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DYNAMICS AND EXTREME VALUE PROBLEMS FOR MOORED FLOATING PLATFORMS

by

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Summary

This research deals with the dynamic response analyses and extreme value problems of moored floating platforms. It can be divided into three major subjects: first, the analysis of single cables and cable induced mooring damping; second, the dynamic analysis of the moored platforms, with special emphasis on the damping mechanisms and generation of the low-frequency excitation force time series; and third, the extreme wave-frequency responses and the combination of the low-frequency and wave-frequency extreme responses.

The catenary equation or shooting method can be used to obtain an initial estimation of the mooring cable configuration in calm water, after which non-linear static analysis is performed to find the final equilibrium position considering cable weight, current force and seabed friction. Around this equilibrium configuration, either a non-linear time-domain step-by-step integration or a linearized frequency domain analysis can be carried out to determine the response of the cable to various excitations. For the frequency-domain analysis, direct integration and statistic linearization methods are implemented. Example calculations show that the linearized frequency-domain solution and non-linear time-domain solution compare well with each other as well as with model tests and results obtained by others. We improve the quality and extend the applications of Huse's original quasi-static approach of estimating mooring-cable induced damping. By doing so, we could use the quasi-static approach to obtain an estimation of the mooring-cable induced damping that is comparable to the more time-consuming and complex time-domain or frequency-domain approaches.

The dynamic response of moored floating platforms to wave-frequency and low-frequency wave excitations is described. Formulae for low-frequency excitations are presented in both the time-domain and the frequency-domain. Four damping mechanisms for moored platforms are reviewed, with emphasis on mooring-cable induced damping, wave-drift damping and viscous damping, which are important for low-frequency response. The commonly used methods of generating wave-frequency and low-frequency excitation time series are discussed, and a one-dimensional convolution approach is proposed. In this approach, a random signal is passed through a filter, the filter coefficients are determined from the low-frequency excitation spectrum and the random signal follows the theoretical probability density function of low-frequency excitations.

The usual way of estimating the extreme mooring cable tensions is to run many time-domain simulations, which is rather time-consuming. Here however, only one or a few simulations plus the extreme value theory are needed to predict the extreme mooring cable tension. The order statistic theory, the generalised extreme value theory and the peaks-over-threshold methods are applied. A new approach is proposed to estimate the correlation coefficient between the low-frequency and wave-frequency extreme responses. This coefficient can then be used when we estimate the total combined platform motion or mooring cable tension.

Kew words: mooring cable, floating platform, low-frequency, wave-frequency, convolution, extreme value, time-domain, frequency-domain, quasi-static.

This thesis is based on the work contained in the following seven papers and the licentiate thesis. A preliminary version of Paper B was presented at the 1st Asia-Pacific Conference on Offshore Systems: Mobile & Floating Structures, 10-11 December 1996, Kuala Lumpur, Malaysia.

A. Liu, Y.G. and Bergdahl, L.(1997) Frequency-domain dynamic analysis of cables. *Engineering Structures*, Vol. 19, No. 6, 499-506.

B. Liu, Y.G. and Bergdahl, L. (1997) Influence of current and seabed friction on mooring cable response: comparison between time-domain and frequency-domain analysis. *Engineering Structures*, Vol. 19, No. 11, 945-953.

C. Liu, Y.G. and Bergdahl, L. (1998) Improvements on Huse's model for estimating mooring cable induced damping. *17th International Conference on Offshore Mechanics and Arctic Engineering*, Paper No. OMAE98-0353, OMAE'98 Lisbon, Portugal, July 5-9.

D. Liu, Y.G. and Bergdahl, L. (1998) Extreme mooring cable tensions due to wave-frequency excitations. *Applied Ocean Research,* Vol. 20, No. 4, 237-249.

E. Liu, Y.G. and Bergdahl, L. (1998) On combination formulae for the extremes of wave-frequency and low-frequency responses. Accepted by *Applied Ocean Research.*

F. Liu, Y.G. (1998) Generation of slowly-varying drift forces by filtering in the time-domain. *Submitted to Marine Structures.*

G. Liu, Y.G. and Rootzén, H. (1998) Application of the peaks over threshold method in estimating wave-frequency induced maximum cable tensions. *Manuscript to be submitted.*

H. Liu, Y.G. (1997) Dynamic analysis of mooring cables and their damping effect on the low-frequency motion of floating platforms. Licentiate thesis, Report Series A:28, Department of Hydraulics, Chalmers University of Technology, Göteborg.

