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EXPERIMENTAL STUDY OF THE PROBABILITY DISTRIBUTIONS OF GREEN WATER ON THE BOW OF FLOATING PRODUCTION PLATFORMS

Carlos Guedes Soares and Ricardo Pascoal
Unit of Marine Technology and Engineering, Technical University of Lisbon
Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

guedess@mar.ist.utl.pt , rpascoal@mar.ist.utl.pt

ABSTRACT

Results of an experimental program with a model of a moored Floating Production Storage and Offloading (FPSO) vessel are used to study the probability distributions associated with various phenomena related with green water loading.

Separate analysis of wave height and crests are performed in order to assess the presence and significance of nonlinearities. Time series of pitch motion and relative motion are analysed to check for linearity of the response process. Probability distributions of the occurrence of water on deck and of the conditional distribution water height above deck are also studied.

INTRODUCTION

Special attention has been given in the recent past to green water on deck in view of some occurrences of damages on FPSO facilities, particularly in the North Sea.

FPSO's have a weathervaning capability associated with the turret system that enables them to align with the prevailing weather. Therefore it is expected that the most affected area is at the bow region and indeed, experience with FPSO systems operating in the North Sea has shown that green water loading can cause serious damages in the bow.

Buchner (1995, 1998) has studied the relative motion between FPSO's and waves and concluded that the relative movements at the bow are highly non-linear for short waves but this effect is small for longer waves. He also found that the pitch motion of the vessel was changed by the effect of green water when there were relatively short waves but this effect became small for longer waves. He also compared the probability distributions of the measurements with the Rayleigh distribution and concluded that the differences are larger for short waves than for long waves.

Stansberg and Karlsen (2001) have also performed tests of a FPSO in North Sea storm conditions. The incoming waves were simulated with a second order theory and thus they were more nonlinear than in other tests in which the waves are generated from linear models. They found that the probability of relative waves exceeding the deck level is higher than predicted by the Rayleigh model and they explained this non-linearity as a result of the nonlinear contributions of the high and steep incoming waves, as the nonlinear effects were found to be of minor importance for the ship motion. However the highest relative wave peaks were close to the Rayleigh estimates. They also observed that the most serious conditions were for a sea state with shorter waves.

Buchner and Voogt (2000) have studied the effect of different bow flare angles and in general of the shape of the bow on green water loads. Vestbøstad (1999) has also extended the scope of the initial study by considering the water on deck on the side of the FPSO.

The complex nature of the phenomena has made it difficult to produce codes capable of predicting green water loading in an accurate and efficient manner. Due to complex local behaviour of the fluid, attempts have been made to assess the probabilities of exceedance based on motion calculations with well established linear diffraction codes (Buchner 1998, Buchner 1995).

Hellan et. al. (2001) have devised an engineering tool for prediction of local loads and responses arising from wave impact on bow and deck structures. They use linear ship motions analysis and predict the probability of water on deck based on relative motions.

Guedes Soares et. al. (2001) compared experimental results of motions of a moored FPSO with theoretical predictions of a strip theory program and WAMIT and found that these codes predicted the motion transfer functions adequately. However, it is known that even in cases when the motions are very close to linear, the wave induced load effects can be non-linear with different hogging and sagging bending moments (Fonseca and Guedes Soares, 1998). Although this non-linearity is mainly expected in ships with fine forms, it was also identified in some forms of tankers (Guedes Soares and Schellin, 1998).

The present study is based on the experimental programme described in Guedes Soares et. al. (2001) but deals with the probabilistic models that describe the wave excitation and the FPSO motions and relative motions. In particular it deals with the characterisation of wave heights, wave crests, heave and pitch motions, relative movement at the bow, water height above deck and water height maxima above deck. The aim of studying all these probabilistic models is to identify which ones deviate more significantly from linear models, and how one can describe the probability of water on deck and the probability of the height of water above deck.

In many sea states even when the wave heights are reasonably well described by the Rayleigh distribution, there is a nonlinearity originating a crest-through asymmetry and this is expected to affect the green water on deck. Thus, even for linear rigid body motions, the relative movement may not be linear, as already observed by Buchner (1998).

This paper starts by studying the relative movements, as the means to predict the probability of water on deck. Then it addresses the conditional probabilities of water height on deck and their peaks.

EXPERIMENTAL PROGRAM

An experimental program was carried out at the Danish Hydraulic Institute Water & Environment, with a wooden model, of a scale 1:75, of a simple turret moored FPSO configuration subjected to different sea states and headings. The sea states are those presented in Table 1 and they can be found at locations ranging from the Campos Basin in Brazil to the Northern North Sea.

Because some sea states turn out to have large peak periods and are not critical for the green water phenomena, their results are only partially presented, namely for peak periods of 18 and 20 seconds corresponding to swell conditions. The results shown for peak periods 12 and 14s are those considered to be the more representative ones for the present problem.

For this study, the heading of main interest is 180º, or head waves, because as mentioned before the structure possesses weathervaning characteristics and this study is concentrating on the probabilities of green water on the bow. Though it is true that the most damaging cases have occurred for this situation, the possibility of damage arising from the side should not be underestimated in the presence of mixed seas or of non-collinear winds and current.

The probe for measurement of the incident wave surface elevation was positioned at 975m (full scale) from the wave maker and was 150m (full scale) in front the model.

The FPSO has a very simple lines plan, characterised by rectangular cross sections and an elliptical bow as represented in Figure 1. At the bow it possess an elevated freeboard. Its main characteristics are presented in Table 2, along with those at model scale. The details of the moorings are not presented here as they are not the main concern but they are described in a previous paper (Guedes Soares et. al. 2001).

