) \tag{2}$$

Where I_{44} is the inertia moments coefficient of the ship mass about the roll axis, A_{44} is a hydrodynamic inertia moment coefficient of the added mass, B_{44} is the hydrodynamic damping moment, C_{44} is the hydrostatic restoring moment of the ship, M(t) is the excitation moment(including wave and wind excitation) and θ is the ship rolling angle. Here

$$I_{44} + A_{44} = \left(\frac{T}{2\pi}\right)^2 \Delta g MG \tag{3}$$

Where T is ship rolling period, Δ g is buoyancy force and MG is the metacentric height. Furthermore, the nonlinear damping term is normally represented as

$$B_{44}(\dot{\theta},\theta) = D_1\dot{\theta} + D_3\dot{\theta}^3 \tag{4}$$

The restoring moment is hydrostatic and given by a nonlinear odd function. It may be represented by a fifth-order polynomial as follows

$$C_{44}(\phi) = K_1\phi + K_3\phi^3 + K_5\phi^5 + K_7\phi^7 \tag{5}$$

Substituting the above formulae (4), (5) into (2), and dividing the result by the virtual moment of inertia, the final form of the differential equation of motion is obtained as follows

$$\ddot{\phi} + d_1\dot{\phi} + d_3\dot{\phi}^3 + k_1\phi + k_3\phi^3 + k_5\phi^5 + k_7\phi^7 = m(t) \tag{6}$$

Where

$$d_i = D_i / (I_{44} + A_{44}) \qquad i = 1,3$$
$$k_j = K_j / (I_{44} + A_{44}) \qquad j = 1,3,5,7$$
$$m(t) = M(t) / (I_{44} + A_{44})$$

4. Evaluations of Dynamic Stability in Heavy Sea

The next part will evaluate the dynamic stability of ship in heavy sea according to the single degree of freedom rolling equation above mentioned.

4.1 Characteristics of the Analyzed Ship

Ship roll and survival analysis are illustrated in the case of ferry with the following particulars(Marta PEDIŠIĆ BUČA and SENJANOVIĆ, 2006). The virtual moment of inertia is defined according to the expression in equation (3) is 29682 tm^2 without the bilge keels. Coefficients of damping moment were d_1= 0.01265913s^{-1} and d_3= 0.4954s^{-1}. The effective coefficients of restoring moment were shown in Table 1.

4.2 Encounter Frequency of Ship and Waves

Waves incident on structures or ships can be described as head seas, following seas, beam seas, or quartering seas depending on the incident direction. The heading angle is defined as the angle between the vessel direction and the wave propagation at a celerity velocity C. The wave direction are changed around the exact beam wave (χ=90º). We consider the heading angle, χ, changes from 60° to 120° as shown in Fig. 2. The ship speed can be chosen as 0 m/s, 1 m/s, 2 m/s, 3 m/s, and 4m/s and the Fn are 0, 0.11, 0.22, 0.34 and 0.45 separately in the simulation.