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Yungang Liu 刘云刚

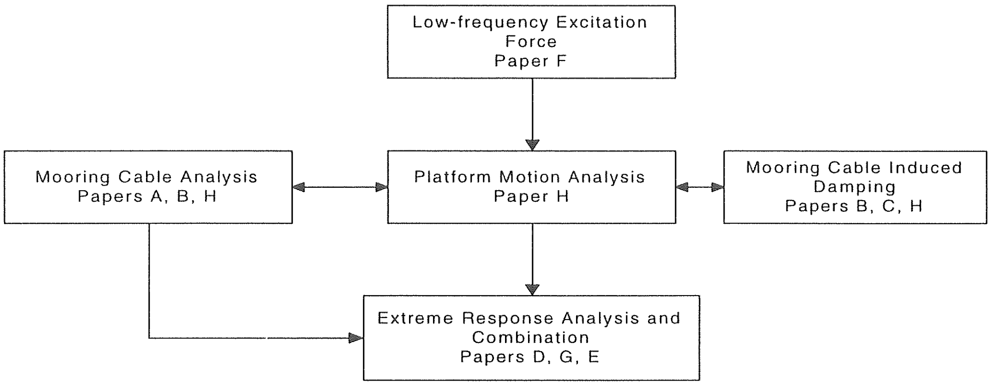
Göteborg, October 1998

Structure of the Thesis

Section 1 of the thesis presents a general review on research topics, such as mooring cable dynamic analysis, mooring cable induced damping, analysis of moored floating platforms, extreme mooring cable tensions, platform motions etc. The scope of the work is also outlined in Section 1. Sections 2 to 4 give an extended summary of the research work. Concluding remarks and references are covered in Sections 5 and 6 respectively.

Refer the appended papers for detailed description of the research work.

The following diagram shows the connection between the different papers.



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1. General Review

During the past twenty years, interest in moored offshore platforms and floating breakwaters has increased both within industry and scientific research. It is anticipated that more effort will be put into moored systems compared to fixed type structures in the future, especially for deep water or for poor seabed conditions.

To design a moored floating platform is a rather tedious and complex project. It includes among others thing, mooring cable dynamic analysis, riser analysis, platform motion analysis etc. Due to the huge investment involved in the floating platforms, a great deal of research work has to be carried out before a final decision is made, and a model test is often conducted for important projects. Some research topics, such as the mooring cable induced damping, coupled floater - mooring cable analysis, extreme mooring cable tensions and platform motions, combined low-frequency and wave-frequency response analysis, the combination of low-frequency response and wave-frequency response etc. are of significant interest.

1.1 Analysis of Single Cables

A single cable may consist of segments of wire rope, chain, and synthetic fibre line. Buoys or clumpweights can be attached to the cable.

Mooring cables and flexible risers may be regarded as long and slender structures, inherently non-linear and three-dimensional owing to a significant change in geometrical configuration under action of random directional seas, current and platform motions. The non-linear drag force and seabed-cable friction also contribute to the nonlinearity. Vortex induced vibrations and low or negative tension make the problem even more difficult to solve (Triantafyllou & Howell 1994, Triantafyllou 1994). The basic concept for numerical analysis of cables is that the cable can be represented as a series of finite inextensible or extensible elements joined at nodes. Up until now, the static analysis techniques are basically matured, as different organisations produce similar results (Larsen 1992) regarding static cable tensions, touchdown point etc. However, the dynamic results still show some scatter (Larsen 1992). This is also reflected in the results of one ISSC1997 committee project (ISSC 1997b).

A detailed review of element type, dynamic analysis techniques etc. can be found in, for instance, Lindahl & Sjöberg (1983) and Patel & Sayed (1992). Lindahl developed the computer program MODEX (Bergdahl, 1996) for static and time-domain dynamic analyses of cables. This program is continuously updated at the Department of Hydraulics, Chalmers. The numerical results were also compared with model tests (Lindahl, 1985, Lei 1996) and other results (Bergdahl, 1994). As non-linear time-domain simulation is rather time-consuming, an efficient and accurate frequency-domain solution is needed, especially for preliminary study and fatigue analyses. The non-linearities in the system must then be linearized or approximated so as to make the frequency-domain solution possible. See Krolikowski & Gay (1980), Roberts & Spanos (1990) and Passano & Brennodden (1990) for drag force linearization and seabed cable interaction simulation. The frequency-domain solution and the time-domain solution were compared by Kwan & Bruen (1991). The major parameters influencing the dynamic response of cables were also treated in Paper A, Paper B and Paper H, both in the time-domain and in the frequency-domain. The comparison is very promising.

