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A Study on the uncertainty and sensitivity in numerical simulation of parametric roll

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Abstract

Uncertainties related to numerical modelling of parametric roll have been investigated by using a 6-DOFs model with nonlinear damping and roll restoring forces. At first, uncertainty on damping coefficients and its effect on the roll response is evaluated. Secondly, uncertainty due to the "effective (equivalent) wave" concept in calculation of restoring moment is studied. Finally, uncertainty to roll response from different methods of GZ calculation has been checked. It is found that the equivalent wave concept is sufficiently accurate for the purpose of GZ calculation. Two different GZ approximations give a good agreement with direct calculation method if relevant coefficients have been properly found in the fitting.

Keywords

Uncertainty; Sensitivity; nonlinear damping; nonlinear restoring; GZ approximation; 6-DOFs model, Effective (Equivalent) wave;

Introduction

For modern container carriers and car carriers, the parametric roll phenomenon becomes important in design and operational consideration for the safety of life, cargo and the ship. The phenomenon and mechanism of parametric roll are well known in shipping and marine industry thanks to many previous studies. However, there are still reports of serious accidents from parametric roll of container and car carriers. Therefore, there is a need for on-board decision support systems to enhance safety against parametric roll.

Several simulation tools, considering 6-DOFs motions and instantaneous wetted surface in the calculation of wave exciting moments and restoring forces, such as LAMP (France et al., 2003 and Shin et al.,2004), WASIM (Vada,1994) and WISH (Kim and Kim, 2008) can accurately deal with the parametric roll dynamics. However these elaborate tools are inadequate in on-board system because of their large computational time. Therefore a simplified model, which is sufficiently accurate and fast for a probabilistic approach, is necessary.

For the application of on-board system, the numerical framework from Jensen (2007) can be a promising candidate. This framework is composed of a 1.5-DOFs equation of motion supplemented with the first order reliability method (FORM) for probabilistic calculations. Vidic-Perunovic (2009) showed that a reasonably good agreement is obtained between FORM and Monte-Carlo method, and moreover FORM requires by far the shortest computational time which would be very beneficial for application to on-board decision support system. However, for the robustness of the system the accuracy of the numerical model needs to be improved. Therefore, this study focuses on uncertainties in the numerical model and their consequence on the roll response.

It is expected that the major uncertainties come from nonlinear effects associated with the damping and restoring forces. On the other hand, uncertainty from the randomness of waves are excluded from the study, because a deterministic wave form only dependent on the spectral shape of the waves is provided by the FORM calculation (Jensen, 2007).

The study is divided into three parts, 1) Uncertainty to roll response from damping coefficients modeled by a combination of a linear, a quadratic and a cubic variation in the roll velocity. 2) Uncertainty due to the "effective (equivalent) wave" concept - one of the most widely used approximation in calculation of nonlinear restoring moments. 3) Uncertainty to roll response from different methods of GZ calculation.

Equation of ship motion

1.5-DOFs equation of motion in the work by Jensen (2007) is extended to the 6-DOFs equation of motion with impulse response function (IRF) approach formulated by Cummins (1962):

$$
\begin{aligned}
&(M_{jk}+a_{jk}^{\infty})\ddot{x}_k(t)+\int_{-\infty}^{t}K_{jk}(t-\tau)d\tau \\
&=F_{jFK}(t)+F_{jDiff}(t)+F_{jC}(t)+F_{jDamp}(t)+F_{jSpring}(t)
\end{aligned}
\quad (1)
$$

The radiation impulse response function K_{jk} and infinite-frequency added mass a_{jk}^{∞} are calculated from pre-computed hydrodynamic coefficients:

$$
\begin{aligned}
&K_{jk}(t)=\frac{2}{\pi}\int_0^{\infty}b_{jk}(\omega)\cos\omega t d\omega \\
&a_{jk}^{\infty}=a_{jk}(\omega)+\frac{1}{\omega}\int_0^{\infty}K_{jk}(t)\sin\omega t dt
\end{aligned}
\quad (2)
$$

where $a_{jk}(\omega)$ and $b_{jk}(\omega)$ are the added mass and damping coefficients, respectively.

The viscous damping F_{jDamp} is modeled as:

$$F_{jDamp}(t) = -2\beta_1\omega_n\dot{\xi}_4 - \beta_2|\dot{\xi}_4|\dot{\xi}_4 - \beta_3\frac{\dot{\xi}_4^3}{\omega_n} \tag{3}$$

where β_1, β_2 and β_3 are non-dimensional damping coefficients, and ω_n is the roll natural frequency which can be taken from the (linearized) frequency domain solution.

