Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering
OMAE2014
June 8-13, 2014, San Francisco, California, USA

OMAE2014-23446

PREDICTION OF MOORING LINE TENSIONS FOR HURRICANE CONDITIONS IN THE GULF OF MEXICO

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ABSTRACT

A probabilistic metocean model for hurricane conditions is briefly described. The model is based on site-specific, hindcast data and defines the time variation of the metocean conditions during the realisation of a hurricane at the site. The annual extreme value distribution of mooring line tension for a large, semi-submersible, mobile drilling unit is computed. Time domain analysis is applied to obtain the short-term, extreme value distribution of line tension, conditional on stationary metocean conditions. A large number of different conditions are considered. A response surface is used to interpolate on the short-term distribution parameters in order to describe the tension response during the varying conditions associated with the passage of a hurricane. The hurricane duration is split into a sequence of 15-minute intervals such that the conditions can be assumed stationary during each such short interval. The tension distribution, conditional on the realisation of a hurricane, is accumulated across the sequence of short intervals. The distribution of hurricanes is taken into account to obtain the tension distribution in a random hurricane. Finally, the frequency of hurricanes is taken into account to give the annual extreme distribution of line tension. The characteristic tension computed using 10-year return conditions and the ISO 19901-7 design standard is found to correspond to a return period of 29 years in the test case. The effects of various assumptions in the design analysis are investigated. Sensitivities to simplifications of the metocean model are considered. The effects of uncertainties in the response calculation and in the distribution of peak significant wave height during hurricanes are quantified and included in the response analysis.

INTRODUCTION

This paper is based on part of the work in the NorMoor joint industry project [1], which aims to calculate the notional probability of failure associated with design standards for mooring lines, in the ultimate limit state. Thus, the annual extreme value distribution of the mooring line tension is required, as is also the distribution of the line strength. The analysis of the line tension in this context is necessarily more complicated than the analysis applied in routine design of mooring lines. The method applied to Norwegian waters, using frequency-domain analysis, in the DeepMoor project [2] is readily applicable to time-domain analysis in the present project [3]. However, available methods for hurricane waters were not seen as entirely satisfactory. Tromans and Vanderschuren's [4] approach is sometimes used, but is based on one dominant, metocean variable, namely the significant wave height, and relies on extrapolation of the response distribution parameters from more moderate conditions up to the extreme conditions that lead to line failure.

The present approach to modeling hurricane conditions is briefly described below and a more detailed description may be found in [5]. The body of the paper starts with the overall probabilistic formulation of the analysis. Then the mooring system used in the case study is described and further details of the analysis are filled in.

NOMENCLATURE

a_L	Linear coefficient of shape function.
a_P	Parabolic coefficient of shape function.
$f_X(x)$	Probability density function for variable X.

$F_X(x)$	Cumulative probability function for variable X.
h	Significant wave height.
h_p	Peak significant wave height in a hurricane.
n	Number of short-term intervals in a hurricane.
v	Average frequency of hurricanes per year.
t	Time.
t_p	Peak wave period.
u_c	Surface current speed.
v_w	Mean wind speed.
Z, z	Line tension.
Θ, θ	Stochastic vector describing a hurricane.
$\psi_i(\theta)$	Vector of short-term metocean conditions during interval i of a hurricane realisation θ.

PROBABILISTIC FORMULATION

The hurricane model includes stochastic variables to describe the peak wind, wave and current conditions in a hurricane and the variation of the corresponding metocean parameters during the passage of a hurricane through a chosen location. These stochastic variables are collected as the components of a stochastic vector Θ which is further defined below. It is assumed that the passage of a hurricane can be split into a sequence of 15-minute intervals, such that the metocean conditions may be considered to be stationary during each such short-term interval, for the purpose of computing the distribution of mooring line response. Metocean conditions during each such interval are described by the components of a deterministic vector $\psi_i(\theta),\ i = 1,2,\ldots,n$ for a given realization of a hurricane θ, where n is the number of intervals in the hurricane. The extreme value distribution $F_{Z|\Theta}(z|\psi_i(\theta); 15\text{min})$ of the line tension Z is determined for each of these short intervals. Then the extreme value distribution of the line tension during the whole hurricane is obtained as

$$F_{Z|\Theta}(z|\theta; \text{hurricane}) = \prod_{i=1}^{i=n} F_{Z|\Theta}(z|\psi_i(\theta); 15\text{min}) \tag{1}$$

where it is assumed that the tension is independent between short-term intervals, beyond the dependency taken into account by conditioning on the same hurricane realisation. This should be a reasonable assumption for tension processes, which are normally fairly wide-banded.

The extreme value distribution in a random hurricane is determined from a probability integral over the hurricane conditions

$$F_Z(z; \text{hurricane}) = \int F_{Z|\Theta}(z|\theta; \text{hurricane}) f_\Theta(\theta)\, d\theta \tag{2}$$

where $f_\Theta(\theta)$ is the joint probability density of the hurricane conditions. This multi-dimensional integral is computed by a second order reliability method (SORM), [6]. Finally, the annual extreme value distribution of line tension is obtained as

$$F_Z(z; \text{annual}) = \exp\{-v(1 - F_Z(z; \text{hurricane}))\},\quad z > z_0 \tag{3}$$

where v is the frequency of hurricanes per year, it is assumed that hurricanes occur as a Poisson process and z_0 is a suitable tension level such that the tension distribution is dominated by hurricanes above this level. Milder, non-hurricane conditions will contribute appreciably to the tension distribution below the level z_0, but have negligible effect above this level. Tensions with return periods of 10, 100, 1000 years are found by inverting the annual extreme value distribution for probability levels of 0.9, 0.99, 0.999, respectively.

