SQUALL: NIGHTMARE FOR DESIGNERS OF DEEPWATER WEST AFRICAN MOORING SYSTEMS

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ABSTRACT
Squalls have been present in the environmental specifications for floating units in West Africa for the last couple of years. However it appears that such phenomena tend to be the designing factor for mooring systems of deepwater FPSO’s (in spread or turret configuration) and offloading buoys. At that stage, due to the lack of proper modelling/characterisation, squalls tend to be represented for design purposes by on-site recorded time series of varying wind velocity and associated relative headings applied from any direction. This leads to rapid changes in offsets and loads in the mooring lines induced by the transient response of the vessel to sudden load increase generated by such squall signal. Through diverse exemplary simplified calculations, this paper illustrates the influence of the consideration of squalls in the design process, together with the present shortcomings in the modelling process, either in terms of extreme conditions, or in terms of operating conditions, knowing that such events are difficult to forecast. In addition the effect of tugs, and associated operating limitations are also discussed. Areas needing further investigation are finally identified.

INTRODUCTION
For floating structures from a mooring/risers/hydrodynamic point of view, current design practice consists of considering extreme events due to combinations of extreme environment components such as wind, waves and currents. Along the coast of West Africa, given the moderate environment, particular phenomena are likely to prevail over other conditions and become governing in the design process: squalls. For this reason, two sets of extreme winds are specified, one for sustained wind conditions, the other for squalls.

West Africa is particularly affected by the position of the Inter-Tropical Convergence Zone (ITCZ), resulting from the convergence of trade winds from the North-East and from the South-East, and which is characterised by a great activity of cumulonimbus vertical formation and by heavy rains and squalls. Squalls are thunderstorms generated on land, which tend to form along lines separating air masses and which usually travel westward over the sea. They trigger a sudden and large increase of wind speeds: a squall event usually lasts less than an hour at one given location.

Squalls are particularly frequent before and after the rainy season, i.e. from April to June and from September to October.

While satellite and hindcast data reproduce quite well sustained wind speeds and directions, local perturbations such as squalls are only captured by on-site measurements. Indeed, satellite data does not provide information about squall winds, as these are not at all stationary events: only measurements with a sampling acquisition period of at least 1Hz may enable to derive squall wind speeds with adequate accuracy. Worth to mention that some gusts extreme values available for various projects have been calculated from in-situ measurements, offshore Nigeria, Angola and Congo, analysed during Phase 1 of the West Africa Gust Joint Industry Project (WAG JIP). In addition, it should be noted that the standard wind speed conversion factors applicable for sustained winds do not apply for strong gusts because regular trade winds and less frequent, stronger winds or squalls, are different phenomena.
Squalls are highly unstationary phenomena: the very rapid change of wind speed intensity is often accompanied by a rapid change of direction. In addition available records show that, although squall winds are usually known to turn East (i.e. from East), this is not always the case.

In order to illustrate the main issues raised by the consideration of squalls in the design process, and to highlight some of the limitations of the current practice, the effects of a squall on a typical FPSO spread moored in the Gulf of Guinea are analysed. Then a simplified squall model is built, in order to assess the sensitivity to some key parameters. The details of the procedure are detailed in the next sections.

WIND MODELING

For such location in West Africa, two sets of extreme winds are usually given, a set for sustained wind conditions and another set for squalls.

It should be noted that these extreme winds have not to be associated to extreme waves, because the phenomena are not correlated, particularly for squalls. Furthermore, the time during which they blow over the sea and their relatively limited extent is not sufficient to significantly modify the existing sea state.

In the design process, 100-year return period squall conditions will be associated with ‘background’ underlying sea states, based on the 95 percent non-exceedance probability values. More details on associated sea states are given in Ref. 1 and Ref. 3 and are currently the subject of on-going joint studies, based on both measurements and theoretical approaches.

For sustained winds, usual design practice consists of using a mean wind speed in combination with a wind spectrum to reproduce the wind speed variations, the intensity by direction being defined by the metocean data.

In terms of analysis procedure, squalls are better accounted for in the time domain, and their impact needs to be assessed for any direction, with the directional extreme gust speeds, if available.

ANALYSIS

In order to investigate the potential impact of squalls on the design of deepwater mooring systems, a typical measured wind squall time series has been considered. Then an idealised simplified model has been used for further numerical analyses. The frequency content of the squall time records is briefly discussed, considering also the filtering brought by the FPSO.

All calculations are based on time domain calculations, performed with the ARIANE software, developed by Bureau Veritas.