Empirical soft spring forces $F_{jSpring}$ are applied for surge, sway and yaw.

Except for the roll mode, the wave exciting forces, F_{jFK} and F_{jDiff} , and the restoring forces, F_{jC} are calculated assuming linearity by the converted IRF from the frequency domain responses and linear restoring coefficients. In the roll mode, the nonlinear excitation is considered by using three different methods: 1) A direct calculation where the pressure on the exact wetted surface is integrated by considering the actual wave elevation and 6-DOFs motions; 2) and 3) Two simplified methods (introduced in later sections).

Uncertainty of the damping coefficients

Uncertainty and sensitivity analysis for damping coefficients have been made to provide useful information for improving robustness of the system. Generally the roll damping coefficients in the numerical calculation are determined from free roll decay tests and used as deterministic values. However, those values might have some degree of uncertainty because of the process of measuring and evaluation. Therefore the uncertainty in roll response from the damping coefficients should be checked if the quantitative characteristics of parametric roll are of interest.

Some useful information about the errors might be provided also from the free roll decay tests. However, in this study, arbitrary errors introduced in a statistical sense are given in the damping coefficients to check the effect on the roll angle. Monte-Carlo simulation with Eq.1~3 is performed for a panamax containership as given in Jensen (2007). The Latin Hypercube Sampling described by McKay and Beckman (1979) is used and it is assumed that the input uncertainty follows a normal distribution without correlation among input parameters. The mean values are taken from Bulian (2005) and standard deviation is chosen as 5% of the mean value. The input parameters are presented in Table 1 and the sampling result is shown in Fig. 1.

The result of the Monte-Carlo simulation is presented in Fig. 2. A regular wave is chosen with the encounter frequency close to twice the roll frequency so that parametric roll easily can occur. To study the uncertainty, maximum roll angles, y, at one particular instant within the steady state period, are selected as output of the system. Then the complete representation of the uncertainty in y is possible using the Cumulative Distribution Function (CDF), which provides the probability that Y is less than or equal to y:

$$F(y) = P(Y \leq y) \tag{4}$$

In this study, the empirical CDF is estimated and shown in Fig. 3 using Kaplan-Meier method from a commercial software package (MATLAB 2014a). Mean values and the 95 percent confidence interval of the roll responses are plotted in Fig. 4. The standard deviation of roll amplitude in the steady state is calculated as 0.0097rad (0.56deg), and the 95 percent confidence interval is calculated as 0.0372rad (2.13deg).

Scatter plots in Fig. 5 provide a visual description of the trend of outputs, y, with respect to sampled parameters. A clear correlation was found between roll response and β_2 which means that the β_2 has the highest impact on the maximum roll angle for this example.

Table 1: Input for sampling

parameter	Mean	Std.
β_1	0.0120	0.0006
β_2	0.4000	0.0200
β_3	0.4200	0.0210

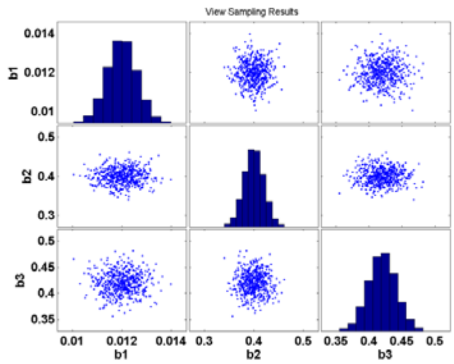

Fig. 1: Latin Hypercube Sampling for damping coefficients (number of sample: 500)

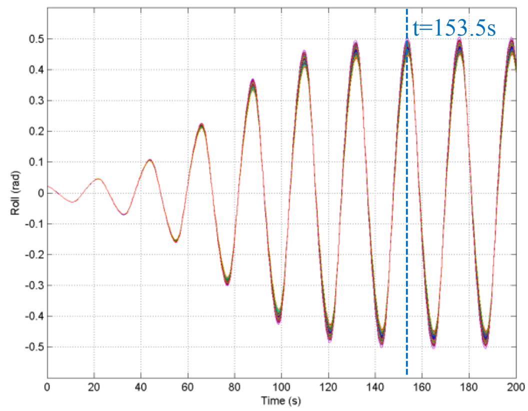

Fig. 2 Result of M-C simulation with uncertainty of damping coefficients ($\omega_e \approx 2\omega_n$, a/L=0.015)

