Wind-induced Dynamic Stability analysis of Derrick with Double Flat Arm

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Abstract. In order to study the stability of a derrick under fluctuating wind load, the dynamic stability analysis is carried out to get the critical wind speed in dynamic instability. Considering the effect of the fluctuating wind, the mean wind speed in dynamic instability is 39 m/s. When the height of the derrick is greater than 80m, the wind-induced vibration coefficient value of time history analysis is greater than the calculation value of GB 50009-2012 code, the vibration coefficient should be raised for derricks with a height greater than 80m, and the wind-induced vibration coefficient of flat arms should be considered separately.

1. Introduction
Derrick with double flat arm has been widely applied to tower construction. It’s very important to guarantee the stability of derrick in the tower construction. Pang [1] conducted safety analysis on the derrick to be put into use through the finite element software, simulating various actual working conditions, and gave the stress characteristics of the derrick and the selection method of slenderness ratio in the design process of the derrick. Kitipornchai [2] analysed the stability of the transmission tower, and considered the influence of the second-order bending moment stress and node flexibility on each simulation unit of the transmission tower. The second-order bending moment stress is mainly generated by the connection stiffness, node eccentricity and chord member continuity. Fu [3] carried out the comparative analysis between the response of a tower crane under static wind load and fluctuating wind load, and found that the response of the structure under fluctuating wind load is larger. Zhang [4] analysed the dynamic stability of a transmission tower considering the influence of fluctuating wind load on the stability. Wang [5] analysed the stability of the derrick, including eigenvalue buckling analysis and nonlinear buckling analysis, summarized the calculation method of the stable bearing capacity of the derrick under the unbalanced lifting, provided the relevant calculation formula and the representative meaning of each parameter, and checked the accuracy of its engineering application. Xu [6] studied the influence of stay wire on the mechanical properties of suspension double rocker arm derrick. The results show that the setting mode of waist ring and the setting angle of support rope have a great influence on the overall stability of derrick structure. Although the above researches have achieved some achievements, most of the existing researches are on the stability analysis of the derrick under the static load, and the researches on the stability of the derrick considering the dynamic load are relatively less. Additionally, the height of derrick in the existing research is relatively low. Therefore, it is necessary to study the stability of the higher derrick.
under the action of wind load. Besides, the wind load is random, only the stability analysis under the static wind load is not comprehensive, and there may be potential instability factors. In this paper, the dynamic stability analysis of the derrick is carried out through the simulation of the fluctuating wind load, in order to obtain the instability mode and the critical wind speed in instability and provide reference for the design of derrick.

2. The finite element model of the derrick
In this paper, a double arm derrick with height of 162m is chose for the wind-induced vibration analysis. 8 waist rings are installed to ensure the stability of the derrick, and the distance between the waist rings is 21m, 18m and 15m respectively.

The spatial rigid frame model was adopted for the finite element model of the derrick [1], and the beam188 unit was adopted for the bar element of the derrick. The connection between the bar members is thought as rigid connection; the elements that only bear tension such as the internal stay wire, waist ring, pull rod were simulated by the link180 unit, and the connection of them with the rod body and flat arm is hinged. Q345 steel is adopted for the derrick, and its yield strength is 310MPa, elastic modulus is 206MPa, and Poisson's ratio of 0.3. The bilinear following reinforcement model is used to describe the stress-strain curve of steel [7].

3. Dynamic stability analysis of derrick with double flat arm

3.1. Fluctuating wind load simulation
The random vibration of wind is mainly reflected by fluctuating wind load. In this paper, the linear filtering method [8] is used to simulate the fluctuating wind speed, and the MATLAB software is used to write the simulation program of the fluctuating wind speed. The derrick is divided into 14 sections, shown in Figure 1, and that’s the simulation of the 14 points in the space. According to the equivalent static analysis [9], the most unfavourable working condition is that the swing angle of the flat arm is 0° and the wind direction angle is 45°, and the analysis in this section is based on this working condition. The classification of the ground roughness is class B, and the ground roughness is 0.03. Kaimal spectrum is adopted for the fluctuating wind speed spectrum. In the simulation, the 10 min average wind speeds at 10 m height are 28 m/s, 30 m/s, 33 m/s and 36 m/s respectively. The time history curve of fluctuating wind speed at different heights can be obtained by simulation. In this paper, the wind load is regarded as the sum of average wind load and fluctuating wind load. According to the corresponding formula [10], the program of wind speed and wind pressure is compiled by MATLAB software, and the wind load time history at the corresponding height is obtained.
3.2. Dynamic stability analysis
The dynamic stability analysis in this paper is mainly based on the dynamic increment method and the displacement equivalence criterion [11]. According to the results of equivalent static analysis [9], the characteristic response point should be Node 4846 at the end of the flat arm. In this section, according to the above results of wind load, a dynamic time history analysis is made for each level of wind speed by the dynamic increment method, and the displacement time history curve under all levels of simulated wind speed is obtained. Figure 2 shows the displacement time history curve of Node 4846 under the fluctuating wind load with the average wind speed of 30m/s, 33m/s, 36m/s and 39m/s.

