

## MODELING OF SHIP MOTION RESPONSES AND ITS APPLICATION TO RISK-BASED DESIGN AND OPERATION OF ENTRANCE CHANNELS

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### ABSTRACT

This paper presents the parametric modeling method of ship motion responses for risk-based optimization and operation of channel depths. The study focuses on computing response motion spectra as a function of the sea states (described by significant wave height  $H_s$  and wave period  $T_z$ ) and transit conditions (ship speed  $V$  and loading  $T$ ) using parametric modeling technique in combination with a numerical ship motion model; and then using these spectra applying a probabilistic model to determine the ship grounding risk. This makes it possible to establish the accessibility policy in which the guidance information for the safe transits will be provided. On the basis of the developed accessibility policy a long-term optimization of entrance channel depths can therefore be implemented. The aforementioned approach has been applied to Cam Pha Coal Port in Viet Nam as a case study.

**Keywords:** Parametric modeling; ship motion response; accessibility policy; long-term optimization; grounding risk

### INTRODUCTION

The response spectrum of wave-induced ship motions,  $S_r(\omega_e)$ , can be achieved either from towing tank experiments or by numerical models based on the ordinary or

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the modified strip theory. The response spectrum is, however, only obtainable for a particular transit condition and a specified sea state. While for a long-term assessment of a ship response, much broader sea states and continuous variation of the parameters  $V$  and  $T$  are to be requested (Cramer and Hansen, 1994). Moreover, these two approaches cannot account for uncertainty present in these parameters in calculating the response spectrum, and later applying to performance of risk analysis. Hence, a demand is emerging for high quality and continuous description of the response spectrum for the problem at hand.

A sample linear regression model of the response spectrum related to the frequency wave spectrum was presented by Savenije (1995). The regression coefficients of the model depending on the transit conditions are defined by minimizing the mean squared error between the observed data and the predicted model values. This model is currently used in the computer program HARAP (HARbour APproach) for optimization of channel depths. A more advanced model was demonstrated by Cramer & Hansen (1994). The authors proposed a stochastic field model in the modulus squared of the frequency response function  $H(\omega_e)$ , which is defined as a ratio of ship motion to wave amplitude for a given wave encounter frequency, and then by use of the Kriging technique to better minimize the variance of the estimate error. However, as pointed out by the authors, there is a significant challenge to formulate a general model for the stochastic field governing the modulus squared of the frequency response function. Unfortunately, no numerically measured error for the qualification of these models has been found in the published papers.

Most recently, U.S. Army Engineer Research and Development Center has been developing a ship motion response model to use on the ship-handling simulator. However, according to U.S. Army Corps of Engineers (USACE, 2006), this model is still considered a research tool and needs further verification.

The present study is an ongoing effort that deals with the problem of modeling the ship motion responses applying parametric modeling method. The application of this model to navigation risk assessment and the model qualification has also been described in a case study.

## PARAMETRIC MODELING OF SHIP MOTION RESPONSES

### The wave-ship motion system

For restricted entrance channels and shallow waterways, the wave climate is generally not excessive; and since the ship dimensions are usually large relative to the wave length, ship response problems can be treated with linear models (all directly proportional to wave height) (Journee, 2002). The response spectrum of the ship motion based on the linear model is directly given by the wave spectrum as

$$s_r(\omega_e) = |H(\omega_e)|^2 s_\eta(\omega_e) \quad (1)$$



where  $\omega_e$  is the encounter frequency;  $|H(\omega_e)|$  is the encounter frequency transfer, which depends on ship speed, sailing angle, loading condition and water depth (or underkeel clearance);  $S_\eta(\omega_e)$  is the wave spectrum at the encounter frequency. For a given wave direction and a loading condition, Eq (1) can be rewritten as

$$S_r(\omega_e|h_s, T_z, V, kc) = |H(\omega_e|V, kc)|^2 S_\eta(\omega_e H_s, T_z) \quad (2)$$

The encounter frequency for shallow waters is determined as

$$\bar{\omega}_e = \bar{\omega} - kV \cos(\theta), \text{ here: } k = \frac{\bar{\omega}^2}{g \tanh(kd)} = \frac{\bar{\omega}^2}{g \tanh[k(kc+T)]} \quad (3)$$

where  $V$  (m/s) is the forward speed of ship;  $kc$  (m) is the average instantaneous underkeel clearance;  $d$  (m) is the water depth;  $\theta$  (degree) is the angle between wave direction relative to the ship speed vector ( $\theta=0$  for waves from astern);  $T$  (m) is the ship draft depending on loading condition;  $\omega$  (rad/s) is the wave frequency;  $k$  is the wave number.

