

Wind-resistant fuzzy comfortability assessment for a super-high tower crane based on the PDEM

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Abstract: The fuzzy comfortability of a wind-sensitive super-high tower crane is critical to guarantee occupant health and improve construction efficiency. Therefore, the wind-resistant fuzzy comfortability of a super-high tower crane in the Ma'anshan Yangtze River (MYR) Bridge site is analyzed in this paper. First, the membership function model that represents fuzzy comfortability is introduced in the probability density evolution method (PDEM). Second, based on Fechner's law, the membership function curves are constructed according to three acceleration thresholds in ISO 2631. Then, the fuzzy comfortability for the super-high tower crane under stochastic wind loads is assessed on the basis of different cut-set levels λ . Results show that the comfortability is over 0.9 under the required maximum operating wind velocity. The low sensitivity to λ can be observed in the reliability curves of ISO II and III membership functions. The reliability of the ISO I membership function is not sensitive to λ when $\lambda < 0.7$, whereas it becomes sensitive to λ when $\lambda > 0.7$.

Key words: comfort reliability; probability density evolution method; fuzzy theory; membership function; tower crane; long-span bridge

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With the flourishing of China's transportation industry, a series of long-span bridges are under the design and construction stages. The Ma'anshan Yangtze River (MYR) Bridge^[1] has been in construction since 2021, and the W12000-450 outer-attached tower crane, which has a height of over 300 m, is utilized in the construction of the MYR Bridge. For this super-high tower crane, the high-level wind-induced vibration is easily induced due to its high structure flexibility^[1-2]. This can cause the perception of discomfort, reduce working ability, and even threaten the health of drivers^[3-4]. Thus,

the super-high tower crane needs a more stringent requirement for comfort reliability assessment.

Recently, common reliability analysis methods have been used, including the Monte Carlo method^[5], the first-order second-moment method^[6], and the response surface method^[7-8]. However, the expense of these good applications is more than thousands of time calculations, which is unaffordable for complex structures. To this end, a class of probability density evolution methods (PDEM) has been developed for random structural responses^[9-10]. It is convenient to implement the quantitative assessment of structural reliability under random excitations within only hundreds of sample realizations. The PDEM follows the first-passage failure criterion^[11-12], which is manifested as the failure of the structure when its dynamic response first crosses the critical value or safety limit. However, this criterion might not be applicable in assessing the comfort reliability of structures. Different sensitivity levels to accelerations of occupants cause different perceptions of comfortability. This indicates that the failure in comfortability might not occur if the vibration acceleration is beyond a defined threshold, which is called the fuzzy characteristic of comfortability^[13]. The PDEM based on the first-passage failure criterion might lead to the misestimation of comfort reliability. Therefore, the solution to connect the PDEM with the fuzzy theory is fundamental in occupant comfort assessment for super-high tower cranes.

To address the aforementioned issues, a method for assessing the fuzzy comfort reliability of a super-high tower crane is proposed on the basis of the PDEM. Then, the fuzzy comfort assessment is implemented for the super-high tower crane in the MYR Bridge under the required maximum operating wind velocity.

1 PDEM via Fuzzy Probability for the Comfortability of a Super-high Tower Crane

Without loss of generality, the motion equation for an n -degree-of-freedom structural system under random wind excitations is written as follows:

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = F(\Theta, t) \quad (1)$$

where M , C , and K denote the mass, damping, and stiffness matrices, respectively; \ddot{X} , $\dot{X}(t)$, and X denote the

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acceleration, velocity, and displacement matrices, respectively; F denotes the random wind excitation vector; Θ denotes the elementary random variable vector, which represents the randomness inherent in wind excitations acting on structures; and t denotes the time variable.

