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Extreme Responses of Turret Moored Tankers

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Abstract

The extreme responses of a turret moored tanker are sensitive to non-aligned wind, wave and current conditions. Such conditions commonly occur in the Gulf of Mexico during the passage of the eye of a hurricane. Conventional design practice often relies on a collinear or, at best, a “guessed” non-collinear combination of 100-year environmental return period wind, wave and current conditions. Hence there is a need to derive response-based design criteria, i.e. that particular combination of wind, waves and current which most likely yields the 100-year return period response. The long term response characteristics of a turret moored tanker in deep water Gulf of Mexico conditions are investigated through the use of a comprehensive hurricane hindcast database. The effects of turret location and wave spreading are considered. The 100-year long term responses are compared against the short-term 100-year design responses derived from a 100-year hurricane design analysis. Response-based design criteria are then derived.

Introduction

Turret moored tanker based FPSO systems are widely used in many deepwater areas. Conventional design of such systems often relies on the assumption of a design storm event comprised of a collinear (or at best a guessed non-collinear) combination of 100-year environmental return period wind, waves and current. However, it is well known that the extreme responses of a turret moored tanker are sensitive to non-collinear wind, waves and current (Refs. 6-8).

With few exceptions, the effect of non-collinear wind, waves and current has received little attention. Such events commonly occur in the deepwater Gulf of Mexico during the passage of the eye of a hurricane. The resulting effects on the motions and mooring line tensions may be significant as such systems have a natural tendency to weathervane, i.e. align themselves against the prevailing direction of wind, waves and current. This then poses the question of how well the “conventional” design recipe really works for these systems in significantly non-collinear environments.

In order to address this problem the actual long-term response characteristics need to be investigated and the 100-year return period responses need to be derived. Response-based design criteria may then be stipulated to capture specific response characteristics, e.g. the 100-year maximum offset storm is that particular combination of wind, waves and current that most likely yield the 100-year return period offset. Notice that the associated wave height, wind speed and current speed for such a non-collinear design event may well be lower than those normally referred to as 100-year return period environmental criteria. Also, the 100-year return period offset storm, say, is merely intended to estimate the 100-year offset while other responses (e.g. roll or mooring line tension) should be ignored.

Theory

The long term Gulf of Mexico environment is described by means of a hurricane hindcast database of 35 storms over an 85 year period since 1900 (Ref. 3). The original database contains some 240,000 records with the hourly values of wind, waves and current parameters. It was derived from a hindcast on 784 grid points in the Gulf of Mexico and contains storms with a significant wave height in excess of 6.1 m. For the present study, the database was culled down to 11,322 records by increasing the wave height threshold to 7.6 m and reducing the number of grid points by a factor of 8 to 98 (Ref.1).

Each record contains the hourly hindcast values of wave height and period, wind speed and current speed and the absolute headings of waves, wind and current. Figure 1 shows histograms of the 11,322 metocean parameters in the hurricane hindcast database.

To explain how the hurricane hindcast database can be used for long-term response analysis, consider, for example, the distribution of wave height. The basic assumption is that the future will be similar to the past or, in other words, that the sample distribution calculated from the hindcasts will approximate the true distribution of wave heights. The wave height distribution can thus be averaged over all sites to produce a smooth distribution for an arbitrary site.

The same assumptions may also be applied to any response Y which is dependent on the environment X. Let P_{ijk} be the short-term cumulative probability that the response Y is less than y during hour k of storm i at site j. For the response to be less than y for a given storm at a given site, it must be less than y for each hour in the storm. Thus, the "medium-term" distribution function $P_{ij}(y)$ for the maximum response during storm i at site j is given by a simple multiplication of the hourly short-term distributions:

$$P_{ij}(y) = \prod_{k=1}^{K_{ij}} P_{ijk}(y)$$

where K_{ij} is the number of hours that storm i persists at site j. This also accounts for the likelihood that the maximum response may not occur during the hour when the environment is "most severe" (e.g. the wave height is maximum).

The distribution functions for the entire 85-year history of the hindcast response at each site can be calculated by forming a product over all 35 storms at each of the 98 sites. Even small differences in the positions of the sites with respect to the tracks of the strongest storms can cause the upper tails of the distributions to differ from each other. Since the historical storm tracks are not expected to be exactly duplicated in the future, the distribution functions from many sites should be averaged. This process in effect randomizes the tracks of future storms relative to a particular site.

In order to derive the distribution of maximum response for exposures other than 85 years, it is assumed that the frequency of arrival of hurricanes, and hence responses, is Poisson distributed. Taking simple arithmetic averages over both storms and sites, a single random storm (SRS) distribution can be defined:

$$P_{SRS}(y) = \frac{1}{I}\sum_{i=1}^{I} \frac{1}{J}\sum_{j=1}^{J} \prod_{k=1}^{K_{ij}} P_{ij}(y)$$

where I = 85 is the number of storms and J = 98 is the number of grid points in the hindcast database. The long term response distribution $P_T(y)$ for an exposure of T years at a random site is:

$$P_T(y) = \exp[-\nu T(1 - P_{SRS}(y))]$$

where $\nu = 35/85$ is the arrival rate, i.e. the expected number of storms per year (35 storms in 85 years).

It is important to realize that the short-term response distribution $P_{ijk}(y)$ is in effect conditional on the environment X. That is, $P_{ijk}(y) = P_{ijk}(y|X)$. The entire process can also be inverted to obtain the multi-dimensional probability distribution of the environment, conditional on a given response Y, and hence the response-based environment which is most likely to yield a prescribed response level.