		***Hs* (m)**			
Head	***Tp*(s)**	8.0	10.0	12.0	14.0
180º	12	✓	✓	✓	✓
	14	✓	✓	✓	
	18	✓	✓	✓	✓
	20	✓	✓	✓	✓
165º	12	✓	✓	✓	
	14	✓	✓	✓	
	18	✓	✓	✓	✓
	20	✓	✓	✓	✓
150º	12	✓	✓	✓	✓
	14	✓	✓	✓	
	18	✓	✓	✓	
	20	✓	✓	✓	
120º	12	✓	✓	✓	
	14	✓	✓	✓	
	18	✓	✓	✓	

Table 1- Wave climate and ship headings.

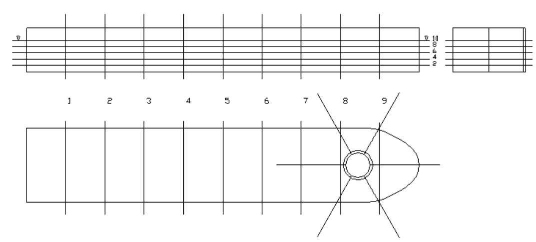

Figure 1.- Lines plan of the FPSO hull.

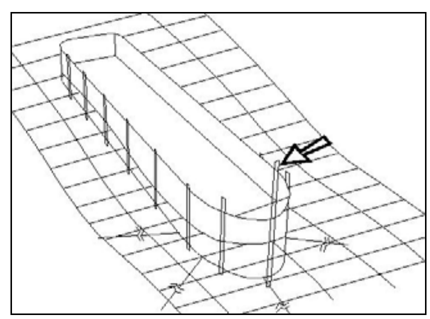

Figure 2.- Representation of probe installation

As represented in Figure 2, the model was fitted with 10 probes at the bow and sides to measure relative movements. The probes mounted at the bow extend above the freeboard deck, thus enabling measurements of the height of green water on entry. The arrow indicates the relative movement probe considered in the present calculations.

	Ship	Model
Δ (displacement)	309656 Ton	734 Kg
Lpp (length betw. pp.)	280 m	3.733 m
B (beam)	52 m	0.693 m
D (Depth)	30.5 m	0.407 m
T (draught)	22.2 m	0.296 m
LCG (aft midship)	5.10m	6.8 cm
KG (vertical pos. of CG)	17.4 m	0.232 m
GM (transv. metac. height)	4.30	0.057 m
I_x (roll inertia)	4.072×10^7 Tm^2	17.16 Kgm^2
I_y (pitch inertia)	1.093×10^9 Tm^2	460.6 Kgm^2
I_z (yaw inertia)	1.093×10^9 Tm^2	460.6 Kgm^2

Table 2- FPSO main particulars.

WAVE HEIGHTS

Given that the motion is excited by the waves, the probability distributions of the wave height close to the bow of the model are considered.

The models that are considered are the classical ones of the Rayleigh distribution as proposed by Longuet-Higgins (1952), the Weibull distribution adopted by Forristal (1978) and the modified distribution proposed by Naess (1985). These distributions have been considered in some previous studies showing that they are appropriate in many situations to describe full-scale data (Guedes Soares and Carvalho, 2001).

The equation representing the Weibull cumulative distribution, as used in these calculations, is:

$$P(X \le x) = 1 - e^{-\left(\frac{x}{a}\right)^c}, \text{ with } x \ge 0$$

and the Rayleigh cumulative distribution is a particular case with the exponent equal to two:

$$P(X \le x) = 1 - e^{\frac{-x^2}{2b^2}}, \text{ with } x \ge 0$$

where the standard deviation of the process $b/2$, is related to the significant wave height.

The Naess distribution describes the peak-to-through excursions and is given by:

$$P(X \le x) = 1 - e^{\frac{-x^2}{4\left(1-\rho\left(\tau/2\right)\right)m_0}}$$

where $\rho\left(\tau/2\right)$ is the first minimum of the normalised autocorrelation function that is expected to occur at half period. This function becomes –1 for a strictly narrow band process (Ochi 1998) and this distribution reduces to the Rayleigh.

The experimental data sets have been adjusted to the different distributions and the Kolmogorov-Smirnov (KS) goodness of fit test was applied at the 5% significance level. The results were that only the wave heights in the sea state with 18s peak period and 14m significant wave height were not accepted as following a Rayleigh distribution at the aforementioned significance level. Thus, at a 95% confidence level, all other tests can be considered realizations of a Gaussian process.

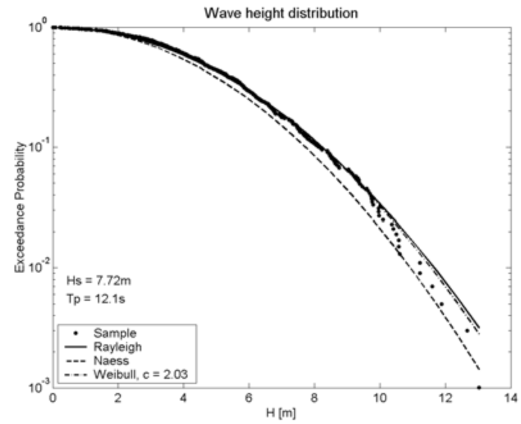

Figure 3- Distribution of wave height for target 8m Hs and 12s peak wave period.

