Journal of Sound and Vibration 332 (2013) 5271–5282

Contents lists available at SciVerse ScienceDirect

Journal of Sound and Vibration

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

Tuned rolling-ball dampers for vibration control in wind turbines

Junling Chen [a,*], Christos T. Georgakis [b]

[a] Department of Building Engineering, Tongji University, Shanghai 200092, China
[b] Department of Civil Engineering, Technical University of Denmark, Building 118, Brovej, 2800 Kongens Lyngby, Denmark

ARTICLE INFO

Article history:
Received 18 September 2012
Received in revised form
2 May 2013
Accepted 9 May 2013
Handling Editor: J. Lam
Available online 16 June 2013

ABSTRACT

With wind turbines growing in size and cost, it is necessary to reduce their dynamic responses and improve their fatigue lifetime. A passive tuned-mass damper (TMD) is a very efficient solution for vibration control in structures subjected to wind excitations. In this study, a tuned rolling-ball damper characterized by single or multiple steel balls rolling in a spherical container is proposed to be mounted on the top of wind turbines to reduce the wind-induced vibration. A 1/20 scale shaking table model was developed to evaluate the control effectiveness of the damper. The wind-induced dynamic responses of the test model with and without TMD were obtained from the shaking table tests. The test results indicated that the rolling-ball dampers could effectively suppress the wind-induced vibration of wind turbines. The damper with three balls in one container had better control effectiveness than that with only one ball because of the impact effect and the rolling friction. The control effectiveness of the damper cannot be improved further when the number of balls is increased beyond a certain point.

1. Introduction

Wind energy is an important part of the global push for clean, renewable energy alternatives. In recent years, the wind turbine tower has grown from 40 m to 100 m with turbine sizes reaching 3.0 MW. Taller towers are desirable because winds are stronger at higher altitudes, thereby producing more power for each turbine installed. The cost of a tower is generally beyond 20 percent of the total cost of a wind turbine. Therefore, it is quite important for the final cost of energy to build towers as optimally as possible. Wind turbines present complex structure problems in the context of natural wind due to the interaction of the rotating blades and the tower. The wind speed and direction do not only vary with time, but also with the swept area. For offshore wind turbines, the influence of wave loads makes their dynamic response more complex. However, because of the slenderness of wind turbine towers, the coupling of wind and wave loads may produce excessive vibrations that will inhibit the mechanical system in the nacelle to convert wind energy into electrical energy and makes support structures susceptible to fatigue damage. Therefore, the vibration control of wind turbine towers is an important issue for the development of wind energy.

Nowadays passive vibration control is a mature technology and the tuned mass damper (TMD) is one of the simplest and the most reliable passive control devices. The application of TMD for tall buildings under wind or earthquakes has been extensively investigated. Park and Reed [1] showed that the uniformly distributed mass system was more effective in

* Corresponding author. Tel.: +86 21 6598 1917; fax: +86 21 6598 4889.
E-mail address: chenjl@tongji.edu.cn (J. Chen).

0022-460X/$ - see front matter
http://dx.doi.org/10.1016/j.jsv.2013.05.019

reducing the peak dynamic magnification factor and the linearly distributed system was more robust under mistuning. Ricciardelli [2] presented the criteria for the choice of the amount of tuned mass to be added on the chimney to reduce its response within prescribed limits and found the fatigue life of chimneys with TMDs were increased almost 50 percent. Casciati and Giuliano [3] investigated the convenience of tuned mass dampers for the reduction of the gust response of the towers of suspension bridges and suggested the adoption of multi-TMD solutions. Park et al. [4] proposed a hybrid mass damper as a damping device in order to mitigate wind-induced responses of an air traffic control tower at Incheon International Airport and showed the optimally designed HMD system by numerical simulations. Many TMDs have been successfully applied to high-rise buildings and towers such as the Citicorp Center in New York City, John Hancock Tower in Boston, Guangzhou TV and Sightseeing Tower in China. All of these dampers were reported to be able to significantly reduce the structural dynamic response.