Short-Term Responses

The short-term cumulative distribution function $P_{ijk}(y)$ represents the probability that the response Y is less than y during hour k of storm i at site j. In this study the short term distributions have been represented by means of empirical Gumbel distribution fits to experimental data from model tests. Typically motion responses such as heave, pitch, roll and offset conform quite well to a Rayleigh distribution, whereas maximum mooring line tension is conforming more to an exponential distribution.

Program SPMsim™ (Ref. 5) has been used to perform a comprehensive dynamic analysis in the frequency domain for each of the 11,322 sea states in the hurricane database to yield the desired mean and RMS responses. Since the analysis is performed in the frequency domain, the quality of the results tends to deteriorate in certain pathological cases where significant fishtailing oscillations may develop (Ref. 4). Also, when considering wave spreading, only first order motions and wave frequency line tensions are affected by short-crested seas and the present study should therefore be seen as merely an effort to numerically investigate the effects of wave spreading, rather than addressing all relevant physical aspects. Despite such limitations, it is noteworthy that the SPMsim™ software has been extensively validated during a large number of model tests under widely varying conditions and is considered to yield very accurate predictions.

Vessel and Mooring System

The tanker has a length of 255 m and beam of 43.4 m and operates at a constant draft of 9.6 m (there is no provision for storage). Three different turret locations are considered at 75, 85 and 95 m from amidships respectively. Static wind and current load estimates have been derived from wind tunnel tests. Estimated averaged natural periods and damping levels are summarized as follows:

mode	period (s)	damping
surge	257	42%
sway	651	65%
yaw	182	37%
heave	10.3	15%
roll	12.7	2.5%
pitch	9.5	15%

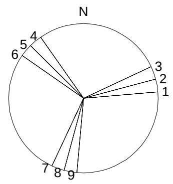
The damping includes contributions from still-water viscous effects, wind, current and wave drift damping and mooring line damping. About half of the total surge damping is due to mooring line damping. Compared to shallow water systems, the present system is rather heavily damped.

The mooring systems features nine legs, clustered in 3 groups with 10 degrees separation between the lines in each group. Each leg is comprised of:

- 900 m of 89 mm ground chain,
- 1,000 m of 87 mm steel lower riser wire,
- a permanent subsurface buoy (net buoyancy 40 MT),
- 300 m of 87 mm steel upper riser wire, and
- 50 m of 89 mm platform chain.

In plan view:

- Lines 1-3 are oriented ENE ± 10 degrees.
- Lines 4-6 are oriented NE ± 10 degrees.
- Lines 7-9 are oriented SWS ± 10 degrees.



An interesting feature of such clustered mooring systems is that maximum offset occurs when wind, wave and current approach "in-between" two clusters, whereas maximum mooring line tension occurs when wind, waves and current approach "in-line" with one of the clusters. In the Gulf of Mexico hurricanes tend to have a prevailing approach direction from the SE (Fig. 1) and, consequently, the present cluster orientation tends to minimize line tension rather than offset. Hence, as will be confirmed later on, long-term mooring line tensions are much higher in the "windward" lines 1-3 and 7-9 than in the "leeward" lines 4-6.

Results

Due to space limitations only a small selection of the results can be presented and discussed in this paper. Unless stated otherwise, the results presented herein refer to the base case turret location of 85 m ahead of amidships without wave spreading. Also, in the discussion below, "heave" refers to the vertical motion at the chain table.

Short Term Responses. Figure 2 shows histograms of the computed short-term extreme (MPM) responses for all 11,322 records in the hindcast database. The dominant absolute ship heading is towards the SE, i.e. against the prevailing approach direction of hurricanes (compare with Fig. 1).

Wave spreading has little effect on most responses, except roll (Figure 3). In long-crested seas most roll amplitudes are well below 5 degrees, but large values (in excess of 10 degrees) are not uncommon. Large roll amplitudes are not necessarily associated with large wave heights, but rather occur at low wave heights (< 10 m) near the lower end of the hurricane hindcast database when the vessel is exposed to quartering to beam seas conditions.

Medium Term Responses. In the context of the present paper, the medium term response is understood to describe the temporal variation of the response for a specified storm and grid point. "Worst-case" storms have been selected by inspection. As an example, Figure 4 shows the temporal variation of environmental parameters during the September 1915 storm at grid point 310. During this event, both maximum roll and mooring line tension occurred, see Figure 5. This sequence of events is rather typical for the kind of erratic behavior that may occur during the passage of the eye of a hurricane, with dramatic fluctuations in both intensity and directions of wind, waves and current. Maximum roll, offset and tension are seen to occur when the relative wave heading is about 250 degrees, i.e. almost beam-on to the ship, even though the wave height, wind speed and current speed are rather low at this instance.

Long Term Response. Figure 6 shows the long term response distributions. Figure 7 shows the 100-year responses as a function of turret location, both for long-crested and short-crested seas (for short-crested seas the 85 m turret location has been extrapolated to 75 m and 95 m by assuming that the same trend applies as for long-crested seas).

It is seen that heave at the chain table increases as the turret is moved forward (trivial). Roll and pitch are virtually independent of turret location. Offset and tension decrease as the turret is moved forward. Note that the maximum tension in the leeward mooring lines 4-6 is almost half of that in the windward lines 1-3. The effect of wave spreading is in general to increase the responses, albeit by very small amounts, except for roll, which is significantly increased.