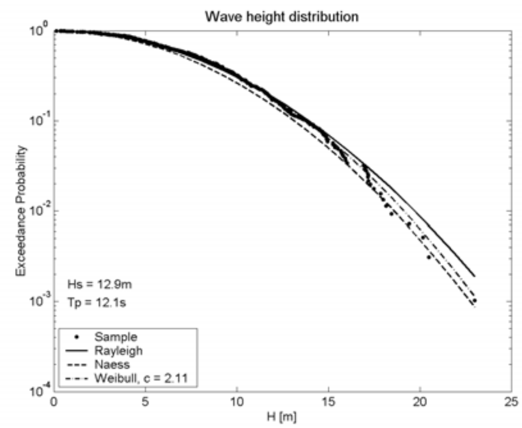

Figure 4- Distribution of wave height for target 14m Hs and 12s peak wave period.

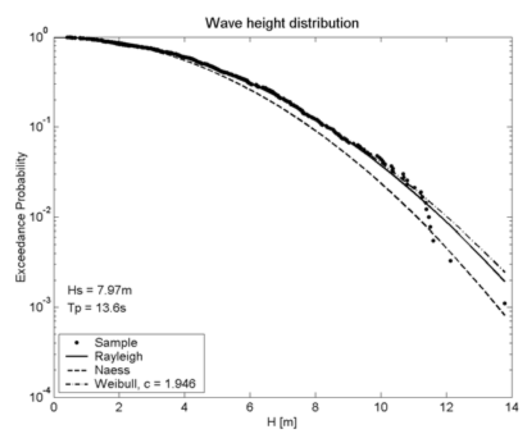

Figure 5.- Distribution of wave height for target 8m Hs and 14s peak wave period.

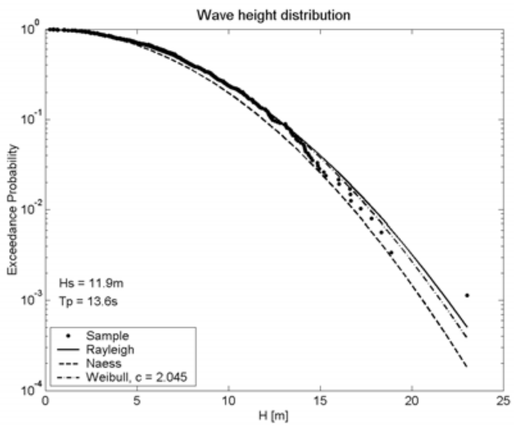

Figure 6.- Distribution of wave height for target 12m Hs and 14s peak wave period.

The results shown in figures 3 to 6 indicate that generally the Rayleigh and Weibull distributions provide a good fit for low and moderate probability levels but at the tails the Naess distribution tends to provide a better representation, which agrees with earlier results on full-scale data (e.g. Guedes Soares and Carvalho, 2001).

The exponent of the fitted Weibull distribution that are shown in figures 3 to 6 are all close to 2.0, reflecting that those distributions are close to the Rayleigh.

WAVE CREST DISTRIBUTION

Forristal (2001) has provided an interesting review of models to describe wave crest distributions. Among them he describes the Kriebel-Dawson model that defines the probability of exceedance, by

$$P(\mathrm{A} \geq \alpha) = e^{-\frac{\alpha^2}{2m_0} + R\frac{\alpha^3}{8m_0^{3/2}}}$$

where the threshold level, α, is the level at which nonlinear crest statistics equal the linear ones if no transformation would be applied (Dawson et. al. 1996), R is a steepness parameter defined as $4\bar{k}\sqrt{m_0}$, where $\bar{k}$ is the mean wave number. This distribution accounts for the crest-through asymmetry.

The reference case for a linear narrow band process would be the Rayleigh distribution, which is indicated in the examples of figures 7 to 10. Inspection of the results clearly shows that the crest distributions deviate significantly from the Rayleigh model, much more than in the case of wave heights, and the Kriebel-Dawson model provides very reasonable fits.

Therefore, while the wave heights could be reasonably well described by a model based on linear assumptions the crest heights are clearly non-linear.

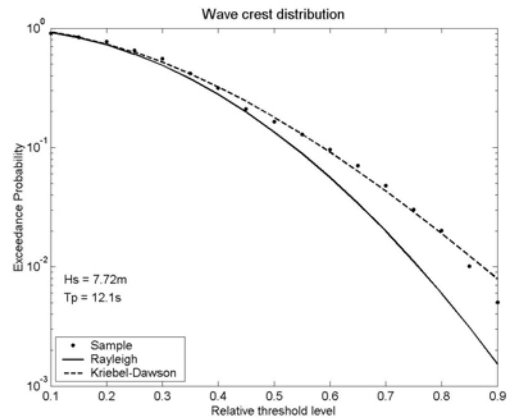

Figure 7.- Distribution of wave crests for target 8m Hs and 12s peak wave period.

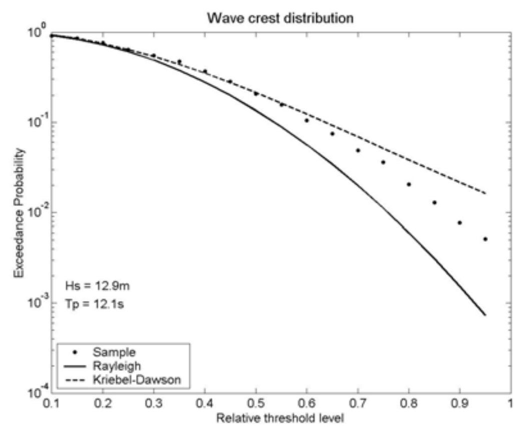

Figure 8.- Distribution of wave crests for target 14m Hs and 12s peak wave period.

