Wind and Structures, *Vol. 29, No. 2 (2019) 87-98*
DOI: https://doi.org/10.12989/was.2019.29.2.087

A review of the transmission tower-line system performance under typhoon in wind tunnel test

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(Received March 19, 2018, Revised August 2, 2018, Accepted August 17, 2018)

Abstract. As a regenerated turbulent wind field process, wind tunnel test has proven to be a promising approach for investigating the transmission tower-line system (TTLS) performance in view of experimental scaled models design, simulation techniques of wind field, and wind induced responses subjected to typhoon. However, the challenges still remain in using various wind tunnels to regenerate turbulent wind field with considerable progress having been made in recent years. This review paper provides an overview of the state-of-the-art of the wind tunnel based on active or passive controlled simulation techniques. Specific attention and critical assessment have been given to: (a) the design of experimental scaled models, (b) the simulation techniques of wind field, and (c) the responses of TTLS subjected to typhoon in wind tunnel. This review concludes with the research challenges and recommendations for future research direction.

Keywords: transmission tower-line system (TTLS); wind tunnel test; experimental scaled models; wind induced response; typhoon

1. Introduction

The evolution of the worsening ecological environment, El Nino alternating and extreme natural disasters about the wind disaster, especially for typhoon disaster, are driving the investigation for safety and stability of transmission tower-line systems (TTLS). Fang (2016) reported that Typhoon Meranti - the strongest recorded tropical cyclone struck Xiamen, China. Two base towers of 500 kV and fifteen base towers of 220 kV were fell down, and more than 3.23 million homes were knocked out power after hit by Typhoon Meranti. From the point of the losses of social and economic, the failure of TTLS can be unacceptable in the electronic age. Generally, the weather conditions, such as downbursts, tornadoes and typhoon, play a critical role to effect the service life of TTLS (Hamada *et al.* 2017, Wang *et al.* 2017a, Aboshosha *et al.* 2016, Damatty *et al.* 2018).

As an extreme weather condition, the typhoon exhibits the specific features such as high turbulence, strong dispersion and strong mutation (Tse *et al.* 2014, Jiang *et al.* 2017). At present, there are currently four options for investigating the field of wind engineering: field measurement, wind tunnel test, theoretical analysis and numerical simulation (Liu *et al.* 2014, Tian *et al.* 2016, You *et al.* 2018). As pointed out by Kepert (2002), the observations of the typhoon and boundary layer wind field play a critical role in the meteorological research. Bowen (2003) indicated that the numerical simulations have shown growing potential in predicting the weather compared to the complexity of the various meteorological processes. Hill and Lackmann (2009) applied the numerical weather prediction model to simulate tropical cyclone intensities. As Cermak (2003) noted, the wind tunnels have been widely used to study the topographic effects on wind characteristics. Furthermore, Zhang *et al.* (2009) reported the turbulence generation and dissipation dominated by the shear mechanism in the typhoon boundary layer. The atmospheric stability is close to neutral under this high wind strength condition based on wind tunnel tests. As a result, it is important that the wind resistance behavior of TTLS based on the wind tunnel test data of the typhoon is further investigated deeply.

This paper aims to provide a review on the design of experimental scaled models, simulation of wind field and responses of TTLS subjected to typhoon in wind tunnel. This paper is structured in the form of five main sections. The introduction is shown in Section 1. Three constructing methods to obtain experimental scaled models are discussed in Section 2. Two different wind field simulation techniques are provided and corresponding components are analyzed in Section 3. The responses of TTLS subjected to typhoon in

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ISSN: 1226-6116 (Print), 1598-6225 (Online)

wind tunnels, including the shape coefficient, aeroelastic model and micro-terrain are evaluated in Section 4. Section 5 presents the conclusions and future challenges.

2. Design of experimental scaled models

At present, the aerodynamic characteristics and the dynamic response of TTLS conducted by applied the experimental scaled model in the wind tunnel with such a consideration based on the total cost optimization. In addition, in view of the characteristics of the structure and working conditions of TTLS, the field measurement tests are hard to be realized (Liang *et al.* 2014). Note that the precision of the experimental scaled models plays a critical role to obtain the wind-induced response of TTLS accurately. Recently, many published investigations have been conducted with respect to the experimental scaled model and the corresponding wind-induced response of TTLS (Sumner 2010, Jiang *et al.* 2011, Tian *et al.* 2014). For example, Loredo-Souza *et al.* (2001) carried out the wind tunnel test successfully by condensing the span value of the wire and proposed a new method to modify the aeroelastic model of wire. Chen *et al.* (2011) evaluated the wind-induced structural responses of the long-span roof model during the typhoon and found that the dynamic characteristics of the complex experimental scaled models can be predicted accurately. Lin *et al.* (2012) studied the response of an overhead electrical power transmission line to two types of wind forcing by applying an aeroelastic model (1/100 length-scaling). Various methods, including the centralized stiffness method, the discrete stiffness method and the method of rigidity section plus V-shaped or U-shaped spring are described as follows.

