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A genetic algorithms optimization framework of a parametric shipshape FPSO hull design

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Abstract. An optimization framework has been established and applied to a shipshape parametric FPSO hull design. A single point moored (SPM) shipshape floating system suffers a significant level of the roll motion in both the wave frequencies and low wave frequencies, which presents a coupling effect with the horizontal weathervane motion. To guarantee the security of the operating instruments installed onboard, a parametric hull design of an FPSO has been optimized with improved hydrodynamics performance. With the optimized parameters of the various hull stations' longitudinal locations, the optimization through Genetic Algorithms (GAs) has been proven to provide a significantly reduced level of the 1st-order and 2nd-order roll motion. This work presents a meaningful framework as a reference in the process of an SPM shipshape floating system's design.

Keywords: 2nd-order wave loads; FPSO; genetic algorithms; optimization

1. Introduction

An SPM floating system is designed to operate in the target areas for a long time and may encounter harsh sea states that have a significant influence on the platform's hydrodynamic performance. The slowly varying oscillations of an SPM system, also known as the fishtailing effect can not only affect the station-keeping ability of the mooring system, but also substantially influence the floating system's motion responses (Pinkster 1975, Paton *et al*. 2006, Munipalli *et al.* 2007, Zhao *et al.* 2011). It has been found that the roll motion of an SPM floating system in irregular waves presents both the wave frequency component and the slow drift component, which is coupled with the horizontal fishtailing effect (Zhao *et al.* 2013). In this scenario, the roll motion that exhibits a nonlinear behavior due to the softening stiffness and viscous damping is of great concern in offshore engineering (Somayajula and Falzarano 2017, Falzarano *et al.* 2015).

An advanced system identification technique has been applied to extract the frequency dependent roll damping from a series of model tests in irregular waves and found to accurately predict the ships roll motion (Somayajula and Falzarano 2017). When the difference wave frequencies approach the roll natural frequency, the floating structure will experience a significant 2nd-order roll motion. To numerically evaluate the 2nd-order wave loads with difference wave frequencies, Newman's approximation (Newman 1974) has been widely applied by using the mean drift wave loads. A time

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domain simulation methodology has been established considering the 2nd-order difference frequency wave loads through different forms of Newman's approximation, to numerically simulate the 2nd-order roll motion of a FPSO in irregular waves (Somayajula and Falzarano 2017). It has been found that these forms of Newman approximation result in similar results in deep water. While numerically evaluating the 2nd-order wave loads with difference frequencies in bi-chromatic waves through the direct pressure integral method, Pinkster's approximation (Pinkster 1980) was proposed to approximate the contribution of the 2nd-order wave potential by using the 1st-order wave exciting loads and shown its efficiency and efficacy in the conditions of deep water, perfect reflection, off-diagonal QTF elements that are close to the diagonals. In the previous research (Xie *et al.* 2019), a full expression of the 2nd-order wave loads was derived and the full quadratic transfer function (QTF) of a vertical cylinder was numerically calculated, through Pinkster's approximation (Pinkster, 1980). A complete evaluation of the 2nd-order QTF including the 2nd-order wave potential have also been conducted (Faltinsen and Løken 1979, Kim and Yue 1991). The numerically obtained QTF along with the incident irregular wave spectra, namely, the 2nd-order slow drift loads, presents the potential level of the floating system's 2nd-order slow drift motion. With the numerical tool of evaluating an SPM floating system's hydrodynamics response, it is possible to establish an optimization framework during the phase of parametric hull design, to minimize or suppress the level of the 1st-order and 2nd-order roll motion.

Design optimization consists of the free variables that describe the design alternatives, the objective functions or metrics of the current design alternative to be minimized or maximized and the constraints to be satisfied during the optimization process (Papalambros *et al.* 2000). Genetic Algorithms (GAs), developed by John Holland (Holland 1973, Holland 1984) keep the balance between the efficiency and efficacy and are theoretically and empirically proven to provide robustness, due to its direct use of coding, search from a population, blindness to auxiliary information and randomized operators (Goldberg 1989), compared with other traditional optimization methods such as the enumerative methods (Bellman 1961).

In the previous research, optimizations have been studied and applied to automated hull, to develop various systems (Clauss *et al.* 1996, Birk *et al.* 2001, Guha *et al.* 2016). By simulated annealing (SA) method, a Semi-Submersible hull form has been optimized with multi-objective functions (Park *et al*. 2015). Hydrodynamics performances of different Semi-Submersible hull forms have been estimated through Neural network prediction method and Inverse Multi-Quadric radial basis function during the optimization process, to suppress the heave motion and the total weight (Qiu *et al.* 2019). In this research, GAs have been applied to establish an optimization framework towards a shipshape parametric FPSO hull design with suppressed the roll motion including both the 1st-order and 2nd-order hydrodynamics quantities, through the direct pressure integral. Compared with the prototype's hydrodynamics performance, this optimization framework shows its efficacy in suppressing the level of the 1st-order and 2nd-order roll motion.

