Wind Tunnel Study on Bidirectional Vibration Control of Lattice Towers with Omnidirectional Cantilever-Type Eddy Current TMD

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Abstract: An omnidirectional cantilever-type eddy current tuned mass damper (ECTMD) for lattice towers is introduced to suppress bidirectional vibration of lattice towers, in a form of a cantilever beam with a tip magnet mass. The damping of the ECTMD can be easily changed by tuning the amount of the current. A typhoon-fashion wind environment is simulated for the wind tunnel test. Test results show that there exists an optimal damping of the ECTMD along with an optimal frequency ratio. The scaled aeroelastic model is tested under various wind conditions, and a good effectiveness of ECTMD is observed. The wind directions, perpendicular and parallel to the cross-arm, are the most critical for the design of ECTMD, as the vibration mitigation in either of these two cases is relatively weaker. Finally, a simplified model is established for theoretical analysis in the frequency domain, whereby the variance responses of the tower with and without ECTMD are computed. The numerical results agree well with the experimental results, which corroborates the feasibility of using the proposed omnidirectional cantilever-type ECTMD in suppressing the vibrations of the tower in both along-wind and across-wind directions.

Keywords: omnidirectional cantilever-type ECTMD; lattice tower; wind tunnel test; frequency domain analysis; bidirectional vibration control

1. Introduction

Lattice towers are widely used for power transmission, telecommunication, wind turbine, and observation towers, etc. Tall lattice towers usually have relatively low natural frequencies and small damping ratios, which may result in large amplitude vibration under dynamic excitation such as wind loads [1,2]. The excessive vibration may diminish the serviceability of the towers, and cause fatigue damage, joint bolt looseness and even structural failure [3–7]. The lattice transmission tower employed in transmission line systems is an important type of lattice tower. Many collapse accidents happened to transmission towers under strong winds [8–10], as shown in Figure 1. The failure of the tower may cause massive blackouts, which results in a lot of economic loss and secondary disasters. With rapid development of power industry, many high-voltage transmission towers with greater height and span were constructed, especially in China. For example, the world’s highest transmission tower currently is located at Zhoushan in China, with a height of 380 m. These tall transmission towers, which are prone to large vibrations, pose new challenges to engineering design. Hence, improving the performance of wind resistance to ensure the structural safety of the tower has become an important issue, and has attracted great attention.
There are two main countermeasures to improve the wind resistance of lattice towers. The first is to increase structural stiffness by enlarging the size of the members or adding secondary members. However, this may significantly increase the material consumption and the project cost, which compromises the advantage of the low self-weight of lattice towers. The second countermeasure is to install vibration control devices to suppress the vibration. In this way, the dynamic response of the internal forces of the members can be mitigated. Consequently, small size members can meet the requirement, which means a lower cost.

Various types of control devices installed on structures were studied, such as tuned mass dampers (TMD) [11–19], tuned liquid dampers (TLD) [20], liquid column vibration absorbers (LCVA) [5], friction dampers [21], etc. Among these control devices, using TMD in tower vibration control seems to be a promising solution due to its efficiency, convenience and low cost [14]. A TMD typically consists of a mass, a spring and a damper. The control effectiveness of a TMD depends on its parameters, such as mass, frequency and damping ratio. Hence, it is of great significance to obtain the optimal parameters for the TMD [15–17]. For TMDs on lattice towers under wind loads, theoretical or numerical studies on it were conducted. Pelc and Kolator [18] performed a three dimensional (3D) finite element (FE) analysis of a truss-type telecommunication tower with a TMD installed, and the TMD effectiveness was found to be favorable in case of wind load. Tian and Zeng [19] conducted a parametric study of tuned mass dampers for a long span transmission tower-line system under wind load, and the influence of TMD parameters on TMD effectiveness was presented.

Though the effectiveness of TMD can be evaluated theoretically or numerically, wind tunnel test is still an important method for physical verification. For high-rise structures under wind loads, the effectiveness of TMD was experimentally examined [22–25], whereas the experimental studies on lattice towers with TMD installed are scarce [26]. Xu et al. [23] studied the along-wind and across-wind performance of a TMD-installed building under different wind speeds and wind directions, and their results clearly show the effectiveness of the TMD. Wang et al. [26] performed wind tunnel tests for a transmission tower-line system with TMDs installed, and the control effectiveness in either along-wind or across-wind direction was favorable under different wind speeds. In these experiments [22–26], the effectiveness of TMD was merely verified with a limited number of TMD parameters, as the adjustment of TMD parameters was inconvenient. The optimal frequency and damping parameters of the TMDs are thus hard to obtain experimentally.

For robustness, the vibration control device installed on a lattice tower needs to be capable of controlling the vibration of the structure under different wind directions. In addition, the device needs to mitigate the along-wind response and across-wind response of the tower simultaneously. Hence, it is of great significance to design an omnidirectional device that is able to accommodate different wind directions and vibration directions. Eddy current tuned mass damper (ECTMD) is a newly developed and promising device for vibration mitigation. It has been implemented in tall buildings [14] and transmission towers [27], and has attracted considerable interest [28–30]. For a traditional TMD in which viscous dampers are used to provide damping, it is found that there exists a concern of fluid

![Figure 1. Collapse of a transmission tower in China caused by wind loading.](image-url)
leakage, and the damping adjustment is difficult. The concerns raised can be attenuated by using ECTMD, in which an eddy current is employed to provide the damping. The relative movement between the magnetic field and the conductor in the device produces a damping force approximately proportional to the relative velocity, which can be considered linear damping [31] in the case of an ECTMD mass swaying in small amplitude. The separation of damping and stiffness in an ECTMD makes it potentially feasible to design an adjustable TMD for performing passive [32,33] or semi-active vibration control in the further study.

