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NONLINEAR DYNAMIC ANALYSIS OF COMPLIANT OFFSHORE PLATFORMS SUBJECTED TO FLUCTUATING WIND

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SUMMARY

This paper discusses wind loading and associated nonlinear dynamic response of compliant offshore platforms subjected to fluctuating wind loads. Special reference is made to a tension leg platform (TLP) which is a positive-buoyant type platform moored by vertical tension members to keep the platform in location. Expressions for the wind loads are developed for the time domain analysis. The time histories of wind velocity fluctuations are simulated as single-point and multiple-point Gaussian random processes using a Monte Carlo simulation technique. Simplified equations of motion for surge, sway, pitch, and yaw are formulated. The desired nonlinear characteristics of the mooring system of a TLP are incorporated at each time step in the numerical scheme. The mean and rms values of response in respective directions are computed with wind approaching normal to one of the faces. The time domain analysis results have good agreement with the values obtained from a frequency domain analysis in which the TLP is assumed to oscillate linearly above the static equilibrium position produced by the mean loading.

1. INTRODUCTION

As the search for crude oil continues, offshore platforms are being installed in deeper and deeper water. These structures have been of fixed type for water depths up to 305 m. The fabrication and installation of these platforms in deeper water becomes difficult and extremely costly. Furthermore, these structures become more susceptible to the dynamic action of waves, since their fundamental frequency approaches the region of significant wave energy. In order to alleviate the problem of platform sensitivity to wave action alternative platform concepts have been developed, which take advantage of the effect of compliance, i.e., yielding to the wave action.

A guyed tower, and a tension leg platform are popular compliant structural systems being investigated presently for the future oil production [1,2]. Primarily the basic motion of these structures is similar to that of an inverted pendulum; the structure is flexible in the horizontal plane and rigid vertically. A guyed tower platform (GTP) is a slender truss-framed structure, derives its support and stability from a spud can or a pile foundation, and it is moored by a system of radial guyed lines [3]. A TLP (tension leg platform, Fig. 1) is basically a semisubmersible type positive buoyant floating platform moored by vertical tubular tension members [4]. A semisubmersible has substantial vertical motion making it difficult to tie-in

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well for production operation; whereas, the restrained vertical motion of a TLP is an attractive feature. The main structural system which connects the platform with the sea bed is always in tension rather than compression. Therefore, the cost of such a structure is relatively insensitive to water depth, since the length of tension members has far less structural significance than in a bottom supported structure. The mooring system of a TLP resists the mean environmental forces, while jacket inertia resists short period loads.

Environmental loading has a predominant role in the design of offshore structures for serviceability and survivability during normal and extreme sea conditions. The predominant loading for the structural design of conventional, i.e., jacket and gravity type structures arises through wave and current action, and the effects of wind fluctuations are insignificant. The flexibility of compliant structures in the horizontal direction results in an increase in their sensitivity to dynamic effects of fluctuations in the wind loading [5]. The sensitivity is more significant in case of a TLP. A typical value of the natural period, in surge, of such a structure is around 80 seconds, which is in the region of dominant energy in the wind spectra [6]. This paper will consider the effects of wind fluctuations on a typical tension leg platform. The effects of waves which have frequencies typically an order of magnitude higher than those in the wind, and the effects of, second-order slowly varying drift forces at low frequencies caused by the cross-modulation between wave components in the wave spectrum are neglected in this study. Any possible effects of wake induced motion, e.g., due to vortex shedding, are also not considered in this study.

2. DYNAMIC CHARACTERISTICS OF A TLP

A tension leg platform is a stable floating platform whose weight is less than the buoyancy. The equilibrium of vertical forces is provided by the vertical mooring cables which are under tension all the time. In this configuration the platform tends to have high natural periods of vibration in surge, sway and yaw, whereas, the period in roll, pitch and heaves are low. Appropriate selection of design parameters can be made to "de-tune" the natural periods of a TLP from significant wave energy periods.

The force displacement relationship in various degrees of freedom of a TLP is generally nonlinear. Large displacements of a TLP result in a nonlinear force-displacement relationship, even if strain remains in the linear elastic range. As the platform moves in the surge direction the buoyancy increases and that results in an increase in the cable tension which influences the surge stiffness. With increasing displacement the behavior of a TLP becomes similar to that of a hard spring.