2. The second-order wave loads

A full expression of the 2nd-order wave loads was derived through the 1st-order quantities in the previous research (Guha and Falzarano 2015, Liu and Falzarano 2017, Xie *et al.* 2019)

$$\boldsymbol{F}^{(2)} = \boldsymbol{\alpha}^{(1)} \times \boldsymbol{F}^{(1)} + \iint_{S_M} \frac{1}{2}\rho \boldsymbol{\nabla}\Phi^{(1)}.\boldsymbol{\nabla}\Phi^{(1)}\boldsymbol{n}'dl + \iint_{S_M} (\frac{\partial}{\partial t}\rho\boldsymbol{\nabla}\Phi^{(1)}).(\boldsymbol{\eta}^{(1)} + \boldsymbol{\alpha}^{(1)} \times \boldsymbol{X}')\boldsymbol{n}'dS$$

$$
\begin{aligned}
&+\ \rho g[-x_{cf}A_{wp}\eta_4^{(1)}\eta_6^{(1)} - y_{cf}A_{wp}\eta_5^{(1)}\eta_6^{(1)} - \frac{1}{2}z_0A_{wp}(\eta_4^{(1)^2} + \eta_5^{(1)^2})]\boldsymbol{k} \\
&-\frac{1}{2}\rho g \int_{WL} \zeta_r^{(1)^2} \frac{\boldsymbol{n}'}{\sqrt{1 - n_3'^2}} dl \\
&+ \iint_{S_M} \rho \frac{\partial \Phi^{(2)}}{\partial t} \boldsymbol{n}' dS + \rho g(-A_{wp}\eta_3^{(2)} - y_f A_{wp}\eta_4^{(2)} + x_f A_{wp}\eta_5^{(2)})\boldsymbol{k}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\boldsymbol{M}^{(2)} \;=\;& \boldsymbol{\alpha}^{(1)} \times \boldsymbol{M}^{(1)} + \boldsymbol{\eta}^{(1)} \times \boldsymbol{F}^{(1)} - \frac{1}{2}\rho g \int_{WL} \zeta_r^{(1)^2} (\boldsymbol{X}' \times \boldsymbol{n}')\, dl \\
&+ \iint_{S_M} [(\frac{\partial}{\partial t}\rho \boldsymbol{\nabla}\Phi^{(1)}).(\boldsymbol{\eta}^{(1)} + \boldsymbol{\alpha}^{(1)} \times \boldsymbol{X}')](\boldsymbol{X}' \times \boldsymbol{n}')dS \\
&-\rho g[I_{XY}^{A}\eta_4^{(1)}\eta_6^{(1)} + I_{YY}^{A}\eta_5^{(1)}\eta_6^{(1)} + \forall z_{CB}\eta_5^{(1)}\eta_6^{(1)} + \frac{1}{2}\forall y_{CB}(\eta_4^{(1)^2} - \eta_6^{(1)^2}) \\
&+\frac{1}{2}y_{cf}z_0A_{wp}(\eta_4^{(1)^2} + \eta_5^{(1)^2}) - \forall x_{CB}\eta_4^{(1)}\eta_5^{(1)} + \forall \eta_1^{(1)}\eta_6^{(1)}]\boldsymbol{i} \\
&-\rho g[-I_{XY}^{A}\eta_5^{(1)}\eta_6^{(1)} - I_{XX}^{A}\eta_4^{(1)}\eta_6^{(1)} - \forall z_{CB}\eta_4^{(1)}\eta_6^{(1)} + \frac{1}{2}\forall x_{CB}(\eta_6^{(1)^2} - \eta_5^{(1)^2}) \\
&-\frac{1}{2}x_{cf}z_0A_{wp}(\eta_4^{(1)^2} + \eta_5^{(1)^2}) + \forall \eta_2^{(1)}\eta_6^{(1)}]\boldsymbol{j} \\
&-\rho g \forall [y_{CB}\eta_4^{(1)}\eta_6^{(1)} - x_{CB}\eta_5^{(1)}\eta_6^{(1)} - \eta_1^{(1)}\eta_4^{(1)} - \eta_2^{(1)}\eta_5^{(1)}]\boldsymbol{k} \\
&+ \iint_{S_B} \rho \frac{\partial \Phi^{(2)}}{\partial t}(\boldsymbol{X}' \times \boldsymbol{n}')dS + \rho g[\forall \eta_2^{(2)} - A_{wp}y_{cf}\eta_3^{(2)} - (I_{YY}^{A} + \forall z_{CB})\eta_4^{(2)} + I_{XY}^{A}\eta_5^{(2)} \\
&+\forall x_{CB}\eta_6^{(2)}]\boldsymbol{i} + \rho g[-\forall \eta_1^{(2)} + A_{wp}x_{cf}\eta_3^{(2)} - (I_{XX}^{A} + \forall z_{CB})\eta_5^{(2)} + I_{XY}^{A}\eta_4^{(2)} + \forall y_{CB}\eta_6^{(2)}]\boldsymbol{j}
\end{aligned} \tag{2}
$$