Another important issue is the mooring cable induced damping. Studies (Wichers & Huijsmans 1990, ISSC 1997a, Paper H, Huse & Matsumoto 1989) show that the mooring cables can provide 10-80% of the total system damping. As the platform low-frequency response is nearly inversely proportional to the system damping, it is important to develop tools to estimate it. There are various approaches available (Huse 1991), e.g., model test, time-domain or frequency-domain dynamic simulations, and quasi-static approximation. Compared with other approaches, the quasi-static approximation is simpler and more efficient, but the results are not stable, especially when the wave-frequency effects are to be taken into account. Paper C makes some improvements on the original quasi-static approximation proposed by Huse (1986). After these improvements, the quasi-static approximation can provide results that are comparable to the more time-consuming time-domain or frequency-domain simulations.

1.2 Analysis of Moored Floating Platforms

There are many issues related to floating platform design, but here, we limit ourselves to the platform motion analysis. The floating platforms are usually simulated as a six degree-of-freedom system, and the wave-frequency response is calculated in the frequency domain. On the other hand, the low-frequency response is strongly non-Gaussian distributed (Stansberg 1991), so even if we could use frequency-domain solution and obtain the response variance, we cannot predict a proper maximum design value. Model tests or numerical simulations with long duration are needed to get good estimates of extreme response (Faltinsen 1990). The interaction between wave-frequency and low-frequency components, as well as the interaction between the platform and the mooring cables and risers, should also be properly accounted for, because in some cases, the separated, uncoupled analysis procedure may not provide good results (Ormberg & Larsen 1997, Dercksen, Huijsmans & Wichers 1992).

As the low-frequency response is a kind of resonance phenomenon, which means that the response is inversely proportional to the damping level, it is important to correctly estimate the damping, e.g., the viscous damping, mooring cable induced damping and wave-drift damping, which are reviewed in Paper H.

The wave-frequency process is often generated by adding a finite number of sine functions with deterministic amplitudes and uniformly distributed random phases, which will not yield a real random Gaussian process (Naess 1978, Tucker, Challenor & Carter 1984, Grigoriu 1993). This concept is also used in the double cosine summation in the bi-frequency domain for the low-frequency excitation forces. Chakrabati & Cotter (1984) use the double convolution of the wave time record to generate the low-frequency excitation forces in the time domain, but the computer time is enormous. In Paper F, a suggestion is given for how to generate the low-frequency excitation forces using the one-dimensional convolution method.

1.3 Extreme Mooring Cable Tensions and Platform Motions

There are two categories of methods to check whether a structure or a structure component is safe or not. The first category is called deterministic approach, or the allowable stress design, where the maximum response and a single safety factor are used. The second category is based on the reliability theory. The reliability design approach is a more advanced tool. However, since it takes time before it can come into full practice, the present offshore industry regulations (API

1993a, DnV 1996) are still using the maximum responses as key design values. Of course, as more data are made available and more research work is carried out, more probability knowledge will be used in every design stage. For example, the limit state formats or the so-called load and resistance factor formats have been adopted by the fixed offshore platforms (API 1993b, Snell 1997) and will also be adopted in the floating platforms (Sogstad et al. 1998).

Even if the wave process can be taken as a Gaussian process, the platform motion response and the mooring cable tensions do not follow the Gaussian distribution because of the non-linearities existing in moored floating platforms. Another issue for the floating platform is the co-existence of wave-frequency response and the low-frequency response. All this makes it rather difficult to obtain the maximum or extreme response values.

Naess (1989), McWilliam & Langley (1994) and Kareem & Zhao (1994) and others have studied the extreme response of moored floating systems under combined low and wave frequency excitations, the main idea being to use a second order Volterra series representing wave-frequency and low-frequency excitations and responses. By assuming a time-invariant model, a closed-form solution is derived. The direct way is to use time-domain simulation, which could take into account the non-linearities, at the expense of more computer times.

The problem related to non-linear time-domain simulation is the variability of the maximum responses. Paper D and Mekha & Roesset (1998) show that the maximum responses due to different generated load processes with the same spectrum deviate significantly from each other. This is why API (1993) suggests performing many time-domain simulations and then taking the average of the maxima of all simulations as the maximum response. Harland et al. (1996) propose a constrained time-domain simulation technique, the idea being to establish an empirical conditional probability distribution for the response. Winterstein, Ude & Kleiven (1994) propose using the Hermite moment approach to account for the deviation of response from the Gaussian distribution and present fitted empirical formulae.

The extreme value theory, which traditionally has been used in hydrology engineering, has attracted a lot of research in recent years, e.g., Castillo (1988), Embrechts, Klüppelberg & Mikosch (1997), Leadbetter, Lindgren & Rootzén (1983), Morton & Bowers (1996). There is a group of extreme value distribution models which can describe the distribution of the extreme events, and some special estimators, such as the moment estimator, probability-weighted moment estimator, maximum likelihood estimator, least-square techniques etc. have been developed. These can be used to estimate the model parameters, see for instance, Castillo (1988), Beirlant, Teugels & Vynckier (1996), Hosking, Wallis & Wood (1985).

