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RESPONSE-BASED ANALYSIS OF FPSO SYSTEMS FOR SQUALL LOADINGS

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ABSTRACT

Squalls can be the major design driver for FPSO systems in offshore West Africa where other environmental loadings are relatively benign. The measured squall time series indicate a transient change in the wind speed, starting with a sudden increase to a peak wind speed followed by a rapid decay, all within a total duration of about an hour. In the design of FPSOs for squall loadings, careful attention needs to be given to the transient characteristics of squalls.

The main objective of this investigation is to characterize the response of FPSO systems subjected to squalls and develop a robust approach for estimating the design value. For this purpose, first, the dynamic behavior of an FPSO in squalls is studied and then the significant squall parameters that affect the dynamic response of the FPSO are identified. The results of this study are utilized to define the upper bound of the dynamic amplification factor and the upper limit of the extreme response of the FPSO. Next, three different response-based approaches: a) based on the long-term statistical analysis of the response, b) based on the long-term statistical analysis of the squall parameters and c) based upon the dynamic amplification limitations, are utilized to estimate the design values. Finally, the design value estimates obtained from the response-based approaches are compared with those estimated from scaling squall time traces to the 100-year peak wind speed. The study is mainly focused on spread moored systems; however, the proposed methods are also tested on turret moored FPSOs, and their application for these dynamically complicated systems is evaluated.

INTRODUCTION

In the common design practice for squalls, a few locally measured wind speed time series are scaled so that the peak wind speed matches the expected 100-year return value. These scaled squalls are then applied in a numerical model and the highest response of the FPSO to the scaled squalls is considered as the design value. In this approach, the time scale characteristics of squalls are neglected which may result in inaccurate representation of the phenomena and may cause unrealistic extreme responses. Another issue in this approach is that the estimation of design value is based on the results of a few simulations only. In recent studies by Duggal et al. [1] and Alvarez et al. [2], the focus has been on the response-based analysis of FPSO systems during squall loadings in order to estimate the extreme responses more robustly and consequently to obtain more representative design values.

This study was initiated due to the concerns on the level of conservatism in the current design practice. The use of the word conservatism may have an emotional association to it. In public opinion, oil and gas projects should always be engineered as safe as possible, reducing the risk of failure to an absolute minimum. From an operator (and investor) point of view, such level of safety would lead to a major increase in CAPEX, the capital required to engineer and build large projects. The optimum solution can be found through a compromise between investment and acceptable risk. As general term, risk is defined as the multiplication of the probability of occurrence and the results of occurrence. In the engineering design process, extra conservatism is required when the uncertainty about the threatening event and/or the consequences of the event is significant. This study is performed to shed light on the response of FPSO systems in extreme wind squalls and thereby improve the required level of conservatism. In turn, the design requirements can be lowered without compromising the overall safety.

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SQUALL CHARACTERIZATION

A typical squall is characterized by a sudden increase in wind speed followed by a rapid decay. The method by Legerstee et al. [3] is adopted to methodically characterize the wind squall timeseries. The parameters extracted from this method are the peak wind speed u_0, the rising slope s_r (or the rise time t_r), and the decay half-life time τ (see Figure 1). It is worth mentioning that this simplification is based on the assumption that the low frequency motions are dominant and the high frequency oscillations are negligible. This is only the case for FPSO systems with relatively large natural period and relative damping (see Duggal et al [1]).

For this study, 58 squall measurements during a total of 5.8 years were available. Based on the available data, no correlations between the squall parameters have been observed and therefore it is assumed that the squall parameters are mutually independent random variables.

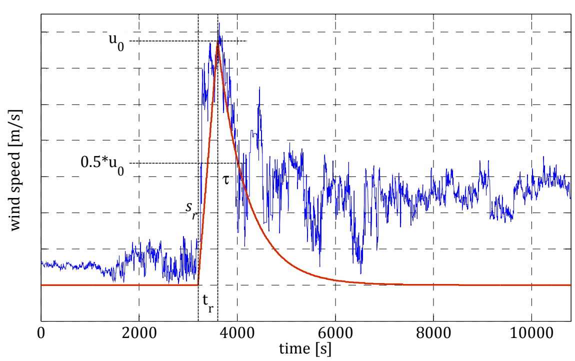

Figure 1. Squall characterization

The sample probability distribution is estimated by fitting an appropriate probability distribution to each parameter sample. The distribution type providing the best fit has been selected for each parameter and no specific type has been imposed to the samples, as is often suggested by metocean designers. This approach has been consistently applied throughout the entire study, whenever fitting has been applied.