It can be seen from Eq (2) that if the transfer function can be formulated as a function of the transit conditions ( $V$  and  $kc$ ), the response spectrum of the motion,  $S_r(\omega_e)$ , can be determined for all possible transit conditions and sea states, described by wave spectrum  $S_\eta(\omega_e)$ .

With the assumption that the wave-ship motion is a linear input-output system, whose transfer function is faithfully modelled by an “all-pole” model:

$$H(z) = \frac{b(0)+b(1)z^{-1}+\dots+b(n+1)z^{-n}}{1+a(1)z^{-1}+\dots+a(m+1)z^{-m}} = \frac{\sum_{k=0}^n b(k)z^{-k}}{1+\sum_{k=1}^m a(k)z^{-k}} \quad (4)$$

Here,  $z$  is the angular frequency vector for which the transfer function  $H(z)$  is determined by the (real or complex) numerator and denominator polynomials represented in the vectors  $b$  and  $a$ , respectively. For known  $H(z)$  and  $z$ , nonlinear optimization to define  $a(k)$  and  $b(k)$  is generally realized in the iterative techniques proposed by Prony or Shank, both are available in the Matlab Signal Processing Toolbox. For the problem under discussion, Eq (4) can be rewritten as

$$H(\omega_e|V, kc) = \frac{\sum_{k=0}^n b(k|V, kc)\omega_e^{-k}}{1+\sum_{k=1}^m a(k|V, kc)\omega_e^{-k}} \quad (5)$$

We assume the form of  $a(k)$  and  $b(k)$  as the polynomial functions of  $V$  and  $k_c$  as

$$a(k | V, k_c) = \sum_{j=1}^{p+1} \left[ \sum_{i=1}^{q+1} \alpha_{i,j} V^{q+1-i} \right] k_c^{p+1-j}, \quad k = 1 \div m \quad (6)$$

$$b(k | V, k_c) = \sum_{j=1}^{p+1} \left[ \sum_{i=1}^q \beta_{i,j} V^{q+1-i} \right] k_c^{p+1-j}, \quad k = 0 \div n \quad (7)$$

The idea given to define the response function is that parametric modeling technique is applied to find the parameters  $a(k)$  and  $b(k)$  in the Eq (5), which corresponds to define the coefficients  $\alpha$  and  $\beta$  in the proposed mathematical model given in Eqs (6) and (7). The estimation of the model parameters is achieved in two steps: the encounter frequencies and response functions considered as the data samples are obtained from either physical model tests or numerical ship motion model for various class values of  $V$  and  $k_c$ , from which the corresponding parameters  $ao(k)$  and  $bo(k)$  can be estimated using Prony's algorithm (Jones, 2005). The estimated parameters are then used to define the coefficients  $\alpha$  and  $\beta$  by doing a least square fit, which minimizes the sum of the squares of the deviations of the data from the model as

$$\varepsilon_\alpha = \min_{\alpha} \sum_{i=1}^M \sum_{j=1}^N [a(\alpha | V_i, k_c j) - ao(V_i, k_c j)]^2 \quad (8)$$

$$\varepsilon_\beta = \min_{\beta} \sum_{i=1}^M \sum_{j=1}^N [b(\beta | V_i, k_c j) - bo(V_i, k_c j)]^2 \quad (9)$$

Thus, the parametric modelling problem for the model given in Eq (5) is reduced to finding the minimum points of the function  $\varepsilon_\alpha$  and  $\varepsilon_\beta$  in Eqs (8) and (9), which is called a prediction error method.

