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Stability and capsizing analysis of nonlinear ship rolling in wind and stochastic beam seas

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ABSTRACT

Considering the actual seaway condition, stability and capsizing of nonlinear ship rolling system in stochastic beam seas is of significant importance for voyage safety. Safe zone are defined in the phase space plan of the unperturbed Hamilton system to qualitatively distinguish ship motions as capsize and noncapsize. Capsize events are defined by solutions passing out of the safe zone. The probability of such an occurrence is studied by virtue of the random Melnikov function and the concept of phase space flux. In this paper, besides conventional wave excitation, the effect of wind load is also taken into account. The introduction of wind load will lead to asymmetry, in other words, it transforms the symmetric heteroclinic orbits into asymmetric homoclinic orbits. For asymmetric dynamical system, the orbital analytic solutions and its power spectrum are not readily available, and the technique of discrete time Fourier transformation (DTFT) is used. In the end, as verification of theoretical critical significant wave height, capsizing probability contour diagram is generated by means of numerical simulation. The contour diagram shows that these analytical methods provide reliable and predictive results about the likelihood of a vessel capsizing in a given seaway condition.

1. Introduction

Stability against capsizing in heavy seas is one of the most fundamental requirements considered by naval architects while designing a ship. Research using scale models in realistic seaway conditions, combined with theoretical developments in nonlinear systems dynamics has led to a better understanding and insight into the nature of ship's capsizing process. Mathematical models and numerical methods which are capable of predicting ship's capsize in different environmental conditions with sufficient engineering accuracy have been developed. Such analyses can aid risk-based ship handling [1]. Generally, the mathematical models involve two different problem areas. One deals with dynamics of ship motion which consists of techniques such as frequency domain or time domain simulation and properties of nonlinear systems [2], while the other deals with the stochastic nature of wave excitation, including the identification of sea wave spectra and encountered wave groups consisting of high waves expected to cause the ship to capsize [3].

For the analysis of dynamic behavior of nonlinear systems such as ship rolling, several methods have been developed. Nayfeh and Khdeir [4] studied nonlinear rolling motion in regular beam seas and acquired second order analytical solution by virtue of multi-scale method. In addition, they studied period doubling bifurcation and chaos phenomenon by using the Floquet theory and bifurcation theory. Virgin [5] indicated that with the increase of external excitation, the ship rolling solution will become chaotic through a series of period doubling bifurcation and capsizing subsequently occurs as a result of instability of motion. EI-Bassiouny [6] studied the nonlinear oscillations by time averaging method. Francescutto and Contento [7] used Krylov–Bogoliubov–Mitropolsky (KBM) method to investigate the bifurcation phenomena in ship rolling and compared it with experimental results. Fan [8] investigated the harmonic balance method and harmonic acceleration method for the nonlinear resolution.

The solution of threshold value of chaos is a critical step in stability analysis and Melnikov method is one of relatively few analytical methods used to predict the onset of chaotic motion in dynamical systems. It measures the intersection of the homoclinic (heteroclinic) orbits, which will lead to chaotic motions in the system. During the last two decades, a great deal of work has been done using Melnikov method to predict possible capsize, with emphasis on roll motion. Nayfeh and Balachandran [9] deduced the Melnikov

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Nomenclature

g	the acceleration of gravity (9.81 m/s^2)
Δ	displacement (m^3)
ϕ	the rolling angle (rad)
GZ	the righting arm (m)
$J_{\phi\phi}$	rotational moment of inertia (kg m^2)
R_1	first order coefficient of righting arm (m)
R_3	third order coefficient of righting arm (m)
R_5	fifth order coefficient of righting arm (m)
D_1	first order coefficient of damping moment (kg m^2 s^{-1})
D_3	third order coefficient of damping moment (kg m^2 s)
$\xi(t)$	wave elevation (m)
$\tilde{M}^*(\Omega)$	the Fourier transformation of $\tilde{M}(t_0)$
$S_y(\Omega)$	the power spectrum of $y(t)$
μ	the mean value of $\tilde{M}(t_0)$
Φ	rate of phase space flux
$M(t_0)$	the Melnikov function
$y(t)$	the parametric orbital equation
$\tilde{M}(t_0)$	the oscillatory part of random Melnikov function
$\bar{M}$	the constant part of random Melnikov function
$\Delta J_{\phi\phi}$	added rotational moment of inertia (kg m^2)
Hs	significant wave height (m)
T_z	zero-crossing period (s)
F_{wave}	wave-excited rolling moment (N m)
F_{wind}	wind-excited rolling moment (N m)
$\xi^*(\Omega)$	the Fourier transformation of $\xi(t)$
$y^*(\Omega)$	the Fourier transformation of $y(t)$
$S_\xi(\Omega)$	the power spectrum of $\xi(t)$
$S_{\tilde{M}}(\Omega)$	the power spectrum of $\tilde{M}(t_0)$
σ	the variance of $\tilde{M}(t_0)$

