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Prediction of Long-Term Offshore Structural Responses Based on Non-linear Wave Modeling

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Abstract

Wind-generated random wave loads are the dominant loads to consider for maintaining the reliability of fixed offshore structures. Based on probabilistic techniques, the inherent randomness of the wave loading can be used to predict extreme offshore structural response, which is Gaussian in nature. However, researchers have found that the hydrodynamic component and structural dynamics substantially impact the frequency spectrum, leading to a non-Gaussian stochastic offshore structural response. A finite-memory non-linear system ($FMNS_{NL}$) has been proven to be an efficient approach to evaluate the non-Gaussian stochastic offshore structural response compared to the conventional method, Monte Carlo time simulation. However, the analysis has been conducted based on short-term distribution only. The most satisfactory analysis is based on long-term distribution. Hence, further investigation in this paper will evaluate the long-term probability distribution of extreme offshore structural responses. As a result, a 100-year extreme offshore structural response prediction achieves 80% to 96% accuracy compared to the Monte Carlo time simulation. The probability distribution has been evaluated using the Gumbel distribution function throughout this investigation. Still, there is a little deviation at the tail end of the distribution between the simulated response values and the fitted line. A different distribution function, such as the Generalised Extreme Value (GEV) distribution, is advised for future work.

Keywords: Offshore structure, non-linear wave theory, finite-memory non-linear system, extreme response.

1. Introduction

For fixed offshore structures, wind-generated random wave loads are the dominant load (Hagen, 1996; Aeran et al., 2017) to consider in maintaining reliability. While these structures can be designed by subjecting them to extreme regular waves for a 100-year return period (Abu Husain et al., 2013; Mat Soom et al., 2015; ABS, 2016), using probabilistic techniques to account for the inherent randomness of the wave loading is far more satisfactory (Syed Ahmad et al., 2022; Ladeira et al., 2022; Gadai & Xing, 2022). Prediction of extreme offshore structural response due to wind-generated random wave load is generally based on linear structural response and the Gaussian distribution of the response time history (API RP 2A, 2014). However, when there are considerable nonlinearities, the Gaussian idealization of the structural response time history might be inadequate (Zhao et al., 2018; Edward, 2021). Researchers have found that the hydrodynamic component and structural dynamics substantially impact the frequency spectrum, leading to a non-Gaussian stochastic offshore structural response (Zheng, 2013; Abdel Raheem, 2014; Gaidai et al., 2022).

Models with multivalued nonlinearities and non-linear functions of two or more variables are difficult to analyze; they are often solved using simulation or piece-wise linear analysis. Several methods (Billings, 1985; Bendat et al., 2010) have been introduced; the square-law and cubic non-linear models are the basic systems, and the Volterra non-linear model involves multidimensional functions for Gaussian random data. Recently, Gadai et al. (2022) applied a second-order Volterra series to extrapolate the statistically extreme values based on a non-linear wave model. The method used data post-processing of direct Monte Carlo simulation results to produce an accurate prediction (Saeedfar et al., 2015; Adcock, 2015; Edward, 2021). Nevertheless, the research focuses on statistical methodology, not structural and hydrodynamic technical details. Simulating the structural response using Monte Carlo is time-consuming, as reliable results require many simulations (Abu Husain et al., 2016).

Mukhlas et al. (2018) and 2019 have discovered an alternative to the Monte Carlo approach. An efficient model has been introduced to generate the non-Gaussian stochastic structural response using a finite-memory non-linear system known as FMNSNL (Mukhlas et al., 2021a). Based on the short-term probability distribution of an extreme non-Gaussian stochastic response, the accuracy of FMNSNL has been validated by the Monte Carlo time simulation method (Mukhlas et al., 2021b). However, the most satisfactory analysis is based on the long-term distribution (ABS, 2016; Raed et al., 2020; Haselsteiner et al., 2022). Hence, further analysis in this paper will be conducted to evaluate the long-term probability distribution of extreme offshore structural responses. The evaluation procedure will be discussed in the following section.

2. Derivation of Long-Term Probability Distribution of Extreme Offshore Structural Responses

Long-term distribution is an analysis that considers the whole sea state condition at the site of the offshore structure. Based on the several approaches in generating the 100-year responses, the all-sea-state approach is selected due to its simple application. The characteristic of long-term extreme values is determined based on the wave scatter diagram that summarises the wave climate and typically represents the combination of significant wave height (H_s) and wave period (mean zero up-crossing period, T_z, or peak period, T_p, or energy period, T_e) during the time period they are encompassing.

