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RESPONSE OF FPSO SYSTEMS TO SQUALLS

Arun Duggal
SOFEC Inc.
Houston, Texas, USA

Caspar Heyl
SOFEC Inc.
Houston, Texas, USA

Amir H. Izadparast
SOFEC Inc.
Houston, Texas, USA

Joerik Minnebo
Delft University of Technology
Delft, The Netherlands

ABSTRACT

Squalls are mesoscale sudden wind-speed increases that can occur worldwide and are a design driver for FPSO systems in areas the other design environmental conditions are relatively benign, e.g. offshore West Africa. Squalls are transient winds which rapidly reach a peak wind speed (up to 50 m/s) and then decay to low speeds in a span of 60 to 90 minutes. As squalls are transient phenomena traditional steady-state analysis techniques cannot be used for the global analysis or the development of the extreme response estimates.

This paper focuses on the characterization of the squall environment and the impact of various parameters on the response of FPSOs. The responses of both spread and turret moored FPSOs are presented and the difference in response is discussed. The paper then focuses on a parametric study on a representative single degree of freedom model of a spread-moored FPSO with an emphasis on the estimation of the extreme response and its dependence on sample size.

INTRODUCTION

Squalls are mesoscale sudden increases in wind speed that sustains for a short duration. These events occur world-wide and are usually associated with severe weather. Squalls routinely occur in a squall line associated with severe thunderstorms or can be more isolated events. For the design of offshore systems, squalls can influence offshore operations, and in many cases drive the design of mooring systems for floating facilities offshore. Offshore West Africa is a region where squalls result in the extreme design loads and offsets for the floating system as the other extreme environmental criteria are relatively mild. There is a long history of squalls affecting offshore operations in West Africa ranging from drilling activities to offloading from CALM buoys and FPSOs. Though squalls occur suddenly and for a short duration, they can be tracked by radar and thus operations and other activities can be adjusted to account for the occurrence.

The West Africa Gust Joint Industry Project (WAG JIP) [1, 2] was developed to collect measurements of squall time histories at various locations offshore West Africa and analyze the data. The database was used to estimate the extreme value distributions and consequently to predict the 100-year peak one minute mean wind speed. These 100-year squall wind speeds range from approximately 30 to 50 m/s depending on the location.

From a global analysis perspective, squalls are transient phenomena and are not typically characterized by a few key parameters like most steady-state environmental conditions. Figure 1 presents a one minute mean wind velocity time history of an actual squall measured in West Africa and transformed to 10 meter height. The squall time history shows the general characteristics of squalls started with a sharp increase in wind speed from the background wind, a sustained peak speed for a relatively short duration, and then a slow decay.

The current design practice is to use actual measurements of the wind speed during squall events and scale the speed only to the appropriate design value. These realizations of squalls are then used as input into a time-domain model of the wind forcing and the resulting response calculated. Figure 1 also presents a squall time history with the wind speed scaled so the peak represents the 100-year one minute mean wind speed. The figure also shows the effect of scaling the wind speed only on the characteristics of the timeseries. The rising slope as well as the decaying slope has been changed due to the wind speed scaling which can affect the dynamic response of the system as will be shown later. This also raises the question on whether the wind speed scaling of the measured wind squall is a good physical representation of a 100-year squall or whether the time scale should also be modified. This question is partially addressed in later sections of this paper.

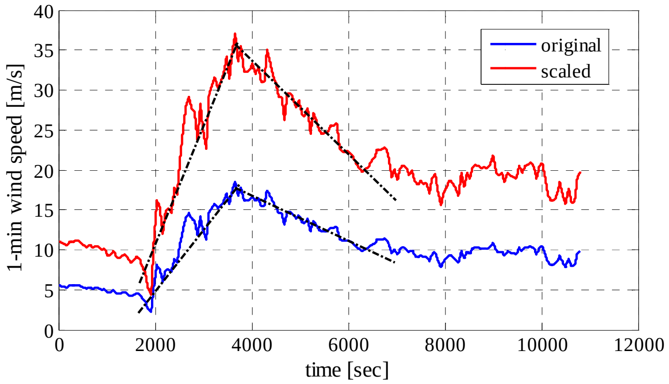

Figure 1. A sample squall time history measured offshore West Africa [1].

Though a range of squall incidence directions are typically prescribed for the squalls, the local directionality of the peak winds is more difficult to define and therefore most design criteria require the squalls to be omni-directional. In addition, the number of squall time histories provided for design may vary depending on the location or project; in our experience this has ranged from 3 to 17. From a design perspective, this raises a few issues and questions ranging from the number of simulations required to be run in the analysis, to the estimate of the design value.

