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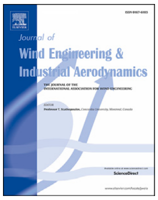

Effects of structural damping on wind-induced responses of a 243-meter-high solar tower based on a novel elastic test model

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ABSTRACT

The effects of structural damping to the responses of the vortex-induced vibration of solar tower should be investigated carefully to provide a reference for the structural designers. A new type of elastic test model for a 243-meter-high solar tower is particularly designed and manufactured. A core beam is designed in the test model to simulate the stiffness of the concrete structure, and a coat with baseplate (like a cup) is designed to simulate the steel structure. A structural damping ratio as low as 0.3% is realized, and four level of structural damping ratio, including 0.7%, 1.0%, 1.5% and 2.0%, can be conveniently achieved. A series wind tunnel tests are carried out to investigate the features of the wind-induced responses of the solar tower at the structural damping level of 0.3%, 0.7%, 1.0%, 1.5% and 2.0%. The results show that obvious vortex-induced vibration could be found within wind velocity range of $U_{10} = 21.5$–28.4 m/s for the structural damping ratio of 0.7%. At this time, the highest vortex-induced responses (at the wind velocity of $U_{10} = 23.2$ m/s), including acceleration at the top, base shear and base moment, are far larger than those at the design wind velocity ($U_{10} = 41.0$ m/s). Moreover, it appears that the wind-induced responses in cross-wind direction are far higher than those in the along-wind direction. The most important point is that the base shear and moment in the cross-wind direction measured from wind tunnel tests are far higher than the values obtained from the Code ACI 307–08. The wind-induced responses of the solar tower are extremely sensitive to the structural damping of the test model. For example, the highest acceleration, base shear and moment in cross-wind direction are respectively reduced by about 67%, 74%, 71% when structural damping ratio slightly increases from 0.7% to 1.0%. It seems that the vortex-induced vibration of the solar tower could be effectively mitigated if the structural damping ratio could be enhanced over 1.0%.

1. Introduction

Solar tower, which is centered in a field of mirrors that reflect sun rays towards the top of the tower, was built all over the world in recent years (González-Roubaud et al., 2017; Ozoegwu et al., 2017; Tahri et al., 2015). This is a new type of structural system, which has no particular Codes or Standards to guide its structural design. The configuration of solar tower is very similar to a chimney, which generally has a circular appearance. However, the inner structures of the solar tower and the chimney are totally different from each other. Even so, the structural engineers have to use the Codes or Standards particularly for the chimney to design the solar tower.

Solar tower often has a circular cylinder shape with the Strouhal number (S_t) about 0.20 (Simiu and Scanlan, 1996). The vortex-induced resonance wind velocity corresponding for the first mode shape of the solar tower is often lower than the design wind velocity. For example, the outer diameter D and the first natural frequency f_1 of the Noor III solar tower, which is located in the Kingdom of Morocco, are about 20 m and 0.28 Hz, respectively. Its vortex-induced resonance wind velocity for the first mode, $U_1 = f_1 D / S_t$, is about 28 m/s, which is far less than the design wind velocity (41 m/s at the height of 10 m). This implies that the structural design of the solar tower should take into account the responses of vortex-induced vibration.

Plenty of studies on the vortex-induced responses of high-rise buildings have been done (Quan and Gu, 2005; Gu and Quan, 2004; Marukawa et al., 1996; Watanabe et al., 1997). People usually pay their attentions into the aerodynamic damping to evaluate the effects of the wind induced vibration. The results obtained from high-rise buildings show

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that a positive aerodynamic damping is always found in the along-wind direction (Boggs, 1991; Holmes, 1996; Quan and Gu, 2005) whereas a negative aerodynamic damping in the cross-wind direction could be observed near the vortex-induced resonance wind velocity (Davenport and Tschanz, 1981; Boggs, 1991; Marukawa et al., 1996; Watanabe et al., 1997), which indicates that large amplitude oscillation in the cross-wind direction could be expected. In fact, the vortex-induced resonance wind velocity of the high-rise building is often lower than the design wind velocity because high-rise building has a lower S_t number (0.1 for rectangular cylinder) and a larger characteristic dimension than the solar tower. Furthermore, some aerodynamic countermeasures, which change the configuration of the high-rise buildings, could be used to effectively reduce the vortex-induced responses of high-rise buildings (Quan and Gu, 2005; Tanaka et al., 2012; Bandi et al., 2013; Kim et al., 2014, 2015).

People found that the chimney, which usually has a circular cylinder shape like solar tower, undergoes the vortex-induced vibration within the design wind velocity (D'Asdia and Noè, 1998; Verboom and van Koten, 2010). Wootton (1969) carried out wind tunnel tests on a chimney with smooth and roughness surfaces to investigate the feature of vortex-induced vibration. Some mathematics models were proposed to predict the across-wind responses of slender structures of circular cross sections (Vickery and Basu, 1983; Basu and Vickery, 1983; Pagnini and Piccardo, 2017). Ruscheweyh (1994) compared the results of mathematics models with full scale measurements. Some effective aerodynamic countermeasures, for example helical wires, were proposed to effectively reduce the responses of vortex-induced vibration of the chimney (Zdravkovich, 1981), and were adopted by some Codes and Standards (CICIND, 1999). However, these kinds of aerodynamic countermeasures could not be used on the solar tower because most of the surface of the solar tower should keep smooth to realize the function of absorbing solar energy. Tuned mass damper was successfully adopted to mitigate the vortex induced vibration of the chimney (Brownjohn et al., 2010), which seems to be a more reliable way to reduce vortex-induced vibration of the solar tower.