SPREAD MOORING CASE STUDY

To demonstrate the response characteristics of spread moored FPSO to wind squalls, a case study representing a spread moored FPSOs in the West Africa deepwater areas is explored. This particular case is modeled after a barge shaped FPSO in 800 meters of water depth. As discussed in Duggal et al. [1], the response of spread moored systems can be reasonably approximated with a tuned Single Degree of Freedom (SDOF). Duggal et al. [1] showed that the largest offset of the spread moored FPSO occurs in sway direction, due to mooring layout and large beam wind area, which can be modeled with an appropriately linearized mass-damper-spring system. The main characteristics of the SDOF model used in this case study are the natural period (T_n) of 290 seconds and the relative damping (ξ) of 0.4. Since the sway offset is governing, all squalls will also be applied beam on.

RESPONSE CHARACTERISTICS

The 58 squalls are applied to the FPSO model and the resulting offsets are plotted against the input parameters in Figure 2. The results depicted below show little to no correlation to rising slope and decay time, but a strong correlation to peak wind speed.

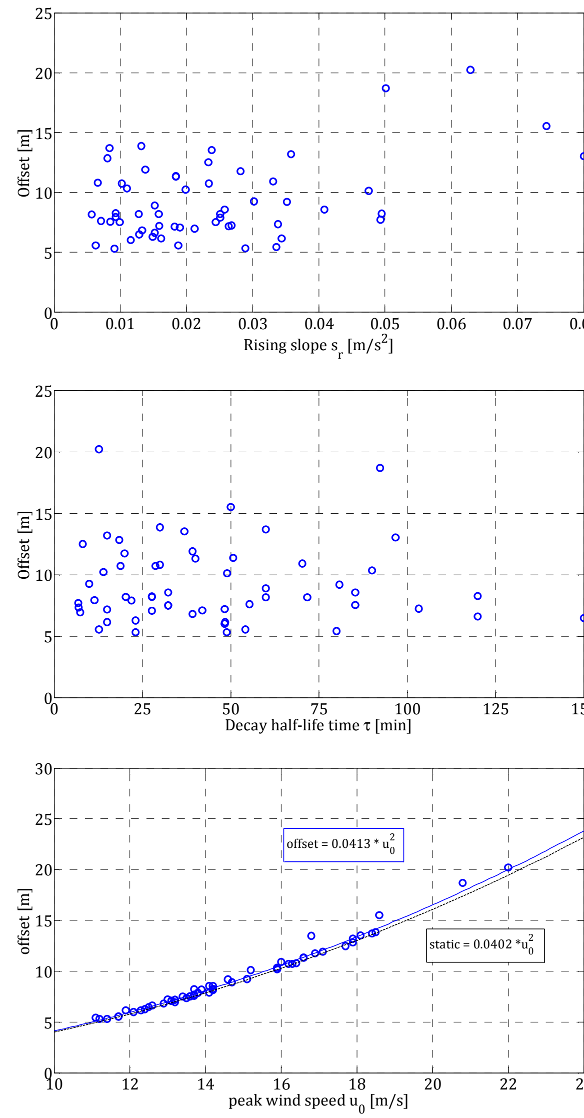

Figure 2. Offset correlations to squall parameters

The strong offset correlation to peak wind speed is explained by the driving wind force, which -in steady state- leads to an expression for the static offset:

$$y_{st} = \frac{\rho C_w A_y}{2k_y} u_0^2 = C_{st} u_0^2 = 0.0402 u_0^2 \quad (1)$$

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The static coefficient C_{st} for this particular system is 0.0402. This static line is also plotted in Figure 2. A quadratic fit has been applied to the offsets from the 58 squalls, which shows a constant of 0.0413. The response of the FPSO model to wind squalls is now described as a function of dynamic amplification; the ratio of dynamic offset over static offset:

$$\alpha = {y_{dyn}}/{y_{st}} \quad (2)$$

The average dynamic amplification factor for the 58 squalls applied to the SDOF model is estimated as 1.027.