The equations of motion in a six-degree-of-freedom model (Fig. 1) are given by

$$[M_T]\{\ddot{y}(t)\} + [C_T]\{\dot{y}(t)\} + [K_T(y(t))]\{y(t)\} = \{F(t)\} \tag{1}$$

in which $[M_T]$ = structural and added mass matrix of the platform, $[C_T]$ = contains velocity dependent forces, $[K_T(y)]$ is a displacement dependent stiffness matrix due to hydrostatic and anchor cables resistance and $\{y\}$ represents surge, sway, heave, pitch, roll and yaw.

The elements of added mass matrix can be analytically estimated [7]. The $[C_T]$ matrix is quite complicated and depends on hydrodynamics of the platform, frequency of motion and wave conditions [8]. The quantification of damping ratio is very essential in order to predict reliably the low frequency response of TLPs. The major contribution to the overall damping comes from the hydrodynamic damping. The drag damping, viscous damping, radiation damping and the influence of waves, their frequency and height on damping need more analytical and experimental studies to develope a functional relationship between the fluid and structural parameters. In this study the $[C_T]$ matrix is developed by assuming Rayleigh damping, which is given by

$$[C_T] = \alpha[M_T] + \beta[K_T] \tag{2}$$

where α and β are constants to be determined from given damping ratios.

The stiffness matrix can be developed using finite element idealization of cables and the hydrodynamic restoring forces acting on a platform [9].

As mentioned earlier that in a TLP the roll, pitch and heave motions are suppressed, therefore, for wind analysis only pitch motion was retained along with surge, sway and yaw. This reduces the degrees of freedom from six to four. It is also assumed that all four degrees of freedom are uncoupled. This is fully justified for pitch, sway and yaw, however, pitch and surge would exhibit some coupling. The influence of coupling will be insignificant since the two degrees of freedom have very well separated frequencies. The natural frequencies in surge, sway, yaw depend on their respective stiffnesses and mass or moment of inertia of the platform. In case of the pitching frequency the effective stiffness depends on the distance between the tension legs and the metacentric height of the platform in the longitudinal direction [15].

3. WIND LOADING

In order to predict the response of a TLP to fluctuating wind load it is necessary to define the spectrum of atmospheric wind fluctuations. The description of turbulence spectrum over the ocean in the low frequency range lacks a universal relationship. All the empirical spectral descriptions agree in that they approach the Kolmogorov limit at high frequencies; all differ in the treatment of low frequencies. Unfortunately, for a greater portion of compliant platforms, the frequencies of importance are in that low frequency range. A detailed review and synthesis of this subject is in progress [10]. Using remotely sensed data, the distribution of energy in the wind field is described in terms of three regions: the synoptic, the mesoscale and the microscale. An appropriate indentification of these scales and the interaction between these scales may help to quantify the spectral energy of wind fluctuations at frequencies of interest to a TLP designer. However, in the absence of such a spectra the existing empirical spectra given by Davenport [11] and Harris [12] are used in this study. The Harris spectrum is also recommended by Det Norske Veritas [13].

For better understanding of the relationship between the spectrum of the overall loads on a structure and the spectrum of atmospheric turbulence, it is customary and convenient to think in terms of wave lengths rather than frequencies ($\lambda = U/n$). The gust size in relation to the size or a typical dimension D of a structure is an important parameter regarding the effectiveness of a gust in terms of producing loads on a structure. Small size gusts ($\frac{\lambda}{D} \ll 1$) resulting from high frequency components of atmospheric turbulence are correlated over small areas of the structure. Therefore, loading induced by the gusts of this size is small. The very low frequency components of gust are associated with values of $\lambda/D > 1$ and in this case their influence is felt simultaneously over the whole, or at least the larger areas, of the structure. These large scale gusts are important for the behavior of a low natural frequency structure like a TLP. In the following sections wind loading is treated as single-point and multi-point random processes.

3.1 Single-Point Loading

The wind loads can be treated as a single-point process if $\lambda/D \gg 1$ which means that the wind velocity field is assumed to be fully correlated. This assumption is quite valid for low frequency structures with small spatial size. The fundamental equations of aerodynamics can be used to formulate the relationship between the incident velocity fluctuations and the fluctuations in the drag force (surge direction) on a structure

$$F_D(t) = \rho C_D A_p U^2(t)/2 \tag{3}$$

where $U(t) = \bar{U} + u$ and A_p is the projected area of the structure. By ignoring the higher order terms $(u/\bar{U})^2$, the mean drag force is

$$\bar{F}_D = \rho C_D A_p \bar{U}^2/2 \tag{4}$$

and the fluctuating drag is

$$F'_D(t) = \rho C_D A_p \bar{U} u(t) \tag{5}$$

The importance of the higher order terms $(u/\bar{U})^2$ and the energy available in the second-order spectrum are discussed by Kareem [5].