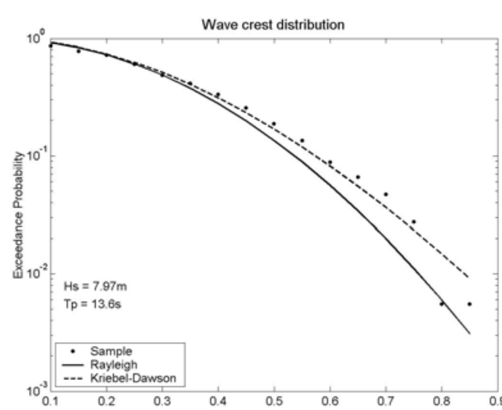

Figure 9.- Distribution of wave crests for target 8m Hs and 14s peak wave period.

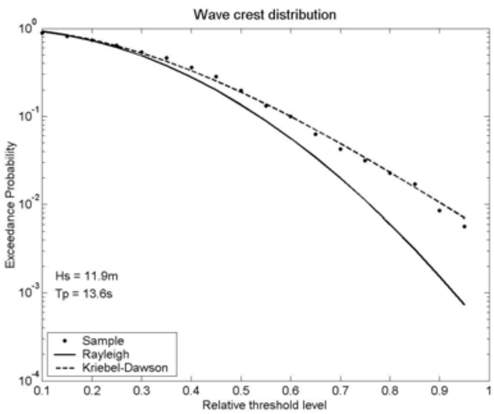

Figure 10.- Distribution of wave crests for target 8m Hs and 14s peak wave period.

HEAVE AND PITCH MOTIONS

In order to assess the linear nature of the pitch transfer function, adjustments were made of the distributions of heave and pitch motion heights.

Figures 11 to 14 show the examples of fitted distributions for four representative cases. It can be observed that the motions show a pattern very similar to the input wave heights, indicating that the transfer functions are very much linear. Indeed, the adjustments are not rejected by the hypothesis tests at 95% confidence level.

The result based on the comparison of probability distributions is a confirmation of earlier observations that compared experimentally determined transfer functions with the ones predicted by linear strip theory and the WAMIT diffraction code (Guedes Soares et al., 2001).

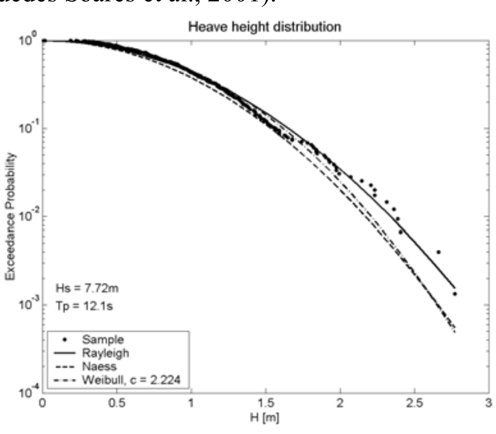

Figure 11.- Distribution of heave height for target 12m Hs and 14s peak wave period.

As may be observed in figure 14, the adjustment of the Rayleigh distribution to the distribution of crests of the pitch response is not perfect but is still adequate. This figure is representative of the ones that were obtained for other sea states and also for the crests of heave response. Thus, heave and pitch motions are described much better by a normal distribution than the exciting wave elevation, which has characteristics, described in figures 7 to 10.

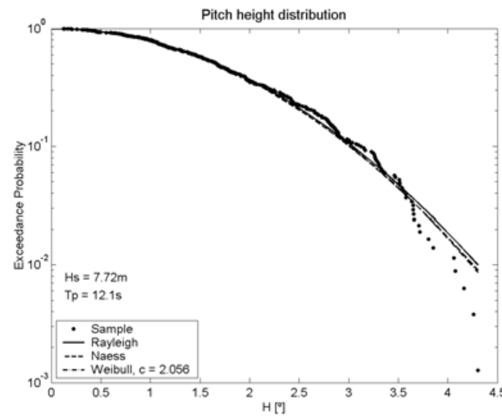

Figure 12.- Distribution of pitch height for target 8m Hs and 14s peak wave period.

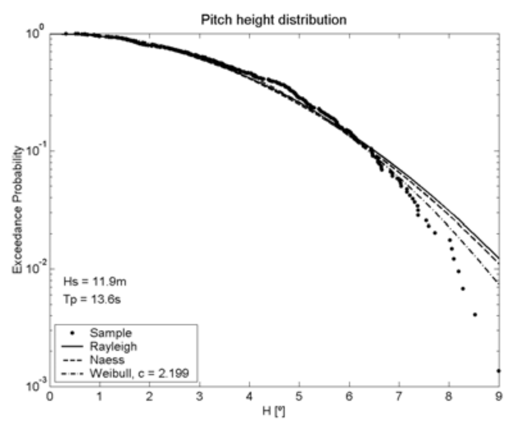

Figure 13.- Distribution of pitch height for target 12m Hs and 14s peak wave period.

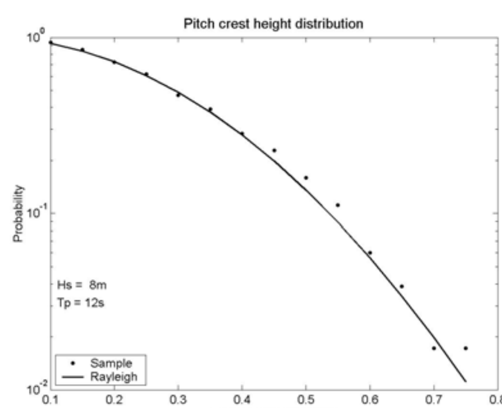

Figure 14.- Distribution of crest height for pitch at 8m Hs and 14s peak wave period.