Response-Based Design Criteria. A simple but effective manner to derive response-based criteria is to filter the database of short-term responses to obtain sea states that yield the desired 100-year long-term target response. Based on the filtered results, an "educated guess" can be made of the desired response-based design storm and subsequently calibrated through a few trial and error runs.

Table 1 shows the results for the turret located at 85 m and long-crested seas. The column labeled "short term" presents the results of a "classical" short-term response analysis using 100-year environmental return period wind, wave and current parameters with wind and current applied 30 and 45 degrees to the left of the waves, following DNV POSMOOR recommendations (Ref. 2). The column labeled "long term" summarizes the desired target 100-year response levels obtained in the present study. The good agreement between the short and long term results (except for roll) is merely fortuitous.

The remaining columns in Table 1 are the proposed response-based design storms, which should only be used to estimate the response for which they are intended (all other estimated responses should be ignored). The response-based offset storm combines relatively low, but collinear waves and wind with a relatively high current acting 70 degrees to the left of waves and wind ("relative" in this context refers to the 100-year hurricane design conditions as specified in the column labeled "short term" in Table 1). The response-based tension storm combines a relatively large wave height with "normal" wind and current conditions. Wind and current are acting 30 and 10 degrees to the right of the waves.

Conclusion

A long-term response analysis technique based on a hurricane hindcast database has been successfully applied to a turret-moored tanker in the deepwater Gulf of Mexico. Although the computational effort involved is quite substantial, it is considered quite feasible using established software and hardware tools. The long-term response analysis for long-crested seas has shown that:

1) Roll and pitch motions are unaffected by turret location (at least within the range of turret locations considered).
2) Offset decreases as the turret is moved forward.
3) Maximum tension in the windward lines decreases as the turret is moved forward.

4) Maximum tension in the leeward lines is about half of that in the windward lines.
5) The effect of wave spreading is to increase all responses by a relatively small amount, except roll, which increases substantially.

For the clustered 3-by-3 type of mooring configuration considered in the present study, it is evident that the leeward lines 4-6 are underutilized and could in principle be reduced in size and/or number. However, further reliability analysis is recommended before embarking on this route.

Amongst the responses considered in the present study, roll is probably the most complex one, both from short and long term points of view. From a short term point of view, the prediction of roll is complicated, especially in the frequency domain, due to the nonlinear nature of the coupled surge-sway-yaw equilibrium and the resulting difficulty which arises when linearizing the frequency domain solution about one particular relative wave heading. Moreover, the quality of short-term roll prediction is affected by nonlinearities stemming from both damping and restoring terms. The long term prediction of roll is hampered by the fact that relatively few but large roll amplitudes occur at low wave heights near the lower end of hurricane database. This makes the present long-term extrapolation somewhat questionable since low sea states (of which there occur many outside the hurricane season) are under-represented in the present analysis. These issues can only be resolved by exploring the coupled surge-sway-yaw-roll response in more detail through dedicated nonlinear time simulations and using an extended hindcast database that also includes winter storms.

Finally, it is noted that many other response have also been considered in the study, but not reported here due to space limitations. These include topsides accelerations and turret loads and moments. Another interesting response for consideration in a follow-up study is the relative vertical motion between the ship and the water in as far as it impacts green water and breakwater designs.

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				response-based storms				
parameter	unit	short term	long term	heave	roll	pitch	offset	tension
significant wave height	m	12.2		12.9	8.9	13.2	10.4	13.0
peak wave period	s	14.2		14.9	14.5	14.5	12.2	15.2
spectral peakedness		2.7		2.9	2.2	2.9	2.9	2.5
Jonswap parameter		2.4		2.8	1.4	2.8	2.7	2.0
wind speed	m/s	36.5					30.9	38.1
current speed	m/s	1.75					2.2	1.8
wave heading	degrees	any		160 [2]	135 [2]	165 [2]	45 [3]	130 [3]
wind heading	degrees	waves-30 [1]					45 [3]	160 [3]
current heading	degrees	waves-45 [1]					-25 [3]	140 [3]
heave	m	10.9	11.4	11.5				
roll	degrees	5.8	9.9		10.2			
pitch	degrees	6.6	7.0			7.1		
offset	m	140	127				128	
maximum tension	MT	421	408					414

[1] That is, wind 30 degrees relative to the waves and current 45 degrees relative to the waves.
[2] Relative heading with respect to ship (180 degrees = bow-on).
[3] Absolute heading with respect to true north (measured anti-clockwise).

Table 1 - Comparison of responses derived from short term analysis, long term analysis and response-based design storms.