2.1 Centralized stiffness method

The centralized stiffness method exhibits excellent properties, including high stiffness-to-density ratio and good strength-to-weight ratio, making it a promising option to fabricate the aeroelastic model, as shown by Zhao *et al.* (2018). However, the anamorphic phenomenon of the aerodynamic force transferring appears due to the inevitable torsional effect. Furthermore, the additional stiffness caused by the lightweight material tends to a rapidly increase for the whole structure.

Many reported studies have been conducted on the experimental scaled models with the method of centralized stiffness. Deng *et al.* (2003) tested the Jiangyin Tower of 500 kV using a “stick” type aerodynamic model, which indicates that the natural frequency of the tower with conductors is slightly larger than that of the tower without conductors and conductors significantly improves the structural damping. Wang *et al.* (2005) applied the centralized stiffness method to build the aeroelastic model of a single-rod transmission tower and analyzed the wind-induced response under the different wind velocity. Tang *et al.* (2011) fabricated an aeroelastic model of an electric transmission tower using the centralized stiffness method and evaluated the wind-induced response in the natural atmospheric boundary layer (ABL) wind tunnel. The similarity of quality, stiffness and aerodynamic profile could be achieved simultaneously. Similarly, Yang *et al.* (2015) established two cross-arm aeroelastic models of a 500 kV double circuit and ultra high voltage (UHV) transmission tower, and broken the coating to avoid the stiffness and damping. The parameters for calculating the skewed wind loads developed from the wind tunnel tests were compared to the regulations in some applicable standards. Suggestions on the drag coefficients, the skewed wind load factors and the wind load distribution factors were proposed. Especially for Chinese standard, the drag coefficient of single member should be substituted by that of the single frame in calculating the global drag coefficients of cross-arms. The transversal wind load for 0° wind incidence angle and the longitudinal wind load for 30° wind incidence angle are conservative. Zhao *et al.* (2018) fabricated an aeroelastic model of 1000 kV Sutong long span transmission tower-line system, and adjusted the rigidity matrix of transmission lines to modifying the similarity ratios of aerodynamic damping of the aeroelastic model of transmission line cannot meet the basic scale laws. Here, the desired profile of the linear tower model is obtained by using the capillary stainless steel as the frame and the frame is covered with plastic. Meanwhile, the sponge rubber is filled between the frame and the covered plastic discontinuously in order to transfer load. Prior to experiment, the lead is also employed to balance the designed quality.

2.2 Discrete stiffness method

The discrete stiffness method is used to simulate the aerodynamic and dynamic characteristics of the original structure as well as the detection of the torsional effect of the tower body. In consideration of the “stiffness similarity” and “geometry similarity” of the model structure, the consistency between the model and original structure can be guaranteed. Previous investigations have been performed in terms of the material selection and machining process for model structures.

Guo *et al.* (2007) designed an aeroelastic model with discrete stiffness method to investigate the wind-induced dynamic response of long span transmission line system. The bars of the transmission tower were fabricated by the thin-walled copper tube and capillary stainless steel tube to meet the requirement of “stiffness similarity”. Then, the bubble paper was used to cover the bars to achieve the desired profile. The wind tunnel tests of the single tower model and tower-line system model were conducted with different wind directions and velocities in the turbulent flow. Deng *et al.* (2013, 2017) employed the discrete stiffness method to design the aeroelastic model and evaluated the wind-induced vibration responses of an UHV TTLS through wind tunnel tests. The tower is simulated by thin-wall copper tubes and capillary tubes, and transmission lines are simulated by stainless steel wires. He *et al.* (2013) proposed to adopt discrete stiffness method to make aeroelastic model for transmission tower. They applied the thin-walled copper tube and capillary stainless steel tube as the model bar and profile mandrel to obtain the desired tension and compression stiffness. Similarly, the bubble paper was used to cover the bars to achieve the desired profile for the windward area. Zhao *et al.* (2014) fabricated an aeroelastic model of the narrow based transmission tower using the discrete stiffness method. The major bars were covered by the lightweight plastic straws and other angle irons replaced by the aluminum foil to meet the requirement of "geometric similarity" compared to the tower. Zhang *et al.* (2017) built an aeroelastic model of a 220 kV double circuit compact narrow based transmission tower using the dispersed stiffness method. The rectangular aluminum tubes were used to simulate the stiffness and the aluminum foil was applied to paste into the surface of the corresponding angle irons. In addition, the lead wire should be considered to balance the auxiliary accessories (e.g., gusset plates and bolts). Meanwhile, Tian *et al.* (2017) proposed the dispersed stiffness approach to establish an aeroelastic model of a 1000 kV large span UHV TTLS and condensed the span of the wire. Here, the brass tubes were used to bear most of the model weight and wind load. The "geometric similarity" was required by employing the polypropylene tubes to cover the model bars. Similarly, the lead wires were located along the tower strut to meet the requirement of the uniformly distributed load.

