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Wind-induced responses of a tall chimney by aeroelastic wind tunnel test using a continuous model

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ABSTRACT

This study aims to investigate wind-induced responses of a 300 m high chimney by using wind tunnel tests on an aeroelastic model. Due to the fact that it is unrealistic to simulate wind flow with a high Reynolds number as high as 1×10^8 for a chimney model in a wind tunnel, roughness paper strips were attached to the model surface to artificially achieve effective high Reynolds number flow in the full-scale condition. An optimal thickness of the roughness paper strips was determined via a series of pressure measurement tests on a rigid model of the chimney. To examine wind-induced responses of the chimney, a continuous aeroelastic chimney model was manufactured with the DEVCON plastic steel liquid. After roughening the aeroelastic model by the paper strips with the optimal thickness, a series of wind tunnel tests were conducted on the model to directly acquire the structural responses, for three different oncoming wind flow conditions. Results show that the response of the roughened model is much smaller than that for the model without roughness element, indicating that ignoring the Reynolds number effect will overestimate the response. The across-wind acceleration response of the chimney is more considerable than that in the along-wind direction, when the reduced wind velocity V_r is larger than 4. In addition, the across-wind acceleration response is usually larger in the more turbulent wind flow, although the lock-in phenomenon is more evident in uniform flow.

1. Introduction

Wind force is one of the dominant external force in the design of tall circular chimneys that are indispensable structures in a power plant. These tall and slender structures with a circular cross-section may experience remarkable wind-induced vibrations, especially for the vibration in the across-wind direction. The across-wind force is recognized as the primary source of wind-induced motion and even collapse of tall chimneys and similar structures [1–11].

To achieve a safe and reliable design of a tall circular chimney, wind-induced structural responses are necessary and crucial to evaluate the performance of the chimney under strong wind. There are numerous studies concentrated on wind-induced responses of tall cylinders [8,12–17]. These studies usually made use of aeroelastic test on a single degree-of freedom (SDOF) model. Nonetheless, the mode shape of the SDOF model is clearly different from that of realistic chimneys that is continuous along the structural height. In addition, the SDOF model cannot reflect the spanwise correlation and determine the correlation length. This correlation length is important when estimating the across-wind responses of tall and slender chimneys [18–20], such as the chimney in this study with a height of 300 m. Due to these limitations, it has been demonstrated that, although the SDOF model is acceptable for low-rise structures, the accuracy of a SDOF model is not high enough for the wind-induced response of tall structures such as chimneys [21,22]. In response to this need, a more complicated aeroelastic model, such as a continuous model, is desirable for aeroelastic test of tall and slender chimneys. The continuous model is capable of simulating both the overall geometry details and structural properties simultaneously [23]. Therefore, the continuous aeroelastic model is an alternative for aeroelastic model of tall chimneys to overcome the limitations of the traditional SDOF model. Furthermore, the continuous aeroelastic model can consider the contribution of higher modes, rather than one particular mode in the SDOF model. It should be mentioned that the aeroelastic effect has also been investigated by a few approaches of numerical modeling, especially for wind turbine blade. For instance, Rafiee's group combined modified blade element momentum

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(BEM) theory and 3D finite element method (FEM) model to investigate the aeroelastic behavior of a wind turbine blade [24–26]. However, this method cannot be directly applied the aeroelastic behavior of high chimneys with circular sections, because the lift and drag coefficients cannot be determined in advance. In addition, the BEM is a quasi-steady method without considering turbulent inflow. Nevertheless, the aeroelstic behaviors of high circular chimneys such as vortex-induced vibration (VIV) are highly related to the turbulent component of wind flow.

Reynolds number is a key parameter for modelling circular chimneys in wind tunnel, because the Reynolds number has an important role in wind pressure distribution on the chimney surface and hence drag and lift forces [12,14,27–29]. Reynolds numbers of chimneys in engineering practice immersed in a natural wind environment usually reach 1×10^7 to 1×10^8. Nevertheless, it is usually unrealistic to achieve a Reynolds number in a wind tunnel as high as that in full-scale conditions [27,30], due to low wind speed (usually less than 50 m/s) and small cross-section size (usually smaller than 10 m × 10 m) of wind tunnels. Fortunately, it has been well acknowledged that attaching roughness elements on the surface of circular cylinders can not only promote the boundary-layer transition from laminar to turbulent, but also substantially change the subsequent flow development at Reynolds numbers far beyond the critical value [28]. In other words, using surface roughness can artificially simulate the flow past a circular cylinder similar to that under full-scale conditions with high Reynold numbers [28,31–33]. There are mainly three types of roughness elements [34]: a) uniform, densely packed roughness such as emery paper, glass beads, etc.; b) technique roughness with randomly varying size, form and distance of roughness element; and (c) discrete ribs and wires. The first type of roughness will be used in the present study to achieve effective high Reynolds number flow around the aeroelastic model of the chimney, as this type of roughness has been widely used for aeroelastic models of circular cylinders and of cooling towers [28,34,35].