Accounting for the offshore structural responses from various short-term wave conditions can yield the long-term distribution of extreme responses. It is defined as follows:

$$\begin{aligned} P_{LT.r_{max}}(q) &= \int_{H_S=0}^{\infty}\int_{T_Z=0}^{\infty} P_{r_{max}}(q|H_s,T_z)dH_s dT_z \\ &= \int_{\mathrm{H_S}=0}^{\infty}\int_{\mathrm{T_Z}=0}^{\infty} P_{r_{max}}(q|H_s,T_z)p(H_s,T_z)dH_s dT_z \end{aligned} \tag{1}$$

where $p(H_s,T_z)$ refer to the joint probability density function for significant wave height and mean zero up-crossing period.

The above equation can be stated as follows using the extended scatter diagram as an approximation for the joint probability density function:

$$P_{LT.r_{max}}(q) = \sum_i \sum_j P_{r_{max}}\left(q|H_{si},T_{zj}\right) * \frac{W_{ij}}{W} \tag{2}$$

in which $Prmax(q|H_{si},T_{zj})$ is the short-term probability distribution of response extreme values for the sea state defined by H_{si} and T_{zj}, W_{ij} is the number of occurrences of the sea states represented by H_{si} and T_{zj} in the scatter diagram and $W=\Sigma_i\Sigma_j W_{ij}$ is the total number of sea states.

To solve Equation (2), the values of $P_{rmax}(q|H_{si},T_{zj})$ for all simulated q values belonging to all sea states must be discovered. All of the simulated extreme values for the provided sea states are numerically arranged from smallest to greatest. The following equation can be used to determine the short-term distributions, assuming that q_n is the smallest simulated extreme value and n=1,2,3,..,N, where N is the total number of simulated records (N =1000 in this study).

$$P_{r_{max}}\left(q\middle|H_{si},T_{zj}\right)=\frac{n-0.44}{N+0.12} \tag{3}$$

where,

$$\begin{aligned} &P_{r_{max}}\left(q<q_1\middle|H_{si},T_{zj}\right)=0\\ &P_{r_{max}}\left(q<q_N\middle|H_{si},T_{zj}\right)=1\\ &P_{r_{max}}\left(q_1<q<q_N\middle|H_{si},T_{zj}\right)=interpolate\ from\ equation\ (16)\end{aligned} \tag{4}$$

As a result, for each sea state, the technique of moments is employed to fit a Gumbel distribution using the simulated extreme values. Equation (2) is used to calculate the long-term distributions of extreme values by convoluting the short-term Gumbel distributions of extreme values with the probability of occurrence of each sea state. Then, using the Monte Carlo time simulation and FMSN$_{NL}$ methods, the foregoing long-term distributions are applied to forecast the 100-year extreme offshore structural responses. The step for predicting 100-year extreme offshore structure reactions is summarised in Figure 1.

3. Long-Term Probability Distribution of the Non-Gaussian Stochastic Extreme Offshore Structural Response using FMNS$_{NL}$

The selection of a suitable offshore platform was made based on the water depth. A fixed offshore platform may operate in water depths of up to 400 metres (also known as shallow water), and a floating offshore platform is used for deeper depths. The industry commonly uses fixed offshore platforms for oil and gas production. Locating a fixed offshore platform in shallow sea waters is still feasible and as a result, this paper focused mainly on simulating the extreme response values of a quasi-static fixed offshore platform according to the non-linear random wave theory. The details of the platform can be referred to Mukhlas et al. (2019). The environmental data chosen is based on the extreme environment experienced by the structure (i.e., North Sea region), while the probability distribution of extreme responses value was analysed based on the first excursion of failure due to the first upcoming extreme response.

The accuracy of the FMNS$_{NL}$ method will be tested by comparing the prediction of 100-year extreme offshore structural response based on long-term analysis. The comparison was made using the ratios between FMNS$_{NL}$ and Monte Carlo time simulation methods for corresponding 100-year responses. The prediction of 100-year responses using the FMNS$_{NL}$ approach is more accurate than the similar prediction using the Monte Carlo time simulation approach when the ratio is near unity. Table 1 represents the ratio of prediction for drag-induced, inertia-induced and total responses of base shear and overturning moment based on zero current, positive and negative current, respectively.