2.3 Method of rigidity section plus V-shaped or U-shaped spring

Recently, the method of rigidity section plus V-shaped or U-shaped spring plays an important role in processing the transmission tower models. Several rigid segments based on the theory of geometric similarity are fabricated and the mass distribution of each segments is consistent with the original structure. Then, the V-shaped or U-shaped spring is applied to connect these segments to ensure the similar stiffness and dynamic characteristics between the experimental scaled model and the original structure.

The TTLS with a large span UHV (1000 kV) was modeled by Li *et al.* (2008). This aeroelastic model of TTLS used the rigidity sections plus V-shaped spring through wind tunnel tests (Li *et al.* 2009, 2011). They fabricated a number of rigid structures based on the principle of "geometric similarity" compared to the transmission tower and the quality distribution of each scaled sections corresponded to a consistent with the tower structure. Then, each sections were connected by using V-shaped springs. The aerodynamic characteristics and geometry similarity could be guaranteed for this aeroelastic model, especially for the consistency of the wind resistance coefficient and eddy current loss. Similarly, Xiao *et al.* (2010) evaluated the comparison analysis between the experimental result in wind tunnel and test analysis result detected by the high-frequency balance force test. The experimental aeroelastic model was also fabricated using the method of the rigidity sections plus V-shaped spring. However, this V-shaped spring is difficult to machine.

Along this line of consideration, Liang *et al.* (2009) proposed the method of the semi-rigidity sections plus U-shaped spring to build an aeroelastic model in view of the stiffness and the aerodynamic response. Here, this U-shaped spring was designed based on the requirement of the similarity ratio for the flexural stiffness and axial stiffness. Similarly, Yu *et al.* (2015) also applied the method of the semi-rigidity sections plus U-shaped spring to fabricate an aeroelastic model of the column tower.

3. Simulation techniques of wind field

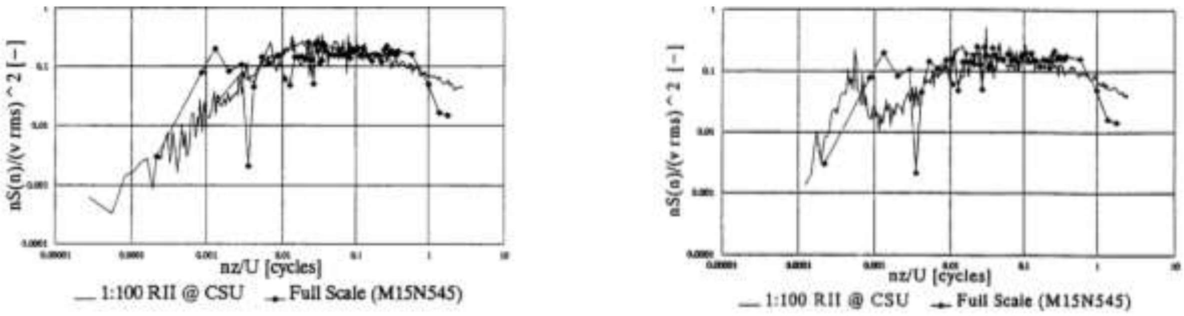
The effective simulation of turbulence characteristics (turbulence intensity, turbulence integral scale, fluctuating wind power spectra) of typhoon wind field play a critical role in promoting the wind tunnel test of TTLS. As stated by Wang *et al.* (2017c, 2017d), the typhoon Meari revealed that the turbulence intensity value ranged from 10% to 30% and the maximum and mean value of turbulence integral scale were 650 m and 165.5 m, respectively. The simulation techniques of the wind field during wind tunnel tests contains the passive-simulation technique and active-simulation technique, which is divided according to whether it includes the control components (Ozono *et al.* 2007).

3.1 Passive-simulation technique

The simulation technology of turbulent flow field is formed by using the turbulence generation system composed of several passive turbulence device such as spire, fence and roughness element. This turbulence generation structure can achieve the expected control goal with few energy input.

