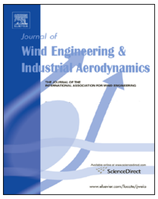
J. Wind Eng. Ind. Aerodyn. 147 (2015) 251–261

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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



Semi-active fuzzy control of edgewise vibrations in wind turbine blades under extreme wind

Jianyun Chen [a,b], Chenyang Yuan [b,*], Jing Li [b], Qiang Xu [b]

[a] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China*
[b] *School of Civil and Hydraulic Engineering, Dalian University of Technology, Dalian 116024, China*

ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
19 October 2015
Accepted 19 October 2015
Available online 14 November 2015

Keywords:
Wind turbines
Semi-active
Fuzzy control
Extreme wind
MR damper

ABSTRACT

In this paper, a new semi-active fuzzy control strategy is proposed for controlling edgewise vibrations of wind turbine blades under extreme wind. The control forces are provided by magnetorheological (MR) dampers mounted inside blades and appropriately manipulated according to a prescribed fuzzy control law. The fuzzy control system produces the required voltage to be input to the damper so that a desirable damper force can be produced. The finite element model of wind turbine with MR dampers is formulated, which considers the blade-tower coupling. Aerodynamic loads corresponding to a combination of steady wind and the effect of turbulence are computed by applying the blade element momentum (BEM) theory. Furthermore, the influence of position and number of the controllers is taken into account. The results of numerical simulations show that the proposed semi-active fuzzy control system can be beneficial in reducing the vibrations of wind turbine blades under extreme wind.

1. Introduction

In the field of renewable energy, wind energy has played a predominant role. At present, wind power has become the fastest growing source of renewable energy (Moriarty and Butterfield, 2009) and it can contribute to reducing greenhouse gases. The Global Wind Energy Council (GWEC) reported that the total global installed wind power capacity will surpass 800 GW by 2020 (Council, 2014). In the design of a wind turbine, maximizing the possible power output is the primary target therefore the large wind turbines have been constructed with tower heights and rotor diameters of over 100 and 140 m, respectively. The increased rotor diameters can extract more available wind resources for power generation and increase the flexibility of the blades, which has led to increased vibrations. What's more, wind turbines have the opportunity to experience extreme wind during its service lifetime, such as a typhoon, which can cause greater blade vibrations. Ahlström (2006) pointed out that large blade vibrations have a great influence on power generation. The uncontrolled vibrations might lead to structural/mechanical damage, causing a significant reduction in the operational efficiency and lifetime of the wind turbine. Thus it has become an increasingly significant area in researching ways to reduce the vibrations of wind turbine blades.

The flapwise and edgewise are the main modes of vibration for the blades. Hansen (2007) and Thomsen et al. (2000) pointed out that the mode of edgewise is lightly damped and may result in violent vibrations. In this paper, the control of edgewise vibrations is considered. For wind turbines, the wind load is the major load. Blades are the primary structural components of wind turbines. To study the stability and safety of wind turbines, investigating the loads on the blades is necessary. The blade element momentum (BEM) theory is an aerodynamic theory used in calculating aerodynamic loads of the blades. This theory is widely used by many scholars (Duquette and Visser, 2003; Giguère et al., 1999; Maalawi and Badawy, 2001; Maalawi and Badr, 2003; Meyer and Kröger, 2001; Varol et al., 2001; Monteiro et al., 2013). These researchers investigated the dynamic characteristics of rotational blades under operational wind speed or cut-out wind speed. However, there are few papers focusing on the extreme loads of wind turbines. The blades are parked or idling when taking situations like extreme wind speeds into account (Hansen, 2008). Ishizaki (1983) studied the relations among the turbulent quantities of typhoon winds. Lee et al. (2013), Saranyasoontorn and Manuel (2004) and Tran et al. (2013) proposed different methods to estimate extreme loads of wind turbines. Yuan and Chen (2009) analyzed the response of blade under extreme wind excitations. On September 11, 2003, the Typhoon Maemi had struck the Miyakojima Island with an average wind speed of 38.4 m/s and a maximum gust of 74.1 m/s, which caused a huge loss of wind turbines, including some blades were broken and the nacelle cover was damaged (Ishihara et al., 2005). And in 2006, the super typhoon Saomai led to serious damages of wind turbines, when it was passing through the Hedingshan wind farm of Zhejiang province (Li et al., 2013). Therefore it is very

---

[*] Corresponding author. Tel.: +86 411 84708549.
E-mail address: chenyang_yuan@yeah.net (C. Yuan).

http://dx.doi.org/10.1016/j.jweia.2015.10.012
0167-6105/

significant to study the control strategy of reducing the aerodynamic response of wind turbine blades under extreme wind.