In this paper, an omnidirectional cantilever-type ECTMD is designed and fabricated. Its adjustability is examined via a free vibration test. Wind tunnel tests are conducted to attain relatively optimal parameters of the ECTMD installed on an aeroelastic model of a lattice tower, in the case of prescribed design wind loading. After applying the parameters to the ECTMD, the dynamical responses of the damped tower under different wind speeds and wind directions are then measured to verify the effectiveness of the ECTMD. Finally, a frequency domain method is presented for evaluation of the dynamic response of the tower, and the numerical results based on the proposed computing method are compared with the experimental results.

2. Cantilever-Type ECTMD

2.1. Configuration of ECTMD

An omnidirectional cantilever-type ECTMD was designed for the wind tunnel test of an aeroelastic tower model. As shown in Figure 2, the vertical cantilever is attached with a circular mass block that moves parallel to the copper plate. The mass block is made of magnet. The copper plate is to be fixed on the tower model. The stiffness of the ECTMD is provided by the cantilevered beam with a circular cross section, while the damping is achieved by the relative movement between the magnet and the copper plate. The four columns of the exterior wooden frame penetrate through the small holes on the copper plate. The connection between the frame and the copper plate was strengthened by removable hot melt adhesive, if the distance between the mass and the copper plate are determined. Thus, the distance can be changed independently from the cantilever length by removing the hot melt adhesive.

![Figure 2. Schematic of ECTMD with and without exterior wooden frame.](image)

The natural frequency of ECTMD can be independently tuned by changing the length of the cantilever while the distance between the magnet and the copper plate remains unchanged. Correspondingly, the damping of ECTMD can be independently changed by adjusting the distance between the magnet and the copper plate while the cantilever length remains unchanged.
2.2. Dynamic Characteristics

The dynamic characteristics of the ECTMD can be estimated theoretically in advance. The estimation results can guide the process of selecting appropriate materials to fabricate the ECTMD. The force resulting from ECTMD, and acting on the main structure takes a form of [29]

$$f_{\text{ECTMD}} = c_d \nu + k_d x$$

(1)

where $c_d$ and $k_d$ are the damping coefficient and stiffness of the ECTMD respectively, and $\nu$ and $x$ are the relative velocity and displacement of the mass to the main structure respectively.

A simplified method to predict the damping ratio of the ECTMD is presented below. Firstly, the magnetic flux density at the copper plate is required. For the cylindrical magnet in Figure 3, the magnetic flux density, $B$, at the point $(0, 0, z)$ is [34]

$$B_u = B(0, 0, z) = B_0 \frac{z}{[r_0^2 + z^2]^{1/2}} \frac{z-1}{[r_0^2 + (z-t)^2]^{1/2}}, \quad z \geq t$$

(2)

where $B_0$ is the magnetic flux density at the point $(0, 0, t)$, $r_0$ and $t$ are the radius and thickness of the cylindrical magnet.

![Figure 3. Magnetic flux density along centerline of cylindrical magnet.](image)

Assume that the center of copper plate is located at the point $(0, 0, z)$, and a uniform magnetic field is assumed to be across the copper plate. Then the damping coefficient of the eddy current can be estimated by [35]

$$c_d = \frac{\alpha \pi D^2 B_u^2 t}{4 \rho}$$

(3)

where $\alpha$ is a non-dimensional parameter, $D$ is the diameter of the magnet, and $\rho$ is the electrical resistivity of copper. With the assumption that the internal resistance of the copper plate at the magnetic field is equal to the external resistance, $\alpha$ is set as 0.5. The corresponding damping ratio of the ground-mounted ECTMD can be obtained by

$$\zeta_u = \frac{\pi B_u^2 D^2 t}{16 \rho \omega m}$$

(4)

where $m$ is the mass of magnet, and $\omega$ is the natural circular frequency of the ground-mounted ECTMD.

The elastic restoring force of ECTMD is provided by the cantilever, and can be approximately computed by

$$f_k = \frac{3EI}{L^3} x$$

(5)

where $E$ is the Young’s modulus of the cantilever, $I$ is the second area moment of the cross-section, and $L$ is the length of the cantilever. The natural frequency of a ground-mounted ECTMD, designated as the frequency of the ECTMD, can be predicted, which is based on an idealized model of a cantilever.
beam with a tip mass. Note that the mass of the cantilevered beam is relatively small and negligible. Thus, the corresponding natural circular frequency can be computed by

$$\omega = \sqrt{\frac{3E}{mL^3}}$$  \hspace{1em} (6)

The parameters of the ECTMD are listed in Table 1.