Concerning one physical quantity Z of interest, the augmented system (Θ, Z) is probability preserved. The generalized PDEM^[10] is then derived as follows:

$$\frac{\partial p_{Z\Theta}(z, \theta, t)}{\partial t} + \dot{Z}(\theta, t) \frac{\partial p_{Z\Theta}(z, \theta, t)}{\partial z} = 0 \quad (2)$$

where $\dot{Z}(\theta, t)$ denotes the “velocity” of Z in the case of $\Theta = \theta$. The initial condition is thus given as follows:

$$p_{Z\Theta}(z, \theta, t)|_{t=0} = \delta(z - z_0) p_{\Theta}(\theta) \quad (3)$$

where $\delta(\cdot)$ denotes the Dirac delta function; z_0 denotes the deterministic initial value.

Afterward, the probability density function (PDF) of $Z(t)$ is finally derived through the finite difference method:

$$p_Z(z, t) = \int_{\Omega_{\Theta}} p_{Z\Theta}(z, \theta, t) d\theta \quad (4)$$

where Ω_{Θ} denotes the distribution space of Θ .

Combining the first-passage failure criterion and the equivalent-extreme-event principle, the dynamic reliability of structures, in terms of an interested physical response quantity Z , can be expressed as follows:

$$P(z) = \int_{\Omega} p_{Z_{\max}}(z) dz \quad (5)$$

where $p_{Z_{\max}}(z)$ denotes the PDF of the extreme value $Z_{\max} = \max_{t \in [0, T]} [Z(\Theta, t)]$, T denotes the duration of the stochastic process, and Ω denotes the distribution space of z .

For a wind-sensitive super-high tower crane, its comfortability under wind excitations was a concern during the construction of the MYB bridge. The comfortability possesses a fuzzy feature due to the different sensitivity levels to accelerations for different occupants. However, there is no consideration of this fuzzy feature in Eq. (5).

According to the fuzzy theory^[14-15], the probability of the fuzzy set \tilde{Z} can be calculated as follows:

$$P(\tilde{Z}) = \int_{\Omega} \mu_{\tilde{Z}}(z) p(z) dz \quad (6)$$

where $p(z)$ denotes the PDF of z and $\mu_{\tilde{Z}}(z)$ in the interval $[0, 1]$ denotes the membership function of \tilde{Z} . The value of $\mu_{\tilde{Z}}(z)$ represents the “grade of membership” of z in \tilde{Z} . The nearer the value of $\mu_{\tilde{Z}}(z)$ to 1, the higher the grade of membership of z in \tilde{Z} .

It can be seen that the membership function $\mu_{\tilde{Z}}(z)$ is the essence of a fuzzy set. With the consideration of fuzzy comfortability, Eq. (5) can be written as follows:

$$P(z) = \int_{\Omega} \mu_{\tilde{Z}}(z) p_{Z_{\max}}(z) dz \quad (7)$$

Therefore, the fuzzy feature of comfort reliability is considered in the PDEM. Then, the cut-set theory^[14] is applied to the calculation of Eq. (7). The fuzzy comfortability is derived as follows:

$$P(z) = \int_0^1 \int_{a_{\lambda}}^{b_{\lambda}} p_{Z_{\max}}(z) dz d\lambda \quad (8)$$

where $\lambda \in [0, 1]$ denotes a given cut-set level. Hence, the cut-set $[a_{\lambda}, b_{\lambda}]$ can be obtained as follows:

$$[a_{\lambda}, b_{\lambda}] = [z | \mu_{\tilde{Z}}(z) > \lambda] \quad (9)$$

2 Membership Function for a Super-high Tower Crane

The vibration acceleration is an index for assessing comfort reliability. Based on a series of previous studies, the relationship between the membership functions of vibration comfortability and vibration accelerations z satisfies Fechner’s law^[15]. The mathematical expression is expressed as follows:

$$\mu_{\tilde{Z}}(z) = \begin{cases} 1 & z < z_{\min} \\ B - A \ln(z) & z_{\min} \leq z \leq z_{\max} \\ 0 & z > z_{\max} \end{cases} \quad (10)$$

where $\mu_{\tilde{Z}}(z) = 0$ and 1 represent the “very uncomfortable,” and “very comfortable,” respectively; z_{\min} and z_{\max} denote the lower and upper thresholds of vibration acceleration; and A and B denote the coefficients related to the structure itself and the surrounding wind environments, respectively.