The objective of this paper is to demonstrate the response of FPSO systems to transient squall loading. Firstly, the behavior of both spread-moored and turret-moored FPSOs to squalls is briefly overviewed. The focus will be on the analysis of extreme response of typical deepwater spread-moored systems offshore West Africa. The sensitivity of the FPSO's response to the characteristics of the squalls is studied and the variability due to sample size effects is evaluated. Finally, design values obtained from different extreme analysis approaches are compared and practical suggestions are given.

RESPONSE OF SPREAD AND TURRET MOORED FPSOS TO SQUALLS

This section presents some general results of the responses of spread-moored and turret-moored FPSO systems offshore West Africa to provide some background to the analysis in the following sections. Both studied systems are representative of deepwater FPSOs with actual riser and mooring systems. The response of spread moored and turret moored FPSOs to wind squalls was previously studied by Legerstee et al. [3] and Zhong et al. [4], respectively.

Spread moored FPSOs are kept at a fixed heading into the primary swell direction, resulting in relatively small yaw motions, and only sway and surge motions govern the extreme offset. Figure 2 depicts the sensitivity of the vessel offset to the wind heading studied for a series of seventeen 100-year scaled squall incidents approaching the FPSO from twenty-four directions. It shows that the highest offset is caused when the squalls are beam-on to the vessel which is expected given the large wind loading area. It is worth mentioning that the studied spread moored FPSO can be considered as a highly damped system with relatively low stiffness in sway.

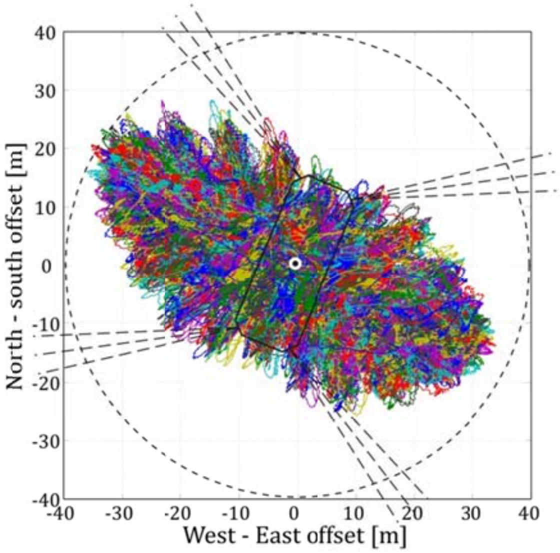

Figure 2. A Spread moored FPSO's offset traces in response to the squall loadings.

In the case of turret moored vessels, the surge, sway and yaw motions as well as angular velocity and angular acceleration play important roles in the global response of the FPSO to the squalls. During a squall event the vessel will rotate to align itself with the wind direction. This rotation causes the relative wind heading, the angle between wind direction and the vessel heading, to vary significantly depending on the initial relative wind, wave and current directions. Knowing that, the relative wind directionality is now an important parameter to be characterized in the response analysis of turret-moored systems.

Generally, a turret moored vessel subjected to a squall event experiences the largest response, i.e. turret loads and offsets, if the relative wind direction is beam-on to the vessel at the time that the wind speed reaches its peak. Whether this occurs depends predominantly on 1) the initial relative wind heading, 2) the rising time and 3) the peak wind speed of the squall.

As an example, the dependency of the resultant wind load to the rise time and the relative wind heading is illustrated in Figure 3 and Figure 4. The studied squalls in this example have equal peak wind speed. Both figures illustrate that a very short rise time (<500s) in combination with a small initial relative wind heading (<15deg from stern) is required in order to see a response in which the vessel is beam-on to the wind direction exactly when the velocity peaks.

Figure 3 and Figure 4 show three graphs with time histories that were obtained from mooring analyses of a turret moored FPSO during a squall event. The graphs show (from top to bottom): the vessel yaw motion, the resultant wind force and the wind velocity. For the yaw motion and wind force, multiple curves show the sensitivity to initial wind heading which was varied from headings almost stern-on (0 deg) to headings roughly beam-on (90 deg). The time histories of yaw motion also contain a circular marker, indicating the moment in time at which the vessel is beam-on to the wind. Figure 3 shows the results for a wind squall with a relatively short rise time (500 sec), while Figure 4 shows the same results for a squall with a longer rise time (1200 sec). The average rise time found for the squalls in the data set is around 900 sec.