RELATIVE MOTION AT THE BOW

The relative motion at the bow is the basic parameter that determines green water loading in this region. The vertical motion at the bow, r, is also expected to be relatively linear as it is given by:

$$r = \eta - z$$

with η the free surface elevation and z the vertical motion that depends on the heave and pitch motions, which have been shown to be reasonably represented by distributions based on the linear assumption.

In the equilibrium position with no waves $r = 0$ and it is positive when the wave approaches the freeboard. There is green water at the bow when r is equal to the freeboard.

The results of the tests are depicted in figures 15 to 18. In most cases the relative movement elevation follows a normal distribution up to the model freeboard, which is indicated by a circumference in the figures, but from that point on it deviates from that distribution. It is expected that the discontinuity encountered on the deck height exceedance will in fact induce a different trend in the probability distribution, which becomes non-linear, an effect that had already been reported by Buchner (1998).

Figures 15 and 16 show that for a $T_p = 12s$. The probability distribution is significantly changed for relative motions larger than the freeboard showing that water on deck has significant effects in reducing the relative motions.

However, figures 17 and 18 show that for a $T_p = 14s$ the tail of the distribution continues following the Rayleigh distribution even after freeboard exceedance, indicating that green water does not affect the motions significantly.

As may be depicted from the figures, the relative movement attained with the 14s peak period, shows less deviation from the tails of the Rayleigh distribution than for a period of 12s. Vestbøstad (1999) found from field data that for a 260m FPSO, for which the worst quasi-static period is 13s, the worst sea states for green water at the bow were at 14s. Drake (2000) used a 13.5s peak period for a 300m vessel.

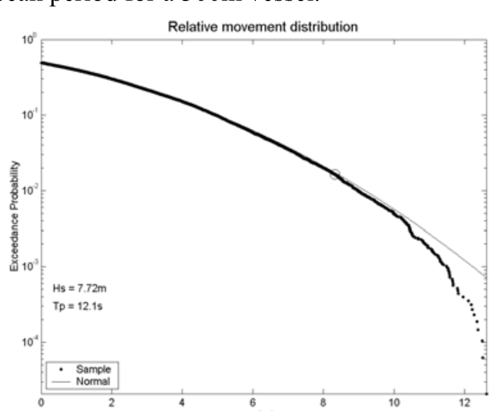

Figure 15.- Distribution of relative movement for target 8m Hs and 12s peak wave period.

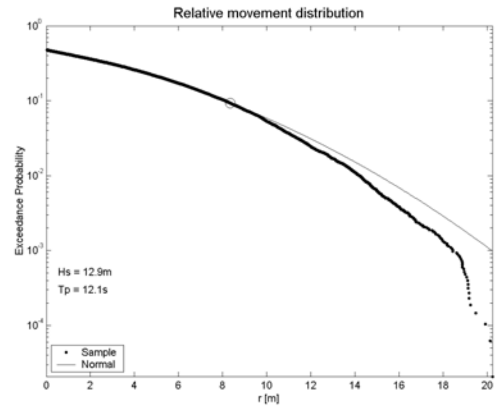

Figure 16.- Distribution of relative movement for target 14m Hs and 12s peak wave period.

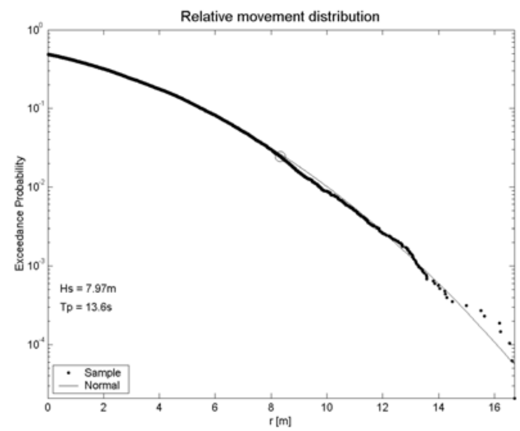

Figure 17.- Distribution of relative movement for target 8m Hs and 14s peak wave period.

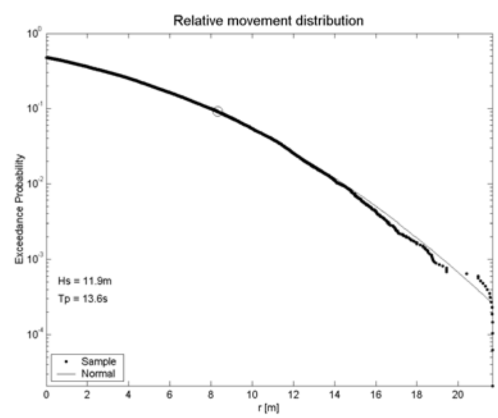

Figure 18.- Distribution of relative movement for target 12m Hs and 14s peak wave period.

RELATIVE MOTION CRESTS

The wave excitation was shown to be relatively well described by a Rayleigh distribution when one considered the heights but this distribution was inappropriate to describe the crests, which are clearly non-linear.

Given that the motions have shown to be well described by a normal distribution, one is led to expect that the crests of the relative motions might show the non-linear aspect of the crests of the wave excitation.

Indeed, figures 19 and 20 show that the distribution of the crests of relative motion derives from the Rayleigh distribution in a manner similar to the wave crests. However, it is interesting to note that for sea state of $T_p = 14s$ the distribution of crests follows closely the Rayleigh (figures 21 and 22), in the same way as the relative motion in figures 17 and 18 followed the normal distribution.

