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Response-based Analysis for Tension Leg Platform

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Abstract: The typical industry practice for Tension Leg Platform (TLP) design focuses on a conventional short-term design recipe, which assumes that an N-year design environment leads to an N-year response. In the response-based design method, the TLP is designed to withstand N-year responses rather than respond to N-year environmental conditions. In this paper, we present an overview and a general procedure for the response-based design method and use a case study to compare the critical TLP responses between the two methods. The results of our comparison show that the conventional short-term design method often contains an element of conservatism and that the response-based design method can reduce the design conditions and thereby achieve cost savings.

Keywords: response-based design, long-term response, short-term response, deepwater, floating platform, tension leg platform

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1 Introduction

For offshore deepwater oil and gas field development, there are four types of floating production systems employed worldwide: ship-shaped units, spars, semi-submersibles, and Tension-Leg Platforms (TLPs).

In general, a floating production platform consists of a hull to provide buoyancy, a mooring system to control its motion, and an arrangement of risers for oil and gas production and export. The environment exerts global loads on all parts of the system, but particularly the hull.

Although the TLP is a floating unit, in the operational mode it behaves like a fixed structure in its heave, roll, and pitch motions due to its unique tendon mooring system.

The TLP design is very sensitive to environmental conditions, and especially to the non-collinear environment and to the large-wave weak-current environment. The common industry practice for TLP design focuses on the conventional short-term design method which assumes the wind, wave, and current to be collinear and associated with peak values. In addition, the short-term design method assumes that an N-year design environment leads to an N-year response. It does not consider the effect of the TLP responses in the selection of the design's environmental parameters.

Per API 2RP 2T, final TLP design configurations must be verified through long-term response analysis. This type of analysis involves developing non-exceedance probability distributions for TLP responses of interest that account for both short-term and long-term variability in sea conditions, from which design level responses (e.g., 100-year return period, 1000-year return period) can be identified/verified (API RP 2T, 2010).

2 Response-Based Design (RBD)

The objective of RBD is to design a structure to withstand N-year return period responses rather than responses in a combination of N-year environments. Therefore, the design is based on parameters of direct engineering significance rather than on secondary metocean parameters (Standing and Eichaker, 2002).

RBD methods have been established in the design of fixed structures (Wen and Banon, 1995), and in recent years have also been applied to floating structures.

The main benefits of RBD are the better considerations of safety and cost savings by significantly reducing design conditions, and the use of long-term response statistics in a risk-based approach to load factors. Studies of the waters off Europe, the USA, and Australia suggest that considering joint probability in the design's environmental conditions can reduce design loads by 10%–40% for drag-dominated structures (Tromans and Vanderschuren, 1995).

2.1 Long-term extreme analysis methods

Long-term extreme analysis originated from the estimation of wave extremes in the metocean field (Jahns and Wheeler, 1973). Since then, numerous long-term analysis methods have been proposed, among which are three mainstream methods: the averaging, convolution and storm extreme methods. In general, these three methods follow a similar procedure, as described in section 2.2, but deal with short- and long-term variabilities in different ways.

The averaging method was proposed by Forristall (Forristall and Larrabee, 1991) to solve the short-term variability averaging of the extreme distributions of all sites and storms. The averaging method is typically used to increase the effective number of extreme environmental events considered during an extreme value analysis, and to reduce the influence of abnormally extreme events.

The convolution method is based on conditional probability distribution, and the Most Probable Maximum (MPM) of a single random storm can be considered as a

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distribution of a random variable *X*, conditional on the random variable *Xmp* (MPM) of a single random storm event (Tromans and Vanderschuren, 2002). The convolution method uses as much data as possible from hindcast databases and thus is less sensitive to noise.

The storm extreme method is relatively simple and efficient compared to the other two methods, at the cost of a simplification of the short- and long-term variabilities (Standing and Eichaker, 2002). The simplification is mainly for the purposes of metocean data, and this method analyzes only the critical sea states from selected storm events filtered by pre-defined metocean criteria.