### Estimating model parameters

Suppose we have sample data of  $H(\omega_e)$  at various values  $V_i$  and  $k_c j$  ( $i=1 \div M$ ,  $j=1 \div N$ ). Using Prony's algorithm, we can find the  $(M \times N)$  vectors  $bo$  each having  $n$  parameters  $bo(k)_j$ ,  $k=0 \div n$  and the  $(M \times N)$  vectors  $ao$  each having  $m$  parameters  $ao(k)_j$ ,  $k=1 \div m$ . The parameter  $ao_j$  (here we omitted "k" to simplify the notation) can be expressed as a nonlinear  $p$ -order polynomial model of  $k_c j$  for a given  $V_i$  as



$$r_{1,i}k^p_j + r_{2,i}k^{p-1}_j + \cdots r_{p,i}k^c_j + r_{p+1,i} = ao_{ji} \quad (10)$$

In the matrix form

$$\begin{bmatrix} k^p_1 & k^{p-1}_1 & \cdots & k^c_1 & 1 \\ k^p_2 & k^{p-1}_2 & \cdots & k^c_2 & 1 \\ \cdots & \cdots & \ddots & \cdots & \cdots \\ k^p_N & k^{p-1}_N & \cdots & k^c_N & 1 \end{bmatrix} \begin{bmatrix} r_{1,i} \\ r_{2,i} \\ \cdots \\ r_{p+1,i} \end{bmatrix} = \begin{bmatrix} ao_{1,i} \\ ao_{2,i} \\ \cdots \\ ao_{N,i} \end{bmatrix} \quad (11)$$

For all  $V_i, i=1 \div M$ , Eq (11) in matrix form is

$$\begin{bmatrix} k^p_N, p+1 \\ r_{p+1,M} \end{bmatrix} = \begin{bmatrix} ao_{N,M} \end{bmatrix} \quad (12)$$

$$\text{here, } k^p_{l,j} = k^{p+1-l}_j, \quad l = 1 \div p+1, j = 1 \div N$$

There are  $N$  equations and  $(p+1)$  unknowns. For regression solution  $N$  must therefore be larger than  $(p+1)$ . We can easily define the coefficients  $r$  represented by the  $M$ -by- $p+1$  matrix using nonlinear regression technique. It is clear from Eq (10) that  $r_{ji}$  is as the coefficient in the  $(p+1-j)$  order polynomial model of  $k^c_j$  for a given value of  $V_i$ . Thus, for instance, the equation of  $r$  at the  $p$ -order of  $k^c$  is

$$\alpha_{1,1}V_i^q + \alpha_{2,1}V_i^{q-1} + \cdots \alpha_{q,1}V_i + \alpha_{q+1,1} = r_{1,i}, \quad i = 1 \div M \quad (13)$$

For all  $V_i, i=1 \div M$  at the  $p$ -order of  $k^c$  in the matrix form

$$\begin{bmatrix} V_1^q & V_1^{q-1} & \cdots & V_1 & 1 \\ V_2^q & V_2^{q-1} & \cdots & V_2 & 1 \\ \cdots & \cdots & \ddots & \cdots & \cdots \\ V_M^q & V_M^{q-1} & \cdots & V_M & 1 \end{bmatrix} \begin{bmatrix} \alpha_{1,1} \\ \alpha_{2,1} \\ \cdots \\ \alpha_{q+1,1} \end{bmatrix} = \begin{bmatrix} r_{1,1} \\ r_{1,2} \\ \cdots \\ r_{1,M} \end{bmatrix} \quad (14)$$

For all orders of  $k^c$  in the matrix form

$$\begin{bmatrix} V_{M,q+1} \\ \alpha_{q+1,p+1} \end{bmatrix} = \begin{bmatrix} r_{p+1,M} \end{bmatrix}^T \quad (15)$$

$$\text{here } V_{l,i} = V_i^{q+1-l}, \quad l = 1 \div q+1, i = 1 \div M$$

We have  $M$  equations in the  $(q+1)$  unknowns with the condition that  $M > (q+1)$ . Having determined the  $r$  from Eq (12) we can then use them to obtain  $\alpha$  from Eq (15) with the prediction error given in the Eq (8). In the same way, we can also define  $\beta$ .

Minimizing  $\varepsilon_a$  and  $\varepsilon_b$  in Eqs (8) and (9) leads to the error of the response function over the  $(N \times M)$  samples is minimized, which is given by

$$\varepsilon_H(\sigma_e) = \sum_{i=1}^M \sum_{j=1}^N \left[ H(\sigma_e | V_i, k c_j) - H_0(\sigma_e | V_i, k c_j) \right]^2 \quad (16)$$

It is clear that the found curve fits in Eqs (10) and (13) in some cases may not perfectly approximate the data. To improve the approximation, the order ( $p$  and  $q$ ) of the polynomial equations can be increased, which subsequently leads to increased sample data and therefore require a higher computational effort. This, however, does not amount to a problem with the mathematical model programmed in recent powerful computers.