(a) the average wind speed of 30 m/s  
(b) the average wind speed of 33 m/s
According to the displacement time history curve of Node 4846 at the end of the flat arm under each wind speed, the maximum displacement value in each curve is extracted, and the relationship curve between the displacement of Node 4846 and the wind speed is obtained, as shown in Figure 3.

According to the wind speed displacement curve of Node 4846 at the end of the flat arm, the wind speed increases with the increase of displacement before the displacement reaches 1.0m, and when the displacement exceeds 1.0m, the wind speed increases slowly with the increase of displacement. Under the action of fluctuating wind load with an average wind speed of 39m/s, the curve begins to level, the wind speed hardly changing, but the corresponding displacement increases greatly. At this time, the maximum displacement of Node 4846 is 1.16m, and the displacement of Node 4846 is 1.2m when the structure is unstable in nonlinear buckling analysis. According to the principle of equal displacement, when the fluctuating wind load with an average wind speed of 39 m/s acts on the derrick, the dynamic instability of the derrick occurs.

3.3. Wind-induced vibration coefficient
The designed wind speed of the double flat arm derrick is 28.4m/s, and the most unfavorable condition is 0º of the horizontal arm rotation and 45º of the wind direction under the non-working condition. According to equation (1), the wind-induced vibration coefficient at the z height of the holding rod under the dynamic time-history analysis is calculated, and the corresponding wind-induced vibration coefficient is calculated and compared in accordance with Chinese Code Building Structure Load Code (GB 50009-2012), as shown in Table 1.

\[
\beta(z) = 1 + \frac{\mu m(z)g(z)}{\beta_{mg}w(z)A(z)}
\] (1)
\(m(z)\) and \(A(z)\) are the concentrated mass and wind area at \(z\) height respectively; \(\sigma_a(z)\) is the mean squared deviation of acceleration at \(z\) height; \(\mu\) is the peak factor, and the value is 2.2 according to the design code for high-rise structure.

| Sections of derrick | Mass (kg) | Mean squared deviation | \(\beta(z)\) |
|---------------------|-----------|------------------------|--------------|
|                     |           |                        | Time history analysis results | Calculated value of GB 50009-2012 |
| 1                   | 2695      | 0.0097                 | 1.005        | 1.016          |
| 2                   | 2695      | 0.0312                 | 1.021        | 1.105          |
| 3                   | 2695      | 0.0734                 | 1.123        | 1.223          |
| 4                   | 2695      | 0.1457                 | 1.256        | 1.320          |
| 5                   | 2695      | 0.2444                 | 1.395        | 1.455          |
| 6                   | 2695      | 0.3434                 | 1.587        | 1.531          |
| 7                   | 2695      | 0.5085                 | 1.665        | 1.607          |
| 8                   | 2695      | 0.6502                 | 1.856        | 1.728          |
| 9                   | 2695      | 0.8220                 | 1.923        | 1.862          |
| 10                  | 2695      | 0.9389                 | 2.036        | 1.926          |
| 11                  | 2300      | 0.6268                 | 2.156        | 1.970          |
| 12                  | 1428      | 0.9715                 | 2.236        | 2.010          |
| 13                  | 3280      | 1.8095                 | 2.532        | 2.000          |
| 14                  | 3280      | 1.8095                 | 2.532        | 2.000          |

It can be seen from Table 1 that the wind-induced vibration coefficient increases with the increase of height. In derrick height of 80 m or so, wind-induced vibration coefficient value obtained by the time history analysis is larger than the value calculated according to Building Structure Load Code (GB 50009-2012), therefore, it is not safe for design of derricks with a height greater than 80 m to use the wind-induced vibration coefficient. The wind-induced vibration coefficient mutation is significantly greater than calculated values of GB 50009-2012, this is due to the derrick flat arm quality focus and wind area is larger. However, in the code of GB 50009-2012 the wind-induced vibration coefficient does not reflect the mutation in the arm, the wind-induced vibration coefficient of the time history analysis is 26.5% larger than the calculated value of code, so in the design of the derrick, the vibration coefficient should be raised for derricks with a height greater than 80m, and the wind-induced vibration coefficient of flat arms should be considered separately.

4. Conclusions

In this paper, the finite element model of the double flat arm derrick is established, and then the dynamic stability of the derrick is analysed. When the average wind speed of the fluctuating wind is 39m/s, the derrick is unstable. When the height of the derrick is greater than 80m, the wind-induced vibration coefficient value of time history analysis is greater than the calculated value of GB 50009-2012 code, the vibration coefficient should be raised for derricks with a height greater than 80m, and the wind-induced vibration coefficient of flat arms should be considered separately.

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