3.2 Multiple-Point Loading

A TLP is generally a very large size structure; therefore, a single-point analysis, assuming that the flow is correlated over the entirety of the structure, may yield conservative estimates of loading. Therefore, to incorporate the effects of partial correlation over the structure, the concept of multiple-point statistics is used. The fluctuating flow field is described by a spatio-temporal function given by

$U(y,z,t) = \bar{U}(z) + u(y,z,t)$

in which $\bar{U}(z)$ = mean wind, and $u(y,z,t)$ = fluctuataing wind component. The fluctuating alongwind (surge), torsional moment (yaw), and pitching moment due to fluctuating wind velocity field are given by

$$\begin{aligned} F(t) &= \rho C_D \iint_A \bar{U}(z)\, u(y,z,t)\, dy\, dz \\ T(t) &= \rho C_D \iint_A y\, \bar{U}(z)\, u(y,z,t)\, dy\, dz \\ M(t) &= \rho C_D \iint_A z\, \bar{U}(z)\, u(y,z,t)\, dy\, dz \end{aligned} \tag{6}$$

The description of spatio-temporal wind velocity fluctuations, $u(y,z,t)$ is necessary to define the overall dynamic loads on a TLP. In this study the fluctuating wind velocity field is digitally simulated as a set of multivariate multidimensional homogeneous random processes [15].

4. DYNAMIC ANALYSIS

The equations of motion with nonlinear stiffness are integrated step-by-step using numerical techniques. This is accomplished by considering the incremental form of the equations of motion using a time integration scheme and an iteration algorithm to establish dynamic equilibrium at each time increment [14,15]. The details of numerical procedure are given in Ref. 15. The stiffness matrix is updated at each time step to incorporate nonlinearities.

For single-point time domain analysis wind is simulated as a homogeneous Gaussian process with zero mean and given power spectral density. The simulation was carried out using a fast Fourier transform technique [15,16,17]. For the multiple-point analysis the wind velocity field is simulated as multicorrelated random processes at n locations on a TLP [15,16,17]. The number of locations and the time steps generated for each location are dependent on the available computer. The projected area of the TLP is divided into n segmental areas and the velocity fluctuations are simulated at the centroid of these areas. The simulated records match the required power spectral density at each location and also satisfy the desired coherence for their respective spatial separation. The expressions for wind loading given in Eq. 6 are modified for discrete loading as

$$
\begin{aligned}
F(t) &= \rho \sum_{i=1}^{n} C_{D_i} A_i \bar{U}_i u_i(t) \\
T(t) &= \rho \sum_{i=1}^{n} C_{D_i} A_i \bar{y}_i \bar{U}_i u_i(t) \\
M(t) &= \rho \sum_{i=1}^{n} C_{D_i} A_i \bar{z}_i \bar{U}_i u_i(t)
\end{aligned}
\tag{7}
$$

in which A_i and C_{Di} are the segmental area and drag coefficients and i represents the ith segment and $u_i(t)$ is the simulated velocity at the ith segment.

The time histories of fluctuating responses obtained from step-by-step integration of Eq. 1 are analyzed to obtain response statistics.

5. EXAMPLE

An example is presented here to illustrate the concepts presented regarding the wind loading and associated structural response of a TLP. Fig. 2 shows the schematic diagram of the TLP used in this example.

The drag coefficient for this structure is synthesized from the component drag coefficients and it is equal to 1.14 [15]. The mass matrix is given in Table 1. The stiffness characteristics of the TLP are given in Table 2. The stiffness is linear for the small range of loads but considering the overall range, it is nonlinear. The natural periods in the surge, sway, yaw, and pitching motion are 88, 88, 67, and 17 seconds, respectively. These periods are corresponding to low values of displacement. With increasing displacement the structure becomes stiffer and its respective natural periods are reduced to 66, 66, 58, and 12 seconds at maximum displacement assoicated with 100 percent loading.