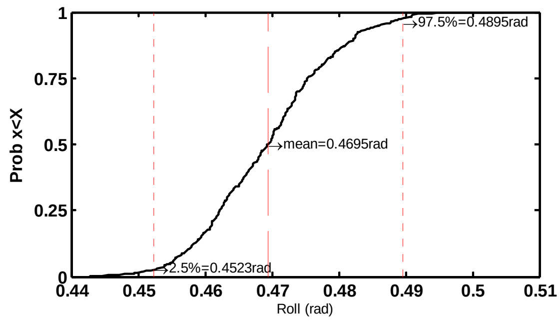

Fig. 3 Empirical CDF from the output y at t=153.5s

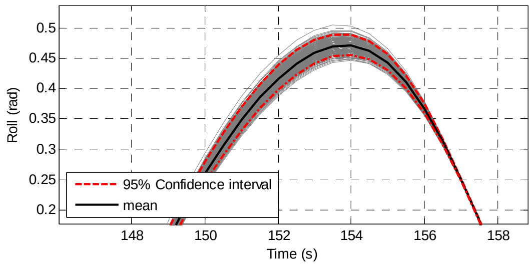

Fig. 4 Mean and 95% confidence interval of the roll response (zoomed in near the maximum peak)

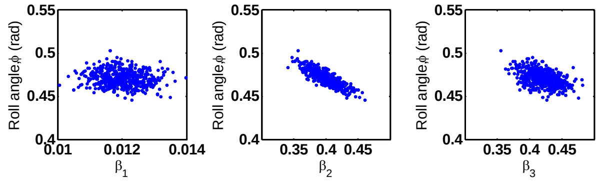

Fig. 5: Sensitivity visualization of three parameters

Wave approximation

The Improved Grim effective wave, Bulian (2008), and a similar concept called the equivalent wave procedure from Kroeger (1986) are widely used in numerical studies of parametric roll in irregular waves because of their simplicity and efficiency in the calculation of roll restoring moment. In both methods, the irregular sea surface is approximated as a regular wave which has one effective wave length, but varying wave height and crest position. This enables the instantaneous restoring moment in roll to be obtained in a simpler way; for example, from either a polynomial expression with fitted coefficients, or interpolation from direct calculation.

To help the choice between the two different approaches and also to check their implications on the uncertainty to the GZ calculation, sample calculations are performed for three different wave expressions, 1) actual wave surface, 2) Improved Grim effective wave (IGEW) and 3) Equivalent wave procedure (Equiv.). A large container vessel with a modern hull design given in Choi et al. (2013) is selected for the calculation (length L=350m, breadth B=48.2m, draft T=14.5m, speed V=8.4 m/s). Stationary sea conditions are assumed and specified by a JONSWAP wave spectrum. Sea states 6 and 7 in the North Atlantic seas are selected as wave conditions, with mean wave lengths equal to the ship length *0.68L* and L, respectively.

Table 2: Wave conditions

Sea state	H_s (m)	T_p (s)	T_z (s)
6	5.0	12.4	8.79
7	7.5	15.0	10.64

The actual wave surface, $Z_{actual}(x,t)$ for the stationary stochastic long-crested wave is expressed as:

$$Z_{actual}(x,t) = \sum_{i=1}^{n} h_i(\omega_i, x, t) \qquad (5)$$

$$\begin{cases} h_i(\omega_i, x, t) = a_i\{u_i \cos(k_i x - \omega_{e,i} t) + \bar{u}_i \sin(k_i x - \omega_{e,i} t)\} \\ a_i = \sqrt{S(\omega_i) d\omega_i} \end{cases} \qquad (6)$$

where $S(\omega)$ is the wave spectrum as function of wave frequency ω, and $u_i, \bar{u}_i$ are statistical independent and standard normal distributed variables.

The Improved Grim effective wave, Bulian (2008), is given by the expressions:

$$Z_{eff}(x,t) = \eta_c(t)\cos\left(\frac{2\pi}{L_e}x\right) + \eta_s(t)\sin\left(\frac{2\pi}{L_e}x\right) \qquad (4)$$

$$\begin{cases} \eta_c(t) = \sum_{i=1}^{n} a_i c_i f_C(k_i)\cos(\omega_{e,i}t + \sigma_i) \\ \eta_s(t) = \sum_{i=1}^{n} a_i c_i f_S(k_i)\sin(\omega_{e,i}t + \sigma_i) \\ f_C(k_i) = 2\frac{Q\sin Q}{\pi^2 - Q^2}, f_S(k_i) = 2\frac{\pi \sin Q}{\pi^2 - Q^2} \\ Q = \frac{\omega_n^2 L_e}{2g}\cos\beta, c_i = \sqrt{S(\omega_i)d\omega_i} \\ a_i = \sqrt{u_i^2 + \bar{u}_i^2}, \sigma_i = \tan^{-1}(u_i / \bar{u}_i) \end{cases} \qquad (5)$$

where k_i is the wave number. It is noted that the fluctuating mean value $a(t)$ in the original work of Bulian is neglected.

