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RESEARCH PAPER

Wind-induced response of large offshore oil platform

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Abstract: In connection with wind sensitivity for the towering and hollowed-out structures (drilling derrick, crane, etc) of large offshore oil platform, the wind-induced response of towering structure was studied. By the similarity criteria, high frequency force balance tests for the large offshore oil platform under 0–360° wind directions were carried out, and the spatial distribution model of fluctuating wind load acting on platform was presented. Also, the characteristics of wind-induced vibration and the changing rule of gust loading factors were obtained precisely through wind-induced assessment in all directions. The results show that: the RMS (Root Mean Square) of the fluctuating across-wind load is about 10% of the fluctuating along-wind load on the platform; the vibration is mainly focused on the towering and hollowed-out structure like derrick, and the RMS of the across-wind acceleration is about 55% of the along-wind acceleration; the towering derrick has a big dynamic magnification of fluctuating across-wind load. The across-wind load can not be neglected in wind resistance design of large offshore oil platform, also the wind-induced response on the top/bottom of derrick and the magnification of fluctuating across-wind load of towering structure should be mainly considered.

Key words: offshore oil platform; derrick; wind-induced response; fluctuating wind load; wind-induced vibration; gust loading factor

Introduction

In recent years, the typhoon occurred frequently, presenting high strength, strong impact and heavy disaster characteristics[1], which caused serious damage to the safety of offshore oil platforms. Meanwhile, the offshore oil platform is developing towards large-scale and deep-water, and the towering and hollowed-out structures (drilling derrick, crane, etc.) on the large offshore oil platform with large flexibility and low natural frequency, are more susceptible to wind. The towering structures of offshore platform were damaged and collapsed in typhoon repeatedly. According to statistics[2–3], since 1947, about 250 offshore oil platforms have been destroyed, more than 600 platforms have been seriously damaged, and thousands of platforms have been forced off production in the Gulf of Mexico due to hurricanes, causing enormous economic loss. Therefore, accurate assessment of wind-induced response is of great significance for the design and safe operation of offshore oil platform. The equivalent static wind load method is usually used to evaluate the wind-induced vibration in the current design and assessment codes for offshore oil platforms, and the equivalent load is the product of static wind load multiply by a dynamic magnification factor (wind vibration coefficient or gust loading factor). But the equivalent method has two shortcomings: first, the dynamic magnification factor is difficult to work out accurately due to the complex structure of large platforms; second, the results may be conservative and large in error since the across wind vibration of the towering structure is neglected in this method.

At present, two methods are commonly used to evaluate the wind-induced response in engineering, one, direct measurement of response[4], the other, the wind response analysis method[5–6]. The direct measurement of response method obtains the response of a structure through actual measurement or aeroelastic model test, and is mainly applied to transmission towers, buildings and other towering structures[7–8]. This method can obtain wind-induced response accurately, but costly, time-consuming and difficult to implement[9], its application to large offshore oil platforms is limited. In the wind response analysis method, the high frequency force balance test or quasi-steady theory is used to obtain the time history of fluctuating wind load, then the wind-induced response is obtained by applying the fluctuating wind load on the structure[10]. With the advantages of simple model making, convenient test, and low cost etc, the high frequency force balance test is widely used in wind resistance design for tall buildings and derricks. With legs and jacket located in seawater, and the topside modules subject to wind load mainly,

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the large offshore oil jacket platform has the characteristics of high stiffness in the lower part and large flexibility in the upper part, which has been seldom investigated by the high frequency force balance test[11].

Therefore, this paper takes a large towering offshore oil jacket platform in the South China Sea as the research object, and a systematic study of high frequency force balance tests of the platform under 0–360° wind directions was conducted. The spatial distribution of fluctuating wind load is estimated based on the results of the tests and the quasi-steady theory of fluctuating wind load. The precise finite element model is established, and by fully considering nonlinear pile-soil interaction and sea-water etc, the characteristics of along/across wind vibration and the variation pattern of the gust loading factor with height and wind direction are obtained precisely based on wind-induced vibration analysis of platform.

1. Methodology

In order to get the wind-induced response of the offshore oil platform in detail, the topside modules are divided into several layers (Fig. 1), the main part of topside modules with higher stiffness is divided into 1-3 layers, and the towering derrick is divided into 4-11 layers. The layers are simplified as multi-degree freedom system, and the dynamic equilibrium equation of platform under wind load can be expressed as:

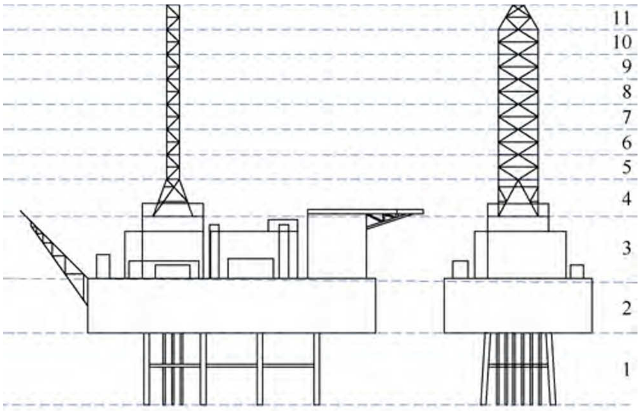
$$\boldsymbol{M}_i\ddot{\boldsymbol{x}}_i(t)+\boldsymbol{C}_i\dot{\boldsymbol{x}}_i(t)+\boldsymbol{K}_i\boldsymbol{x}_i(t)=\boldsymbol{F}_i(t) \quad (i=1,\ 2,\ \cdots,\ 11) \tag{1}$$

