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Stochastic Response of Tension Leg Platforms to Wind and Wave Fields

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ABSTRACT

The dynamic behavior of tension leg platforms (TLPs) under the simultaneous action of random wind and wave fields is investigated in this study. Computationally efficient time and frequency domain analysis procedures are developed to analyze wind-wave-current-structure interaction problems. The aerodynamic load effects are described by the space-time description of the random wind field. The hydrodynamic loads are expressed in terms of a combination of viscous and potential effects. A numerically accurate and computationally efficient computer code based on the boundary element method (BEM) is developed for evaluating diffraction and radiation forces. In the time domain, ARMA (autoregressive and moving average) and discrete convolution and differentiation, and a hybrid combination of these are utilized to generate the time histories describing wind- and wave-related processes and the resulting response. In the frequency domain, the concept of Hermite polynomial expansion of the nonlinear drag force is extended to describe the multi-directional drag forces in terms of bivariate and trivariate expansions correct up to the quadratic terms. A stochastic decomposition technique is developed which significantly enhances the efficiency of the frequency domain analysis of complex systems. A numerical scheme involving iterative and perturbation techniques is utilized to evaluate the second-order response statistics. The response of a typical TLP in six degrees of freedom shows excellent agreement between the time and frequency domain analyses. The influence of the various loading components on the TLP response is delineated. The sensitivity of the platform response to environmental loading conditions and the mechanical and hydrodynamic characteristics of the platform is studied. The frequency domain approach developed here retains the effects of nonlinear interactions and offers accuracy that is comparable to the time domain approach at a fraction of the computational effort. The utilization of the analysis procedure developed here is not limited to the analysis of compliant offshore structures, rather immediate applications exist for other nonlinear stochastic dynamic systems.

INTRODUCTION

Several new structural systems have been proposed for enhancing the water depth capability of offshore structures. The tension leg platform (TLP) is one of the more promising concepts. A TLP is a semisubmersible type of buoyant platform which is vertically moored to the sea bed by a system of pretensioned tethers. By virtue of their compliant behavior, tension leg platforms are more sensitive to low frequency loads, e.g., wind fluctuations and slowly varying wave drift loads, than typical offshore structures.

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The TLP response includes components at the wind-frequency, wave-frequency and slowly varying drifts. The drift forces originate from the potential and viscous effects of the second-order forces, fluctuation in the wave surface elevation and contribution of the feedback effects due to the displaced position of the platform. The complex nature of the environmental load effects, combined with the nonlinearities of the TLP mooring system, interaction between the response components at different frequencies and the feedback of the structural motion to the loads, renders the straightforward application of the numerical methods employed in conventional offshore structures inapplicable. Previous researchers have used numerical methods for the simplified analysis of TLPs in which some of the applied loads that result from feedback and interaction of various terms in the equation of motion were ignored. However, these terms may have a significant influence on the overall structural response. A sample of studies dealing with the dynamic analysis of TLPs is given in the references.

The objective of the present research is to analyze numerically the dynamic behavior of TLPs subjected to stochastic wind and wave loads in the presence of currents. The governing equations of motion are described in terms of the inertial, structural damping and restoring forces, and the wind and wave loads (which are, in turn, functions of structural response). In this study, the equations of motion are analyzed in both the time and frequency domains. The results from both techniques are compared, using a typical TLP as an example.

The load effects on a typical TLP may be described in terms of an aerodynamic and a hydrodynamic system. In the aerodynamic system, the wind field comprised of mean and fluctuating velocity is transformed to aerodynamic loads utilizing space-time structure of the wind field and aerodynamic characteristics of the structural shape. The fluctuations in wave surface profile introduce hydrodynamic loads on structures at both the wave and low frequencies that can be described in terms of potential and viscous effects. A schematic representation of the aerodynamic and hydrodynamic systems is given in Fig. 1. Details concerning these systems are discussed in the following sections.