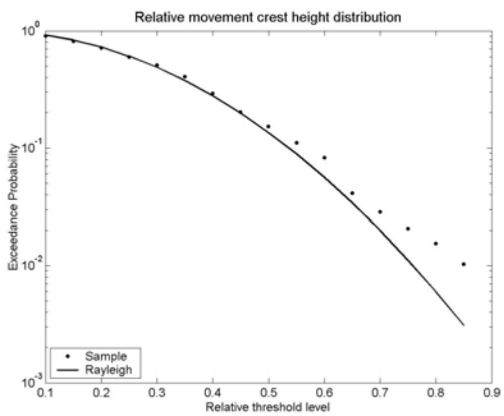

Figure 19- Distribution of relative movement crest height for target 8m Hs and 12s peak wave period.

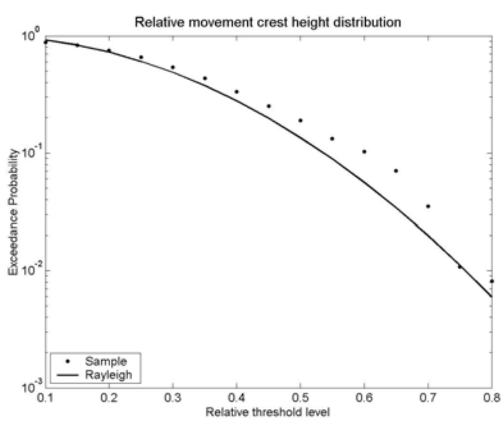

Figure 20- Distribution of relative movement crest height for target 14m Hs and 12s peak wave period.

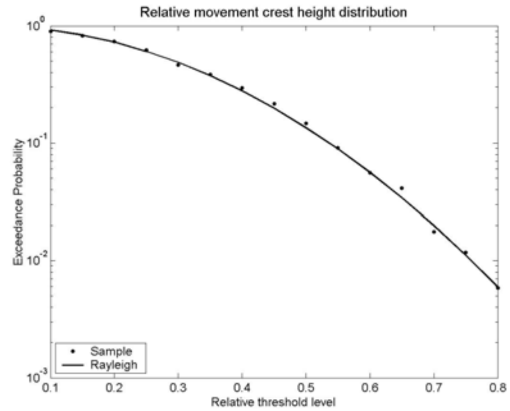

Figure 21.- Distribution of relative movement crest height for target 8m Hs and 14s peak wave period.

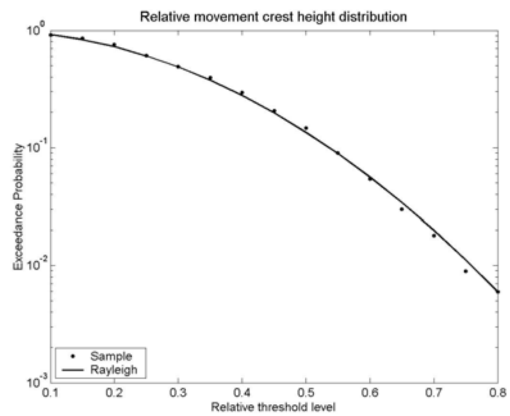

Figure 22- Distribution of relative movement crest height for target 12m Hs and 14s peak wave period.

WATER HEIGHT ABOVE DECK

The importance of green water depends of the frequency with which it occurs and also how severe it is. This severity can be related with the height of water above the deck level. This height of water was measured by a wave probe that was installed at the bow, as shown in figure 2.

The probability distribution of water height above deck, conditional on the occurrence of green water, or in other words of freeboard exceedance, is the tail of the empirical distribution relative motion. The cases shown in figures 23 to 26 indicate clearly that these distributions do not follow a normal distribution. Instead a Weibull distribution seems to be acceptable in several cases. In the examples shown the exponent of the Weibull ranged from 1.0 to 1.1, indicating that it was relatively close to the exponential distribution.

In order to calculate the probability of exceedance of the water height above deck, given that the relative movement has exceeded the freeboard, that is $P(h > H \mid r > fb)$, the probability is calculated from:

$$P(h > H \cap r > fb) = P(h > H \mid r > fb)P(r > fb)\ .$$

The product of the conditional probability distribution and the probability of having exceedance, which is indicated below the peak period on each figure, give the total probability.

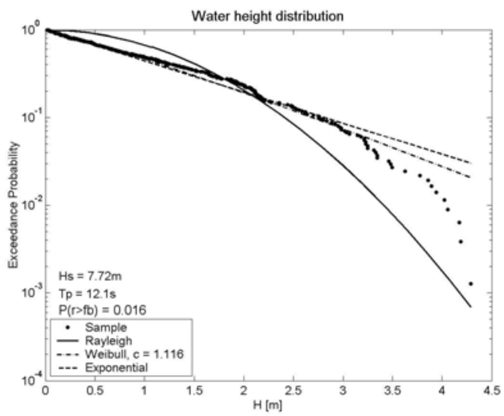

Figure 23- Conditional distribution of water height above deck for 8m Hs and 12s peak wave period.

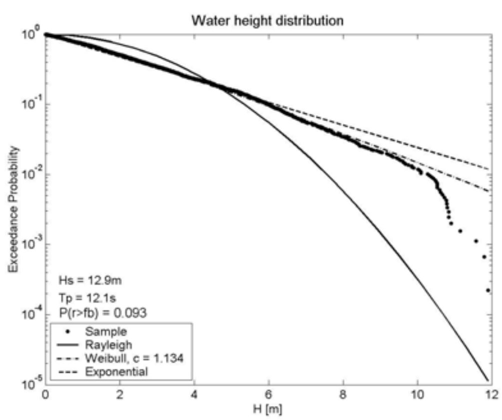

Figure 24- Conditional distribution of water height above deck for 12m Hs and 12s peak wave period.

