The 2018 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Vision-based response measurements for an aeroelastic model of a wind-excited tall building

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ABSTRACT

This study focuses on the wind-induced structural response measurement for aeroelastic building models in wind tunnel tests. In order to eliminate the deficiencies of the traditional sensors, meanwhile ensuring good accuracy of the response data in wind tunnel tests for building structures, we proposed a new flexible non-contact measuring system which is based on computer vision. The best feature of our system is that it can fulfill both displacement and acceleration measurement of the top of the building model at the same time with only one CMOS camera. A series of wind tunnel tests were conducted to verify the feasibility and accuracy of our system and results indicated that the proposed vision-based measuring system performed well with in wind-induced response measurement.

1. INTRODUCTION

Due to the slenderness and lightness, modern super tall buildings tend to suffer from wind, which leads to safety and discomfort problems (Kareem 1983). To analyze the wind-induced behavior of high-rise buildings, scaled aeroelastic model tests were conducted, and vibration response at the top of the models were measured (Wang et al. 2015; Lu et al. 2017). Traditionally, sensors such as accelerometers, LVDT, laser displacement sensors are utilized to obtain vibration time history data of the model in wind tunnel tests, however, all these instruments need to be attached to the structure or to be set very close to the target, which will probably lead to additional obstruction in wind field tests. Moreover, traditional sensors are only available for one-sensor-to-one-point measurement, which are not flexible and tend to be affected by wind in the wind tunnel. Based on computer vision, which is a heated topic these days, vision-based measurement method can help overcome such limitations. Various vision-based measurement systems have been proposed by researchers, with application in displacement measurements of shaking table (Chang and Ji 2007; Feng et al. 2015) and bridges (Fukuda et al. 2013; Busca et al. 2014). However, there still lacks evaluations on the performance of vision-based system for wind tunnel tests. In this paper, a vision-based measurement system is proposed and was applied in the wind tunnel tests for an aeroelastic model of a wind-excited tall building. With only one CMOS camera, both displacement and acceleration responses of the top of the building model can be obtained. The accuracy of the proposed system was validated by

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accelerometers, and results showed that the acceleration error was less than 10%.

2. VISION BASED MEASUREMENT SYSTEM

To reconstruct the 3D world coordinates from 2D images, the relationship between the target plane and the camera is needed. Through a camera calibration process (Zhang 2000), the 3D world coordinates can be obtained:

$$s\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{A}\begin{bmatrix} \mathbf{R} & \mathbf{t} \end{bmatrix}\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \tag{1}$$

where s is a scale factor for coordinate transformation; $[X\ Y\ 1]^T$ is the homogeneous coordinates of a 3D point in the world coordinate system; $[x\ y\ 1]^T$ is the homogeneous coordinates of the 2D image point; [**R t**] is the camera extrinsic matrix obtained through camera calibration; and **A** is the camera intrinsic matrix obtained through camera calibration.

After the camera calibration process, target locations in different images are needed to be found. The template matching technique with normalized cross-correlation coefficient (Lewis 1995) can be utilized to track the target in the image during the vibration process:

$$\beta(i,j) = \frac{\sum_{x=1}^{m}\sum_{y=1}^{n}(f(x,y)-\bar{f})(r_t(x+i,y+j)-\bar{r})}{[\sum_{x=1}^{m}\sum_{y=1}^{n}(f(x,y)-\bar{f})]^{1/2}[\sum_{x=1}^{m}\sum_{y=1}^{n}(r_t(x+i,y+j)-\bar{r}_t)]^{1/2}} \tag{2}$$

where $\beta(i, j)$ is the normalized cross-correlation coefficient at position (i, j) in a image(i = 0, 1, 2, …, M-1; j = 0, 1, 2, …, N-1); $r_t(x, y)$ is the gray value at (x, y) in the searching template of the t^{th} image; $\bar{f}$ is the average gray value of the predefined template; $\bar{r}$ is the average gray value of the searching template; M and N are the length and width of the region of interest (ROI), respectively; and m and n are the length and width of the predefined template, respectively.