On the other hand, the Equivalent wave, Kroeger (1986), is calculated according to:

$$Z_{equiv}(h(t), x_c) = \frac{h(t)}{2}\cos\left(\frac{2\pi}{L_e}(x_c - x)\right) \qquad (6)$$

$$\begin{cases} a(t) = \frac{2}{L_e}\int_0^{L_e} H(X(x,t),t)\cos\left(\frac{2\pi}{L_e}x\right)dx \\ b(t) = \frac{2}{L_e}\int_0^{L_e} H(X(x,t),t)\sin\left(\frac{2\pi}{L_e}x\right)dx \\ X(x,t) = (x + Vt)\cos\beta \\ h(t) = 2\sqrt{a^2(t) + b^2(t)} \\ x_c(t) = \begin{cases} \frac{L_e}{2\pi}\cos^{-1}\left(\frac{2a(t)}{h(t)}\right) & \text{if } b(t) \geq 0 \\ L_e - \frac{L_e}{2\pi}\cos^{-1}\left(\frac{2a(t)}{h(t)}\right) & \text{if } b(t) < 0 \end{cases} \end{cases} \qquad (7)$$

where the wave crest position x_c is measured relative to the aft end of the vessel. In both approaches, the effective wave length L_e is chosen to be the ship's length L.

The calculated wave surfaces are first visualized in Fig. 6 and Fig. 7 for sea state 7. As shown in the figures, the differences from the approximations are negligible and successfully follow the overall shape of the actual wave surface retaining a regular wave form, except that the short waves, which are far from the selected L_e, are filtered out.

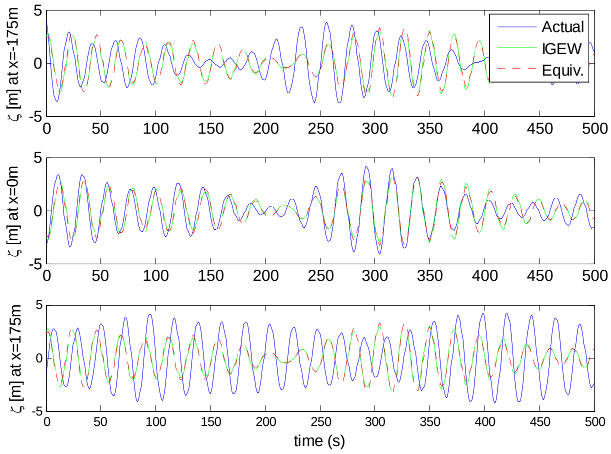

Fig. 6: Time histories of wave elevation at three different position (F_n=0.0495, H_s=7.5m, T_z=10.64s, following seas)

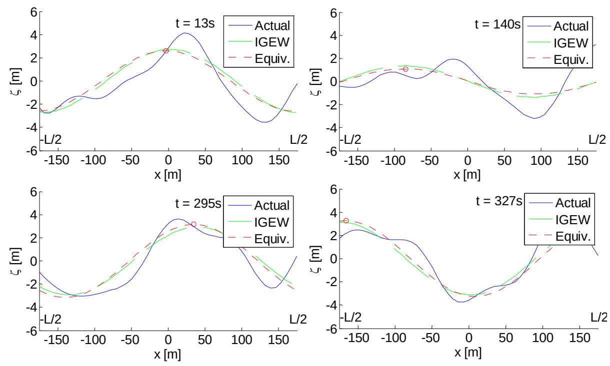

Fig. 7: Examples of instantaneous wave surface along the vessel (F_n=0.0495, H_s=7.5m, T_z=10.64s, following seas)

The nonlinear restoring moments and roll responses for the three different wave expressions are calculated. The restoring moments are obtained from pressure integration on the actual wetted surface considering 6-DOFs ship motions.

The calculated restoring moment and corresponding roll response for sea state 7 are presented in Fig. 8. It is seen that, only around t=400s, the roll restoring moments from the effective wave approximations are underestimated. Except for this particular deviation, the results from the approximations are in good agreement with the results based on the actual wave profile. Table 3 summarizes the statistics for the same wave condition but with an increased time window of 3,000 seconds. Differences in statistics for the roll motion are not significant and, as expected from the comparison of wave profile, the different wave approximations give almost the same results.

Another calculation has been done for sea state 6 to check if the approximations are reasonable for a wave condition which has a smaller mean wave length (λ≈0.68L for sea state 6 in Table 2). Fig. 9 compares the results obtained from the different wave expressions. Although there is some discrepancy at t=800~900s, there is a good match along the actual wave surface and the two different wave approximations.