2.2 General procedure of RBD

Due to its simplicity and efficiency, the storm extreme method is commonly used in real projects. The general procedure for RBD using the storm extreme method is described as follows (Tromans and Vanderschuren, 2002):

1) Develop a long-term metocean database;

2) Use peak-over-threshold (POT) method on metocean data to identify independent storms;

3) Select sea states from identified storms that may cause critical responses;

4) Generate short-term responses for each selected sea state;

5) For each storm event (multiple sea states), select the most critical response and associated sea state. The selected response is the peak response of the storm and the associated sea state is the representative sea state of the storm;

6) Rank the selected peak responses of all storms and calculate their probabilities;

7) Statistically fit the peak response and probability and calculate the design response for the N-year return period;

8) Estimate the design environmental conditions likely to produce the responses of a chosen N-year return period;

9) Estimate the safety (load) factors required to ensure target reliability (optional).

2.2.1 Metocean database

Long-term metocean database development is one of the key tasks in RBD and analysis. Due to the lack of sufficiently long-term accurate measurements in environmental data records, the hindcast method is commonly employed.

A hindcast database is a numerical simulation of the time series of winds, waves, and currents for a given historical period. It provides environmental information for three-hour, one-hour or twenty minute intervals of storms over a given period (e.g., 100 years). It is a far more comprehensive data set than any measured time series. In principle, it contains all the statistical information required for deriving joint statistics of the environmental variables and performing RBD (Tromans and Vanderschuren, 2002).

Significant wave height can be hindcast with reasonable accuracy. Wave periods may sometimes be biased and floaters are sensitive to wave period.

Currents are very difficult to hindcast because they are neither tidal nor driven fairly directly by winds. Although their major features may be captured and their variance may be broadly correct, point-wise comparisons with measurements are often not very good. In TLP design, both current direction and weak currents with large waves are very important considerations.

Usually, winds can be hindcast well. The main issue for floaters is direction, which can have great effects as it departs from the main wave direction.

2.2.2 Peak over threshold (POT) filtering

It is inefficient to work through all storm events and associated sea states since this involves conducting a response analysis of many sea states that do not contribute to the final results. The long-term extreme is only governed by large storm events. As such, the most obvious approach to generating long-term structural response statistics is to identify storm events classified above some threshold of severity. Then, response calculations can be performed for only a selection of representative sea states. This filtering procedure is normally accomplished by the POT method.

POT threshold values are based on key response characteristics and should result in a manageable but sufficient number of sea states and storm events. Each storm event may contain multiple sea states.

For TLP design, all large waves should be considered even if in low wind and weak current, because these sea states may lead to a small offset and, more critically, a minimum tendon tension. For other types of floating platforms, the minimum mooring line tension is not as critical a design issue.

2.2.3 Responses analysis model

Another key task in RBD and analysis is to develop a realistic numerical analysis model that can capture extreme behaviors of the platform and its mooring system in each design environment. This model must provide realistic estimates of key responses relevant to design considerations.

The key responses of interest in TLP design typically include:

- Maximum offset
- Minimum airgap
- Maximum tendon tension
- Minimum tendon tension
- Maximum acceleration

With respect to the response-based analysis model, convenience of use and high-quality results are required. Convenience of use implies high computation speed with minimal user intervention, which are both essential if several hundred or thousand sea states are to be analyzed. High-quality results relates to their consistency rather than their absolute accuracy, i.e., the response-based analysis should employ the same software and methodology as employed by the conventional analysis. Calculated responses should correctly balance the effects of the metocean variables: the model must have roughly the correct sensitivity to changes in wave height, period, and direction, current speed and direction, and wind speed and direction (Tromans and Vanderschuren, 2002).

Analysis models normally include:

- physical model tests,
- frequency-domain analysis, and
- time-domain analysis.

The physical model test in a three-dimensional (3D) wave tank is standard in the design of floating systems. This test serves to confirm the performance of the design, to calibrate the numerical tools used in testing extreme environments, and to investigate the presence of any effects overlooked in the engineering analysis. However, these tests involve huge cost and time and suffer all kinds of problems, such as model scaling, instability, non-uniformity, and reflections in the wave field.

Frequency-domain analysis is simple and easy to implement, but its most significant limitation is that all nonlinearities in the equations of motion must be replaced by linear approximations.

Time-domain analysis utilizes the direct numerical integration of equations of motion, thus allowing the inclusion of all system nonlinearities, such as fluid drag loads, mooring loads, and viscous damping. Today, time-domain analysis has become a common practice in the offshore oil and gas industry.