This study tries to obtain and examine wind-induced responses, especially for the across-wind responses, of a 300 m high circular chimney by wind tunnel tests. A high Reynolds number flow is first simulated by attaching the roughness paper to the chimney model surface. An optimal thickness of the roughness paper in terms of the targeted high Reynolds number flow distribution is then determined via a series of pressure measurement tests on a rigid model of the chimney. Subsequently, an aeroelastic model of the chimney is manufactured by the DEVCON plastic steel liquid, according to the structural and geometry scale ratios. The roughness paper with the optimal thickness is then attached to the aeroelastic model and a series of wind tunnel tests are conducted on the model to directly measure the structural responses, for different oncoming wind flow conditions. The measured responses are then discussed in detail and a few key results of this study are summarized in Conclusions.

2. Wind tunnel tests

2.1. Project details

The chimney in this study is a 300 m high reinforced concrete circular chimney of a 2 × 1000 MW power plant in Hubei province, China. The outer diameter of the circular cross-section above the height of 175 m is a constant of 21.2 m, whereas the outer diameter below 175 m gradually increases from 21.2 m to 33.8 m with height, as shown in Fig. 1. Due to symmetry, the natural frequencies of the chimney in the two translational directions are identical. According to the results from the finite element method model of the chimney, the first and second frequencies in each direction are 0.25 Hz and 1.16 Hz, respectively. Since the chimney is tall and slender, wind forces and the subsequent wind-induced responses are a primary concern in the design.

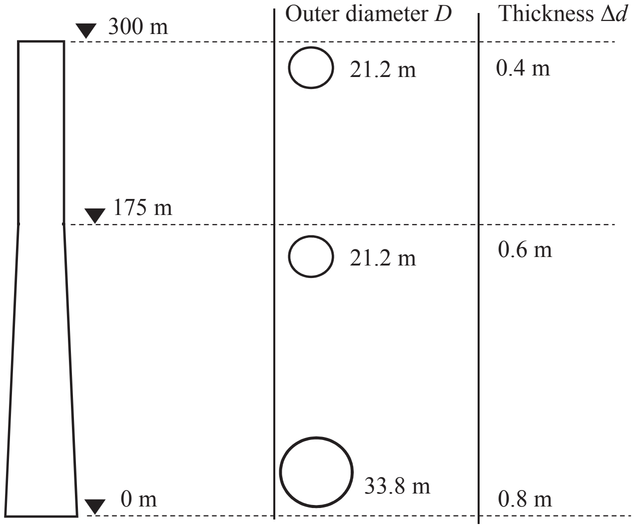

Fig. 1. Full-scale geometry of the chimney.

2.2. Determination of surface roughness to simulate high Reynolds number flow

In view of circular cross-sections of the chimney, Reynolds number plays an important role on wind pressure distribution on the chimney surface and eventually drag and lift forces. The Reynolds number of the prototype chimney in this study is in the range of 10^8 ($Re = UD/\nu \approx U \times 21.2/(1.48 \times 10^{-5})$, substituting a mean wind velocity $U = 60$ m/s at the top of the chimney leads to $Re = 0.86 \times 10^8$). As mentioned in the introduction, it is usually unrealistic to simulate wind flow with a Reynolds number of prototype circular chimneys in wind tunnels, because of the limitation of simulated wind speed and cross-section size of wind tunnels (the Reynolds number of the chimney model in the wind tunnel is usually less than 10^6). Increasing the surface roughness of chimney models, as an alternative, can artificially create flow features past the cylinder similar to that of high Reynolds numbers of and hence achieve an equivalent effect of high Reynolds number [9,10,27,28,30,36,37].

In order to determine the configuration of longitudinal roughness strips that can achieve wind flow with an equivalent high Reynolds number, a series of pressure measurement wind tunnel tests, using a synchronous multi-pressure measurement system (SMPMS), are carried out on a rigid model of the chimney (as shown in Fig. 2a), in the boundary layer wind tunnel at Wuhan University. The wind tunnel has a test-section of 16 m long with a cross-section of 3.2 m wide × 2.1 m high, in which the wind velocity can be continuously adjusted in the range of 1 m/s to 30 m/s.

The length scale of the rigid model of the chimney is 1:250, which is determined by test operation and blocking ratio of the wind tunnel. There are 12 levels of taps along chimney height and each level's height in the prototype scale is shown in Fig. 2b. Each level has 40 taps that are equally distributed around the section circumference, and the distribution of the 40 taps on the circumference of one section is shown in Fig. 2c. There are, therefore, 480 taps on the surface of the chimney model in total. Considering possibility of the potential construction sites, two categories of terrain according to China's code of practice (GB 500009), i.e., Category A (exponent of mean wind profile $\alpha = 0.12$) and Category B (exponent $\alpha = 0.15$), are considered. In addition, a uniform flow is also considered for comparison. The mean wind velocity and turbulence intensity of the above three types of the oncoming flow are shown in Fig. 3.

In line with 40 taps, 40 paper strips with a uniform width of 4 mm, as roughness elements, are longitudinally pasted on the area between two adjacent columns of tap. It has been reported that thickness of the