In this example the wind was assumed to approach the TLP at zero angle. A power law exponent of 0.16 was used for the boundary layer approaching the structure. The coefficients of damping matrix, α and β, are both assumed to be 0.01. The damping coefficient can be varied for a parametric study to examine their influence on the structural response. The structure was analyzed first considering single-point wind loading, and wind velocity fluctuations were simulated according to the procedure described earliler, using spectra given by Harris and Davenport. The simulation based on the Harris spectrum gives higher values of response since the energy in Harris spectrum at low frequencies is relatively higher than that of Davenport spectrum [6].

A multiple-point wind velocity simulation was carried out for twelve locations on the TLP, and a typical plot of velocity fluctuations is shown in Fig. 3. This plot refers to a 20 m/s (65.72 ft/sec) wind velocity at the reference height of 10 m (33 ft). The resulting time histories of forcing function, according to Eq. 7, and the associated response histories are plotted in Fig. 4. A summary of surge response computed from the single-point and multiple-point simulations is plotted in Fig. 5. The multiple-point loading includes partial spatial correlation over the entire structure which results in response estimates lower than the single-point formulation where it is tacitly assumed that the wind fluctuations are fully correlated. The mean and rms yaw and pitching motion are plotted in Fig. 6 as a function of the mean wind velocity at the reference height. The results obtained from the time domain analysis in this study have very good agreement with the values derived from a frequency domain analysis reported in Ref. 15. The surge and pitching motions are not very significant in magnitude, which is very desirable from design considerations. The yaw response can increase due to aerodynamic eccentricity if the structural geometry is not symmetrical. Generally there is no eccentricity in the mass and elastic centers of a TLP, which prohibits any amplification from dynamic inertial coupling. The response in the sway direction is not computed here since only the excitation due to the alongwind velocity fluctuations is considered, which does not contribute in the sway direction. However, the scope of this study does not preclude the sway response of a TLP which may result from the lateral component of turbulence and/or any possible contribution from vortex shedding.

6. CONCLUSIONS

The methodology presented here enables the prediction of the dynamic response of a TLP subjected to fluctuating wind. The time domain analysis though expensive yields very reliable response estimates for a nonlinear structure. However, the frequency domain analysis, in which the TLP is assumed to oscillate linearly above the static equilibrium position produced by the mean loading [15], provides good estimates for the preliminary design and it is also computationally more economical. From the examples presented here and in Ref. 15, it is concluded that a low frequency TLP is very vulnerable to the static and dynamic effects of wind. The surge motion is the most sensitive to the wind action. The yaw motion of a TLP can be controlled by keeping the aerodynamic center as close to the vertical axis of symmetry as possible. The pitching frequency can be "de-tuned" in such a manner that it falls out of the range of dynamic wind excitation. The potential of the methodology presented here is fully realized by synthesizing the results with meteorological statistics of local wind climate to provide predictions of the behavior of a platform expected for certain levels of probability.

ACKNOWLEDGEMENTS

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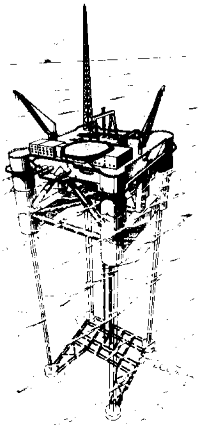
Table 1 Mass Matrix

$$\begin{bmatrix} 1.0358 \times 10^{7} & 0 & 0 \\ 0 & 2.212 \times 10^{10} & 0 \\ 0 & 0 & 3.615 \times 10^{10} \end{bmatrix}$$

Table 2 Stiffness Levels

% of Loading	Stiffness		
	Surge Nm	Yaw Nm/Rad	Pitch Nm/Rad
0.0	5.19E + 5	1.94E + 8	4.98E + 9
20.0	5.19E + 5	1.94E + 8	4.98E + 9
40.0	6.14E + 5	2.23E + 8	6.66E + 9
60.0	7.22E + 5	2.39E + 8	7.86E + 9
80.0	8.65E + 5	2.49E + 8	8.66E + 9
100.0	9.34E + 5	2.61E + 8	9.51E + 9