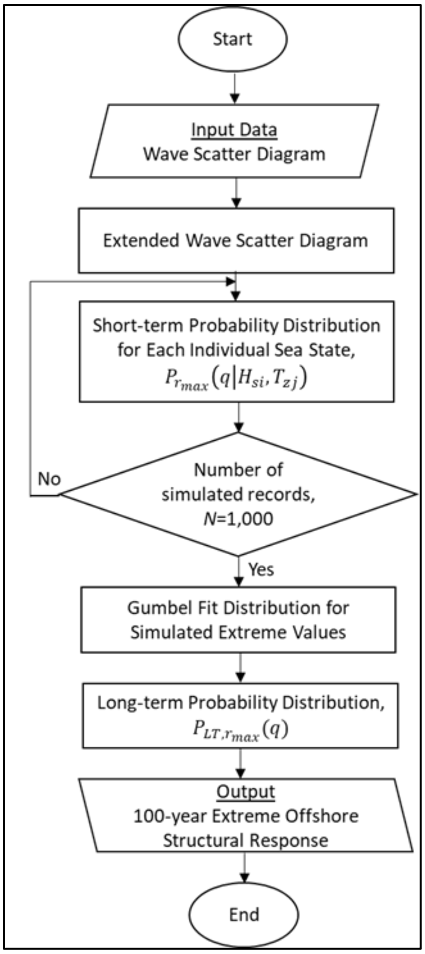

Figure 1. Prediction of 100-year Response According to Long-term Probability Distribution

Table 1. Comparison of 100-year response from Monte Carlo time simulation with FMNS$_{NL}$ method.

Responses	Base Shear		Overturning Moment	
	Monte Carlo (MN)	$\frac{\text{FMNS}_{NL}}{\text{Monte Carlo}}$	Monte Carlo (MN.m)	$\frac{\text{FMNS}_{NL}}{\text{Monte Carlo}}$
$\bar{U} = +0.90\ m/s$				
Drag-induced	7.429	0.945	671.429	0.809
Inertia-induced	1.447	1.022	132.333	0.959
Total	7.600	0.919	680.328	0.807
$\bar{U} = 0.00\ m/s$				
Drag-induced	5.077	0.879	488.889	0.795
Inertia-induced	1.209	1.046	108.254	0.957
Total	5.067	0.895	493.333	0.797
$\bar{U} = -0.90\ m/s$				
Drag-induced	2.889	1.300	337.500	1.259
Inertia-induced	1.061	1.058	96.667	0.943
Total	3.056	1.200	355.556	1.253

In general, the prediction of a 100-year extreme offshore structural response using FMNSNL provides better accuracy as compared to the corresponding prediction using the Monte Carlo time simulation method. As compared to base shear and overturning moments, base shear gave a better prediction of 100-year extreme offshore structural responses. This is related to the formulation of both responses, in which the base shear only involved two variables (force and member length), while the overturning moment involved three variables (force, member length, and elevation). Fewer variables numerically minimized the random error, hence leading to better accuracy.

Overall, without the presence of current along the wave propagation, the accuracy level of the $FMNS_{NL}$ method is in the range of 80% to 96%. If there exists a current with the same direction of the wave (positive current), the accuracy is improved with an increment of 1% (drag-induced overturning moment) to 7% (drag-induced base shear). Negative current, on the other hand, has a significant impact on its prediction, reducing accuracy by 1% (inertia-induced base shear) to 18% (drag-induced base shear). It is as expected since the accuracy performance of $FMNS_{NL}$ follows strictly as per previous analysis for short-term distribution (initial indicator). Hence, the following long-term distribution analysis represent the real performance of the $FMNS_{NL}$ method, which considers the whole sea state condition, with 1,000,000 sea states and can be used to analyse the reliability of offshore structures.

For example, Figure 2 illustrates the highest accuracy of prediction 100-year response using the $FMNS_{NL}$ method without the presence of current. It examines inertia-induced overturning moment based on the long-term probability distribution. The simulated distribution was fitted with a Gumbel fitted line to predict the 100-year response value. Both $FMNS_{NL}$ and Monte Carlo time simulation methods are well correlated based on the distribution, with a ratio prediction of 0.957. There is no issue for inertia-induced component since the $FMNS_{NL}$ model works well and provides the best accuracy level.