The fact that the offset does not show a strong correlation to rising slope and decay time does not mean that the system is not sensitive to those parameters. For a given peak wind speed (in this case the mean of the observed 58 squall peak wind speeds), the systems sensitivity plot is depicted in the grey curve in Figure 3.

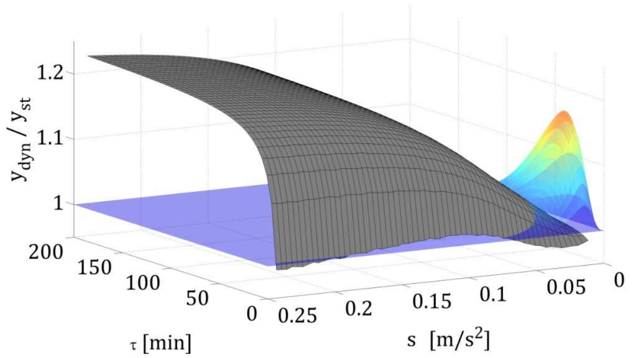

Figure 3. System sensitivity (grey surface) to and joint probability distribution (colored surface) of rising slope and decay time.

As can be seen in the above figure, the dynamic amplification increases with steeper rising slopes and longer decay times. This was also shown by Legerstee et al. [3]. There is a limit for the dynamic amplification, where the surface becomes flat. This limit represents the maximum dynamic amplification resulting from an input with infinite steep rising slope and decay time, representing a step function [4]. It should be noted that the sensitivity curve is a function of the natural period and relative damping of the system, the limits however are a function of relative damping only, which is shown in Figure 4.

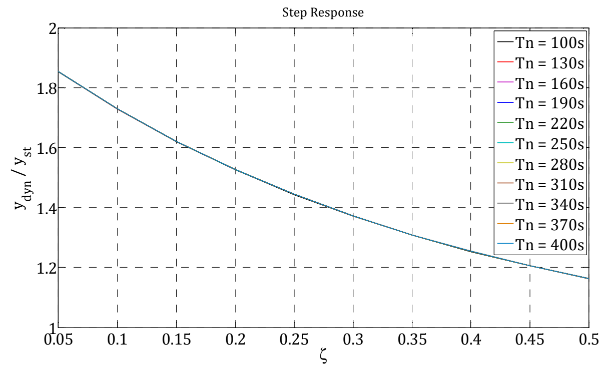

Figure 4. Dynamic amplification due to a stepfunction input

Also presented in Figure 3 is a graphic representation of the joint probability density distribution of the observed rising slopes and decay times. The dynamic amplification corresponding to the mean rising slope and mean decaying time is 1.024, which is close to the value found from the results shown in Figure 2 and considering the small sample size they can be concluded to be the same.

DESIGN VALUE ESTIMATION

The Current Design Practice (CDP) for FPSOs subject to squalls is to scale the measured time series to an expected 100 year peak wind speed, determined from the peak wind speed distribution. The goal is to create something that resembles a 100 year input. However, during this scaling process (see an example in Figure 5), the transient behavior of the squalls is altered due to the increase in the rising slope. The extrapolation of the peak wind speed distribution results in an expected 100-year return value of 27.3 m/s. The 58 squalls are scaled to that peak value and applied to the numerical model. The distribution of estimated offsets is shown in Figure 6. Following the current design practice procedure, the highest observed offset of 35.8 meters is taken to be the design value.

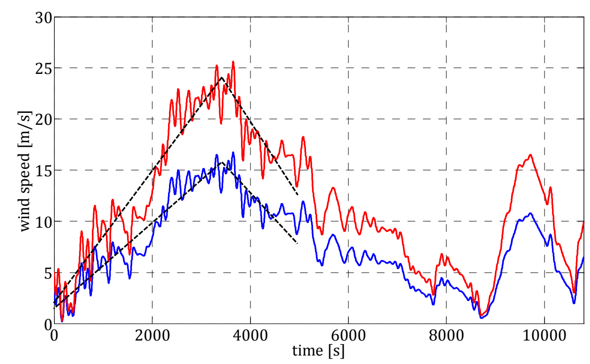

Figure 5. Effect of scaling on the squall characteristics

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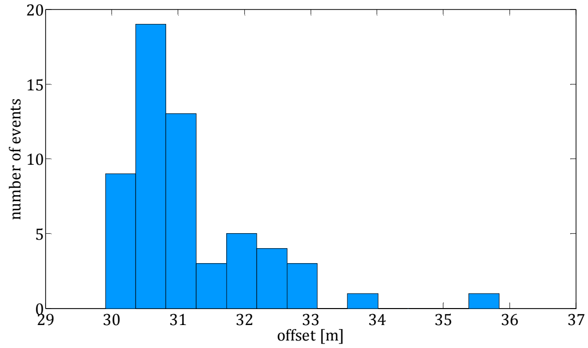