Model Data

A typical West African FPSO has been considered for the present study: it consists of a 2 million-barrel FPSO, spread-moored by 4 bundles of 3 lines in about 1,000 m water depth.

As the focus is essentially on wind effect, only wind force coefficients were necessary for the purpose of this study. These wind coefficients were originally established through wind tunnel testing. In addition some damping has been implemented, based on Ref. 1.

The principal characteristics of the FPSO are given in Table 1 and Figure 1.

The 4x3 spread mooring system consists of the following segments, from anchor to fairlead:

• 300 m of R3 studless chain,
• 1,500 m of sheathed spiral strand wire rope,
• 200 m of R4 studless chain (adjusted according to pretension)

The mooring pattern is illustrated in Figure 2.

As the natural period of the moored FPSO is expected to have a significant influence on the dynamic response to a squall, two sets of pretensions have been considered: 100 t and 300 t leading respectively to natural periods in surge and sway of 400 s and 250 s.

Squall time record and averaging periods:

Time records depend from the acquisition equipment and data processing. Most of the time, averaged values will be given and stored to a specific time step. A typical wind squall recording time series is given in Figure 3.

This time series is applied to the numerical model defined above, and the dynamic response in sway is analysed (cf Figure 4).

From Figure 4, firstly a transient response to the rise time of the squall signal is observed, followed by more or less damped oscillations at the motion natural period. Remarkably, the high frequency oscillations of the input signal are completely filtered by the FPSO.

This strongly suggests that the high frequency part of the wind signal has absolutely no effect on the overall response of the FPSO, and can be safely removed from the signal. This can be further demonstrated by using running average of the signal...
over different lapses of time and then analysing the FPSO response.

Figure 5 shows that there is no noticeable difference between the response to the original signal and the signal averaged over 1 minute. However, for averaging periods longer than 1 minute, the response becomes clearly underestimated. This can be linked to the increase of the rise time by half of the averaging period, due to the averaging process. The rise time therefore appears to be the key factor for the dynamic response to a squall.

Thus, the time series of the 1-minute wind speed can be in a first approach characterised by a rise time (time from instant of minimum recorded wind speed just before the peak and instant when the peak is reached) and a decay time. In the numerical models used in next section, the rise has been modelled as a linear function of time, whereas the decay section has been modelled by an exponential function, characterised for instance by the half-decay time, ie the time to decrease from the peak value to half of this value (cf Figure 6).

### Parametric Study

The response is that of a single degree of freedom oscillator and therefore depends essentially of the natural period of the system, and the damping level.

Two natural periods have been considered, corresponding to the two sets of pretensions mentioned above, with the same level of damping, corresponding to a real situation.

From this series of runs, the following conclusions can be drawn:

1. The maximum response is generally higher than the static response. The dynamic amplification depends of the rise and decay times, and of the natural period (Figure 7). This confirms the results that can be obtained from theoretical approaches, published in the literature.
2. The dynamic amplification factor is maximum for a rise period to natural period ratio in the range of 0.2 – 0.3. For the two systems considered in this paper, this corresponds to rise times ranging from 50 to 120 seconds, matching what can be observed from actual recordings. Beyond this, dynamic effects generated by a unidirectional squall can be considered negligible (Figure 7a).
3. The decay time has also a notable effect: it can be seen from Figure 7b that for the same rise time to natural period ratio, a longer decay time will lead to higher dynamic amplification.

The observations made above are to be taken with caution: the direction changes, not considered in this study, will introduce additional terms in the response.

### Spatial distribution

It is current conservative industry practice to assume that the same wind speed is simultaneously applied to the whole volume of the FPSO.

Under sustained winds, a static wind speed $v_t$ is assumed, averaged over a period $t$ of the dimensions of the object to which it is applied (e.g. 3s for local action, 1 minute for larger structures, cf Ref. 2). For a floater, where the low frequency actions of the wind are significant, like for deepwater systems, a spectrum is used. However, the components with period less than 1 minute in the resulting signal will be filtered by the FPSO, as illustrated in the previous section for squalls. Their spatial coherence is therefore of no interest as regards the overall response.

For squalls, there is currently no available data concerning the characteristics of the wind field and the spatial coherence. It is worth pointing out that wind speed measurements are generally acquired using one single anemometer.

Appropriate measurements are necessary to resolve the current uncertainties as regards the wind field characterisation. However, as of today, there is no other alternative for the designer but to apply the same conservative assumptions.