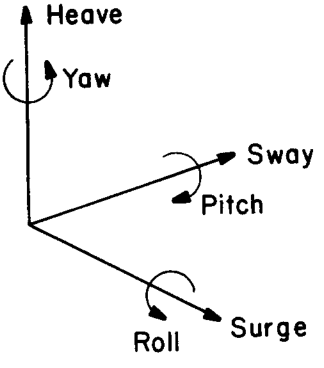


Fig. 1 A View of a TLP and Coordinate System

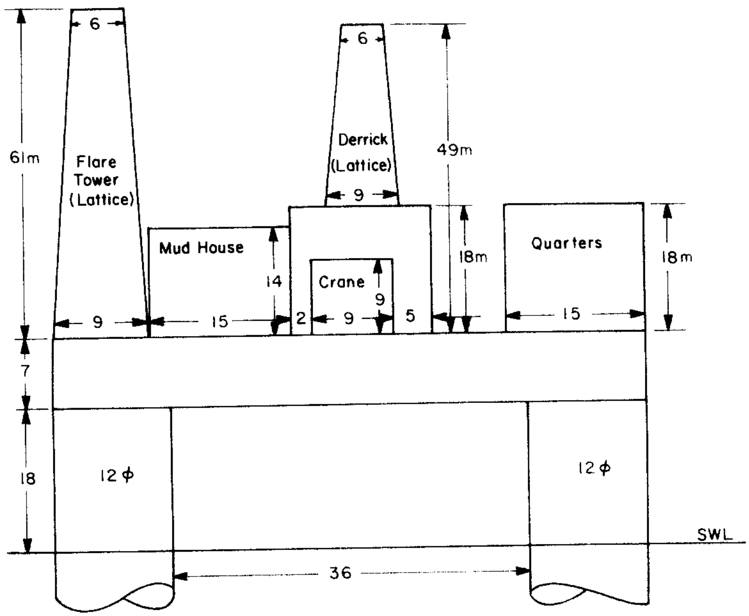
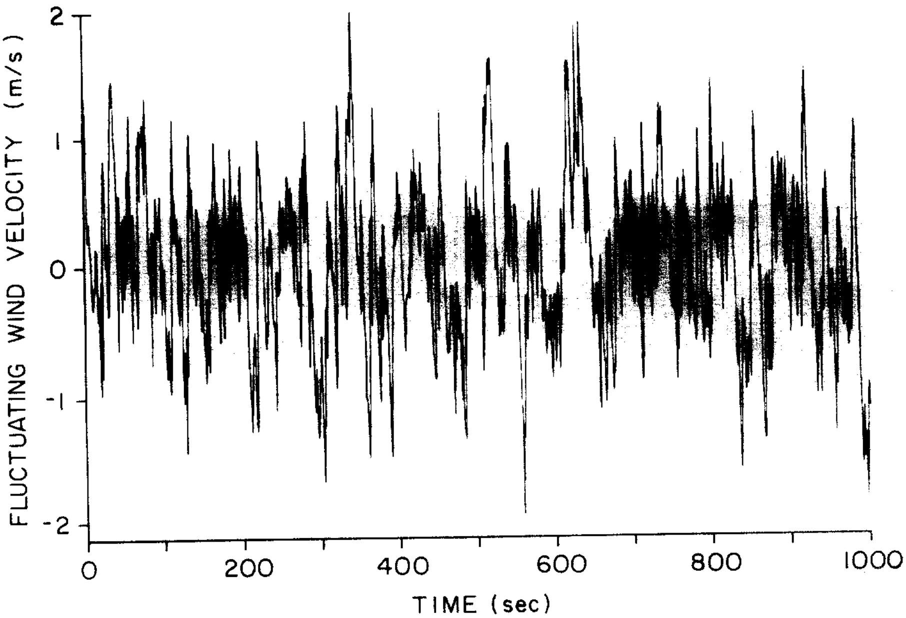


