

Parametric modeling of ship motion response for risk-based optimization of channel depths

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Abstract

Parametric modeling method of ship motion response is presented in this paper. The study focuses on computing response motion spectra as a function of the sea state (H_s and T_z) and transit conditions using parametric modeling technique in combination with a numerical ship motion model; and using these spectra then 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 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; optimization; grounding risk.

1 INTRODUCTION

There is a growing tendency in the application of probabilistic approach to risk-based optimization of entrance channel depths both in design (Andrew & John, 1998; Briggs et al., 2003; Vantorre & Laforce, 2002) and navigational operation (Howell, 2002; Moes et al., 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 optimization of channel depths in long-term 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. They are even conservative (Zeki Demirbilek & Sargent, 1999). Simple general guideline for minimum depth clearance requirements in channels influenced by waves are given by (PIANC, 1997). It is defined by ratios of water depth to ship draft, which is not smaller than 1.3 when H_s (significant wave height) is not higher than 1m and at least 1.5 when H_s is higher than 1m; and wave periods and directions are unfavourable. This guideline gives rather unrealistically deep depth under moderate wave actions. Whereas U.S. Army Corps of Engineers (USACE, 1998) states that "net depth allowance for waves is $1.2H_s$ for deep-draft and $0.5H_s$ 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 systems 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 (Briggs et al., 2003; Moes et al., 2002; Savenije, 1995; Vantorre & 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 for installation and operation of such systems are still very expensive to the developing countries like Viet Nam; Moreover, this system can not be applicable during design stage.

The objective of this study aims at formulating a parametric model of ship motion response by which the guidance for the ship accessibility can more accurately be developed. The results can also be useful for a long-term optimal design of the channel depths.

2 PARAMETRIC MODELING OF SHIP MOTION RESPONSE

The response spectrum of the wave-induced motions can be achieved either from towing tank experiments or by numerical models based on the ordinary or the modified strip theory. The response spectrum is, however, only obtainable for a particular transit condition (ship speed V and loading T) and a specified sea state (wave height H_s and period T_z). 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. Moreover, two these approaches can not account for uncertainty present in these parameters in calculating the response spectrum, and later applying in performance of risk analysis. Hence, there is emerging demand for high quality and continuous description of the response spectrum for the problem at hand. A simple 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 has been currently used in some computer programs, like CHOP (CHannel OPTimization) and HARAP (HARbour APPROach), for optimization of the channel depths. More advanced model was demonstrated by (Cramer & Hansen, 1994). The author proposed a stochastic field model in the modulus squared of the frequency response function, and then by use of the Kriging technique (Lucifredi et al., 2000), to better minimize the variance of the estimate error.

However, there is a significant challenge to formulate a general model for the stochastic field governing the modulus squared of the frequency response function (Cramer & Hansen, 1994). This study is an ongoing effort that deals with this problem applying parametric modeling method, as has been presented in the following sections.

2.1 The wave-ship motion system

For the restricted entrance channels and shallow waterways, wave allowances are regularly not so serious; and since the ship dimensions are usually large enough relative to the wave length (Journee, 2002), ship response problems can be treated with linear models (all directly proportional to wave height). 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 ω_e is the encounter frequency; $|H(\omega_e)|$ is the encounter frequency transfer function as a ratio of ship motion to wave amplitude for a given wave encounter frequency, which depends on ship speed, sailing angle, loading condition and water depth (or underkeel clearance); $S_\eta(\omega_e)$ is 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

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

where V (m/s) is the forward speed of ship; kc (m) is the average instantaneous underkeel clearance; d (m) is the water depth; θ (degree) is the angle between wave direction relative to the ship speed vector ($\theta=0$ for following wave); T (m) is the ship draft depending on loading condition; ω (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 kc as

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

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

The ideal 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 α and β 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 kc , 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 α and β by doing a least square fit, which minimizes the sum of the squares of the deviations of the data from the model as

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

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

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

2.2 Estimating model parameters

Suppose we have sample data of $H(\omega_e)$ at various values V_i and kc_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 $bo(k)_{ji}$, $k=0 \div n$ and the $(M \times N)$ vectors ao each having m parameters $ao(k)_{ji}$, $k=1 \div m$. The parameter ao_{ji} (here we omitted "k" to simplify the notation) can be expressed as a nonlinear p -order polynomial model of kc_j for a given V_i as

$$r_{1,i} kc_j^p + r_{2,i} kc_j^{p-1} + \dots + r_{p,i} kc_j + r_{p+1,i} = ao_{ji} \quad (10)$$