MOORING CASE

A large, semi-submersible, mobile drilling unit (MODU) with 43000 tonnes displacement is selected for the case study, intended to be typical of practice in the Gulf of Mexico. A water depth of 1500m is considered. Natural periods and linear damping ratios are listed in Table 1.

Table 1 Natural periods and damping of MODU.

Motion mode	Natural periods [s]		Damping ratios [%]
	With moorings	Without moorings	
Surge	236	-	52
Sway	288	-	52
Heave	18.5	18.5	5
Roll	42.9	58.3	10
Pitch	42.3	56.1	10
Yaw	80	-	9

A chain-wire-chain mooring system with 12 identical lines, arranged in four groups of three lines, is dimensioned according to ISO 19901-7 [7]. Metocean criteria from Table 4 are applied with a 10-year return period. A current speed of 131 cm/s is taken from the 10-year wind and current contour; i.e. slightly less than the 10-year current speed, for consistency with the 10-year wind and wave parameters. The top chain of the mooring line is selected to exactly satisfy the ultimate limit state with a safety factor of 1.67. The wire diameter is selected so that the minimum breaking load (MBL) of the wire is slightly larger than the MBL of the chain. No offset requirements are applied in the ultimate limit state, with 21 m survival draught and the pretension is set to 1650 kN. The mooring line properties are listed in Table 2 and the arrangement is indicated in Figure 1. The platform motions are calculated in the time domain and applied in a finite element analysis of the tension in the most exposed mooring line.

Table 2 Mooring line properties. Total line length=3470m.

Segment	Diameter [mm]	MBL [kN]	Type
1 Top chain	76	6001	Studless R4
2 Middle wire	76 + 8 (sheath)	6540	Sheathed spiral strand wire
3 Bottom chain	76	6001	Studless R4

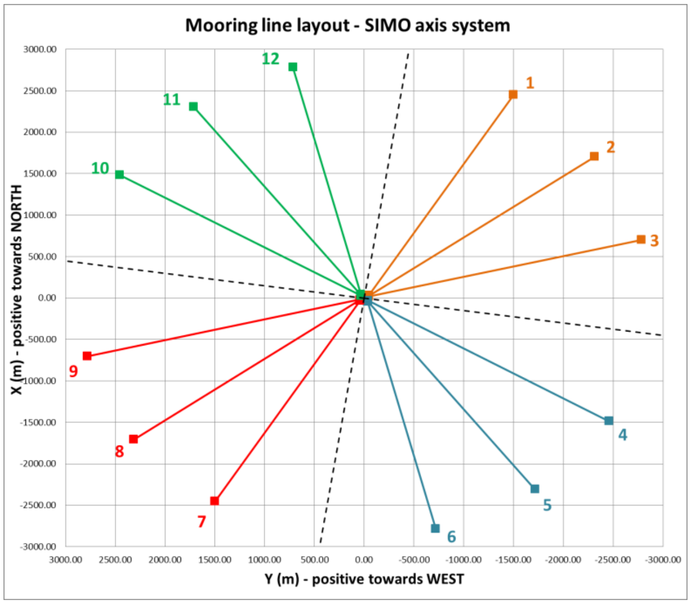

Figure 1 Mooring line layout.

HURRICANE MODEL

The stochastic hurricane model is designed to include a description of the time variation of the metocean conditions during the passage of a hurricane through a chosen location.

Shape functions for hurricanes

Two simple shape functions are used for this purpose:

a) a symmetric, linear plus parabolic function, as shown in Figure 2, for wind speed, significant wave height and current speed,

b) a linearly varying model for wind, wave and current directions and for peak wave period (in two parts).

Using the linear plus parabolic model, the time variation of the significant wave height is given by

$$h(t) = h_p\left[a_L\left(1 - 0.4\left|\frac{t}{d}\right|\right) + a_P\left(1 - 0.8\left(\frac{t}{d}\right)^2\right)\right], \quad -\frac{d}{2} < t < \frac{d}{2} \qquad (4)$$

where h_p is the peak value of the significant wave height, a_L is the linear coefficient, $a_P = 1 - a_L$ is the parabolic coefficient and d is the time duration, defined as the time interval while the height is above 80% of the peak value. A similar model is applied to the wind speed. Wind and wave processes are fairly symmetrical, but the current process is markedly unsymmetrical and trails behind the other two. Hence, the shape function is fitted to the rising part of the current process only. The falling part of the current process is of less importance, because wind and wave conditions are much reduced. The linear coefficient should not be much less than zero, because this leads to a double peak, as indicated in Figure 2, for $a_L = -0.5$.

