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Life Cycle Vibration Sensation Rate Evaluation Model for the Optimal Human Comfort Design of Super Tall Buildings

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1. Abstract

The wind-induced vibrations of super tall buildings become excessive due to strong wind loads, super building height and high flexibility. In view of individual uncertainty and diversity of wind-induced vibration response, a life cycle vibration sensation rate model based on AIJES-V001-2004 was proposed to evaluate human comfort performance of super tall buildings under wind load. The maximum acceleration was adopted as the quantitative index of the performance. Pseudo excitation method was employed in the frequency domain analysis for the calculation of the vibration sensation rate of the super tall building under random wind load. The randomness of the wind speed being taken into consideration, the vibration sensation rate of human comfort was obtained for the whole life cycle. A cost model for the wind-induced human comfort of super tall buildings was derived based on the vibration sensation rate model. This model evaluated the life cycle cost of different design schemes, which could help make design choice based on the minimum life cycle cost criterion. The proposed method was applied to the human comfort design choice of a super tall building with and without tuned mass damper (TMD), tuned liquid column damper (TLCD) or combined tuned damper (CTD) device to illustrate its effectiveness and applicability.

2. Keywords: super tall building; AIJES-V001-2004; life cycle cost; human comfort performance; optimal design

3. Introduction

The design method widely adopted nowadays is strictly subjected to the design code criteria. However, it is hard for the house owner to master the specific performance of tall buildings under different wind pressures. For example, the engineer is aiming to meet safety usage, but the owner hopes to raise the human comfort significantly. Besides, as structural performance has no economic assessment, the owner cannot understand benefits from the initial investment to determine whether a damper and what kind of the damper to be installed to control the vibration of tall buildings. Most importantly, it is not only the subjective feeling of vibration but also the acceptable failure risk level of occupants that determines the goal of structural performance. [1] In all above, it is a key problem that both the owner and the engineer are needed to pursue for a balance or a reasonable design standard between economic benefits and comfort performance.

The performance based design methodology is a significantly useful approach to solve the above problem, which aims at guaranteeing the safety and comfort performance, implement specific different performance levels and lead to the minimum life cycle cost when suffering possible random wind [2]. Guoxiong Bo et al [3]carried out the beneficial exploration and perfection of the wind-resistant performance based design, in which the concept of benefit-cost ratio is taken to assess the economical efficiency. However, the authors did not consider the failure effect of the human comfort performance, which made the performance assessment for buildings with a TMD impossible. The author originally proposed a life cycle cost model to evaluate human comfort performance of tall buildings and to decide the human comfort design choice whether to install a TMD or not [4]. It is a pity that the failure effect of the TMD itself on the structural human comfort performance was not considered in that model.

In order to better serve real objects, a further study is investigated in this paper, in which the internationally adopted Japanese AIJES-V001-2004[5] is adopted. A vibration-sensation model is proposed to estimate the human comfort performance and a life cycle cost with the consideration of damper failure is explored. The proposed method is applied to the human comfort design choice of a super tall building with and without tuned mass damper (TMD), tuned liquid column damper (TLCD) or combined tuned damper (CTD) device [6] to illustrate its effectiveness and applicability.

4. Human Comfort Performance Based Life Cycle Cost Model

The existing vibration-induced human comfort performance criteria are closely relative to the acceleration limitation of the vibration environment. That is to say, according to the limitation given by the selected criterion, it is easy to judge whether a building performance meets the performance requirement or not with structural acceleration known. However, for convenience of mastering and utilizing these human comfort criteria, it is necessary to further understand these criteria [7]: (1)the allowed vibration limitation given by vibration comfort standards is artificially divided by ensuring a certain significant level, the allowed vibration limitation itself also has kind of uncertainty; (2)nowadays there has been no effective method to evaluate the whole-system performance just according to vibration comfort performance of each part; (3)there is no criterion with the economic failure evaluation if the performance is beyond standard limitation and this no doubt has to be considered by engineers and designers. Therefore, it is essentially important to improve the existing standard.

4.1 Vibration-Sensation Rate Model

4.1.1Wind-induced human comfort performance criterion

Nowadays Japanese wind-induced human comfort performance criterion of building structures (AIJES-V001-2004) [5] is generally recognized. The 10-minute peak acceleration of the structure under 1-year wind loads is taken as the evaluation index. Japanese criterion determines five levels (H-10~H-90) of comfort performance depending on the proportion of people who have the vibration sensation, in which H-10 represents 10% of people feeling vibration without discomfort, H-30 with a similar meaning and rest on. Most importantly, the each-level performance of Japanese comfort standard is associated with the vibration frequency.

$$\alpha_{\max} = af_1^b \tag{1}$$

Where $\alpha_{\max}$ = the maximum acceleration response (cm/s^2), f_1 = the vibration frequency, a and b are related coefficients which shows in figure 1.

