Thin-Walled Structures 127 (2018) 809–821

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Sensitivity analysis and estimation method of natural frequency for large cooling tower based on field measurement

Shitang Ke[a,b,*], Lu Xu[a], Yaojun Ge[b]

[a] Department of Civil Engineering, Nanjing Univ. of Aeronautics and Astronautics, 29 Yudao Road, Nanjing 210016, China
[b] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji Univ., 1239 Siping Road, Shanghai 200092, China

ARTICLE INFO

Keywords:
Cooling tower
Natural frequency
Sensitivity analysis
Field test
Modal identification
Estimation equation

ABSTRACT

The natural frequency is a key factor for estimation of dynamic deformation and mechanical performance. As simple and effective estimation equation for natural frequency of cooling tower is absent, current investigations of natural frequency of cooling towers are basically based on finite element analyses. In this study, 38 models of a 179 m cooling tower were established by tuning key structural parameters (e.g., tower height, throat height, throat diameter, inlet height, and pillar sectional area) and dynamic characteristics of these models were analyzed. Also, effects of structural parameters on fundamental frequency and overturning frequency were investigated. The sensitivity analysis of structural natural frequency for cooling towers was executed using the perturbation method and the Latin hypercube sampling method and sensitivity factors of different parameters corresponding to different orders were obtained. Based on that, multi-parameter empirical estimation equations for fundamental frequency and overturning frequency considering weighted sensitivity factor were proposed. Then, the estimation equation of natural frequency is verified by field tests of eight cooling towers with typical tower heights and configurations. Specifically, the measured acceleration signals were pre-treated using random decrement method (RDT) and natural excitation technique (NExT) and the first 10 order natural frequencies of the cooling tower using three time-domain modal identification methods (ARMA, ITD, and STD). Finally, structural parameters of cooling tower obtained by field tests were fitted. The results indicated that the fundamental frequency of cooling towers decreases as tower height and throat height increase and increases as throat diameter, inlet height, and pillar sectional area increase. Although sensitivity factors obtained by the two methods are similar, the LHS method shows higher accuracy. The effect of tower height on natural frequency is most significant among all parameters, which means the sensitivity factor of tower height is higher than those of other parameters. The measured fundamental frequencies of cooling towers were between 0.6 Hz and 1.9 Hz and heights and configurations of cooling towers have significant effects on their dynamic characteristics. The field test results of eight cooling towers demonstrated reasonable effectiveness of the proposed empirical estimation equations for the fundamental frequency and overturning frequency of cooling towers (the maximum goodness of fit of fundamental frequency and overturning frequency were 0.996 and 0.975, respectively). Error analysis indicated that the proposed estimation equation for natural frequency is highly accurate and reliable. This study provides references for determination of structural natural frequency of large cooling towers and future studies on structural natural vibration characteristics.

1. Introduction

Owing to their particular external configurations and internal structures, the dynamic characteristics of cooling towers are highly complicated [10,18]. The natural frequency, which is a key parameter for the dynamic characteristics, is usually obtained by complicated and tedious finite element calculations or field tests and simple and effective estimation equation for natural frequency of cooling tower is still absent. She et al. proposed a multi-parameter fitting equation for natural frequency of cooling tower but didn't involve sensitivity analysis for structural parameters [19]. National standards [3,5,6] haven't involve any empirical estimation equation for natural frequency. As a result, it is challenging to estimate structural natural frequency at early stages, thus difficult to estimate effects of structural parameters on dynamic responses. Therefore, it is of great significance to investigate sensitivity of dynamic characteristics of cooling towers to multiple parameters and develop estimation equation for natural frequency. Also, verifications of the proposed estimation equation for natural frequency by field tests

* Corresponding author at: Department of Civil Engineering, Nanjing Univ. of Aeronautics and Astronautics, 29 Yudao Road, Nanjing 210016, China.
E-mail addresses: keshitang@163.com (S. Ke), luxunuaa@163.com (L. Xu), yaojunge@tongji.edu.cn (Y. Ge).

https://doi.org/10.1016/j.tws.2018.03.012
Received 1 September 2017; Received in revised form 14 February 2018; Accepted 11 March 2018