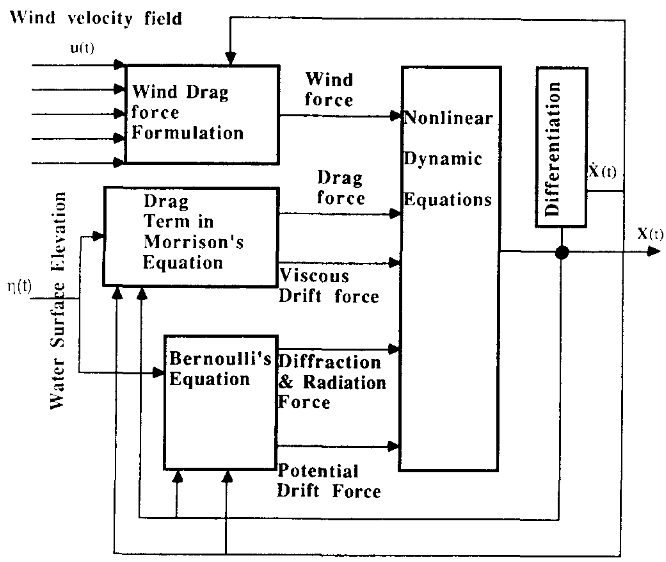

Fig. 1. Schematic Representation of Aerodynamic and Hydrodynamic Systems

LOADS

Wind Loads

Under the influence of wind, the portion of a TLP that is above the water level is subjected to a force in the windward direction, primarily resulting from drag. In order to formulate the total fluctuating wind load acting on a TLP, it is first necessary to establish a description of the multi-point statistics of the wind velocity fluctuations. Appropriate aerodynamic transfer functions are then needed to relate wind velocity fluctuations to corresponding wind loads.

The projected area of the portion of a TLP above the sea water level is divided into several segmental areas and velocity fluctuations are defined at the centroids of these areas. In the frequency domain, the space-time structure of the velocity field is described by the cross-spectral density matrix. In the time domain, simulated records match the required cross-power spectral density. Appropriate aerodynamic transfer functions are introduced to relate the wind velocity fluctuations to corresponding wind loads. The transformation from the local coordinates to the global coordinates then yields the global wind loads in terms of the TLP's six degrees of freedom.

For the spectral description of the wind effects, the wind loads are decomposed into the mean wind loads, first-order exciting wind loads, aerodynamic damping forces, and second-order wind loads. This decomposition permits the evaluation of the spectral description of wind effects by means of a conventional spectral technique and the spectral convolution approach.

The local wind load is given by

$$f_{A_m}(t) = 0.5\ \rho\ A_m\ C_a\ [U_{A_m} + u_{A_m}(t) - \dot{x}(t)]^2 \tag{1}$$

in which ρ = air density, A_m = segment area, C_a = drag coefficient, U_{A_m} = mean wind speed at mth segment, $u_{A_m}(t)$ = fluctuating wind speed at mth segment, and $\dot{x}(t)$ = platform velocity. The corresponding global wind force (6 D-O-F) is given by

$$\mathbf{F}_A(t) = \sum_m \mathbf{T}_m\, f_{A_m}(t) \tag{2}$$

in which $\mathbf{T}_m$ is the transformation matrix. The aforementioned decomposition of wind loads is shown in Fig. 2.