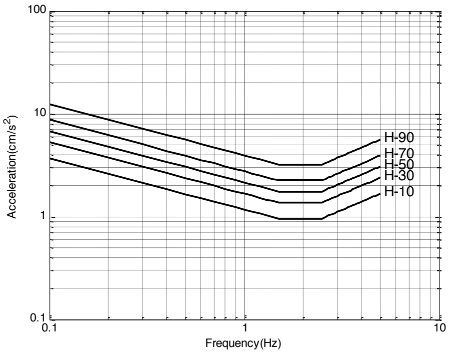


Figure 1: The building horizontal vibration performance evaluation curves under wind load

4.1.2 Vibration-sensation rate model under once random vibration

For the view of psychophysics, the uncertainty people reacting to vibration subjectively can be divided into two categories: (1) ambiguity due to the subjective reacting criteria not clear in the concept; (2) random caused by people's sensation differences in vibration stimulation. The ambiguity of uncertainty can be described by psychophysical Fechner law.

$$v(u) = c\ln(u) + d \tag{2}$$

Where u= the vibration acceleration, v= degree of membership of subjective response, c and d are undetermined coefficients which can be determined by the above Japanese criterion.

Besides, Griffin et al. [8] hold the view that the distribution of people's vibration feeling is subject to the normal or lognormal distribution and it has been proved in later studies that the variability of human ability to feel vibration can be approximately taken as the lognormal distribution:

$$f(x \mid u) = \frac{1}{\sqrt{2\pi}u\sigma}\exp\left(\frac{-\left(\ln(u) - \mu_{\ln(x)}\right)^2}{2\sigma^2}\right) \tag{3}$$

Where $\sigma^2 = \ln(1+\delta^2)$, $\mu_{\ln(x)} = \ln(x) - \sigma^2/2$, in which x and δ are respectively the expectation value of the variable μ and the coefficient of variation. Equation (9) means that for once random vibration with the acceleration x, people have different feelings due to differences of human sensibility. And people actually feel vibration stimulation with equivalent acceleration u, although these feelings are different from each other, they generally remain stable at an average equivalent stimulation x.

According to Japanese wind-induced human comfort performance criterion, taking the ambiguity and random of human sensation into account, a vibration-sensation rate model is proposed as follows:

$$A(x)=\int_{u_{\min}}^{\infty}\frac{1}{\sqrt{2\pi}u\sigma}\exp\left(\frac{-(\ln(u/x)+0.5\sigma^2)^2}{2\sigma^2}\right)v(u)\,du \tag{4}$$

The physical meaning of the equation (4) is the rate of people that have feelings without discomfort under once random vibration.

4.1.3 Vibration-sensation rate model under one-year strong wind

Cao Hong et al. [9] believe that it is reasonable to utilize normal distribution to describe the distribution of wind-induced structural peak acceleration response.

$$f_{x_m}(x)=\sqrt{\frac{2}{\pi\sigma_x^2}}\exp\left(-\frac{x^2}{2\sigma_x^2}\right) \tag{5}$$

Therefore, the probability distribution function of peak acceleration response will be:

$$F_{x_m}(x)=\frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{\sqrt{2}\sigma_x}}e^{-t^2}\,dt \tag{6}$$

Assuming that there are N structural peak acceleration responses during the period $(0,T)$ and these peak acceleration responses x_m ($m=1, 2, 3\ldots N$) are mutual independent. So the distribution of $z_m=\max\{x_m\}$ can be showed in the following equation:

$$F_{z_m}(x)=\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{\sqrt{2}\sigma_x}}e^{-t^2}\,dt\right]^N \tag{7}$$

$$f_{z_m}(x)=N\left[F_{x_m}(x)\right]^{N-1}\sqrt{\frac{2}{\pi\sigma_x^2}}\exp\left(-\frac{x^2}{2\sigma_x^2}\right) \tag{8}$$

Where $F_{z_m}(x)$ and $F_{x_m}(x)$ are the probability distribution functions of peak acceleration response x_m and the maximum of them z_m respectively, $f_{x_m}(x)$ and $f_{z_m}(x)$ are the probability distribution density functions of x_m and z_m respectively. T represents the time of gustiness which usually is 10 minutes.