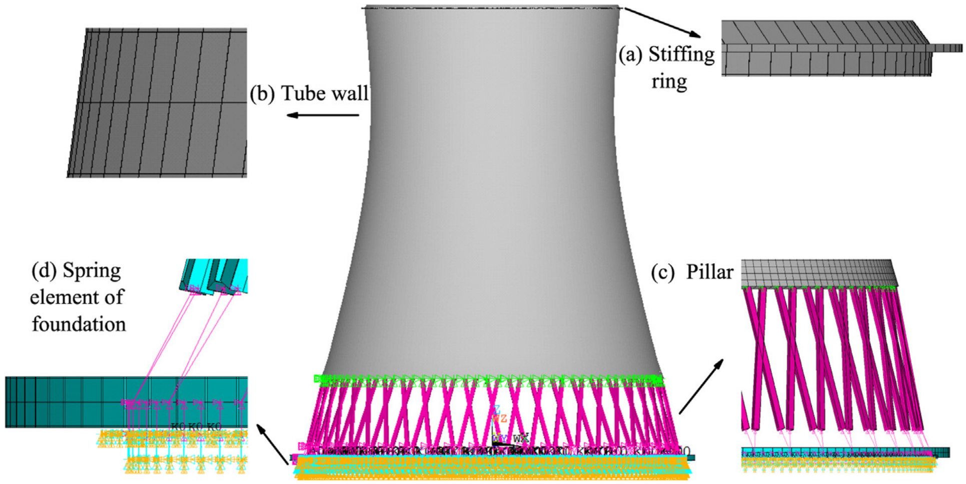

Fig. 1. Finite element modeling of the object tower.

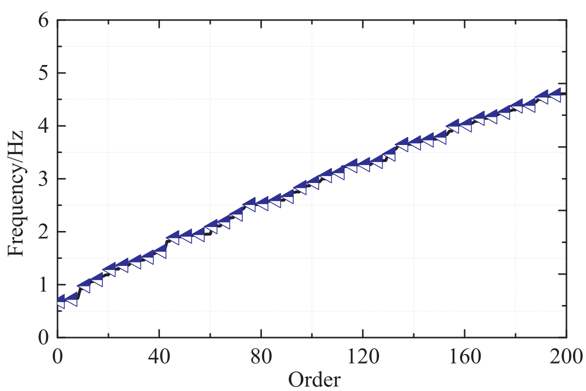

Fig. 2. Distribution of natural frequency of cooling towers.

based modal identification are highly essential.

The dynamic characteristics of large cooling towers have been investigated using field tests [16,2,24]. Zhang et al. demonstrated that low frequencies of cooling towers are mainly determined by circumferential stiffness and the meridian type is related to the overall overturning moment [28,13]. Shen et al. investigated dynamic characteristics and wind induced responses of the cooling tower in Ferrybridge power stations and a model of this tower (same wall thickness, tower height, and herringbone pillar) (Shen et al., [20]). The results suggested that unreasonable tower configuration is one of the key reasons behind the tower collapse. Also, dynamic characteristics of three cooling towers with different characteristic sizes were analyzed [11,22] and the results indicated that the resonant frequencies of cooling towers with low fundamental frequencies are dominant and the dynamic amplification effect of wind induced response increases as the fundamental frequency decreases. Additionally, sensitivity analyses of structural dynamic characteristics focused on long-span bridges and roofs. A Gaussian process model based global sensitivity analysis method was proposed [21,23] and used for sensitivity analysis of dynamic characteristics uncertainty of real bridges. Multi-parameter sensitivity analysis of structural natural frequency for a long-span roof was executed using the perturbation method and the LHS method [14,7] and the results demonstrated that effects of the six design parameters on structural natural frequency are consistent in these two cases.

In this study, 38 models of a 179 m cooling tower were established by tuning key structural parameters (e.g., tower height, throat height, throat diameter, inlet height, and pillar sectional area) and dynamic characteristics of these models were analyzed. Also, effects of structural parameters on fundamental frequency and overturning frequency were investigated. The sensitivity analysis of structural natural frequency of cooling towers were executed using the perturbation method and the LHS method and sensitivity factors of different parameters corresponding to different orders were obtained. Based on that, multi-parameter empirical estimation equations for fundamental frequency and overturning frequency considering weighted sensitivity factor were proposed. Finally, structural parameters of eight cooling towers with typical tower heights and configurations obtained by field tests and

Table 1
First 10 order natural frequencies and vibration mode of cooling towers.

Order	1,2	3,4	5,6	7,8	9,10
Natural frequency	0.68	0.71	0.72	0.74	0.92
Vibration mode