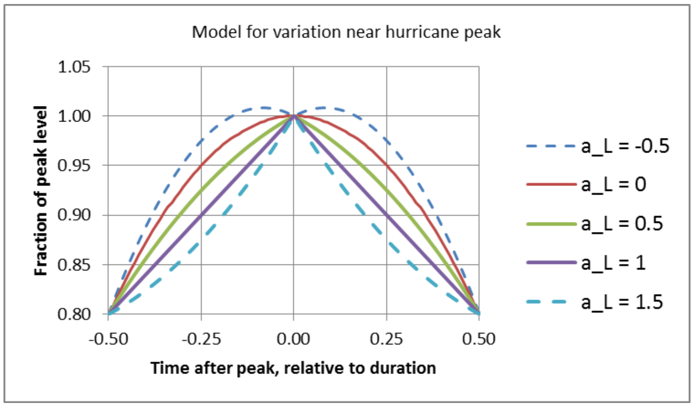

Figure 2 Linear plus parabolic shape function, for different values of linear coefficient a_L.

The largest tensions are likely to occur near the peak wind or wave conditions, but it is not obvious how much of the hurricane duration needs to be taken into account to predict the distribution of the extreme tension, as in equation (1). The 80% level, introduced above, was assumed initially and has been confirmed to be more than adequate.

Components of hurricane vector

The following components are included in the stochastic vector Θ that defines a random hurricane:

peak significant wave height,
peak wind speed,
peak current speed,
peak wave direction,
peak wind direction,
central current direction coincident with peak wind speed,
linear shape coefficients for wave height, wind speed and current speed,
rates of change for peak wave period, wave direction, wind direction and current direction,
duration of waves above 80% of peak height,
duration of wind above 80% of peak speed,
twice rise time of current from 80% to peak speed,
lead time of peak wind before peak waves and
lag of peak current after peak waves.

Components of short-term vector

For a given realization of the hurricane vector, the short-term conditions in each 15-minute interval of the hurricane are defined with the use of the shape functions. The components of the short-term vector ψ_i are as follows:

significant wave height,
mean wind speed (1-hour average at 10 m above sea level),
surface current speed,
wave direction,
wind direction,
current direction and
peak wave period.

These parameters are combined with assumptions of a JONSWAP wave spectrum, long-crested waves, an NPD wind spectrum and a linear current profile in order to provide a sufficient description of the stationary, short-term conditions to allow tension response calculations. A 15-minute average wind speed might seem more consistent, but the 1-hour average is the output of a hindcast model, not an averaging process, and is convenient as an input parameter to the wind spectrum.

Joint distribution of hurricane vector

The joint distribution of the hurricane variables is fitted to hindcast metocean data from GOMOS08 [8] for the years from 1950 to 2008. Data are provided at 15-minute intervals. Data from 3 adjacent grid points (35055, 35067, 35079) were available, in deep water (951 to 2521 m depth), all at latitude 28.1875N and longitude from 87.75W to 89.25W. Thus, these grid points are about 83 km apart in the East-West direction. A total of 201 tropical storms and hurricanes are included in the hindcast, but all these tropical cyclones do not necessarily affect the present grid points to a significant effect.

Please refer to [5], [9] for full details of the joint distribution of the hurricane variables. Distributions of a few of the variables are included here for illustration. The 3-parameter Weibull distribution is applied to these variables and may be written as

$$F_X\,(x) = 1 - exp\{-\left(\frac{x-\gamma_X}{\alpha_X}\right)^{\beta_X}\} \qquad (5)$$

The distribution parameters are listed in Table 3. It is important to take account of the dependencies between these variables. The Nataf approach [10] is applied here. The following correlation coefficients are estimated from the data for the normalised variables above the threshold levels:

- 0.81 between peak significant wave height and peak wind speed,
- 0.77 between peak wind speed and peak current speed.

Table 3 Distribution parameters for peak waves, wind and current during hurricane events.

	Peak sign. height H_p (m)	Peak wind speed V_p (m/s)	Peak current speed U_p (cm/s)
Scale parameter α_X	3.95	8.88	51.9
Shape parameter β_X	1.36	1.05	1.20
Threshold parameter γ_X	6	18.8	75

Metocean criteria

Metocean design criteria derived from the marginal distributions in the hurricane model are listed in Table 4.

Table 4 Omni-directional metocean criteria.

Return period (yr)	Peak significant wave height (m)	Peak wind speed, (m/s)	Peak surface current speed (cm/s)
10	10.70	29.8	139
100	16.04	48.5	226
1000	20.46	66.6	303
10 000	24.44	84.4	375

Statistical uncertainty

The number of hurricanes that are encountered at the chosen location, with conditions above the threshold level is assumed to be 25. There are actually 20 to 22 at each of the three locations utilised, making a total of 63 hurricane data, but the correlation coefficients are high; e.g. up to 0.97 for the peak wave heights. Monte Carlo simulation is applied to estimate the uncertainty in the parameters for the distribution of peak significant wave height, as a function of sample size. Results are shown in Figure 3. The effect of including statistical uncertainty is illustrated in Figure 4. Clearly, the statistical uncertainty is appreciable and should be taken into account in the reliability analysis of the mooring line, when small probabilities of failure are considered. However, this is a little awkward. There may well be some physical limitation on peak wave heights that implies that some of the heights indicated in Figure 4 are impossible in practice. Such a limitation is difficult to determine and no attempt is made to allow for it here.