The potential consequences of a different assumption on the spatial distribution are shown in Figure 8 to Figure 10.

Two types of runs have been performed:
- The first one applying instantaneously a quartering wind to the FPSO
- The second one consisting of a beam wind profile, travelling along the FPSO axis as shown in Figure 8.

Depending on the propagation speed of this front, a dynamic response greater than that generated by a unidirectional quartering squall can be observed.

That means that even a beam squall unidirectional, but propagating longitudinally may generate an unexpected dynamic response of an FPSO, having similar effects with that generated by an oblique environment or by a wind speed reversal as it is often observed during squalls.

This in turn may explain some discrepancies observed when trying to correlate on-site simultaneous measurements of environment and motions of a floating unit with numerical models.

### Vertical profile

Wind force coefficients are usually derived from wind tunnel tests, using a controlled flow, in terms of intensity,
direction, turbulence intensity and vertical profile. This is well established for ocean wind but, given the different nature of physical phenomena intervening in the generation of squall winds, the question whether a standard exponential profile (Ref. 2) is applicable to squall is legitimate. As there is no or little data concerning vertical distribution of wind speed during squalls, the effect of a different vertical profile cannot be quantified. It is expected that at least isolated structures such as flares might be affected even though the overall response is kept unchanged.

This gap may be bridged by on-site measurements, using the adequate vertical distribution over the exposed areas of an FPSO in order to update the present state-of-the-art. Wind load coefficients derived through the procedure mentioned above may no longer be valid in case of squalls.

OFFLOADING OPERATIONS

Limiting operating conditions

Offloading operations, either from an FPSO or an offloading buoy, are likely to be affected by squall events, since these cannot be forecasted with sufficient time to allow proper disconnection. Typical time for disconnection ranges from 45 minutes to 1 hour (from decision to effective disconnection), and cannot be reduced without compromising flushing of the floating hoses. This is about the order of magnitude for squall forecast. Furthermore, as forecasts are mainly based on visual observations, events occurring at night are difficult to forecast, unless proper radar detection is in place.

Consequently, design procedure for offloading operations should take into account squall events, in general rescaled to 1-year return period values (typical maximum offloading conditions for West Africa).

Beyond wind speed sudden increase, changes in wind direction will have a significant influence on the behaviour of the shuttle tanker, and dynamic effects will be prevailing, not only in terms of tensions in the mooring lines or in the hawser but also in terms of relative heading.

Tug assistance is generally provided during offloading operations; however, as tugs are experiencing the same squalls as the shuttle tankers, they have only limited control on the bollard pull, and tend to act so as to maintain the tension in the tug line to acceptable levels, either through repositioning or line pay-out. As a result, tug action cannot be considered effective during squall event.

Line failure during squall event

In light of the above, a line failure might occur during a squall event, and possibly during an offloading operation. Although the probability of such combination of events appears to be lower than that for usual design conditions, it has not been quantified yet and is not addressed in the present versions of mooring codes. There is a trend in the industry to consider such events in the design loop, as transient effects, thus allowing lower safety factors.

Further work is also needed in this area, in order to keep consistency between probability levels and applied safety factors.

CONCLUSIONS

The present paper shows the influence of the consideration of events such as squalls in the design process of floating units in West Africa.

The uncertainties linked to this phenomenon have also been highlighted.

Further research is needed to understand the physical phenomenon associated to squall events, and should lead to better description for design purpose, and better forecasting from the operating point of view.

Active participation of operators of West African units needs to be pursued, through dedicated instrumentation, sharing of collected data and statistical processing. Such work will give a proper ground to guidance for design, when the major uncertainties listed in this paper have been understood and satisfactorily resolved.

ACKNOWLEDGEMENTS

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Table 1: FPSO Characteristics

AERODYNAMIC DRAG FORCES PER (VELOCITY UNITY)

Figure 1: FPSO wind load coefficients

Figure 2: FPSO mooring system

Figure 3: Typical wind squall recording time series

Figure 4: FPSO dynamic response in sway

Figure 5a&b: Effect of different averaging periods of wind velocity on FPSO response
**Figure 6: Theoretical model**

- Wind speed
- Vmax
- Vmax/2
- Rise time
- Half decay time

**Figure 7a&b: FPSO Response to different theoretical squalls**

- Response increases when rise time $T_r$ decreases

**Figure 8: Definition of a forward travelling front**

**Figure 9: Loads generated on an FPSO by a quartering squall vs. a travelling front**

**Figure 10: FPSO response to a forward travelling front**

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