The best matching template, which has the largest β, can be found through Eq. (2). Then the target point in the best matching template can be recognized through a corner detection algorithm (Shi and Tomasi 1994):

$$\mathbf{M}=\sum_{u,v} e^{-\frac{(u^2+v^2)}{2\sigma^2}}\begin{bmatrix} \left(\frac{\partial I}{\partial x}\right)^2 & \frac{\partial I}{\partial x}\frac{\partial I}{\partial y} \\ \frac{\partial I}{\partial x}\frac{\partial I}{\partial y} & \left(\frac{\partial I}{\partial y}\right)^2 \end{bmatrix} \tag{3}$$

$$\lambda_{min} > \lambda_{threshold} \tag{4}$$

where u and v are the coordinates of a pixel in the $n \times n$ window (u, v = 0, 1, 2, …, k-1); I = the pixel value; λ_{min} is the smaller eigen value of matrix **M**; and $\lambda_{threshold}$ is a predefined threshold.

If Eq. (4) is fulfilled, then the center of the $n \times n$ window is detected as the target point. The target point tracking process of the proposed vision-based measurement system is shown in Fig. 1.

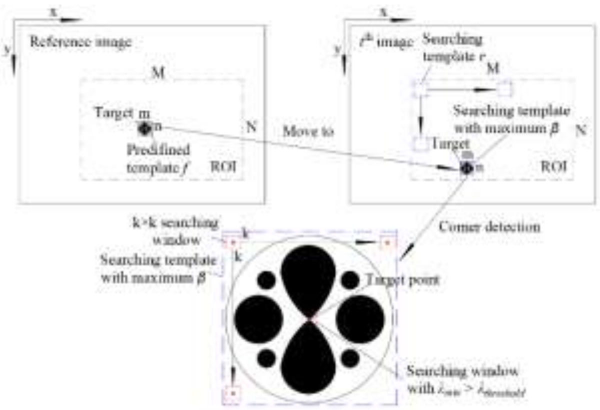


Fig. 1 Target point tracking process of the proposed system

After locating the target point, displacement can be obtained by comparing the location of the target point in t^{th} image and the reference image. And acceleration can be obtained through double numerical differentiation process:

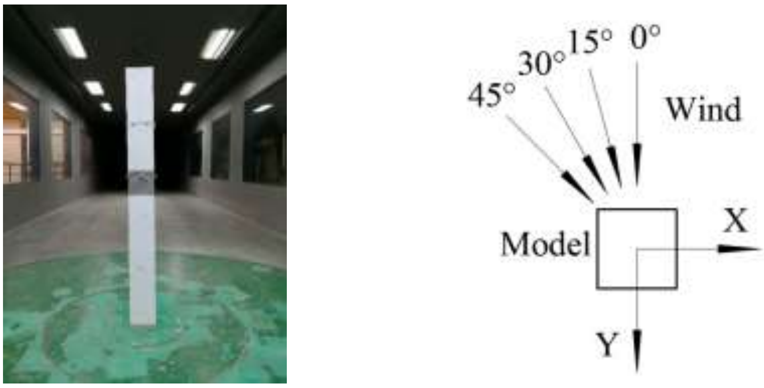
$$a(t_0) = f''(t_0) \approx \frac{1}{\Delta t^2}\left[f(t_0) - 2f(t_1) + f(t_2) \right] \tag{5}$$

where f(t) is the displacement of the target point at t_0 moment; $a(t_0)$ is the acceleration of the target point at t_0 moment; and Δt is the time interval of the displacement data.