| Part         | Property                  | Symbol | Value               |
|--------------|---------------------------|--------|---------------------|
| Cantilever   | Young’s modulus           | $E$ (N·m$^{-2}$) | $1.4 \times 10^{10}$ |
|              | Moment of inertia of the cross-section | $I$ (m$^4$) | $1.02 \times 10^{-11}$ |
| Magnet       | Mass                      | $m$ (g) | 11.5                |
|              | Magnetic flux density at the surface | $B_0$ (T) | 0.16                |
|              | Diameter                  | $D$ (m) | 0.025               |
| Copper plate | Electrical resistivity    | $\rho$ (Ω·m) | $1.8 \times 10^{-6}$ |
|              | Thickness                 | $t$ (mm) | 6                   |

Dynamic characteristics of the ground-mounted ECTMD were identified through free vibration tests. The experimental setup of the free vibration tests is shown in Figure 4. To achieve a free vibration of the magnet, the magnet is given an initial displacement and is then released. A computer vision-based approach with corresponding identifying method [36] for dynamic displacement response is employed in the free vibration test of the ground-mounted ECTMD. A Huawei Mate 20 Pro cellphone was employed to record the video of motion, and the frame rate is 235 frames per second.

$$y(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{\tau(t)}{t-\tau} \, d\tau$$  \hspace{1em} (7)

where $x(t)$ is the input signal. Combining $x(t)$ and $y(t)$ leads to

$$z(t) = x(t) + iy(t) = a(t)e^{i\varphi(t)}, \quad i = \sqrt{-1}$$  \hspace{1em} (8)

where $a(t)$ and $\varphi(t)$ are the instantaneous amplitude and phase of $x(t)$ respectively. By using the least square method, the frequency and damping ratio can be identified.

Free vibration tests were performed in two orthogonal directions individually. After exploring the results attained via the tests in these two directions, it is found that either the natural frequencies or
the damping ratios of the ECTMD in the two directions are very close. The difference between the results in two directions is less than 2% for natural frequency and 8% for damping ratio, which verifies the direction independent characteristic of the ECTMD used herein. Figure 5 shows the free vibration responses of the ground-mounted ECTMD with and without the copper plate, where the identified damping ratios are 9.2% and 2.4%, respectively.

![Figure 5. Free vibration of ECTMD. (a) Without copper plate; (b) With copper plate.](image)

It is found that, given various lengths of the cantilever, the measured ECTMD frequencies agree well with the predicted values attained via Equation (6), as shown in Figure 6a. In Figure 6b, the damping ratio of the ground-mounted ECTMD, \( \zeta \), originates from the intrinsic damping of the cantilever and the additional damping caused by the eddy current. As the magnetic flux density of the magnetic field increases with the decrease of the distance between the mass and the copper plate, the smaller the distance is, the larger the damping is. The theoretical damping ratio predicted by Equation (4) matches well in general with the measured curve, though there is a slight discrepancy, which may be attributed to the simplified assumption of magnetic flux density. It is also found that a wide range of damping ratio can be achieved. The results show that the frequency and damping of the ground-mounted ECTMD are fully adjustable.

![Figure 6. Dynamic characteristics of ECTMD. (a) ECTMD frequency varying with cantilever length; (b) Damping ratio varying with distance between copper plate center and magnet surface at ECTMD frequency of 24 Hz.](image)
3. Experimental Setup

3.1. Finite Element Model of Prototype Transmission Tower

The full-scale transmission tower, i.e., the prototype structure, has a height of 43.6 m, and $7.2 \times 7.2$ m base. It is recognized that the lower the fundamental frequency is, the more significant the resonant dynamic response of a lattice tower will be [2], and the control effectiveness of ECTMD can be expected to be better. Consequently, with a relatively high fundamental frequency of 1.88Hz, the selected prototype structure is appropriate to examine the lower bound of the ECTMD's effectiveness.

A finite element model of the prototype structure is established by using ANSYS software. The first six natural frequencies are listed in Table 2, with corresponding mode shapes shown in Figure 7.

| Mode | Frequency (Hz) |
|------|----------------|
| 1    | 1.879          |
| 2    | 1.898          |
| 3    | 5.356          |
| 4    | 6.668          |
| 5    | 7.037          |
| 6    | 7.079          |

Table 2. First six natural frequencies of prototype structure.

Figure 7. Mode shapes of prototype structure. (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode; (f) 6th mode.

3.2. Aeroelastic Model for Wind Tunnel Test

In the wind tunnel test, similarities of some important parameters such as Strouhal number, elastic parameter and inertial parameter need to be fulfilled. The similarity of Reynolds number is not satisfactorily achieved in the wind tunnel test. However, for the angle steel tower, the Reynolds number does not significantly affect the results [38], and the similitude requirement of Reynolds number was thus relaxed. Froude number similarity mainly affects lifting aerodynamic force of the scaled model.
It plays an important role in wind tunnel test of free-flying models, such as wings. However, for cantilever-type structures, the deflection due to the vertical gravitational loading is relatively small, compared to that caused by horizontal wind loadings. As only the horizontal vibration is considered herein, the similitude requirement of Froude number was relaxed [39].

An aeroelastic model with a scale factor of 1:30 was designed and fabricated, having a height of 1.45 m, as shown in Figure 8. In the figure, the aeroelastic model consists of eight segments in a vertical line and connected by copper tubes. Each segment consists of angle steel members that meet the similitude requirement of windward area. To simplify the design, the members with a relatively small size are discarded, and the corresponding windward areas are incorporated into the remaining members. Generally, the natural frequencies of the steel tower model in which only geometric similarity is considered in scaling, are too high for an aeroelastic model-based wind tunnel study. Hence, copper tubes are placed between the segments as substitutes of the steel member, to reduce the overall lateral stiffness of the aeroelastic model. The details of the connection are depicted in Figure 9.