Liu & Bergdahl (Papers D), and Liu & Rootzén (Paper G) apply the extreme value theory in predicting the maximum mooring cable tension due to wave-frequency excitation. Some special issues, such as the selection of independent maxima, domain of attraction, threshold or number of data to be used, model parameter estimation etc., are addressed. The results are quite promising. We do not apply the extreme value theory to the low-frequency responses, because we do not have access to a low-frequency response that is long enough to constitute a large sample.

When the wave-frequency and the low-frequency responses are determined separately, then there is the question of how to obtain the combined extreme response. API (1993) recommends the modified linear sum formula, while Naess (1994), Kinoshita & Takase (1995) and Naess &

Røyset (1998) study the modified SRSS (square root of the sum of squares) formula. Liu & Bergdahl (Paper E) compared different combination formulae based on some model test data. They found that the modified SRSS is superior for the mooring cable tension and comparable to the modified linear sum formula for the platform motion. A simple approach is also proposed to estimate the correlation coefficient used in the modified SRSS formula.

1.4 Scope of Work

The present work includes, among other things:

Mooring cable:

Frequency-domain dynamic analysis for a single cable incorporated into MODEX;

Mooring cable induced damping estimation, both for a single cable and for a group of cables. Time-domain, frequency-domain and quasi-static approaches;

Comparison of time-domain and frequency-domain analysis, parameter studies such as the influence of current, seabed friction etc.

Floating platform analysis:

Review of analysis methods and damping mechanisms;

Generation of low-frequency excitation force time records.

Extreme value analysis:

Application of the order-statistics theory;

Application of the peaks-over-threshold model;

Combination of extreme low-frequency and wave-frequency responses.

2. Mooring Cable Dynamics and Mooring Cable Induced Damping

2.1 Mooring Cable Dynamics

The detailed procedures for static, time-domain and frequency-domain analyses of single cables are described in Papers A and B as well as in Lindahl & Sjöberg (1983).

For the static analysis not taking current and seabed friction into account, a numerical shooting technique is used to create a two-dimensional initial configuration. Then the cable is divided into a series of straight finite elements, and a load incremental method is adopted to reach equilibrium, i.e. the reference configuration. If current is present, a Newton-Raphson non-linear iteration can be run to consider drag forces and seabed friction. The reference configuration is the starting point for time-domain or frequency-domain dynamic analyses.

By means of the principle of virtual work, the governing equations of the cable (non-linear partial differential equations) are transformed into ordinary differential equations. Then an explicit numerical integration is performed, by which all non-linearities can be taken into account in the time domain, including drag forces, seabed friction, change of cable configuration etc.

In the frequency-domain solution, the vibration amplitude is assumed to be insignificant and to act around the final reference configuration as determined from the static cable analysis. The quadratic non-linear drag forces are linearised by use of either the direct integration method (equal work done in a period of time by non-linear drag forces and linearised drag forces) or the statistic linearisation method (minimum errors of non-linear drag forces and linearised drag forces in a period of time). Regular or random excitation, with or without wave/current, can be considered. The interaction between seabed friction and cable can be simulated by a simple lumped stiffness model or by a statistical linearisation technique.

In Paper A, static and time-domain methods for non-linear dynamic analysis of single cables are described and then a frequency-domain analysis method is presented. The formulae to calculate characteristic response values from frequency-domain analyses are given, including standard deviation, significant and most probable response values etc. The equations for direct integration linearization of non-linear drag forces are derived, and convergence criteria for iteration are defined. The effect of seabed friction on cables is not considered in this paper.

Three examples are analysed in the time-domain and the frequency-domain, respectively. The examples are a free-hanging cable (towing cable), a mooring cable and a lazy-wave riser. The eigen-periods of the cables are calculated first, and then harmonic excitations with varying periods and amplitudes are applied to the attachment point of each cable. An irregular excitation is also applied for the lazy-wave riser. Results from the time-domain and frequency-domain analyses are compared and discussed.

The basic conclusion from this study is that the frequency domain solution can provide reliable results. For the free-hanging cable, frequency-domain calculations compare well with those of time-domain simulations. For cables partly resting on the seabed, including the lazy-wave riser, frequency-domain solutions can provide a good estimation for those parts of the cables which are adjacent to the upper attachment point, usually of interest for system analyses.

The emphasis of Paper B is on the influences of current and seabed friction on the dynamic response of single cables. In the time domain, the non-linear drag forces and the Coulomb friction model can be simulated directly. In the frequency-domain, the statistic linearisation technique is introduced to account for the non-linear drag forces. If the relative motion between cable and seabed is obvious, the statistically linearised Coulomb friction model can be used, but for small or no relative motions, a simple lumped stiffness model is introduced to consider the seabed effects.