One might prefer to use a regression coefficient  $R^2$ , as given in Eq (17), for assessment of the estimated response function, and thus we have to choose  $p$  and  $q$  that satisfy the condition  $R > R_0$  ( $R_0$  is an expected fitting coefficient). Hence, minimizing  $\varepsilon_H$  in Eq (16) is equivalent to maximizing  $R$  in the following

$$R^2 = 1 - \frac{\sum (H_{oi} - H_i)^2}{\sum (H_{oi} - \bar{H}_o)^2} \quad (17)$$

where  $H_{oi}$  is the sample value of transfer function; and  $H_i$  is the regression prediction value; and  $\bar{H}_o$  is the mean of the sample values.

The above procedure for defining the parametric model of the transfer function given in Eq (5) as well as for determining the response spectrum  $S_r$  in Eq (2) can be summarized as follows:

Use either numerical ship motion model or physical model to calculate the transfer functions for the concerned ranges of ship speeds and water depths. The numerically calculated transfer functions are considered as the sample functions, denoted here  $H_0(\omega_e)$ , for the parameter modeling progress. Note that the sample function values are calculated at the relatively discrete encounter frequencies, which are derived from Eq (3).

The estimated sample functions  $H_0(\omega_e)$  and  $\omega_e$  are then used to define the model parameters  $a_0(k)$  and  $b_0(k)$  by solving invert function of Eq (5) using Prony's algorithm. We calculate the parameters  $b_0(k)$  and  $a_0(k)$  by trying to find appropriate values of  $n$  and  $m$ .



Define  $a(k)$  and  $b(k)$  as the functions of  $V$  and  $k\epsilon$  as given in Eqs (6) and (7). This leads to a system of  $M \times N$  equations in  $(q+1) \times (p+1)$  unknowns which can be solved to find the best fitting coefficients ( $\alpha$  and  $\beta$ ) to fit the data,  $a(k)$  to  $a_0(k)$  and  $b(k)$  to  $b_0(k)$ .

Finally,  $H(\omega_e)$  will be found at the relatively discrete encounter frequencies using Eq (5), the corresponding  $\varepsilon$  and  $R^2$  will also be estimated in Eqs (16) and (17). In practical, we usually consider choosing parameters  $a(k)$  and  $b(k)$  to maximize  $R^2$ .

## SOME APPLICATIONS

There is a growing tendency in the application of probabilistic approach to risk-based optimization of entrance channel depths both in design (Briggs, 2003; Vantorre and Laforce, 2002) and navigational operation (Howell, 2002; Moes, 2002; O'Brien, 2002). The optimization of channel depths is aimed at determining a depth to balance between the benefit of transport increment, downtime reduction and increase in costs of initial/maintenance dredging for a long-term channel project. It should be realized that the long-term optimization of channel depths requires guidance for minimum underkeel clearance allowances for the entrance accessibility to facilitate a required navigation safety. A level of the safety for the accessibility, in this context, can mainly be expressed in terms of probability of ship grounding risk.

However, the present design guidelines for underkeel clearance allowances for coastal entrance channels and shallow waterways are not comprehensive and practical (Zeki Demirbilek and Sargent, 1999). A simple general guideline for minimum depth clearance requirements in channels influenced by waves is given by PIANC (1997). It is defined by ratios of water depth to ship draft, which should not be less than 1.3 when  $H_s$  is not higher than 1 m and at least 1.5 when  $H_s$  is higher than 1 m; and wave periods and directions are unfavourable. This guideline results in rather unrealistic depth under moderate wave actions. Whereas U.S. Army Corps of Engineers (USACE, 1998) states that "net depth allowance for waves is 1.2  $H_s$  for deep-draft and 0.5  $H_s$  for shallow-draft channels". It should be noted that the wave period contributes a significant effect on ship motion. Hence, an adequate guidance for ship accessibility, so called accessibility policy, should consider wave conditions (both  $H_s$  and wave period,  $T_z$ ) in association with transit conditions (sailing speed and minimum underkeel clearance) for the navigation safety.

Recent efforts have focused on development of a system to predict ship dynamic underkeel clearance (DUKC) along ship passage. The predicted results are found by using a numerical ship motion model in combination with probabilistic computation (Briggs et al., 2003; Moes et al., 2002; Vantorre and Laforce, 2002). Based on these results, a minimum underkeel clearance allowance can be selected, which indicates a safety level of the particular channel transit. However, the cost of installation and operation of such systems is still prohibitive; Moreover, such system is not applicable during design stage.

