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Full-scale measurements and damping ratio properties of cooling towers with typical heights and configurations

Shitang Ke[a,b,*], Wei Yu[a], Peng Zhu[a], Yaojun Ge[b], Xian'an Hou[c]

[a] Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[c] Department of Civil Engineering Technology, Northwest Electric Power Design Institute of China Power Engineering Consulting Group, Xi'an 710075, China

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ABSTRACT

The standard damping ratio for cooling towers is equivalent to that of high-rise reinforced concrete structures, which is 5%. But considering the unique configuration and material properties of the cooling towers, the actual damping ratio of cooling towers is far smaller than the standard value. Damping ratio is an important input parameter for wind and seismic analyses, its value directly determines the anti-wind and anti-seismic safety of the cooling towers. However, few field tests and damping ratio experiments have been conducted for cooling towers at home and abroad. In this paper, we performed field tests of 8 cooling towers with typical height and configuration in the inland areas of China. Acceleration response signals (vibration signals) at typical points of the tower body were obtained under ambient excitation. The measured acceleration signals were preprocessed using the random decrement method (RDM) and natural excitation technique. The natural frequencies and damping ratios of the first ten modes were obtained by combining three modal recognition methods, namely, auto-regressive and moving average (ARMA) model, Ibrahim time domain (ITD), and spare time domain (STD). The measured values were compared against the results of finite element analysis (FEA) and the errors were assessed. Then the equivalent synthetic damping ratios of the 8 cooling towers were estimated based on modal combination. Finally we provided the calculation formulae for the damping ratios and equivalent synthetic damping ratios of the first ten modes by using the fundamental frequency as the objective function and the measured damping ratios of the 8 cooling towers. The measured frequencies were consistent with the results of FEA for the 8 cooling towers, and the maximum difference in fundamental frequency was 4.4%. The damping ratios recognized of each mode showed a dispersed distribution. The maximum damping ratio of the first ten modes was 2.86%. The equivalent synthetic damping ratios of the 8 cooling towers ranged from 1.13% to 2.16%. Error analysis indicated that the fitting formula for the damping ratio had high precision and high stability. The present research provides valuable clues for the determination of damping ratio for large cooling towers and enhances the understanding on the damping mechanism.

1. Introduction

According to the specifications in Load Code for the Design of Building Structures [1] and Code for Design of High-Rising Structures [2], the recommended damping ratio for reinforced concrete structures is 5%. However, for structures with natural period of vibration above 1.0 s, the measured damping ratio is only about 2%, which is far lower than the standard value. Cooling towers are typical high-rise rotating thin-shell structures [3,4]. The actual damping ratio of cooling towers should be lower than that of ordinary high-rise structures due to its unique configuration and material properties. Field measurements are the easiest way to understand the structural response and dynamic features of the cooling towers. The existing measurements of wind-induced responses generally focus on the wind load distribution on the surface of the cooling towers. As more ultra-high cooling towers are emerging, wind load and seismic responses have become the controlling factors for the design of large cooling towers. Damping ratio is an important input parameter for wind and seismic analyses. Its value directly influences the anti-wind and anti-seismic safety of the cooling towers. However, only a few field measurements and experiments on damping ratios in large cooling towers have been conducted so far. This apparently restricts the development of large cooling towers.

The first field measurement of cooling towers was performed in the 1960s for the four-tower arrangement of West Burton power station in

* Corresponding author at: Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
E-mail addresses: keshitang@163.com (S. Ke), yuweinuaa@163.com (W. Yu), pengzhunuaa@163.com (P. Zhu), yaojunge@tongji.edu.cn (Y. Ge), houxianan@163.com (X. Hou).

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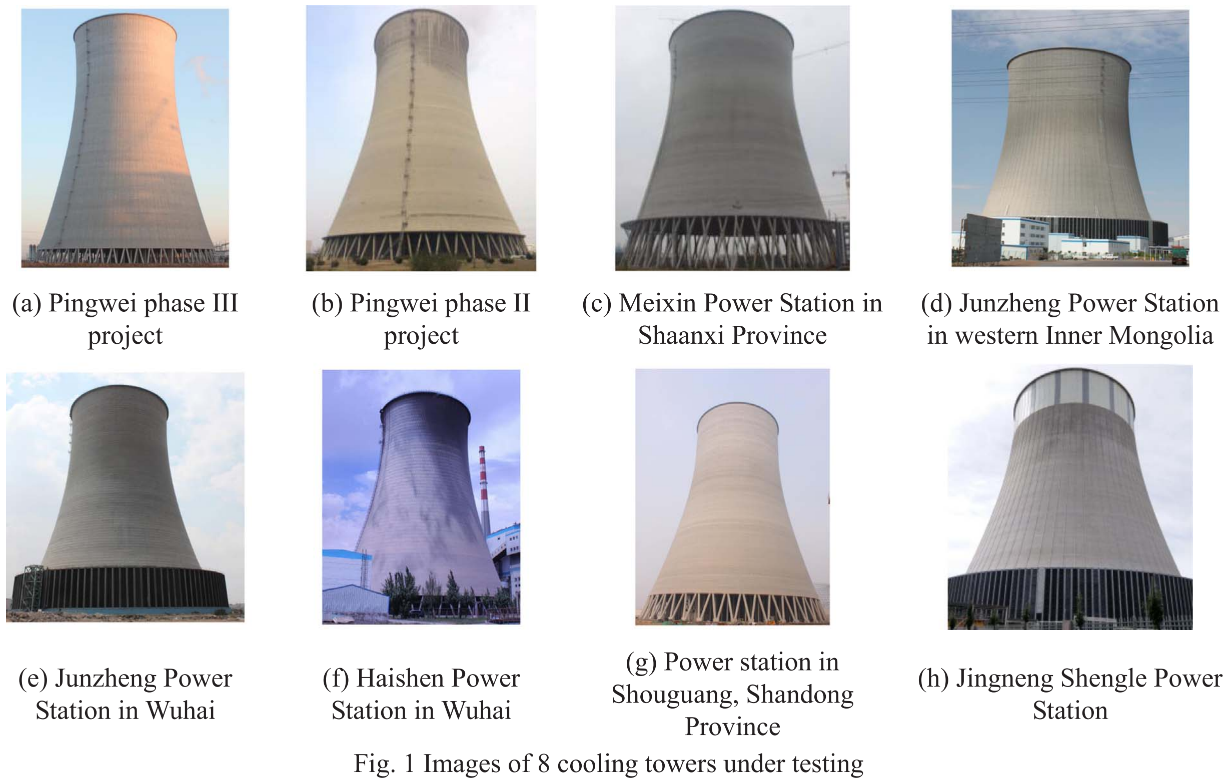