The acceleration responses of the aeroelastic model are measured by the sensors installed at the height of 0.60 m, 0.90 m, 1.11 m, 1.34 m and 1.44 m respectively, as shown in Figure 10. The sensors are sequentially numbered, and the ‘X’ and ‘Y’ in the sensor names denote the measurements in X direction and Y direction respectively. The acceleration sensors were produced by Kistler Group, and
the mass of each sensor is about 4.0 g. The sampling frequency adopted in the data acquisition system is 2048 Hz. The experimental setup of the aeroelastic model with an ECTMD installed on its top for wind tunnel test is shown in Figure 11.

Through free vibration tests, the primary natural frequencies of the aeroelastic model were identified and these are listed in Table 3, and the damping ratios of the aeroelastic model are 1.9% and 2.0% for the first mode in the X-direction and the first mode in the Y-direction respectively. The scale factors for the aeroelastic model are listed in Table 4. As the scale factor for frequency is determined experimentally in advance, the corresponding scale factors for dynamical similarity, e.g., scale factors for acceleration and wind speed, can then be deduced. According to similarity principles, the non-dimensional parameters of the scaled ECTMD determined in this study are the same as those for a full-scale ECTMD, which benefits the design of full-scale ECTMDs. The mass ratio, $\mu = 6.3\%$, is denoted as the ratio of the ECTMD mass to the modal mass (0.183 kg) of the first mode in Y direction.

| Prototype Frequency (Hz) | Scaled Model Frequency (Hz) |
|--------------------------|-----------------------------|
| First mode in X direction | 1.879 | 20.9 |
| First mode in Y direction | 1.898 | 21.2 |

Figure 10. Locations of acceleration sensors.

Figure 11. Experimental setup.
| Table 3. Natural frequencies of towers. |
|----------------------------------------|
| **Prototype Frequency (Hz)** | **Scaled Model Frequency (Hz)** |
| First mode in X direction | 1.879 | 20.9 |
| First mode in Y direction | 1.898 | 21.2 |

| Table 4. Scale factors of aeroelastic tower model. |
|-----------------------------------------|
| **Scale Factor** | **Value** |
| Geometry $C_L$ | 1:30 |
| Density $C_{PS}$ | 2.05:1 |
| Mass $C_M$ | 1:13185 |
| Lateral bending rigidity $C_{EI}$ | $1.58 \times 10^6$ |
| Frequency $C_F$ | 11.2:1 |
| Acceleration $C_A$ | 2.03:1 |
| Wind speed $C_V$ | 1.269 |

3.3. Wind Environment Simulation

The wind tunnel test was carried out in an atmospheric boundary layer (ABL) wind tunnel, name as ZD-1, in Zhejiang University. ZD-1 has a testing segment with a size of $4 \times 3 \times 18$ m, and a testing wind speed ranges from 3 m/s to 55 m/s. To simulate the ABL wind, several triangle spires are settled at the inflow entrance for forming vortex. In addition, rows of roughness elements are placed on the ground of the wind tunnel to simulate the turbulence induced by the terrain. An ABL wind flow that matches the characteristics of a typhoon was simulated. The power-law exponent of 0.14 was specified, and the corresponding wind profile is in a form of

$$v = v_{10} \left( \frac{z}{10} \right)^{0.14}$$  \hspace{1cm} (9)

where $v_{10}$ is the mean wind speed at the height of 10 m, and $z$ is the height. The terrain category B in the code of China, namely “Load Code for the Design of Building” (GB 5009-2012) [40], was chosen for the turbulence intensity setup. For a typhoon on terrain category B, the turbulence intensity is amplified by the factor of 1.48 according to Sharma’s recommendation [41]. That is to say

$$I_T = 1.48 I = 0.207 \left( \frac{z}{10} \right)^{-0.15}$$  \hspace{1cm} (10)

where $I$ is the standard turbulence intensity profile for terrain category B.

The measured wind speed profile, turbulence profile and wind power spectrum are shown in Figure 12, and they agree well with the theoretical results. In Figure 12b, Kaimal spectrum is used to generate the theoretical results [42], and has a form of

$$S_v(z, n) = \frac{100 \sigma_v^2}{3v(1 + 50 \frac{n}{v})^{5/3}}$$  \hspace{1cm} (11)

where $n$ is the frequency, and $\sigma_v^2$ is the variance of the fluctuating wind speed.
Define the reduction ratio, $\beta$, as

$$\beta = \frac{R_0 - R_1}{R_0} \times 100\%$$ (12)

where $R_1$ and $R_0$ are the RMS acceleration responses of tower top ('tower top' is indicated in Figure 10), with and without ECTMD respectively. The measurements of the acceleration sensors at 1.34 m, namely 3(X) and 4(Y), are employed as the representative measurements for the aeroelastic model response in wind tunnel tests. That is to say, the results in the following Sections 4 and 5 are of the tower top.

Since the first natural frequency predominates in the vibration of transmission towers under ABL wind, the frequency ratio, $\lambda$, is defined as

$$\lambda = \frac{f_{ECTMD}}{f_1}$$ (13)

where $f_{ECTMD}$ is the natural frequency of the ground-mounted ECTMD, and $f_1$ is the first natural frequency of the tower in Y direction. Note that $f_1 = 21.2$ Hz in this paper.