The short-term extreme responses of each sea state can be obtained by fitting an extreme value distribution to the simulated response time series.

2.2.4 Long-term responses

For each key response, the long-term extreme value can be derived by statistically fitting the peak responses and associated probabilities. The peak responses are the most critical extreme responses of each storm event, which may include multiple selected sea states. The probability for each peak response can be calculated based on the duration of the storm to which the sea state belongs. Statistical fitting can be performed by means of various empirical extreme distributions, e.g., Weibull or Gumbel distribution.

For example, to calculate a 100 a extreme response, we use the top selected extreme responses of the representative sea states from the short-term distribution to fit the long-term distribution curve. Then, we apply the 100 a exceedance probability to the curve to obtain the 100 a long-term design response.

3 Case study–Gulf of Mexico TLP

Our case study is based on a conventional round-column TLP moored in the Gulf of Mexico (GOM) at approximately 1 000 m water depth.

3.1 Metocean data

The hindcast metocean time series were developed based on the principle of superposition and the measurements of five grid points in Oceanweather Inc.'s GOMOS study in the GOM. Each grid point contains about 22000 sea states covering about 100 years. By the superposition method, a total of about 500 years of metocean data have been derived.

The metocean parameters in the database include:

- Wind direction and 1-hr average wind speed (*Vw*)
- Significant wave height (*Hs*), spectral peak period (*Tp*), mean wave direction
- Current velocity and direction along the water column
- Water level, including storm surge and tide

Figure 1 shows sample time-history plots of the metocean parameter *Hs*.

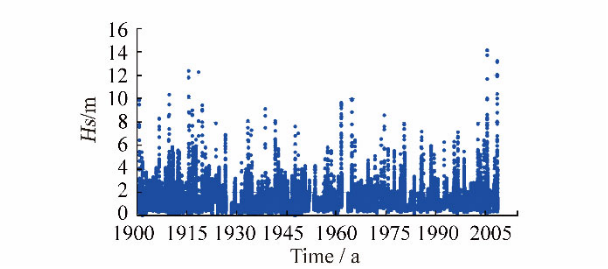

Fig. 1 Sample wave *Hs* time history

3.2 Responses vs wave *Hs*

The key responses we investigated in this case study are the maximum and minimum tendon tensions.

Tendon tension includes both wind- and current-induced mean tension and wave-induced dynamic tension. Dynamic tension is mainly caused by heave, roll, and pitch motions.

Although low sea states have short peak periods close to the natural heave/roll/pitch periods (around 2–4 seconds), their responses are comparably small, as shown in Figs. 2 and 3. These figures show that the dynamic tendon tension (RMS) increases almost linearly with wave *Hs*.

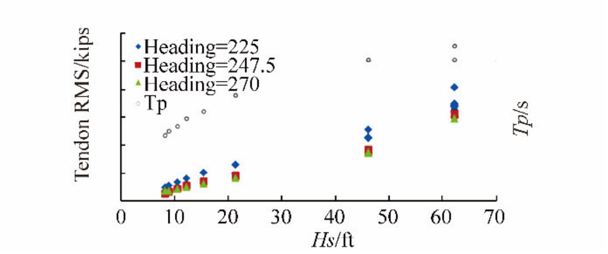

Fig. 2 Upwave tendon tension RMS vs wave *Hs*

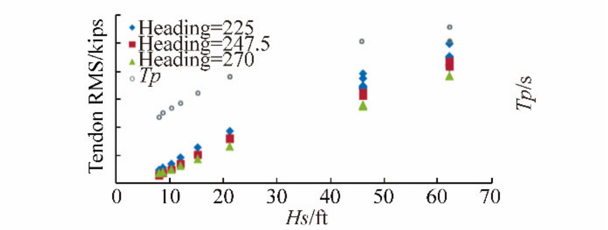

Fig. 3 Downwave tendon tension RMS vs wave *Hs*

The maximum tendon tension occurs when both large mean tension (high winds and/or strong currents) and large dynamic tension (large waves) occur.

The minimum tendon tension occurs when small mean tension (low winds/weak currents or opposite wind/current) and large dynamic tension (large waves) occur.