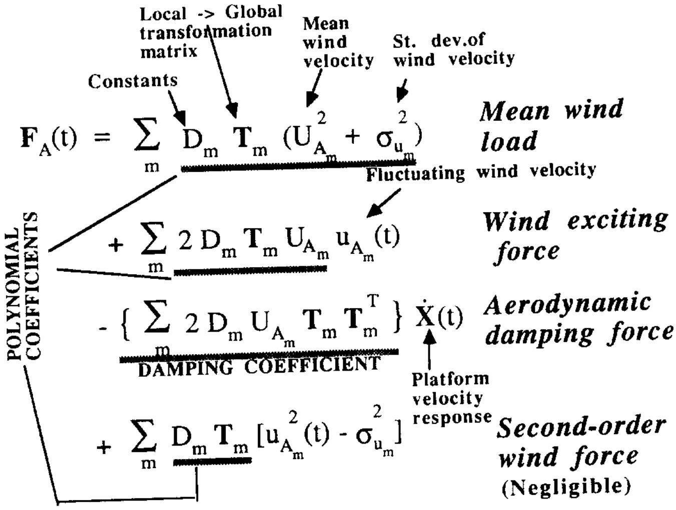

Fig. 2. Wind Load Expansion

Wave Loads

For conventional offshore structures, depending on the ratios of their projected member dimensions to the wavelengths, wave loads are computed either by the Morison equation in terms of drag and inertia terms, or by diffraction theory which describes the potential flow as a summation of the incident flow and the disturbance (diffraction and radiation) caused by the presence of the body. A hybrid combination of viscous and potential effects is used in this study. The viscous forces are obtained through the drag term of the Morison equation, and the diffraction and radiation forces are based on linear diffraction theory. An efficient computer code utilizing the boundary element method is developed to generate added mass, added damping coefficient matrices, and diffraction forces on a multicomponent body of arbitrary shape. The code is developed on a VAX-8500 and validated on a CRAY X-MP. The diffraction code is compared with the data assembled by Eatock Taylor and Jeffreys (1986) for the ITTC TLP configuration and the results from a recent code WAMIT (Korsmeyer et al., 1988). The comparison suggests that the present code provides force predictions that are close to the mean values of the scatter envelopes and show good agreement with the results obtained by utilizing WAMIT.

TIME DOMAIN ANALYSIS

Time domain simulation is often used to calculate the dynamic response of nonlinear systems, however, it generally requires a major computational undertaking which can be quite costly and, for a large-scale system, may be beyond the capacity of many computers.

One of the key problems in the time domain analysis concerns the simulation of the samples of time histories of various loads that must conform to the prescribed space-time structure of the wind velocity field. The total number of simulated points for each time series can be quite large due both to the small time increment required by the high wave frequencies and also the length of time required by the low wind and slowly varying wave drift forces. The customary summation of numerous trigonometric functions consumes a significant amount of computing time. Even though the use of the FFT technique improves computational efficiency, it results in an increased demand in computer storage. This difficulty increases many-fold in the event that the simulated loads are required over a long period of time or the problem in hand encompasses multivariate and/or multidimensional processes. Recursive digital filtering methods, in which weighted recursive relations connect random quantities of a set of time series at adjacent increments, facilitate savings in both computer time and memory. The digital filters in this research include the Autoregressive and Moving Averages (ARMA) model, the discrete convolution model, the discrete differentiation model, the discrete interpolation model and their hybrid combinations. These models are described here briefly.

The multiple-point simulation of the wind velocity fluctuations is carried out using the space-time description of the wind field. A multivariate ARMA model for this simulation is derived based on a two-stage matching technique in which an AR model of order 25 is used to fit an ARMA model of order (3 x 3). Two elements of the cross-spectral density matrix of the simulated wind field are compared with the corresponding target spectral functions in Fig. 3. The results show an excellent agreement.

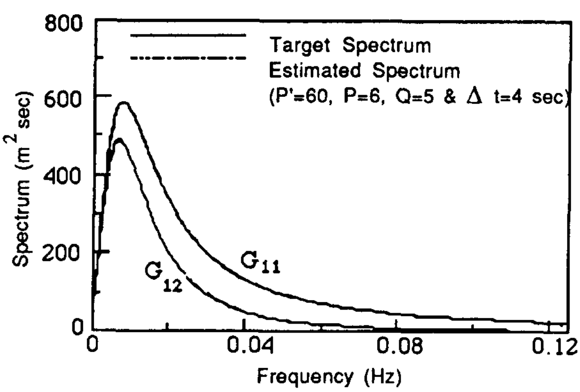

Fig. 3. Comparison of Estimated and Target Single- and Multiple-Point Spectral Descriptions

The wave surface profile is simulated similarly, based on the Pierson-Moskowitz and JONSWAP spectra. An AR model of order 59 is used in the two-stage matching process to develop an ARMA model of order (8 x 7). The power spectral density functions pertaining to the simulated and target functions provided almost coincident values.

Details concerning the sensitivity of the ARMA model to the time increments and the role of the selection of the Nyquist frequency in the formulation of the AR model, choice of equal or unequal AR and MA orders in the ARMA model may be found in Kareem and Li (1988).

A random process may be numerically generated by the convolution of a reference random process, which is fully coherent with the process being simulated, with an appropriate kernel. The wave surface profile and its kinematics and the associated wave-induced forces which are all fully coherent processes are simulated in this study by the convolution of a reference process, i.e., wave surface elevation with the corresponding kernels. This approach is referred to as a discrete convolution model. The convolution filter weights are derived from the Fourier transform of the corresponding transfer function. The transfer function that relates the wave surface elevation to the wave diffraction force in surge may be derived either by experimental methods or computational techniques such as the boundary integral method.