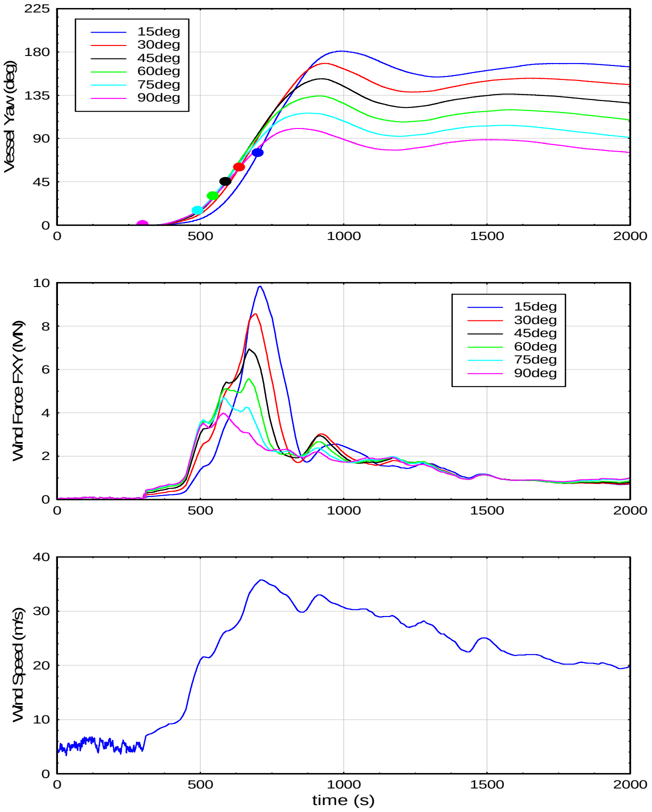

Figure 3. Effect of initial wind heading on wind load for a squall with a short rise time t_r = 500 sec.

From Figure 3, it can be seen that only the initial heading of 15 deg (blue line) results in the vessel being beam-on to the wind at the moment of the peak wind velocity. When the initial angle is greater than 15 deg, the vessel rotates to the beam-on condition before the wind velocity peaks and the resultant wind force on the vessel is reduced. As the initial relative wind heading is increased the resultant wind force is reduced.

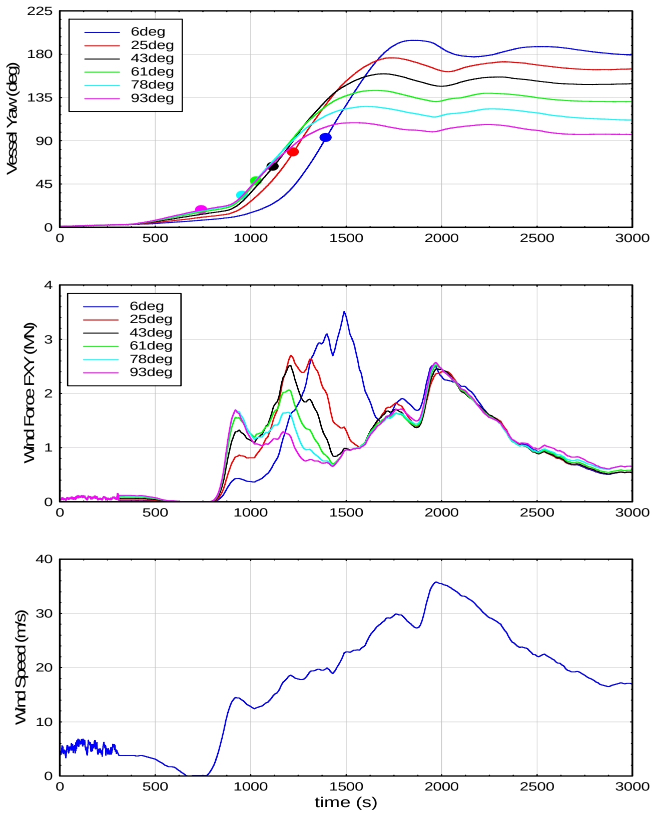

Figure 4. Effect of initial wind heading on wind load for a squall with a long rise time t_r = 1200 sec.

From Figure 4, it can be seen that when the rise time of the squall is sufficiently large, the vessel rotates to the beam-on condition before the peak of the wind velocity, even for small initial relative wind headings. As a consequence, the resultant wind force is much smaller for the squall with a long rise time compared to a squall with a short rise time, regardless of the initial relative wind heading.

These results demonstrate that, in order to accurately predict the extreme responses of a turret moored vessel in a squall environment, it is necessary to account for the actual variability of initial relative wind heading and rise time of wind velocity. This variability is ignored in the current design practice of turret moored FPSOs. Instead, a conservative approach is used in which the maximum design value is found by combining the most unfavorable initial relative wind heading with the scaled squall timeseries that has the shortest rise time.