Figure 13 shows the wind direction angles used in the test. The wind speed in this paper refers to the mean wind speed at the prototype height of 10 m.

The experiment procedure can be divided into two phases. In the first phase, in the case of wind direction angle of 0° and wind speed of 24.7 m/s, the aeroelastic model is tested with various combinations of ECTMD frequency and damping ratio. By surveying the maximum amount of the reduction ratio, the favorable parameters of the ECTMD can be identified. In the second phase, using the favorable parameters of ECTMD determined, the aeroelastic model is tested with and without the
ECTMD, under wind speeds of 18.5, 22.6 and 24.7 m/s and wind direction angles in the range of $0^\circ$ to $90^\circ$.

4. Results

4.1. Parametric Study of ECTMD

In wind tunnel tests, by changing the length of cantilever beam and the distance between the magnet and the copper plate, the frequency and damping parameter of the ECTMD are thus adjusted to fulfill the experimental requirements. Meanwhile, the values of the frequency and damping ratio of the ECTMD can be approximated conveniently by interpolation, according to the curves shown in Figure 6. Given different frequencies and damping ratios of the ECTMD, corresponding reduction ratios are obtained and shown in Figure 14.

![Figure 14](image)

**Figure 14.** Variation of reduction ratios with ECTMD parameters under wind speed of 24.7 m/s and wind direction angle of $0^\circ$. (a) Variation of reduction ratio with frequency ratio of ECTMD; (b) Variation of reduction ratio with damping ratio of ECTMD.

It is found that, in both along-wind and across-wind directions, there exists a favorable frequency ratio with a corresponding favorable ECTMD damping ratio, using which a maximum reduction ratio can be achieved. The favorable frequency ratio is 0.97 and the favorable ECTMD damping ratio is 0.14 for both along-wind and across-wind directions. With the favorable frequency ratio and ECTMD damping ratio obtained in the first phase of the experiment, the corresponding reduction ratios are 23.1% for the vibration in the along-wind direction and 22.3% for the vibration in the across-wind direction.

Figure 15 shows the dynamic acceleration responses of the tower top in both time domain and frequency domain, in the case of the favorable frequency ratio and damping ratio tuned for ECTMD. It is found that both the vibration amplitude in the time history and the resonant component of frequency response at the fundamental frequency are significantly suppressed by the ECTMD. In addition, only the first mode has a significant contribution to the response, and the modes with higher modal frequency are not accessible within the frequency range. Figure 16 presents a diagram of bi-directional responses of the tower top, in which the along-wind data is the data in Figure 15a within the duration of 10.9 s to 11.0 s. It is clearly observed that the ECTMD can mitigate the vibrations in the across-wind direction and the along-wind direction in the meantime.
where the amplitudes of the vibrations in two directions are very close. This finding accounts for the effectiveness of ECTMD.

Across-wind vibrations simultaneously. It is found that, with the presence of the ECTMD, the along-wind vibration of the tower is a little smaller than the across-wind vibration, except for the top segment of the tower where the amplitudes of the vibrations in two directions are very close. This finding accounts for the motivation of using omnidirectional ECTMD which is capable of suppressing both along-wind and across-wind vibrations simultaneously. It is found that, with the presence of the ECTMD, the vibrations in the two directions are mitigated, demonstrating the effectiveness of ECTMD.

Figure 15. Acceleration response under wind speed of 24.7 m/s and wind direction angle of 0°. (a) Along-wind time history; (b) Along-wind Power-spectral density of acceleration; (c) Across-wind time history; (d) Across-wind power-spectral density of acceleration.

Figure 16. Across-wind vibration versus along-wind vibration.

Figure 17 illustrates the measured RMS accelerations, along with the corresponding reduction ratios obtained in the wind tunnel test. It is found that the tower vibrates in a fashion of its first mode mainly, whether the ECTMD is involved or not. Without the ECTMD, the along-wind vibration of the tower is a little smaller than the across-wind vibration, except for the top segment of the tower where the amplitudes of the vibrations in two directions are very close. This finding accounts for the motivation of using omnidirectional ECTMD which is capable of suppressing both along-wind and across-wind vibrations simultaneously. It is found that, with the presence of the ECTMD, the vibrations in the two directions are mitigated, demonstrating the effectiveness of ECTMD.
without ECTMD increase continuously with the increasing wind speed, and the vibration responses in Figure 18. Figure 18 shows that under all wind directions, the vibration responses of the tower with ECTMD are significantly lower than those of the tower without ECTMD. This proves that the ECTMD employed is capable of suppressing vibration responses at different principal axis directions of the tower under various wind conditions.

It is also found that the maximum reduction ratio appears at the measuring point that is located at the tower top rather than the top point. Theoretically, if only the first mode contributes to the vibration, the reduction ratio is expected to be the same along the height. However, the contributions of the other modes, which may not be well controlled by the ECTMD, can also affect the reduction ratio. The frequency response of the point on the tower top shown in Figure 15b indicates that except for the first mode, the contributions of the other modes are negligible. This may account for the observed phenomenon.

4.2. Effect of Wind Condition

Using the determined favorable parameters of the ECTMD, i.e., frequency ratio of 0.97 and damping ratio of 0.14, the aeroelastic model is tested with and without the ECTMD, under wind speeds of 18.5, 22.6 and 24.7 m/s and wind direction angles in the range of 0° to 90°.

