On the assessment of ship grounding risk in restricted channels

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Abstract
The paper describes a procedure to assess the risk of ship grounding in restricted channels. The admittance policies (sailing speed and minimum safe underkeel clearance) for safe navigation will be established. First-passage failure and extreme theory of a stationary random process, which is considered as the ship motion response, are investigated. Due to the stochastic variation of the ship speed, $V_s$, and dynamic underkeel clearance, $KC$, the ship motion response characteristics are predefined and stored in a computer model as functions of $V_s$ and $KC$, which have to cover a broad range of wave conditions. This makes it possible for a "closer" analysis in real time to refine the assessment. A numerical example is given and the procedure is therefore quantitatively described. The procedure can be used not only in the prediction of grounding risk some hours before the ship enters the channel but for the optimal design of channel depths with respect to an acceptable probability of ship grounding.

1 Introduction
Shipping fleets have been steadily increasing both in size and quantity over the last decades; how can these larger ships enter into present ports and maximize the loadings has drawn much attention to both port managers and designers. The technology [1-3] to enable deeper draft or minimize underkeel clearance, in other words, without compromising navigation safety is the most effective and economical. This approach essentially focuses on development of a system to predict ship dynamic underkeel clearance (DUKC) along ship passage. The predicted results are implemented by using a numerical ship motion model in combination with probabilistic computation [2, 4-7]. Based on these results, a minimum underkeel clearance allowance can be selected, which indicates a safety level of the particular channel transit.

The most important assumptions for assessment of the grounding risk in the probabilistic model are that the motions of ship in wave are considered as a stationary Gaussian random process, probability of ship grounding can be estimated by using the Poisson description, which is as a function of the tide, ship response characteristics (mainly depending on wave conditions and ship parameters) and ship speed. However, due to the stochastic variation of ship speed and dynamic underkeel clearance; and since ship response characteristics are also functions of these factors, estimating the risk of ship grounding for DUKC as well as predicting the changes in minimum safe underkeel clearance is still challenging. Furthermore, the assessment should also be refined in association with the ability for a closer analysis in real time during ship passage [1]. None of these studies have fully considered these conditions.

2 Theoretical background

First-passage failure
The first-passage failure is a event that a random process $x(t)$ cross a level $x=\beta$ (m) at once during a period $T$ (sec). It is widely used for estimating the chance of ship touching the bottom, which is considered as the risk of ship grounding.

This method is based on the assumption that successive up-crossing of a specified level are independent and constitute the Poisson process [8]. Under this assumption probability of the first-passage failure, $P(\beta,T)$, of a response $x(t)$ when is a stationary can be estimated by

$$P(\beta,T) = 1 - \exp(-v_\beta T)$$  \hspace{1cm} (1)

Where $v_\beta$ is the mean rate of crossing with level $\beta$, if $x(t)$ has the Gaussian distribution and zero mean, $v_\beta$ can be then expressed as
Where $m_0$ and $m_2$ represent zero and second moments of the response respectively, which can be determined by the following equations

$$m_0 = \int_{-\infty}^{\infty} S_\omega(\omega) d\omega$$

$$m_2 = \int_{-\infty}^{\infty} \omega^2 S_\omega(\omega) d\omega$$

$S_\omega(\omega)$ is the power spectral density function describes the distribution of the mean-square value of the response $x(t)$ over the frequency domain $\omega$.

In the engineering design, it is highly desirable to know a certain level for which probability of first-passage failure is smaller than an acceptable value $\alpha$. For example, before ship enters the approach channel we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding. So let $P(\beta, T) = \alpha$, from Eqs. (1) and (2), crossing level for probability of first-passage failure $= \alpha$ can be expressed by

$$\beta = \sqrt{m_0} \sqrt{2 \ln \left( -\frac{\ln(1-\alpha)}{16 \pi^2 \beta^2} \frac{m_2}{m_0} \right)}$$

The non-dimension of crossing level, denoted by $\beta_0$, is given by $\beta_0 = \beta / \sqrt{m_0}$. Figure 1 shows the non-dimensional crossing level $\beta_0$ for $T=10$ hours computed from Eq. (5) as a function of the first-passage failure $\alpha$ when $\beta$ and $\sqrt{m_2 / m_0}$ are independent each other. As can be seen in this figure that there is no significant difference in the values of $\beta_0$ for $\sqrt{m_2 / m_0}$ up to 0.7, this is true for $\beta_0$ derived as a function of time $T$ as shown in Figure 2 for first-passage failure $\alpha=10^{-4}$.