In the matrix form

$$\begin{bmatrix} kc_1^p & kc_1^{p-1} & \dots & kc_1 & 1 \\ kc_2^p & kc_2^{p-1} & \dots & kc_2 & 1 \\ \dots & \dots & \ddots & \dots & \dots \\ kc_N^p & kc_N^{p-1} & \dots & kc_N & 1 \end{bmatrix} \begin{bmatrix} r_{1,i} \\ r_{2,i} \\ \dots \\ r_{p+1,i} \end{bmatrix} = \begin{bmatrix} ao_{1,i} \\ ao_{2,i} \\ \dots \\ ao_{N,i} \end{bmatrix} \quad (11)$$

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

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

here, $kc_{l,j} = kc_j^{p+1-l}$, $l = 1 \div p+1, j = 1 \div N$

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 kc_j for a given value of V_i . Thus, for instance, the equation of r at the p -order of kc is

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

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

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

For all orders of kc in the matrix form

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

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

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 α from Eq (15) with the prediction error given in the Eq (8). In the same way, we can also define β .

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

$$\varepsilon_H(\varpi_e) = \sum_{i=1}^N \sum_{j=1}^M \left[H(\varpi_e | a(\alpha | V_i, kc_j)) - H_0(\varpi_e | ao(V_i, kc_j)) \right]^2 \quad (16)$$

It is clear that the found fit curves in Eqs (10) and (13) may not perfectly, in some cases, approximate the data. We could increase the order (p and q) of the polynomial equations and this leads to increase the sample data and therefore to require a higher computational effort. It, however, does not a problem with the mathematical model programmed in the recent power computer.

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 ε_H in Eq (16) is equivalent to maximizing R in the following

$$R^2 = 1 - \frac{\sum (H_{oi} - H_i)^2}{\sum (H_{oi} - \overline{H_o})^2} \quad (17)$$

where H_{oi} is the sample value of transfer function; and H_i is the regression prediction value; and $\overline{H_o}$ 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:

1. Use either numerical ship motion model or physical model to calculate the transfer functions for the interested 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).

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

3. Define $a(k)$ and $b(k)$ as the functions of V and kc 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 (α and β) to fit the data, $a(k)$ to $ao(k)$ and $b(k)$ to $bo(k)$.

4. Finally, $H(\omega_e)$ will be found at the relatively discrete encounter frequencies using Eq (5), the corresponding ε 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 .

3 GROUNDING MODEL: FIRST-PASSAGE FAILURE

The first-passage failure is an event that a random process $x(t)$ cross a level $x = \beta$ (m) at once during a period T (s). 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-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 $x(t)$ when is a stationary 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 β , if the response $x(t)$ has the Gaussian distribution and zero mean, v_b can be then 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 α . For example, before the ship entrance we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding, α . So let $P(\beta, T) = \alpha$, from Eqs (18) and (19), crossing level for probability of first-passage failure = α can be expressed by (Quy et al., 2006)

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

4 LONG-TERM OPTIMIZATION OF THE CHANNEL DEPTHS

Having determined the model of ship motion response, a computer simulation can therefore be developed. It can be used as a decision support tool for channel performance evaluation and optimization. In general, the procedure of the optimal design process of the channel depth is presented in Figure 1.

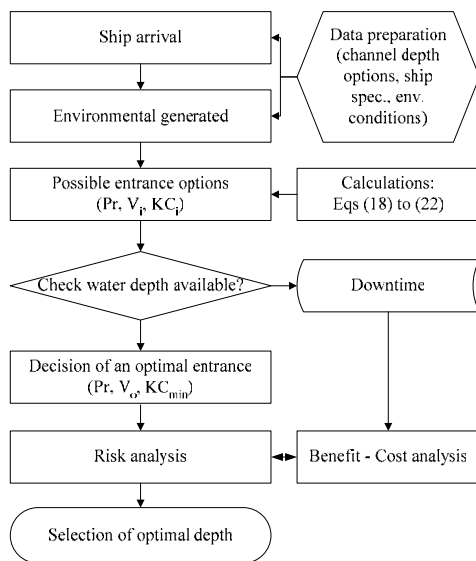


Figure 1: General procedure for optimization of channel depth

As discussed in Section 1, the long-term optimization of channel depths should be considered a two-stage process, consisting of: (1) first, establishing ship entrance guidance to facilitate a required navigation safety with respect to a possibility of touching the channel bed as discussed previously. This step is so-called the short term establishment of admittance policy for safe navigation. (2) Secondly, using the Monte Carlo method and based on the established accessibility policy, a simulation model is developed to define a minimum underkeel clearance allowance and simultaneously determine downtimes that correspond to an acceptable grounding risk for a specified ship and generated wave conditions. The process can be repeated over for a given time period and for all possible alternatives of channel depths. To enable this, a stochastic model of the environmental conditions and ship arrivals on the basis of historical recorded or forecasted data will be set up. The model can account for all uncertainties in the description of the transit conditions and sea states involved in the simulation. The final results derived from the computer model can be considered as the key parameters in analysis and selection of an optimal depth.