A flexible riser and a deep water mooring cable are selected for comparison, for which the effect of in-plane and out-of-plane currents on cable tensions and energy dissipation is studied. The amplitudes of low-frequency excitations and seabed friction coefficients are also varied in order to determine their influences on energy dissipation by the cables. The displacements predicted by direct integration linearisation and statistic linearisation techniques are discussed.

In Paper H, our time-domain and frequency-domain solutions are used to carry out dynamic analysis for mooring cables in a practical example. For wave-frequency excitation, our results are very close to the results of model tests, both for the windward cables and for the leeward cables. For the low-frequency excitation, our solutions under-predict the maximum cable tensions for the windward cables, the main reason being that we use only one cosine function with constant amplitude to represent the low-frequency fairlead motions.

Another phenomenon is the interaction of wave-frequency and low-frequency excitations. For the leeward cables, the wave-frequency response is suppressed, and therefore only the low-frequency response dominates. However, for the windward cables, both the wave-frequency component and the low-frequency component are important.

2.2 Mooring Cable Induced Damping

There are various methods to estimate the mooring cable induced damping, e.g., model tests, time-domain simulation, frequency-domain simulation and quasi-static approach. Of these, the quasi-static approach is the simplest one, but its quality is not always acceptable.

In Paper B, the formulae for energy dissipation and the corresponding equivalent linearised damping by a single cable are presented. Paper B shows that the energy dissipation by a taut cable is less sensitive to the current than is the energy dissipation by a slack cable. If the current tends to make the cable stiff, then the energy dissipation will be less, as smaller lateral relative motions will occur for a stiff cable. Seabed friction will generally increase the energy dissipation. Frequency-domain solutions give similar results to those of time-domain simulations, which means that the linearisation method of drag forces and the friction model used in the frequency-domain analyses are reliable.

In Paper C, we propose some improvements to enhance the quality and broaden the applications of the quasi-static approach. The first improvement concerns how to calculate the energy dissipation by a small element along the cables, two half cycles with different amplitudes are suggested instead of one complete cycle with averaged amplitude. The other improvements deal with how to consider the effects of the wave-frequency component. Huse's original idea is to introduce one modification factor to account for the wave-frequency effects. What we have done is to estimate the energy dissipation due to the combined low-frequency and wave-frequency amplitude and then to break down the dissipated energy into four components, only the component dominated by the wave-frequency amplitude being modified. The vertical wave-frequency motion can easily be considered in the new procedure.

The energy dissipation predicted in such a new procedure is compared with more rigorous time domain non-linear dynamic simulations as well as a small number of experimental results. The comparisons indicate that the overall performance of the proposed method is better than Huse's original approach, regardless of whether the superposed wave-frequency motions are taken into account or not. For deep water situations, the quasi-static energy dissipation corresponding to the combined low-frequency and wave-frequency amplitude at the low-frequency period can be taken as a first approximation. In addition, the vertical fairlead wave-frequency motions should be considered when estimating mooring cable induced damping for low-frequency motion analysis.

3. Dynamics of moored Floating Platforms

3.1 Dynamic Analysis and Damping Mechanisms

In Paper H, which is a part of the licentiate thesis, we describe how the equations for the platform motions can be solved. Both the time-domain formats and the frequency-domain formats are presented, including the wave-frequency and low-frequency components. Many researchers have tried to solve the coupled floater - mooring cable system under the combined wave-frequency and low-frequency excitations and have shown that the traditional separated analysis procedures provide unconservative results in some cases.

We also review and discuss the damping mechanisms of moored floating platforms. There are basically four sources of damping, namely radiation damping, mooring cable induced damping, wave drift damping and viscous damping. Viscous damping seems to be the most difficult term to determine. Wave drift damping, mooring cable induced damping and viscous damping are important for the low-frequency motion analysis. For a semi-submersible moored with 16 cables, these three terms account for 8%, 17% and 14% of the critical damping, respectively.

3.2 Generation of Low-frequency Excitation Forces

The usual way of generating random ocean waves is to add a finite number of sine or cosine waves with deterministic amplitudes and uniformly distributed phase angles, which generally results in wrong spectrum variances and envelope lengths. This concept is also used in the generation of low-frequency excitation forces or the slowly-varying drift forces (SVDF), i.e., the double cosine summation procedure.