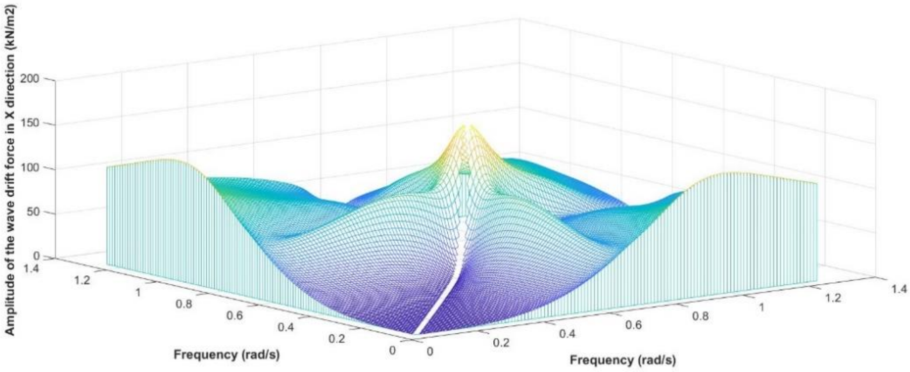
The full QTF of a vertical cylinder has been numerically evaluated in Fig. 1, according to the derived full expression of the 2nd-order wave loads (Xie *et al*. 2019). The diameter of the vertical cylinder is 40 meters and its draft is 10 meters. The center of the gravity is 5 meters above the equilibrium free surface. The incident wave direction in this numerical evaluation is 180 deg and the water depth is 1500 meters.

The principal diagonal elements in the full QTF matrix are the mean wave load coefficients with zero difference wave frequencies in bi-chromatic waves. The off-diagonal elements are the wave drift load amplitudes with difference wave frequencies. To numerically evaluate the off-diagonal elements in the full QTF matrix, one approximation method that has been widely applied is Newman's approximation (Newman 1974). Newman's approximation and several following modified approximations' (Molin 2002, Chen and Duan 2007) basic assumption is that the difference wave frequency is relatively low, leaving the off-diagonal elements geometrically close to the principal diagonal line in the full QTF matrix. Therefore, the off-diagonal elements with interest can be approximated directly with the mean wave load coefficients. Variants of Newman's approximation can be presented as

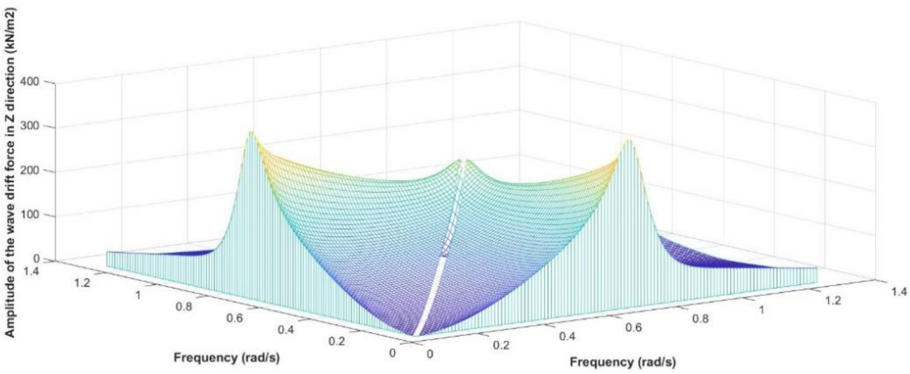
$$F(\omega_1, \omega_2) \approx F(\omega_1, \omega_1) \tag{3}$$

from the original Newman's approximation (Newman, 1974).

$$F(\omega_1, \omega_2) \approx sign(F)\sqrt{F(\omega_1, \omega_1)F(\omega_2, \omega_2)} \tag{4}$$



(a)