In ISO 2631-1:1985^[16], there are three main human criteria for evaluating the vibration practically, namely the reduced comfort boundary (ISO I), the fatigue-decreased proficiency boundary (ISO II), and the exposure limit (ISO III), as shown in Fig. 1. It provides a series of grade assessment indexes to calculate the structural vibration comfortability with natural frequency 1 Hz. Based on Fig. 1, the membership functions can be constructed for the three boundaries, respectively.

Getting the values of A and B in Eq. (10) is the first step, which can be calculated as follows:

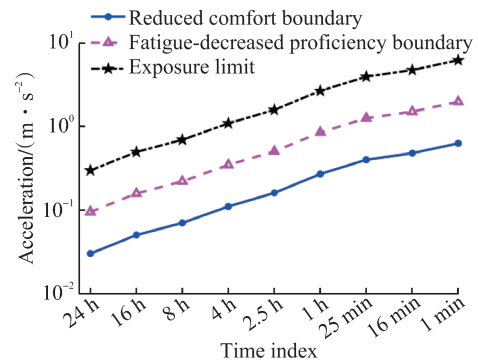


Fig. 1 Criteria for evaluating the vibration in ISO 2631-1:1985

(1) Determination of (z_{\min}, z_{\max}) . In ISO 2631-1: 1985, the root-mean-square (RMS) accelerations corresponding to 24 h and 1 min in each boundary represent “very comfortable” and “very uncomfortable” sensations, respectively. It is equivalent with the $\mu_z(z) = 0$ and $\mu_z(z) = 1$ in Eq. (10). Thus, the values of (z_{\min}, z_{\max}) are (0.03, 0.63) in the reduced comfort boundary, (0.095, 1.985) in the fatigue-decreased proficiency boundary, and (0.190, 3.970) in the exposure limit.

(2) Calculation of A and B . With the continuity criterion of boundary conditions, the two equations are obtained in the reduced comfort boundary: $B - A \ln 0.03 = 1$, $B - A \ln 0.63 = 0$. Therefore, the values of A and B can be calculated. Then, the membership function curves for each boundary are plotted in Fig. 2, and the corresponding parameters A and B are also listed in Fig. 2.

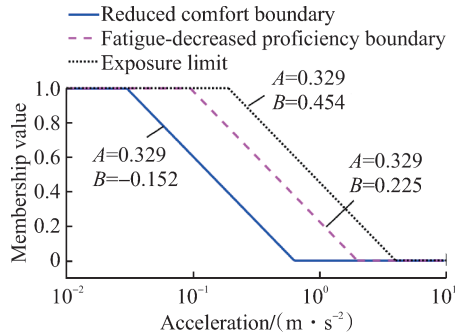


Fig. 2 Membership functions

Because the vibration of a super-high tower crane is usually a low-frequency horizontal motion, its natural frequency is lower than 1 Hz. However, the ISO 2631-1: 1985 in Fig. 1 is for structures with a natural frequency of 1 Hz. Therefore, the frequency weight function is the second necessary item. It realizes the equivalence of accelerations between $f = 1$ Hz and $f < 1$ Hz.

Based on ISO 6897: 1984^[17] for fixed structures with natural frequencies between 0.063 and 1 Hz, the structural frequency and its corresponding RMS acceleration are defined for special high-rise buildings, which denote the super-high tower crane in this study. There is a significant linear relationship between the logarithmic form of frequency and the logarithmic form of acceleration. Its mathematical expression is expressed as follows:

$$\frac{\ln z - \ln z_1}{\ln f - \ln f_1} = -0.45 \quad (11)$$

where $f_1 = 1$ Hz and z_1 denotes the RMS acceleration corresponding to f_1 . Based on Eq. (11), the frequency weight function can be written as follows:

$$z_1 = z f^{0.45} \quad (12)$$

It is noted that Eq. (12) is applicable for fixed structures with a natural frequency of 0.063 to 1 Hz, according to the requirement in ISO 6897: 1984. Therefore, the

equivalence of accelerations between $f = 1$ Hz and 0.063 Hz $< f < 1$ Hz can be realized based on Eq. (12).