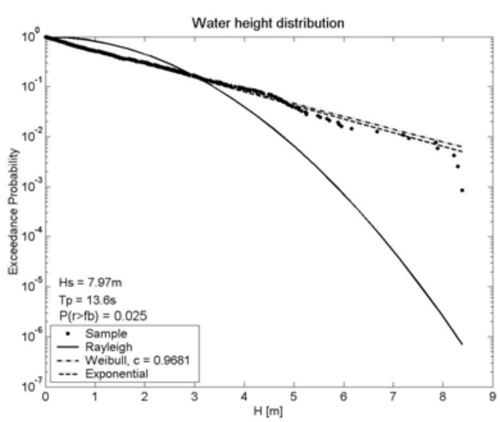

Figure 25- Conditional distribution of water height above deck for 8m Hs and 14s peak wave period.

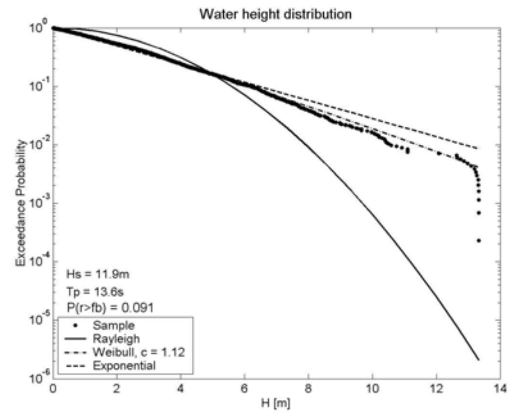

Figure 26- Conditional distribution of water height above deck for 12m Hs and 14s peak wave period.

WATER HEIGHT MAXIMA ABOVE DECK

The distribution of peaks of water height above the freeboard was calculated by taking only the local maxima from the sample of water height used in the preceeding analysis.

The results shown in figures 27 to 29 show that the Rayleigh distribution adjustment is poor. It is also seen that the two-parameter Weibull distribution adjusts relatively well, passing the statistical tests of fit at a 5% significance level. In the examples shown, the exponent of the distributions was in the range between 1.3 and 1.4, i.e. somewhere between the exponential and the Rayleigh distributions.

For water height maxima it is difficult to depict any tendency for the Weibull shape parameter modification with significant wave height or period variation. The parameter is relatively close to unity, which motivated a hypothesis test for the exponential distribution.

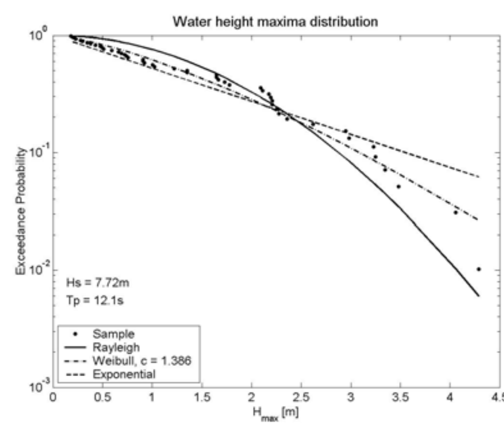

Figure 27- Conditional distribution of water height above deck for 8m Hs and 12s peak wave period.

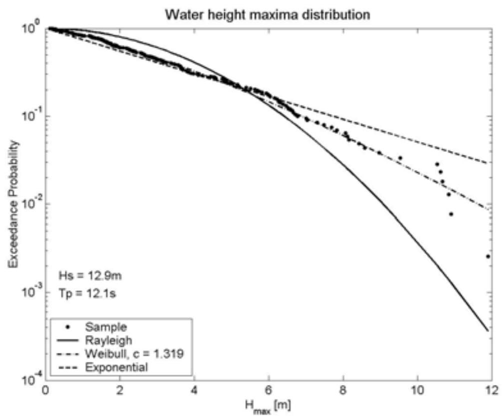

Figure 28- Conditional distribution of water height maxima above deck for 14m Hs and 12s peak wave period.

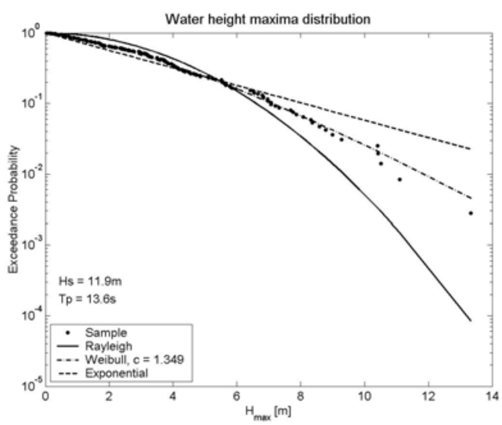

Figure 29- Conditional distribution of water height maxima above deck for 12m Hs and 14s peak wave period.

Table 3 shows the results of the hypothesis test the distribution of water height maxima is exponential. In Table 3, 0's mean that: the hypothesis is not rejected at a 0.05 significance level and 1's means that it is rejected at that significance level.

	***Hs* (m)**			
***Tp*(s)**	**8.0**	**10.0**	**12.0**	**14.0**
12	0	0	0	1
14	0	0	1	
18	0	0	0	0
20	0	0	0	0

Table 3- Results of the KS hypothesis test.

The Kolmogorov - Smirnov test of the exponential distribution, did not reject the hypothesis in most sea states at a 95% confidence level. More work should be carried out in assessing the real significance of this conclusion.

Table 4 shows the exponential cumulative distribution parameter and mean, μ, estimated from the samples. The exponential cumulative distribution is defined as

$$1-e^{-\frac{x}{\mu}}, \text{ with } x\in[0,\infty[.$$

The plot of the mean of the water height maxima as a function of incident wave Hs, shown in figure 30 exhibits a clear linear regression for each value of peak period.