The new parametric model developed in this study is useful for overcoming the above mentioned limitations, as presented in the following.

### Development of a risk-based policy for ship entrance: first-passage failure model

The first-passage failure is an event that a random stationary process  $X(t)$  cross a level  $x=\beta$  (m) at once during a period  $T$  (s). It is frequently used for estimating the risk of a ship touching the bottom, which is assumed as a measure of the risk of ship grounding. This method is based on the assumption that successive up-crossings of a specified level are independent and constitute a Poisson process (Lin, 1967). Under this assumption probability of the first-passage failure,  $P(\beta, T)$ , of a response  $X(t)$  can be estimated by

$$P(\beta, T) = 1 - \exp(-v_b T) \quad (18)$$

where  $v_b$  is the mean rate of crossing with a level  $\beta$ , if the response  $X(t)$  has the Gaussian distribution and zero mean,  $v_b$  can then be expressed as

$$v_b = \frac{1}{2\pi} \sqrt{\frac{m_2}{m_0}} \exp\left(-\frac{1}{2} \frac{\beta^2}{m_0}\right) \quad (19)$$

where  $m_0$  and  $m_2$  represent zero and second moments of the response, respectively, which can be determined by the following equations

$$m_0 = \int_0^\infty S_r(\omega_e) d\omega_e \quad (20)$$

$$m_2 = \int_0^\infty \omega_e^2 S_r(\omega_e) d\omega_e \quad (21)$$

$S_r(\omega_e)$  is the response spectrum as defined in the previous section.

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 the ship enters we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding,  $\alpha$ . So let , from Eqs (18) and (19), crossing level for probability of first-passage failure =  $\alpha$  can be expressed by

$$\beta = \sqrt{m_0} \sqrt{-2 \ln \left[ \frac{\ln(1-\alpha)}{\frac{T^2}{2\pi} \sqrt{\frac{m_2}{m_0}}} \right]} \quad (22)$$



## Long-term simulation-based optimization of the channel depths

Having determined the model of ship motion responses, a simulation model can therefore be developed. It can be used as a decision support tool for channel performance evaluation and optimization. In general, the procedure of a long-term optimization of channel depths is presented in Figure 1.

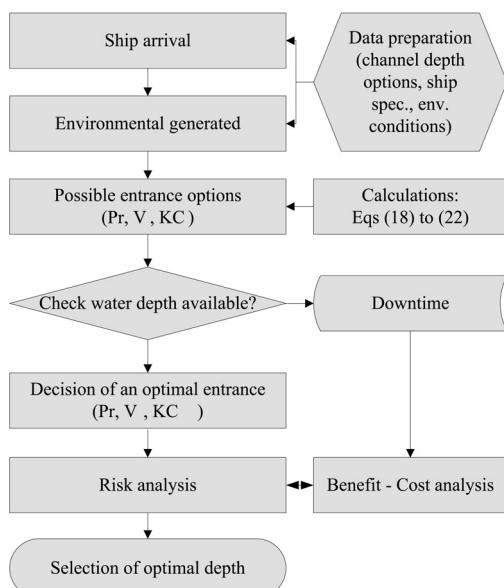


Figure 1: General procedure for the optimization of channel depths

od and for all possible alternatives of the channel depths. To enable this, a stochastic model of the environmental conditions and ship arrivals on the basis of historical recorded or forecasted data have to be set up. Since the ship response spectrum has been defined as a function of the transit conditions and sea states, the model uncertainties can be assessed and included in the simulation. The final results derived from the simulation model can be considered as the key parameters in analysis and selection of an optimal depth.

## THE CASE STUDY

### Project description

The entrance channel at Cam Pha Coal Port in the North Sea of Viet Nam is the largest specialized port in Viet Nam serving export of coal to Europe, Japan and

China. In recent years, the demand on exporting coal to Europe and Japan has increased rapidly and ships entering the port are becoming larger which are beyond the present capacity of the entrance channel. Therefore, in 2001, Viet Nam Coal Incorporation initiated an expansion project of the Port (Quy, 2001) in which the entrance channel will be enlarged to allow the ships of up to 65,000DWT (full loaded) using a high tide for leaving the port. But till now, the rehabilitation of the channel has not been commenced yet. The main reason of this delay is that a part of the channel with the length of 7.5 km is very shallow (only -7.4 m from the sea datum) and the seabed is rocky, this results in very high costs in dredging work. Hence, economic and environmental pressures have revealed the need to minimize the dredging when determining the depth of the entrance channel. Establishment of an appropriate and reliable policy for the ship entry also gives an opportunity to reduce the dredging depth requirement. This study, as a part of the mentioned project, deals with the rehabilitation of the entrance channel with the following objectives:

Establishing an accessibility policy by which pilots can use it with a sufficient confident to decide the transit conditions before leaving the port.