Figure 6. Offset results from the CDP

Two issues arise from this method. The first is the shift of the rising slope distribution due to scaling, as is depicted in Figure 7. It is unknown whether the new slope distribution represents the physical processes. In the other word, it is not known whether such steep slopes are physically possible. The resulting dynamic amplifications are now much higher, as can be concluded from the sensitivity plot in Figure 3.

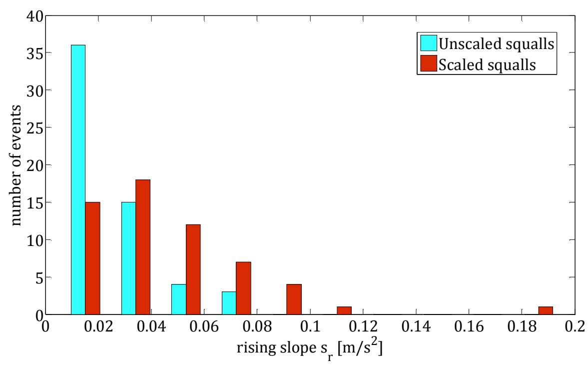

Figure 7. Shift of rising slope distribution

The second issue with the CDP is the fact that only the highest maximum is taken into account. Since all the applied scaled squalls are 100 year events, similar to design for storm condition other sample statistics (e.g. the expected maximum, the most probable maximum) could be opted as the design value, as was already suggested by Zhong et al. [5]. Selecting the highest maximum may result in undesirably conservative design value estimate.

In order to keep the physical properties of the squall events intact, several response-based approaches have been suggested in recent research studies. The first is direct extrapolation proposed by Alvarez et al. [2]. Instead of extrapolating the squalls to a 100 year event, the responses of the FPSO to the original squalls are extrapolated to an expected 100 year return offset. The results of this approach are depicted in Figure 8. As it is clear from this figure, the expected 100 year offset obtained from the direct extrapolation (37.6 m) method is higher than the estimate of the CDP (35.8 m). This is an unexpected result, as the CDP is thought to be quite conservative. However, from the confidence intervals shown in Figure 8, it can be concluded that the 100-year estimate of this extrapolation is highly uncertain due to the limited sample size. Besides, by extrapolating the offsets, the dynamic amplification is extrapolated as well. It has however been shown that the dynamic amplification has a firm upper limit, being the flat level of the sensitivity surface in Figure 3.

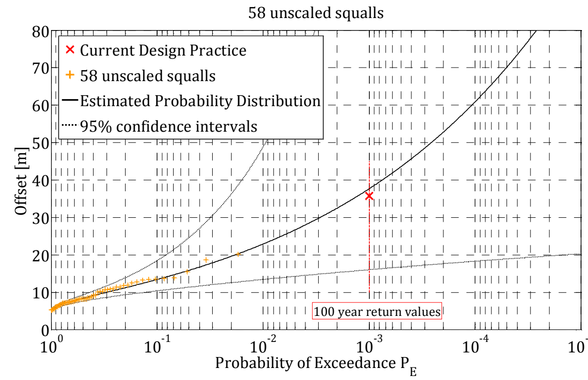

Figure 8. Results of direct extrapolation

In order to keep both the physical properties of the squall distributions as well as the response characteristics intact, Duggal et al. [1] proposed Monte Carlo simulations to get to the 100 year offset. Random picks from the fitted distributions to peak wind speed, rising slope and decay half-life time are now used as inputs into creating 100,000 squalls and the resulting offsets. The results are plotted in Figure 9 and the tail has been fitted with a Generalized Pareto distribution. The resulting 100 year offset value is 30.0 meters in this method.