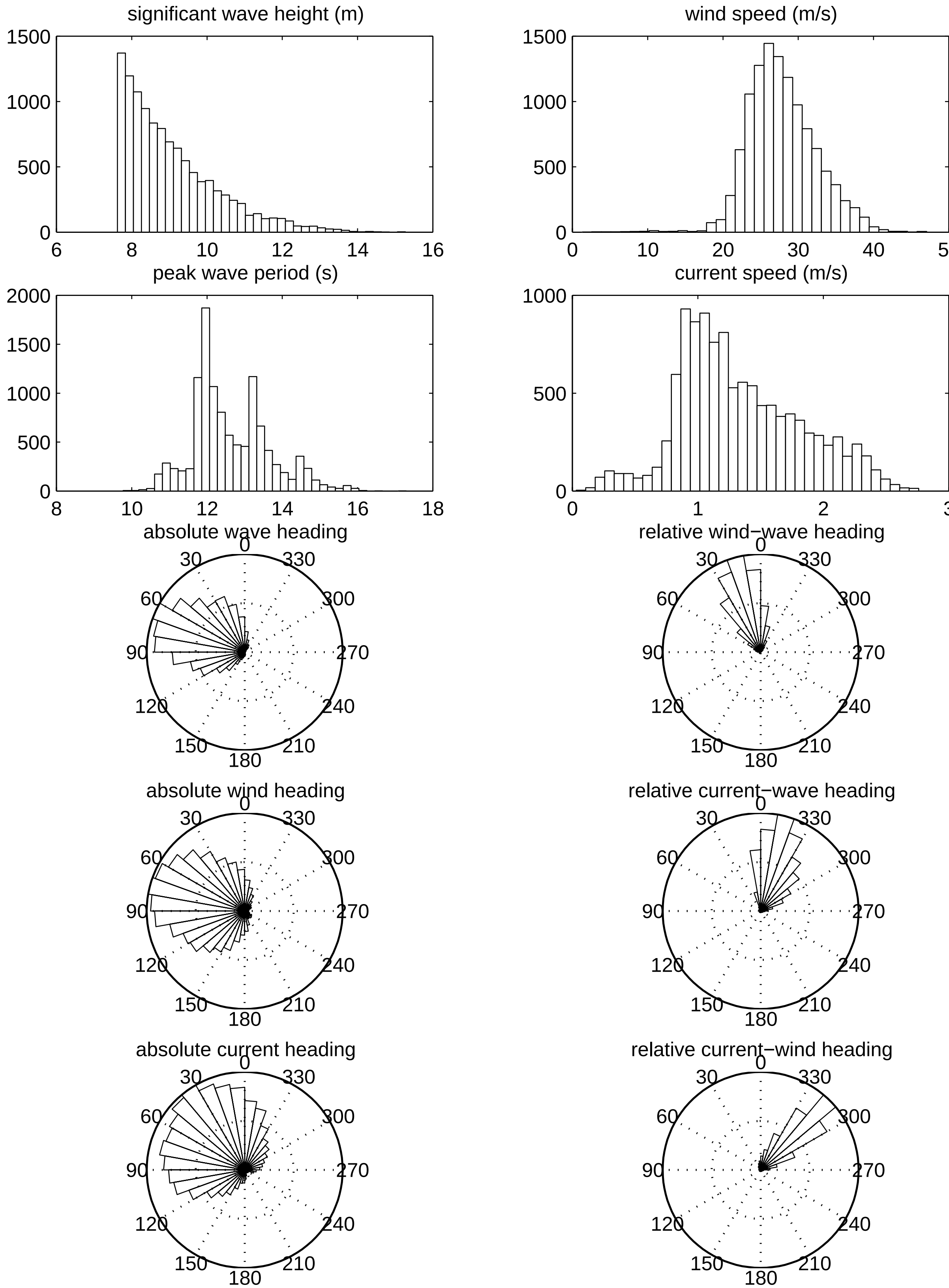

Figure 1 - Histograms of 11,322 metocean parameters in hurricane hindcast database.