From all above, the expectation of vibration-sensation rate, that is, the vibration-sensation rate with random acceleration distribution can be illustrated as:

$$E\left[A(x)\right]=\int_0^{\infty}f_{z_m}(x)A(x)dx=\int_0^{\infty}N\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{\sqrt{2}\sigma_x}}e^{-t^2}\,dt\right]^{N-1}\sqrt{\frac{2}{\pi\sigma_x^2}}\exp\left(-\frac{x^2}{2\sigma_x^2}\right)A(x)dx \tag{9}$$

It is needed to note that the expectation of vibration-sensation rate showed in equation (9) is under a certain wind pressure w_0 [10].Taking one-year wind pressure distribution into consideration, the expectation of vibration-sensation in one year is:

$$\bar{A}(x)=\int_0^{+\infty}E\left[A(x)|w=w_0\right]f(w_0)dw_0 \tag{10}$$

In order to simplify the calculation, equation (10) can be replaced by equation (11).

$$\bar{A}(x)=\sum_{i=1}^{m}E\left[A(x)|w=w_i\right]\times[F(w_i)-F(w_{i-1})] \tag{11}$$

Where $F(w_i)$ is the probability distribution function of the maximum average wind pressure during 10 minutes, m

is the number of wind pressure grades [22].

4.2 Failure Cost Model of Human Comfort Performance

It is well known that for different building usages, even the same vibration level can result in different failure costs. For example, hospitals, superior hotels and superior offices which need higher level human comfort performance suffer more than tour towers with low comfort performance requirement. Therefore, referring to estimating failure costs of human comfort performance, the building usage, the number of occupants, vibration-sensation rate and local economic level are needed to consider. For different building usages, the recommended failure cost model is shown as follow:

$$c(x) = n(\alpha C)\left[\chi \bar{A}(x)\right] \tag{12}$$

For the whole building, the failure cost can be shown in equation (13):

$$c_1 = \int_{x_{\min}}^{x_{\max}} c(x)dx \tag{13}$$

Where $n =$ the number of people in the vibration environment; αC represents the economic evaluation index, $C =$ the local average annual income, $\alpha =$ the coefficient which can be calculated by regression analysis; $\chi \bar{A}(x)$ represents the vibration-sensation rate of different structural usage, $\chi =$ the effect coefficient of building usage (e.g. 1.0 for superior hotels and superior offices and 0.8 for tour towers).

4.3 Life Cycle Cost Model

The discount rate of money is utilized to calculate the whole life cycle cost. For convenience, assuming that the structure is time-independent and the failure cost is the same in every year, the life cycle cost model is illustrated as follow [11-13]:

$$L_{CC} = C_0 + C_m + C_f = C_0 + C_m + \theta \sum_{i=1}^{T_{life}} c_1 \frac{1}{(1+r)^i} \tag{14}$$

Where $C_0 =$ the initial investment cost, $C_m =$ the maintenance cost, $C_f =$ the failure cost, $T_{life} =$ structural service life period (like 100 years for the super tall building), $r =$ money discount rate, $\theta =$ the adjustment coefficient representing policy maker's attitude to risk (e.g. $\theta > 1$ for optimistic, $\theta < 1$ for pessimistic and $\theta = 1$ for intermediate, especially for research and consulting institutions [14]).

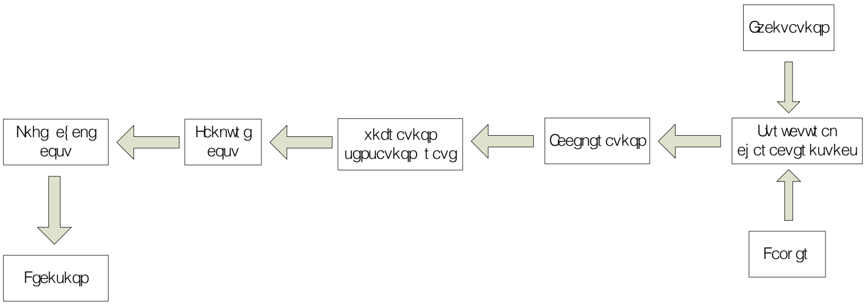


Figure 2: Process Diagram of Life Cycle Cost Calculation

4.4 Life Cycle Cost Model for the damper-structure system

4.4.1 Wind-induced Vibration Control Theory

In order to raise human comfort performance, dampers are usually installed in the structure to suppress the amplitude of vibration. The effectiveness of a damper can be illustrated by vibration control coefficient and finally result in the decrease of life cycle cost. The vibration control coefficient η is defined as follow:

$$\eta = \frac{\sigma_x - \sigma_x^{damper}}{\sigma_x} = 1 - \frac{\xi_{sa}}{\xi_e} = \frac{\bar{A}_x - \bar{A}_x^{damper}}{\bar{A}_x} \tag{15}$$