It can be realized that $\beta$ can be seen as average simultaneous underkeel clearance, $KC$, for which the probability of first-passage failure (grounding) is $\alpha$. The problem become more complicated since the response characteristics, $m_0$ and $m_2$, are also a function of $KC$ and ship speed (i.e. time $T$), which vary along ship passage. This problem will be discussed in later sections.

**Extreme values**

Supposing the first-passage failure is viewed as ship grounding is somewhat pessimistically. It can be realized in the fact that even with a number of the bottom touches during a transit; the ship can be still underway without grounding. The study [4] indicated that the possibility that the vessel touches the bottom and penetrates 0.25m does not always resulting in the grounding and the major damage. It is, of course, only true for the soft bottom. The application of extreme theory in evaluation of penetration is therefore meaningful. It means that for the probability of first-passage failure with the crossing level, $\beta$, with the corresponding extreme value, $\bar{\eta}$, a penetrated depth onto the bottom is thus defined by

$$\bar{\eta} = \frac{1}{2\pi} \sqrt{\frac{m_0}{m_2}} \exp \left( -\frac{1}{2 \beta^2} \right)$$
The non-dimension of is defined as $\eta = \bar{\eta} / \sqrt{m_0}$.

3 Methodologies

As revealed in the previous section, definitions of the crossing level and extreme value in Eqs. (5) and (11) are no longer valid since the response characteristics $m_0$ and $m_2$, are also subject to the period $T$ (i.e., ship speed) and average instantaneous underkee clearance $KC$, which can be seen as a crossing level with a specified value $\alpha$.

A solution to this problem is that response characteristics $m_0$ and $m_2$ can be predefined and stored in a computer model as functions of ship speed $v_s$ and $KC$, which have to cover a broad range of wave condition and ship parameters. In near ship time arrival, the information on
environmental condition should be provided and based on that extrapolating this forecast along approach channel.

Partitioning the whole channel into segments by which the variations of tide and bottom profile in each segment can be neglected. The Eq. (1) must be rewritten as

\[ P_g = 1 - \exp \left( - \frac{1}{\int v_i(t) dt} \right) \]  

\[ \int v_i(t) dt \approx \sum_{i=1}^{n} v_i(\Delta t_i) \Delta t_i \]  

Where \( n_s \) is the number of segments; \( \Delta t_i \) is the duration that a ship passes through segment \( i \). Let \( P_i \) be the probability of ship grounding in segment \( i \), we consider all the segments as members in a series system and suppose they are equally correlated, the probability of ship grounding for the channel as whole can be defined as \[ 11 \]

\[ P_g = 1 - \prod_{i=1}^{n_s} (1 - P_i) = \alpha \]  

Now let \( P_i \) be equally for all segments and \( \rho = 0 \), Eq (14) converges to

\[ P_g = 1 - \prod_{i=1}^{n_s} (1 - P_i) = \alpha \]  

Next we can obtain other form of Eqs (5) and (11) for each segment as

\[ \beta_i = \sqrt{m_{00}} \left( -2 \ln \left( \frac{\ln(\sqrt{1 - \alpha})}{\Delta t_i 60^2 \frac{m_{zz}}{2 \pi}} \right) \right) \]  

\[ \eta_i = \sqrt{m_{00}} \left( -2 \ln \left( \frac{\Delta t_i 60^2 \frac{m_{zz}}{2 \pi}}{1 - \alpha} \right) \right) \]  

From Eqs (16)-(17) and the computer model of the response characteristics, various values of \( \beta_i \), \( \eta_i \) and \( \Delta \) can be quickly determined for all possible ship speeds \( v_s \), the underkeel clearances \( KC \) and a predefined value of \( \alpha \). To maximize the loading, the values of \( v_s \) and \( KC_{min} \) can be selected which are considered as a part of decision support information before ship entry for which the following condition must hold

\[ KC_{min} - \eta_i \geq 0 \]  