The viscous drag force on the platform members below the mean water level and in the splash zone and the potential drift force are evaluated similarly by means of appropriate filters. The time histories of fluctuations in the wind field and wave surface profile may not be simulated at the time increments equal to that required by the numerical integration schemes used to solve the equations of motion. This is primarily due to different frequencies of interest in loading mechanisms and the structural response. In order to capture the entire spectrum of frequency contents of the wind field and wave surface profile and, at the same time, to ensure the numerical stability and accuracy of the integration scheme, different time increments for the simulation of loading and evaluating response are unavoidable. In this study, a discrete convolution model is introduced to interpolate a time series with a given set of time increments to another with a desired value of time increments. This model involves local interpolation to ensure continuity of the derivatives and the stability. A discrete form of the differentiation model is employed utilizing the central difference scheme to obtain the derivatives of a reference process, e.g., wave particle acceleration from wave particle velocity. The discrete convolution and differentiation models are combined to establish a hybrid model to benefit from the individual characteristic features of each model.

Finally, the equations of motion in their discrete form are numerically evaluated by means of a digital filter based on the discrete differentiation model. The resulting time series of the response are analyzed by statistical and spectral techniques. The schematic diagram of the entire time domain simulation of the TLP response is described in Fig. 4.

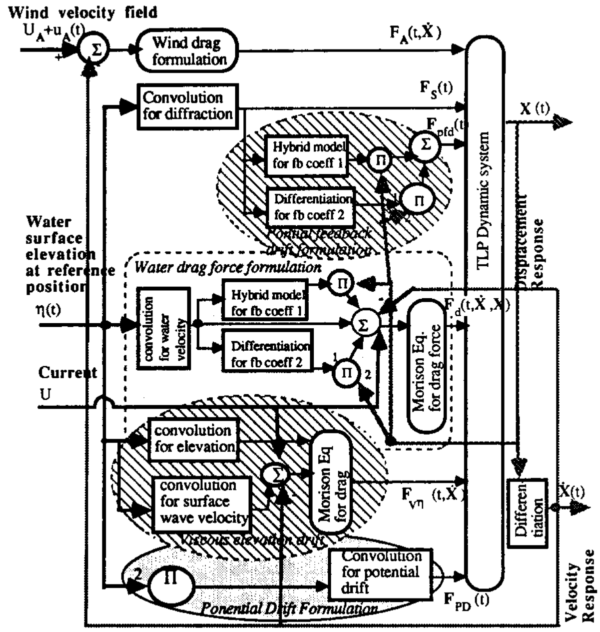

Fig. 4. Schematic Representation of Time Domain Simulation

FREQUENCY DOMAIN ANALYSIS

Unlike the time domain analysis, a frequency domain approach relates the input and output of a system through a transfer function. A frequency domain analysis is basically suitable for linear systems or systems that can be linearized conveniently. The analysis of the nonlinear system at hand is possible if the nonlinear terms can be expanded into multivariate orthogonal polynomials. In these polynomials, the zeroth-order terms describe the mean forces. The first-order terms are the wave- and wind-exciting forces or the damping forces, which can be expressed in terms of their spectral density functions in a straightforward manner. The second-order terms are slowly varying drift forces, their spectral descriptions can be obtained by the techniques addressed in this study, e.g., spectral convolution and quadratic transformation. The multi-directional wave-induced drag forces are described in terms of bivariate and trivariate Hermite polynomials correct up to quadratic terms.

The dynamic equations with the applied loads expressed as polynomials may be solved by a perturbation, or iteration technique in conjunction with spectral convolution and quadratic transformation approaches. These techniques require information on the statistical relationships, e.g., cross-spectral density matrix, involving the input, output and intermediate outputs in the analysis. This feature adds significantly to the computational effort involved and renders the frequency domain analysis less attractive. The frequency domain analysis, however, can be recast following a new spectral decomposition approach that has been developed to alleviate this difficulty. This approach involves the decomposition of a set of mutually coherent random processes into component random processes, the relationship between any two of which is either non-coherent or fully coherent. This decomposition permits the expedient evaluation of the statistical relationships required in the perturbation and iteration techniques and offers a convenient and computationally efficient frequency domain analysis procedure applicable to TLPs and other multi-input/output mechanical systems.