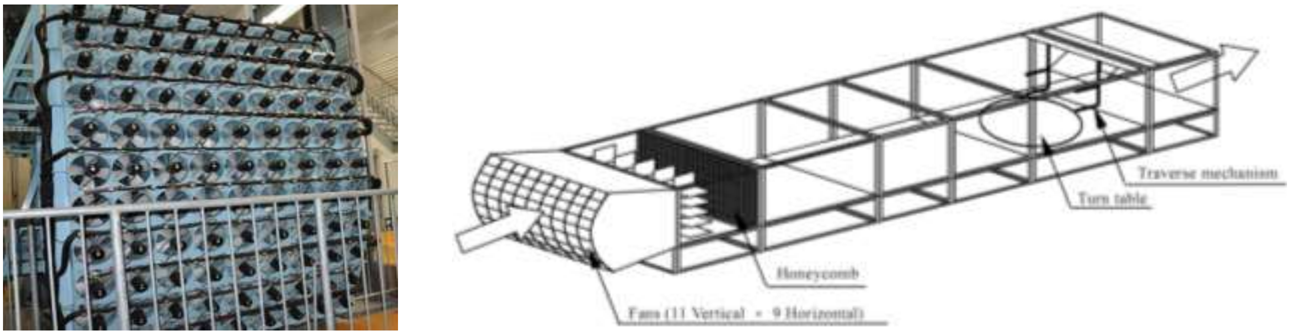
Chuang and Cermak (1965) adopted the roughness element passive simulation device to simulate the atmospheric boundary layer wind field through the wind tunnel test in Colorado State University for the first time. Since the 1980s, various kinds of spires (i.e., triangle, semi-elliptical, trapezoidal) based on the resistance of spire-roughness element and the momentum analysis theory was proposed by Irwin (1981) and Sill (1988).

Pang *et al.* (2004) applied the spire combined with different arrangements of roughness element device to simulate the profiles of wind speed and turbulence intensity through the boundary layer wind tunnel named the TJ-3 Wind Tunnel located in Tongji University. The desired precision of the turbulence power spectra and the integral scale was obtained within a certain height range compared to the natural atmospheric boundary layer (ABL). However, a negative correlation between the integral scale and the height value was obtained as the height increases and the density curve of the turbulence power spectrum tends to the higher frequency values. In addition, the fence simulator was used to investigate the turbulence in the boundary layer wind tunnel named the TJ-2 Wind Tunnel located in Tongji University, as shown by Wang *et al.* (2001). They found that the smaller of the distance between the measuring points and the fence, the larger the turbulence. Recently, the influence of the distance between two grilles and the widths of grilles on the turbulence characteristics at different cross section through wind tunnel tests has also been evaluated by Bai *et al.* (2016).



(a) Static oscillating spires (b) Dynamic oscillating spires

Fig. 1 Comparison of the simulation results of the lateral velocity spectra based on the static and dynamic controllable oscillating spires. (z (m) is the roof height, U (m/s) is the velocity at z and n (Hz) is the frequency) (Cermak *et al.* 1995)



(a) Photograph (Ma *et al.* 2013) (b) Schematic (Butler *et al.* 2010)

Fig. 2 The 99 multiple fans active controlled wind tunnels

At present, the wind field of ABL can be simulated by using the passive-simulation technique in a certain degree. However, it is not competent qualified to simulate the low frequency turbulence and the value of the high frequency turbulence power spectral density function is high. Along this line of consideration, the active-simulation techniques should be developed to enhance the simulation of low-frequency turbulence in wind tunnel tests.

3.2 Active-simulation technique

Active-simulation techniques for simulating the wind field of ABL by injecting the random turbulence energy into the wind flow based on the controllable motion mechanism, including the controllable oscillating spire or fence and the active controlled multi-fan (Cermak 1995, Li *et al.* 2019).

3.2.1 Controllable oscillating spire or fence

The wind tunnel should be developed by employing active-simulation techniques to enhance the simulation of low-frequency turbulence with the small turbulent integral scale. According researchers at Colorado State University (CSU), two columns controllable oscillating spires have been added to generate the wind field of ABL (Kareem *et al.* 1984, Cermak 1992). The better result of the low frequency lateral velocity spectra is shown in Fig. 1 (Cermak *et al.* 1995). However, the value of high frequency lateral velocity spectra was still high. A similar result was obtained by Kawatani and Kim (1992). Pang *et al.* (2004, 2008) evaluated the effect of the controllable oscillating fence on the wind field of ABL in China. The maximum value of turbulent integral scale can reach 0.65 m. However, the turbulent integral scale of wind tunnel test cannot reach the required value (15 m). In addition, the value of high frequency lateral velocity spectra was still high.