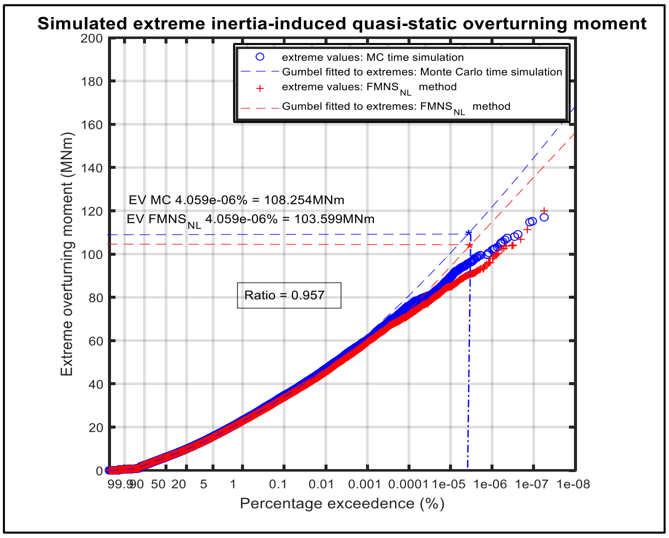

Figure 2. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation and FMNSNL Methods, 1000 Response Records, Inertia-induced Quasi-Static Overturning Moment, Current = 0.00 m/sec

Since this investigation was according to the extreme offshore structural response that is dominated by the drag-induced component, it is of practical importance to see the performance of the $FMNS_{NL}$ method for that component of response. At the same current condition, the drag-induced component had an accuracy with an accuracy level of 87.9%, in which the accuracy error was 12.1% for base shear response as shown in Figure 3. In fact, the presence of positive current has improved the accuracy of the prediction of 100-year response using the $FMNS_{NL}$ method by reducing the accuracy error to only 5.5% (refer Figure 4). Meanwhile, Figure 5 illustrates the accuracy performance of the $FMNS_{NL}$ method with the presence of negative current. As demonstrated, the accuracy performance was reduced by 17.9% (difference of inaccuracy) compared to without current (ratio = 0.879), with a ratio of 1.30. As such in this case, the $FMNS_{NL}$ method over-predicted the 100-year response

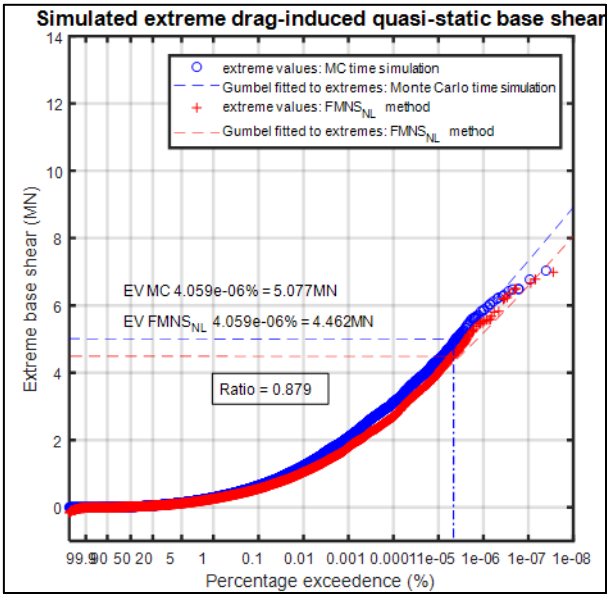

Figure 3. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation and $FMNS_{NL}$ Methods, 1000 Response Records, Drag-induced Quasi-Static Base Shear, Current = 0.00 m/sec

The contribution of positive and negative current definitely has a significant effect on the wave phase. This is due to the addition of current velocity to the drag force component, which depends on the water particle velocity. In addition, negative current tends to shorten wave length and lead to a higher magnitude of frequency spectrum. Negative current also increases the steepness of the wave crest, thereby increasing the nonlinearity of the wave. All of this eventually affects the wave-induced force and leads to higher frequencies in the resultant responses. A large wave length causes the loading on all the legs to be simultaneously large and highly correlated with each other. Hence, the positive current results in a very significant increase in 100-year responses as compared to zero current, which gives similar results to Taniguchi & Kawano (2001) results. For example, the relative difference between 100-year response drag-induced base shear using the FMNSNL method between positive and zero currents is (7.020 - 4.462) / 4.462 = 0.573. On the other hand, negative current leads to a lower response with a relative difference of (3.756 - 4.462) / 4.462 = 0.158 compared to the response without current. In fact, the responses are not well correlated with the shorter wave length.