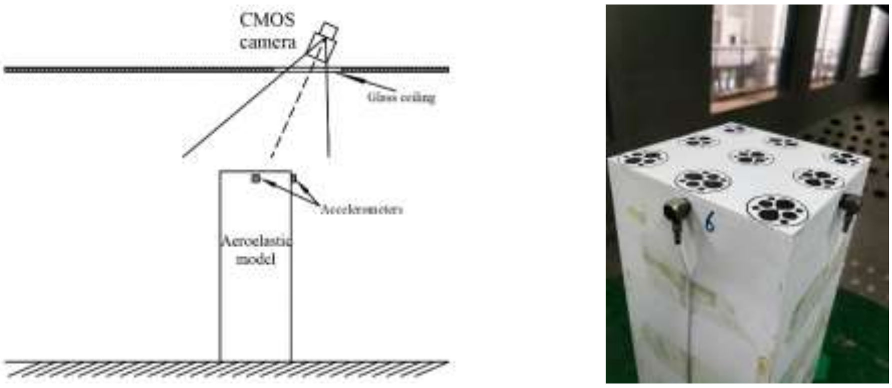
3. WIND TUNNEL TESTS

3.1 Experimental setup

A series of wind tunnel tests were conducted to validate the accuracy of the proposed system. Tests were carried out in the ZD-1 wind tunnel at Zhejiang University. The test section of the wind tunnel is 15 m long, 4 m wide and 3 m high. The shape of the aeroelastic high-rise building model was a cuboid, as shown in Fig. 2-(a), and the scaling ratio was 1:300. The model had two degrees of freedom, the local coordinate system and incident wind angels are defined in Fig. 2-(b). Two accelerometers were mounted at the top of the model and a CMOS camera was installed outside the glass ceiling of the wind tunnel to capture images for the proposed system. The overall experimental setup is illustrated in Fig. 3.

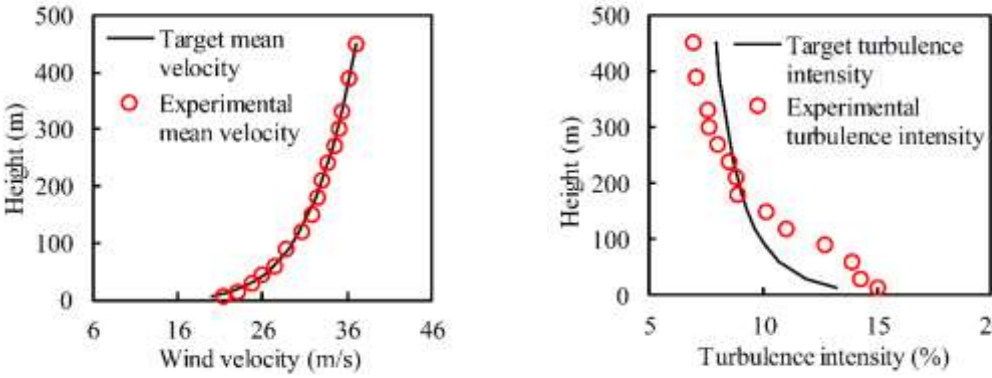


(a) Aeroelastic model (b) Local coordinate system
Fig. 2 Aeroelastic model and local coordinate system



(a) Schematic diagram (b) Experiment picture
Fig. 3 Overall experimental setup

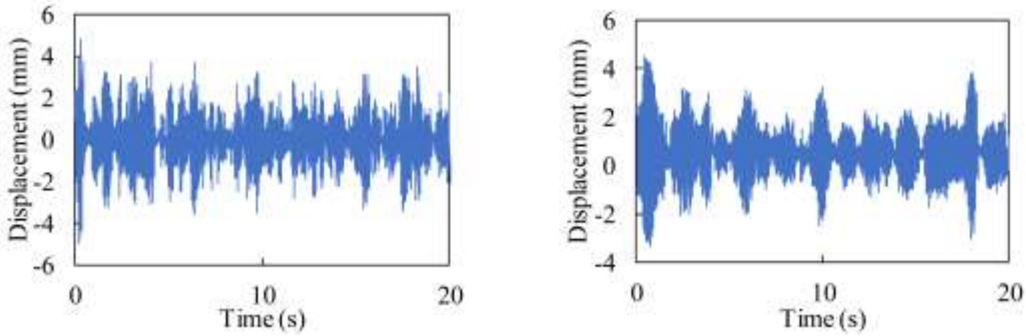
B-type terrain in Chinese load code (GB50009-2012 2012) was simulated, and the simulation results are shown in Fig. 4. The test wind speed was 13 m/s and four different wind angles (0°, 15°, 30°, and 45°) were tested. The sampling rate of the accelerometer and CMOS camera were 2048Hz and 100Hz, respectively. The sampling time was 20 s.