3.2.2 Active controlled multi-fan

Recently, the active controlled multi-fan techniques have been developed owing to the deficiency of the small turbulence integral scale and the rapid decline in turbulence intensity with the height. Teunissen (1972) simulated the turbulent boundary layer flow field with the integral scale over 1 m by combining the controlled roughness of the test section. Teunissen’s wind tunnel provided research direction for designing the multi-fan active controlled wind tunnel to produce desired flow conditions.

According researchers at Miyazaki University, Japan, they constructed the 2D and 3D active control wind tunnels by employing different arrangements of multi-fans (Nishi *et al.* 1993, 1995, 1997, 1999). Fig. 2 illustrates the schematic of the multiple fans wind tunnel consisting of an array of 9 rows, each with 11 fans arranged horizontally (Ma *et al.* 2013, Butler *et al.* 2010). The characteristics of this multi-fan active controlled wind tunnel are avoiding the extremely complicated work in the passive controlled wind tunnel by altering the speeds and phases for each fans (Cao *et al.*

Fig. 3 The full-scale 12-Fan WOW in the FIU (Fu 2013)

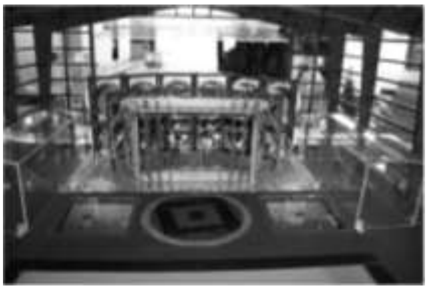


Fig. 4 Small-scale 12-Fan WOW in the FIU (Fu 2013)

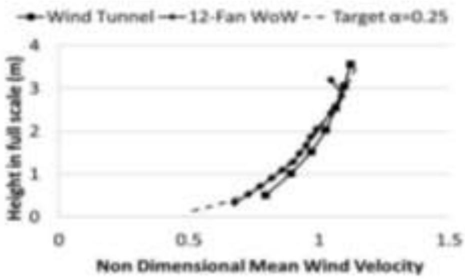


Fig. 5 Curve of ABL profile of wind tunnel in the small scale 12-Fan WOW with respect to target ABL profile (Fu 2013)

2001, 2002, Ozono *et al.* 2006). However, the wind load test of typhoon for TTLS in this multi-fan active controlled wind tunnel can't be carried out due to the limitation of the size of turn table.

Researchers of Florida International University (FIU) have developed the full-scale 12-Fan Wall of Wind (WOW) to evaluate the wind-induced pressure acting on the pavers, as shown in Fig. 3 (Fu 2013). The Category 5 Saffir-Simpson Scale hurricane wind speed was achieved. Furthermore, the mean wind speed and partial turbulence characteristics of real hurricane winds were reasonably replicated (Leatherman *et al.* 2007, Blessing *et al.* 2009, Aly *et al.* 2012, Baheru *et al.* 2014). Particularly, a cost effective small-scale 12-Fan replica (Fig. 4) was established for developing the requisite flow management devices due to the limited design time and resource (Fu 2013). A good agreement between the target and measured non dimensional mean wind velocity with height was found by Fu (2013) in Fig. 5.

Recently, Aly *et al.* (2014, 2017) from Louisiana State University (LSU) have conducted the aerodynamic tests for small-scale models (including 15 fans in a 3×5 array) to simulate the hurricane-force winds in near-ground boundary layer, as shown in Fig. 6. They found that the mean and peak pressure coefficients were consistent with available results from wind tunnel testing.

A multiple controlled fan boundary layer wind tunnel (Fig. 7(a)) consisted of an array of 7 rows, each with 15 fans arranged horizontally was constructed at the Insurance Institute for Business & Home Safety (IBHS) Research Center, United States (Morrision *et al.* 2012). Fig. 7(b) illustrates the schematic of 1:10 scale model of the IBHS Research Center Full-Scale Test Facility (Smith *et al.* 2011, 2012). Note that the highest speed of wind field can reach approximately 58 m/s and the test section of the inlet jet has dimensions 19.8 m wide by 9.1 m tall (Quarles *et al.* 2012, Standohar *et al.* 2017). The results obtained reveals that the percentage of the similarity is up to 95% between the input RPM and measured RPM (Liu *et al.* 2009).