The above discussion provides some background and motivation for the analysis performed in the following sections of the paper which focuses on the extreme responses of FPSOs to squalls and the influence of sample size on the extreme values. As shown in the section above the response of turret-moored FPSOs to squalls is complex and dependent on a number of parameters and initial conditions, and is part of an ongoing research study. The focus of the remainder of the paper is on the response of spread moored FPSOs to the squall loadings.

EQUIVALENT SINGLE DEGREE OF FREEDOM

Our studies on deepwater spread moored FPSOs indicate that the response of the structure to the beam-on wind squalls can be accurately represented by a single degree of freedom (SDOF) system with appropriate parameters, i.e. natural period T_n, damping coefficient $\zeta = C/C_{crt}$, and mass M. As an example, the comparison is carried out for a sample squall timeseries measured off of Angola coastline shown in Figure 5. In this figure the measured wind speed u is normalized with u_0 the peak 1-min averaged wind speeds. Figure 6 shows the response time histories of a spread-moored deep water FPSO to the sample squall heading in the beam-on direction. The studied FPSO is a representative of spread-moored FPSOs offshore West Africa.

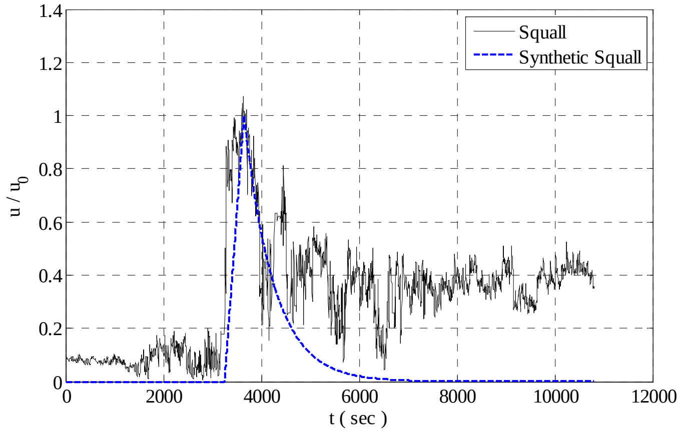

Figure 5. Actual squall timeseries and the simplified squall timesries.

In Figure 6, the offset timeseries y_{dyn} obtained from dynamic analysis is normalized with the static response Y_{st} defined as,

$$Y_{st} = F_0/k_y \tag{1}$$

where $F_0 = C_D {u_0}^2$ is the peak wind force, C_D is the wind force calculation constant, and k_y is the linearized spring stiffness. The FPSO response time history shown in Figure 6 is obtained from the time domain analysis of the FPSO utilizing OrcaFlex software and is compared with the response of a SDOF with corresponding mass and wind area, and tuned $T_n = 300$ (sec) and ζ = 0.4. To obtain more realistic results, the effect of wave and current damping is included in the FPSO response calculation. As shown in Figure 6 and also observed for other squall time histories, the finite element dynamic analysis and SDOF model converge to similar results. It is worth mentioning that for the estimated range of offsets, the relation between sway offset and the restoring forces remains linear.

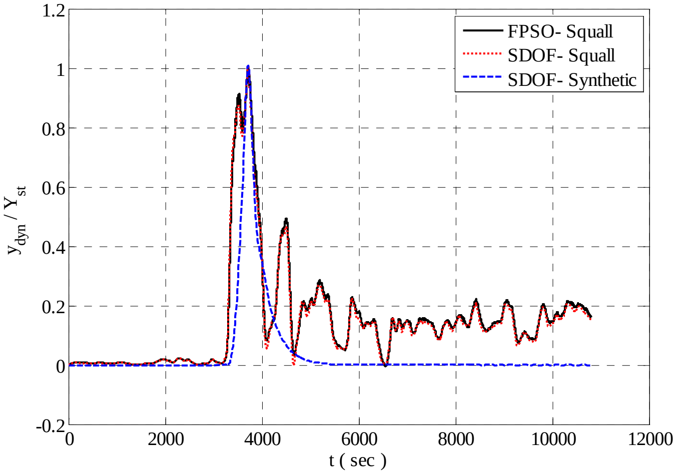

Figure 6. Comparison between estimated response time histories of different systems.

SYNTHETIC WIND SQUALL TIMESERIES

Following an analogous methodology used by Legerstee et al. [3], a synthetic wind squall is introduced to simplify the actual wind squall timeseries. The synthetic squall has three characteristic parameters, i.e. peak speed u_p, rising time t_r, and decaying half-time τ. The schematic of the synthetic wind squall timeseries and the definition of the parameters are presented in Figure 7. In this simplification, it is assumed that the wind speed rises linearly in time till the peak point and then decays exponentially as

$$u = u_p \left(\frac{1}{2}\right)^{\left(\frac{t-t_p}{\tau}\right)} \tag{2}$$

It has been observed that the peak 1-min averaged wind speed u_0 is a reasonable estimate for the peak speed u_p. The rising time t_r, and decaying half-time τ are estimated from the original squall timeseries.