Due to the major contribution of the drag-induced component in the evaluation of 100-year extreme offshore structural responses, the same conclusion is valid with the investigation on the total response values. For example, Figure 6 represents the prediction of 100-year response of total base shear with the presence of a positive current. It reached the highest degree of accuracy, including zero and negative current, with a ratio of 0.919 between the prediction using $FMNS_{NL}$ with Monte Carlo time simulation methods. It is, however, shown that the Gumbel fitted distribution is deviated slightly from the corresponding distribution of simulated extreme values. There may be a need for a more accurate provision of other types of distribution, such as the Generalized Extreme Value (GEV) distribution. Nevertheless, it is not a major concern since the main purpose of this research is to compare the accuracy performance of 100-year response between $FMNS_{NL}$ and Monte Carlo time simulation method.

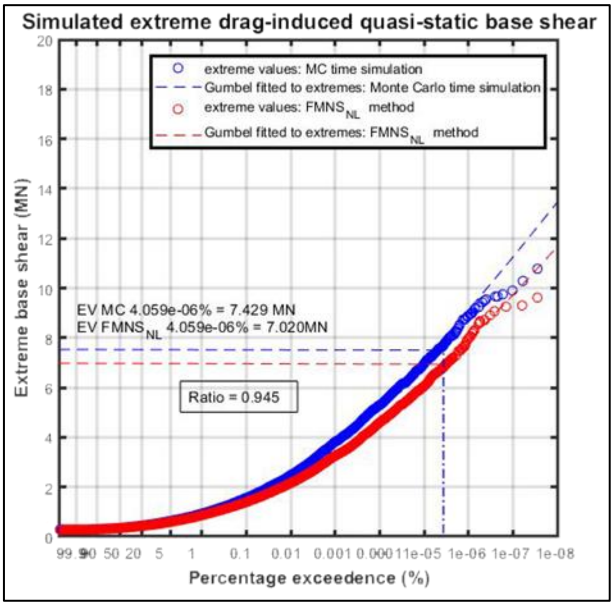

Figure 4. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation and FMNSNL Methods, 1000 Response Records, Drag-induced Quasi-Static Base Shear, Current = +0.90 m/sec.

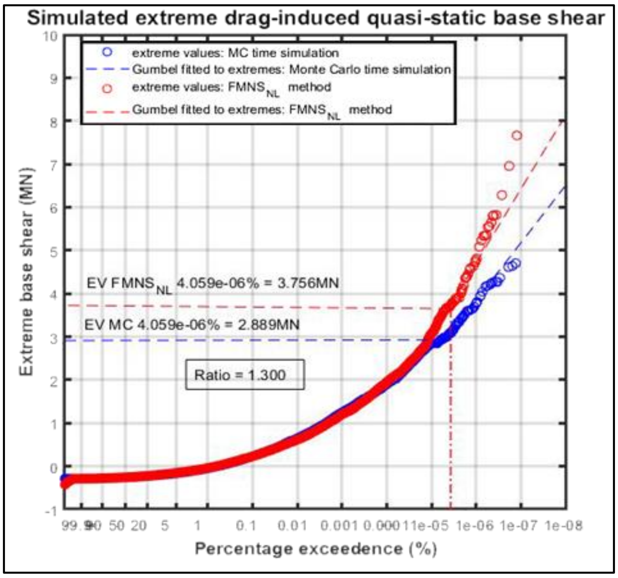

Figure 5. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation and FMNSNL Methods, 1000 Response Records, Total Quasi-Static Base Shear, Current = +0.90 m/sec.

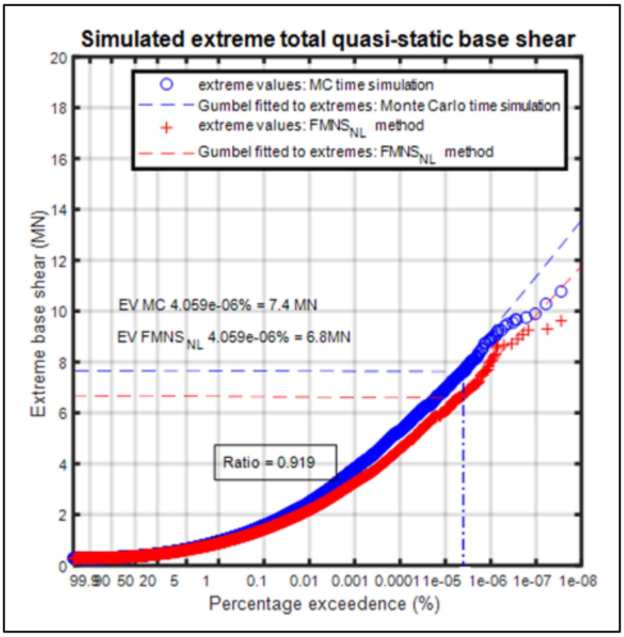

Figure 6. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation and FMNSNL Methods, 1000 Response Records, Total Quasi-Static Base Shear, Current = +0.90 m/sec.