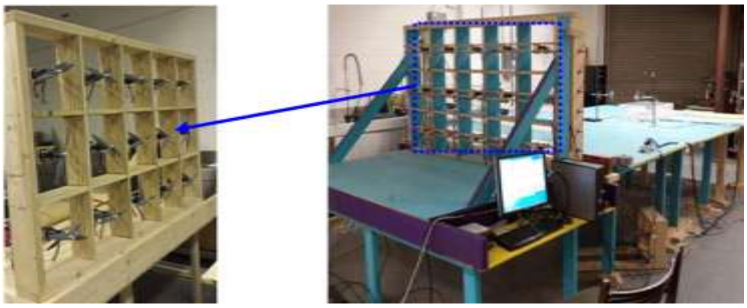
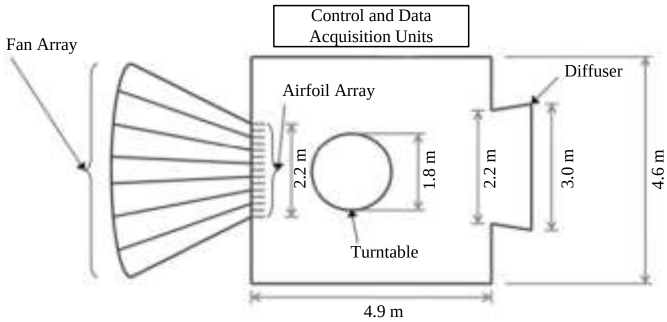


Fig. 6 Prototype of the open-jet simulator in the LSU (Aly *et al.* 2014, 2017)

(a) Photograph (Morrision *et al.* 2012)



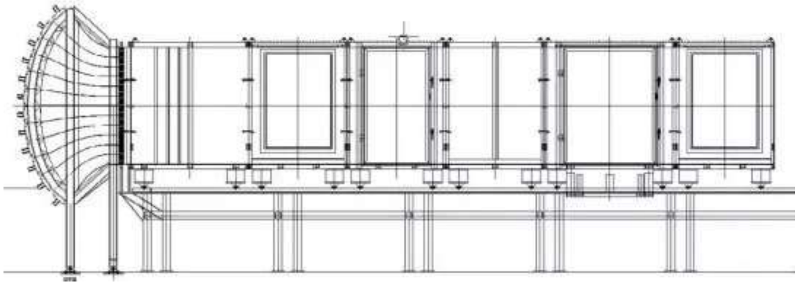
(b) Schematic (Smith *et al.* 2011, 2012)

Fig. 7 The IBHS Research Center and the 1:10 scale model of the IBHS Research Center

Table 1 Comparison between active simulation technique and passive simulation technique

Simulation technique	Passive simulation technique	Active simulation technique	
Device	Spire, fence and roughness element (Pang *et al.* 2004, Bai *et al.* 2016)	Controllable oscillating spire or fence (Pang *et al.* 2008)	Active controlled multi-fan (Aly *et al.* 2012, Cao *et al.* 2017)
Turbulence intensity	The value of low frequency turbulence is low, the value of high frequency turbulence is high, inconsistent with the natural situation	The value of high frequency turbulence is high, inconsistent with the natural situation	Close to the natural wind field
Turbulence integral scale	Value: 0.3-0.5 m; Small-scale (1/500-1/300); It is difficult to meet the requirement of the large turbulent integral scale (1/100)	Value: 1.5-3.0 m; Large-scale (1/100-1/50); The requirement of the large turbulent integral scale (1/100) can be satisfied	Close to the natural wind field
Power spectral density function	The value of low frequency turbulence is low, the value of high frequency turbulence is high, inconsistent with the natural situation	The value of high frequency turbulence is high, inconsistent with the natural situation	Close to the natural wind field
Advantages	Simplified device; Low-cost	Easy adjustment for turbulence intensity and turbulence integral scale	Easy operation; Shorter test section; Highly correlation (90%) of generated flow with respected to the target flow
Disadvantages	Heavy workload; Long test section; Small value of the turbulence integral scale	Complicated device and hard to control	Short service life of the motor and the blade due to the large value variable frequency movement

(a) Photograph (Wang *et al.* 2017b)



(b) Schematic (Cao *et al.* 2017)

Fig. 8 The TJ-5 Wind Tunnel

According researchers at Tongji University, China, the multi-fan active controlled wind tunnel (i.e., TJ-5 Wind Tunnel) was constructed with 12 rows of 10 fans horizontally (Fig. 8) (Wang *et al.* 2017b, Cao *et al.* 2017). The wind speed of each fan was controlled independently. In addition, the highest wind speed can reach approximate 18 m/s and the test section has dimensions 10 m long, 1.5 m wide by 0.8 m tall. However, the wind load test of typhoon for TTLS cannot be carried out due to the small size of the test section.