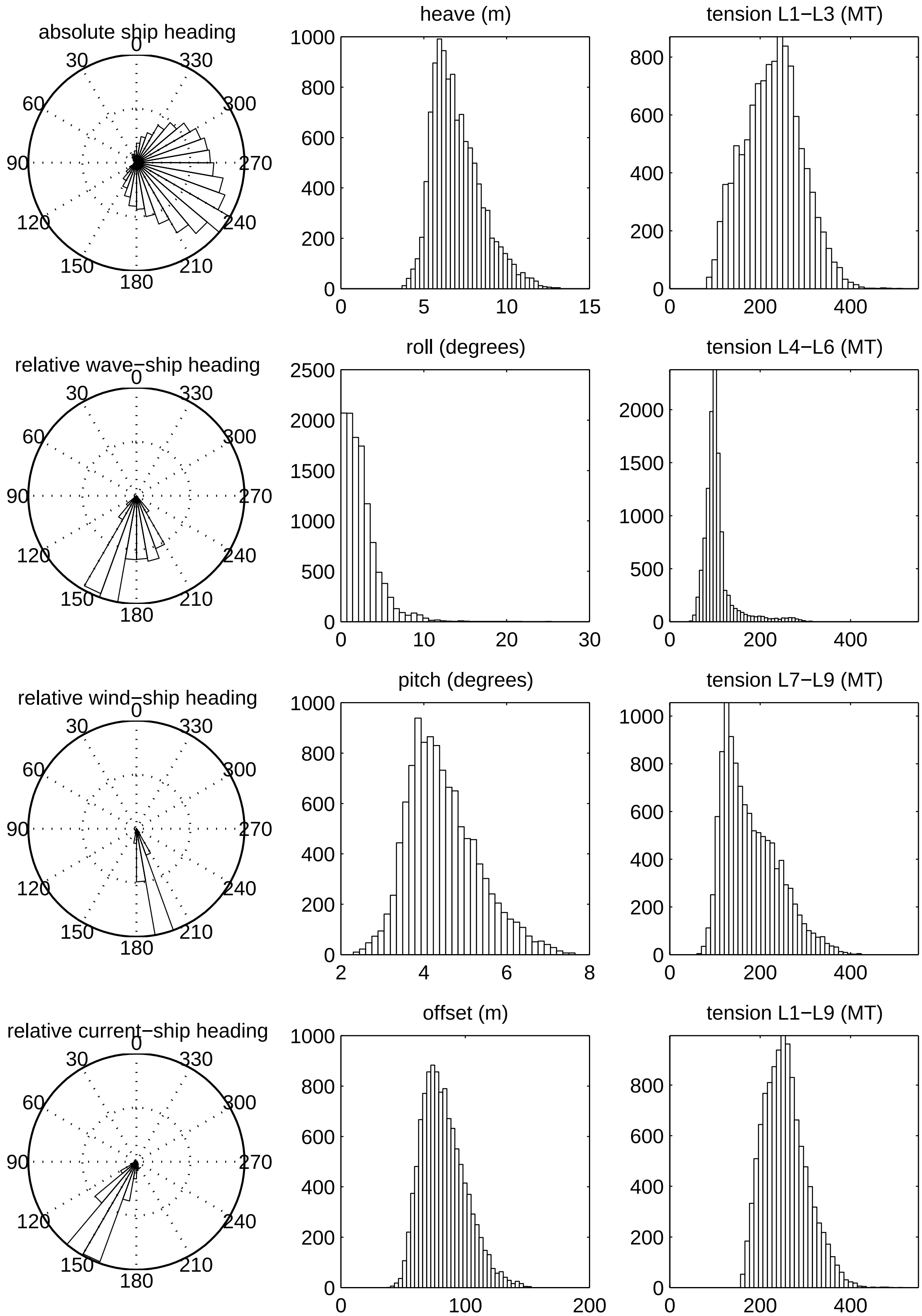

Figure 2 - Histograms of 11,322 response parameters (turret at 85 m - long crested seas).

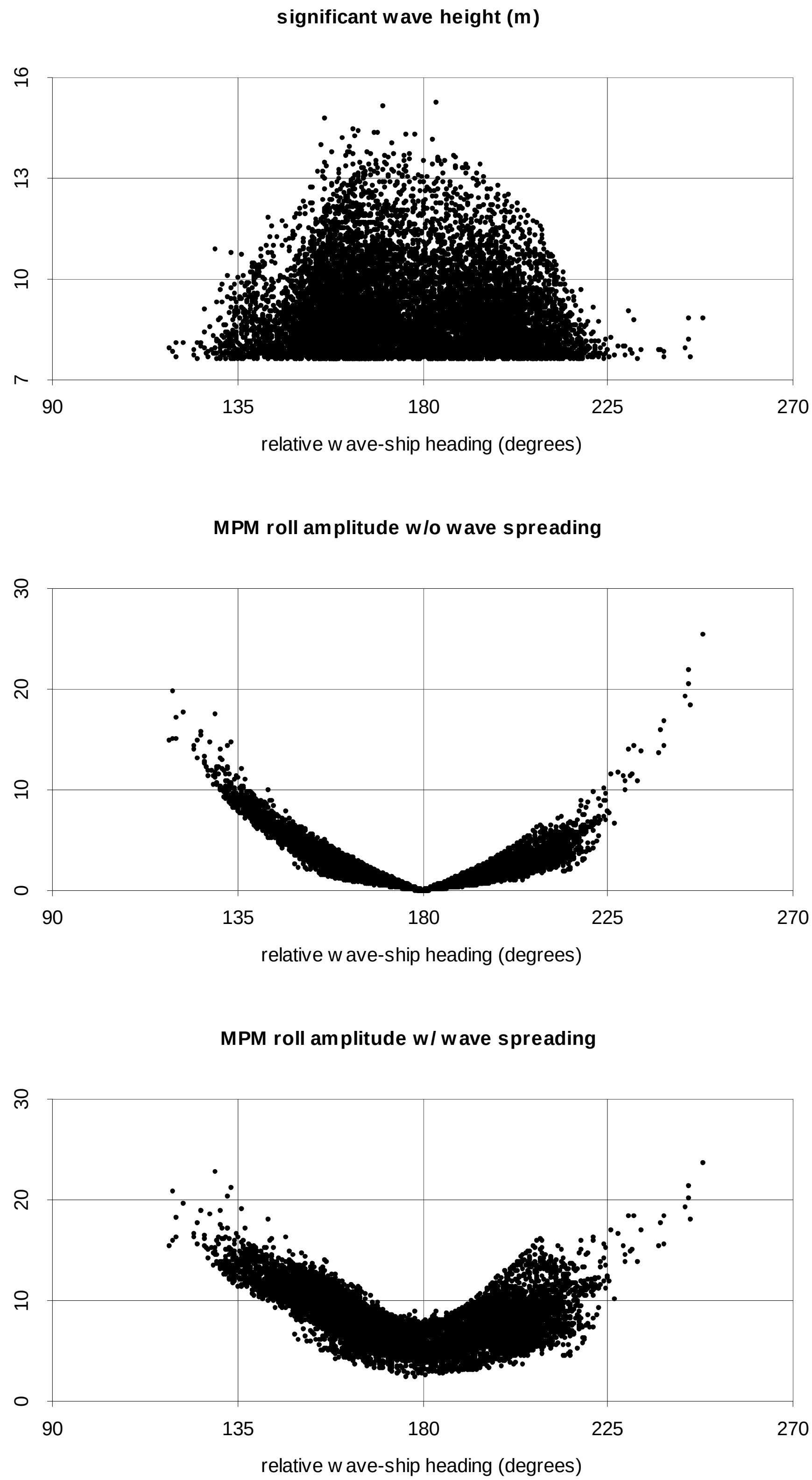

Figure 3 - Roll amplitude versus relative wave heading and wave height (turret at 85 m).