Paper F shows how a SVDF time record can be generated by one-dimensional filtering in the time domain. The idea is to pass a random signal through a filter, the filter coefficients being determined from the low-frequency force spectrum, and the random signal following the theoretical probability density function (pdf) of the SVDF. The primary benefits of using such a procedure are that arbitrarily long SVDF time records can be generated, whereby the problems associated with adding a finite number of sine waves with deterministic amplitudes can be avoided.

We use the pdf formulae derived by Vinje and Naess to generate the random signal, and use an ISSC wave spectrum to design a nonrecursive finite impulse response (FIR) symmetrical filter with even number of coefficients, the filter coefficients being determined by the frequency sampling method. For a horizontally half-submerged circular cylinder in long-crested beam sea waves, we generate some SVDF records and compare with the double cosine summation approach.

The proposed procedure is time-saving compared to the double cosine summation procedure. We find that using Vinje's pdf formula produces results that are between the results from using Naess pdf formula, one invoking Newman's approximation and the other one using full quadratic transfer function. Comparing the efforts needed, Vinje's pdf should be the first choice provided Newman's approximation is valid.

As we use one-dimensional convolution to simulate a two-dimensional problem, the pdf of convoluted SVDF time record is less skewed than the theoretical one, but the difference mainly covers the lower levels, so that the effect on the maximum responses may be negligible.

4. Extreme Mooring Cable Tension and Platform Motion

4.1 Application of the Order-Statistics Theory

Paper D describes how the order statistics can be used to predict the maximum response from a time simulation. As the envelope maxima can be considered as an independently and identically distributed sample, they are suggested to be used. A procedure is proposed to select the envelope maxima. The domain of attraction for the maximum sample can be determined based on either the curvature method, Pickands III method or the probability paper method.

Usually only a fraction of a sample should be used, therefore we propose using a least-square fitting technique to determine an optimised number of points. Both the weighted least-squares method and the maximum likelihood method are implemented. Eight 3-hour fairlead motion time records are generated and used to excite one windward and one leeward cable. The order statistics theory is then applied for the obtained tension time records and for the fairlead in-plane horizontal motion components.

We find that the use of order statistics theory results in very close predicted extreme tensions for different realised excitations. For the analysed cases, both the envelope maxima and the above mean maxima indicate the Gumbel type domain of attraction for maxima as valid for fairlead motions and cable tensions. Further more the quality of extrapolation for a longer time interval based on the results of a shorter simulation length is not good, but the opposite operation is acceptable.

4.2 Application of the Peaks-over-threshold Model

In Paper G, another approach to modelling extreme events, the peaks-over-threshold (POT) method, is applied to estimate the maximum cable tension. The POT method uses the generalised Pareto distribution to model the exceedances of a random variable over a high threshold.

Different methods of selecting the independent maxima are presented, including the smoothing local maxima method, the equal subinterval method and the Hilbert transform envelope method. Their influence on the final extreme value is discussed. Both the mean excess plot and the adapted Hill estimator are used to select a proper threshold, which is a very important parameter for the POT method. The general Pareto distribution parameters can be estimated by the moment method, the probability weighted moment method and the maximum likelihood method.

Based on the analysis results of eight 3-hour and six 9-hour mooring-cable tension time records, we find that the POT model is relatively not sensitive to the methods of selecting extreme value sample, but it under-predicts the extreme values. The Gumbel model in general provides a good estimation of the extreme tensions.

However, as it is quite new to apply the extreme value theory for the non-linear responses in the field of moored floating platforms, obvious more work should be carried out in order to obtain a stable estimation of the extreme values. For example, more robust estimators of the shape index of the general Pareto distribution and a better way of choosing threshold should be developed. In addition, experiences of using the extreme value theory should also be gained. The Workshop on Extremes – Risk and Safety (held at Göteborg August 18-22 1998, organised by Chalmers Mathematical statistics Centre) may provide some hints for the research in applying POT model.

4.3 Combination of Low-frequency and Wave-frequency Responses

For the mooring cable tensions and platform motions, there are primarily two kinds of combination formulae used or recommended by industry regulations: the modified linear sum (LS) and the modified square root of the sum of squares (SRSS). Paper E reviews and discusses these formulae. For the modified SRSS formula, a new procedure is proposed to determine the correlation coefficient between the low-frequency and the wave-frequency extreme responses. This coefficient is chosen from the cross-correlation information between the low-frequency process and the wave-frequency envelope process. This procedure is rather easy to implement and use, which makes the modified SRSS formula more practical.

Based on some model test data, the results of the use of different combination formulae for the wave-frequency and the low-frequency components are compared. We find that the modified SRSS formula provides superior results for mooring cable tensions, while it is comparable to the API recommended practice for platform motions.

5. Concluding Remarks

Time-domain and frequency-domain analyses have been performed for various cable configurations, and the effect of seabed friction, current and excitation intensity etc. on mooring cable tension and energy dissipation has been studied.