The statistical results in Table 4 show that the error level is slightly increased compared with the case for sea state 7, but still in the acceptable level as the absolute values of error are less than 1.0 degrees.

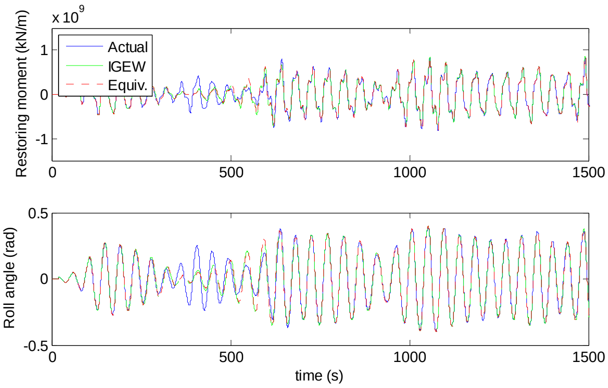

Fig. 8: Computed roll restoring moment and roll response (F_n=0.0495, H_s=7.5m, T_z=10.64s, JONSWAP spectrum, following seas)

Table 3: Statistical results of roll response (Fn=0.0495, Hs=7.5m, Tz=10.64s, JONSWAP spectrum, following seas, duration: 3,000s)

Roll (rad)	*Actual wave*	*IGEW*	*Equiv.*
RMS	0.2207	0.2238 *(1.4%)*	0.2239 *(1.4%)*
Maximum	0.4265	0.4266 *(0.0%)*	0.4266 *(0.0%)*
Minimum	-0.4301	-0.4382 *(1.9%)*	-0.4385 *(2.0%)*

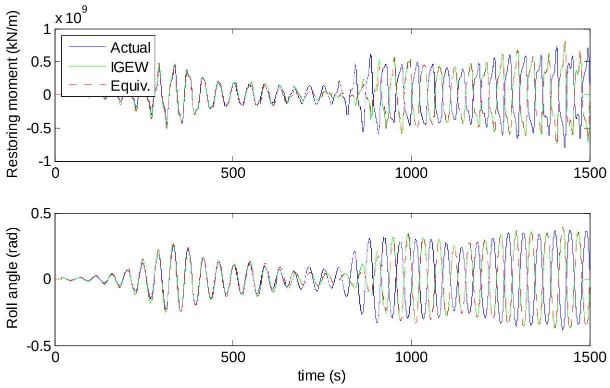

Fig. 9: Computed roll restoring moment and roll response (Fn=0.0495, Hs=5.0m, Tz=8.79s, JONSWAP spectrum, following seas)

Table 4: Statistical results of roll response (Fn=0.0495, Hs=5.0m, Tz=8.79s, JONSWAP spectrum, following seas, duration: 3,000s)

Roll (rad)	*Actual wave*	*IGEW*	*Equiv.*
RMS	0.1697	0.1754 *(3.4%)*	0.1745 *(2.8%)*
Maximum	0.3716	0.3917 *(5.4%)*	0.3896 *(4.8%)*
Minimum	-0.3873	-0.3760 *(-2.9%)*	-0.3784 *(-2.3%)*

GZ approximation

In this section, the consequence related to uncertainty from the GZ calculation is dealt with. For the GZ calculation, two different simplified methods are selected. The first method, (A), is similar to that by Jensen (2007), while the second method, (B), resembles that by Lee (2016).

GZ approximation method (A)

In the first method, similar to that by Jensen (2007), the GZ curve is approximated as a function of the roll angle, the wave amplitude and the wave crest position along the ship:

$$GZ(\phi,t) = GZ_{sw}(\phi) + \frac{h(t)}{0.05L}\left(GZ(\phi,x_c(t)) - GZ_{sw}(\phi)\right) \quad (8)$$

where $h(t)$ is the instantaneous wave height calculated from the equivalent wave procedure, which was validated in the previous section.

GZ_{sw} is the GZ curve in still water, and it is calculated either by interpolation from measurements data or in analytic form using:

$$GZ_{sw}(\phi) = A_0\sin\phi + A_1\phi + A_3\phi^3 + A_5\phi^5 \quad (9)$$

The instantaneous GZ in a regular wave with amplitude 0.05L wave is estimated from the empirical approximation:

$$GZ(\phi,x_c(t)) = \left(C_0\sin\phi + C_1\phi + C_3\phi^3 + C_5\phi^5\right)\cos^4\left(\frac{\pi x_c}{L_e}\right) + \left(D_0\sin\phi + D_1\phi + D_3\phi^3 + D_5\phi^5\right)\sin\left(\frac{\pi x_c}{L_e}\right) \quad (10)$$

The coefficients (C_0, C_1, C_3,C_5,D_0,D_1,D_3,D_5 and L_e) have been found by the least square method with the data obtained from direct calculation for a regular wave for different crest positions x_c, with a wave length equal to the length L of the ship and a wave height equal to 0.05L. Eq. 8 then assumes a linear variation of GZ with wave amplitude.