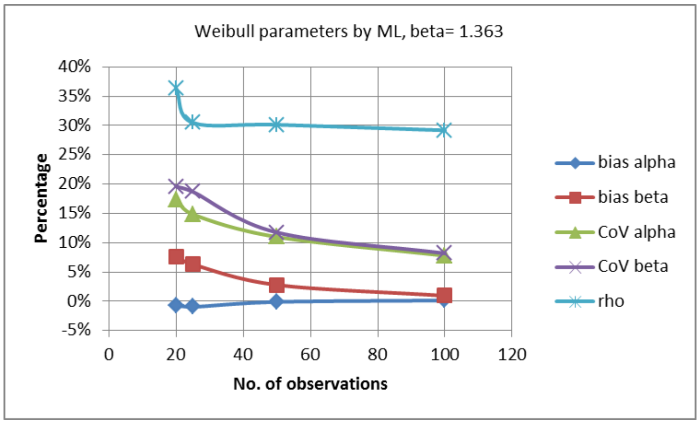

Figure 3 Statistical uncertainty in Weibull parameters for shape parameter, beta = 1.363. (The scale parameter is denoted alpha and rho is the correlation between the two parameters. The threshold param. is determined a priori.)

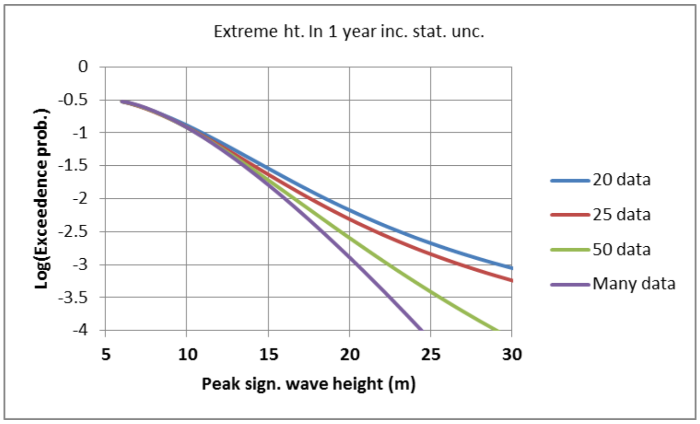

Figure 4 Annual extreme peak significant wave height including statistical uncertainty for different numbers of independent observations.

It is inappropriate to include any statistical uncertainty in the hurricane distribution in the probability integral in equation (2), because this variable does not vary from one hurricane to the next. This uncertainty needs to be taken into account in the evaluation of the probability of line failure. Hence, the annual extreme distribution of line tension needs to be made conditional on the statistical uncertainty. Rather than computing the dependency on several distribution parameters, a simplification is introduced to limit the dependency to one distribution parameter; viz. the scale parameter in the Weibull distribution of peak significant wave height. For a sample size of 25, similar results to Figure 4 can be obtained by setting the coefficient of variation of the scale parameter to 0.4 without any bias and neglecting any uncertainty in the shape parameter. Since peak wind and wave conditions are strongly dependent, it seems appropriate to apply the same uncertainty to the scale parameters of both distributions. Various values of this statistical uncertainty can then be included in the calculation of the annual extreme distribution of the line tension in order to quantify the required dependency.

SHORT-TERM RESPONSE CALCULATIONS

Transfer functions for first order platform motions and 2nd order drift forces are computed from a panel model of the MODU using the Wadam program [11]. Together with these transfer functions, wind and current drag coefficients provide input to the Simo program [12], which is used to compute the time history of platform motions under stationary, short-term conditions. These platform motions are, in turn, used as input to the Riflex program [13], which computes the time history of the line tension under the same conditions. Thus the effect of dynamic mooring line response on the platform motions is neglected while the quasi-static line response is taken into account. The line tension at the upper end of line number 4 is considered. This line is collinear with the most severe hurricane conditions and the largest tensions arise at its upper end. Thirty hours of time history (equivalent to 120 x 15-minutes) are simulated in each case, in order to reduce statistical uncertainty to a level that may be neglected.

Tension maxima are extracted from the tension time history and a 2-parameter Weibull distribution is fitted to these maxima. A Gumbel distribution of the extreme tension during an interval of 15 minutes is derived from the Weibull distribution of maxima and the average period between maxima. The Gumbel distribution may be written as

$$F_{Z|\Psi}(z|\psi; 15\text{min}) = \exp\{-\exp[-a_z(\psi)(z - b_z(\psi))]\} \quad (6)$$

where $a_z(\psi)$ is the scale parameter and $b_z(\psi)$ is the location parameter for metocean conditions ψ.

Short-term results are computed for a large set of metocean conditions, intended to span the hurricane conditions that may be encountered in the evaluation of equation (2). For example, Figure 5 shows the combinations of wave height and wind speed that are included. About 5300 different, short-term conditions are analysed.