Optimizing the channel depths in the long-term with regarding to an acceptable probability of the ship grounding on the basis of the established accessibility policy.

However, only the results of the first objective have been presented in the following. The calculation procedure of the optimization has been developed, as will be reported in future publication.

### Input data

The design ship is a bulk carrier 65.000 DWT with the main representative dimensions as:

|                                    |             |
|------------------------------------|-------------|
| overall length (loa): .....        | 274.000 m   |
| beam (b): .....                    | 32.000 m    |
| full loaded draft (T): .....       | 13.000 m    |
| block coefficient ( $C_B$ ): ..... | 0.8142      |
| wetted hull surface: .....         | 3.487 $m^2$ |

To obtain sample data for parametric modeling of the frequency transfer function, a numerical ship motion model, called SEAWAY (Journee, 2001), has been used. The program is a frequency-domain ship motion model, which - based on the modified strip theory - calculates the wave-induced loads and motions with six degrees of freedom of ship hull. The program has been validated for the motion calculation in a very shallow water area (Marc Vantorre and Journee, 2003).

Five values of ship speed ranged from 5 knots to 15 knots and seven values of water depth,  $d$ , with ratio of  $d/T$  varied from 1.25 to 1.55 were used in the calculation, amounting in total to thirty five transit conditions. In the absence of study on the shape of wave spectrum in this area for the time being, two parameters,  $H_s$  and



$T_z$ , of Pierson-Moskowitz spectrum has been proposed to calculate the ship motions. The calculation focused on the hull motion at stern, because the risk of bottom touch is most critical for this part of the ship. The reason for this is the export function of the port where the outbound ships - loaded to full draft - faces incoming waves (Quy, 2006).

The ship squat has also been taken into account to reduce the underkeel clearance. The empirical expression, proposed by Barrass II (PIANC, 1997), has been used as follows:

$$S_{\max} = \frac{C_B S_2^{2/3} V^{2.08}}{30} \quad (23)$$

where  $C_B$  is the block coefficient;  $V$  is the ship speed (knots);  $S_2$  is the blockage factor defined as a ratio of midship section area to the wetted cross section area of the waterway.

### Modeling results and comparisons

The parameters in vectors  $ao(k)$  and  $bo(k)$  were found with the average regression coefficient over all the sample data was 0.994 for the orders  $n$  and  $m$  in the numerator and denominator polynomials of 25 and 16 respectively, where the fit presented in Figure 2 with  $V=10$  knots and  $kc=3.25$  m represents the case having the smallest value of all fits performed. These results confirmed that the “all-pole” model represents well the behavior of the ship response in the linear wave-motion system.

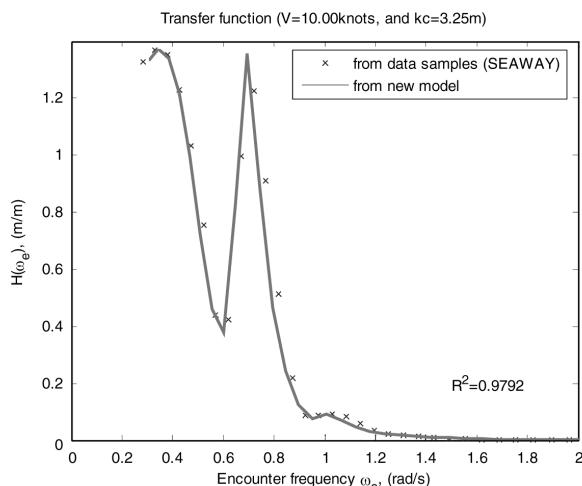


Figure 2: Comparison between the theoretical transfer function calculations (SEAWAY) and the results from the parametric model.