	***Hs* (m)**			
***Tp*(s)**	**8.0**	**10.0**	**12.0**	**14.0**
12	1.54	2.27	2.79	3.36
14	1.85	2.55	3.51	
18	1.08	1.59	2.51	3.07
20	0.67	1.29	2.24	2.62

Table 4- Estimation of the Mean of the Exponential Distribution

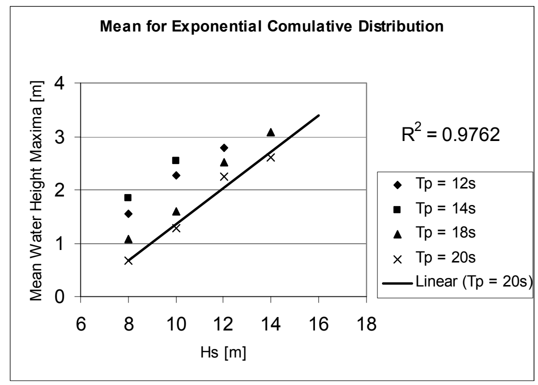

Figure 30- Linear regression on the exponential parameter.

CONCLUSIONS

Probabilistic models have been established for the wave excitation, ship motions and relative motions. The statistics of wave and heave and pitch height confirm previous results that motion of this FPSO are essentially linear.

The distributions of crest height deviate from the Gaussian model but the probability of water on deck can be predicted on the basis of this distribution for large peak periods. For smaller peak periods deviations occur, as Buchner (1998) has also identified.

When there is green water on deck, the water elevation above deck is well described by an exponential distribution. The maxima of the water height above deck were well modelled by a Weibull distribution with exponent between 1.3 and 1.4 although the exponential distribution was not rejected also by a test of fit. These conclusions based on limited data need to be checked for a wider set of situations.

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REFERENCES

Buchner, B., (1998), A New Method for the Prediction of Non-Linear Relative Motions, *Proceedings of the 17th International Conference on Offshore Mechanics and Arctic Engineering (OMAE'98)*, ASME, New York, Paper OMAE98-0592.

Buchner, B., (1995), On the Impact of Green Water Loading on Ship and Offshore Unit Design, *Proceedings of the Sixth International Symposium on Practical Design of Ships & Mobile Units (PRADS'95),* H. Kim, JW Lee (Eds), Seoul, Korea, Vol I, 430-443.

Dawson, T.H., Kriebel, D.L., Wallendorf, L.A., (1996), "Markov Description of Wave-Crest Statistics", *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 118, pp.37-45.

Drake, K.R., (2000), Transient Design Waves for Green Water Loading on Bulk Carriers, *Transactions of the Royal Institution of Naval Architects*, Part C Vol. 142, pp 217-229.

Fonseca, N. and Guedes Soares, C., (1998), Time-Domain Analysis of Large-Amplitude Vertical Ship Motions and Wave Loads, *Journal of Ship Research*, Vol. 42, nº2, pp. 139-153.

Forristall, G.Z., (1978), On the Statistical Distribution of Wave Heights in a Storm", *J. Geophys. Res*., Vol. 83, pp 2553-2558.

Forristal, G. Z. (2000), Wave Crest Distributions: Observations and Second Order Theory, *Journal Phys. Oceanography*, Vol 30, pp. 1931-1943

Guedes Soares, C. and Carvalho, A.N. (2001), Probability Distributions of Wave Heights and Periods in Measured Two-Peaked Spectra from the Portuguese Coast, *Proceedings of the 20th International Conference on Offshore Mechanics and Arctic Engineering (OMAE'01);* ASME, New York, Paper OMAE2001/S&R-2178.

Guedes Soares, C.; Fonseca, N., and Pascoal, R., (2001), Experimental and Numerical Study of the Motions of a Turret Moored FPSO in Waves. *Proceedings of the 20th International Conference on Offshore Mechanics and Arctic Engineering (OMAE'01);* ASME, New York, Paper OMAE2001/OFT-1071.

Guedes Soares, C. and Schellin, T. E., (1998), Nonlinear Effects on Long-Term Distributions of Wave-Induced Loads for Tankers, *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 120, nº2, pp. 65-70.

Hellan, Ø., Hermundstad, O.A., Stansberg, C.T., (2001), Design Tool for Green Sea, Wave Impact, and Structural Response on Bow and Deck Structures, *Offshore Technology Conference*, Paper OTC 13213, Houston, Texas, U.S.A..

Kriebel, D.L. and Dawson, T.H. (1993), Distribution of crest amplitudes in severe seas with breaking, *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 115, pp 9-15.

Longuet-Higgins, M. S., (1952), The Statistical Distributions of the Height of Sea Waves, *Journal of Marine Research*, Vol. 11, pp. 245-266.

Naess, A., (1985), On the Statistical Distribution of Crest to Trough Wave Heights, *Ocean Engineering*, Vol. 12, pp 221-234.

Ochi, M.K., (1998), Ocean Waves. The Stochastic Approach, Cambridge Ocean Technology Series, Cambridge.

Stansberg, C.T., Karlsen, S.I., (2001), Green Sea and Water Impact on FPSO in Steep Random Waves, *Proceedings of the 12th International Symposium on Practical Design of Ships & Mobile Units (PRADS'01)*, Shanghai, China.

Vestbøstad, T.M. (1999), Relative Wave Motion Along the Side of an FPSO Hull, *Proceedings of the 18th Conference on Offshore Mechanics and Arctic Engineering (OMAE'99)*, ASME, New York, Paper OMAE99/MAT-4239,.