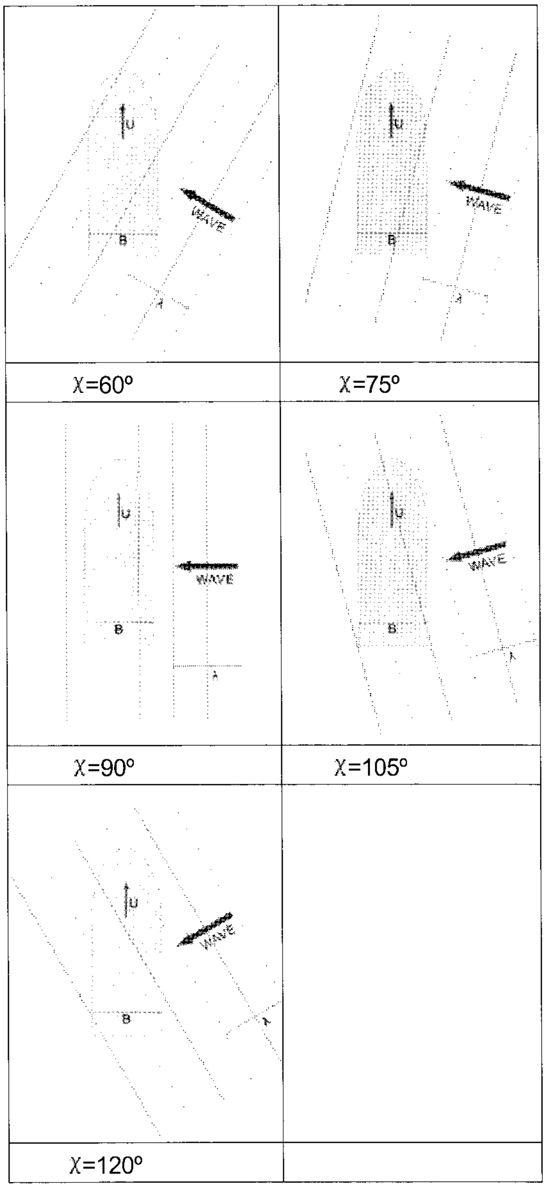

χ=60°
χ=75°
χ=90°
χ=105°
χ=120°

Fig. 2 Definition of heading angle

Table 1 Coefficients of relative restoring moment

	3rd polynomial	5th polynomial	7th polynomial
k_1(s^{-2})	0.671997033	0.630620936	0.536133048
k_3(s^{-2})	-0.53920393	-0.40482026	0.21992815
k_5(s^{-2})	0	-0.08679720	-1.128716074
k_7(s^{-2})	0	0	0.4885682579

When ship is moving, the motion of ship, forward or otherwise, affects the way incident waves are viewed by someone aboard the vessel. If the waves are incident on the ship at some angle χ, then the component of the speed of the ship in the direction of wave propagation is U_a= -U ×cos (χ). The wave crests move at the phase speed, $C_p=\omega/k$ and the relative speed between the ship and the wave is

$$U_r = U_a + C_P = -U\cos\chi + \omega/k \qquad (7)$$

Then the waves have a phase speed such as

$$U_r = \frac{\omega_e}{k} = -U\cos\chi + \omega/k \qquad (8)$$

Using the dispersion relationship for waves in deep water we can rewrite the equation for encounter frequency as

$$\omega_e = \omega - \frac{\omega^2 U}{g}\cos\chi \qquad (9)$$

4.3 Excitation Moment from Waves of Sea

The outer excitation moment from wave of the regular wave can be approximated by a harmonic sinusoidal function M(t), which is presented in the following form(Senjanovic, Cipric et al. 2000).

$$M_{wave}(t) = (I_{44} + A_{44})a_0\omega_n^2\pi\frac{H}{\lambda}\sin\chi\cos\omega_e t \qquad (10)$$

$$\omega_n = \left[\frac{g\Delta\overline{GM}}{I_{44}+A_{44}}\right]^{\frac{1}{2}} \qquad (11)$$

Where a_0 is an effective wave slope coefficient, ω_n is the initial rolling natural frequency, H is the wave height, λ is the wave length and ω_e is the encounter frequency. The excitation equation (10) divided by the effective roll inertia of the ship $I_{44}+A_{44}$:

$$m_{wave}(t) = a_0\omega_n^2\pi\frac{H}{\lambda}\sin\chi\cos\omega_e t \qquad (12)$$

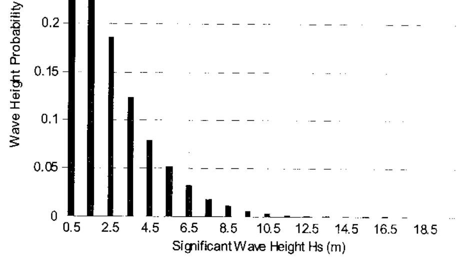


Fig. 3 Distribution of significant wave height

Where a_0 is also the effective wave slope coefficient, which is taken to a constant 0.729(Gu, 2004), ω_n and ω equal 1.32 rad/s and 3 rad/s respectively. The terms of wave significant height $H_{1/3}$=5m and wave length λ are chosen according to the probability distribution as Fig. 3 and Fig. 4(Soliman and Thompson, 1991; McTaggart, 1999), distribution of significant wave heights and nominal wave steepness. The wave climate statistics of the North Atlantic are taken from Bales(McTaggart, 1999) .