(a) Wind velocity profile (b) Turbulence intensity
Fig. 4 Simulation results of B-type terrain in Chinese load code

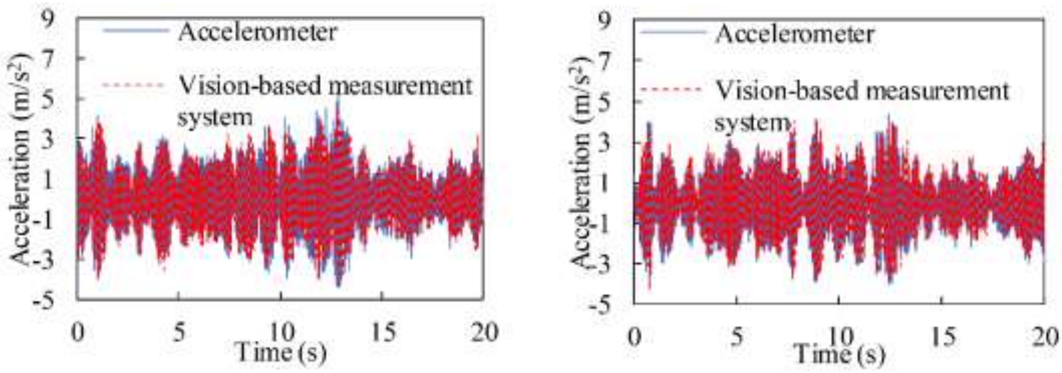
3.2 Results and analysis

As shown in Fig. 5, it is obvious that the crosswind effect was significant when the incident wind angle was 0°. The displacement at the top of the model fluctuated significantly in the X and Y directions. The proposed system could clearly recognize displacement in both directions.



(a) Displacement in X direction (b) Displacement in Y direction
Fig. 5 Displacement response of the model with 0° wind angle

The acceleration data obtained by the proposed system fit well with that measured by accelerometers, as shown in Fig. 6, the trends of both acceleration curves were very close. As listed in Table 1, percentage differences of acceleration standard deviations obtained by the proposed system were less than 10%.



(a) Acceleration in X direction (b) Acceleration in Y direction
Fig. 6 Comparison of acceleration response with 45° wind angle

Table 1 Comparison of acceleration standard deviation

Wind angle (°)	X direction			Y direction		
	Accelerometer (m/s^2)	Proposed system (m/s^2)	Percentage difference	Accelerometer (m/s^2)	Proposed system (m/s^2)	Percentage difference
0	4.377	4.325	1.2%	4.245	4.021	5.3%
15	2.996	3.104	3.6%	2.255	2.060	8.7%
30	1.300	1.406	8.2%	1.312	1.398	6.5%
45	1.386	1.525	10.0%	1.376	1.466	6.5%

3. CONCLUSIONS

A vision-based measurement system for wind tunnel tests of aeroelastic high-rise building models is proposed in this paper. It is capable of measuring both wind-excited displacement and acceleration response at the top of the model simultaneously, with only one CMOS camera. A series of wind tunnel tests were conducted and comparison results demonstrated the feasibility and accuracy of the proposed system.

ACKNOWLEDGEMENTS

The work described in this paper was partially supported by the National Natural Science Foundation of China (Project No. 51578504).

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