Figure 3 presents the results of the model parameters in Eqs (6) and (7) as function of  $kc$  and  $V=10$  knots with the index  $k=3$  based on the estimated values of  $ao(k)$  and  $bo(k)$ . The  $q$ - and  $p$ -orders of the polynomials were 3 and 2, respectively. It can be primarily concluded that the polynomial model can fit well the data with only low orders. It is more interesting to find out that the error in the estimated response spectrum is very insensitive with

the errors in the model parameters  $a(k)$  and  $b(k)$  because the “all-pole” model is usually computed with the high  $n$ - and  $m$ -orders.

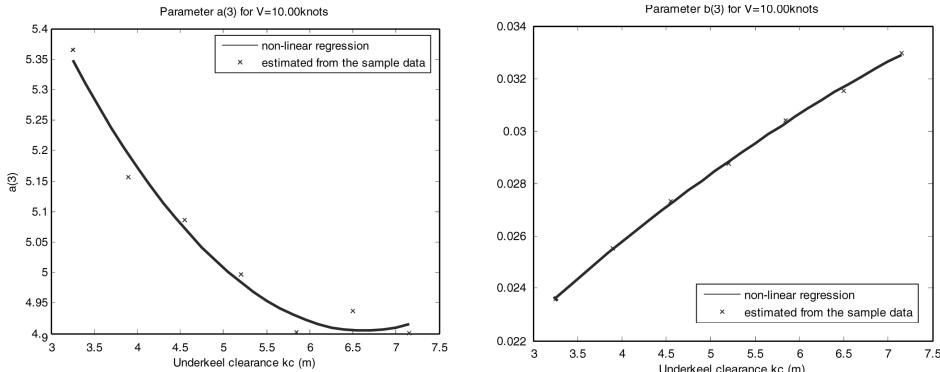


Figure 3: Examples of non-linear regression of parameters  $a$  and  $b$

The response spectral estimations based on the parametric model were also compared well to those obtained from the numerical ship motion model, as presented in Figure 4. Many sea states were randomly generated from which five hundred of response spectra with thirty five transit conditions (five speed classes and seven values of  $k_c$ ) were estimated to test the model fit. The average fit coefficient was 0.991 and the smallest fit was 0.9716 as shown in Figure 4. Finally, the probability of ship grounding for a certain transit condition and a minimum allowable underkeel clearance with a predefined acceptable grounding risk can be estimated using the first-passage failure model given in Eqs (18) and (22) respectively.

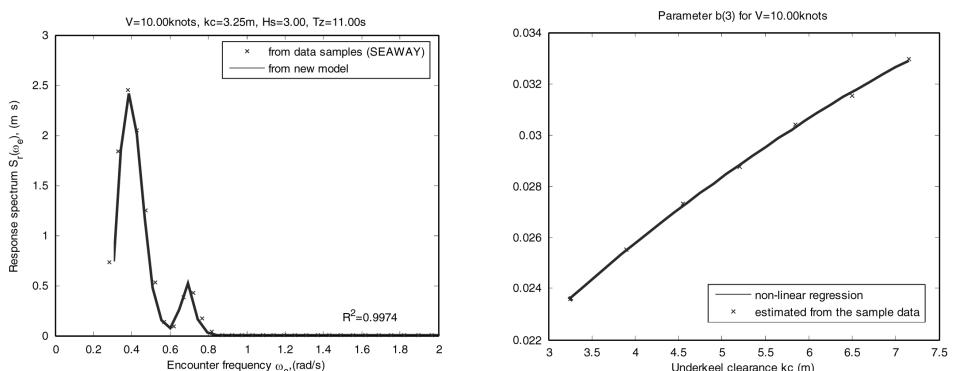


Figure 4: Comparison between the theoretical ship response calculations (SEAWAY) and the results from the parametric model.



## Discussions

Concerning the PIANC guideline, the ratio of water depth to ship draft ( $d/T$ ) has been investigated for various sea states and transit conditions, as shown in Figure 5 and Figure 6. It can be seen from Figure 5 that the risk levels indicated by the probabilities of ship grounding are strongly dependent on the wave period. The probability increases quickly with slowly decreasing ratios of  $d/T$  or with increasing wave period. However, for small value of the acceptable probability of grounding, let say  $\alpha=3\times10^{-5}$  (3 per 100,000 ship movements) as an observed value for Northern European Ports (Vrijling, 1995), the results are less sensitive to the wave period. But with the ratio  $d/T = 1.5$  for the  $H_s$  is higher 1 m as suggested in PIANC seems very high and unrealistic, which is equivalent to the  $H_s=6$  m for  $\alpha=3\times10^{-5}$ . From an operational point of view, it is almost impossible for a ship to navigate in restricted channels with such a wave height.