Fig. 2 Schematic Diagram of the TLP



Fig, 3 Typical Time History of Velocity Fluctuations

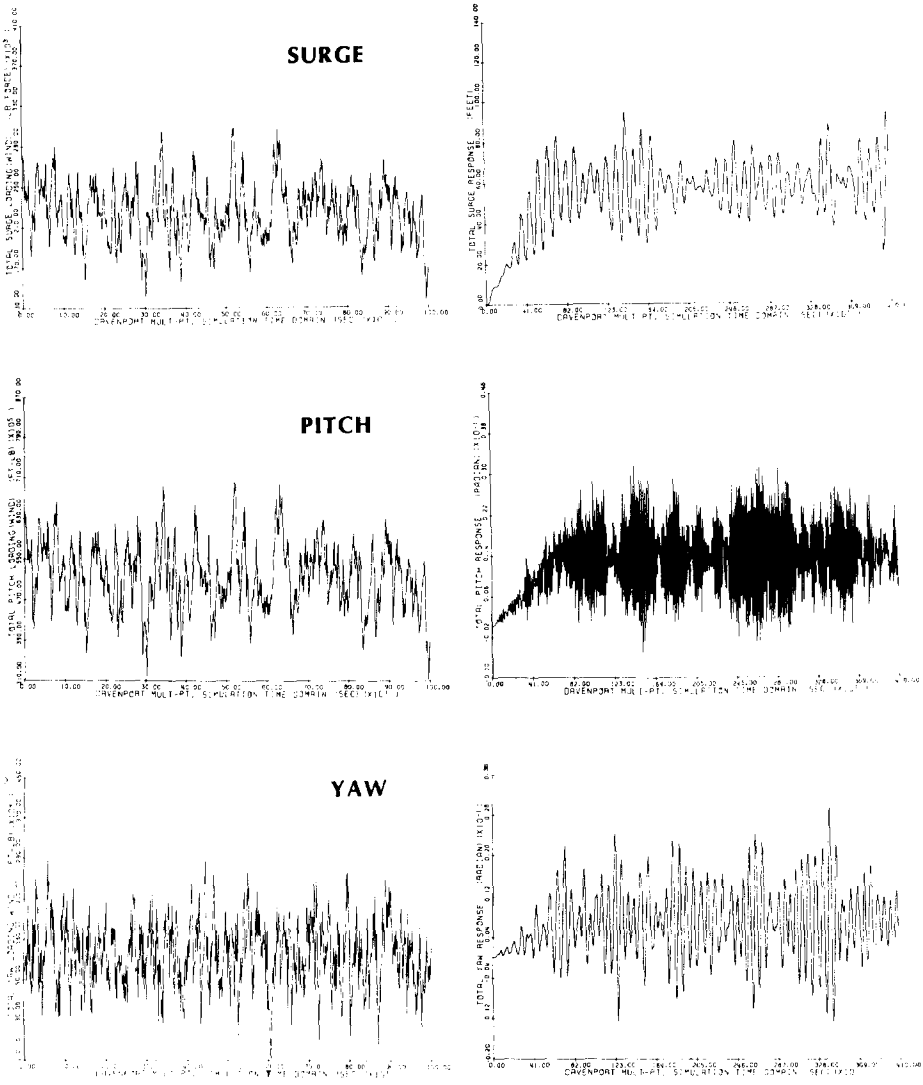


Fig. 4 Time Histories of Force and Response Fluctuations

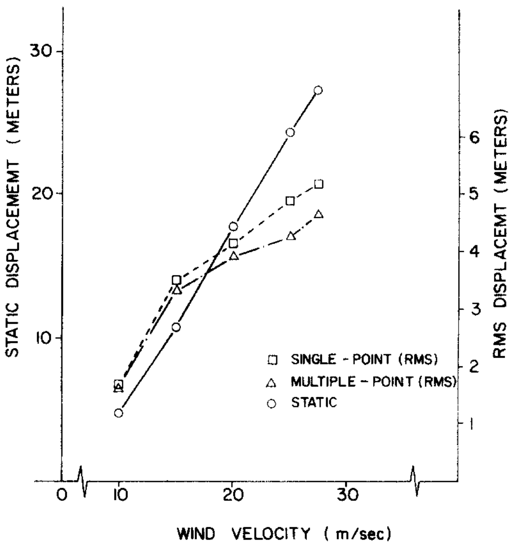


Fig. 5 Mean and RMS Surge Motion

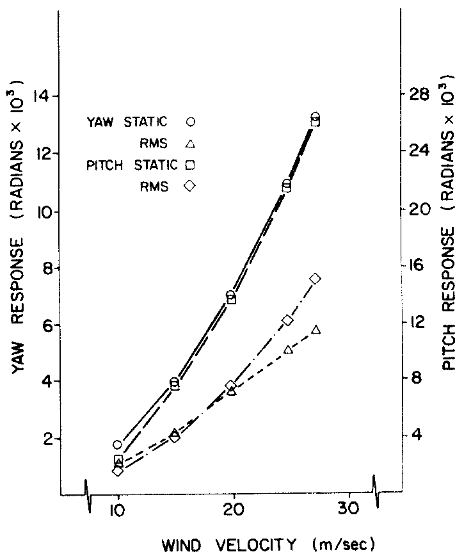


Fig. 6 Mean and RMS Yaw and Pitching Motion