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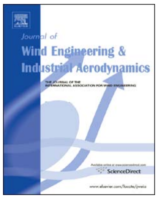

Dynamic analysis of transmission tower-line system subjected to wind and rain loads

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ABSTRACT

In order to study the dynamic response of transmission tower-line system induced by wind and rain loads, the calculating method of wind and rain loads acting on the transmission conductor is presented. The wind tunnel test, conducted by Kikuchi et al. (2003), is introduced to determine the drag coefficient under both wind and rain excitations, which is a key parameter to estimate the wind and rain loads for the transmission conductor. Then the three-span conductor and tower-line system are modeled to perform the dynamic analysis subjected to wind and rain loads, of which the results demonstrate that the maximum percentage of average displacement induced by the rain loads relative to the wind loads can reach to 22.00%, indicating strongly that the effect of rain load on the response of tower-line system is not negligible. Meanwhile the influence of wind attack angle on the response of tower-line system induced by wind and rain loads is investigated, and the results show that the most unfavorable wind attack angle is 90° and the rain load has no effect on the most unfavorable wind attack angle. The conductors made up of trapezoidal wires are used to examine the effects of wind and rain loads, and therefore some of the models and findings of the present contribution may not always be applicable. All in all, it can be stated that the rain load has an important effect on the response of tower-line system and should be given more attention.

1. Introduction

The transmission tower-line system is an important lifeline engineering and undertakes the task of transporting electricity. Though it's very important to guarantee the structural safety of transmission tower-line system during its service, the collapse cases often happen during typhoons or hurricanes and cause great economic loss and many accidents (Fu et al., 2016). Hence the primary issue is to develop the design theory and further understand the mechanism of load acting on structures in order to avoid the accidents. Typhoons or hurricanes are always accompanied by the strong rainfall, while the collapse accidents are usually attributed to strong wind and effects of rainfall are always ignored. Therefore it is necessary to study the mechanism of rain load acting on the transmission tower-line system to better guide the design and avoid the collapse accident.

Wind-driven rain (WDR) is the rain that has a horizontal velocity component. Choi (1993, 1994, 1997) made major breakthroughs in the numerical simulation of the WDR by using the computational fluid dynamics. Blocken and Carmeliet (2000a, 2000b, 2002) extended the Choi's simulation technique by adding a temporal component and developing a new weighted data averaging technique, allowing for the determination of both the spatial and temporal distribution of the WDR. Li et al. (2013) proposed a new computational approach for the rain load on the transmission tower, and carried out the dynamic response analyses and experiments of the transmission tower under the wind and rain excitations. Their results showed that the proposed approach agrees well with the wind tunnel test and the rain load influence on the transmission tower should not be ignored during the strong rainstorm. Fu et al. (2015b) modified the existing rain load model (Li et al., 2013) by introducing the velocity ratio of raindrop horizontal velocity to the corresponding wind speed. Furthermore Fu et al. (2015a) proposed a method for calculating the rain load based on the single raindrop impinging experiment, and a wind tunnel test was carried out to validate its effectiveness. Fu et al. (2016) developed the concept of equivalent basic wind speed to conduct the fragility analysis of transmission tower subjected to wind and rain loads which avoid the complex formula of rain load and the choice of different combinations of basic wind speed and rain intensity. Furthermore, the concept of critical collapse curve was proposed to evaluate the collapse status of

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transmission tower. Zhou and Liu (2014, 2015) and Zhou et al. (2015) studied the rain-wind induced vibration of transmission line assuming that the remaining water on conductor be formed as upper rivulet and lower rivulet, and the conductor used in the experiment was a circular bar.

For the transmission conductor, one of the most important tasks is to measure the aerodynamic properties which are used to calculate the wind load acting on it. Wardlaw et al. (1975) have measured the mean force acting on bundled conductors based on wind tunnel test, and the relationship of drag coefficient and Reynolds number were provided. The aerodynamic drag coefficients of electrical power conductors, as measured in wind tunnel experiments, are generally much higher than those inferred from field observations of operating lines. To identify the causes of these discrepancies, Ball et al. (1992) conducted a series of experiments to investigate the importance of the model aspect ratio and the end conditions present at the junction of the model and the wind tunnel wall. The results showed significant errors are possible in the wind tunnel experiments due to these effects but none can account for the large discrepancy between the wind tunnel and field data. However Shan et al. (1992) developed an experiment to directly determine the conductor drag coefficients in the open air using a tunnel-like test setup, and the results illustrated that the conductor drag coefficients obtained in open air are in agreement with the wind tunnel drag data in the wind velocity range of field data. Tabatabai et al. (1992) studied the drag properties of trapezoidal and circular wire conductors, and indicated that, at high wind speeds, the trapezoidal wire conductors had lower drag coefficients than comparable standard circular wire conductors due to the smooth surface of trapezoidal conductor. Eguchi et al. (2002) gave a new type of electric wire for overhead transmission lines to reduce the drag force under a typhoon condition, and the drag reduction mechanism of the newly designed wire was discussed using a water similitude experiment. Kikuchi et al. (2002) presented a reduced-drag (LP) conductor having reduced conductor wind load and a reduced-noise and -drag (LNP) conductor combining the two functions of conductor wind load reduction and conductor wind noise reduction, and then conventional and LP conductors were installed during fiscal 1998 at the Miyakojima Test Line to obtain in-the-field verification of the drag-reduction effect in the LP conductors. Kikuchi et al. (2003) measured the drag properties of the LP conductor under both wind and rain excitations, and the experimental results revealed that the influence of heavy rainfall is not negligible on the new-design wire. Xie et al. (2013) observed the global drag coefficients of multi-bundled conductors with the wind tunnel test, and showed that the global drag coefficients of multi-bundled conductors were much smaller than those of a single conductor in the same wind velocity with any attack angle and the biggest global drag coefficients corresponding to different conditions investigated in this study are less than those recommended in the design codes worldwide.

