Dynamic Reliability Analysis of Tower Crane with Wind Loading

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Abstract. The wind-induced dynamic reliability of tower cranes was studied. A linear filter autoregressive (AR) model is used to simulate the time history of multi-dimensional fluctuating wind samples, and the corresponding wind load is applied to the finite element model of tower crane to analyze the wind vibration response. Based on Poisson process method, wind vibration reliability analysis of tower crane is carried out. The results show that under the action of wind speed of 20m/s, the probability of strength reliability is over 0.99, and the structural strength reserve of this type of tower crane is relatively sufficient; the displacement reliability is 0.98, when the wind speed is large, the displacement reliability decreases obviously, and the stiffness reserve is slightly insufficient.

1. Introduction

Tower cranes are important mechanical equipment in the building industry, they have such advantages as wide adaptability, large turning radius and high lifting height. They have been widely used in industrial and civil fields. Owing to the long-term high altitude state and the large slenderness ratio of the boom, the wind load effect is particularly evident, easily resulting in large deformation and vibration [1]. Continuous vibration will not only cause fatigue damage to the structure and impact the safety of the structure, but also lead to the operator's discomfort.

In recent years, scholars at home and abroad have made a lot of research efforts on safety assessment of tower cranes under wind load. Since the wind load on a tower crane is complex in size and direction, Chen analyzed the characteristics of wind load on the body and lifting boom of a tower crane using the computational fluid dynamics method [2]. Cuianalyzed the influence of wind load on the luffing boom of a tower crane under operating and non-operating conditions using the finite element method, and established the maximum stress position of a luffing boom tower crane under different wind directions [3]. Heanalyzed the influence of wind load on the safety performance of tower cranes under operating conditions of different wind scales [4]. Fucalculated the vibration response of a type of tower crane under static and fluctuating wind loads [5]. Jiang analyzed the random wind-induced vibration response of a tower crane using the virtual excitation method, the results show that lower-order frequencies will cause relatively large vibration [6]. Wang analyzed the structural vibration characteristics of a type of tower crane using the numerical simulation method, and verified the reliability of numerical simulation through actual test [7]. Qin proposed a finite element model modification method based on non-
dominated sorting genetic algorithm, which accurately reflected the mechanical characteristics of tower cranes [8].

The safety degree of high-rise structures involves the destruction or failure of structures under strong wind. There are three main forms: first, the stress of structures exceeds the allowable value; second, the displacement or deformation of structures exceeds the allowable value; and third, the fatigue of structures or components. Except for the third kind, the others can be regarded as displacement response of some key points in the structure or stress response related to it which exceeds the safety limit, and such exceeding limit can generally be regarded as the first exceeding problem. Based on the Poisson process method of dynamic reliability analysis, the dynamic reliability of Tower Crane Jib under different wind loads is analyzed in this paper, which provides a theoretical basis for the wind-resistant design of tower crane.

2. Simulation of time-history of wind load

The premise for analysis of wind-induced response of a structure is to obtain accurate wind load data. Since there are few measured wind load data, this paper uses a linear filtering AR model to realize the time history of multi-dimensional fluctuating wind samples. The so-called AR method is to derive the random variables at a specific time point from the random variables at the previous successive time points. Its working principle is that a series of random numbers with a mean of zero and with white spectrum are generated artificially, they are inputted into an AR filter, and the filter outputs random numbers with given characteristic spectrum, i.e., wind speed time history or wind pressure time history sequence. The specific method of AR method can be found in reference [9].

According to the simulated wind speed time history, the corresponding normal wind load time history can be obtained with the Bernoulli's equation [10]:

\[ P = \frac{1}{2} \rho \mu A_i v_i^2 \]

Where, \( \rho \) is air density; \( \mu \) is the mean wind pressure coefficient of the corresponding node, which is usually determined through wind tunnel test; and \( A_i \) is the corresponding area of the node.

In this paper, the Davenport wind speed spectrum, which did not vary with height, was selected as the given characteristic spectrum. The mean wind speed at 10m height is 20m/s, the ground roughness index is 0.16, the sampling frequency is 100Hz, the simulation time is 300s, the time interval is 0.1s, and the number of AR orders is 4. A Matlab program was compiled according to the principle of the AR method, and the wind speed time history of each simulation point on the boom was obtained. Figure 1 shows the wind speed time history curve of node 325 on the head of the boom.