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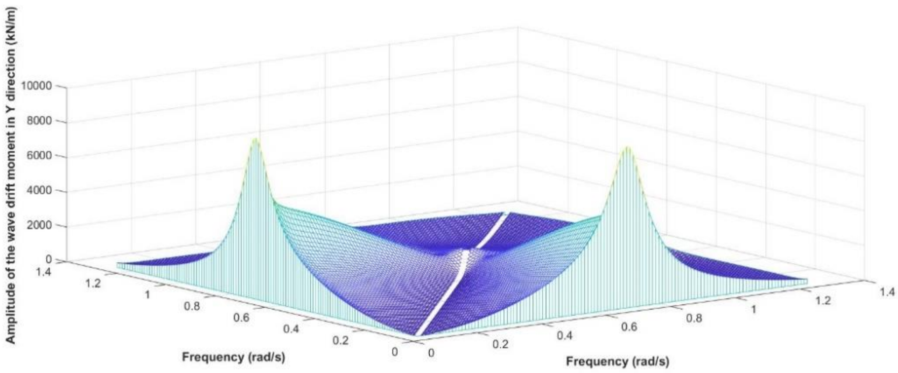


(c)

Fig. 1 The amplitudes of the drift force coefficients with respect to wave frequencies (rad/s): (a) Amplitude of the wave drift force in X direction (kN/m^2),(b) Amplitude of the wave drift force in Z direction (kN/m^2) and Amplitude of the wave drift moment in Y direction (kN/m) from the modification suggested by Molin (2002).

$$F(\omega_1, \omega_2) \approx \frac{F(\omega_1, \omega_1) + F(\omega_2, \omega_2)}{2} \tag{5}$$

from the modification suggested by Chen and Duan (2007).

Figs. 2 to 4 present the comparisons of the 2nd-order wave loads with difference frequencies in the heading sea through the direct pressure integral method and various Newman's approximations. It should be noted that the 2nd-order wave potential's contribution through the direct pressure integral method is calculated through Pinskter's approximation (Pinkster 1980), by taking the 1-st order wave exciting loads into consideration. It can be observed that the differences of the off-diagonal QTF elements among different methods are relatively small in the motions of surge and heave, while the difference wave frequency is 0.05 rad/s. As the difference wave frequency increases to 0.25 rad/s, obvious discrepancies can be observed among these numerical evaluations, which means if an off-diagonal element geometrically far away from the principal diagonal in the full QTF matrix is to be evaluated, Newman's approximation may meet its limitation and may not provide an accurate result. Therefore, the direct pressure integral method is necessary to be applied to evaluate the 2nd-order full QTF matrix.

It should be noted that the 2nd-order wave potential's contribution is approximated through Pinkster's approximation in this research, which shows its efficacy for a vertical cylinder in this section and the proposed vertical-wall-sided vessel in the next section that can present a relatively small 1st-order diffraction and radiation contribution.

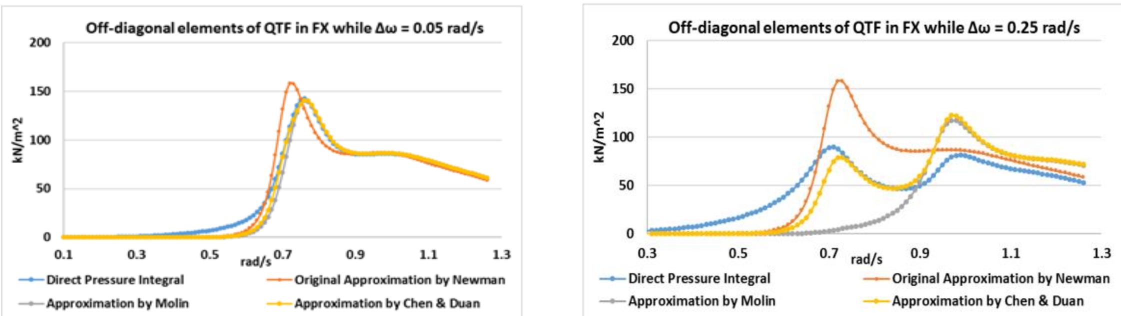


Fig. 2 Comparison among various numerical evaluations of the wave drift force in X direction

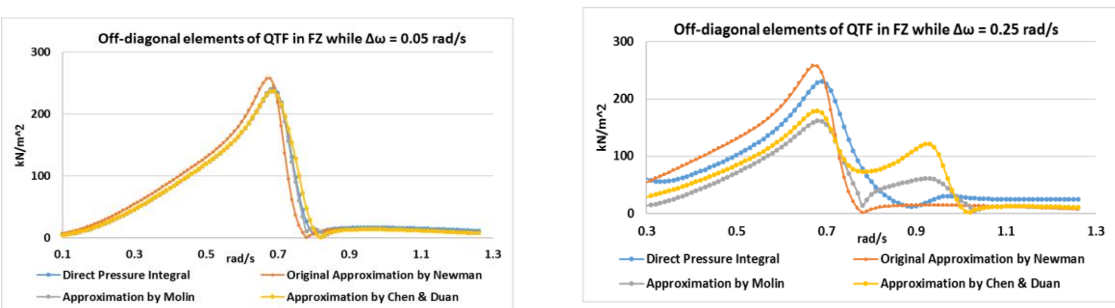


Fig. 3 Comparison among various numerical evaluations of the wave drift force in Z direction