3 Numerical Simulation

The W12000-450 tower crane was used in the construction of the bridge towers of the MYB Bridge, and the detailed components and finite element model information can be referred to Ref. [1]. The first three mode shapes and corresponding modal frequencies with the specified damping ratio of 1% are shown in Fig. 3. The mode shapes corresponding to f_1 , f_2 , and f_3 are the first Z-axis

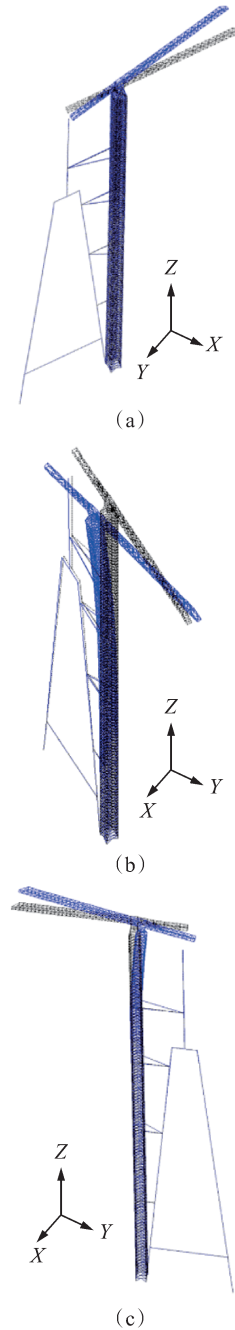


Fig. 3 Former three vibration modes and frequencies of the pylon-crane system. (a) $f_1 = 0.094$ Hz; (b) $f_2 = 0.187$ Hz; (c) $f_3 = 0.241$ Hz

torsion, the first XZ-plane translation, and the first YZ-plane translation, respectively.

3.1 Simulation of stochastic wind field

In the Chinese national standard JTG/T D60-01—2004^[18], the maximum operating wind velocity is required to be 20 m/s at the height of the crane cab, which was 371.8 m in this study. Meanwhile, the stochastic fluctuating wind field was simulated through the dimension-reduction spectral representation method (DR-SRM)^[1], and the two-sided Kaimal spectrum and Davenport coherence function were adopted in this simulation. The simulated parameters for stochastic wind fields are listed in Table 1. In addition, 233 representative samples of stochastic wind velocity were generated in this study.

Table 1 Simulation parameters and their corresponding values

Parameters	Values
Mean wind velocity at the height H , $U_H/(\text{m} \cdot \text{s}^{-1})$	20
Height of the tower crane cab H/m	371.8
Duration T/s	1 024
Number of time N_t	4 096
Frequency interval $\Delta\omega/(\text{rad} \cdot \text{s}^{-1})$	0.006 1
Number of frequencies N	2 048
Distance between two adjacent points $\Delta z/\text{m}$	11.4
Ground roughness index α	0.1
Roughness length z_0/m	0.005

The representative samples of wind velocities at the height of the tower crane cab is represented in Fig. 4. To demonstrate the validity of the simulation, the auto-power spectral densities (PSDs) of 233 simulated wind samples at the height of the tower crane cab are compared with the corresponding theoretical targets in Fig. 5. Meanwhile, the spatial coherence functions for the crane between $H = 371.8$ m and $h = 250.8$ m are compared with the corresponding theoretical targets in Fig. 6. It can be seen that both the auto-PSDs and spatial coherence functions conform well to the targets, indicating the high validity of the simulated wind field.