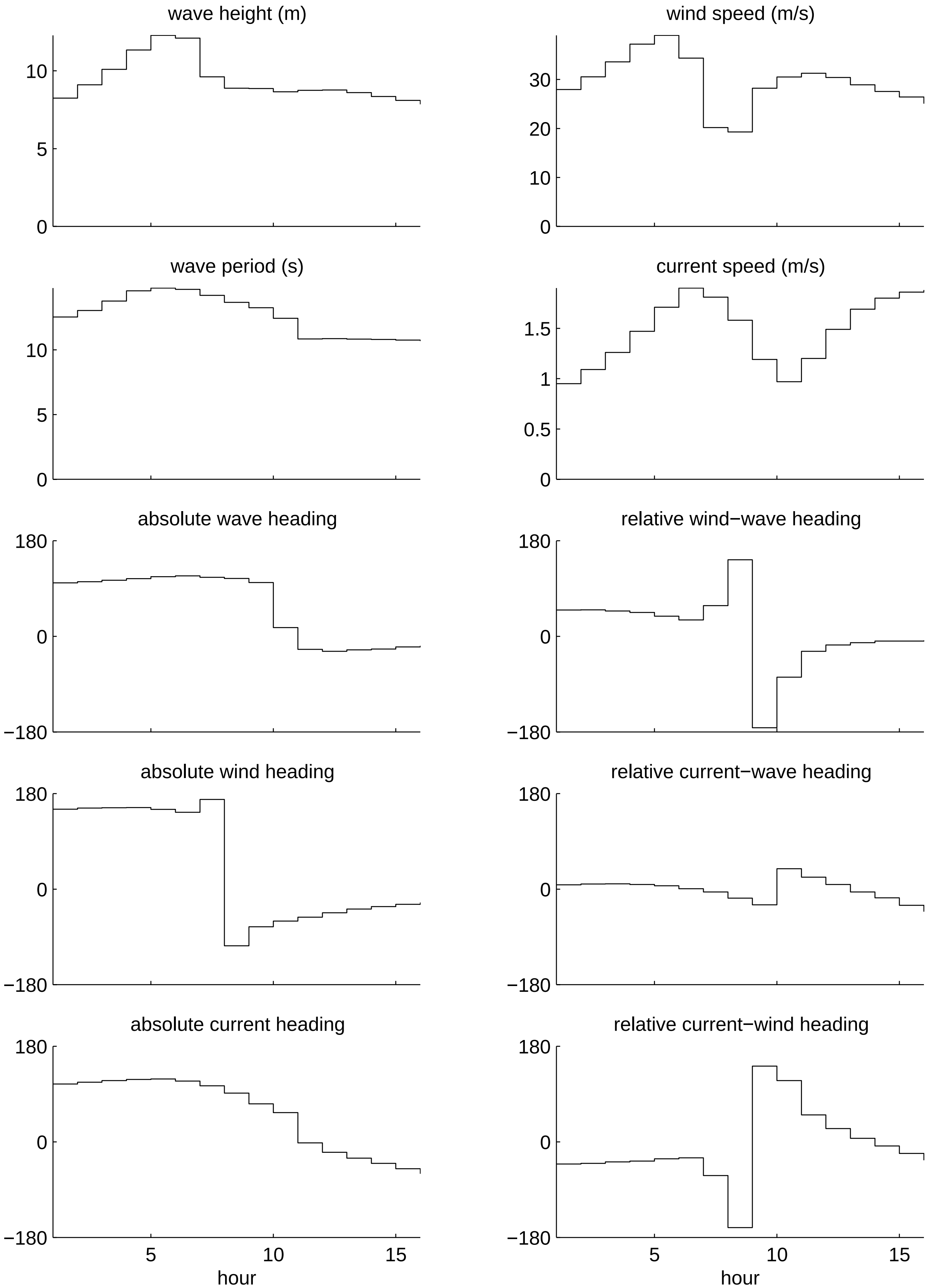

Figure 4 - Maximum roll/tension event (storm 6, October 1915, grid point 310).

