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Vortex-induced vibration tests of circular cylinders connected with typical joints in transmission towers

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ABSTRACT

Vortex-induced vibration (VIV) tests on full-scale cylinders are undertaken to study the vibration performance of steel tubes connected with typical joints in transmission towers, including [-shaped gusset plate connection, U-shaped gusset plate connection, cross-gusset connection and the flange. Due to the asymmetric flexural stiffness for the cross section of the [-shaped or U-shaped gusset plate, VIV is only generated about the minor axis. The paper presents the relationship between the slenderness ratio and the occurrence wind speed of VIV about the minor axis. Moreover, it has been shown that VIV can occur not only in laminar flows, but also in turbulent flows, and the amplitude decreases as the turbulence intensity rises. The amplitude is affected by the wind attack angle, and drops as the wind attack angle decreases. It is revealed that for the cylinders connected with [-shaped gusset plates with the slenderness ratio of 100~200, the value of Strouhal number ranges from 0.20 to 0.21and the reduced velocity from 5.0 to 5.5.

1. Introduction

Transmission towers with steel tubes, named tubular towers, have smaller force coefficient for wind loads, better torsion resistance and lighter weight than traditional angular towers. They are widely used, especially in the long-span transmission system, and there have hitherto been 38 long-span projects using tubular towers in China. For example, the Huainan–Shanghai 1000 kV double-circuit transmission line with a full length of 647 km, which is still under design, is entirely composed of tubular towers above 100 m in height (Deng and Si, 2008). Vortex-induced vibration (VIV) is a critical problem for the steel cylinders used in tubular towers. VIV often occurs in the sub-critical Reynolds number range ($Re < 3 \times 10^5$) with low critical wind velocity. Even though this velocity is much lower than the design velocity, the continued vibration of the members is liable to cause fatigue failure and endanger the system safety. In fact, there have been several accidents caused by VIV of cylinders in China, such as the failure of cross arm members supporting the ground wires in the Zhejiang–Zhoushan 220 kV long-span transmission towers, and the VIV failure of the diaphragm members aroused by VIV in the tower body in Nanjing 220 kV long-span transmission tower (Liu, 2002).

Until now, no reference has been provided for VIV of cylinders in transmission towers in latest Chinese code (China Electric Power Press, 2002). However, the VIV occurrence wind velocity can be identified in Chinese code, depending on the slenderness ratio of the cylinder and the boundary condition—ideal hinged or rigid connection, and the VIV occurrence wind velocity should be no less than 15 m/s. The cylinder is neither hinged nor rigid in the real, due to various connection types used for transmission towers. Thus, the assumption that connections are ideal hinged, will lead to conservative estimation for structural design, which has been reported in the previous experiment (Deng et al., 2009). Moreover, the restriction that VIV occurrence wind velocity should be no less than 15 m/s is also conservative for design. Based on the Chinese code, the slenderness ratio of the steel cylinders should be less than 87 for an ideal hinged connection under the VIV occurrence wind velocity of 15 m/s, which results in the huge increase in tower weight, while the slenderness ratio can reach to 220 or 250 for angles. Therefore, a reasonable value of the VIV occurrence wind velocity should be defined by the fatigue calculation of steel cylinders (Li, 2008).

It is proved that wind tunnel test is the best way to study VIV of the cylindrical members. Pastò (Pastò, 2008) conducted wind tunnel tests on VIV of truncated cylinder models in wall thickness of 5 mm, in diameter of 0.155 m and in length of 2.3 m, which were manufactured from composite materials. The models were elastically suspended outside the wind tunnel by means of eight springs (four for each side) connected to the cylinder axes.

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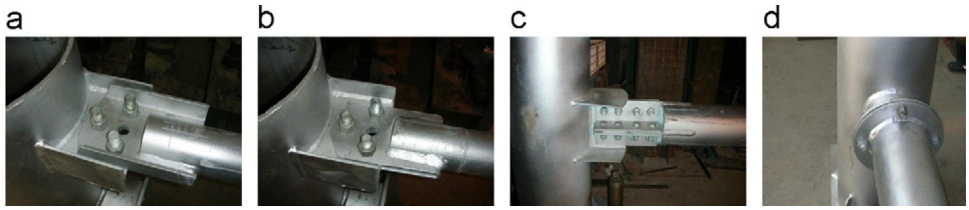

Fig. 1. Connection types. (a) [-shaped gusset plate. (b) U-shaped gusset plate. (c) Cross-gusset. (d) Flange.

