J. Wind Eng. Ind. Aerodyn. 140 (2015) 10–18

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Design wind loads for tubular-angle steel cross-arms of transmission towers under skewed wind loading

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ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form
18 December 2014
Accepted 25 January 2015
Available online 17 February 2015

Keywords:
Transmission tower
Tubular-angle steel cross-arm
Wind tunnel test
Reynolds number effects
Skewed wind
Wind load

ABSTRACT

Wind tunnel tests on two cross-arm models of a 500 kV tubular-angle steel transmission tower at three mean wind speeds were carried out. The drag coefficients in wind directional axis for 19 incidence angles were obtained. The skewed wind load factors, the wind load distribution factors in transversal and longitudinal direction were calculated. Two fitting functions for the skewed wind load factors of tubular-angle steel cross-arms were determined by nonlinear fitting analysis. The wind incidence angle corresponding to the maximum skewed wind load is near 80° or 85°. With the assumption that the drag coefficients are valued based on the experimental results, the effective projected areas (EPA) of the cross-arms were calculated. 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.

1. Introduction

Transmission tower is one of the most wind-sensitive structures. Wind load is the main control load case of transmission towers. In China, many accidents including damage and even collapse of transmission towers have been induced by strong wind (Xie et al., 2006). Wind loads are very important for the structural design of transmission towers. The parameter values and the calculation methods for the wind loads are basis of the structural design of transmission towers.

The natural wind usually has an incidence angle with the direction of transmission lines. The wind loads of transmission towers should be decomposed in the transversal direction and the longitudinal direction of transmission lines for design purpose (Holmes, 2008). Therefore, the calculation method of the wind loads under skewed wind loading for transmission towers needs to be studied, which plays an important role in the structural design of transmission towers. Transmission towers are typically made of two different components: the vertical tower body and the horizontal cross-arms. Much research on the evaluation of drag coefficients of the tower bodies has been completed (Støttrup-Andersen, 2002; da Silva et al., 2005). The calculation method of the wind loads of tower bodies based on solidity ratios now can often be up to an acceptable accuracy. However, the wind loads of cross-arms especially for the tubular-angle steel cross-arms have not been studied in a sufficient depth. The cross-arms are usually located near the top of transmission towers with a higher mean wind speed. If the projected areas normal to the wind direction are identical, the wind loads acting on cross-arms are usually higher than most of tower bodies. Lou et al. (2013) investigated on the wind pressure distribution and the drag coefficients along main members, diagonal members and auxiliary members of a transmission tower. The characteristics of wind load functioning on each member were obtained. The varying law of the drag coefficients along with wind incidence angle was summarized. It shows that the experimental drag coefficients of tower bodies are smaller than the Chinese standard values, while the other standard values well agree with the experimental values. Xiao et al. (2009) studied on the varying rules of the drag coefficients of transmission towers in the vertical direction. The global drag coefficients of three typical transmission towers were compared. Deng et al. (2010) carried out a tunnel test on a combined model of a tower body and a cross-arm for a 1000 kV

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http://dx.doi.org/10.1016/j.jweia.2015.01.012

tubular transmission tower. The mean wind loads acting on the model and the corresponding drag coefficients were obtained. The test results show that the least favorable wind incidence angle for the combined model is 15°. The test model comprised by a tower body and two cross-arms was used by Mara and Ho (2011). The design wind loads of cross-arms under skewed wind were studied by wind tunnel tests. The differences between the experimental wind loads and the calculated values by adopting ASCE standard were discussed. It shows that the experimental wind loads in transversal direction are near to the calculated values by ASCE standard (ASCE, 1991). However, the calculated wind loads in transversal direction by using ASCE standard (ASCE, 2010) are much lower than the experimental values. ASCE standard (ASCE, 2010) underestimates the transversal wind loads acting on cross-arms, and it may lead potential safety hazards to transmission towers.

With regards to the calculation method of the wind loads of transmission towers especially for the cross-arms under skewed wind, coincident conclusions have not been appeared in different standards. Based on the conclusion that the maximum effective wind on the tower structures occurs at a yaw angle of 45° developed by Bayar (1986), the skewed wind load factors are used in IEC standard (IEC 60826, 2003), ASCE standard (ASCE, 1991), European standard (EN 50341-1, 2001), British standard (BS-8100, 1986), Australia/New Zealand standard (AS/NZS 7000, 2010). While the wind load distribution factors in transversal and longitudinal direction along the transmission lines are adopted in Japanese standard (JEC-127-1979, 1979) and Chinese standard (DL/T 5154-2012, 2012). Only European standard, JEC standard and Chinese standard proposes the calculation methods of skewed wind loads for tower bodies and cross-arms, respectively. An identical calculation method is used for tower bodies and cross-arms in other standards. For a specific incidence angle between wind direction and longitudinal axis of the cross-arm which is defined as θ, an invariant skewed wind load factor K_θ is used in most of the standards except for British standard and AS/NZS standard. In British standard and AS/NZS standard, K_θ is relevant to two parameters including the solidity ratio, the ratio of the projected areas of tubular members and angle members to the total projected area.