Fig. 1. Images of 8 cooling towers under testing.

the UK [5]. The height of the tower under testing was 113.5 m. Along the circumferential and meridional directions 72 measuring points were uniformly arranged on the external surface; and on inside 36 measuring points were uniformly arranged. The average wind pressure distributions on the internal and external surfaces of the cooling towers were obtained. In 1972 Niemann [6,7] performed field measurements on cooling towers at Weisweiler Power station in Germany. The height of the tower was 104 m, and the wind pressure sensor was installed to the height of 63.5 m, with uniform arrangement of 19 measuring points along the circumferential direction. In 1974 Sollenberger and Scanlan [8] carried out a field measurement of wind pressures for Martin's Greek cooling tower in Pennsylvania, USA. The tower height was 126.8 m and along the circumferential direction 16 measuring points were uniformly arranged at the height of tower throat. They studied the correlation between wind pressure spectrum and wind pressures at the measuring points. In 1980 Bamu et al. [9] summarized the measured results of Weisweiler, Matin Cereek and Schmeehausen cooling towers. They performed dynamic response analyses of the three cooling towers and discussed the wind-induced responses and determination of gust factor. In 1981 Pirner [10] compared the results of field measurement with the results of wind tunnel and presented the wind pressure spectrum and fitting formula for coefficient of coherence. In 1983 Peking University [11,12] performed wind pressure measurements of two cooling towers in Matou, Hebei Province and Maoming, Guangdong Province. On this basis, China's first wind load code provisions of cooling towers were formulated. In 2009 Tongji University [13,14] measured the circumferential pulsating wind pressures of a cooling tower standing 166.7 m in Xuzhou Power Station in Jiangsu Province at the height of 90 m and 130 m. The existing field measurements of cooling towers are generally intended to obtain the average and pulsating wind pressure distributions on the internal and external surfaces of the towers. But few of them are concerned about the structural responses and dynamic features of the cooling towers. Only Winney [15] performed field measurements and modal recognition test of the cooling tower in Didcot Power Station. The height of tower under testing was only 114 m, with as few as 6 measuring points arranged circumferentially at the bottom of the tower. However, there is a considerable difference in the height of this tower as compared with the large cooling towers put into operation nowadays ($\geq$ 180 m), and their research findings may not apply to other cooling towers.

In view of the dynamic response of the cooling tower structure, the results of both linear and nonlinear analyses are reported for cooling towers under earthquake excitation, and the effects of dynamic and gravity loading were considered to stability analysis [16]. Along with the structural adjustment of national energy and increasing installed capacity of generator sets, super-large cooling towers with hyperbolic structure and thin shell (more than 200 m in height) have been proposed [17]. In the years 1999–2001, a 200 m new natural draft cooling tower has been built at the RWE power station at Niederaussem. Busch et al. [18] optimized the structure and analyzed the safety of the structure under the action of loads. Also damage evolution has been executed in order to maintain the structure's durability. Yu et al. [19] carried a shaking table test for a proposed natural draft cooling tower, which is 252 m high. Structural dynamic responses corresponding to different levels of seismic actions were measured and analyzed. The results show that columns were the first to be damaged under strong-motion earthquakes.

In this paper, we performed field tests of 8 cooling towers with typical height and configuration in the areas of China. Acceleration response signals (vibration signals) at typical points of the tower body were obtained under ambient excitation. The measured acceleration signals were preprocessed using the random decrement method (RDM) and natural excitation technique (NExT). The natural frequencies and damping ratios of the first ten modes were obtained by combining three modal recognition methods, namely, auto-regressive and moving average (ARMA) model, Ibrahim time domain (ITD), and spare time domain (STD). The measured values were compared against the results of finite element analysis (FEA) and the errors were assessed. Then the equivalent synthetic damping ratios of the 8 cooling towers were estimated based on modal combination. Finally we provided the