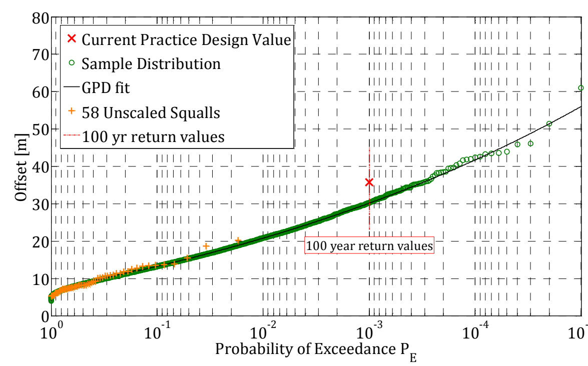

Figure 9. Results of Monte Carlo simulations

In order to compare the results from the three methods mentioned above (CDP, direct extrapolation and Monte Carlo simulations), a new simplified response-based approach is developed based on the strong correlation between offset and peak wind speed (for the linearized system), shown in Figure 2. In this approach, the dynamic offset is linked to the peak wind speed as:

$$y_{dyn} = \alpha y_{st} = \alpha C_{st} u_0^2 \quad (3)$$

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Knowing the peak wind speed distribution (fitted with a Generalized Extreme Value (GEV distribution[1]), the probability distribution of the dynamic response is derived in the form of,

$$P_E(y_{dyn}) = 1 - \exp\left(-\left[1 + \xi\left(\frac{\sqrt{\left({y_{dyn}}/{\alpha\, C_{st}}\right)} - \mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right) \quad (4)$$

In which ξ, μ and σ are respectively the shape, location and scale parameters of the GEV peak wind speed distribution.

The results of aforementioned response based approaches are shown in Figure 10. In this figure, the distribution estimated from Eq. (4) with parameter α representing the maximum dynamic amplification (1.255 for the step response, derived from figures Figure 3 and Figure 4) is also shown. This distribution can be considered as the maximum physical limit for the response of the studied FPSO.

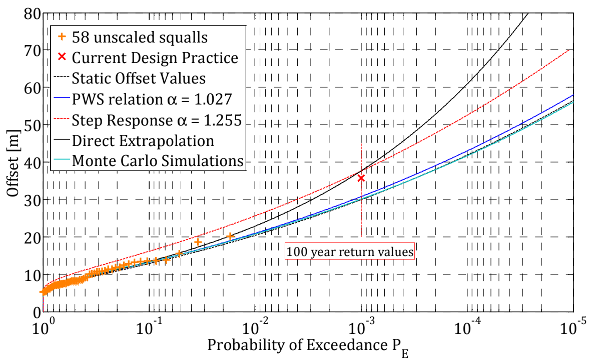

Figure 10. Comparing the different methods

It is clear from the distributions shown in Figure 10 that the direct extrapolation of responses exceeds the physical limit of the step function response. (In non-linear systems, where the mooring characteristics differ drastically from small to large offsets, the direct extrapolation method would ignore the proper offset characteristics curve, and extrapolate the smaller offset properties. This would result in even bigger deviation from the proper response characteristics curve).

The Monte Carlo simulations, as expected, follow the same distribution as in Eq. (4) with the parameter α obtained from the expected rising slope and decay time. Specifically, the dynamic amplification of 1.024 is calculated from the 100-year peak wind speed, mean rising slope and decay time. Since an increase of rising slope and decay time result in an increase of dynamic amplification, specific values of the two squall parameters can be selected for increased levels of conservatism. The three cases selected are listed below:

- Case I: Use the mean values for rising slope and decay time.
- Case II: Use the maximum observed values from the 58 squalls for both the rising slope and decay time.
- Case III: Use the extrapolated 100 year return values.

The corresponding dynamic amplifications for these cases are respectively: 1.024, 1.110 and 1.213. The probability distributions estimated from Eq. (4) with these dynamic amplification factors are presented in Figure 11. The offset design value for cases I, II and III are respectively, 30.8, 33.3 and 36.4 meter.