Where σ_x and σ_x^{damper} are acceleration responses of the primary system and the damper-structure system respectively, ξ_{sa} =the sum of structural damping ratio and aerodynamic damping ratio, ξ_e =the equivalent damping ratio of the damper-structure system [15].

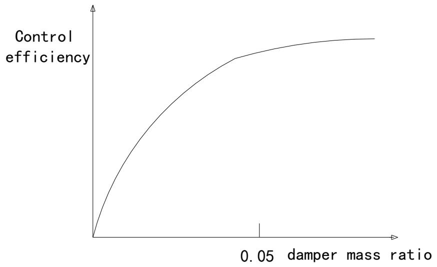


Figure 3: Vibration control coefficient and mass ratio [3].

4.4.2 Dynamic reliability of wind-resistant damper

The damper (e.g. a TMD) installed in the building to suppress the vibration response usually has large amplitude of vibration response itself, which may lead to itself or other surrounding structural damage. Therefore, it is necessary to install a snubbing system in the building to snub the damper to guarantee the damper's safety. Most importantly, even if it does not cause damage, the damper tends to be locked-in when the structure suffers a quite strong wind in some real objects, which no doubt causes the failure of damper. For a large given limitation b , the expectation of passage times that the relative displacement of the damper with respect to the main structure exceeds the limitation meets the Poisson distribution shown in the following equation:

$$v_b = \frac{\sigma_y}{2\pi\sigma_y}\exp\left(-\frac{b^2}{2\sigma_y^2}\right) \tag{16}$$

Based on first-passage failure criterion, the dynamic reliability of the damper which means the transcendence degree is equal to zero ($N=0$) is given as follow:

$$P_{s1}\left(b > y(t)\right) = \exp\left[-\frac{\sigma_y T}{2\pi\sigma_y}\exp\left(-\frac{b^2}{2\sigma_y^2}\right)\right] \tag{17}$$

For the dynamic reliability with both-side limitation:

$$P_{s2}\left(-b < y(t) < b\right) = \exp\left[-\frac{\sigma_y T}{\pi\sigma_y}\exp\left(-\frac{b^2}{2\sigma_y^2}\right)\right] \tag{18}$$

However, with a relatively small limitation b , the Poisson distribution is unreasonable. The Vanmarcke approach, which is based on the Markov model, is proposed as follow [9].

$$P_{s2}\left(-b < y(t) < b\right) = \exp\left[-\frac{\sigma_x T}{2\pi\sigma_x}\exp\left(-\frac{r^2}{2}\right)\frac{1-\exp\left(-\sqrt{\frac{\pi}{2}}qr\right)}{1-\exp\left(-\frac{r^2}{2}\right)}\right] \tag{19}$$

Taking the wind-field-environment random of the structural site into consideration, the failure probability of the damper under one-year wind is P_f which is shown in equation (26) and equation (21).

$$P_{f2} = 1 - P_{s2} \tag{20}$$

$$P_f = \int_0^{+\infty} P_{f2}\left(-b < y(t) < b \mid \omega = \omega_k\right) f(\omega)\, d\omega \tag{21}$$

Where $f(\omega)$ is the probability distribution density function of maximum wind pressure during 10 minutes of once strong wind.

4.4.3Life Cycle Cost Model of the structure-damper system

For different building usages, the human comfort performance based failure cost of the structure-damper system can be calculated by the following equation:

$$c(x) = \alpha n \chi C \left[P_f \cdot \overline{A}(x) + \left(1 - P_f\right) \cdot \overline{A}(x)^{damper} \right] \tag{22}$$

And the life cycle cost model of the structure-damper system is the same as before:

$$c_1 = \int_{x_{\min}}^{x_{\max}} c(x) dx \tag{23}$$

$$L_{CC} = C_0 + C_m + C_f = C_0 + C_m + \theta \sum_{i=1}^{T_{life}} c_1 \frac{1}{\left(1+r\right)^i} \tag{24}$$

The parameters in the above equation are the same as before. It is needed to note that Guoxiong Bu et al. had studied the initial investment cost C_0 and the maintenance cost C_m of TMD [3]. Therefore, these data of other dampers (e.g. a TLCD or a CTD) can be studied in a similar manner to the analysis of a TMD.

4.5 Life Cycle Cost Model Based Optimal Design

4.5.1 Optimal Design Theory

As the damper is installed in the building, the initial investment and maintenance costs increase when the damper mass increases, however, the failure cost even decreases to a constant value (see figure 4). Therefore, there is a minimum value of life cycle cost which needs to be analyzed and calculated in detail.

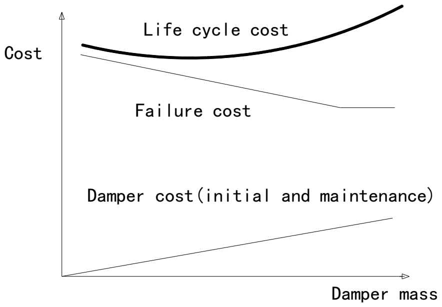


Figure 4: Diagram of optimal design theory

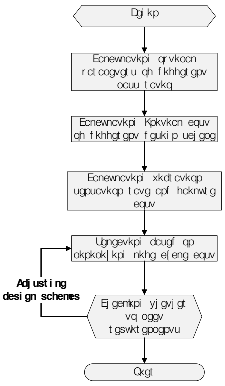


Figure 5: selection method of the damper

4.5.2 Process of Optimal Design

The optimal design process of wind-induced human comfort performance, which is based on minimizing life cycle cost, is shown as follows: (1) calculating the optimal parameters of different mass ratios to maximize the effectiveness of the dampers; (2) calculating the initial investment and maintenance costs according to different damper parameters; (3) calculating the acceleration response, the vibration-sensation rate and the performance-failure cost according to different damper parameters; (4)calculating the life cycle cost of the whole building and finding out the minimum value; (5) checking whether human comfort performance meets the criterion and the owner's requirement or not. If not, go back to step 4.

The main steps of damper selection are shown in figure 5.

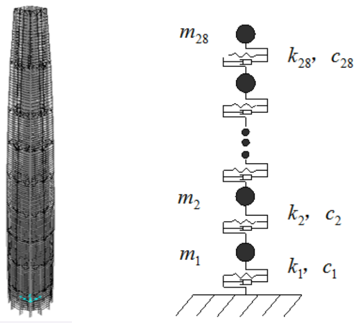
5. Response Analysis

As the wind loads are usually describing as random processes, the analysis of random vibration response is the basis to calculate the vibration-sensation rate. For the random process characteristic of the wind load, the structural response under the wind load can be described with the response power density spectrum which can be calculated by load spectrum and frequency-response function . Also, the pseudo excitation method can be employed to help analyze the random process that has the dense vibration modes or the nonlinear damping [17]. The along-wind response is caused by the fluctuating wind and the fluctuating wind can be described by a Gaussian stationary random process with zero mean. Moreover, the spectrum of longitudinal turbulence proposed by Davenport (1961) is adopted in this study. It is easy to calculate the acceleration response of the along-wind load. As is generally known, the cross-wind load is stronger and may be the chief control load for the wind-sensitive structure with the increasing building height. However, it is so complicated that the cross-wind load spectrum cannot be calculated similarly to that of the along-wind which is according to the quasi-steady theory and the strip assumption. Nowadays high frequency force balance test is widely used to simulate the cross-wind load spectrum based on an assumption that the first mode of vibration is linear [18]. Yong Quan and Ming Gu [19] had studied super tall buildings with four different kinds of wind environments and fifteen types of structural shapes and proposed a closed equation of the cross-wind load spectrum which can be used to calculate the standard deviation of the cross-wind acceleration response.

When the structural shape is unsymmetrical and changeable, there exists torsional vibration under the wind load. The structural torsional vibration is due to asymmetries of windward, leeward and lateral wind pressures associated with turbulence and wake excitation. That is to say, owing to the deviation between the structural mass centre and stiffness centre, the bending vibration mode and the torsional vibration mode couple with each other, in which case, the structural response is quite different from that of the single direction. Therefore, the torsional response needs to be considered for these asymmetry-shape buildings [20].

6. Case Study

A 729m high 69m wide 141-storey super building whose building function contains commercial shop, office, hotel and tourism is studied in this study. The 3-D model and lumped mass multi-degree-freedom model are showed in figure 6. The damping ratio is 2%, the local wind environment is C and the 50-year wind pressure is 0.45 kPa. The human comfort performance and the optimal design scheme are studied.

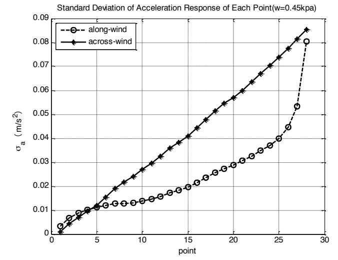


（6a）3-D model （6b）lumped mass model

Figure 6: A super tall building model

6.1 Response and Vibration Sense Rate of Structure

The possibility wind pressure in one year can be separated in 6 grades of 0.1, 0.3, 0.45, 0.5, 0.57, 0.67 Kpa, which is in consistent with the velocity grades of 10.62, 22.03, 26.54, 28.44, 30.34, 32.85 ms^{-1} respectively. The fluctuating wind load spectrum can be calculated by the above spectrum function mentioned in section 4 and the structural response can be with the pseudo excitation method. Taking 26.54ms^{-1} （0.45Kpa） for example, the structural response of standard deviation acceleration is shown in figure 7. It is concluded that the response under the cross-wind is larger than that under the along-wind. It is needed to point out that the cross-wind response is approximately linear because the structural generalized first-order power spectrum is based on the assumption that structural first mode of vibration is approximately linear according to the high frequency force balance test. However, all modes are involved and the structural first mode of vibration is a bending-shearing type. The vibration-sensation rates of the primary structure are calculated by taking all grades of one-year wind pressure into consideration showing in figure 8.



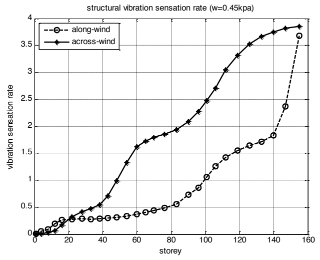
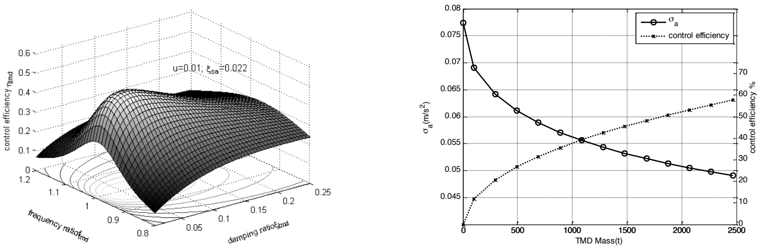


Figure 7: Root mean square of acceleration Figure 8: Vibration sense rate without damper

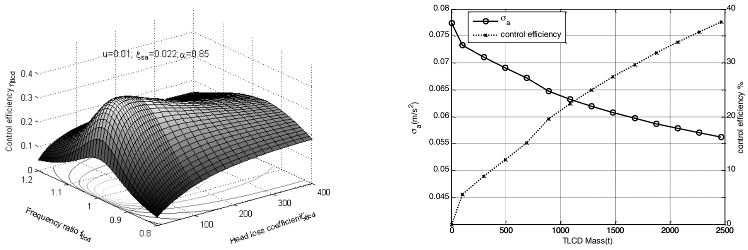
6.2 Optimal Parameters of Dampers

The optimal parameters of dampers can be calculated by maximizing the vibration control efficiency. Because the cross-wind response is dominant, the structural responses under the cross-wind are calculated. The relationships between parameters and vibration control efficiency of the TMD and the TLCD are shown in figure 9 and figure 10 respectively.



(9a) damping ratio and frequency ratio (9b) mass ratio

Figure 9: Relationship amongst parameters and vibration control efficiency of TMD

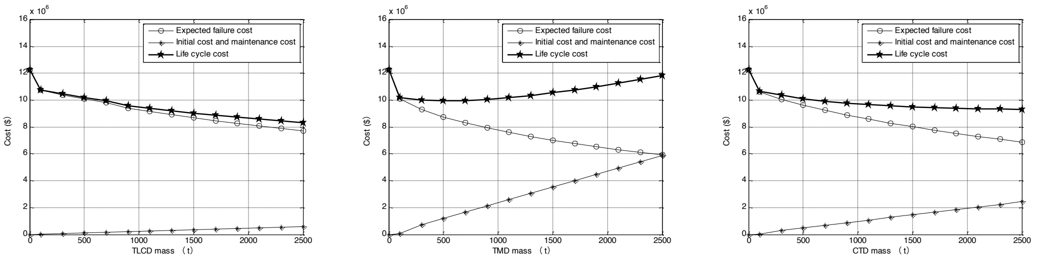


(10a) head loss coefficient and frequency ratio (10b) mass ratio

Figure 10: Relationship amongst parameters and vibration control efficiency of TLCD

6.3 Life Cycle Cost Evaluation and Design Choice

With the vibration-sensation rate of the structural human comfort performance known, it is available to evaluate the design schemes to minimize the life cycle cost. Assuming that the life cycle and the discount rate of money are 100 years and 3.5% respectively, the structural life cycle costs of different design schemes are shown in figure 11 and table 1.



(11a)Costs and TLCD mass (11b) Costs and TMD mass (11c) Costs and CTD mass

Figure11: Relationship of life cycle cost and damper mass

Table 1 Expected life cycle cost

Structural scheme		Damper mass t	C_0 10^6\$	C_m 10^6\$	C_f 10^6\$	L_{CC} 10^6\$
Primary structure		0	0	0	12.26	12.26
TMD-structure system		500	1.12	0.056	8.76	9.94
TLCD-structure system		1000	0.22	0.011	9.27	9.50
TLCD-structure system	TLCD	650	0.15	0.008	8.74	9.73
	TMD	350	0.79	0.039		

It is highly efficient to improve the human comfort performance by installing a damper. Also, the total life cycle cost decreases. From the data in the table 1, it is easily concluded that in terms of life cycle cost, the design scheme with a TLCD-structure system is the best. After that, the design scheme with a CTD-structure system ranks second.

Then, the design scheme with a TMD-structure system follows and the primary structure system without any damper. It is worth being noted although the life cycle cost drops continuously with the mass rising, the damper mass of the TLCD or the CTD is decided twice as high as that of the TMD for the consideration that the volume of the TLCD filled with water is usually several times as large as that of the TMD.

6.4 Human comfort performance check

The selected design scheme based on the minimum life cycle cost should also meet the limitation requirements of Chinese code criterion and the owner's thoughts. For this study case, the structural peak-acceleration response can be obtained by calculating the structural root mean square under 10-year wind pressure and selecting the peak factor of 2.5 (99.3% for insurance) with assumption that the structural response meets Gaussian distribution with a zero-mean value.

Table 2 Check for human comfort performance

Structural scheme	10-year wind pressure	
	Root mean square（m/s2）	Peak value（m/s2）
Primary structure	0.0773	0.193
500t TMD-structure system	0.0584	0.146
1000t TLCD-structure system	0.0604	0.151
1000t CTD-structure system	0.0572	0.143

It is easily concluded that the human comfort performance of all different design schemes can meet limitation requirements of Chinese code for hotels and offices but exceed slightly that for apartments. Measurements such as selecting larger damper mass can be taken to obtain more optimal design schemes when the owner has higher requirements.

7. Conclusion

Due to strong wind loads, super building height and high flexibility, the wind-induced vibrations of super tall buildings become excessive. Aiming to assess the human comfort performance of super tall building conveniently and effectively, a brand-new life cycle cost model based on AIJES-V001-2004 is studied in this paper. The proposed method is also applied to the human comfort design choice of a super tall building with and without tuned mass damper (TMD), tuned liquid column damper (TLCD) or combined tuned damper (CTD) device to illustrate its effectiveness and applicability, which could help make design choice based on the minimum life cycle cost criterion. Some conclusions are drawn as follows:

(1) The damper has high effectiveness to improve the human comfort performance of super tall buildings. And properly increasing the initial investment can help to reduce the total life cycle cost. These have great significance to the decision of damper installation, which can be used for the structural early optimal design and provide a quite efficient method to solve the later related problems.

(2) The initial investment and vibration control performance are different among the TMD, the TLCD and the CTD, the life cycle cost of them are also different. The life cycle cost of the TLCD-structure system is much less than that of the TMD-structure system, but the volume of TLCD is several times as large as that of TMD with the same mass ratio, which is no doubt with larger space required. The life cycle cost of the CTD-structure is between that of the TMD-structure and that of the TLCD-structure. It is concluded that the CTD can fully utilize the high effectiveness of a TMD and economical advantage of a TLCD, which makes it a competitive option.