The RMS accelerations of the tower with and without the ECTMD are plotted against wind speed in Figure 18. Figure 18 shows that under all wind directions, the vibration responses of the tower without ECTMD increase continuously with the increasing wind speed, and the vibration responses in the X and Y directions remain relatively close to each other. It is found that the vibration responses of the tower with ECTMD are significantly lower than those of the tower without ECTMD. This proves that the ECTMD employed is capable of suppressing vibration responses at different principal axis directions of the tower under various wind conditions.

Figure 17. Acceleration responses and reduction ratios along height under wind speed of 24.7 m/s and wind direction angle of 0°. (a) Acceleration responses; (b) Reduction ratios.

Figure 18. Cont.
Figure 18. Variation of RMS acceleration with wind speed and wind direction. (a) 0°; (b) 15°; (c) 30°; (d) 45°; (e) 60°; (g) 90°.

Under the wind speed from 18.5 to 24.7 m/s, the RMS accelerations of the tower with and without the ECTMD are plotted against wind direction angle in Figure 19, and the corresponding reduction ratios are plotted against wind direction angle in Figure 20. Figure 19 shows that, for the tower without ECTMD, under all wind speeds, the vibration responses maintain a high level at the wind direction angles from 0° to 45°, and the responses drop significantly at the angles from 45° to 90°. For the tower with ECTMD, the vibration responses decrease continuously in general with the wind direction angle increasing from 0° to 90°. Figure 20 shows that under all wind speeds, the reduction ratios in the X and Y directions are generally higher at the wind direction angle ranging from 30° to 60°. The reduction ratios at 0° and 90° wind directions are generally lower, compared to other wind directions. The results indicate that the control effectiveness of the ECTMD becomes not favorable when the wind direction approaches the principal axis directions of the tower, similar to the results shown in the work by Xu et al. [23] in which a tall-building structure was studied. Consequently, 0° and 90° wind directions are the critical cases to be studied preferentially, for design of ECTMDs. In the case of the wind speed of 24.7 m/s, the lower bound of reduction ratio identified (the smallest reduction ratio among those in all wind directions), is higher than that found for the other wind speeds, which means that the ECTMD effectiveness is most favorable in this case. The corresponding reduction ratio ranges from 21.7% to 35.7% for the vibration in the X direction, and from 18.3% to 29.2% for the vibration in the Y direction.
Figure 19. Variation of RMS acceleration with wind direction and wind speed. (a) 18.5 m/s; (b) 22.6 m/s; (c) 24.7 m/s.

Figure 20. Variation of reduction ratio with wind direction and wind speed. (a) 18.5 m/s; (b) 22.6 m/s; (c) 24.7 m/s.

5. Numerical Verification

5.1. Methodology

The frequency domain approach is introduced herein to attain the numerical dynamic response of the tower. As shown in Figure 21, for a structure with \( n \) degree of freedom (DOF), the governing equation of motion is

\[
\begin{bmatrix}
\mathbf{m} + \mathbf{L} \mathbf{L}^T \mathbf{m}_d & \mathbf{L} \mathbf{m}_d \\
\mathbf{L}^T \mathbf{m}_d & \mathbf{m}_d
\end{bmatrix}
\begin{bmatrix}
\ddot{\mathbf{x}} \\
\dot{\mathbf{v}}
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{c} & 0 \\
0 & \mathbf{c}_d
\end{bmatrix}
\begin{bmatrix}
\dot{\mathbf{x}} \\
\dot{\mathbf{v}}
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{k} & 0 \\
0 & \mathbf{k}_d
\end{bmatrix}
\begin{bmatrix}
\mathbf{x} \\
\mathbf{v}
\end{bmatrix}
= \begin{bmatrix}
\mathbf{f}(t) \\
0
\end{bmatrix}
\tag{14}
\]

where \( \mathbf{m} \), \( \mathbf{c} \), and \( \mathbf{k} \) are the mass, damping and stiffness matrices of the primary structure respectively, \( \mathbf{x} \) is the displacement vector, \( \mathbf{v} = \mathbf{x}_d - \mathbf{x}_p \), \( \mathbf{x}_p \) is the \( p \)th nodal displacement at the attaching point of the ECTMD, \( \mathbf{x}_d \) is the displacement of the ECTMD, \( \mathbf{m}_d, \mathbf{c}_d \) and \( \mathbf{k}_d \) are the mass, damping coefficient and stiffness of the ECTMD respectively, \( \mathbf{L} \) is the location vector of the ECTMD, and \( \mathbf{f}(t) \) is the vector of wind loading. Note that for the simplified model shown in Figure 21, \( \mathbf{m} \) is a diagonal matrix, i.e.,

\[
\mathbf{m} = \text{diag}(m_1, m_2, \ldots, m_n)
\tag{15}
\]

where \( m_r \) \( (r = 1, \ldots, n) \) is the \( r \)th lumped mass.
The vector of the frequency response function is then obtained by [43]

\[
\begin{bmatrix}
H_q \\
H_0
\end{bmatrix} = A^{-1} [1, \cdots, 1, 0]^T
\]  

(16)

where

\[
A = \begin{bmatrix}
-\omega^2 (M + \varphi^T L L^T \varphi m_d) + i\omega C + K & -\omega^2 \varphi^T L m_d \\
-\omega^2 L^T \varphi m_d & -\omega^2 m_d + i\omega c_d + k_d
\end{bmatrix}
\]  

(17)

\(H_q\) is the vector of frequency response function for the primary structure, \(H_0\) is the frequency response function of the ECTMD, \(M = \varphi^T m \varphi\), \(C = \varphi^T c \varphi\), and \(K = \varphi^T k \varphi\) are the modal mass, modal damping, and modal stiffness matrices of the primary structure respectively, \(\varphi\) is the mode shape matrix, and \(\omega\) is the circular frequency of the excitation.