Some researchers have also conducted the wind tunnel test of transmission tower-line system with different objectives. In order to examine the difference in structural response to the two different types of wind forcing (boundary layer and downdraft outflow) and understand why transmission line failures occur in downdraft winds, Lin et al. (2012) performed a wind tunnel test with an aeroelastic model of a single transmission line span and support structure. A substantial imbalance between the peak load on the upstream and downstream conductors was observed for both types of wind forcing and was particularly severe for the downdraft outflow simulations. Liang et al. (2015) investigated the effects of coupling between electrical transmission tower and line using a full aeroelastic model with one tower two lines model. The experimental results indicated that the effects of coupling between transmission tower and line on the wind-induced responses of the tower, as well as the across-wind vibration of the tower, must be taken into consideration in the wind-resistant design of electrical transmission tower.

Based on the abovementioned research studies, it can be seen that some pioneering work of rain load on transmission tower has been performed, most researchers focusing on the aerodynamic properties of transmission conductor and bundled conductors under wind load. However, the research of rain load on the transmission conductor is very limited. Though Zhou and Liu (2014, 2015) and Zhou et al. (2015) introduced the theory of rain-wind induced vibration on the stay cable in transmission conductor, the surface conditions of stay cable and transmission conductor are very different. Therefore it is necessary to study the rain load and its mechanism acting on the transmission conductor. Section 2 introduces the theoretical method of calculating raindrop impinging force, and the couple of wind and rain loads on the transmission conductor is presented in Section 3. In Section 4, the wind tunnel test of transmission conductor made up of trapezoidal wires under the wind and rain excitations is introduced to obtain the key parameter. Sections 5 and 6 conduct the numerical simulations of transmission conductor and tower-line system under wind and rain loads, respectively. At last Section 7 concludes the study.

2. Theoretical method of calculating raindrop impinging force

The mean wind speed as a function of altitude can be described by the following power-law wind speed profile:

$$V_a = V_{10}\left(\frac{H}{10}\right)^{\alpha} \tag{1}$$

where V_{10} is the basic wind speed representing the mean wind speed during 10 min at the altitude of 10 m, H is the altitude, and α is the power-law exponent.

The wind pressure in a free wind field and wind load acting on structures are written by:

$$P_w = \frac{1}{2}\rho_a V_a^2 \tag{2}$$

and

$$F_w = C_D\left(\frac{1}{2}\rho_a V_a^2\right)A \tag{3}$$

where the air density $\rho_a = 1.235$ kg/m^3, C_D is the drag coefficient for the specified structure, and A is the projected area of structure in the windward direction.

There exist two different sources which are actually responsible for the influence of rain on wind loads on transmission conductors: the first is the increase of the specific mass of air ρ_a as a consequence of the presence of water droplets, while the second is the change of the drag coefficient, affected by the presence of a water layer around the generally rough conductor surface. In the following wind tunnel test, the conductor drag coefficient is calculated by Eq. (3), in which ρ_a is regarded as constant and the effect of the increase of ρ_a under rainfall is integrated into drag coefficient.

The rain pressure for a specified raindrop diameter yields (Fu et al., 2015a, 2015b, 2016):

$$P_r(V_a, R, D, H, \alpha) = k\rho_w S(\gamma(H, D, \alpha)V_a, R)n(D, R)\gamma^3(H, D, \alpha)V_a^3 D^3 \tag{4}$$

where k is a factor with the value of 102.0 in $1/m$, the raindrop density $\rho_w = 1000$ kg/m^3, D is the raindrop diameter, R is the rain intensity in mm/h, $n(D, R)$ is the raindrop spectrum which means the raindrop size distribution, γ is the velocity ratio, and