Recently, the dynamic response reduction of wind turbines using tuned mass dampers has been investigated. Bazeos et al. [5] presented the load bearing capacity and the seismic behavior of a prototype steel tower for a 450 kW wind turbine with a horizontal power transmission axle. Chen et al. [6] investigated the blade-tower coupling effect, to analyze wind-induced response characteristics of a wind turbine tower more accurately. Murtagh et al. [7] proposed an approach to investigate the along-wind forced vibration of a wind turbine tower and rotating blades assembly subjected to rotationally sampled stationary wind loading. Colwell and Basu [8] presented the structural responses of offshore wind turbines with an attached tuned liquid column damper for controlling the structural vibration.

In this study, a novel tuned rolling-ball damper characterized by single or multiple steel balls rolling in a spherical bowl is proposed to be mounted on the top of wind turbines. The simple implementation of this kind of TMD makes the tuning process easy and inexpensive. The spherical container allows the damper to be tuned along the vibration direction at any time, thus making the damper "multi-directional". Particularly, for offshore wind turbines, when the wave motion and the wind direction do not coincide, the damper will work very well because the steel balls will always roll along the vibration direction. The shaking table tests were carried out to verify the control effectiveness of the damper to suppress wind-induced vibration. The wind-induced dynamic responses of the test model were obtained from the equivalent ground accelerations on the shaking table.

2. Prototype of a wind turbine tower

2.1. Wind turbine tower

Fig. 1(a) illustrates the elevation of a wind turbine with a height of 102.4 m. It has a rated power output of 3 MW and a hub height 105 m. The tower is constructed of steel with grade Q345 and has an external diameter of 4.15 m at its base and 2.3 m at the top. The tower body weighs 371.3×10^3 kg (including the flanges and internals) and the nacelle weighs 121.0×10^3 kg (including the rotor blades). Q345 steel has a Young's modulus of $E=206$ GPa, a Poisson ratio of $\nu=0.3$, and a yield stress of $f_y=345$ MPa. The tower body is divided into 25 segments according to its diameter and thickness variations, and each segment has its own geometric parameters, moments of inertia, flexural rigidity (EI) and shear stiffness.

2.2. Equivalent single degree of freedom (SDOF) model

For wind turbine towers, since the first vibration mode plays a dominant role in the dynamic analysis, a generalized SDOF model can be developed to study the vibration properties. The tower can be simplified as a tapered tubular cantilever beam, with a concentrated mass, M, at the top representing the rotor and nacelle (shown in Fig. 1(b)). Therefore, for the first

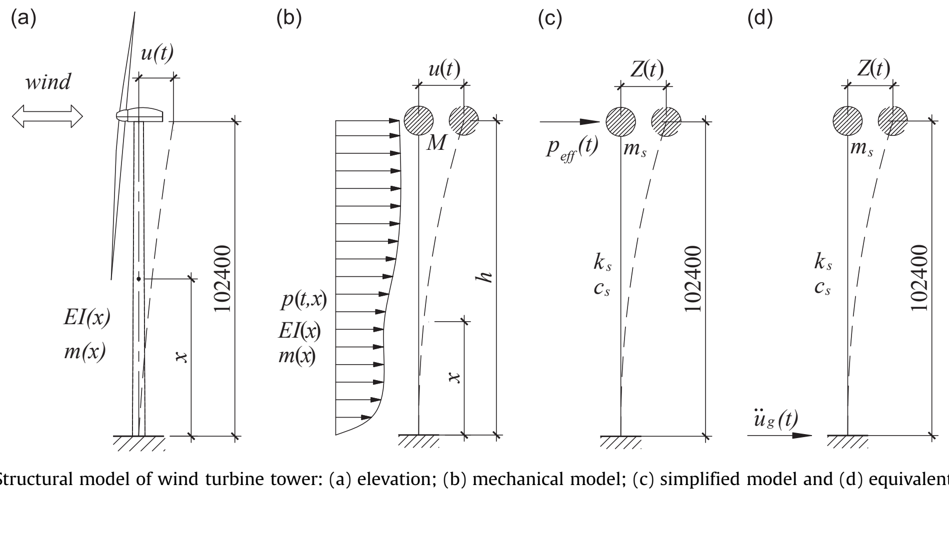

Fig. 1. Structural model of wind turbine tower: (a) elevation; (b) mechanical model; (c) simplified model and (d) equivalent model.