The structural control has been an active area of research in building for several decades, but it is still a new and developing area of research applying structural control techniques to wind turbines. According to control methods, there are three categories for vibration control in the structure; namely, passive control, active control and semi-active control. Gerges and Vickery (2003) studied the effectiveness of a class of nonlinear tuned mass dampers (TMDs) in suppressing across-wind structure oscillations through a wind tunnel test. Murtagh et al. (2008) used TMD to mitigate the vibrations of a simplified wind turbine. Colwell and Basu (2009) developed the tuned liquid column damper (TLCD) for controlling the vibrations induced within the structure. Lackner and Rotea (2011) investigated TMD devices incorporated into aero-elastic code FAST to realize structural control of offshore wind turbines. However, the effect of passive control is limited because that the control system provides no extra assistance and cannot adapt to varying loading conditions. Staino et al. (2012) and Staino and Basu (2013) proposed a new blade design with active controllers to control edgewise vibrations. Fitzgerald et al. (2013) investigated the use of active tuned dampers (ATMDs) and Fitzgerald and Basu (2014) investigated cable connected active tuned mass dampers (CCATMDs) for the control of in-plane vibrations in rotating wind turbine blades. Although the active control system reduces the structural response by using external energy supplied by actuators to impart forces on the structures, there are still some problems such as stability, cost effectiveness, reliability, power requirements etc. (Choi et al., 2004). The semi-active control has the ability to cater to changes in the behavior of the primary system and requires significantly less power (Arrigan et al., 2011). So some researchers concentrate on the semi-active control method. Hrovat et al. (1983) concluded that the semi-active TMD presents an extremely promising alternative to both the fully passive and ATMD. Pinkaew and Fujino (2001) used semi-active tuned mass dampers (STMDs) to mitigate the vibrations in structures excited by harmonic loads. Arrigan et al. (2011) also used STMDs to reduce vibrations in the flapwise direction with changing parameters in the turbine.

The magnetorheological (MR) damper is one of the semi-active devices that can provide reliable vibration control force (Carlson and Spencer, 1996), and the control device used in this paper is also MR damper. The MR damper has a small power requirement, great yield stress (Yao et al., 2002), and is reliable, fail-safe, robust, and relatively inexpensive (Dyke et al., 1996; Spencer et al., 1997). Based on a MR damper, Dyke et al. (1996) proposed a semi-active clipped-optimal control algorithm and carried out a reduction in its structural response. In their approach, a linear optimal controller combined with a force feedback loop was used to adjust the command voltage of the MR damper. However, it is very important to calculate the appropriate command voltages according to the desirable control forces and then add them to the MR damper so that MR damper can produce control forces relatively close to the desired ones. Spencer et al. (1997) proposed a model that can effectively portray the behavior of a typical MR damper. The model has strong non-linear characteristics and it is difficult to calculate the appropriate command voltages. It is a good choice to use a fuzzy controller, which can produce the appropriate command voltages according to the responses of structures. Zadeh (1965) introduced the fuzzy set theory and Mamdani (1974) successfully used the 'IF–THEN' rule on the automatic operating control of a steam generator. Choi et al. (2004) developed a semi-active fuzzy control strategy for seismic response reduction using a MR damper.

In this paper, the objective is to propose a new semi-active fuzzy control method for edgewise vibration reduction of wind turbine blades under extreme wind. A mathematical model describing the response of the blades is formulated by using the D'Alembert principle (Clough and Penzien, 2003). In the model, the interaction between the blades and the tower is considered. The supplemental damping devices are MR dampers, located inside the blade. A fuzzy algorithm is used to produce the required voltage to be applied to the damper so that the MR damper produces the desirable control forces. Considering that the extreme wind direction is easily changeful, two directions of wind are considered. The position and number of the controllers are investigated and compared. Simulation results show that the proposed semi-active fuzzy control system is able to successfully reduce the blade vibrations under extreme wind.

2. Semi-active fuzzy control strategy

The modern multi-megawatt wind turbine has several structural components, including blades (always the number is three), nacelle (consisting of gears, converters, transformers), tower, etc. For commercial wind turbines the mainstream mostly consists of horizontal-axis wind turbines (HAWTs) (Hansen, 2008); this paper focuses on this type of machine (Fig. 1). Because the external load considered in this paper is extreme wind load, in this case the blades are parked.

2.1. Structural model with controller

Several researchers have formulated the mathematical model describing the dynamics of blades vibrations by assuming blades to be cantilever beams (Arrigan et al., 2011; Chen et al., 2009; Fitzgerald and Basu, 2014; Fitzgerald et al., 2013; Murtagh et al., 2005; Staino and Basu, 2013; Staino et al., 2012). When the blades are parked, the rotational speed is zero, the azimuthal angle is also constant and the pitch angle is 90°. The azimuthal angles are $\Psi_1=0°$, $\Psi_2=120°$ and $\Psi_3=240°$, respectively (Fig. 1). In this paper, the blade is simplified to a variable cross-section rectangular cantilever beam (Fig. 2a), as well as the tower (Fig. 2b). The blade-tower coupling effect has been included through the horizontal motion of a lumped mass M at the top of the tower, which represents the modal mass of the nacelle and the mass of the second and third blades, as shown in Fig. 2c. The tower is rigidly

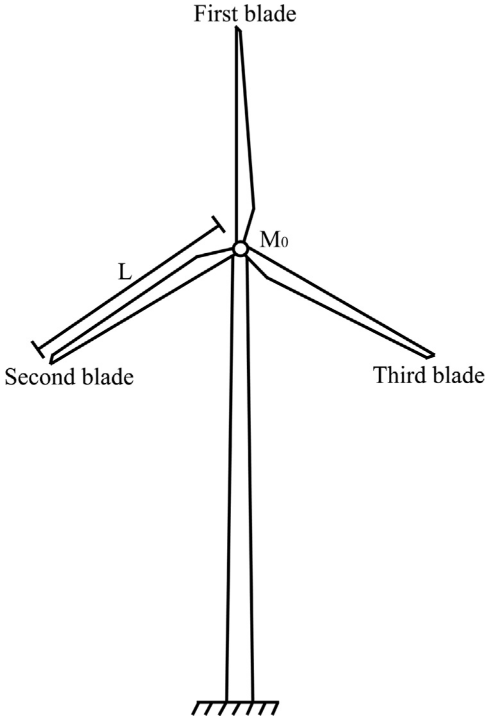


Fig. 1. Horizontal-axis wind turbine.