The same container vessel as used in the previous section is considered. It was found that negative values of GZ are obtained when the wave crest is located amidships (x_c=L/2) for this modern hull form, because the center of gravity KG is high while BM has small value with the minimum waterplane area (GM=KB+BM-KG), see Fig. 10.

In this approach four GZ curves (crest locations at AP, AP+L/4, AP+L/2, AP+3L/4 and FP) should be fitted by using one analytic approximation, therefore any dependent output, such as the roll response, inherently will have uncertainties. On the other hand, if the GZ curves at x_c=0 and x_c=L/2 (the maximum and minimum case which are crucial for this phenomenon) are well-fitted, the model gives satisfactory agreement with the direct calculation (Vidic-Perunovic, 2011). However, for this sample calculation, the negative GZ curves increase the uncertainty as can be seen from Fig. 11.

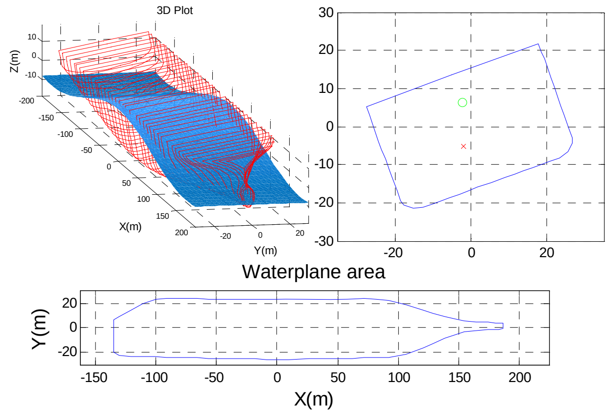

Fig. 10 An example of the case for unstable condition with negative GZ (h=0.05L, x_c=L/2, ϕ=5deg)

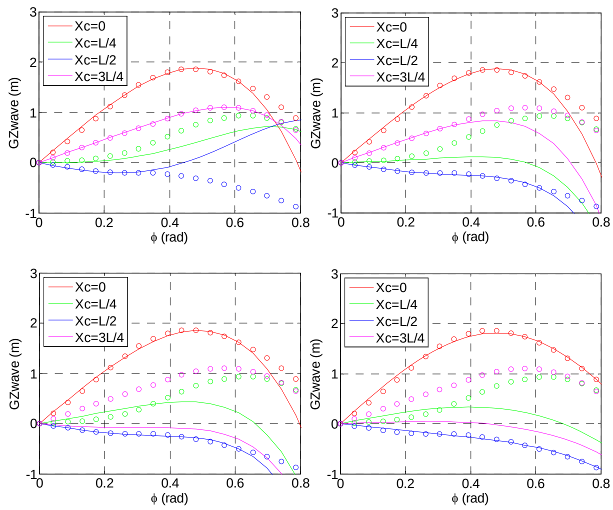

Fig. 11 Uncertainties in GZ curves with h=0.05L≈15m (symbol 'o' represents the results from direct pressure integration) - a) fitting with four different x_c, b) fitting with x_c at 0, L/2 and 3L/4, c) fitting with x_c at 0, L/4 and L/2, d) fitting with x_c at 0 and L/2

From the previous section the maximum roll angle was found as 0.43 rad for sea state 7 (See Table 3). Therefore, among the four different cases (a-d) in Fig. 11, the first case was selected as the best one considering only roll angle up to 0.43 rad.

For the time domain simulation, the Froude-Krylov and the restoring moments in the roll mode, F_{4FK} and F_{4C} in the Eq.1 are substituted by Eq.8. The result from the time domain simulation is presented in Fig. 12. There is a significant difference in restoring moment between the case of GZ approximation and the direct calculation of GZ. The fitting with roll angle might not be the reason for this because it was satisfactory in the range of roll angle up to 0.43 rad. A more plausible reason might be that the wave height of 5 percent of the ship length (h=0.05L≈15m) used in this approximation is much higher than the significant wave height used in the time domain simulation (H_s=7.5m). If h=0.05L is used in the calculation of GZ curves and in Eq. 8, the nonlinearity from hull shape can be very severe as shown in Fig. 10. However, as the present condition does not lead to so high wave heights, a significant uncertainty may arise from the excessive nonlinear effect. Therefore it is suggested that the wave amplitude should not be fixed as h=0.05L but determined according to a significant wave height of the target wave condition.