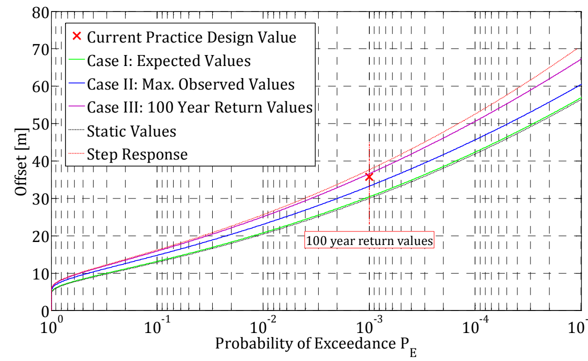

Figure 11. Results for the 3 Dynamic Amplifications cases

The distributions in Figure 11 indicate that the result of the CDP is reasonably close to the estimates of Case III which is calculated from the combination of a 100 year peak wind speed, a 100 year rising slope and a 100 year decay time. Since the parameters are independent of each other, this combination results in an event which resembles not a 100 year squall, but more a 1 million year squall. This once more indicates that the CDP is very conservative for spread moored systems.

To conclude this part of the research, the three different cases are compared from a design point of view. While case I makes most sense from a statistical point of view, the resulting dynamic amplification is however negligible, nearly reducing this method to a static solution, while it has been shown that squall are dynamic, transient processes. Case III on the other hand has been shown to be very conservative and would therefore incorporate too much conservatism to be economically feasible. Therefore Case II seems reasonable as it incorporates some conservatism over selecting the expected values, but keeps the squall physics intact, since the applied rising slope and decay time have been observed in nature.

[1] The authors are aware of the controversy of the GEV distribution for peak wind speed and acknowledge the reasoning of Harris [6] that this fitted type of distribution (GEV type II) is most likely caused by mixed environments. However, like stated before, all fittings have been applied without bias.

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TURRET MOORING ANALYSIS

For the dynamically more complex turret moored systems, a simplification to a single degree of freedom oscillator is not feasible. The second case study here considers the response of turret moored FPSOs in squalls. In this case study, three horizontal degrees of freedom, i.e. surge, sway, and yaw around the turret are considered. The FPSO is modeled after a 1.6 MMBOE, 330 meter long floater in over 1000 meters of water. For an easier comparison and to eliminate the directionality in the mooring system stiffness, the original mooring system has been substituted with 8 linear springs and dampers. Since the original system already had taut mooring lines, the linearization of the stiffness has minimal impact.

The directionality is very important for turret moored systems. In order to come to some general conclusions, the squall directional distribution is assumed to be uniformly distributed from 0 to 180 degrees relative heading. This relative heading is defined as:

$$\theta_r = \theta - \Psi \quad (5)$$

Where θ is the absolute wind heading and Ψ is the vessel heading, as shown in Figure 12.

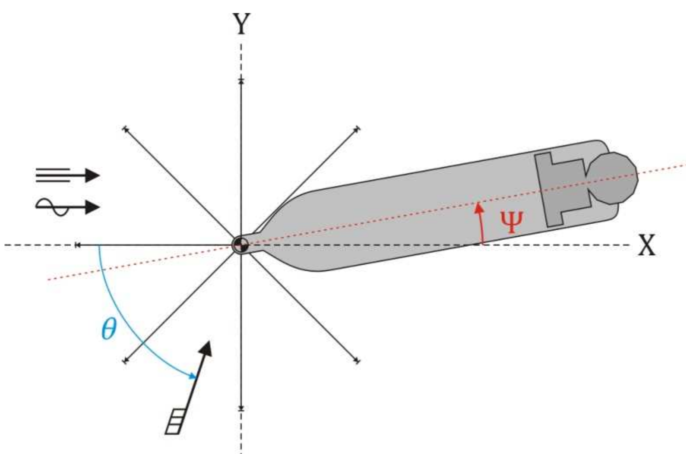

Figure 12. Heading definitions

In this example, background wave and current actions have been applied on the vessel to give the vessel an initial heading. The resulting turret offset from wave and current is negligible compared to offsets from wind squalls.

Similar to the spread moored system, the major driver for offset is the peak wind speed. The correlation between the offset and the peak wind speed for the studied turret moored system is depicted in Figure 13.

