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Short Note

The influence of self-excited forces on wind loads and wind effects for super-large cooling towers

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ABSTRACT

The self-excited force induced by the interaction between the structure and airflow has been technically ignored in previous studies conducted on wind loads and wind effects for super-large cooling towers. Moreover, no criteria could be used for qualitative and quantitative studies of the effects resulting from the self-excited force. In this study, by taking a Chinese super-large cooling tower for nuclear power with a height of 215 m as an example, the wind tunnel test of cooling tower aero-elastic model with simultaneous pressure and vibration measurement through a modified equivalent beam-net design method was firstly carried out, in which external wind loads of super-large cooling towers were obtained with the presence of the self-excited force. Firstly, the effects of self-excited force on distribution characteristics of external mean and fluctuating wind pressures were analyzed. Through the refined frequency-domain algorithm of wind-induced responses from our previous studies, wind-induced responses of super-large cooling towers were calculated by considering two cases of wind tunnel tests with or without self-excited force. Subsequently, the effects of self-excited force on wind-induced responses and Gust Response factors of super-large cooling towers were discussed. The results showed that the self-excited force had weak influence on the distribution of external mean wind pressure of the super-large cooling tower, while it significantly affected distribution and values of fluctuating wind pressure. Moreover, the effects of self-excited force on wind-induced mean response were negligible for the super-large cooling tower. The response differences calculated using two aerodynamic parameters were mostly below 5%, and regardless of whether or not to consider the influence induced by self-excited force. The excitation mode of wind-induced resonant response was consistent even at the maximum error (i.e. 10%). Furthermore, this study indicated that the influence of self-excited force on wind effects was advantageous to majority of regional structures. To overcome the problems existing in aero-elastic model, e.g., accuracy, accessibility and cost of test, this study suggested that external wind load model without self-excited forces obtained by pressure test of rigid body could be used to calculate the wind-induced responses of super-large cooling towers, in which the differences were within an acceptable range.

1. Introduction

Along with the structural adjustment of national energy and increasing installed capacity of generator sets, Chinese nuclear power developed rapidly. Super-large cooling towers with hyperbolic structure and thin shell (more than 200 m in height) have been proposed, in which wind-induced responses of structure are a key bottleneck impeding leapfrog development of large cooling towers. Furthermore, the large cooling tower is an important structure in nuclear power or thermal power plant; hence its damage induced by wind will lead to serious consequences. Therefore, it is of great significance to deeply study on wind loads and wind-induced responses of large cooling towers.

Great efforts have been made to study wind loads and wind effects for large cooling towers, since three cooling towers in the Ferrybridge power plant were destroyed by wind in 1965 (Harte and Wittek, 2009). Niemann and Kopper (1998) investigated the effect of surrounding buildings and group of towers on extreme value distribution of wind loads on external surface of large cooling towers. Goudarzi et al. (2008) proposed a fitting formula and a coherence function of spectral characteristics of external wind pressure, by comparing measured wind pressure to simulated wind pressure of large cooling towers in Iranian power plant.

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Nomenclature

Symbols	definitions
M	Mass matrix
C	damping matrix
K	stiffness matrix
n	Total number of degrees of freedom
p	external stochastic wind load
ω	The structural circular frequency
I	influence coefficient matrix
Λ	$\mathrm{diag}(\omega_{1,\ldots,}^2 \omega_{\mathrm{m}}^2)$
Φ	matrix of modes of vibration
$P_{eqq,r}$	Resonant elastic restoring force
$P_{eqq,t}$	Generalized elastic restoring force
$C_{pp,r}$	covariance matrix of resonant elastic restoring force
$C_{pp,b}$	covariance matrix of external wind load
$C_{pp,c}$	covariance matrix of coupling elastic restoring force
m	The mode number for calculating resonant response
g	Peak factor
q	generalized displacement vector
W_B, W_R, W_C	weighting factor of different components
σ_r, σ_b, σ_c	root-mean-square value of response component vector
P_{er}, P_{eb}, P_{ec}	Resonant, background and coupled components of ESWL

To obtain the disturbance factors of wind loads in various combinations of group of towers, Bartoli et al. (1997) and Sun and Gu (1995) studied the interference effects of surrounding buildings on wind loads of group towers through pressure measurement in wind tunnel tests of rigid body. Ke et al. (2010) proposed a criteria for the classification and discrimination of non-Gaussian area through detailed study on non-Gaussian characteristics of external fluctuating wind pressure on single large cooling tower. In addition, based on the pressure measurement of rigid body and random vibration theory, Busch et al. (2002) calculated wind-induced responses of large cooling towers, and the influences of damping ratio and other surrounding interference were also analyzed. Based on Load-response theories, equivalent static wind loads of large cooling towers were proposed by Ke et al. (2012). As a result of aforementioned research studies, wind-resistant design of large cooling towers has been optimized, and a large number of profits was achieved.