3.3 Metocean screening

The metocean database contains about 100 000 sea states and each sea state has a 3-hour duration. It is not practical to perform time-domain analyses for all sea states. Therefore, we first screened the metocean database in order to filter out obviously "non-critical" sea states and to collect a manageable number of sea states and storm events for our time-domain analysis.

Based on the response–*Hs* relationship: i) for the max tendon tension, sea states with high winds/large waves or strong currents should be selected; and ii) for the min tendon tension, sea states with large waves but low winds/weak currents or opposite wind/current should be selected.

In this study, we performed a two-step screening based on the environmental data and responses.

We used the following criteria for the Step 1 screening: i) large waves, ii) high winds, iii) strong surface current with reasonably large wave. Based on these criteria, we selected a total of 775 sea states. Figs. 4 to 6 show plots of the metocean parameters from the Step 1 screening results.

For the selected 775 sea states, we performed a statistical analysis to estimate the responses. In this analysis, we explicitly considered wind/current effects and estimated the wave effect based on the relationship between the dynamic response (RMS) and wave *Hs*. Based on our results, we established the criteria for the Step 2 screening.

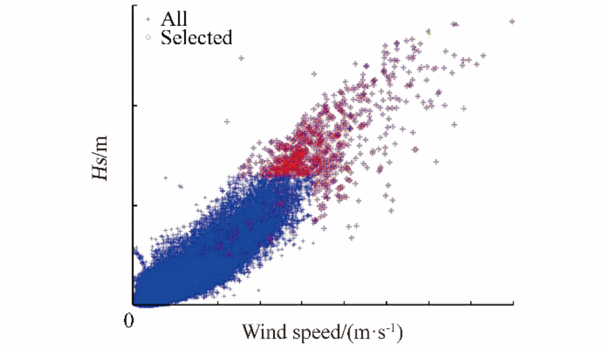

Fig. 4 Wave *Hs* vs wind *Vw* (Step 1 screening)

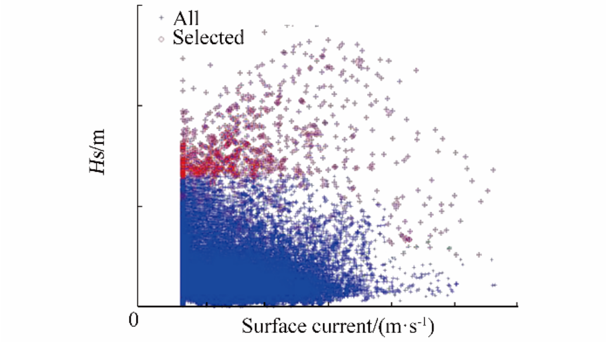

Fig. 5 Wave *Hs* vs surface current *Vc* (Step 1 screening)

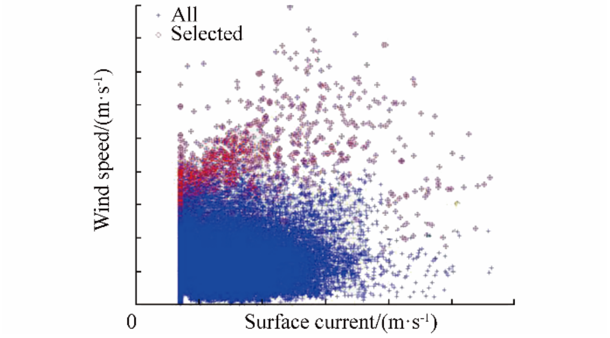

Fig. 6 Wind *Vw* vs surface current *Vc* (Step 1 screening)

Based on the tendon tension criteria, we selected a total of 366 sea states for our final time-domain analysis. Figs. 7 and 8 show the statistical screening analysis results, which confirm that the selected cases cover all the critical responses.