3. Analysis of wind-induced response of tower crane

3.1. Modal analysis of tower crane

The research object in this paper was QTZ25 tower crane, which consisted of tower body, boom, balance arm, tie rod, tower top and auxiliary structures. These structures are composed of steel pipes, angle steel, channel steels and square steel of different sizes. The maximum operating range was 30m, the maximum independent lifting height was 26m, and the maximum lifting weight was 2.5T. The material of the main members of the tower crane was Q235. Owing to the calculation scale, a finite element model was established after reasonable simplification of the tower crane. Beam element Beam 188 was selected for the tower body, boom and balance arm, and bar element Link 180 was selected for the tie rod. Each connection point for structural members of the tower body, boom, balance arm and tower cap was taken as a node. The finite element model formed is shown in Fig2. There are 337 nodes and 840 elements in total. To obtain the modal vibration shape of the boom, modal analysis was carried out in ANSYS. The vibration shapes of the first 10 orders with significant influence were selected, and the damping ratios
of all vibration shapes were taken as 0.02. The modal frequencies of the first 10 orders are shown in Table 1.

![Pulsating wind speed time history at head of boom.](image1)

![Finite element model of tower crane.](image2)

**Figure 1.** Pulsating wind speed time history at head of boom.

**Figure 2.** Finite element model of tower crane.

**Table 1.** Vibration shapes of the first 10 orders.

| Order | 1   | 2   | 3   | 4   | 5   |
|-------|-----|-----|-----|-----|-----|
| Frequency/Hz | 0.25 | 0.58 | 0.65 | 1.64 | 2.56 |
| Order | 6   | 7   | 8   | 9   | 10  |
| Frequency/Hz | 3.85 | 4.04 | 5.25 | 6.86 | 7.54 |

### 3.2. Wind-induced response of tower crane

A loading program was compiled with the APDL language using the transient dynamic analysis module of the Ansys software. The simulated fluctuating wind load was applied on the finite element model of tower crane. The loading direction was the worst operating condition, in other words, the direction of wind speed was perpendicular to the operating plane of the tower crane. The wind-induced dynamic response of the structure was analyzed, and the analysis time was 300s.

The analysis results show that the maximum along-wind displacement is undergone by node 325 at the end of the boom, while the cross-wind displacement is relatively small. Figure 3 shows the along-wind displacement time history of node 325. Figure 4 shows the along-wind displacement time history of node 157 at cab. The tower body pillar mainly bears compressive stress. On the boom, member bars 638 and 659 bear the largest tensile stress. Figures 5 and 6 show the tensile stress time history curves of member bars 638 and 659, respectively. From the stress time history curves, it can be seen that the tensile stress fluctuates in a large range in the initial stage of wind load, and the fluctuation range decreases gradually with the increase in action time. For clarity, only the stress time history of the first 100 s is given in the figure.
4. Wind-induced dynamic reliability of tower crane

4.1. First Passage failure criterion

Under random wind loads, tower crane structures will fail to work properly if the local stress exceeds the allowable limit or the deformation exceeds the allowable limit. This kind of problem is generally regarded as the first Passage failure. Assuming that the stress or displacement time history of a checking point is $y(t)$, and the limit is specified as $a$, the average frequency of the positive slope of $y(t)$ passing through $a$ in a specified time is $v^+$. According to Rice's theory, the crossing frequency $v^+$ can be obtained from the joint probability density function $p(y, \dot{y})$[11]:

$$v^+ = \int_0^\infty p(a, \dot{y}) \dot{y} \, d\dot{y}$$

(1)

Formula (1) is suitable for any probability distribution. For response $y(t)$, such as displacement, internal force and stress, if the square term of fluctuating wind speed is not considered, it can be regarded as a stationary Gauss process. We can make $x = y - \mu y$, $x(t)$ a random process with zero mean, because any stationary random process $x(t)$ is not related to its derivatives. Then there are:

$$p(a, \dot{y}) = p(b, \dot{x}) = \frac{1}{\sqrt{2\pi\sigma_y\sigma_\dot{x}}} \exp \left[ -\frac{1}{2} \left( \frac{-b^2}{\sigma_y^2} + \frac{\dot{x}^2}{\sigma_\dot{x}^2} \right) \right]$$

(2)
There, $b = a - \mu_y v'$. $v'$ can be obtained from formula (1) and formula (2):

$$v' = \frac{1}{2\pi} \frac{\sigma_y}{\sigma_s} \exp\left( - \frac{a^2}{2\sigma_s^2} \right)$$

(3)

According to the first transcendental failure criterion, the structural reliability is the probability that the response $y(t)$ does not exceed the given limit once in a given time period $[0, T]$. When the bound $y=a$ is very high, the probability of the intersection between $y(t)$ and bound $y=a$ is very small. The probability that $y(t)$ does not exceed the safety limit $y=a$ is:

$$P(a) = P\{\max_{0 \leq t \leq T} y(t) \leq a, 0 \leq t \leq T\} = \exp\left[ - \int_0^T v' \, dt \right]$$

(4)

That is, the probability that the number of intersections of $y(t)$ with $y=a$ in time $[0, T]$ is zero. Formula (4) is a general formula for the dynamic reliability of random response under the assumption that the number of intersections between $y(t)$ and the limit is Poisson process in $[0, T]$.