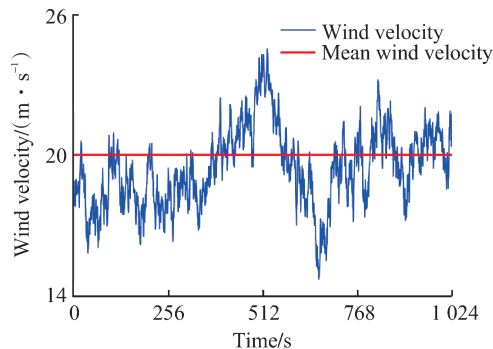


Fig. 4 Representative samples of stochastic wind velocities

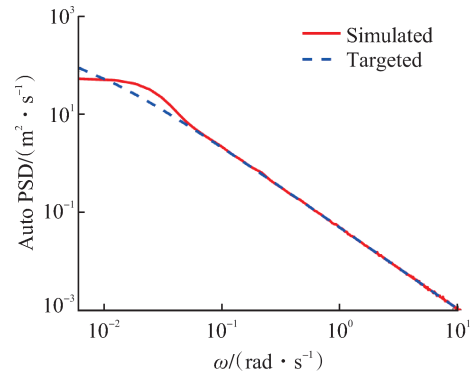


Fig. 5 Comparison of the auto-PSDs between the simulated wind field and the targeted wind field

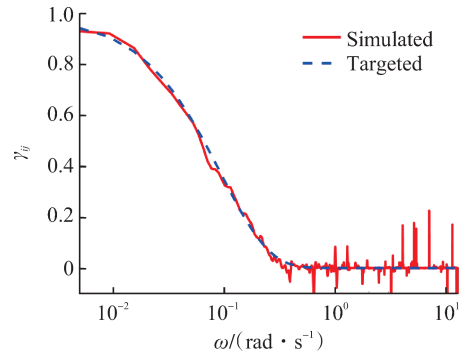


Fig. 6 Comparison of the spatial coherence function between the simulated wind field and the targeted wind field

3.2 Comfort reliability assessment for the super-high tower crane

To obtain the refined wind-induced vibrations of the structure, the established method for super-high pylon-crane systems is introduced to calculate the structural buffeting responses^[1]. Then, the representative sample of horizontal acceleration, which is composed of longitudinal responses a_x and lateral responses a_y at the height of the tower crane cab, is shown in Fig. 7.

In Fig. 7, the a_x and a_y curves have the maximum values of 0.15 and 0.21 m/s^2 , respectively. The acceleration in the lateral direction is close to that in the longitudinal, which is consistent with the observation that the response in two sway directions is approximately equal^[1]. Then, the total horizontal acceleration $a = \sqrt{a_x^2 + a_y^2}$ is calculated for the comfort assessment of the super-high tower crane.

Based on the PDEM, the PDF of 233 representative samples of total horizontal acceleration responses is shown in Fig. 8(a). The PDF represents the three-dimensional function corresponding to acceleration responses and time variables. Combining the equivalent-extreme-event principle, the PDF and cumulative density function (CDF) curves of extreme accelerations a_p are plotted in Fig. 8(b).

It is noted that the comfort index is the RMS acceleration considering its frequency weight, which is denoted