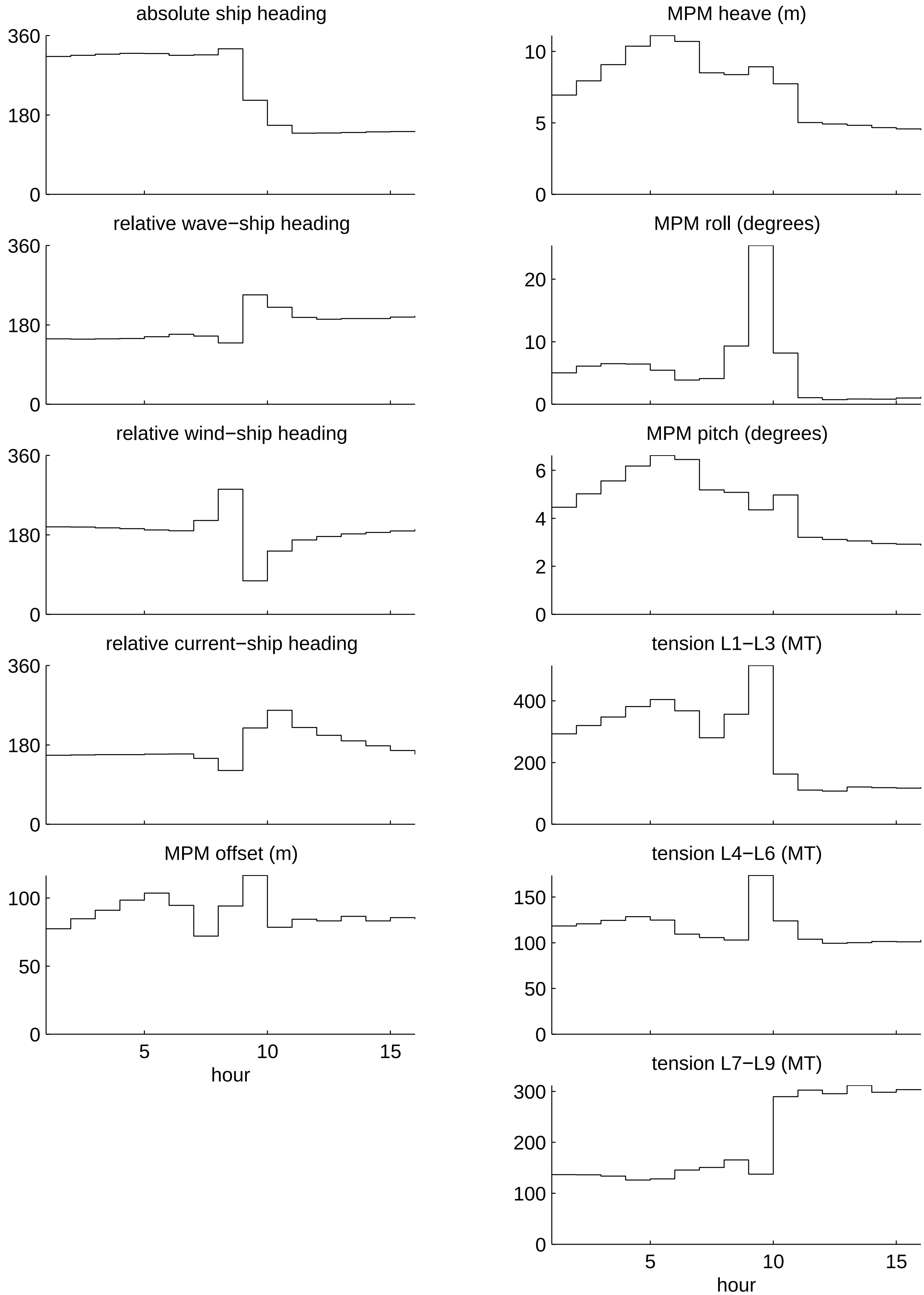

Figure 5 - Variation of responses during maximum roll/tension event (turret at 85 m).