In Chinese standard, the transversal wind loads of cross-arms are calculated according to the longitudinal wind loads by multiplying some regulated ratios. The multiplying ratios are only regulated for four special skewed angles of 0°, 30°, 45° and 90°. With the development of the ultra high voltage (UHV) power grids and the construction of long-span crossing transmission line projects, structure types of the tower body and the cross-arm have been greatly changed. An identical calculation method of skewed wind loads is not adaptable for all types of tower bodies especially for cross-arms. The rationality and accuracy of the calculation method of skewed wind loads in applicable standard should be further studied.

Tubular transmission tower is often used in UHV and long span crossing transmission lines. In this study, wind tunnel tests on two cross-arm models of a tubular-angle steel transmission tower at three mean wind speeds of 10 m/s, 15 m/s and 20 m/s were carried out. The drag coefficients in wind directional axis for 19 incidence angles were obtained. The skewed wind load factors, the wind load distribution factors in transversal and longitudinal direction were calculated. Two fitting functions for the skewed wind load factors of tubular-angle steel cross-arms were determined by nonlinear fitting analysis. The effective projected areas (EPA) of the cross-arms based on experimental results and different standards were calculated. The parameters for the calculation of the skewed wind loads from the wind tunnel tests were compared to the regulations in Chinese standard and some other standards. Suggestions on the drag coefficients, the skewed wind load factors and the wind load distribution factors were proposed for determining the design wind load of cross-arms under skewed wind.

2. Wind tunnel test survey and test models

2.1. Test survey

Wind tunnel test is one of the most important means to study on the wind loads and vibration responses of lattice towers (Deng et al., 2011; Célio et al., 2003). The No. 1 cross-arm and the No. 2 cross-arm of a tensioned angled transmission tower of a 500 kV double circuit transmission line were selected for wind tunnel test. The No. 1 cross-arm and the No. 2 cross-arm are used to support the middle layer conductors and the bottom layer conductors, respectively. The wind tunnel test on the drag coefficients and lift coefficients of cross-arms belongs to force measuring tests of rigid models. It is not necessary to meet the stiffness similarity between the prototype model and the reduced-scale model. All the materials with high elastic modulus can be applied to make the wind tunnel test models. Tubular steel members and angle members were used for making the test models. The wind tunnel tests were completed in the HD-2 wind tunnel of Hunan University (China). The dimension of the HD-2 wind tunnel is 3.0 m in width and 2.5 m in height. The range of the wind speed is from 0 m/s to 58 m/s. All experiments were carried out in smooth flow. The nonuniformity of the wind velocity field in the test region is not higher than 1%. The turbulence intensity of the smooth flow is not higher than 0.2%. The reference height of the mean wind speed is 0.5 m. The force measuring equipment is a shaft type strain-gauge balance with six components developed by China Aerodynamics Research and Development Center (CARDC). The signal collecting and analyzing system can realize synchronous collection of the signals from six force components of the balance.

2.2. Test models

The ratio of the mean width to the mean height (b/a) of the No. 1 and the No. 2 cross-arm is 1.369 and 1.508, respectively. The

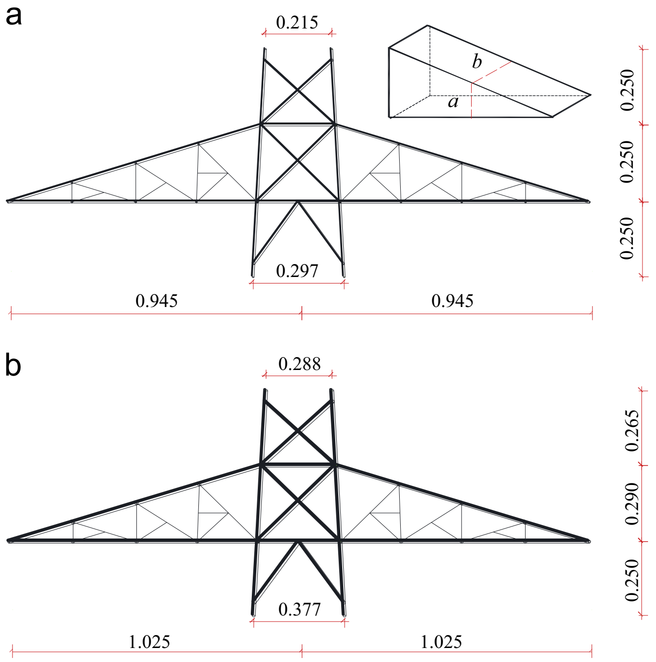

Fig. 1. Dimensions of the cross-arm model (unit: m). (a) The No. 1 cross-arm, (b) the No. 2 cross-arm.