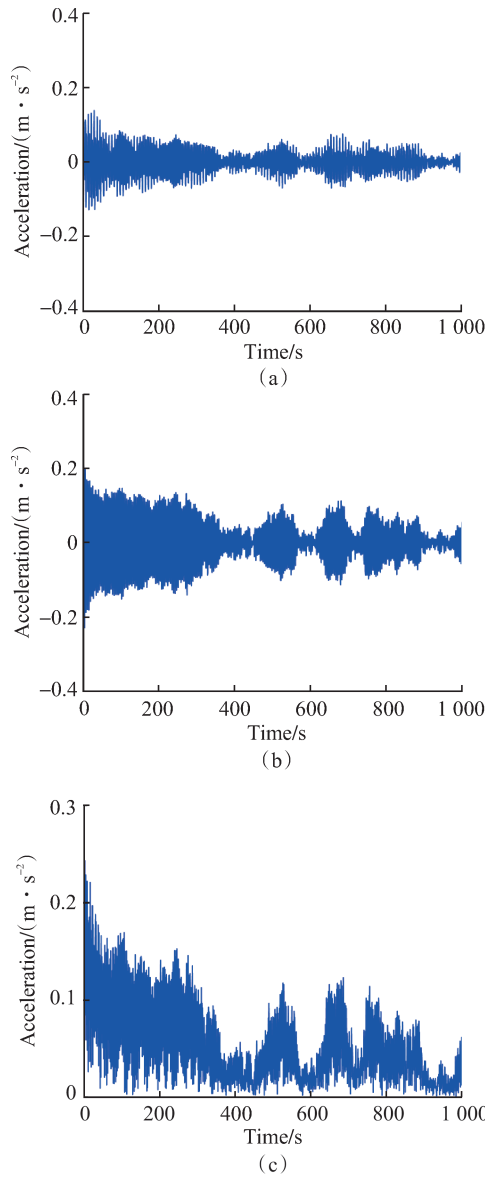


Fig. 7 Horizontal acceleration time history responses at the height of the tower crane cab. (a) Longitudinal component; (b) Lateral component; (c) Total horizontal direction

by RMS a_w . Accordingly, Fig. 9 shows the CDF curves of RMS a_w and the fitted generalized extreme value (GEV) distribution curves. Observing Fig. 9, the GEV distribution can describe the CDF of RMS a_w quite well. The Kolmogorov-Smirnov test is then employed, and the distributed form is found appropriate at a 5% significance level.

Therefore, the probability distribution of RMS a_w can be depicted by the GEV distribution. The PDF curve is shown in Fig. 9, which is expressed as follows:

$$f(x) = \frac{1}{\sigma} \exp\left(-\frac{x-\mu}{\sigma}\right) \exp\left[-\exp\left(-\frac{x-\mu}{\sigma}\right)\right] \quad (13)$$

where $f(x)$ denotes the PDF; x denotes the random variable; $\mu = 0.03$ and $\sigma = 0.005$ denote the location and scale parameters, respectively.

Combining Eqs. (10) and (13), the fuzzy comfort of the

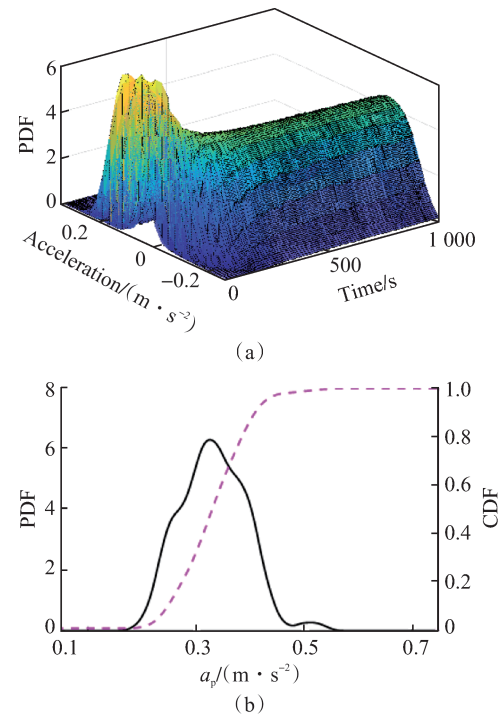


Fig. 8 Probability information of the total acceleration responses. (a) Acceleration response time histories; (b) Extreme accelerations a_p