If the random process $y(t)$ is a stationary random process, then $v'$ is independent of time. Formula (4) can be simplified to:

$$P(a) = \exp\left[ - \int_0^T v' \, dt \right] = \exp(- v' T)$$

(5)

Considering the randomness of mean wind load and fluctuating wind load, the reliability analysis of tower crane is generally based on the dynamic reliability of the structure under fluctuating wind load given $\bar{\tau} = v$ [12].

$$P_s(a, T_c, \tau) = P\{y(t) \leq a, t \in T_c, \tau\}$$

(6)

There, $T_c$ is the duration of a gust. If the value of $T_c$ is larger, the dynamic reliability will be lower.

4.2. Calculation results of dynamic reliability

According to the reliability theory of structural wind-induced vibration, the wind-induced vibration strength and displacement reliability of tower crane under different wind speeds are calculated respectively. When calculating strength, the maximum tensile stress is 638 bar stress time history, and the tensile strength of material is $f=486$ MPa. Considering that the stability of tower crane is poor when the displacement is large, the maximum horizontal displacement of the roots of the lifting arm under normal working condition is not more than 26 mm according to the requirements of safety technical specifications of tower crane. Therefore, the allowable displacement value $d=26$ mm. Taking gust duration of 2 s, 10 s and 1 min respectively, the reliability probability of the tower crane under the action of a gust is calculated as shown in Tables 2 and 3.

| $\bar{\tau}$ (m/s) | 10  | 20  | 30  |
|---------------------|-----|-----|-----|
| $\mu_s$ (MPa)       | 36.48 | 47.37 | 76.62 |
| $\sigma_s$ (MPa)    | 8.75  | 11.23 | 20.43 |
| $P_s(f, T_c=2s)$    | 1.0000 | 1.0000 | 0.9986 |
| $P_s(f, T_c=10s)$   | 1.0000 | 0.9999 | 0.9899 |
| $P_s(f, T_c=1min)$  | 0.9997 | 0.9985 | 0.9707 |
Table 3. Displacement reliability.

| $\nu$(m/s) | 10  | 20  | 30  |
|------------|-----|-----|-----|
| $\mu$(mm) | 5.88| 9.15| 15.56|
| $\sigma$(mm)| 1.26| 2.27| 4.45|
| $P_s(d,T_c=2s)$ | 1.0000 | 0.9997 | 0.9875|
| $P_s(d,T_c=10s)$ | 1.0000 | 0.9835 | 0.8879|
| $P_s(d,T_c=1min)$ | 1.0000 | 0.9678 | 0.8212|

From the calculation results, it can be seen that the strength reliability of this type of tower crane is better. If calculated according to $T_c=10s$, under the action of 20m/s wind speed, the probability of strength reliability is 0.9999. Even if the wind speed reaches 30m/s, the probability of strength reliability can reach 0.9899, which indicates that the structure strength reserve of this type of tower crane is more adequate. When the wind speed is not more than 20m/s, the displacement reliability of the structure is 0.9835, but when the wind speed is 30m/s, the displacement reliability decreases obviously, which indicates that the stiffness reserve of the tower crane is slightly insufficient.

5. Conclusion

To study the wind-induced fatigue of a tower crane under wind load, the Davenport wind speed spectrum, which did not vary with height, was used to simulate the time history of wind speed load acting on the tower crane, and it was applied to the finite element model of tower crane, obtaining the stress and displacement time histories of key members of the tower crane through analysis. Based on Poisson process method, the reliability of tower crane under wind load is calculated. The main conclusions are as follows:

1) The maximum along-wind displacement is undergone by node 325 at the end of the boom, while the cross-wind displacement is relatively small. The tower body pillar mainly bears compressive stress. On the boom, member bars 638 and 659 bear the largest tensile stress. The tensile stress fluctuates in a large range in the initial stage of wind load, and the fluctuation range decreases gradually with the increase in action time.

2) Under the action of 20m/s wind speed, the probability of strength reliability is over 0.99. Even if the wind speed reaches 30m/s, the structural strength reserve of this type of tower crane is relatively sufficient. The displacement reliability is 0.9835, which meets the requirements of the code. However, when the wind speed is high, the displacement reliability decreases obviously, which indicates that the stiffness reserve of this type of tower crane is slightly insufficient.

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