If \(m\) and \(\varphi\) are available, then the modal mass matrix, \(M\), can be obtained in the form of

\[
M = \operatorname{diag}(M_1, M_2, \cdots, M_n)
\]  

(18)

Then the modal stiffness matrix, \(K\), can be obtained by

\[
K = \operatorname{diag}(K_1, K_2, \cdots, K_n), \quad K_r = \omega_r^2 M_r, \quad r = 1, 2, \cdots n
\]  

(19)

where \(\omega_r\) is the \(r\)th natural circular frequency. Furthermore, the modal damping matrix, \(C\), is in a form of

\[
C = \operatorname{diag}(C_1, C_2, \cdots, C_n), \quad C_r = 2\xi_r \omega_r M_r, \quad r = 1, 2, \cdots n
\]  

(20)

where \(\xi_r\) is the modal damping ratio of the \(r\)th mode. If the two modal damping ratios of the prescribed modes are specified, the \(\xi_r\) can be thus computed by using Rayleigh damping [44].

The spectral density matrix for acceleration is therefore

\[
S_{aa} = \omega^4 \left\{ \sum_{r,s=1}^{n} \varphi_r \varphi_s^T H_r^* H_s S_{F_r F_s} \right\}
\]  

(21)

where \(H_r^*\) is the complex conjugate of frequency response function of the \(r\)th mode, \(H_s\) is the frequency response function of the \(s\)th mode, and \(S_{F_r F_s}\) is the cross-spectral density of the generalized load. The variance of acceleration at the \(j\)th point can be computed by

\[
\sigma^2_{a_j} = \int S_{a_{jj}} d\omega
\]  

(22)

where \(S_{a_{jj}}\) is the power-spectral density of acceleration of the \(j\)th point.
The cross-spectral density of along-wind fluctuations between the points at height \( z \) and \( z' \) is
\[
S_v(z, z', n) = \sqrt{S_v(z, n)S_v(z', n)} \cdot \text{Coh}(z, z', n)
\]
(23)
where the Kaimal spectrum shown in Equation (11) is adopted herein for computing \( S_v(z, n) \), and \( \text{Coh}(z, z', n) \) is the coherence function in a form of [45]
\[
\text{Coh}(z, z', n) = \exp\left(-\frac{7n|z - z'|}{\bar{v}}\right)
\]
(24)
where \( \bar{v} \) is the mean wind speed between the points at height \( z \) and \( z' \). Thus, the power-spectral density of the wind pressure is
\[
S_w(z, z', n) = \rho^2 \mu_s(z)\mu_b(z')\bar{v}(z)\bar{v}(z')S_v(z, z', n)
\]
(25)
where \( \rho \) and \( \mu_b \) are the air density and shape coefficient respectively. The cross-spectral density of the generalized wind loads is
\[
S_{F_i,F_j} = \int_0^H \int_0^H D(z)D(z')\phi_i(z)\phi_j(z')S_w(z, z', n)dzdz'
\]
(26)
where \( D \) is the nominal width of the windward area.

5.2. Numerical Results

The tower is divided into 17 segments, as shown in Figure 22, and the relevant parameters are listed in Table 5. Thus, for numerical analysis, a simplified model with 17 corresponding nodes is employed. The location of each node is set at the center of the corresponding segment. Therefore the \( r \)th lumped mass is the mass of the \( r \)th segment. The mode shapes used herein are derived from the finite element analysis of the prototype structure, in which seventeen mode shapes with corresponding natural frequencies are obtained. The modal damping ratios of the first two modes in the Y direction are set as 4.4%, which is identified from the experimental dynamic response results. Thus, the modal mass, modal damping and modal stiffness matrixes can be computed, according to Equations (18)–(20).

Figure 22. Segments of prototype structure.
Table 5. Segment parameters of the prototype tower.

| Segment No. | Segment Mass (kg) | Segment Height (m) | Shape Coefficient | Windward Area (m²) |
|-------------|-------------------|--------------------|-------------------|-------------------|
| 1           | 87.5              | 0.5                | 2.03              | 0.26              |
| 2           | 498.0             | 2.1                | 1.63              | 1.71              |
| 3           | 858.0             | 0.9                | 2.05              | 2.38              |
| 4           | 418.4             | 1.4                | 2.01              | 1.50              |
| 5           | 686.3             | 3.9                | 2.15              | 1.78              |
| 6           | 699.9             | 1.6                | 2.18              | 2.98              |
| 7           | 1006.3            | 4.8                | 2.23              | 2.45              |
| 8           | 603.9             | 1.4                | 2.16              | 2.36              |
| 9           | 767.9             | 2.5                | 2.21              | 1.63              |
| 10          | 269.0             | 1.3                | 2.37              | 0.70              |
| 11          | 422.1             | 2.5                | 2.37              | 1.47              |
| 12          | 454.4             | 2.6                | 2.43              | 1.58              |
| 13          | 524.3             | 3                  | 2.48              | 1.82              |
| 14          | 842.7             | 4.2                | 2.51              | 2.62              |
| 15          | 640.5             | 2.6                | 2.56              | 1.58              |
| 16          | 723.1             | 1.4                | 2.43              | 1.48              |
| 17          | 1612.2            | 6.9                | 2.59              | 4.19              |