In conventional frequency domain analysis, a vector input or output is characterized by the cross-spectral density function that describes the spectral distribution of the random field and its structure in space or time, or both. The decomposed processes, instead of being described by conventional cross-spectral density functions, are defined by a decomposed spectral function. From the computational efficiency point of view, the lowest decomposition order is sought. The rank of the cross-spectral density matrix of a random field is equal to the minimum order of decomposition. The concept of stochastic decomposition is extended to the quadratic systems to facilitate computation of the low frequency drift forces. In this context, a decomposed bi-spectral matrix is introduced, which is related to the cross-spectral density of the function described by a linear transform of a product of two random variables.

A schematic representation of the frequency domain analysis is presented in Fig. 5. The input to the complex system is comprised of the aerodynamic and hydrodynamic loads, in terms of their respective spectral descriptions. The diagram highlights the sequence of the several computational steps involved and the contribution of the response feedback to different loading components. The wave-induced effects are partitioned into viscous and potential effects. The first-order viscous and potential wave effects and wind loads are expressed in terms of the corresponding decomposed spectral functions. The order of the decomposition in the case of wave-induced effects is unity due to the coherent nature of the processes involved. Whereas, for the six-component wind loading vector, the order of decomposition is equal to six.

The TLP response is also expressed in terms of the decomposed space, i.e., the mean static response, first- and second-order wave-induced response, and wind-induced response. The decomposed spectral and bi-spectral matrices are derived through multiplication of the appropriate transfer functions with the corresponding decomposed spectral and bi-spectral matrices of the loading. The response covariance is obtained by integrating the cross-power spectral density matrix of the response derived from the corresponding decomposed spectral, or bi-spectral matrix. In the response analysis, the relative fluid-structure velocity is required which is also transformed to the decomposed space. The entire frequency domain response analysis is accomplished by a combination of an iterative and a perturbation approach.

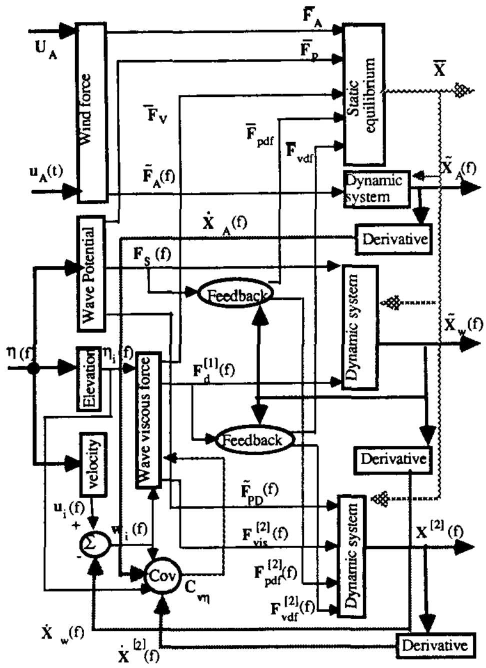

Fig. 5. Schematic Representation of Frequency Domain Analysis

EXAMPLE

A typical TLP configuration is considered to illustrate the response analysis procedures developed in this study. Only a summary of the results is discussed here, details are available in Kareem and Li (1988). For the sake of brevity only, the TLP response in surge is presented in Fig. 6. The time and frequency domain analyses provide very close agreement. The spectral estimates obtained from the time domain approach near the spectral peaks exhibit departure from the frequency domain results at a few frequencies. This is attributed to the frequency resolution being different in these analyses, which results in the discrepancy due to the absence of data at a particular frequency. A comparison of the mean and standard deviation of the response components obtained from the time and frequency domain approaches is presented in Table I. The mean response exhibits good comparison between the two approaches. The standard deviation is partitioned in the two frequency ranges: one below 0.022 Hz and the other between 0.022 and 0.2 Hz. These frequency ranges typically represent the low and high frequency response components. It is noted that the results from the time and frequency domain analyses show excellent agreement. The influence of the various loading components on the TLP response has been delineated. The sensitivity of the platform response to environmental loading conditions and the mechanical and hydrodynamic characteristics of the platform are studied. The space limitation here precludes a discussion of these results.