4. Comparison between Linear and Non-linear Wave Analysis

The impact of non-linear wave analysis will be discussed based on the comparison of the prediction 100-year response using FMNS and FMNS$_{NL}$ methods. The output is to verify the significant of application FMNS$_{NL}$ method in offshore structural analysis. Based on the current development of FMNS method done by Mukhlas et. al. (2021a; 2021b), it is proven that the method was relevant to be used in constructing reliable and optimum platform design. The method has achieved 99.9% accuracy level in predicting 100-year extreme offshore structural response based on linear wave analysis. Hence, the ratio of 100-year prediction between FMNS$_{NL}$ and FMNS methods indicates the importance of considering nonlinearities in the wave analysis. Table 2 represent the ratio of prediction 100-year extreme offshore structural response using FMNS$_{NL}$ against FMNS method.

As expected, prediction using FMNS method always underestimates the 100-year extreme offshore structural response value compared to prediction using FMNS$_{NL}$. The differences are in the range of 4% to 45.5%. The highest difference with a ratio of 1.455 represents the prediction for drag-induced base shear with the presence of negative current, as illustrated in Figure 7. The huge difference indicates the effect of considering the nonlinearities in the evaluation of wave. It is known that the nonlinearities of the wave on the drag-induced component are due to its water particle kinematics motion that provides higher velocity especially at the shallow water depth, as discussed by Bremer van den and Taylor (2013).

Besides, the presence of a negative current also increases the nonlinearities. As proven by Yao & Wu (2005), negative current tends to shorten the wavelength and increase the steepness of wave crest, hence increasing the nonlinearities. Therefore, contributes to the higher magnitude of response as present using FMNS$_{NL}$ method compared to the response value obtained by FMNS method.

While the lowest difference of 1.040 is the prediction of 100-year response for the total base shear without the presence of current. Even though the result shows less impact of nonlinearities with only 4% different based on the prediction using $FMNS_{NL}$ and FMNS methods; however, the $FMNS_{NL}$ method actually still has a defect in its accuracy compared to Monte Carlo time simulation based on non-linear wave analysis. As illustrated in Figure 8, there is still an error in the accuracy of about 10.5% for the prediction of 100-year response between $FMNS_{NL}$ with Monte Carlo time simulation methods (ratio = 0.895). Hence, provided a ratio of 1.162 (ratio = 5.067/4.361) on the 100-year prediction using Monte Carlo time simulation against FMNS methods.

Table 2. Comparison of 100-year Response From $FMNS_{NL}$ with FMNS Method

Responses	Base Shear		Overturning Moment	
	FMNS (MN)	$\frac{FMNS_{NL}}{FMNS}$	FMNS (MN.m)	$\frac{FMNS_{NL}}{FMNS}$
$\bar{U} = +0.90\ m/s$				
Drag-induced	6.408	1.096	505.263	1.083
Inertia-induced	1.031	1.097	80.263	1.115
Total	6.421	1.098	505.263	1.063
$\bar{U} = 0.00\ m/s$				
Drag-induced	4.018	1.109	363.636	1.125
Inertia-induced	1.018	1.088	72.547	1.240
Total	4.361	1.040	367.273	1.094
$\bar{U} = -0.90\ m/s$				
Drag-induced	2.640	1.455	296.552	1.433
Inertia-induced	1.000	1.115	77.778	1.229
Total	3.600	1.156	373.333	1.143

For the case of inertia-induced component, the ratio on the prediction of 100-year response using FMNS and $FMNS_{NL}$ methods should not be so obvious since less contribution of nonlinearities on that component. Hence, it provided a better ratio compared to the drag-induced component. However, some cases did not follow that kind of pattern. As such, for the case of inertia-induced overturning moment without the presence of current, the ratio is 1.240, while the drag-induced component provided a better ratio of 1.125

This related to the level of accuracy of $FMNS_{NL}$ method compared to Monte Carlo time simulation method. As refer to Figure 9 and Figure 10, for drag-induced component, there are still some defects in the accuracy of $FMNS_{NL}$ method, while it works well with inertia-induced component. Hence, the comparison of 100-year responses between $FMNS_{NL}$ and FMNS methods can be totally accepted for inertia-induced component, while for drag-induced component, the error in accuracy of $FMNS_{NL}$ method needs to be considered to get a precise effect of nonlinearity.