In the case of the along-wind direction, by using the aforementioned theoretical approach in the frequency domain analysis, the dynamic responses of the tower with and without the ECTMD are attained. For different mass ratios, the reduction ratios varying with the damping ratio of ECTMD and frequency ratio are illustrated in Figure 23. There exists an optimal frequency ratio and ECTMD damping ratio, whereby the maximum reduction ratio can be achieved. The maximum reduction ratios for mass ratios of 0.02, 0.04, and 0.063 are 15.8%, 21.2%, and 25.1% respectively. For the mass ratio of 0.063 used in the experiment, it is found that the optimal frequency ratio and ECTMD damping ratio in theory are 0.98 and 0.11 respectively.

![Figure 23. Reduction ratio over damping ratio and frequency ratio. (a) Mass ratio = 0.02; (b) Mass ratio = 0.04; (c) Mass ratio = 0.063.](image)

By using the parameters in the experiment, the theoretical results are compared with the experimental results in the along-wind direction, as shown in Figure 24 and Table 6. It can be found from Figure 24 that the theoretical reduction ratios generally match well with the experimental values as the frequency ratio and damping ratio of the ECTMD change, though the experimental reduction ratios are a little lower. The theoretical highest reduction ratio corresponds to the frequency ratio of 0.97 and the ECTMD damping ratio of 0.11, whereas the experimental highest reduction ratio corresponds to the frequency ratio of 0.97 and the ECTMD damping ratio of 0.14. Under the frequency ratio of 0.97 and the ECTMD damping ratio of 0.14, the experimental reduction ratio is 23.1%, whereas the theoretical reduction ratio is 24.8%.
The wind tunnel study on the lattice tower shows that there exists a significant across-wind producing a good prediction of the dynamic responses of the tower with or without ECTMD.

The wind tunnel study on the vibration of a lattice tower with an ECTMD mounted indicates that to gain insight into the performance of the ECTMD used in suppressing vibration of lattice towers. A wind tunnel study of a lattice tower with an ECTMD was conducted comparison shows that the theoretical approach in frequency domain introduced herein is capable of frequency domain approach is slightly higher than the experimental results. Generally speaking, the reduction ratio match well with the experimental results. In case of the wind speed of 18.5 m/s, the theoretical results of acceleration are a litter lower, whereas the reduction ratio computed via the.

Table 6 shows that at wind speeds of 24.7 and 22.6 m/s, the theoretical results of acceleration and reduction ratio match well with the experimental results. In case of the wind speed of 18.5 m/s, the theoretical results of acceleration are a litter lower, whereas the reduction ratio computed via the frequency domain approach is slightly higher than the experimental results. Generally speaking, the comparison shows that the theoretical approach in frequency domain introduced herein is capable of producing a good prediction of the dynamic responses of the tower with or without ECTMD.

6. Conclusions

An omnidirectional cantilever-type ECTMD is introduced herein for vibration control of lattice towers under wind loading. A wind tunnel study of a lattice tower with an ECTMD was conducted to gain insight into the performance of the ECTMD used in suppressing vibration of lattice towers. Conclusions can be drawn as follows.

1) The wind tunnel study on the lattice tower shows that there exists a significant across-wind vibration, and it deserves efforts made to design and manufacture an omnidirectional ECTMD to suppress the bidirectional vibration. The parameter adjustability of the newly designed ECTMD in a wide range is verified experimentally. Thus, the vibration of the tower can be suppressed by tuning the frequency of the ECTMD to a value close to the first natural frequency of the tower. The parametric study of ECTMD in wind tunnel test shows that with a frequency ratio of 0.97 and an ECTMD damping ratio of 0.14, the vibration of the tower can be effectively mitigated.

2) The wind tunnel study on the vibration of a lattice tower with an ECTMD mounted indicates that the newly designed ECTMD is capable of effectively reducing the bidirectional response under various wind speed and wind directions. This may be attributed to the fact that the first two natural frequencies of the tower are very close. The ECTMD technique presented in this paper can be applied to tall structures and long-span bridges that undergo significant vibration induced by wind/earthquake loadings.
3) It is found that the effectiveness of the ECTMD model is least favorable when the wind direction is consistent with the principal axis directions of the lattice tower. Therefore, these cases should be considered in the preliminary design of ECTMDs. That is to say, if the vibration of the tower in these cases can be well mitigated, the vibration under other wind conditions can be also suppressed very well.

4) A governing equation is established for the motion of the simplified model, and the equation is transformed in modal space to obtain the frequency response function of each mode. A frequency domain approach is presented to achieve variance of dynamic response. The comparison of numerical and experimental results indicates that the theoretical approach introduced herein is capable of capturing the optimal settings of the ECTMD, and producing a good prediction of the dynamic responses of the tower with or without the ECTMD.

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