Table 1
Profiles of samples (cylinders with a diameter of 0.07 m and a wall thickness of 3.5 mm).

Slenderness ratio (λ)	Length l (mm)	Connection type						
		[-shaped gusset plate			U-shaped gusset plate		Cross-gusset	Flange
100	2354		S100-2					
120	2825		S120-2					
140	3296	S140-1	S140-2	S140-3	U140-2	U140-3		
160	3766		S160-2					
180	4237		S180-2					
200	4708		S200-2				C200-8	F200-4
220	5179		S220-2					

S, U, C and F are the symbols of [-shaped gusset plate, U-shaped gusset plate, cross-gusset and intersecting joint/flange, respectively, following which the 3-digit numbers stand for the slenderness ratio. The figure after "-" is the number of bolts for connection.

The longitudinal displacement was restrained by means of four prestressed cables placed upstream and downstream starting from each cylinder extremity. Two additional devices, providing damping to the system, were placed at the extremities of the cylinder. Damping was ensured by a bar immersed in a water tank. The test investigated the turbulence intensity, turbulence scale, the surface roughness of models, the parameters of mass and damping and the effect of Reynolds number to VIV. Beside the Reynolds number, Re, the Strouhal number, St, was proved to be related to the surface roughness of models, the turbulence intensity and the turbulence scale in the wind field. However, it was difficult to preserve the end condition of the truncated models and the damping, as per the real structure. Therefore, the current research has initiated wind tunnel tests on the VIV of cylinders with typical connections commonly used in transmission towers. As shown in Fig. 1, the specimens are hollow cylinders with the dimensions of Φ70 mm in outer diameter, 3.5 mm in shell thickness and with the slenderness ratio of 100$\sim$220, which are connected with [-shaped gusset plates, U-shaped gusset plates, cross-gussets and flanges. Moreover, tests have also been performed in the laminar and turbulent wind flows, and the variation of wind attack angle was considered. In this way, the natural frequency of specimens, the critical wind velocity of VIV, the amplitude, the Strouhal number and the range of lock-in, have been investigated. Finally, the VIV performance in different connection types is discussed and the relationship between the critical wind velocity and slenderness ratio of cylinders is proposed in this paper.

2. The specimens tested

The specimens tested in the wind tunnel have circular hollow section with 0.07 m in outer diameter, 3.5 mm in thickness and the slenderness ratio λ ranging from 100 to 220 ($\lambda = l/i$, where l is the cylinder length and i is the gyration radius of the cross section). The cylinders are supported by [-shaped gusset plates, U-shaped gusset plates, cross-gussets and flanges, all of which are commonly used for the transmission towers (Fig. 1). Grade 6.8 steel bolts[1] (China Electric Power Press, 2002) are used for the connections. The specimens are hot-dipped galvanized to achieve the same surface roughness as the real members of transmission towers. Details are listed in Table 1 for slenderness ratio, connection type and number of bolts.

3. Experimental procedures

The wind tunnel tests have been performed in TJ-3 wind tunnel, Tongji University, which has a working section of 15 m width, 2 m height and 14 m length and continuously adjustable wind velocity ranging from 1.0 to 17.6 m/s. Two-element spires have been placed upstream the models to generate turbulent flows, and the turbulence intensity can been varied by adjusting the distance between spires. Shown in Fig. 2, the wind attack angle β is defined as inclination angle between the horizontal structural axis of the cylinder and the wind direction inclination in the horizontal plane. In the test, the wind attack angle keeps 90°, except when the effect of the angle is investigated. Accelerometers and laser transducers have been installed as the arrangement shown in Fig. 2. The cross-wind and along-wind displacements of models have been measured by laser 2 and 1, and the cross-wind and along-wind accelerations by accelerometer 2 and 1, respectively. Furthermore, the wind velocity has been measured by the means of a pitot-tube micro-manometer, located at the same height as the cylinder. The test view is shown in Fig. 3.

Data have been collected under the wind velocity varied in steps of 1 or 0.5 m/s beyond lock-in range and 0.2 or 0.1 m/s during lock-in range in every case. For each wind velocity, time histories of accelerations and displacements have been recorded

[1] For bolts in Grade 6.8 defined in the Chinese code (China Electric Power Press, 2002), the design value is 300 Mpa for tensile strength and 240 Mpa for shear strength.