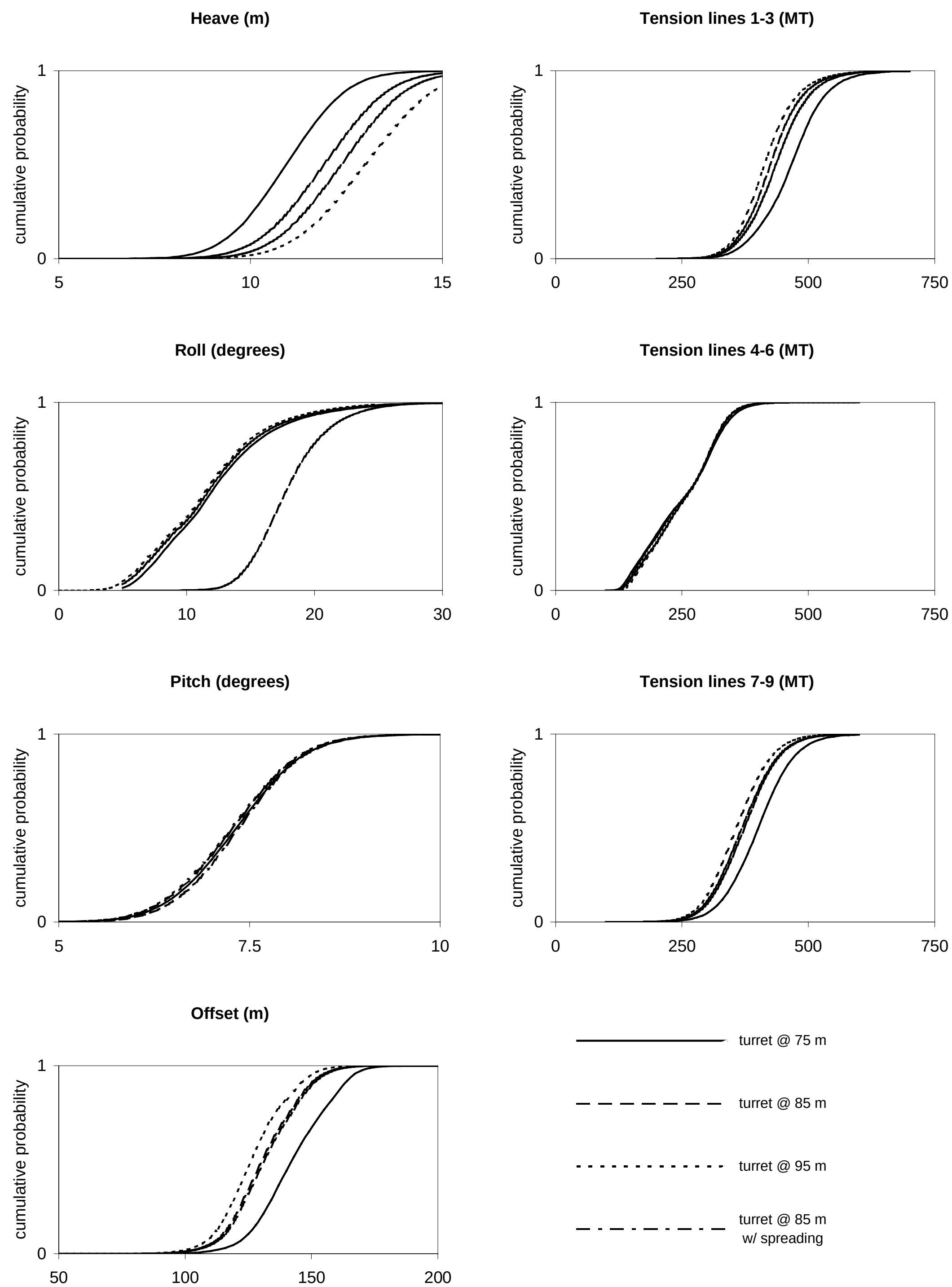

Figure 6 - Long-term response distributions.

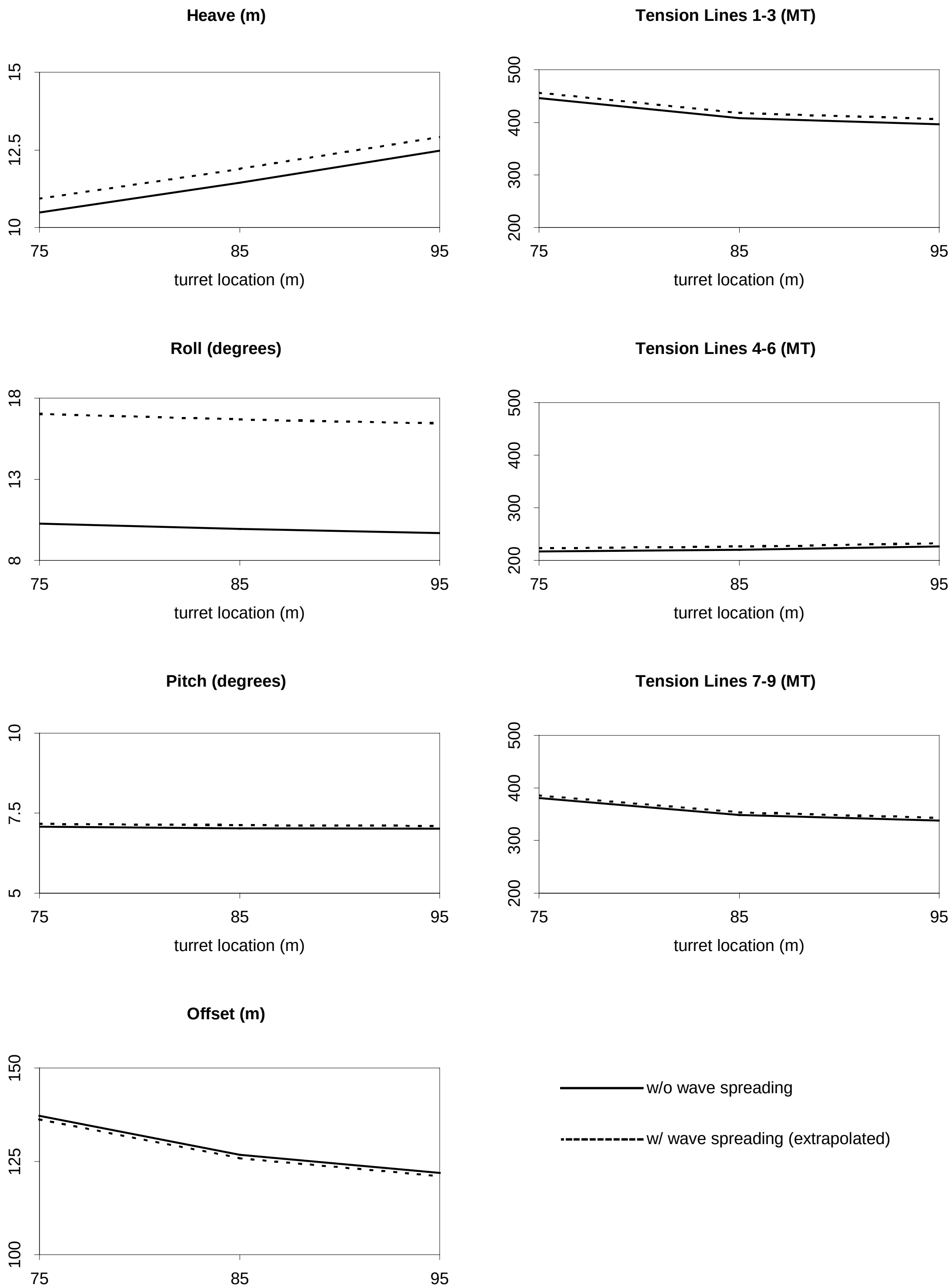

Figure 7 - Long-term 100-year responses versus turret location.