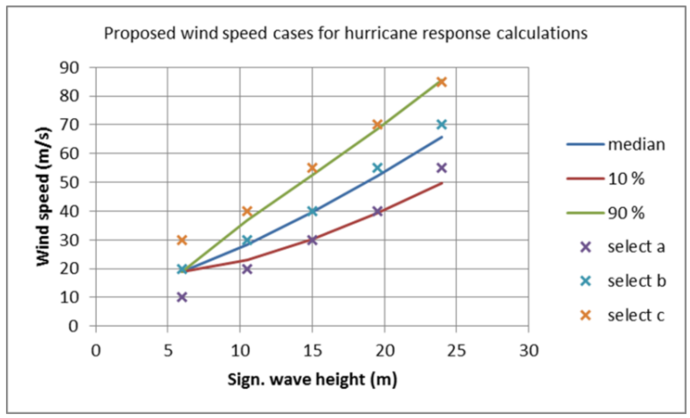

Figure 5 Short-term wind and wave parameters. Fractiles of the distribution of wind speed conditional on wave height are also shown for guidance.

RESPONSE SURFACE

A response surface module [14] is used to interpolate on the short-term results for the parameters of the extreme value distribution of line tension. The components of the short-term metocean vector ψ_i form the 7 interpolation variables. The location parameter b_Z and the inverse of the scale parameter $1/a_z$ of the Gumbel distribution are the output from the interpolation. The SORM applied in the evaluation of equation (2) performs a search through the domain of the metocean conditions to find the design point (where a tension level is most likely to be exceeded) and associated derivatives. Hence, a smooth, continuous description is required, as provided by the response surface, rather than the original discrete values. However, the response surface only needs to cover the domain involved in this search and need not cover the entire domain of the metocean variables.

Some tuning is involved in fitting the response surface to the data and “cut-plots” are utilised in checking this fit; i.e. graphs of response against a single input parameter while the other input parameters are held constant. A couple of examples are shown in Figure 6 and Figure 7. Good fits to the raw data points are obtained.

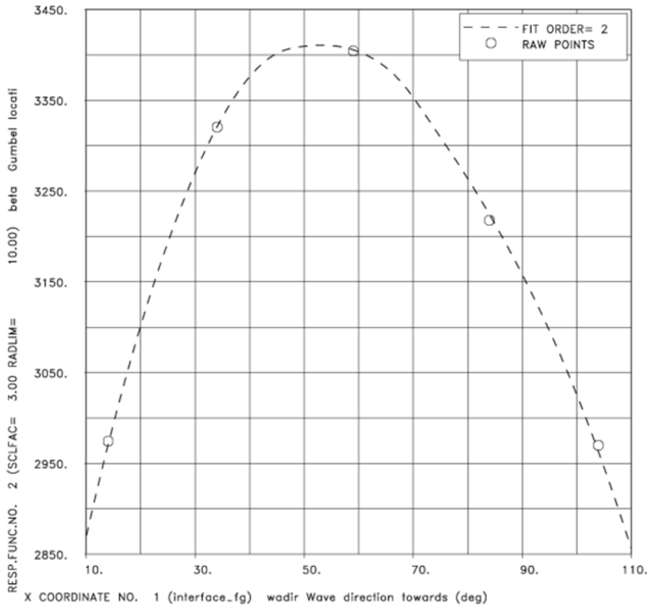

Figure 6 Cut-plot for Gumbel location param. as a function of wave dir., through rel. wind dir.=0°, h=10.5m, t_p=13.5s, v_w=30m/s, u_c=1.3 m/s & rel. curr. dir.=0°.

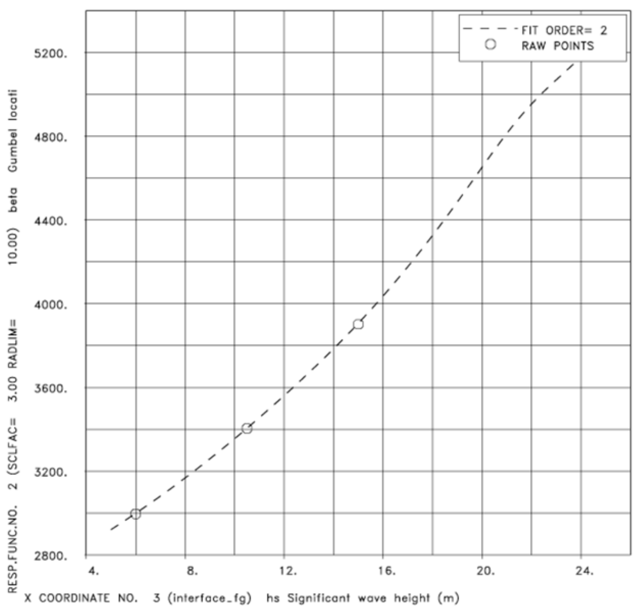

Figure 7 Cut-plot for Gumbel location param. as a function of sign. wave height, through wave dir.=59°,rel. wind dir.=0°, t_p=13.5s, v_w=30m/s, u_c=1.3 m/s & rel. curr. dir.=0°.