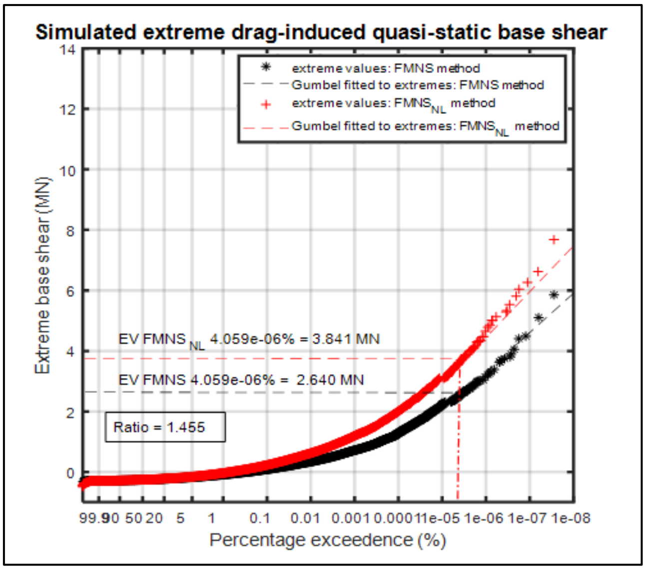

Figure 7. Comparison of Long-term Probability Distribution of Extreme Response Values From FMNS and $FMNS_{NL}$ Methods, 1000 Response Records, Drag-Induced Quasi-Static Base Shear, Current = -0.90 m/sec

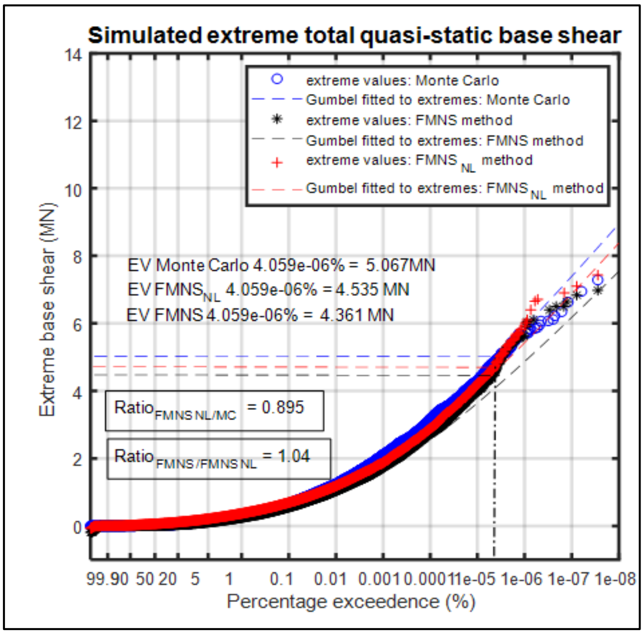

Figure 8. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation, FMNS And $FMNS_{NL}$ Methods, 1000 Response Records, Total Quasi-Static Base Shear, Current = 0.00 m/sec