During a passage the average instantaneous \( KC \) and ship speed \( v_s \) should be automatically measured and updated in the computer model. For a mariner making decision, these data should be extended some time near future during ship progress and the predicted results should be visually supervised by displaying them on the screen. The prediction process can be illustrated in Figure 4.
The regression coefficients are found as 0.998 and 0.996 respectively. Figure 5 shows the values of $m_0$ are calculated from Eq (19) at various $v_s$ and $KC$. The points, denoted by symbols, are obtained from the numerical ship motion model [12], which has been validated for very shallow waterway. The values of $m_2$ can also be quickly obtained from Eq (20).

![Figure 5](image1.png)

Substituting $m_0$ and $m_2$ from Eqs (19) and (20) into Eqs (1) and (2) we can define the probability of touching the bottom as function of $v_s$ and $KC$ as shown in Figure 6.

![Figure 6](image2.png)

We can obtain some information from this figure for the prediction as well as for mariner making the decision on navigation condition before ship entry as follows:

The ship speed is most critical within the range of 12-18 knots because it results in the highest probability, $\alpha$, of touching the bottom. The values of $\alpha$ at lower and upper bounds outside this range are quickly dropped with decrease and increase in the ship speed respectively. On the other hand, the values of $\alpha$ increase rapidly with the decrease in the value of $KC$.

The figure provides several options of $KC$ and $v_s$ to facilitate a predefined value of $\alpha$. An optimal one with maximum of ship draft (i.e. the maximum loadings or minimum value of $KC$) adapting a "possible tide window" available at certain time of ship entry can be then defined.

![Figure 7](image3.png)

Extending the condition for foregoing example, it is assumed that using the data on meteorology and topographic measured simultaneously near real time along the channel, the change of $KC$ can therefore be instantaneously forecasted and extrapolated during ship progress as shown in the horizontal lines of Figure 7. In which the whole channel is divided into three segments with the length of 3000m, 3000m and 4000m and $KC=6.5m$, 5.5m and 5m respectively. Suppose that these segments are uncorrelated the crossing levels can be defined as a function
of $KC$ and $v_{s}$ given in Figure 7 in the dotted lines for $\alpha=10^{-4}$. As can be seen that in the first two segments, the transit will be safe for all the values of ship speed because the estimated crossing levels, $\beta$, are under available forecasted underkeel clearances, $KC$; while the ship speed, $v_{s}$, is not allowed to exceed 5,0 knots in the third segment to satisfy the condition in Eq (18). The penetrated depth, $\Delta$, onto the bottom along the third segment as defined in Eq. 6 can also be found.

4 Conclusions

Since the response characteristics, $m_{0}$ and $m_{2}$, can be defined as a function of ship speed and underkeel clearance, the assessment can be carried out not only real time before ship entry but also continuously refined along the ships passage by taking the data which are measured into consideration.

Ship speed is an important factor; the probability of touching the bottom can be decreased by either speed up or speed down within the specified ranges as indicated in Figure 6. In some circumstances, high speed may be chosen because it is more difficult to maintain ships track in cross current or wind with low speed. It can primarily be concluded that underkeel clearance affects rather greatly possibility of touching the bottom than the response characteristics, $m_{2}$ and $m_{0}$.

As indicated in the literatures [4, 13] acceptable probability of touching the bottom, $\alpha$, is very small, the penetrated depth onto the bottom is thus extremely low. This means that for a soft soil foundation bottom, the ship damage due to one touch is insignificantly. It is therefore recommended that acceptable probability of grounding can somewhat be increased.

Stochastic squat of ship due to the sailing speed has not been considered in the paper. For a specified ship, however, the stochastic squat can be estimated in the reduction of the instantaneous underkeel clearance $KC$ by using an empirical formula.

Using a parametric estimate method, the wave parameters can be introduced into the regression equations to enhance the assessment process. However, this work requires much more effort.

The correlation coefficient $\rho$ can not be easily determined for all environmental and transit conditions. Fortunately, the probability of ship grounding is rather insensitive to $\rho$. The present study has been extended for three last points, as will be reported in a future publication.

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References: