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Novel Damper of Nonlinear Energy Sink Mitigating Wind-induced Responses of Super High-rise Buildings

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SUMMARY:
Super high-rise buildings with low stiffness and damping are prone to large amplitude vibration under strong wind excitations. Large amplitude vibration leads to interaction effects of wind and buildings and hence aero-stiffness and and aero-damping varying with wind velocity have to be considered during wind-structure vibration control. In this case, conventional control devices e.g., tuned mass damper(TMD), tuned liquid damper(TLD) and so on, may not be precisely tuned to the natural frequency of the structure, and lose the robustness of vibration control effect. To this end, a novel device of nonlinear energy sink (NES), which is comprised of nonlinear spring, mass and inerter element, is proposed to control wind-induced responses of super high-rise buildings with high robustness performance. Firstly, mathematical model of NES mitigating wind-induced responses are established based on datum of wind tunnel tests. And then a super high-rise building with 300m height is employed as a case to demonstrate wind-induced vibration mitigation performance of NES. Finally, the robustness of vibration control of NES is analyzed and compared with other control devices.

Keywords: Nonlinear Energy Sink, Vibration Control, Wind-induced Responses, High-rise Buildings

1. INTRODUCTION

With development of construction material and technology, a growing number of super high-rise buildings will be constructed. Due to its low stiffness and damping, this kind of building is susceptible to large amplitude vibration under wind excitations. To assure comfort of inhabitant living on super high-rise buildings, vibration control devices are employed to decrease excessive wind-induced acceleration responses.Some conventional control devices, e.g., TMD and TLD suffer loss of robustness owing to wind-structure interaction(Elias & Matsagar, 2017; Kim, et al, 2006; Rana & Soong, 1998). To overcome this deficiency, this research will explore vibration mitigation effect of NES(Wang, et al, 2015) on wind-induced responses of high-rise buildings.

2. MATHEMATICAL MODEL OF NES MITIGATING WIND-INDUCED RESPONSES

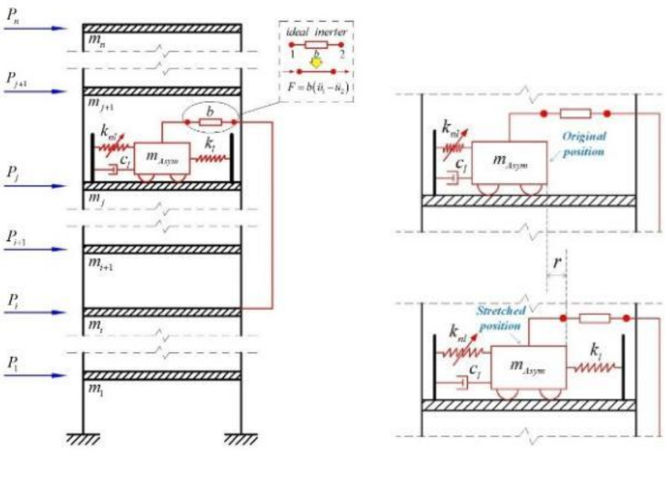
To illustrate NES controlling wind-induced responses of high-rise buildings, a high-rise building with n-stories is simplified to a lumped-mass model, and NES is installed on the j^{th} story as shown in Fig.1(a). The red line in Fig.1(a) shows an Asym NESI installation with a mass block connected to the building by linear and nonlinear springs at both ends, respectively. The nonlinear spring is termed as the cubic stiffness spring in reference(McFarland, et al, 2005). If the nonlinear spring is removed, the control device is named as TMDI(Giaralis A., et al, 2017). If the linear spring is removed, the device is called as NES with an inerter. The mass m_{Asym} of the control device installed on the j^{th} floor is linked by a linear spring of stiffness k_l and a nonlinear spring with coefficient k_{nl}. To generate an asymmetric restoring force, the nonlinear spring is pre-stretched by a set distance r, and the linear spring is used to keep the mass statically balanced as shown in Fig.1(b). The total restoring force of Asym NESI can be expressed as below(Wang, et al, 2021):

$$F_A = k_{nl}\left(x_{Asym} + r\right)^3 + k_l x_{Asym} + f_s \tag{1}$$

where x_{Asym} is the displacement of the mass relative to the j^{th} story. $f_s = -k_{nl} r^3$ is the initial force in the linear spring when x_{Asym} is equal to zero. Substituting f_s into Equation (1), the total restoring force can be rewritten as:

$$F_A = k_{nl} x_{Asym}^3 + 3k_{nl} r x_{Asym}^2 + \left(3k_{nl} r^2 + k_l\right) x_{Asym} \tag{2}$$

In addition, c_l is the damping coefficient in Fig.1 (a). The ideal linear inerter with inertance b is two-terminal element, one terminal is connected with the mass m_{Asym}, and the other terminal is linked with the i^{th} floor.



(a) (b)

Fig.1 Simplified model of NESI controlling wind-induced responses of the high-rise building:(a)the lumped-mass model with NES; (b)formation of NES

According to the simplified model, the equation of motion of NES mitigating wind-induced responses of high-rise buildings can be expressed as follows:

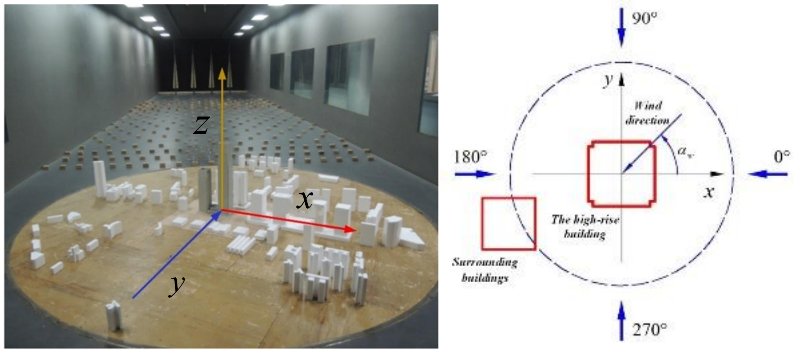
$$[M]\begin{Bmatrix} \ddot{x}(t) \\ \ddot{x}_{Asym}(t) \end{Bmatrix} + [C]\begin{Bmatrix} \dot{x}(t) \\ \dot{x}_{Asym}(t) \end{Bmatrix} + [K]\begin{Bmatrix} x(t) \\ x_{Asym}(t) \end{Bmatrix} = \begin{Bmatrix} p(t) \\ 0 \end{Bmatrix} \tag{3}$$

3. CASE STUDY

3.1. Brief Introduction of a Super High-rise building and it's Wind Tunnel Tests

A super high-rise building is located in the typhoon-prone areas along the southeast coast of

China as a case study. The high-rise buiding has a height of 300 m (69 stories) and a weight of 23,384 t. Due to lateral stiffness along the y-axis being less than that along the x-axis, the wind-induced responses along the y-axis may be larger than that of the x-axis. The first three natural frequencies of the high-rise buildings along the x-axis are 0.143, 0.357, and 0.564 Hz, respectively. The wind tunnel tests of synchronous multi-point pressure measurement for the high-rise building were carried out in the boundary layer wind tunnel laboratory as shown in Fig.2(a). The definitions of reference coordinates and wind directions α_w for the wind tunnel tests are shown in Fig.2(b). The specific parameters of the wind tunnel tests are listed in Table 1.



(a) (b)

Fig.2 Wind tunnel tests and wind directions: (a)wind tunnel tests of the building; (b) definition of wind direction

Table 1. The parameters of the wind tunnel tests.

Geometric Scale	Wind Speed	Sampling Frequency	Sampling Length	Incremental Step	Measure Taps
1:400	9.26m/s	299Hz	20480	10°	264

3.2. Vibration Mitigation Performance of NES

The mitigation effects of these control devices on peak wind-induced acceleration on the top floor at 36 wind directions are presented in Fig.3(b).