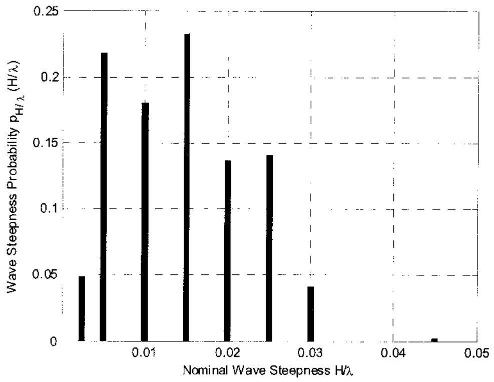


Fig. 4 Distribution of nominal wave steepness

5. Calculation Results and Conclusion

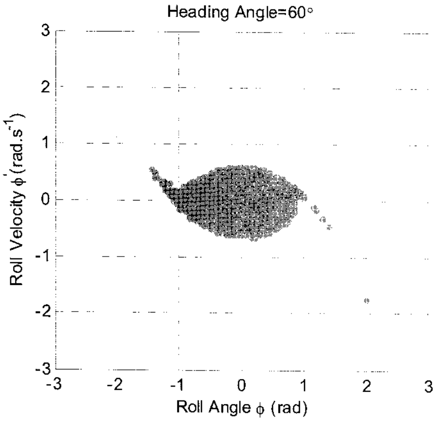
For the calculation of rolling and capsizing of the intact ship in harmonic excitations, The safe basins of the nonlinear dynamical system can be defined using a bounded area A in the space of phase trajectories. The trajectory start from the safe basins will remain in the area A when the time t tends to infinity. Otherwise, the trajectory start beyond the safe basins will escape the area A such a trajectory is unstable and may destroy or collapse the system. The acreage and shape of the safe basins will change when the parameter of the system changes.

5.1 Calculation Results

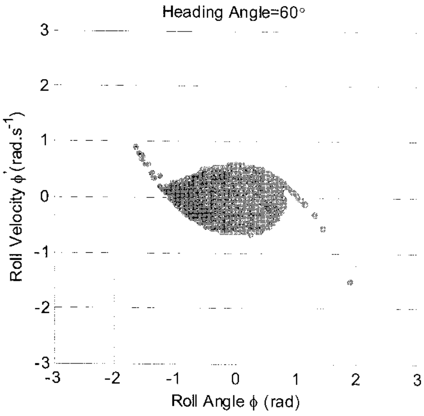
Firstly, the evolution of the safe basins is studied numerically when the excitation wave changes and the other parameters are chosen from above discussed. The surrounded area A is defined as follows(Lee and Long, 2009):

$$R = \left\{(x,y): -2 \le x \le 2, -2 \le y \le 2, x = \theta, y = \dot{\theta}\right\} \qquad (13)$$

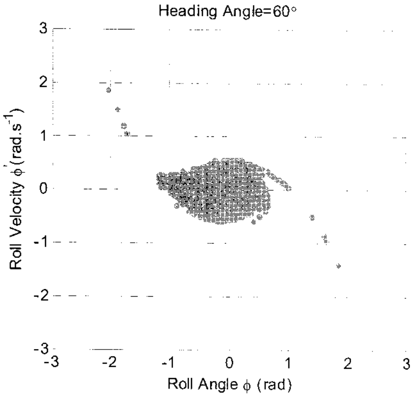
Then area A is divided into 80×80 lattices, and the lattice points are taken as the initial values for the solutions of system. If the solution of system remains in the area R for a sufficiently long time up to t=2000s, such a solution can be approximately taken as a safe solution, and the corresponding lattice may be taken as part of the safe basins; if the solution of system escapes the area A, such a solution is taken to be an unsafe solution, and the corresponding lattice is beyond the safe basins. The whole governing equation is numerically integrated by the fourth-order Runge-Kutta algorithm, and the numerical results are shown in following.