Improvements on Huse's original quasi-static approach of estimating mooring cable induced damping are made. After these improvements, the quality of the quasi-static approach is improved, and its applications are broadened.

A one-dimensional convolution procedure is proposed to generate low-frequency excitation force time record, which is efficient compared to the double cosine summation approach.

The extreme value theory is applied to predict the maximum mooring cable tension based on one or a few time simulations. Various issues associated with application of extreme value theory are addressed.

A simple approach is proposed to estimate the correlation coefficient between the wave-frequency and the low-frequency extreme responses. This coefficient is needed when the modified SRSS (square root of the sum of squares) combination formula is used.

Many computer programs related to the above topics have been developed, and may find areas of practical use.

The following investigations are worthy of further efforts:

Developing simulation tools for the time-domain response analysis of moored floating platforms, and comparing the differences between the results of using differently generated low-frequency excitation forces, i.e., the double cosine summation and the one-dimensional convolution procedure;

Carrying out simulations with combined wave-frequency and low-frequency excitations, as well as with separated excitations, and comparing the differences in results;

Applying more robust estimators for the extreme models, and gaining experiences of using the extreme value theory;

Applying the bi-variate extreme value theory to obtain the joint response probability of wave-frequency and low-frequency components.

6. References

API RP 2FP1 (1993a) Recommended practice for design, analysis, and maintenance of moorings for floating production systems. American Petroleum Institute, Washington, D.C, First Edition.

API RP 2A-LRFD (1993b) Recommended practice for planning, designing and constructing fixed offshore platforms - Load and Resistance Factor Design. American Petroleum Institute, Washington, D.C, First Edition.

Beirlant, J., Teugels, J.L. and Vynckier, P. (1996) Practical analysis of extreme values. *Leuven University Press*, Leuven.

Bergdahl, L. (1994) Dynamics of mooring cables. *Svensk Sjöfarts Tidning* (The Scandinavian Shipping Gazette), No. 40, Oct. 7.

Bergdahl, L. (1996) User's manual for MODEX, Version 3. Report Series B:62, Department of Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

Castillo, E. (1988) Extreme value theory in engineering. *Academic Press*, San Diego, California

Chakrabarti, S.K. & Cotter, D.C. (1984) Nonlinear wave interaction with a moored floating cylinder. *Offshore Technology Conference*, OTC 4814, Houston, Texas.

Dercksen, A., Huijsmans, R.H.M. and Wichers, J.E.W. (1992) An improved method for calculating the contribution of hydrodynamic chain damping on low-frequency vessel motions. *24th Offshore Technology Conference*, Houston, Texas, May 4-7. OTC 6967, pp. 209-218.

Det norske Veritas (1996) Rules for classification of mobile offshore units, Position Mooring (POSMOOR). January 1996.

Embrechts, P., Klüppelberg, C., and Mikosch, T. (1997) Modelling extremal events. *Springer-Verlag Berlin Heidelberg.*

Faltinsen, O.M. (1990) Sea loads on ships and offshore structures. *Cambridge University Press.*

Grigoriu, M. (1993) On the spectral representation method in simulation. *Probabilistic Engineering Mechanics*, Vol. 8, 75-90.

Harland, L.A., Vugts, J.H., Jonathan, P., and Taylor, P.H. (1996) Extreme responses of non-linear dynamic systems using constrained simulations. *15th conference on Offshore Mechanics and Arctic Engineering (OMAE)*, Vol. I-A, pp. 193-200, Florence, Italy.

Hosking, J.R.M., Wallis, J.R., and Wood, E. F. (1985) Estimation of the generalised extreme value distribution by the method of probability-weighted moments. *Technometrics,* Vol. 27, No. 3, 251-261.

Huse, E. (1986) Influence of mooring cable damping upon rig motions. *18th OTC conference*. Paper No. 5204, May 5-8, Houston.

Huse, E. and Matsumoto, K. (1989) Mooring line damping due to first and second-order vessel motion. *Offshore Technology Conference*, Houston, Texas, May 1-4. OTC 6137, pp. 135-148.

Huse, E. (1991) New development in prediction of mooring system damping. *OTC 6593*, Houston.

ISSC (1997a) Report of Committee V.6 - Structural design of floating production system. *Proc. 13th int. Ship and Offshore Structures Congress*, Vol. 2, pp. 167-209, Trondheim, Norway, 18-22, August.

ISSC (1997b) Report of Committee I.2 - Loads. *Proc. 13th int. Ship and Offshore Structures Congress*, Vol. 1, pp. 59-122, Trondheim, Norway, 18-22, August.

