Probability Distributions for Wave Loading on Single Point Mooring Systems

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Abstract

In the design of single point mooring systems, wave loading is a dominant factor. Usually a distinction is made between wave frequency and low frequency excitation. In the wave frequency regime, a Rayleigh distribution is often employed to obtain the extreme values required for the design. In the low frequency range, extreme values are usually derived from an exponential distribution. Although the justification is based on theoretical considerations and experimental investigations in laboratory conditions, the lack of reliable full-scale data to verify the underlying assumptions is often mentioned. In this paper the results obtained from large-scale, long-duration in-situ measurements are presented. The probability distributions derived for the surge forces in both the wave frequency and the low frequency regime, confirm the theoretical considerations, provided crest-to-trough values are used. In the experiments a consistent difference was observed between crest-amplitudes and trough-amplitudes, in the order of ten to twenty percent, which could not completely be accounted for, but could be due to the particular test configuration. From numerical simulations the damping of the mooring system was established at around five percent of the critical damping value.

Keywords

Single point mooring systems; wave loading; probability distributions; large scale experiments; wave frequency excitation; low-frequency excitation; numerical simulations; experimental verification.
Introduction

In the offshore industry the use of permanently or semi-permanently moored ships as a production station and as a temporary storage vessel for crude oil, has been well established during the last decade. In moderate and severe environmental conditions the stationing system of such a ship is almost invariably of the single point mooring type, which allows the ship to weather-vane as a result of environmental forces due to wind, current and waves. A large variety of single point mooring systems has been developed in the past: catenary moored buoys to which the ship is connected by means of a hawser or a yoke, single anchor leg moorings, permanent or disconnectable turret type moorings, etc.

The behaviour of single point moored vessels under environmental loading due to wind, current and in particular waves is complicated; low-frequency surge and yaw motions play an important role and although the direct excitations are quite low compared to the first order wave loading, resonance effects may result in high sub-harmonic loads in the mooring system. Extensive research, both based on model testing (e.g. Stansberg (1992)) and theoretical analysis combined with model testing (e.g. Wichers (1988)), has resulted in a better understanding of single point mooring systems. Still for practical design the tools and procedures need improvements ('d Hautefeuille et al., 1992). Classification societies and governmental institutions only recently have started to formulate (tentative) regulations for single point mooring systems (see e.g. American Petroleum Institute 1991) which, probably due to the fact that the underlying technique is not yet well established and leaves the designer with several options for analysis (Shoup et al., 1992).

In order to determine the reliability of the mooring system and its components, it is important that the extreme wave loads can be estimated with sufficient accuracy. The overall probability distribution is used to estimate fatigue behaviour, while the tail of the distribution provides information on the extreme loading. It is well known from literature that the low-frequency distribution of mooring loads deviates from the Rayleigh distribution due to quadratic transfer properties. Estimates for the distribution of surge motions and the resulting mooring loads were first reported by Pinkster (1984) and Wichers (1988).

Recently, additional results have been reported by Dogliani et al.(1993) and Stansberg (1992). Dogliani derived the distributions entirely from theoretical simulations; Stansberg established the distributions from model tests in a wave basin. Both methods have their limitations. Because sub-harmonic effects are not completely mastered yet, the computations should be verified by experimental investigations; on the other hand, in case of model tests in a wave basin it is difficult to realize tests of sufficiently long duration to establish the tail of the distribution with sufficient accuracy. In particular, special care should be taken in laboratory basins to simulate realistic low-frequency wave characteristics and to avoid spurious results due to resonance associated with basin oscillations. Hence, there is a considerable need to verify these laboratory observations and to establish reliable statistical distributions that can be used to determine extreme values required for the design of mooring systems. In the experiments described in this paper, the opportunity was available to measure wave loads on a relatively large scale (1:20) model of a ship moored in open water in one of the Dutch estuaries, over a long period of time during several weeks.
Large Scale In-situ Experiments

General scope
As part of an on-going research project on structural fatigue due to wave loading, an extensive experimental measurement campaign was set up to measure exciting forces and bending moments over a long period of time under natural sea state conditions. It was decided to use this measurement campaign to obtain the required information on mooring forces, by installing an additional force measurement device. The experiments were set up by the Delft University Ship Hydromechanics Laboratory with a large scale model (1 : 20) which was moored in one of the estuaries of the southern part of The Netherlands. In order to be able to determine the probability distributions and extreme values of the maxima in the loads on a moored vessel, sufficiently long measurements were carried out in realistic natural wave conditions. The results were recorded and stored on computer on-site, and were later processed in detail.

Measurement site
The measurements were carried out at a site with appropriate environmental conditions. For this and logistic reasons the choice was made to use the 'Hollandsch Diep' near the town Willemstad. The Hollandsch Diep is one of the closed estuaries in the southern part of The Netherlands. On this particular location the minimal undisturbed fetch of the wind was approximately one nautical mile enabling measurements with spectra having approximately 0.30 to 0.40 meters significant waveheight and a peak period of 2.0 to 3.0 seconds. With easterly or north westerly winds however the fetch increased to approximately 10 to 15 nautical miles and significant waveheights of 1.0 meters or even higher could be obtained. The waterdepth in the area varied between 15 and 6 meters. A global chart of the area is depicted in Figure 1.