Note that the synthetic squall is simplified to not contain any of the high frequency gustiness present within measured data. Comparisons between the responses of a SDOF system to the actual timeseries and the equivalent synthetic wind squall indicate that the simplification is only applicable for systems with relatively high damping coefficient ($\zeta \geq 0.2$) and natural period ($T_n \approx 300$). As an example, the peak responses of the SDOF system with damping coefficient and natural period varying in the range of ($0.01 \leq \zeta \leq 0.50$) and $100 \leq T_n \leq 300$ (sec), respectively, to both actual and synthetic time histories are compared in Figure 8. It is observed that the frequency content of the squall timeseries has considerable effect on the response of stiff and lightly damped structures and the energy content cannot be ignored. For the studied wind squall, the synthetic squall significantly underestimates the peak response of systems with small T_n even with large damping coefficient. However, for the highly damped systems with large natural period, which commonly is the case for the deepwater spread moored FPSOs, the synthetic squall adequately represents the transitional behavior of the wind squall time history.

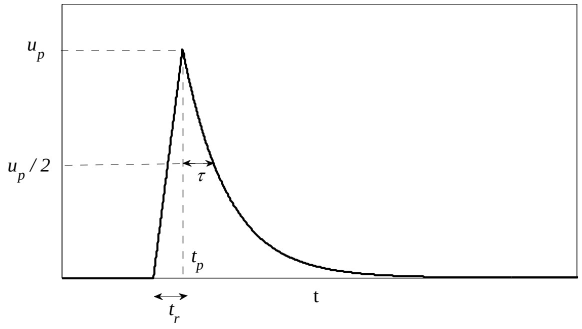

Figure 7. Synthetic wind squall timeseries.

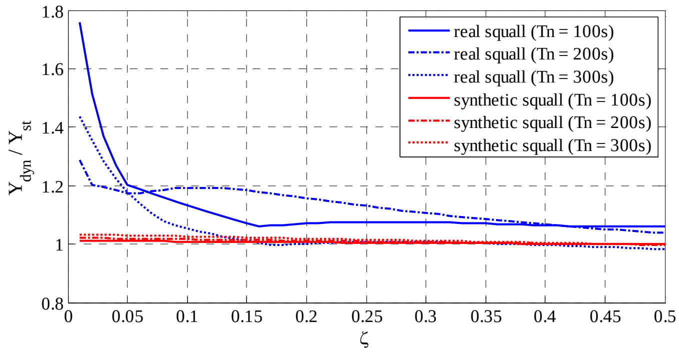

Figure 8. Comparison between the dynamic responses of a SDOF to actual and synthetic squalls.

In Figure 6, the response of the tuned SDOF to the synthetic wind profile is compared with those estimated from the finite element dynamic analysis and the SDOF excited with the actual squall timeseries. The squall timeseries and the synthetic squall used in this example are shown in Figure 5. As can be seen from the response time histories in Figure 6, the peak response is well approximated with the application of the synthetic squall.

In common practice, the squall time histories are scaled so that u_0 is equal to the 100-year u_0. This obviously changes the rising and decaying slopes of the squall time histories and may affect the dynamic response of the system. To investigate this, the sensitivity of dynamic response of a SDOF to the variation of t_r and τ is studied. For this purpose, t_r and τ of the synthetic squalls are varied in the range of $(140-2500)$ (s) and $(415-9000)$ (s), respectively. The ranges are specified based on the characteristics of 58 available measured squall time histories off West Africa. The analysis is performed for a SDOF with $T_n = 300$ (s) and varying damping coefficient ζ in the range of $(0.2-0.5)$ of the critical damping. The results of this sensitivity analysis are presented in Figure 9. In this figure, the peak offset Y_{dyn} obtained from dynamic analysis is normalized with the corresponding static offset Y_{st}.

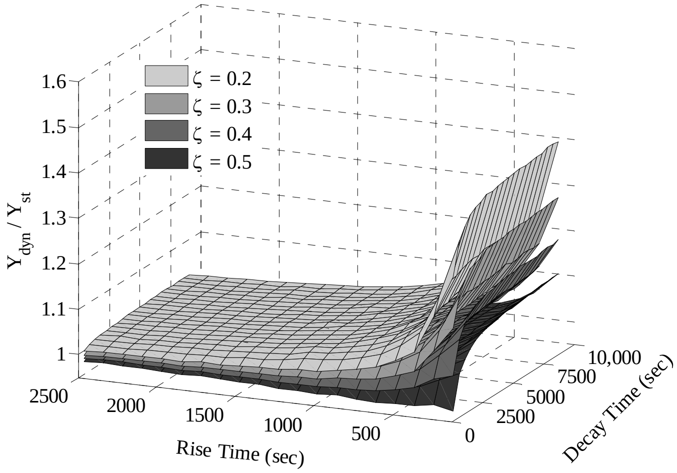

Figure 9. Sensitivity of the SDOF system's peak dynamic response to the characteristics of the synthetic squall.