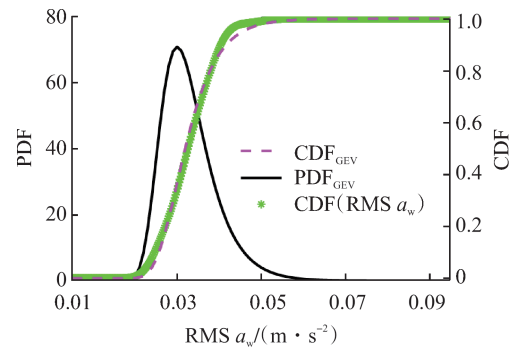


Fig. 9 Probability information of the RMS a_w

super-high tower crane can be evaluated based on Eq. (8). In addition, it can be observed that the given cut-set level λ in Eq. (8) does have an influence on the cut-set $[a_\lambda, b_\lambda]$, which is correlated with the fuzzy comfort. Therefore, Fig. 10 gives the comfort reliability of the super-high tower crane considering a different cut-set level λ .

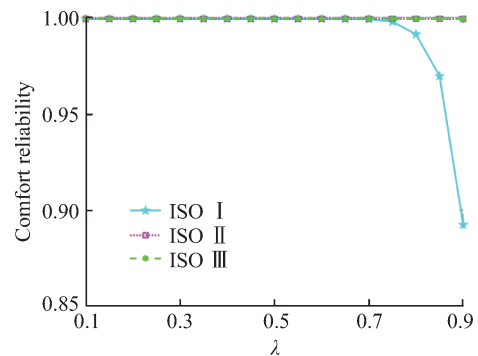


Fig. 10 Comfort reliability of the tower crane

In Fig. 10, all values of comfort reliability of the tower crane are higher than 0.9, given the maximum operating wind velocity of 20 m/s. Therefore, the comfort reliability of the tower crane satisfied the requirement during the construction of MYR Bridge. In addition, the sensitivity to cut-set levels λ is quite different in different membership functions. The low sensitivity to λ exists in ISO II and III. The reliability of the ISO I membership function is not sensitive to λ when $\lambda < 0.7$, whereas it becomes sensitive to λ when $\lambda > 0.7$.

4 Conclusions

In this paper, the wind-resistant fuzzy comfortability of a super-high tower crane in the MYR Bridge site has been analyzed on the basis of the PDEM. First, the membership function model was introduced into the PDEM for assessing the structural comfortability, which realized the refined calculation of the fuzzy comfortability. Meanwhile, it maintained the high efficiency of the PDEM, which can evaluate structural reliability with just hundreds of samples.

Second, the graded membership functions for the super-high tower crane were constructed by defining acceleration as the independent variable. This is based on the different-level occupant comfort standards, which should be applied in interested structure projects under construction according to these requirements.

Finally, the comfort reliability values of the super-high tower crane in the MYR Bridge are over 0.9 based on ISO I, II, and III membership functions. Compared with the other two, the reliability curve of the ISO I membership function is more sensitive to cut-set level λ , which might be due to the high sensitivity of this membership function to low acceleration in the case of structural nonsignificant vibration level in this paper.

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基于概率密度演化理论的超高塔吊风振模糊舒适度分析

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摘要: 为保障施工人员健康和提高施工效率, 需要对超高塔吊的施工舒适性能进行精细评估。因此, 本文以马鞍山公铁长江大桥为工程背景, 通过将隶属度函数引入概率密度演化理论中, 建立了超高塔吊风振模糊舒适度评估方法。基于Fechner定律, 给出了ISO 2631中3类不同加速度限值下的隶属度函数曲线。在此基础上, 通过 λ -截集技术实现了超高塔吊的风振模糊舒适度评估。结果表明, 在规范允许最大施工风速下, 超高塔吊的模糊舒适度大于0.9, 满足施工舒适度要求。基于ISO II和ISO III隶属度函数的舒适度对 λ 的敏感性较弱。基于ISO I隶属度函数的舒适度在 $\lambda < 0.7$ 时对 λ 的敏感性较低, 而在 $\lambda > 0.7$ 时对 λ 的敏感性显著增加。

关键词: 舒适可靠度; 概率密度演化理论; 模糊理论; 隶属度函数; 塔吊; 大跨度桥梁

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