Figure 1. Location of Measurement Site
The area is normally without any tidal current, although when the sluices at the sea side of the estuary are opened for the disposal of water, a current of approximately 0.5 knots east to west may occur. The prevailing winds in the area in the autumn period in which the measurements took place are southwest to west and moderate (Beaufort 4 to 5), sometimes northwest and strong (Beaufort 5 to 7).

Model characteristics

The model that has been used for these experiments was a large scale version of a supply tanker of the Royal Dutch Navy 'H.M.S. Zuiderkruis'. The main dimensions of this model are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Model dimensions</th>
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<tbody>
<tr>
<td>Length over all</td>
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<tr>
<td>Length between perpendiculars</td>
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<tr>
<td>Beam over all</td>
</tr>
<tr>
<td>Draft</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>Freeboard at midship</td>
</tr>
<tr>
<td>Block coefficient</td>
</tr>
<tr>
<td>Prismatic coefficient</td>
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<tr>
<td>Modelscale</td>
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The model was constructed of glass fibre reinforced polyester and wood. It had its actual sheerline but no superstructure. On the bow of the model a steel 'A-frame' was constructed which was free to rotate in pitch but restrained in all other directions by using horizontal hinges on the deck of the model. This steel A-frame extended approximately 1.5 meters in front of the model where it was connected to a cylindrical floater with a diameter of 0.35 m. This floater was rigidly connected to the A-frame except for a freedom in yaw rotation. The main dimensions of this floater buoy are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Buoy dimensions</th>
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<tr>
<td>Diameter of cylinder</td>
</tr>
<tr>
<td>Draft</td>
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<tr>
<td>Displacement</td>
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The mooring lines of the three anchors which kept the floater buoy were connected to the bottom of the floater. The mooring lines used were 10 mm nylon ropes commercially available. No attempt has been made to match the elasticity and the weight of the mooring lines with any real anchoring system. A global view of the model and the A-frame with the buoy and its mooring layout may be obtained from Figure 2.
Figure 2. Mooring layout and measurement configuration.

**Wave buoy characteristics**

In order to be able to measure the waves under these specific conditions, an anchored wave buoy was developed, capable of measuring both the relative short and long waves of interest during the experiments. The regular disposable wave buoy of the Ship hydromechanics Laboratory or the Waverider buoy do not have sufficient capabilities in this range due to their size (spheres of approximately 0.8 to 1.0 meter) and the use of accelerometers. So the choice was made to use a vertical displacement meter connected to a pile. The displacement meter with a range of 2.0 meter was activated by a small floater sliding along the pile. The pile itself with a diameter of 0.05 meter and a vertical length of 2.5 meter was supported by a fully submerged buoy at 1.0 meter below the free surface. The anchorline by which the buoy was kept stationary was connected to the buoy in such a way that only minimal inclination of the pile occurred due to drift forces coming from either the waves or any current velocity present.

The natural period of heave of the buoy with pile due to its small waterplane area and large weight of displacement was large, i.e. approximately 15 seconds. This was quite remote from the wave period range of interest. However to be able to compensate for any residual vertical motions of the buoy itself an accelerometer was placed into the buoy. By double integration of this signal the vertical displacement of the buoy could be obtained. The measured vertical wave elevation using the displacement of the small floater following the wave surface along the pile has
been simultaneously corrected for this to yield the proper wave elevation signal. An extended description of this wave buoy is given by Ooms (1994). During the tests the heave and pitch motions and the horizontal forces in the hinges connecting the A-frame to the model have been measured. All data were stored on disk for later processing.

**Measurement Results**

**Wave conditions**

From the vast amount of data collected during the entire measurement period, a selection was made of appropriate conditions that were both sufficiently extreme as well as stationary in time. The selected period as presented in Figure 3 includes a window of some 36 hours where the wave conditions are relatively stationary, and yet of adequate magnitude (corresponding to a full scale significant wave height of about 6 metres) to enable statistical analyses. The corresponding mean-zero-crossing wave periods are presented in Figure 4.

![Figure 3. Measured wave heights during the experiments.](image)

From these data it can be observed that over 50000 waves were available for statistical analysis, which is more than adequate for statistical reliability, even in the low-frequency regime. The analyses for the extreme forces were carried out by collecting the extreme values during each of the 20 minutes measurement runs, and then performing a statistical analysis on the entire dataset of all 70 runs.
Mooring forces

A typical energy density spectrum for the measured forces on the A-frame during the measurement period is presented in Figure 5. The results indicate that the wave-frequency components were dominant in the measurements, but low-frequency force components were also clearly present.

The results as presented in Figure 6 clearly demonstrate that the tail-end of the distribution of the wave-frequency forces is quite well represented by the Rayleigh distribution.