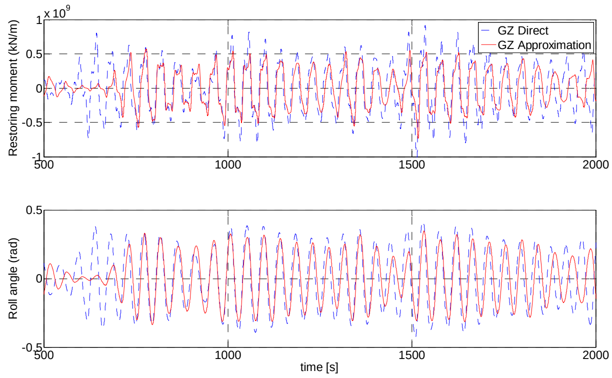

Fig. 12: Calculated restoring moment and roll angle from GZ approximation with h=0.05L (F_n=0.0495, H_s=7.5m, T_z=10.64s, following seas)

In order to verify this presumption, the wave height in the direct calculation is modified to h=0.02L=7m which is nearly similar to a significant wave height of 7.5m. It is noted that the denominator in the second term in Eq. 8 is also modified as 0.02L.

The coefficients in Eq.10 are updated and the result is shown in Fig. 13. The GZ curve for x_c=L/2 still has the negative values in some range, but the new result is much improved compared with the previous one.

The updated results from time domain simulation are shown in Fig. 14. Interestingly, a good agreement with the result from direct calculation is now obtained both in the restoring moment and roll response. It is seen that an unexpected phase-change occasionally happens, e.g. around t=1,500s. The reason for this is not clear and may be due to the uncertainty from the GZ approximation. Table 5 shows that the agreement in the statistical characteristics of roll motion between the direct method and the approximation with h=0.02m is quite acceptable.

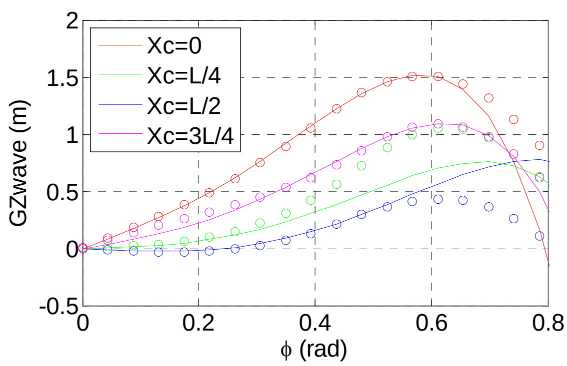

Fig. 13: Approximated GZ curves with h=0.02L≈7m

GZ approximation method (B)

The second method of GZ calculation applied in this study is suggested by Lee (2016):

$$GZ(\phi,t) = GZ_{sw}(\phi) + \frac{GM(t) - GM_{sw}}{GM_{sw}} f(\phi) \qquad (11)$$

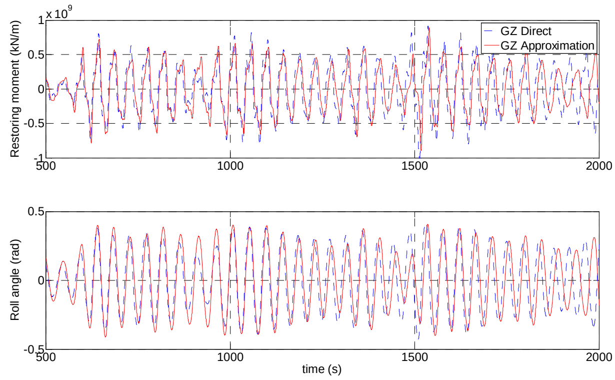

Fig. 14 Calculated restoring moment and roll angle from GZ approximation with h=0.02L (F_n=0.0495, H_s=7.5m, T_z=10.64s, following seas)

Table 5: Comparison of statistical results of roll angle for different wave amplitude in GZ curve fitting (H_S=7.5m, T_Z=10.64s, duration: 3000s)

Method	GZ_{direct}	$GZ_{approx.}$ (h=0.05L)	$GZ_{approx.}$ (h=0.02L)
RMS roll (rad)	0.2066	0.1621	0.2034
Max. roll (rad)	0.4181	0.3310	0.4053
Min. roll (rad)	-0.4301	-0.3151	-0.3945

where $f(\phi)$ is the GZ factor function expressed as:

$$f(\phi) = GM_{sw}\left(\sin(\phi) - \frac{\sin^{\alpha}(\phi)}{\sin^{\alpha-1}(\phi_{\max})}\right) \qquad (12)$$

The advantage of this model is that the factor α can be adjusted to represent nonlinearity in the shape of GZ curves and it has been shown that the results from this model are promising compared with the method of Belenky and Umeda, see IMO SLF (2010). In the present study, α is determined to be 6.0 from a global optimization method by using the results from direct calculation shown in Fig. 13. The obtained GZ curves from the approximation are presented in Fig. 15. The optimization focused on the range 0.0~0.5 rad of roll angles. The calculated curves seem in fair agreement with data from the direct calculation.