The slope of distributions shown in Figure 9 indicates the sensitivity of the response to the variation of the parameter of interest. It is observed that the response distributions in both t_r and τ start with a relatively sharp slope which decreases with increase of t_r and τ and eventually asymptote to zero. Generally, the decrease in the t_r increases the peak dynamic response, while the decrease in the decay has the opposite effect. This was previously observed in the study by Legerstee et al. [3]. As expected, the sensitivity to variation of t_r and τ decreases with the increase in the damping coefficient.

EXTREME ANALYSIS

The focus in this study is on the extreme analysis of spread-moored deep-water FPSOs response to the squall loading. For this purpose, two response based approaches are utilized in which the extreme analysis is performed on the response of the tuned SDOF system. The main difference between the two approaches is that in the first approach the long-term analysis is performed on the peak offset to obtain the 100-year peak offset while in the second approach the 100-year 1-min mean wind speed is applied to obtain the expected peak response.

In the first approach the three parameters of synthetic squall, i.e. peak speed u_0, rise time t_r, and half-time decay time τ are modeled as random input to the SDOF system. Next, the extreme long-term analysis is performed on the structural response. Note that the effect of long term variation of squall direction is not considered in this analysis which will frequently result in conservative predictions. The probability distributions of u_0, t_r, and τ are estimated from samples obtained from 58 wind squall time histories measured off West Africa. The small sample size will definitely add uncertainty to the estimated extreme statistics which is inevitable at this point. As shown in Figure 10, the observations indicate minimal correlation between the parameters u_0, t_r, and τ and therefore it is assumed that u_0, t_r, and τ are mutually independent random variables. To obtain reliable extreme values, 100,000 Monte-Carlo samples are generated and the response of the SDOF is estimated for each simulation. The exeedance probability distribution of the peak offset is presented in Figure 11. The estimated distribution in this figure is a Generalized Pareto Distribution (GPD) commonly used for the peak-over-threshold analysis, specifically (Pickands III [5]),

$$F\,(x) = \begin{cases} 1 - \left(1 + \frac{\xi(x-\mu)}{\delta}\right)^{-1/\xi} & \xi \neq 0, \\ 1 - exp\left(-\frac{x-\mu}{\delta}\right) & \xi = 0 \end{cases} \tag{3}$$

where μ is the location parameter (limit value), ξ is the shape parameter, and δ is the scale parameter. For the response sample Y_{dyn}, the GPD parameters are estimated as $\hat{\mu} = 12.0$, $\hat{\xi} = 0.128$, and $\hat{\delta} = 3.6$. Note that, in the case of $\xi > 0$, the random variable is only defined for $x > \mu$. Based on the estimated parameters, the extreme values with return period in the range of 1 to-10,000 year are marked in Figure 11 and the values are presented in Table 1. One should use the extreme statistics with return period larger than 100-year with care as those values are obtained from extrapolation of the probability distribution. From the results of this analysis, one can expect a 100-year sway offset of 37.7m for the FPSO.

In the second approach, it is assumed that u_0 is the dominant random variable which is aligned with the common practice used in the design of FPSOs in West Africa. Similar to the pervious approach, Monte-Carlo simulation is performed with independent random t_r and τ while the peak velocity kept constant as the 100-year u_0. Since long-term analysis is performed on u_0, no extrapolation is required on the response and therefore the number of simulations is limited to 1000. The statistics of interest are the expected value and standard deviation of the peak offset which are estimated as $E\left(Y_{dyn}\right) = 36.6\,(m)$ and $\sigma\left(Y_{dyn}\right) = 1.2\,(m)$, respectively. The $\sigma\left(Y_{dyn}\right)$ is an indication of the sensitivity of the peak offset to the variability of t_r and τ which for the studied case with relatively high damping is not significant. The difference between the expected value of 36.6 (m) calculated in this approach and the 100-year offset of 37.7 (m) estimated in the previous approach is about 3% of the 100-year offset. This relatively small difference justifies the assumption that the dominant random variable is the peak velocity for the studied FPSO. From these analyses, the second approach seems to be more appropriate for design studies where limited number of squall samples and an estimate of 100-year u_0 are available.