5 THE CASE STUDY

5.1 Project description

The entrance channel at Cam Pha Coal Port in the North Sea of Viet Nam is the largest specialized port on serving to export 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 the year 2003, Viet Nam Coal Incorporation has 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 tide up 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 the channel with the length of 7,5km is very shallow (only -7.4m 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 accessibility 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 grounding risk 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.

5.2 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 surface hull:	3487 m ²

To obtain sample data for parametric modeling of the transfer function, a numerical ship motion model, called SEAWAY (Journee, 2001), has been used. The program is frequency-domain ship motion model, based on both the ordinary and modified strip theory, to calculate the wave-induced loads and motions with six degrees of freedom of hull ships. The program has been validated for the motion calculation in a very shallow water area (Marc Vantorre & Journee, 2003). Five values of ship speed ranged from 5knots to 15knots and seven values of water depth, d , with ratios of d/T varied from 1.25 to 1.55 were used in the calculation, making in total 35 transfer functions are calculated. 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 in heading wave; because of the exporting port, the ship leaving with full loaded draft faces to coming waves, a critical point was found at stern from the point of view of bottom touch.

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 wetted cross section area of waterway.

5.3 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.

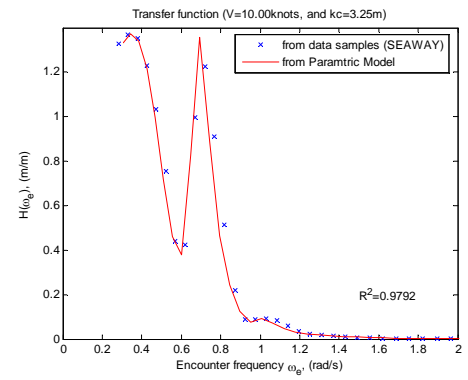


Figure 2: Comparison between the theoretical transfer function calculations (SEAWAY) and the results from the parametric model

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 order. 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.

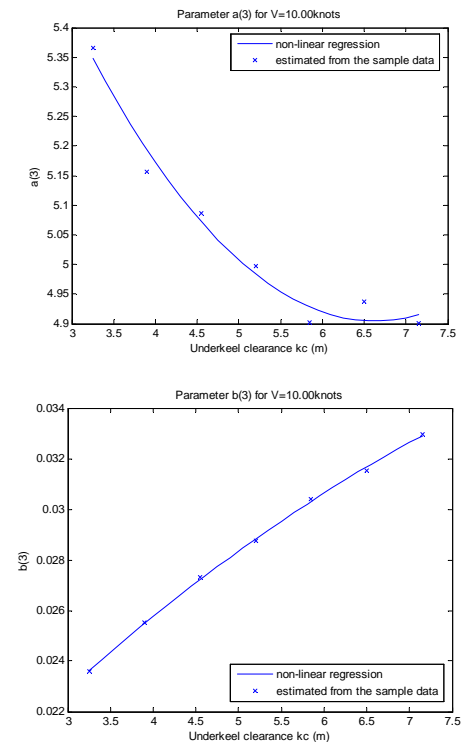


Figure 3: Examples of non-linear regression of parameters a and b

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 for the reason. Many sea states were randomly generated from which five hundreds of response spectra for thirty five transit conditions (five speed classes and seven values of kc) 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 kc and

V or a minimum allowable underkeel clearance with a predefined acceptable grounding risk can be estimated using first-passage failure model given in Eqs (18) and (22) respectively.