RESULTS FOR ANNUAL EXTREME RESPONSE

Main result

The annual extreme tension, computed according to equation (3), is shown in Figure 8. Curves are plotted for both first order (FORM) and second order (SORM) reliability methods. The FORM result over-estimates the tension for a given probability level. SORM has been confirmed to provide acceptable accuracy by comparison with Monte Carlo simulations in Norwegian waters, with a somewhat different metocean model. SORM can handle non-monotonic response, as in Figure 6, while FORM does not.

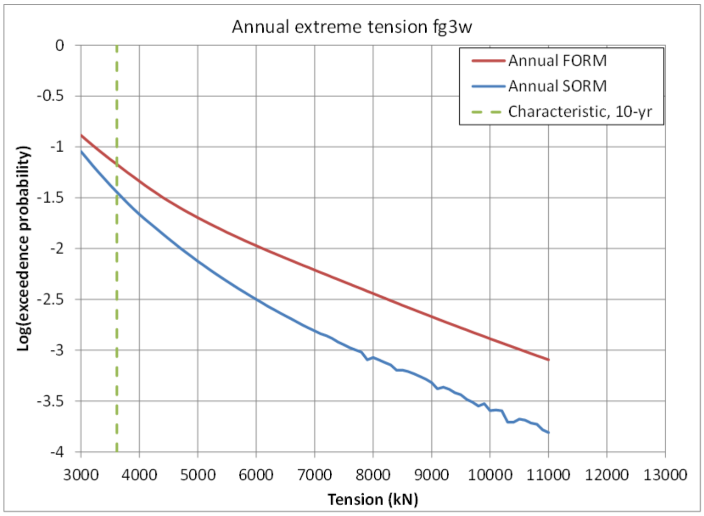

Figure 8 Annual extreme tension distribution in base case; FORM and SORM results.

The characteristic tension of 3616 kN, based on 10-year metocean criteria, corresponds to an exceedence probability of $10^{-1.45}$; i.e. a return period of 29 years. Possible reasons for this apparent conservatism are:

- Use of 10-year values from the marginal distributions of waves and wind, whereas the return period of such a combination is likely to be somewhat more than 10 years.
- Application of collinear wind, wave and current actions in the most unfavourable direction with respect to the specific mooring line, while the probabilistic model takes account of the distribution of the directions of the metocean actions,
- Application of simultaneous peak values of these actions while the probabilistic model takes account of the time lag of peak current after peak wind and waves,
- The assumption of stationary, peak conditions for a period of 3 hours, while the probabilistic model takes account of the time variation around the peak values.

On the other hand, the characteristic tension is taken as the most probable maximum tension in the sea state and there is 63% probability that this level is exceeded. Thus, any non-conservatism in this definition of the characteristic value seems to be more than balanced by other conservative factors in the calculation of the characteristic tension, if a 10-year return period is accepted as appropriate.

A Gumbel distribution tends to be fairly linear for large arguments in the format applied in Figure 8, whereas the numerical results show appreciable curvature. Hence, the Gumbel distribution would be expected to provide an inaccurate, optimistic fit to the numerical distribution. A Weibull distribution provides a better fit. The ratio between tensions for 10000-year and 100-year return periods is about 2.5, partly due to the curvature. The corresponding ratio of significant wave heights is about 24/16=1.5. Thus, we might suggest that the extreme tension increases more than linearly with the significant wave height and be wary of analysis procedures that do not take adequate account of this behaviour. This behaviour also indicates that the reliability level is relatively insensitive to changes in safety factor.

Design points

The SORM analysis provides information about the design points associated with each probability level and the corresponding tension level. Peak significant wave heights from design points are plotted as a function of tension level in Figure 9 and provide a useful check on the behaviour of the probabilistic analysis. The characteristic tension of 3616 kN is found at a significant wave height somewhat above the 10-year value of 10.7 m. The tension increases more than linearly with height.

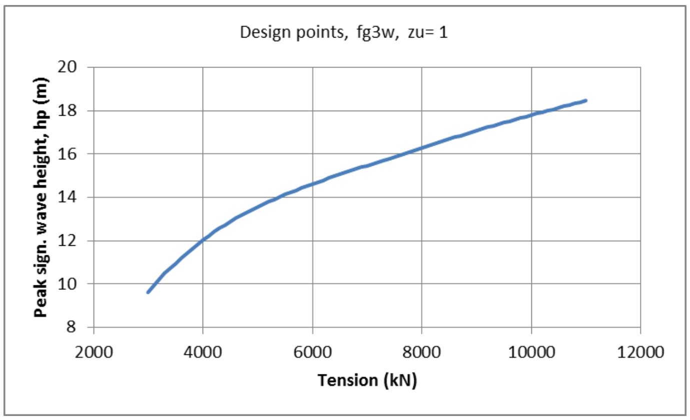

Figure 9 Design points for peak significant wave height as a function of tension level.

The design points in Figure 10 show how the stochastic model indicates that the time lag of the peak current after the peak wave height decreases with increasing tension. This is not surprising and it seems to be a useful feature of the analysis. It is simply based on a distribution fitted to the empirical hindcast data. It might be worthwhile to check if the time lag seems physically reasonable when extrapolated beyond the range of the observed data.