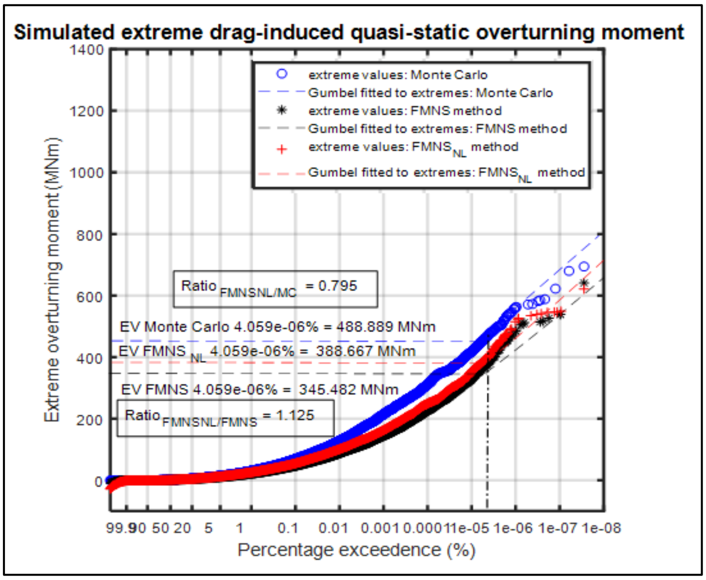

Figure 9. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation, FMNS And FMNS$_{NL}$ Methods, 1000 Response Records, Drag-Induced Overturning Moment, Current = 0.00 m/sec

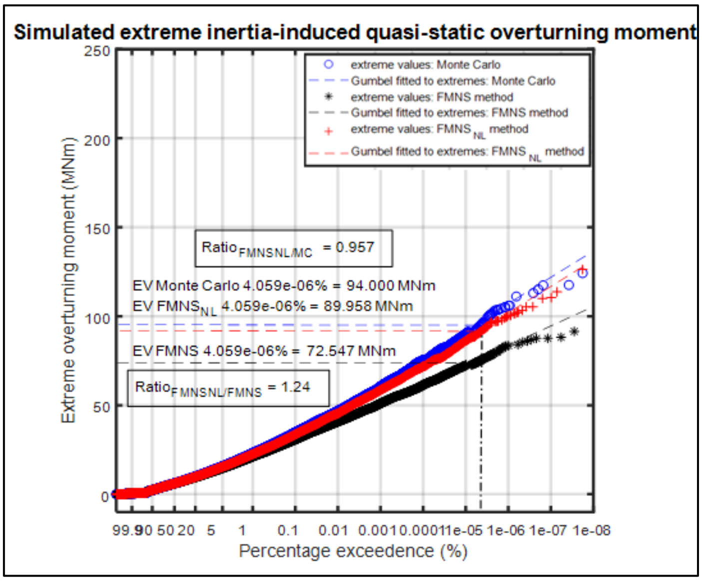

Figure 10. Comparison of Long-term Probability Distribution of Extreme Response Values From Monte Carlo Time Simulation, FMNS And FMNS$_{NL}$ Methods, 1000 Response Records, Inertia-Induced Overturning Moment, Current = 0.00 m/sec

5. Conclusion

As a preliminary analysis to assess the overall integrity of the structure, a structure analysis based on linear wave analysis is suggested. If there are extreme results of the preliminary analysis with several critical conditions, it is suggested that a more detailed structural analysis is carried out to carry out a non-linear wave. An effective model has been developed recently, based on the non-linear wave analysis and the time-domain approach, to test the extreme offshore structural response. It is the derivation of an offshore structural response from non-Gaussian stochastics by the finite-memory non-linear system, known as FMNS_{NL}.

An analysis of the performance of FMNS_{NL} based on its accuracy according to the prediction on the 100-year extreme offshore structural response of long-term probability distribution has been conducted. A dominant offshore structure based on base shear and overturning moment has been considered. FMNS_{NL} provided a good accuracy to predict the 100-year extreme offshore structural response with 80% to 96% accuracy level compared to the corresponding prediction using Monte Carlo time simulation method, with zero current value. However, the presence of current contributes to the significant impact on its accuracy, in which positive current improved its accuracy by 1% to 7%, while negative current reduced the accuracy by 1% to 18%. As compared between base shear and overturning moment, base shear gave a better prediction of 100-year extreme offshore structural responses. This has to do with how the two reactions were put together, where the overturning moment had three variables (force, member length, and elevation), whereas the base shear only had two (member length and force). With fewer variables, the random error was quantitatively reduced, improving accuracy.

Besides, an analysis has been done to observe the importance of nonlinearities in the evaluation of offshore structural responses. A comparison has been made between the prediction of 100-year extreme offshore structural response obtained using FMNS and FMNS_{NL} methods. Based on the finding, the impact of nonlinearities was significant for the drag-induced component, and it became more obvious with the presence of negative current. The highest difference of 45.5% shows that the nonlinearity is very important to consider in the structural analysis.

Throughout this analysis, the offshore structural responses have been evaluated using Gumbel distribution function; however, there is a slight deviation at the end of the tail between the simulated response values and the fitted line. Therefore, it is recommended to analyse using other distribution functions such as Generalised Extreme Value (GEV) distribution.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

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