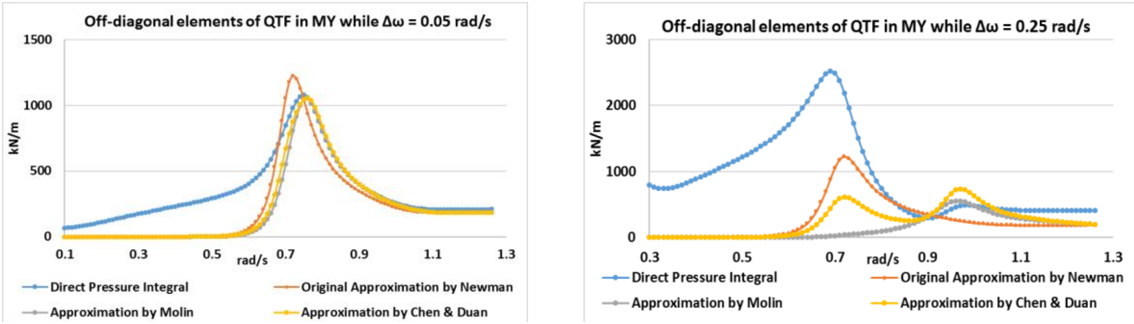


Fig. 4 Comparison among various numerical evaluations of the wave drift moment in Y direction

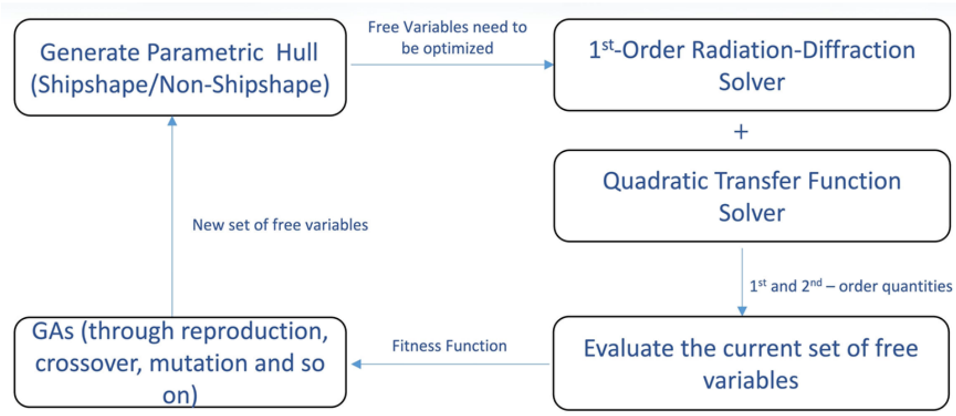


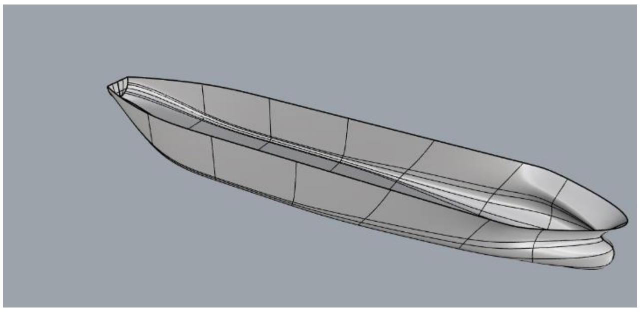
Fig. 5 Optimization framework of the floater hull design

3. Optimization

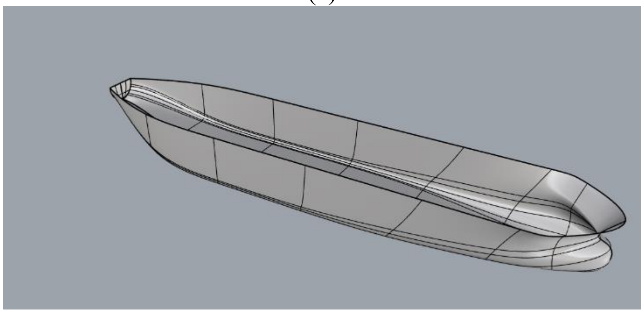
In the previous research (Zhao *et al*. 2011), it has been found that the level of the 2nd-order roll motion can be as significant as the 1st-order roll motion for a single point moored (SPM) floating system. Moreover, the 2nd-order roll motion of an SPM floating system develops a coupled effect with the yaw motion in the time domain. Considering the security of the operating instruments installed on board, minimizing or suppressing the level of the roll motion in both the 1st-order and 2nd-order is a principal object during the phase of hull design. In this scenario, the framework by using the Genetic Algorithm that is shown in Fig. 5 has been applied to a shipshape parametric FPSO hull design, to improve the hydrodynamics performance in the roll motion.