(3) Due to the lack for data of initial investment and maintenance cost of a TLCD, the relative costs of a TLCD are calculated in a similar way to TMD in this study, which, of course, needs further research in real objects.

(4) It is strongly noted that it is hard to evaluate the costs of human comfort failure accurately because of strong variability of human subjective feelings and economic factors. There is also a large amount of work to do before the proposed method to be widely used. However, the proposed method provides an innovative idea for the optimal design of wind-induced human comfort performance for super tall buildings.

8. Acknowledgement

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9. Reference

[1] Griffin M. J., *Handbook of human vibration*. Academic press, 2012.

[2] Petrini F., and Ciampoli M., Performance-Based Wind Design of Tall Buildings. *Structure and Infrastructure Engineering*, 2012, 8(10SI): 954-966.

[3] Guoxiong Bu, Ping Tan, and Fulin Zhou, Optimal design of the TMD device based on cost-effectiveness

criterion. *Journal of Civil Engineering*, 2011, 44(5): 24-31.

[4] Xin Zhao, and Tianyi Yu, Human comfort performance-based life cycle cost model of high-rise structures under wind load. *Journal of Tongji University* (natural science), 2013, 41(12): 1793-1798.

[5] Aij A I O J, *Guidelines for the Evaluation of Habitability to Building Vibration*. Tokyo, 2004.

[6] Tongji Architectural Design (Group) Co., Ltd. (China). *A combined tuned damper for wind-induced vibration control of super tall buildings.* CN, 20553346.X, 2015- 01-14.

[7] *Bases for Design of Structures - Serviceability of Buildings and Walkways Against Vibrations*. ISO10137, 2007.

[8] Griffin M. J., and Whitham E. M., Individual variability and its effect on subjective and biodynamic response to whole-body vibration. *Journal of Sound and Vibration*, 1978, 58(2): 239-250.

[9] Hong Cao, Qiusheng Li, Guiqing Li, and Da Huo, Calculation of wind-resistant structure safety. *Journal of Civil Engineering*, 1994, 27(1): 40-48.

[10] Naidong Luo, and Guofan Zhao, Analysis of dynamic reliability for resisting wind loading of high-rise building. *Journal of Dalian University of Technology*, 2002, 42(2): 208-212.

[11] Frangopol D. M., and Lin K. Y., Estes A.C., Life-cycle cost design of deteriorating structures. *Journal of Structural Engineering*, 1997, 123(10): 1390-1401.

[12] Wen Y. K., and Kang Y. J., Minimum building life-cycle cost design criteria. II: Applications. *Journal of Structural Engineering*, 2001, 127(3): 338-346.

[13] Wen Y. K., Kang Y. J., Minimum building life-cycle cost design criteria. I: Methodology. *Journal of Structural Engineering*, 2001, 127(3): 330-337.

[14] Blair A. N., Ayyub B. M., and Bender W.J., Fuzzy stochastic risk-based decision analysis with the mobile offshore base as a case study. *Marine structures*, 2001, 14(1): 69-88.

[15] Weilian Qu, Muhua Tao, and C. C. Chang, Practical Design Method for Effect Kinds of Passive Dynamic Absorbers on Fluctuation Wind-induced Vibration Response Control of Tall Buildings. *Journal of Building Structures*, 2004 (2): 29-34.

[16] Ping Tan, Guoxiong Bu, and Fulin Zhou, Study on wind-resistant dynamic reliability of TMD with limited spacing. *Journal of Vibration and Shock*, 2009, 28(6): 42-45.

[17] Y.L. Xu, W.S. Zhang, J.M. Ko, and J.H. Lin, Pseudo-excitation method for vibration analysis of wind-excited structures. *Journal of Wind Engineering and Industrial Aerodynamics*, 1999, **83**(1-3): 443-454.

[18] Yong Quan, Huilan Cao, and Ming GU, Cross-wind Effect of High-rise Buildings. *Journal of Tongji University* (natural science), 2010, 38(6): 810-818.

[19] Yong Quan, and Ming GU, Power Spectra of Across-wind Loads on Super High-rise Buildings. *Journal of Tongji University* (natural science), 2002, 30(5): 627-632.

[20] Yi Tang, Ming Gu, and Xinyang Jin, Research on Wind-induced Response of Structurally Asymmetric Tall buildings. *Journal of Tongji University* (natural science), 2010, 38(2): 178-182.