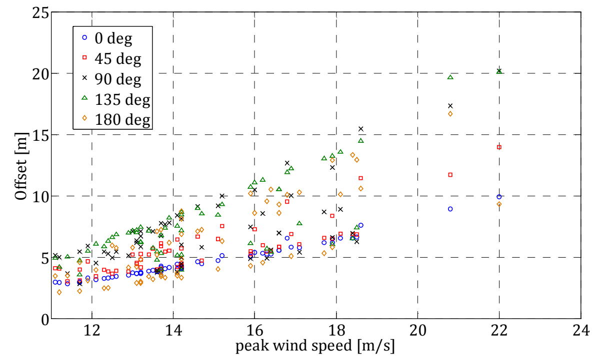

Figure 13. Offset correlation to peak wind speed

Interestingly, the quadratic relation that was seen in the spread moored system is observed in Figure 13 as well, even though the dynamic amplifications are much bigger than those of the spread moored system. More importantly, the wide spread in the results of turret moored leads to the anticipation that the system is very sensitive to the variability of the squall parameters. It is worth mentioning that the correlation between the FPSO response and both the rise time and decay time is negligible. Note that for the turret moored systems the rise time is now utilized instead of the rising slope.

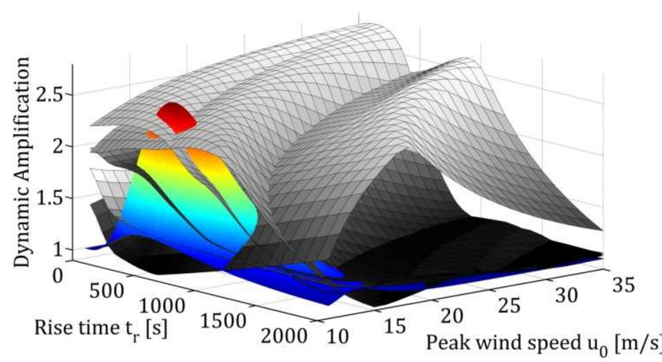

Figure 14. Sensitivity plot for turret moored analysis

The grey-shaded surface plots in Figure 14 show the sensitivity curves for 5 relative headings (0, 45, 90, 135 and 180 degrees) while the colored surface is the joint probability distribution of rise time and peak wind speed. Most importantly, this graph shows that the highest dynamic amplifications occur right in the range of the joint probability of the rise time and peak wind speed.

Following the Current Design Practice (with all squalls scaled to 27.3 m/s), it is observed that the highest offsets occur in the >90 degree sector, but it is difficult to determine the exact worst case direction, as was done in the spread moored case. After running numerous cases (see Figure 15), the design value from the CDP is estimated as 35.7 meters, occurring in the 108° direction.

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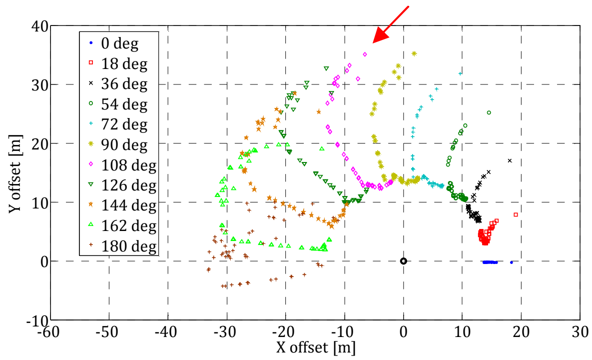

Figure 15. Maximum offsets per trace resulting from the Current Design Practice, with the highest value indicated by the arrow.

For the spread moored system, it was easy to distinguish 3 cases for the critical dynamic amplification factors; since an increase in the rising slope and the decay time automatically resulted in a higher dynamic amplification. From Figure 14, it is clear that these cases cannot be as easily defined for the turret moored system. As a conservative option, the maximum dynamic amplification factor associated with the 100 year peak wind speed (purple surface in Figure 16) is selected to estimate the design value. Similarly, the maximum dynamic amplification factor in the surface defined by the highest observed peak wind speed (green surface in Figure 16) is selected. It appears that for the maximum observed values, the dynamic amplification is 2.60, while for the 100 year peak wind speed this is 2.67.

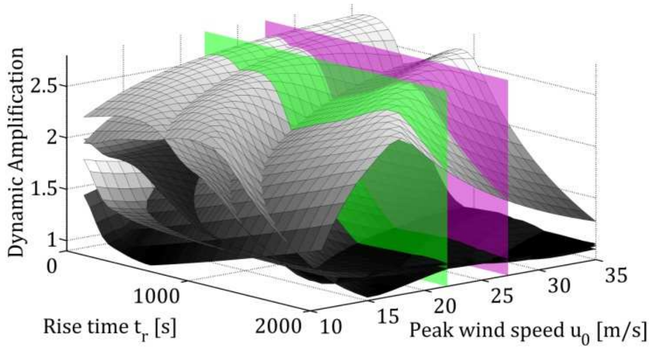

Figure 16. Areas of interest for dynamic amplifications. Green surface is the maximum observed peak wind speed, purple the 100 year equivalent.