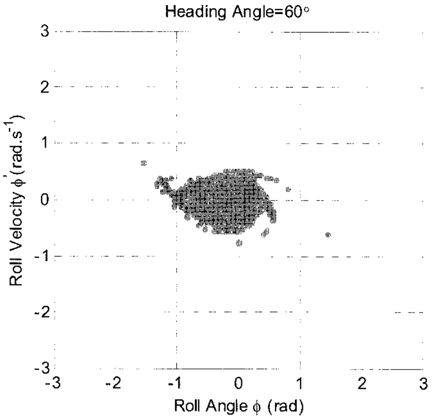
(a) H/λ =0.015



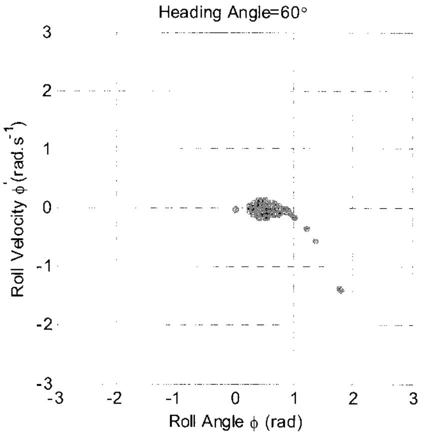
(b) H/λ =0.025



(c) H/λ =0.045



(d) H/λ =0.065



(e) H/λ =0.15

Fig. 5 Erosion of safe basins V=4 m/s, heading angle=60°

According to the distribution of nominal wave steepness, the steepness of wave is chosen as 0.015, 0.025, 0.045, 0.065 and 0.15. The heading angle is chosen as 60°and others are chosen as shown in Table 2. Erosions of the safe basin in different steepness are shown in Fig. 5. The black region in the basins denotes the safe area while the blank region represents the unsafe area.

Table 2 Coefficients variables of the excitation moment

ω_n (rad/s)	ω (rad/s)	$H_{1/3}$ (m)	U (m/s)	a_0	χ (°)
1.32	3	5	4	0.729	60

Calculation results show that in the case when H/λ=0.0025 (Fig. 5 (a)), the boundaries of the safe basins are smooth without any erosion. When the steepness H/λ>0.0025, the safe basins are eroded increasingly with an increase value of steepness as shown in Fig. 5(b) and when H/λ>0.15, as shown in Fig. 5(e), the safe basins disappear nearly. Hence, the wave steepness 0.0025 and 0.15are two significant critical points for the evolution of erosion.

5.2 Concluding Remarks

Risk analysis and development of risk based criteria requires estimation of probability of capsizing in various dangerous situations simulating respective capsizing scenarios. Risk analysis may be quite complex task, but would reveal weak points of ships. So it is very important in operational procedures and management. For the ship intact stability, the most important hazards are incidents created by forces of the sea. What the hazard scenarios from the beam seas are shown in the section of hazards identification. This paper also proposes a preliminary approach for the risk based method.

1) The calculation results shown that the instantaneous states of ship roll and the forces of the seas have intensive effect to the probability of ships capsizing. We should consider both of them simultaneously when estimating the safety of ships rather than one of them. The simulation results have also shown that there is no safe basin erosion when the ship is in the calm sea, which is consistent with the reality.

2) The method of evaluating the survival probability of ship capsizing in time domain has pointed out. The safe basin erosion is very sensitive to the alteration of the excitation forces. So it is an effective technique for analysis the stability assessment when ship navigates in the condition ofrandom waves and excited by the forces of the sea.

3) Wave heading angle of 60º is only selected in this paper for the whole structures and readability. And other heading angle will be considered in the next step in order to get the whole survival probability of ships in different seas.

Acknowledgments

The authors would like to thank all those who have contributed to the paper. The authors are also grateful to the organization of the Underwater Vehicle Research Center (UVRC) and the Agency for Defense Development (ADD) of Korea for supporting the research.

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Received 21 May 2009
Revised 4 June 2009
Accepted 30 June 2009