The solar tower, which has few structural joints and furniture, should have lower structural damping than the high-rise building, which contains a large amount of structural joints and furniture. Some field observations on the high-rise buildings and the chimneys found that the structural damping ratio for the first mode is as low as 0.5% (Satake et al., 2003; Cho et al., 2001). A higher value of the structural damping ratio is used in the design of the building and the chimney in practice, for example 1% in America code ACI 307–08 (ACI 307-08, 2008), 2% and 5% in Chinese Code GB 50051-2013 (GB 50051-2013, 2013) respectively for concrete and steel structures. In a word, it is controversial for the structural designers to choose a reasonable level of structural damping. On the other hand, the response of the vortex-induced vibration of the solar tower is extremely sensitive to the structural damping. The effects of structural damping to the responses of the vortex-induced vibration should be investigated carefully to provide a reference for the structural designers.

In this paper, the effects of structural damping to the responses of the vortex-induced vibration are investigated through wind tunnel tests based on a novel elastic test model. First, a new type of elastic test model for a 243-meter-high solar tower is particularly designed and manufactured to realize a low structural damping ratio as low as 0.3%. Several levels of structural damping could be conveniently achieved by pasting different types of adhesive tapes upon the gaps between the coats. Second, a series wind tunnel tests are carried out to study the feature of the wind-induced responses of the solar tower at the structural damping ratios of 0.3%, 0.7%, 1.0%, 1.5% and 2.0%. The effects of the structural damping to the responses of the vortex-induced vibration of the solar tower are studied in detail.

2. Elastic test model

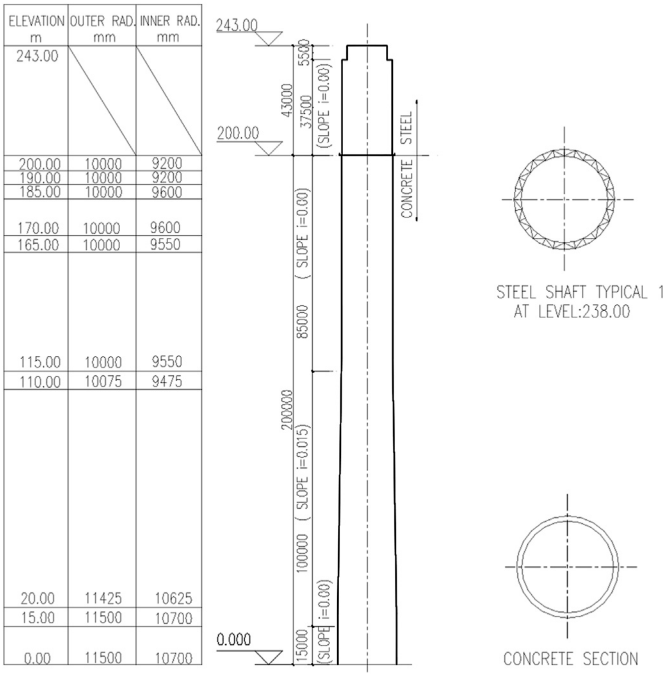
2.1. Background of this study

The background of this study is a 243-meter-high solar tower in the Kingdom of Morocco, as shown in Fig. 1. Steel structure is adopted for the top 43 m and reinforced concrete (RC) structure for the bottom 200 m. The RC structure has a ring shaped cross section with its outer diameter varying from 23.0 m at the ground level to 20.0 m at the level of 200 m, and the thickness of the RC wall varying from 800 mm at the ground level to 450 mm at the level of 200 m. The outer diameter of the steel structure is 20.0 m. An analysis based on the finite element method (FEM) by using ANSYS shows that the first three natural frequencies of this solar tower are 0.28, 1.12 and 2.03 Hz, respectively.

2.2. Considerations of similarity criteria

Some non-dimensional similarity parameters, for example Reynolds number, Froude number, Strouhal number, Cauchy number, mass ratio and damping ratio, and so on, should be reasonably simulated in the design of the elastic test model to ensure the reliability of the experimental results. However, it is difficult to satisfy all of similarity parameters in the wind tunnel tests. First, Reynolds number could not be exactly satisfied because of the large geometric scale and the limitation of the wind velocity in wind tunnel. Second, it is not necessary to precisely simulate the Froude number because the wind forces and wind-induced vibrations of the solar tower are in the horizontal direction whereas the gravity is in the vertical direction. This implies that the wind velocity scale is not directly determined from the length scale, and a higher test wind velocity could be adopted to ensure the measurement sensitivity. The length scale of the test model, λ_L, is 1/200, which means that the total height of the test model is 1.215 m and the diameter of the test model is around 0.1 m. The velocity scale, λ_V, is preliminarily selected to be 1/5 in this study, which will be finally determined according to the exact natural frequency of the elastic test model (as shown in Section 3). The density scale, λ_ρ, is 1.0 because of testing in the air of same density as that surrounding the prototype. Once the scales of λ_L, λ_V, λ_ρ are given, other scales could be determined based on similarity theory, as shown in Table 1.

Actually, Reynolds number has significant effect on the responses of the circular-shaped solar tower in wind tunnel test. A series wind tunnel tests have been done to reduce the effect of Reynolds number by increasing the surface roughness of the test model, which will be introduced in detail in the future.



ELEVATION m	OUTER RAD. mm	INNER RAD. mm
243.00		
200.00	10000	9200
190.00	10000	9200
185.00	10000	9600
170.00	10000	9600
165.00	10000	9550
115.00	10000	9550
110.00	10075	9475
20.00	11425	10625
15.00	11500	10700
0.00	11500	10700

Fig. 1. Elevation and cross section of the 243-meter-high solar tower.