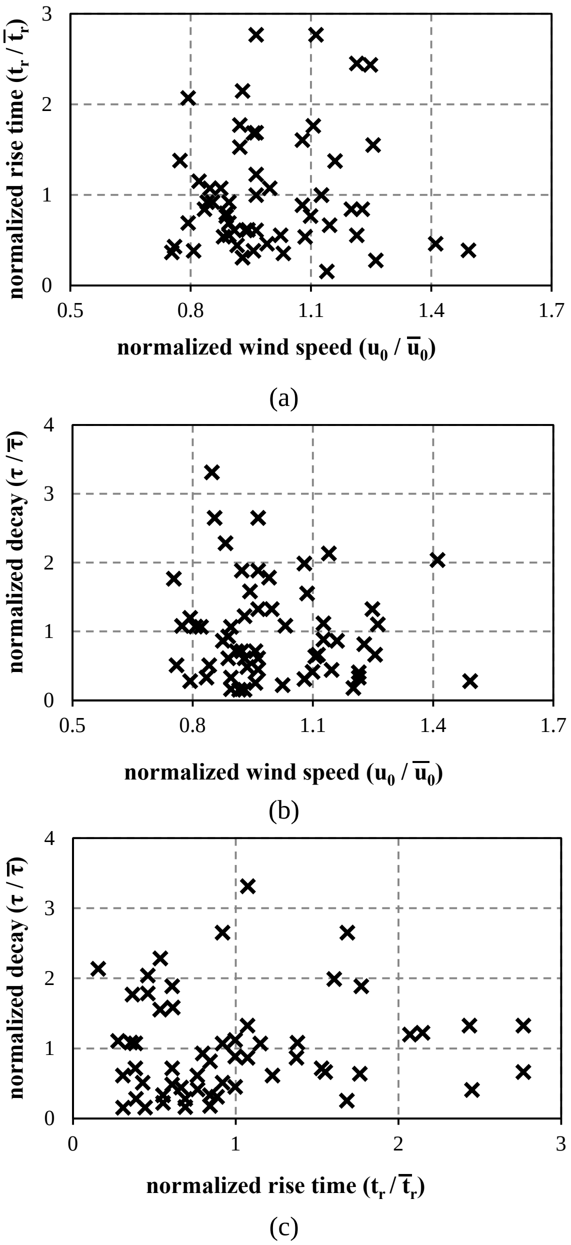

Figure 10. Correlation between the synthetic squall parameters. (a) u_0 versus t_r, (b) u_0 versus τ, (c) t_r versus τ.

Table 1. Extreme offsets obtained from response-based Monte-Carlo simulations.

Return Period	Y_{dyn} (m)
1	13.7
10	24.0
100	37.7
1000	56.2
10000	81.1

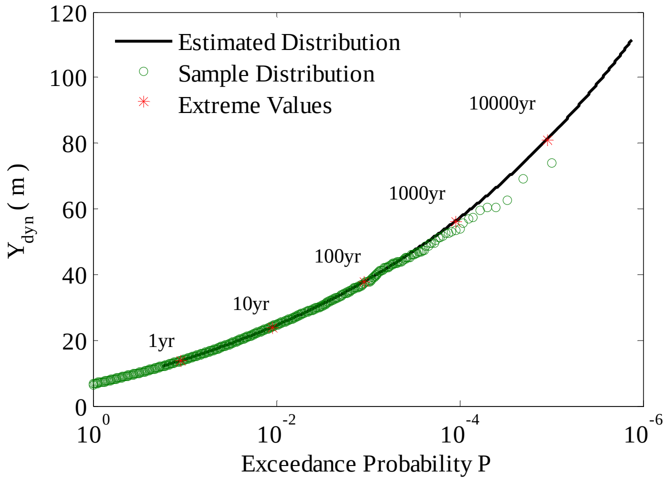

Figure 11. Probability distribution of SDOF response to the random synthetic squall loading.

SAMPLE SIZE EFFECT

As mentioned earlier, in common design practice, the response of FPSOs to a limited number of scaled squall time histories is utilized to estimate the design value. Here, a similar situation is modeled utilizing 1000 Monte-Carlo simulations. In each simulation, N synthetic squalls with randomly selected rise time t_r and half-life decay time τ and peak velocity of 100-year u_0 are generated and the response of the tuned SDOF to each synthetic squall is estimated. Next, the sample statistics including the mean, standard deviation, and maximum responses are estimated. This gives us 1000 mean peak and maximum peak values to estimate the variability of these statistics. To investigate the sample size effects, the study is performed for $N = 10, 20, \text{and } 50$. The mean and standard deviation of mean value $E\left(Y_{dyn}\right)$ and maximum peak $Max\left(Y_{dyn}\right)$ offsets obtained from 1000 simulations are given in Table 2. As expected, the variability of statistics decreases with the sample size increase. Note that the mean of $E\left(Y_{dyn}\right)$ is not a function of sample size while obviously the mean of $Max\left(Y_{dyn}\right)$ varies with sample size. For a sample of size $N = 20$ the standard deviation of $E\left(Y_{dyn}\right)$ and the upper 95% confidence limit of $E\left(Y_{dyn}\right)$ are estimated from 1000 Monte-Carlo samples to be 0.3 and 37.1 (m), respectively. The small variation in the extreme statistics indicates that the sample size of approximately 20 is large enough for estimating the design value. It should be noted that this is only the case for highly damped and low stiffness systems. For lightly damped and/or stiff system the variability is expected to be more significant and therefore larger size samples may be required.