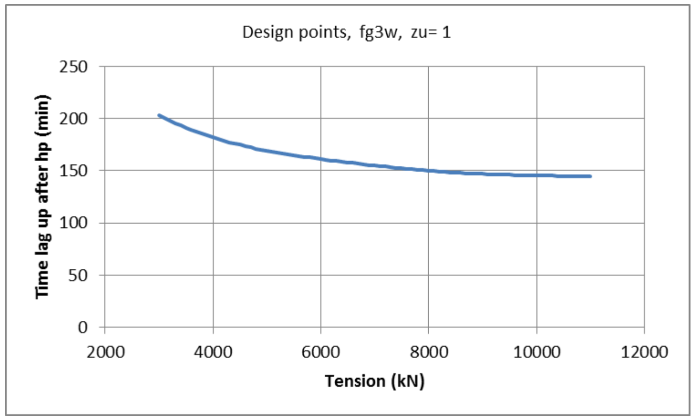

Figure 10 Design points for lag time of peak current after peak wave height as a function of tension level.

Another reasonable feature of the model is exhibited in Figure 11 and Figure 12; viz. the duration of the hurricane in the vicinity of the peak conditions decreases with increasing tension levels. Furthermore, the duration of the wind speed decreases more strongly than the duration of the wave height.

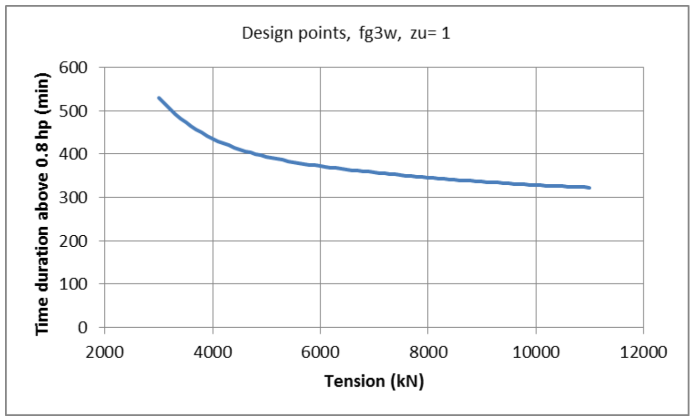

Figure 11 Design points for duration of waves above 80% of peak height as a function of tension level.

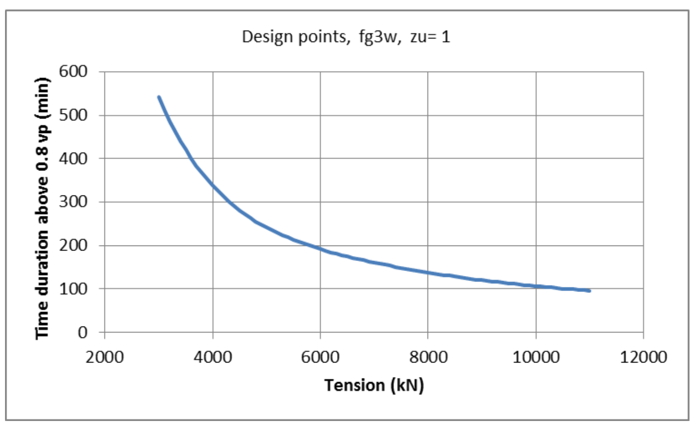

Figure 12 Design points for duration of wind above 80% of peak speed as a function of tension level.

Simplification of the hurricane model

Sensitivity analyses are carried out in which the distribution of one random variable is replaced by its expected value. Various random variables are considered in sequence. The results indicate that the hurricane model can be simplified in this way, with respect to the following variables:

duration of waves above 80% of peak height,
linear shape coefficient for wave height,
rates of change for peak wave period,
rate of change for wave direction,
duration of wind above 80% of peak speed,
linear shape coefficient for wind speed,
rate of change for wind direction,
linear shape coefficient for current speed,
rate of change for current direction.

Note that these expected values are constants in some cases, but functions of peak wave height or peak wind speed in other cases and that it is important to maintain this functional dependency. Strictly speaking, these simplifications are only justified for the present mooring case and might be unjustified in a different case.

Sensitivity to model for metocean directions

The present analysis model takes account of a continuous, joint distribution of wind wave and current directions. It seems interesting to investigate how this model differs from some simplified models. Results from a couple of alternative models are compared to the base case in Figure 13:

a) The results labeled as "collinear" are obtained while retaining the random model for wave direction and setting both wind and current directions collinear with the wave direction. This leads to about a 25% increase in tension for a 100-year return period.

b) The results labeled as "coll_fixh_sametime" are obtained while making the wave, wind and current directions collinear with mooring line number 4 and making the wave, wind and current actions peak at the same time. This leads to about a 55% increase in tension for a 100-year return period, relative to the base case. Furthermore, the tension for a 10-year return period is fairly close to the characteristic tension.