The calculated time histories for restoring moment and roll angle are shown in Fig. 16. As it can be seen in the restoring moment, the improvement is obvious in the details of shape and the phase-change. The reason for this is that the $GM(t)$ in Eq. 11 is directly calculated for the instantaneous wave elevation, while in Eq. 8, GZ is assumed to have a linear variation with the wave elevation. If the $GM(t)$ is approximated, in some way, the accuracy should be checked as it may play a major role in the total consequence due to uncertainty in the model. It is noted that the uncertainty from approximating GM is not dealt with in this study, and further research should be undertaken where associated results/effects of several models, e.g., a fluctuation of GM by linear transfer function introduced by Song et al. (2013), are considered.

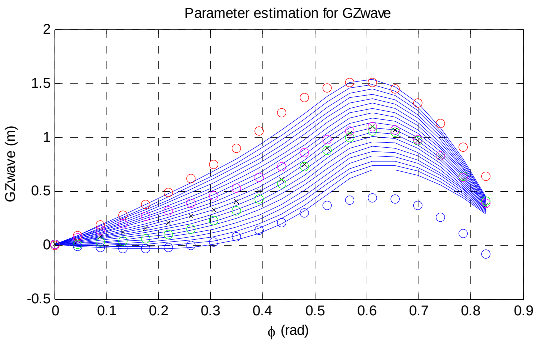

Fig. 15 Calculated GZ curves from the second GZ approximation (for h=0.02L, α=6.0)

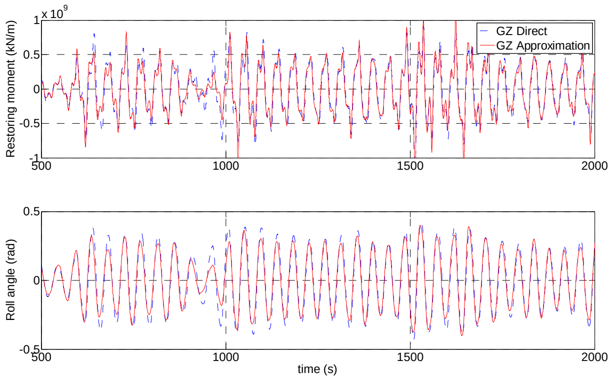

Fig. 16 Calculated restoring moment and roll angle from the second GZ approximation (h=0.02L, F_n=0.0495, H_s=7.5m, T_z=10.64s, following seas)

Conclusions

This study has investigated the phenomenon of parametric roll and, specifically, the consequence of uncertainties in the input data and governing conditions of the numerical model has been studied. The purpose of the study is to a large extent related to on-board decision support systems, where a computational efficient framework, such as that considered by Jensen (2007), is required. In contrast to the 1.5-DOFs equation of motion studied by Jensen (2007), the present study considers an extended variant with all 6-DOFs to better quantitatively evaluate the effect of the introduced uncertainties.

The 6-DOFs equation of motion with an IRF approach is selected as the governing equation, and a nonlinear model is applied for the roll damping and roll restoring moment. The uncertainty and sensitivity from damping coefficients are evaluated by using Monte-Carlo simulation. The uncertainty from the effective (equivalent) wave concept to the roll restoring moment and roll response is checked by comparison with the results from the actual wave profile. Finally, simplified GZ calculation procedures are applied, and associated uncertainties are investigated.

The results of uncertainty of and sensitivity to damping coefficients might provide useful information for the robustness of an on-board system. Based on experimental data, the measured errors from free roll decay tests should be used in the sampling of Monte-Carlo simulation. It is found that the effective (equivalent) wave concept is sufficiently accurate in the calculation of nonlinear restoring moment and the difference between two simplified methods ("IGEW" and "Equiv.") is negligible. Similarly, two different GZ approximations give acceptable agreement with the results from a direct calculation. It is suggested that the ratio of wave amplitude to length, a/L, in the fitting procedure should be selected according to the actual wave conditions, otherwise the ration may cause a significant uncertainty.

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