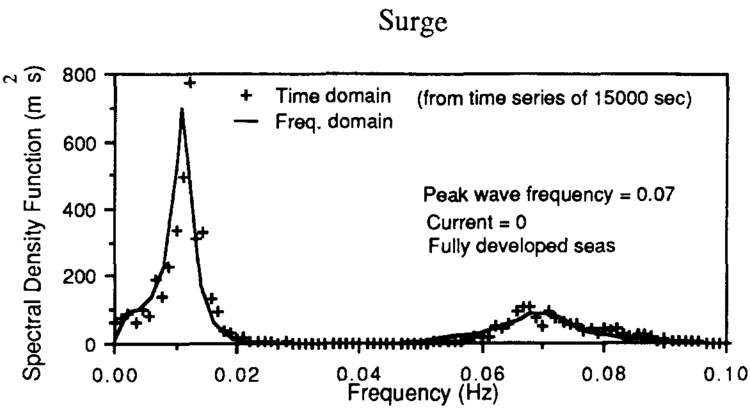

Fig. 6. PSD of TLP Surge Response

D-O-F	Mean		St. Dev (<0.022Hz)		St. Dev (0.022 ~0.2Hz)		Unit
	Time	Freq.	Time	Freq.	Time	Freq.	
Surge	7.55	7.66	1.04	1.18	0.70	0.75	m
Sway	5.81	5.81	0.57	0.62	0.31	0.32	m
Heave	-9.23	-8.75	2.25	2.45	1.77	1.81	cm
Roll	1.43	1.06	0.87	1.01	1.26	1.30	x0.0001 rad
Pitch	6.55	6.22	1.01	1.11	1.63	1.77	x0.0001 rad
Yaw	2.94	2.80	0.47	0.48	0.35	0.34	x0.01 rad

Table I. TLP Response Under Wind, Waves, and Currents

CONCLUDING REMARKS

In this study, computationally efficient time and frequency domain analysis procedures are developed to examine the stochastic response of TLPs (six degree-of-freedom) exposed to wind and wave fields. The analysis procedures involve new techniques to facilitate the frequency domain analysis and efficient parametric time series models to describe the multiple-point-correlated wind field characteristics and the space-time fluctuation in the wave surface elevation. Discrete convolution, differentiation, and interpolation models are developed to enhance the efficiency of the time domain approach. The response of a typical TLP in six degrees of freedom provides excellent agreement between the time and frequency domain analyses. The frequency domain approach developed here retains the effects of nonlinear interactions and offers accuracy that is comparable to the time domain approach at a fraction of the computational effort. The space limitation precludes a discussion of the sensitivity study.

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REFERENCES

Botelho, D. L. R., et al., "Model Test Evaluation of a Frequency-Domain Procedure for Extreme Surge Response Prediction of Tension Leg Platforms," OTC 4658, Offshore Technology Conference, Houston, Texas , 1984.

de Boom, W. C.; Pinkster, J. A.; and Tan, P. S. G., "Motion and Tether Force Prediction for a TLP," Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. 110, No. 4, 1984.

Deleuil, G. E., et al., "A New Method for Frequency Domain Analysis of Offshore Structures: Comparison with Time Domain Analysis," OTC 5303, Offshore Technology Conference, Houston, Texas., 1986.

Eatock Taylor, R. and Jeffreys, E. R., "Variability of Hydrodynamic Load Predictions for Tension Leg Platform," Ocean Engineering, Vol. 15, 1986.

Faltinsen, O. I., et al., "Theoretical and Experimental Investigation of Tension Leg Platform Behavior," Behavior of Offshore Structures (Proceedings of the 3rd International Conference, MIT), Vol. 1, 1983.

Kareem, A. and Li, Yousun, "Stochastic Response of Tension Leg Platforms to Wind and Wave Fields," Department of Civil Engineering, Technical Report No. UHCE88-18, 1988.

Kareem, A., et al., "Aerodynamic Loads on a Typical Tension Leg Platform," Ocean Engineering, Vol. 14, No. 3, 1987.

Kareem, A., "Wind-Induced Response Analysis of Tension Leg Platforms," Journal of Structural Engineering, ASCE, Vol. III, No. 1, 1985.

Korsmeyer, F. T., et al., "The Analysis of Wave Effects on Tension Leg Platforms," OMAE '88, Houston, Texas, 1988.

Nordgren, R. P., (1987), "Analysis of High-Frequency Vibration of Tension Leg Platforms," Journals of Offshore Mechanics and Arctic Engineering, Vol. 109, May, 1987.

Salvesen, N., et al., "Computation of Nonlinear Surge Motion of Tension Leg Platforms," OTC 4394, Offshore Technology Conference, Houston, Texas, 1982.

Simiu, E. and Leigh, S. D., "Turbulent Wind and Tension Leg Platform Surge," Journal of Structural Engineering, ASCE, Vol. 110, No. 4, 1984.