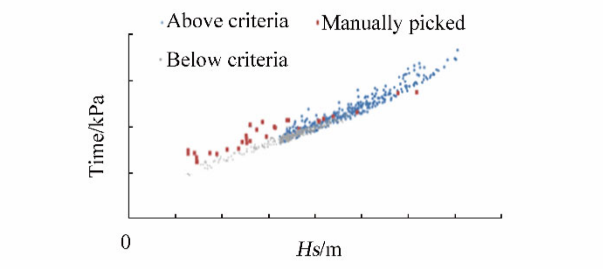

Fig. 7 $T_{\max}$ vs wave *Hs* (Step 2 screening)

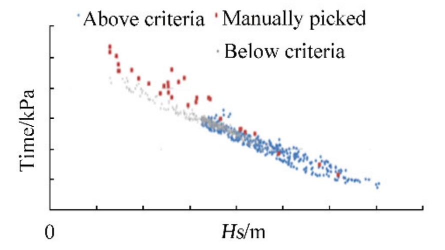

Fig. 8 $T_{\min}$ vs wave *Hs* (Step 2 screening)

3.4 Storm events

Based on the time series of the metocean data, we identified a total of 348 storm events for each grid point. It total, there are 1740 storm events in the roughly 500-year metocean database.

For each storm event, the duration ranged from 4 days to 20 days, including both build-up and decay. Fig. 9 shows a sample storm time series, and Fig. 10 shows storm max wave height and duration.

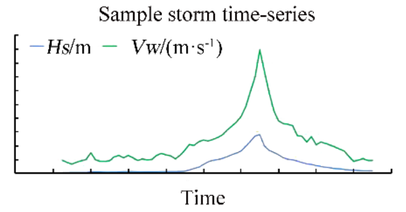

Fig. 9 Sample storm time series

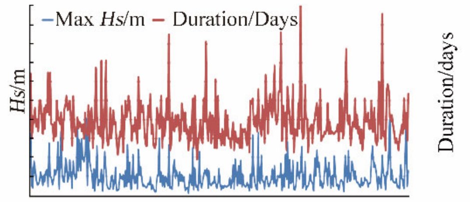

Fig. 10 Storm max *Hs* and duration

The 366 selected sea states belong to 112 storm events. Fig. 11 shows selected sea states within a storm and Fig. 12 shows selected storms for a sample grid.

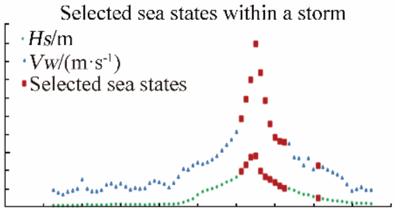

Fig. 11 Sample selected sea states within a storm

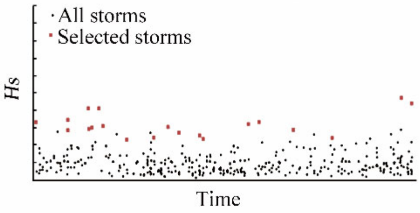

Fig. 12 Selected storms of a sample grid

3.5 Analysis methodology

We used the same numerical analysis methodology for each selected sea state as that used in the conventional short-term design method.

We performed non-linear fully coupled time-domain analysis in the case study using the DNV DeepC program, which captures various nonlinear load/response effects, including tendon and riser stiffness, riser loads, finite wave height effects, viscous drift forces, and wind dynamics effects.

We used 3D finite elements based on rod theory to explicitly model the tendons and risers. These 3D elements not only possess hydrodynamic properties such as added mass and viscous drag force, but also possess the properties of a structural member with the appropriate self-weight, buoyancy, and structural stiffness. We discretized each of the tendons and risers into a number of beam elements.

For the hydrodynamic analysis, we used the DNV Wadam/HydroD program to calculate both the first and second (sum and difference frequency) order transfer functions. For the submerged hull, we generated a diffraction panel model up to a draft at the mean offset position of each sea state to ensure that we captured the appropriate amount of hydrodynamic response for each sea state. In our hydrodynamic analysis, we modeled no Morrison member in the hull diffraction model, but applied appropriate additional damping based on past project experience. We refined the mesh close to the water line to fulfill the very short period requirements.

Figure13 shows the coupled time domain analysis model.

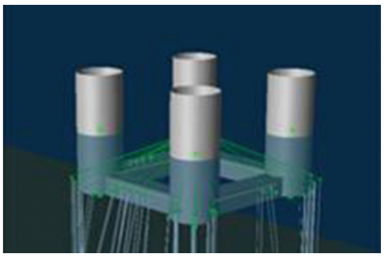

Fig. 13 Analysis model

For each sea state, we used three random seeds in our analysis and the simulation duration for each seed was 10800 seconds, excluding the first 200-second ramp-up time.