In order to further understand the turbulence characteristics and performance of the active and passive simulation technique, the comparison of the above techniques is listed in Table 1.

4. Responses of TTLS subjected to typhoon in wind tunnel

4.1 Wind tunnel test of shape coefficient

The shape coefficient of the rod piece as the important parameters to design the structure of TTLS plays an important role in investigating the wind induced vibration response through the wind tunnel test.

There are some published reports on the studies of the shape coefficient of TTLS in the wind tunnel. For example, Liang *et al.* (2007) applied the base balance technique in a boundary layer wind tunnel to study the along-wind, across-wind as well as torsional dynamic wind loads on the models of three kinds of lattice towers. The results indicated that the interaction of the wake of each member of the lattice tower was a leading cause of the formation of the dynamic wind load. In addition, the analytical models were simple on the basis of the whole tower (Liang *et al.* 2008). Zhang *et al.* (2008) evaluated the characteristics of wind forces acting on the superstructures using a high frequency force balance (HFFB) technique based on two types of typical superstructures of latticed transmission tower (SLTT) in wind tunnel. Meanwhile, the variations of these coefficients with wind angles and the effects of wind turbulence and the shapes of SLTT on wind force were also discussed using the analytical models obtained by least-square method. They found that the displacement gust response factor and the base bending moments (BBM) response factor have similar trends. Meanwhile, the maximum displacement gust response factor in along wind direction of key nodes was no more than 1.8 and the maximum moment gust response factor was about 1.5 (Zhang *et al.* 2014). Yang *et al.* (2016) and Zhang *et al.* (2015) applied the scaled models of the triangular transmission tower to evaluate the structure parameter under different wind angles through the wind tunnel test. They employed the totally structured multi-block meshes to design the transmission tower structure and optimize the required wind load on the tower poles. In addition, the wind field of the lattice transmission tower model can be obtained by dealing with the N-S equation under different wind angles. Furthermore, Deng *et al.* (2010) obtained the mean wind load acting on the models and corresponding pressure coefficients by investigating the HFFB test in wind-tunnel for both models of steel tubular transmission tower. The most unfavorable wind direction angles for steel tubular transmission tower revealed 15° and 75°. Then, the corresponding pressure coefficients of steel tubular tower body and steel tubular cross arms were suggested to be 0.80 and 0.85 in view of the design requirement, respectively (Deng *et al.* 2011). Liu *et al.* (2013) evaluated the influence of the ABL wind and typhoon on the wind-induced response of transmission tower by using the 500 kV double-circuit three-tower and four-line model through wind tunnel test. The wind-induced response of the TTLS was found an increase in typhoon environment and the wind-induced coefficient value of the tower in typhoon area was greater than that in ABL wind field.

4.2 Wind tunnel test of aeroelastic model

The TTLS offering peculiar properties, such as large-span, high-flexible and small damping reveals strong nonlinear characteristics resulting in the coupling action between the tower and line that is impossible to ignore (Wang *et al.* 2011, Rao *et al.* 2012, Belloli *et al.* 2014). At present, the validity and accuracy to analyze the dynamic wind effect play a critical role in designing the desired structure of TTLS, which is hard to solve clearly and completely in theory. As a result, the wind tunnel test of shape coefficient of transmission tower has been considered a suitable option to detect the wind induced vibration response and aerodynamic parameters in view of the economic and effective control measures.

Deng *et al.* (2017) investigated the influence of different wind speeds on wind induced vibration response and control of TTLS using an aeroelastic model based on a typical large-span 500 kV double circuit transmission line. Lou *et al.* (2000) evaluated the aerodynamic responses of a tall lattice transmission tower using a 1/100 full aeroelastic model in the wind tunnel. Meanwhile, the aerodynamic force coefficients, acceleration responses and wind load factors at various wind velocities and wind attack angles were discussed (Huang *et al.* 2012). Li *et al.* (2011) analyzed the wind induced vibration response of the aeroelastic model based on the single-tower and tower-line system of the large-span TTLS under the uniform as well as turbulent flow field. They found that the acceleration of the single-tower and tower-line system increased with increasing height. Li *et al.* (2017) revealed the mechanism of load transfer acting on an aeroelastic model based on the single-tower and tower-line system and evaluated the characteristics of the wind induced vibration response of TTLS in the wind tunnel. Xie and Sun (2012) investigated the failure mechanism of TTLS under extreme load of freezing rain and promoted the corresponding strategy to improve the capacity of load-carrying. The results revealed that the partition acting on the two subassemblages could improve the mechanical performance of TTLS by considering the capacity of load-carrying and deformability. Zhang *et al.* (2017) investigated the displacements and accelerations of the area-elastic model for the transmission tower with narrow base under various heights and wind directions through wind tunnel test. The fluctuating displacements and accelerations were found no effect on the variation of wind directions and different influences on fluctuating displacements and accelerations were discovered above the ground. Similarly, Liang *et al.* (2015) studied the displacements and accelerations of a full aeroelastic model with one tower two lines under various wind speeds. They pointed out that the survival ability of the tower under strong wind could be increased effectively by enhancing the weak parts of TTLS. The above reported literatures reveals the fact that the dynamic characteristics and wind response of TTLS can be investigated effectively through the wind tunnel test.