function and applied the function to three typical oscillators. When the zero point of Melnikov function needs to be computed, analytical solutions of homoclinic or heteroclinic orbits were obtained in their works. Falzarano [10] and Falzarano et al. [11] applied Melnikov's method to the single-degree-of-freedom equation of roll motion using a cubic polynomial for the GZ curve with a nonlinear damping term for both heteroclinic and homoclinic cases. When encountered with stochastic seaway conditions, Melnikov function has no simple zero point in the sense of mean value and therefore random Melnikov function is derived and described in terms of its statistical properties to deal with this kind of stochastic dynamical system. Its results are linked to the likelihood of capsize through measurement of the rate of phase-space flux. Frey and Simiu [12] firstly obtained the relationship between phase flux function and Melnikov function and subsequently random Melnikov function was established by Hsien et al. [13] on this basis. Since then, random Melnikov function has been adopted in many works [14–17].

When using random Melnikov function, the parametric orbital equations of heteroclinic or homoclinic need to be determined. For simple symmetric system, there are usually two methods, namely precise analytical solution and approximate analytical solution [18–20]. However, when subjected to a constant wind load or an imbalance in cargo loading, the symmetry breaking occurs [21]. In this paper, the discrete time series of orbit equations are first obtained and then the technique of discrete time Fourier transformation (DTFT) is adopted to get the power spectrum of orbit equations. By virtue of rate of phase space flux, the threshold values of significant wave height are obtained and capsizing probability contour diagram is generated in the end as a numerical verification.

2. The nonlinear rolling system in wind and stochastic beam seas

In this paper, we use a second-order non-autonomous system to model ship rolling motion. We assume that the ship does not possess any forward speed and the ship rolling motion is uncoupled from other motions. The latter assumption is not a good one in the presence of internal resonances. In the context of ship motions, an internal resonance can occur when the pitch frequency is about twice the roll frequency. This phenomenon is likely to occur in fishing vessels in which the pitch frequency is about 1.5–3 times the roll frequency. The damping models used in this study are all assumed to be independent of the frequency of the roll oscillations [21]. The transverse sections of the studied ship are shown in Fig. 1.

2.1. The excitation terms in the rolling system

To consider the actual environmental factors in ship's voyage, we take stochastic wave excitation and wind force moment into account. In the following sub-sections, we discuss perspectives of these two parts while focusing on how these excitation terms are determined.

2.1.1. Crosswind model

For container ships, the effect of crosswind on roll motion cannot be ignored because the area subjected to above-water wind is huge. As shown in Fig. 2, the wind heeling moment can be expressed as

$$F_{wind} = F_{wind|\phi=0} \cos\phi \tag{1}$$

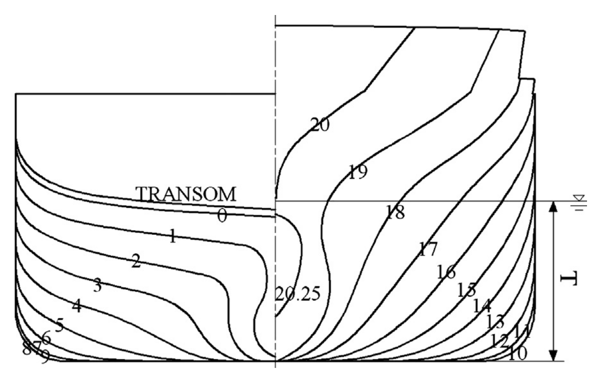

Fig. 1. Transverse sections of studied ship.

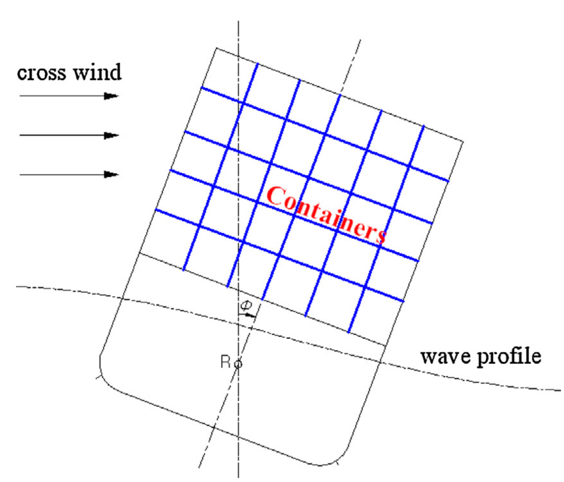

Fig. 2. Container ship rolling schematic plan.