However, the self-excited force induced by interaction between the structure and airflow is always ignored in previous research studies on wind loads and wind-induced responses for super-large cooling towers. Moreover, the previous research studies mainly focused on surface aerodynamic mode obtained from pressure measurement on rigid models in wind tunnels, and no criteria was proposed for qualitative and quantitative research studies on the effects of the self-excited force. Importantly, the increasing height of large cooling towers leads to reduction of fundamental frequency, which could induce high self-excited force. Thus, it is necessary to urgently carry out research on the influence mechanism of self-excited force on resonant component and fluctuating component of wind-induced responses, and on coupling effect between different modes.

Herein, based on the previous researches about wind tunnel tests by Ke et al. (2012, 2013), the effects of self-excited force on distribution characteristics of external mean and fluctuating wind pressure were further analyzed. The characteristics of the spectral density of displacement responses were also investigated. Subsequently, through measurement analysis of wind-induced responses by CCM, Gust Response factors and equivalent static wind loads, the effects of self-excited forces on wind-induced responses and wind loads are qualitatively and quantitatively studied.

2. Wind tunnel test

2.1. Description of the representative cooling tower

The main geometrical dimensions of super-large cooling tower are as follows: height of the tower = 215 m, top diameter of the tower = 104 m, throat height of the tower = 160 m, throat diameter of the tower = 100 m, inlet opening diameter = 156 m, diameter at base = 169 m, area of water drenching = 18,300 m^2, diameter of herringbone column = 1.3 m, and number of herringbone columns in supporting structure = 96. Of these, height and area of water drenching will be the largest in the world.

In order to obtain structural dynamic characteristics, the finite element method of discrete structure is used to carry out ensemble modeling via ANSYS software. SHELL63 element is used in shell, and BEAM188 element is employed for herringbone diagonal columns. Herringbone diagonal columns and lower toroidal beams in shell bottom are connected by rigid domain. As shown in Fig. 1, fundamental frequency of the structure was 0.658 Hz, and the frequency was maintained at below 1.0 Hz, even for modes as high as 10. More dynamic characteristicses of this super-large cooling tower can be found in the literature (Ke et al., 2012, 2013).

2.2. Design methods of the aero-elastic model

The aero-elastic models of large cooling towers were tested in the wind tunnel by Isyumov and Abu-Sitta (1972), Armitt (1980) and Zhao and Ge (2010) in previous studies. Design methods of the aero-elastic model mainly consist of the continuous medium method and the equivalent beam-net method. Our previous research indicated that the former was suitable for destructive tests of cooling towers, and the latter could be used to study on wind-induced responses of cooling towers.

In the scale stiffness simulation process of cooling tower aero-elastic model, the axial stiffness and bending and torsional stiffness of thin-walled component have two to three orders of magnitude in

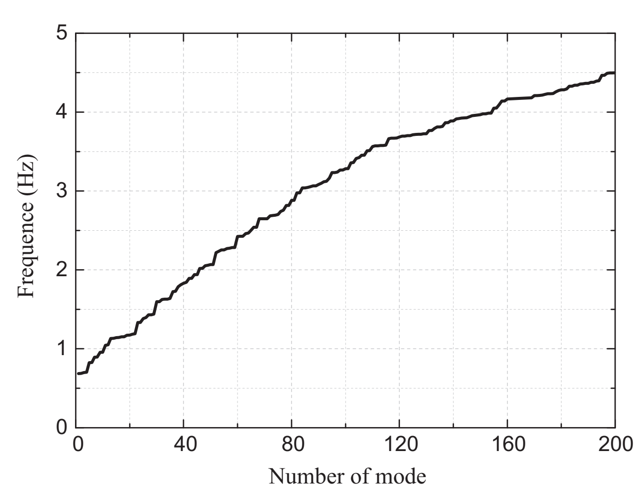

Fig. 1. The distribution curve of structural natural frequency.