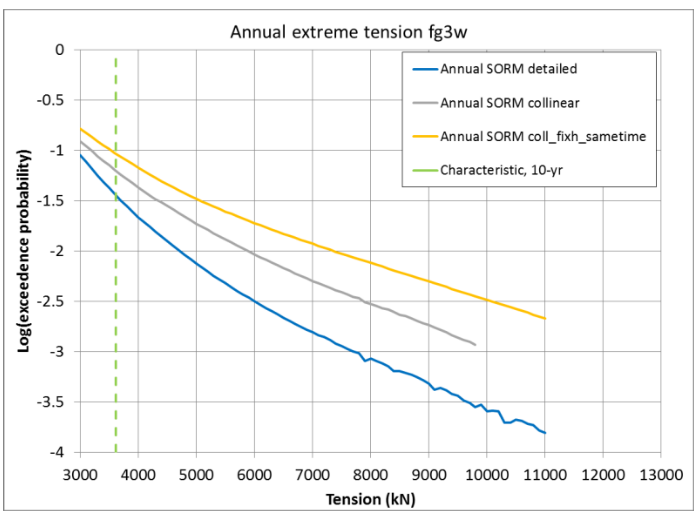

Figure 13 Annual extreme tension distribution – sensitivity to model for metocean directions.

Effect of statistical uncertainty

Figure 14 illustrates the effect of the statistical uncertainty factor applied to the scale parameters in the distributions of peak significant wave height and peak wind speed. An appreciable effect is seen on the tension distribution, which should be taken into account in a reliability analysis of the mooring line. Note that this variable is important when the number of hurricanes in the data set is relatively small. If a very much larger set of hurricane data could be employed, then it might be omitted. In Norwegian waters, the number of storms encountered at any one location during 50 years is much larger and allowance for statistical uncertainty in the distribution of significant wave heights has not been considered essential.

In practice, a Weibull distribution may be fitted to each of the curves for annual extreme tension in Figure 14. An appropriate function of the statistical uncertainty parameter can, in turn, be fitted to the parameters of the Weibull distribution. Hence, an annual extreme distribution of tension is obtained, conditional on the statistical uncertainty factor, which can conveniently be employed in a subsequent reliability analysis. A similar approach is also employed to make the tension distribution conditional on a model uncertainty factor for the uncertainty in the calculation of the tension response under given metocean conditions.

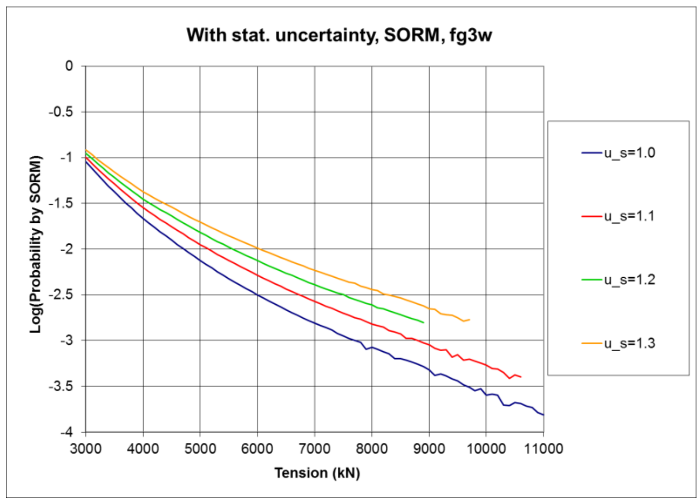

Figure 14 Annual extreme value of tension, conditional on statistical uncertainty factor u_s on scale parameters of distribution of peak wave height and peak wind speed.

Further details of the analysis may be found in [15].

CONCLUSIONS

A method to predict the annual extreme value distribution of mooring line tensions under hurricane conditions is described and applied to a test case, representative of mobile drilling units in the Gulf of Mexico. The method takes detailed account of the time variation of wind, wave and current conditions during the passage of a hurricane. Continuous distributions for the directions of these three metocean effects are also included. The method is more complex than is convenient for ordinary design calculations, today, but is intended for use in structural reliability analysis. It may well be useful for other types of response variables, too.

Results from the test case illustrate the effects of various simplifications in design analyses on the annual extreme distribution of line tension. In particular, the characteristic tension calculated from short-term metocean criteria with a 10-year return period is found to correspond to a return period of 29 years. A response surface is applied to interpolate on the short-term results for discrete metocean conditions, such that the tension response is available as a continuous function of the metocean conditions. This allows the continuous, joint distribution of the directions of wind, wave and current to be taken into account in the analysis. The effects of simplifications in the modelling of these directions is quantified and appears to be appreciable, at least in the context of reliability analysis.

The statistical uncertainty arising from limited hurricane data is discussed and quantified. It appears to be significant. A procedure to include this random variable in a reliability analysis of the ultimate limit state is described.

ACKNOWLEDGMENTS

The present model has been developed within the NorMoor joint industry project, with the following participants: BP, Det norske oljeselskap, Statoil, GDF Suez Norge AS, Shell, Total, BG Norge Limited, Petrobras, Delmar, Vryhof, Single Buoy Moorings, APL, Transocean, Det Norske Veritas, Petroleum Safety Authority in Norway, Norwegian Maritime Directorate, UK Health and Safety Executive, Vicinay Cadenas, Ramnäs and Bexco. Permission to publish this paper is gratefully acknowledged. The material presented herein should not necessarily be taken to represent the views of these companies.

Tore Hordvik has carried out the design calculations and the systematic short-term response analyses.

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[1] NorMoor JIP reports are confidential for 2 years after the termination of the project and public later.