When these values are plotted within the peak wind speed relation, it is obvious that the green line (maximum observed dynamic amplification) indeed passes through the maximum observed offsets, and the purple line is just slightly higher. The resulting 100 year offset from the purple line is 34.9 meters which is close to the Current Design Practice.

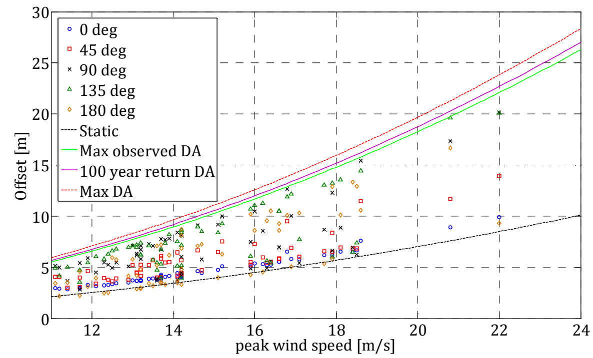

Figure 17. Peak wind speed relationship and dynamic amplification limitations

The close resemblance to the CDP is explained by the fact that during the scaling process, the rise time is not altered. Therefore the distribution remains intact, and still overlaps the areas of highest dynamic amplification, as became clear from Figure 14. Although the distribution is not altered, the question still remains if the scaled combinations of rise times and peak wind speed (hence slopes) can exist in nature.

It should be noted that the dynamic amplification used for calculation of the design value indicates an upper limit since the maximum possible amplification factor considering various relative heading, rise time, and decay time is selected. Therefore, it can be concluded that the CDP is indeed a conservative approach to estimate the design value.

CONCLUSIONS

After studying the squall parameters, the response characteristics, and several Design Value Estimation methods, the following conclusions can be drawn:

The governing squall parameter concerning FPSO offset is the peak wind speed, both for spread moored and turret moored vessels.

For spread moored systems, the offset is uncorrelated to the rising slopes and decay time for the observed range of values. The system can be sensitive to those parameters though, but careful consideration is needed to compare whether this sensitivity is in the range of the observed squall parameter values.

The Current Design Practice creates a big shift in rising slope distribution, creating rising slopes much steeper than observed in nature. It is unknown whether these steep rising slopes can physically exist in nature. The distributions are however shifted towards the range where the spread moored FPSO is much more sensitive to these parameters.

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It is known that the dynamic amplification has a strong upper limit, being the response to a step-function (for a single-degree-of-freedom oscillator). The response based method of direct extrapolation will result in values exceeding this limit, since not only the offsets are extrapolated but also the dynamic amplifications are magnified over the response limitations.

The method of Monte Carlo simulations results in good estimates of the Expected values (by definition) and shows great resemblance to the dynamic amplification of the 58 offsets resulting from the original squalls. The Monte Carlo simulations however require major computational effort and are therefore perhaps less suitable for engineering purposes.

The method of dynamic amplification limitations shows great potential to be used as a Design Value Estimating method, as it combines the physical correctness of the squalls and the response characteristics of the FPSO system. It seems to be applicable for both spread moored as for turret moored vessels.

The confidence of each methodology studied in this report is depending on the accuracy of the measured squalls and the fitted distributions. In this report, only 58 squall time series were available for research, but recently the major oil and gas companies have measured more squall events. Statistically processing more of these series will deliver more accurate results, but it has to be reminded that the characteristics of squalls are local phenomena. The mixing of data from different areas may lead to incorrect conclusions.

In this study, the squalls timeseries are simplified by an equivalent transient wind distribution. The approximation ignores the gustiness in the wind squalls and therefore is not appropriate for systems with small natural period and relative damping, which could be sensitive to this “high” frequency signal. Additionally, it is assumed that the squall direction remains constant within a squall event. However, the squall measurements indicate considerable variability in the squall direction within the duration of a squall. This variability should also be considered in estimation of the design value for systems that are sensitive to the wind directionality and is expected to have more significant effect on the turret-moored systems.

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