Assuming that the squall samples are representative, one can use the design value estimation approach recommended by Bureau Veritas [6] in which the design value is defined as the summation of the sample mean value $E\left(Y_{dyn}\right)$ and a fraction of the sample standard deviation $\sigma\left(Y_{dyn}\right)$. Specifically,

$$Design\,Value = E\left(Y_{dyn}\right) + \alpha\,\sigma\left(Y_{dyn}\right) \tag{4}$$

For instance, the response of the tuned SDOF system to 17 synthetic squalls with parameters obtained from measured time histories used in a real project has been estimated. For the studied realizations $E\left(Y_{dyn}\right) = 36.4$ (m) and $\sigma\left(Y_{dyn}\right) = 1.24$ (m) which leads to the design value of 36.5 (m) obtained using $\alpha = 0.06$. As expected the design value is consistent with the estimates obtained from previously discussed approaches.

Table 2. Sample size effect on the statistics of the peak response.

Sample size	$E\ (Y_{dyn})$		$Max\ (Y_{dyn})$	
	Mean	Std	Mean	Std
10	36.6	0.4	38.9	1.3
20	36.6	0.3	39.5	1.2
50	36.6	0.2	40.5	1.0

CONCLUSIONS

The paper presents the general behavior of turret and spread moored FPSOs to squalls and identifies some key parameters that influence the response of the system. The paper also focuses on obtaining a more basic understanding of squall parameters based on studying the response of a simplified single degree of freedom system. In addition, Monte-Carlo simulation technique is used to develop response based extreme estimates, and also to evaluate the sample size effect on the variability of extreme values.

The combination of analysis and study made with the multi-degree of freedom FPSO systems (both spread and turret moored) along with the single degree of freedom spread moored model allowed us to draw some conclusions on the system response and estimates of extreme. Though the analysis performed is not complete in terms of addressing all the dependent parameters, sufficient detail is achieved that allows us to make the following conclusions.

1. Measurements of squall wind speeds show that the squalls have certain characteristics that can influence the response of the FPSO. The paper shows that based on system characteristics the rise time to the peak speed can have an impact on the response of the system. The paper also shows that based on a number of measured squall time histories, there is no correlation between the rise time to the peak wind speed, raising questions whether the current approach of scaling the velocity of measured squalls to the design value is physically correct.

2. The response of FPSO systems to squalls varies as a function of system stiffness and damping. Typically lower stiffness and highly damped systems (deep water) are less susceptible to dynamic amplification of the response due to squalls. For shallow water (typically stiff mooring systems) with low damping, e.g. a tower yoke mooring system, the influence of both the rise time and the gustiness associated with a squall can have a more pronounced influence on the system response with the dynamic amplification expected to be higher. The analysis of this type of FPSO is part of an ongoing research study.
3. In the case of turret moored vessels, the variability in the wind direction and rise time of the squall realizations has a large influence on the response.
4. It was illustrated that the 100-year extreme response of spread moored FPSOs can be well estimated from long term response analysis and application of un-scaled squall timeseries. The long term response analysis has added benefits of using un-scaled squall time histories which eliminates issues related to modifying the rise time and decay time. However, the details of this long term analysis of turret-moored FPSOs are not clear due to the importance of additional parameters dependent on wind speed and rise time. This is another topic for future research.
5. The paper demonstrate that the variation in extreme response of deepwater spread moored FPSOs for a number of squalls ranging from 10 to 50 was not very different due to the low level of dynamic amplification. This implies that the current design practice of using 10 – 20 independent squall time histories should be adequate for estimating the extreme response of deep water FPSOs, especially those that are spread moored. The expected value of the extreme response should be used as the design value for the system as long as the variability of the extreme value due to sample size is accounted for.

A final objective of this study was to also provide some quantitative feedback to the metocean community on the impact of the current methodology of defining squalls for design on the analysis and design of the mooring system. We hope that this paper provides some insight that can refine design criteria for future projects.

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