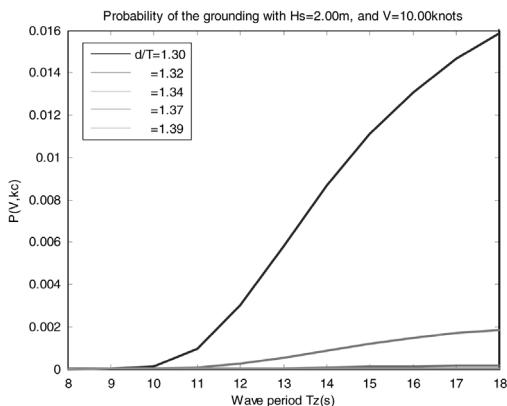


Figure 5: Relationship between probabilities of the grounding and wave periods for different values of  $d/T$  (relates to the PIANC).

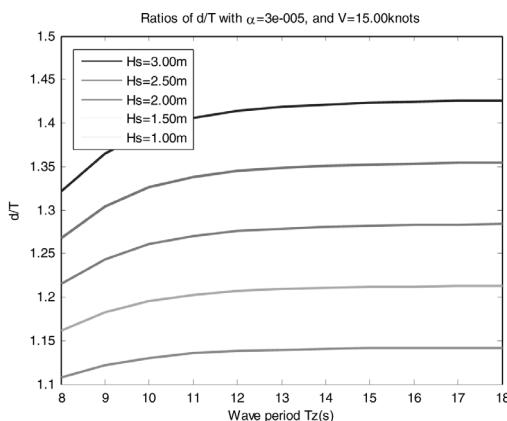


Figure 6: Relationship between ratio of  $d/T$  and wave periods for different values of  $H_s$  with an acceptable grounding value  $\alpha=3\times10^{-5}$ .

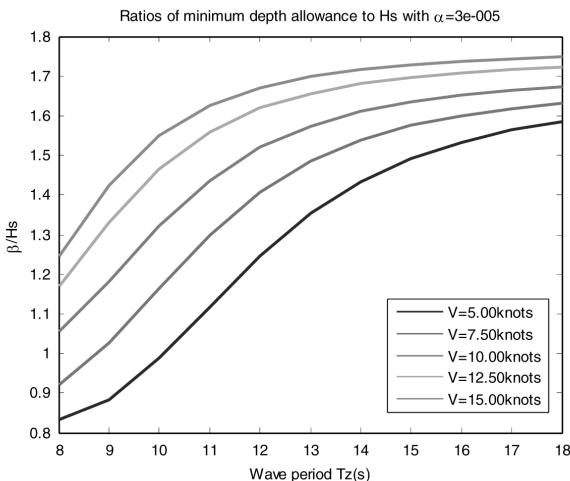


Figure 7: Relationship between ratio of  $\beta/H_s$  and wave periods for different ship speeds with an acceptable grounding value  $\alpha=3 \times 10^{-5}$  (relates to the USACE).

analysis" in near real time to predict ship dynamic underkeel clearance along ship passage (Howell, 2002) for maximizing allowable ship draft. An actual bulk export terminal in Viet Nam was used to demonstrate the applicability of this model for decision making relating to improving the channel operation and capacity expansion.

The results of the regression confirmed that the new model with its parameters expressed by polynomial functions represents well the behavior of the ship motion response in the linear wave-motion system.

The limitations of the PIANC and USACE guidelines for the underkeel clearance allowances have been investigated by taking wave parameters and transit conditions into consideration. It should be concluded that the wave periods have great effect on the ship grounding risk with very different degrees depending on the transit conditions. These results could be useful for improvement of the existing guidelines with a condition that an acceptable probability of ship grounding should be allowed; the accessibility policy for the ship entrance as well as for approach channel design will therefore be more accurately and practically established.

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#### CONCLUSIONS

Parametric modeling of ship motion responses, of how transit conditions and waves affect the ship motion and grounding risk, has been presented. The model is useful for many purposes: risk management of ship operation in harbor and waterways; simulation-based optimization of channel depths in which all uncertainties involved can be introduced into the simulation; for use on ship handling simulator; and study behavior of ship structure itself. The model could be applicable for "closer



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