The prototype and the optimized design are shown in Fig. 6. The parameters such as the longitudinal locations of the various parallel stations from the stern to generate a parametric FPSO hull design are selected as the free variables to be optimized during the optimization process. The upper and lower boundaries of these parameters are based on engineering consideration. These free variables of the prototype and the optimization design are listed in Table 1.

Two objective functions that consider both the 1^{st}-order roll motion spectrum and the 2^{nd}-order wave loads of the roll motion in irregular waves are established as the metrics during the



(a)



(b)

Fig. 6 Parametric FPSO hull design: (a) prototype and (b) the optimized hull design

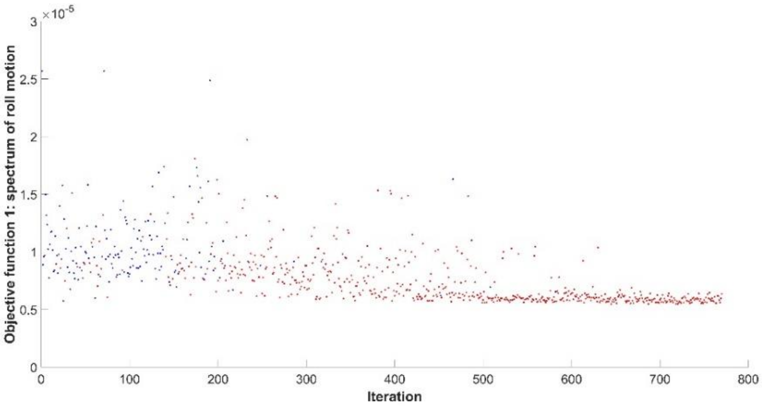
Table 1 Free variables

Parameters (m)	Original Design	Optimization	Lower Boundary	Upper Boundary
Parallel Midship I	53.68	46.28	33.60	81.20
Parallel Midship II	99.21	97.54	84.00	137.20
Parallel Midship III	159.24	155.34	140.00	179.20
Flat of Side I	186.66	199.27	182.00	207.20
Flat of Side II	252.2	255.43	210.00	257.60
Forward Shoulder	274.54	277.19	260.40	285.60
Bow Contour	301.46	290.32	288.40	313.60

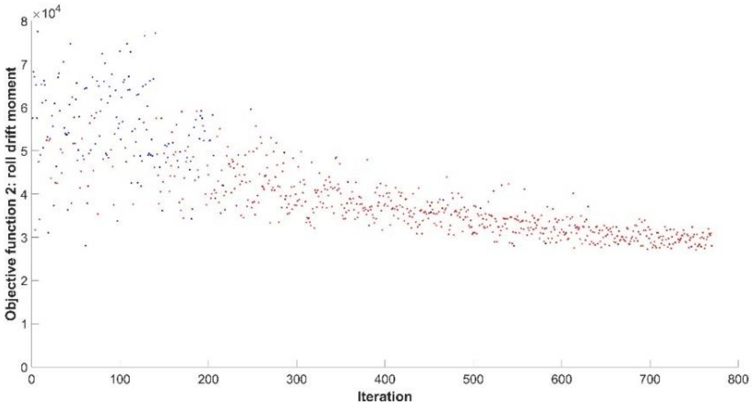
optimization process. A fully developed Pierson-Moskowitz incident wave spectrum with $U_{19.5} = 15$ m/s (Tp = 10.94 s, Hs = 4.82 m) is selected in this study. Considering that the 2nd-order roll motion presents a significant response at relatively low difference wave frequencies, there is a boundary regarding the difference wave frequency pairs in bi-chromatic waves in the objective function.

$$F1 = \int RAO_4^2(\omega) \cdot S(\omega) d\omega \quad (6)$$

$$F2 = \sum_{m=1}^{N} \sum_{n=1}^{N} 2\sqrt{S(\omega_m)S(\omega_n)}\, QTF_4(\omega_m, \omega_n) d\omega \quad |\omega_m - \omega_n| < 0.3 \;\; rad/s \quad (7)$$



(a)