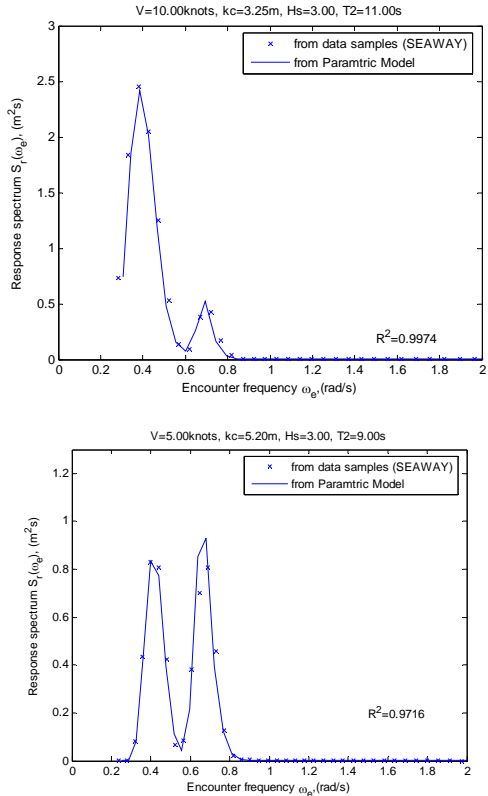


Figure 4: Comparison between the theoretical ship response calculations (SEAWAY) and the results from the parametric model

5.4 Risk analysis

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 differences between them increase quickly with either decreasing slowly in the ratio d/T or increasing in the wave period. However, for small value of the acceptable probability of grounding, let say $\alpha=3 \times 10^{-5}$ (3 per 100,000 ship movements) as an observed value for Northern European Ports (Vrijling, 1995), the results present 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 $\alpha=3 \times 10^{-5}$. In the operation point of view, it is almost impossible for ship navigated in restricted channels with such the case of the wave height.

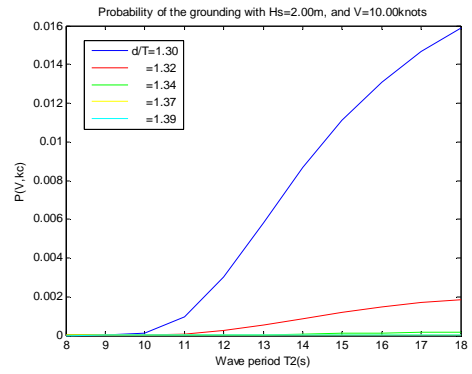


Figure 5: Relationship between probabilities of the grounding and wave periods for different values of d/T (relates to PIANC)

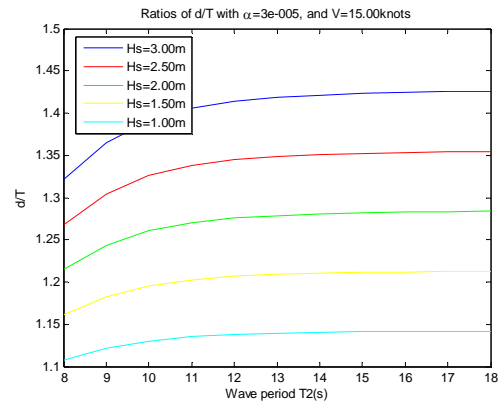


Figure 6: Relationship between ratio of d/T and wave periods for different values of H_s with an acceptable grounding value $\alpha=3 \times 10^{-5}$

Regarding the USACE guideline, considering the ratio of net depth allowance to wave height, the wave period has considerably effective to the results of the grounding risk, as shown in Figure 7. For $\alpha=3 \times 10^{-5}$ and $V=5$ knots, net depth allowance required varies from $0.90H_s$ for the wave period of 8 second to $1.8H_s$ for wave period of 18 second. This requirement is higher with the faster ship speeds and wave periods. With the value of $1.2H_s$ as recommended by USACE for deep-draft channel, the ship speed should be less than 10 knots with the wave periods are lower than 10 second. It is almost not allowable for the higher sea state.

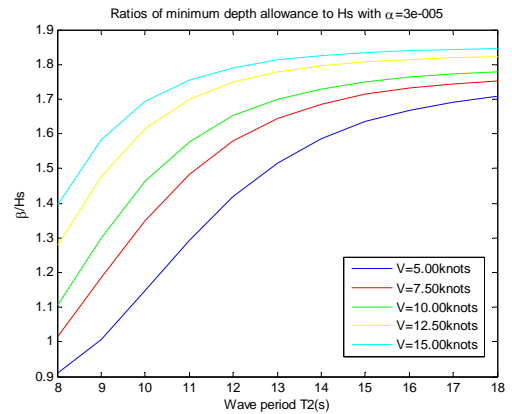


Figure 7: Relationship between ratio of β/H_s and wave periods for different ship speeds with an acceptable grounding value $\alpha=3 \times 10^{-5}$ (relates to USACE)

6 CONCLUSIONS

Parametric modeling of the ship response, 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; simulation-based optimization of channel depths in which all uncertainties involved can be introduced into the simulation; and study behavior of ship structure itself. The model could be applicable for "closer 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; 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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