Kareem, A. & Zhao, J. (1994) Response statistics of tension leg platforms under wind and wave loads: a statistical quadratization approach. *ICOSSAR'93 Conference of Structural Safety and Reliability*, Vol. 1, pp. 497-503.

Kinoshita, T., and Takase, S. (1995), Response of statistics of moored offshore structures. *Journal of Offshore Mechanics and Arctic Engineering*, **117**, 159-165.

Krolikowski, L.P. and Gay, T.A. (1980) An improved linearization technique for frequency domain riser analysis. *12th Offshore Technology Conference*, Houston, Texas, USA, May 6-8.

Kwan, C.T. and Bruen, F.J. (1991) Mooring line dynamics: comparison of time-domain, frequency-domain and quasistatic analyses. *23rd Offshore Technology Conference*, Houston, Texas, USA, May 6-9.

Larsen, C.M. (1992) Flexible riser analysis---Comparison of results from computer programs. *Marine Structures* 5, pp. 103-119.

Leadbetter, M.R., Lindgren, G., and Rootzén, H. (1983) Extremes and related properties of random sequences and processes. *Springer-Verlag New York Inc.*

Lei, A. (1996) Dynamic characteristics of floating breakwaters. Ph.D thesis, Report Series A:26, Dept. of Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

Lindahl, J. and Sjöberg, A. (1983) Dynamic Analysis of Mooring Cables. Report Series A:9, Dept. of Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

Lindahl, J. (1985) Modellförsök med en förankringskabel (In Swedish: Model Tests with a Mooring Cable). Report Series A:12, Department of Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

McWilliam, S. & Langley, R.S. (1994) Response statistics of non-linearly moored vessels under the action of first and second order wave forces. *Applied Ocean Research* 16, pp. 295-311.

Mekha, B.B. and Roesset, J.M. (1998) Statistical response of spar platforms to irregular waves. *17th international conference on offshore mechanics and arctic engineering*, OMAE'98, Paper No. OMAE98-0605. Lisbon, Portugal, July 5-9.

Morton, I.D., and Bowers, J. (1996) Extreme value analysis in a multivariate offshore environment. *Applied Ocean Research*, **18**(1996), pp. 303-317.

Naess, A. (1978) On experimental prediction of low-frequency oscillations of moored offshore structures. *Norwegian Maritime Research*, No. 3, pp. 30-37.

Naess, A. (1989) Prediction of Extremes of Combined First-order and Slow-drift Motions of Offshore Structures. *Applied Ocean Research*, Vol. 11, No. 2, pp. 100-110.

Naess, A. (1994), Statistics of combined linear and quadratic springing response of a TLP in random waves. *Journal of Offshore Mechanics and Arctic Engineering*, **116**, 127-136.

Naess, A. and Røyset, J.Ø. (1998) The SRSS formula for prediction of extremes of linear combination of load effects. *17th International Conference on Offshore Mechanics and Arctic Engineering*, OMAE'98, Paper No. OMAE98-1392. Lisbon, Portugal, July 5-9.

Ormberg, H. and Larsen, K. (1997) Coupled analysis of floater motion and mooring dynamics for a turret moored tanker. *Behaviour of Offshore Structures, BOSS'97 Delft*, Vol. 2, pp. 469-493.

Passano, E. and Brennodden, H. (1990) Model for pipe/sea floor interaction. FPS2000 /Flexible Risers and Pipes. Report 2.1-9, SINTEF, Trondheim, Norway.

Patel, M.H. and Sayed, F. B. (1992) Review of flexible riser design and engineering. *Marinflex,* 1992.

Roberts, J.B. & Spanos, P.D. (1990) Random vibration and statistical linearization. *John Wiley & Sons.*

Snell, R. (1997) ISO offshore structures standard. *Proc. Offshore Technology Conference*, OTC Paper 8421, Houston.

Sogstad, B.E., Mathisen, J., Hørte, T. and Lie, H. (1998) Modifications to DnV mooring code (POSMOOR) and their consequences. *17th International Conference on Offshore Mechanics and Arctic Engineering*, OMAE'98, Paper No. OMAE98-1460. Lisbon, Portugal, July 5-9.

Stansberg, C.T. (1991) A simple method for estimation of extreme values of non-gaussian slow-drift response. *Int. Offshore and Polar Engineering Conference*, Edinburgh, UK, 11-16 August 1991.

Triantafyllou, M.S. & Howell, C.T. (1994) Dynamic response of cables under negative tension: an ill-posed problem. *Journal of Sound and Vibration*, 173(4), pp. 433-447.

Triantafyllou, M.S. (1994) Cable mechanics for moored floating systems. *Behaviour of Offshore Structures, BOSS'94 MIT*, Vol. 2, pp. 57-77.