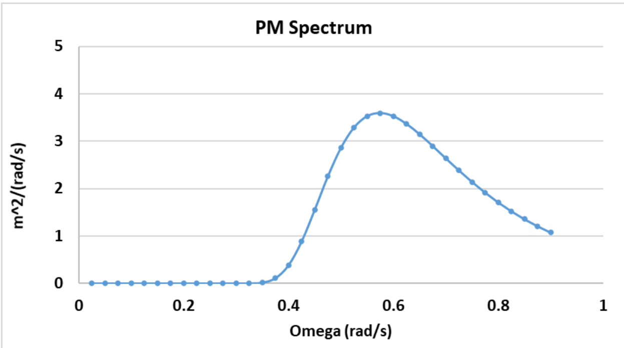


(b)

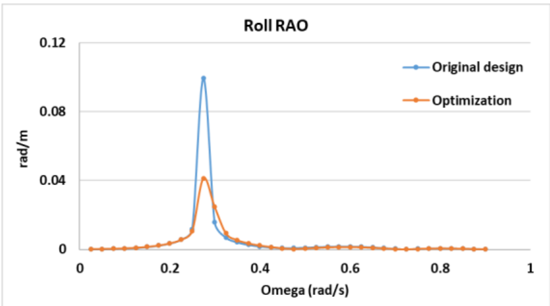
Fig. 7 Optimization iterations: (a) Objective function of the 1st-order roll motion and (b) Objective function of the 2nd-order wave load in the roll motion (red point: constraint successfully satisfied, blue point: constraint unsuccessfully satisfied)

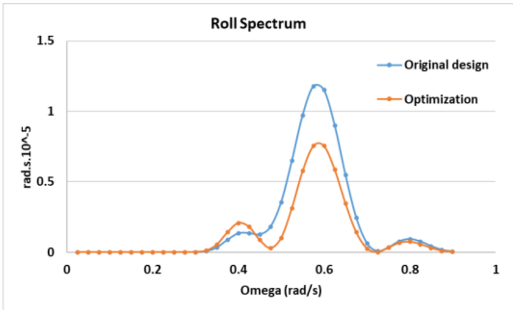
In Fig. 7, it can be seen that both objective functions regarding the 1st-order roll motion and the 2nd-order wave loads of the roll motions in irregular waves converge and decrease through the iterations during the optimization process. It should be noted that the constraint condition in the optimization process is that the difference of total displacement of the hull design in each optimization iteration and the prototype should be within 3% difference. In each iteration, the new hull shape and the corresponding mesh are generated automatically.

Compared with the original design, the optimized parametric FPSO hull presents a significant decrease in the 1st-order roll motion's RAO and response spectrum in irregular waves, which is shown in Fig. 8. The roll motion's natural frequency (0.275 rad/s) for both designs is out of the incident wave spectrum, whose peak frequency is 0.574 rad/s. Therefore, the roll spectrum at the roll motion's natural frequency is not apparent. It should be noted that the roll motion's spectra in irregular waves present a quadratic relation with the roll RAO: the roll RAOs for both designs decrease sharply around 0.4 rad/s and present a peak around 0.8 rad/s, although it is too small to be viewed in Fig. 8(b). Therefore, there are two peaks (0.4 rad/s and 0.8 rad/s) in Fig. 8(c), due to the contribution of the square of the roll RAO. Figs. 9 and 10 present the full QTF in the roll motion and the off-diagonal elements with various difference frequencies of the prototype and the optimized parametric hull design as an illustration.



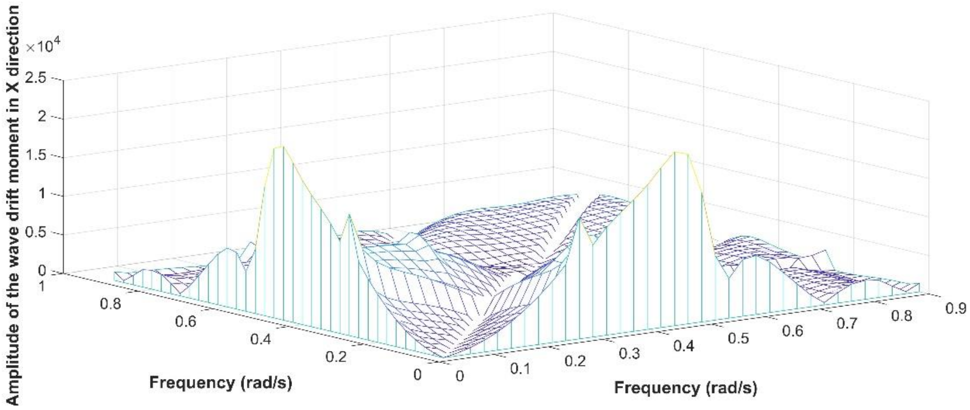
(a)