The distribution of low-frequency forces was obtained by filtering the measurement signal before performing the statistical analysis. Due to the considerable record length, the number of low-frequency oscillations was still very large, in the order of 5000 or more. The results as presented in Figure 7 clearly indicate that the tail-end of the distribution is in this case very well described by the exponential distribution, in accordance with theoretical considerations and experimental observations in model basins.

In addition to the mean values used above, the crest and trough amplitudes are presented separately in Figure 8. The minimum values correspond to compression in the mooring frame, while the maximum values represent tension. In these experiments it was observed that the values for compression consistently exceeded those for tension by some ten to twenty percent.
Figure 5. Typical energy density spectrum during the experiments.

Figure 6. Measured distribution of extreme wave-frequency forces.
Numerical Simulations of Damping Effects

Since extensive monitoring of the overall system dynamics was rather difficult to carry out on-site, and was not the primary objective of the measurement campaign, numerical computations were carried out to investigate the dynamic behaviour of the mooring configuration. A numerical diffraction programme developed by Pinkster was used to determine the hydrodynamic characteristics in both the wave-frequency and in the low-frequency regime. In order to determine the unknown damping value of the mooring configuration, computations were carried out using the measured wave spectra as input and the computed surge force in the A-frame as output.

A simplified model was used to generate the time records of the wave drift forces. The model was developed by Pinkster et al. (1987) and is based on a band-width limited white noise representation of the low frequency force components with an exponential distribution. The spectral density of the simplified excitation force is equal to the spectral density of the 'true' wave drift force with zero mean. In terms of mathematical expressions the generated wave drift force is given by

\[ F = \sigma_F (A + 1) + \bar{F} \]

in which

\[ A = \ln(\text{rnd}(a)), \quad \text{for} \quad 0 < \text{rnd}(a) < 1 \]

The quantity \( A \) represents an exponential distribution with average of minus one and standard deviation equal to unity. For the white noise representation the total energy of the wave drift force is obtained from

\[ m_0 F = S_F(\mu = 0) \cdot \frac{\pi}{\Delta t} \]

in which \( \frac{\pi}{\Delta t} \) corresponds to the Nyquist-frequency, being the maximum observed frequency. The variance of the drift force is given by

\[ \sigma_F^2 = E[F^2(t)] - E^2[F(t)] \]

or, alternatively, by

\[ \sigma_F^2 = S_F(\mu = 0) \cdot \frac{\pi}{\Delta t} \]

Using a sample frequency of once every timestep \( \Delta t \), the function \( F \) can be computed. This simple model for the drift force is applicable due to the fact that the natural frequencies of the moored vessel is near to zero and the motion damping is small. A consequence of this method of representing the wave drift force excitation is that comparison between results of time domain simulations and model tests can be based on statistical parameters, and not on a deterministic comparison. By varying the damping value from 1% to 20% of the critical damping, a comparison was made between measured and computed probability distributions of the low-frequency forces. The results indicated that the level of damping in the experiments was likely to be around 5% of the critical damping value. Given the fact that the mooring configuration in the experimental set-up consisted of only a single mooring line, this result seems quite reasonable. For catenary moored systems used in practice, the damping values may be considerably higher, as investigated by Stansberg (1992). Still, the resulting distribution for the low-frequency forces is in both cases quite well described by the exponential distribution.
Conclusions

In order to establish the probability distributions of both wave frequency and low frequency excitation on single point mooring systems, large-scale, long-duration, in-situ experimental investigations were carried out. The measurement site was located in open water in one of the estuaries near the Dutch coast. In this way, natural conditions could be used for long-wave generation, avoiding possible resonance effects due to wave basin oscillations. Horizontal forces were measured in the A-frame connecting the vessel to the mooring buoy. The large scale of the model (1:20) enabled adequate measurement of force levels under these natural conditions. The measurement campaign extended over a period of several weeks. From the entire period, a time span with adequately stationary conditions was chosen for detailed analysis. The time span covered some 36 consecutive hours of measurements, corresponding to about one week of full scale conditions, and containing well over fifty thousand waves.

Both spectral and statistical analyses were carried out on all measured wave and force signals. Special emphasis was on determining the 'tails' of the probability distributions of the forces, both in the wave-frequency regime and in the low-frequency regime. Filtering was used to isolate the low-frequency wave conditions. Due to the long duration of the measurements, adequate statistical information was available even in the low-frequency wave regime. The probability distributions derived for the surge forces in the wave-frequency regime were found to be quite well described by the Rayleigh distribution. In the low-frequency regime, the analysis results confirmed the theoretical considerations, that in this range range, extreme values are better described by the exponential distribution, provided the system contains adequate damping. Numerical simulations indicated that the damping of the mooring system was typically some five percent of the critical damping value, which is adequate in relation to the measurement observations. In the experiments a consistent difference was observed between crest-amplitudes and trough-amplitudes, in the order of ten to twenty percent, which could not completely be accounted for, but could be due to the particular test configuration.

Acknowledgments

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References