4.3 Wind tunnel test of micro-terrain

The micro-terrain, such as hills, cliffs, and cols. plays an important role in designing and constructing the ultra-high voltage large-span TTLS. However, the actual micro-terrain varies significantly from place to place and a big difference appears sometimes between the actual wind speed and the design value, which leads to the broken of over head transmission and distribution lines and towers from time to time (Momomura *et al.* 1997, Morgan *et al.* 2008, Jing *et al.* 2008, Yao *et al.* 2017).

Okamura *et al.* (2003) reported that the downwind of the leeward of the mountain has a strong impact on the wind responses of the transmission tower based on the full-scale measurements of the wind field in the mountainous area through the wind tunnel test. Li *et al.* (2010) evaluated the wind-induced vibration of transmission tower effected by the mountain topography through the wind tunnel. They indicated that the displacement response of transmission tower under mountain topography increases within the range from 23.0% to 59.6% than that in flat terrain. Furthermore, Zhang *et al.* (2013) investigated the influence of various gradient, height and spacing of the interfered hills on the characteristics of the wind field. The results revealed that the fatigue life of transmission tower is increased early and decreased late with the increase of slopes of occluding hills, the fatigue life at hill base in lee side is the shortest. In addition, the height of occluding hills with the same slope is of little effect on the fatigue life and the fatigue life will become longer with increasing distance of the occlusion. Meanwhile, Yao (2014) analyzed the influence of slope on wind field of single hill, and that of slope, spacing of hills and wind direction on wind field of double hills through the wind tunnel test and computational fluid dynamics (CFD) simulation, respectively. They found that the response of a transmission tower under typical hilly terrain wind field is significantly larger than the case of the flat terrain at the top and lateral slope of the hill. Similarly, Xu *et al.* (2017) proposed an effective model for estimating a jumper wire swing under wind actions and investigated wind-induced swing characteristics of jumper wires under hilly terrain. The results revealed that the horizontal wind speed increases significantly with the decreasing of the turbulence intensity at the hill top. In addition, the hill top had higher horizontal wind speeds but lower vertical wind speeds compared to hillside (Lou 2015).

5. Conclusions

The comprehensive review of the progress and state-of-the-art research on the theme of the wind resistance performance of TTLS in the wind tunnel is presented. The design of experimental scaled models, simulation of wind field and responses of TTLS subjected to typhoon are important to improve the capacity of the wind resistance performance of TTLS. Although a series of research achievements have been made to improve the wind resistance of the TTLS under typhoon winds, there are still significant challenges:

• The cross section size and wind field gradient between the actual TTLS and corresponding scaled models in the wind tunnel test chamber are difficult to achieve the small scale ratio and high accuracy. In addition, the desired stiffness of models is hard to obtain due to the small cross section of the trusses of TTLS regardless of material properties. Therefore, the design method play a crucial role for the further investigation to optimize these models in terms of the experimental design, equivalent-simplification and similarity theory.

• Although many progresses on the multi-fan active controlled wind tunnel have been made, there are still many problems to be solved. At present, the open-jet multi-fan active controlled wind tunnel has been widely used to simulate the wind field and thus the energy losses are remarkably large. In addition, the wind induced response simulation of TTLS in the wind tunnel is restricted to the dimension of test sections.

• As indicated from previous literatures, the wind load of the TTLS and corresponding wind induced response is three dimensional. Furthermore, not only the along-wind load to the TTLS is significant, but also the across-wind and torsional-wind load should be considered in typhoon wind field. This is to say, the analysis method of 3D wind induced response of the lattice transmission tower should be established for the further investigation on the excitation mechanism of the wind field.

• The mechanism of vibration and failure of TTLS structures suffered various types of wind load are remarkably different. Therefore, the influence of the wind load under the extreme weather condition coupled with the accompanying rain or ice should be further studied. In addition, other high intensity wind fields such as tornadoes and downbursts should also be investigated.

Acknowledgments

The research described in this paper was financially supported by the Funding of Postgraduate Research & Practice Innovation Program of Jiangsu Province (No. KYCX19_0166).

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