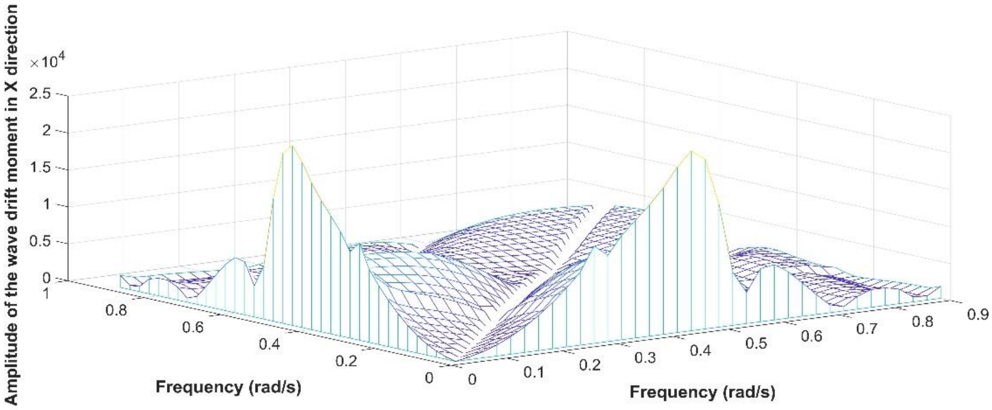
(b) (c)

Fig. 8 Comparison of the original and the optimizations: (a) incident wave spectrum, (b) RAO of the roll motion and (c) spectrum of the roll motion in quartering sea



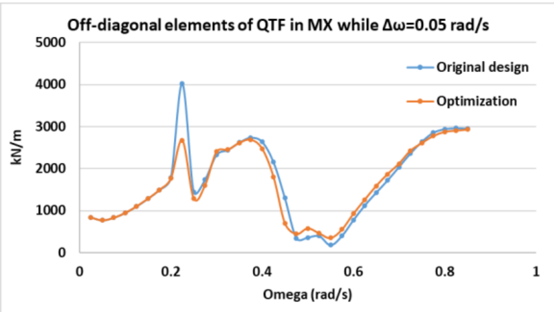
(a)

Fig. 9 Full QTF in the roll motion: (a) original and (b) the optimized hull design

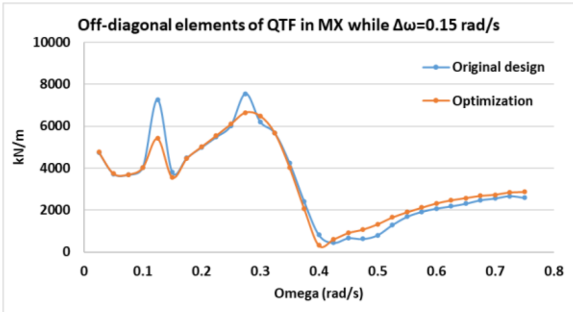


(b)

Fig. 9 Continued-



(a)



(b)

Fig. 10 Off-diagonal elements of QTF in the roll motion direction: (a) Δω=0.05 rad/s and (b) Δω=0.15 rad/s

The optimized parametric hull design presents a 37.70 and 14.56 percent decrease in two objective functions respectively, which validates this optimization framework's capacity of reducing the level of the shipshape FPSO's roll motion in both the 1st-order and 2nd-order quantities. In the future research, the time series of both the 1^{st}-order and 2^{nd}-order roll motion can be numerically simulated with the applications of the direct pressure integral method in evaluating the 2^{nd}-order wave loads. Moreover, the current framework can be extended to the applications of the wind turbine floating platform's optimization.

4. Conclusions

An optimization framework has been established by using the Genetic Algorithms (GAs) and applied to a parametric FPSO hull design. By numerically evaluating the full quadratic transfer function (QTF) through the direct pressure integral method and Pinkster's approximation, both the 1st-order and 2nd-order hydrodynamics quantities have been numerically calculated to evaluate the level of the FPSO's roll motion response in irregular waves. The free variables that describe the parametric hull's various station's longitudinal locations have been updated in each iteration and the corresponding objective functions considering the 1^{st}-order and 2^{nd}-order roll motion can be hence calculated. Compared with the prototype, the optimized parametric FPSO hull design presents a significantly suppressed level of roll motion in both the 1st-order and 2nd-order hydrodynamics quantities. This optimization framework shows its capacity of optimizing a shipshape parametric FPSO hull and provides a meaningful reference during the phase of shipshape hull design.

Acknowledgments

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