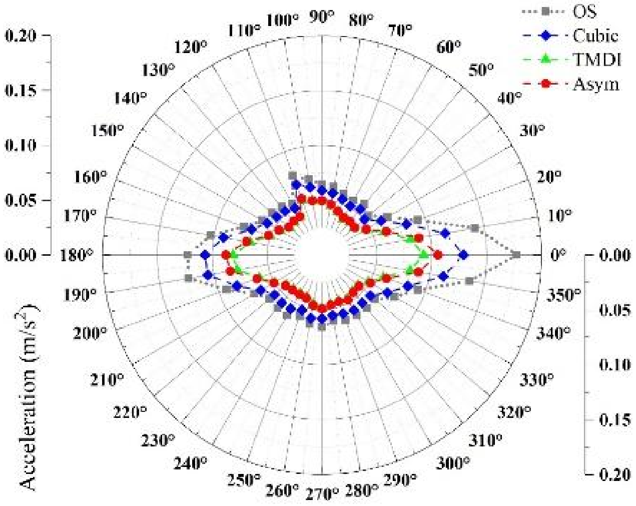
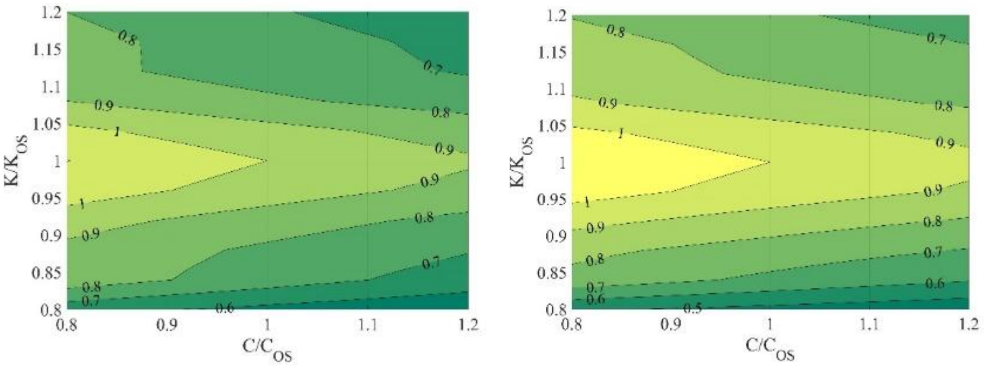


Fig.3 variation of peak acceleration responses on the top floor along y-axis with wind directions.

3.3. Robustness analysis of NES

The performance evaluation of the vibration absorber mainly includes two aspects: the vibration reduction effect and the robustness against the disturbance of the structural dynamic characteristics. Due to structural reconstruction, aerodynamic stiffness, aerodynamic damping, and other factors, the uncertainty of dynamic characteristics of super high-rise buildings is relatively common, which may adversely affect the mitigation performance of the vibration absorbers. The uncertainty of structural dynamic characteristics can be simulated by applying ±20% perturbation to the original stiffness and damping of the building.



(a) (b)

Fig.4. Robustness analysis of acceleration responses on the top floor at 0° wind direction under perturbation of stiffness and damping of the building: (a) asymmetry NES; (b) TMDI

4. CONCLUSION

In terms of vibration reduction effect, all three types of vibration absorbers can control the wind-induced response of the building under 36 wind direction . Taking the 0° wind direction (across-wind direction)as an example, Asym NESI can reduce the wind-induced acceleration of the top floor from 0.178 m/s^2 in the uncontrolled state to 0.104 m/s^2 , the corresponding reduction coefficient is 41.3%, while that of TMDI and Cubic NESI are 47.8% and 27.4%, respectively.By changing the dynamic characteristics of the main structure, the robustness of the three vibration absorbers is compared. The results show that the robustness of Asym NESI is the best among these control devices.

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