If only the wind action on the structure is considered while the reaction of the structure to the wind ignored, the generalized fluctuating wind load of n-order mode for the platform can be obtained by decoupling equation (1) based on quasi-steady theory.

$$F_n'(t)=\sum_i \varphi_{ni}F_i(t)=\sum_i \varphi_{ni}C_{\mathrm{p}i}A_i\rho_{\mathrm{a}}u_iu_i'(t) \tag{2}$$

In equation (2), the average wind velocity u_i in i layer can be obtained by converting the landform between wind tunnel test and sea level.

$$u_i=\left(\frac{z_i}{H'}\right)^{\alpha'}\left(\frac{H}{z_i}\right)^{\alpha}\left(\frac{z_i}{z_{\mathrm{b}}}\right)^{\alpha}U_{\mathrm{b}} \tag{3}$$



(a) The front view (b) The side view

Fig. 1. Model of the offshore oil platform.

The generalized cross-spectrum density of wind load between different layers can be obtained by Fourier transform of equation (2).

$$S_{F,ij}(f)=\varphi_{ni}\varphi_{nj}C_{\mathrm{p}i}C_{\mathrm{p}j}A_iA_j\rho_{\mathrm{a}}^2u_iu_jS_{u_i'u_j'}(f) \tag{4}$$

Reference [12] indicates that the fluctuating wind load of towering structure has a larger coherence than the fluctuating wind speed, which can be modified by aerodynamic admittance based on quasi-steady theory. There is a phase difference of wind speed in different height, and by considering the impact of the argument of cross power spectrum, equation (4) can be written as:

$$S_{F,ij}(f)=\varphi_{ni}\varphi_{nj}C_{\mathrm{p}i}C_{\mathrm{p}j}A_iA_j\rho_{\mathrm{a}}^2u_iu_j coh_F(z_i,z_j)\times S_{u_i'}(f)\chi(f)\exp\left[\mathrm{i}\psi_{ij}(f)\right] \tag{5}$$

The relationship between the base moment power spectrum based on the high frequency force balance test and the cross-spectrum density of wind load in different height is as follows.

$$S_{M,ij}(f)=S'_{M,ij}(f)\lambda_{\mathrm{M}}=\sum_i\sum_j S_{F,ij}(f)z_iz_j \tag{6}$$

Combining equation (6) with equation (5):

$$S_{u_i'}(f)=\frac{S_{M,ij}(f)}{\sum\limits_i\sum\limits_j z_iz_j\varphi_{ni}\varphi_{nj}C_{\mathrm{p}i}C_{\mathrm{p}j}A_iA_j\rho_{\mathrm{a}}^2u_iu_j}\times \frac{1}{\exp\left[-\left|z_i-z_j\right|/L_{\mathrm{z}}\right]\exp\left[\mathrm{i}\psi_{ij}(f)\right]} \tag{7}$$

The spatial distribution of wind load power spectrum can be obtained by combining equation (5) with equation (7).

$$S_{F,ij}(f)=\frac{S_{M,ij}(f)\varphi_{ni}\varphi_{nj}C_{\mathrm{p}i}C_{\mathrm{p}j}A_iA_ju_iu_j}{\sum\limits_i\sum\limits_j z_iz_j\varphi_{ni}\varphi_{nj}C_{\mathrm{p}i}C_{\mathrm{p}j}A_iA_ju_iu_j}\times \frac{\exp\left[-\left|z_i-z_j\right|/L_{\mathrm{z}}\right]\exp\left[\mathrm{i}\psi_{ij}(f)\right]}{\sum\limits_i\sum\limits_j\exp\left[-\left|z_i-z_j\right|/L_{\mathrm{z}}\right]\exp\left[\mathrm{i}\psi_{ij}(f)\right]} \tag{8}$$

At present, the linear digital filtering method, harmony superposition method, wavelet analysis method etc. are commonly used to simulate the time history of fluctuating wind load, among them, the harmony superposition method, based on the sum of the power spectrum trigonometric series, is simple and intuitive, rigorous in mathematics theory and strong in applicability[13]. Therefore, the harmony superposition method is adopted in this study. The Cholesky decomposition matrix of the wind load cross-spectrum density matrix is as follows:

$$S_{F,ij}(f)=\boldsymbol{H}(f)\boldsymbol{H}^{*\mathrm{T}}(f) \tag{9}$$

The fluctuating wind load can be obtained from the following equation.

$$F_i(t)=2\sqrt{\Delta f}\sum_{i=1}^{m}\sum_{q=1}^{N}\left|H_{iq}(f)\right|\cos\left[ft+\psi_{im}(f)+\phi_{iq}\right] \tag{10}$$

2. Spatial distribution of fluctuating wind load

2.1. High frequency force balance test

Taking a large towering offshore oil jacket platform in the