We obtained the three-hour peak response value for each seed by fitting a Weibull distribution to the calculated response time series and obtained the peak response for each sea state by averaging the peak values from all three seeds.

The Weibull probability of non-exceedance for response amplitude x is expressed as follows:

$$P(x)=1-\exp\left[-\left(\frac{x}{\beta}\right)^m\right]$$

where β and m are Weibull parameters.

3.6 RBD analysis results

Figures 14 and 15 show the RBD analysis results for the max and min tensions, respectively.

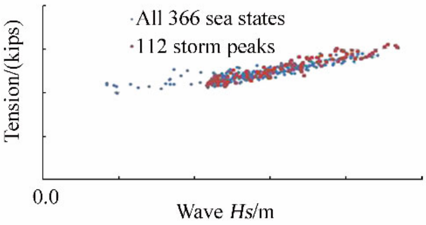

Fig. 14 Analysis results for max tension

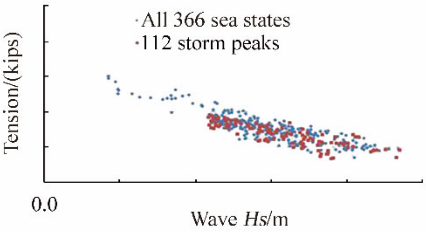

Fig. 15 Analysis results for min tension

3.7 Long-term fitting results

Figures 16 and 17 show the Weibull fitting results of the design values of various return periods for the max and min tendon tensions, respectively. The fitted extremes vary with the number of peaks used in the Weibull fitting. In the case study, we used all the peaks and the results are conservative.

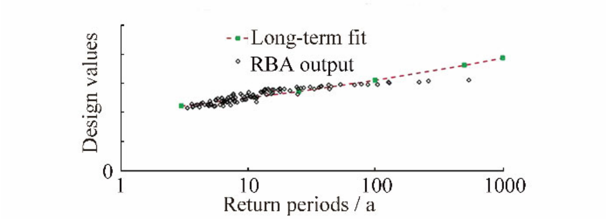

Fig. 16 Long-term fitting results for max tension

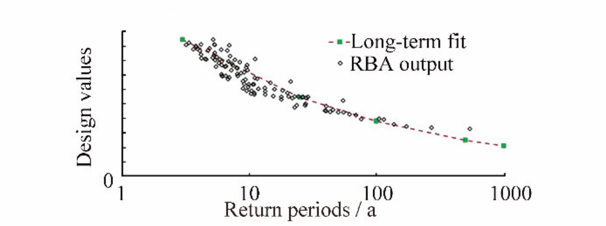

Fig. 17 Long-term fitting results for min tension

3.8 Results comparison

Figure 18 shows a comparison of the RBD and conventional design methods for the max and min tendon tensions.

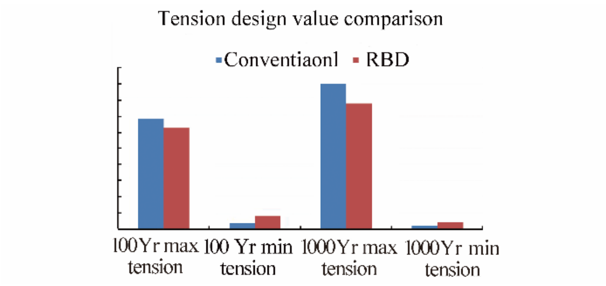

Fig. 18 Comparison of tendon tension results

From these figures, we can see that the conventional method is conservative with respect to both the max and min tensions. We obtained similar findings for other global performance design variables, such as offset and acceleration, which are not presented here.

4 Summary

Based on the above findings, we can conclude that for the selected TLP case study, the conventional metocean-based global performance analysis results are more conservative than the response-based design long-term fitted results for both 100-year and 1000-year conditions. This finding is consistent with the conclusions of another study (Tromans and Vanderschuren, 1995).

By adopting the response-based design analysis method for TLP design, both the tendon pre-tension and the TLP hull size can be reduced, which will thus also reduce the associated project cost.

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