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An experimental investigation on the characteristics of fluid–structure interactions of a wind turbine model sited in microburst-like winds

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ABSTRACT

An experimental investigation is performed to assess the characteristics of the fluid–structure interactions and microburst-induced wind loads acting on a wind turbine model sited in microburst-liked winds. The experiment study was conducted with a scaled wind turbine model placed in microburst-like winds generated by using an impinging-jet-typed microburst simulator. In addition to quantifying complex flow features of microburst-like winds, the resultant wind loads acting on the turbine model were measured by using a high-sensitive force–moment sensor as the turbine model was mounted at different radial locations and with different orientation angles with respect to the oncoming microburst-like winds. The measurement results reveal clearly that, the microburst-induced wind loads acting on the turbine model were distinctly different from those in a conventional atmospheric boundary layer (ABL) wind. With the scales of the wind turbine model and the microburst-like wind used in the present study, the dynamic wind loadings acting on the turbine model were found to be significantly higher (i.e., up to 4 times higher for the mean loads, and up to 10 times higher for the fluctuation amplitudes) than those with the same turbine model sited in ABL winds. Both the mean values and fluctuation amplitudes of the microburst-induced wind loads were found to vary significantly with the changes of the mounted site of the turbine model, the operating status (i.e., with the turbine blades stationary or freely rotating), and the orientation angle of the turbine model with respect to the oncoming microburst-like wind. The dynamic wind load measurements were correlated to the flow characteristics of the microburst-like winds to elucidate underlying physics. The findings of the present study are helpful to gain further insight into the potential damage caused by the violent microbursts to wind turbines to ensure safer and more efficient operation of the wind turbines in thunderstorm-prone areas.

1. Introduction

Wind power market is growing rapidly in recent years in many countries around the world. With an average growth rate about 30% during the past 10 years, the total installed wind energy capacity has reached 321 GW globally by the end of 2013 (Wiser and Bolinger, 2014). As both the total number and the size of wind turbines increase, the structural integrity and

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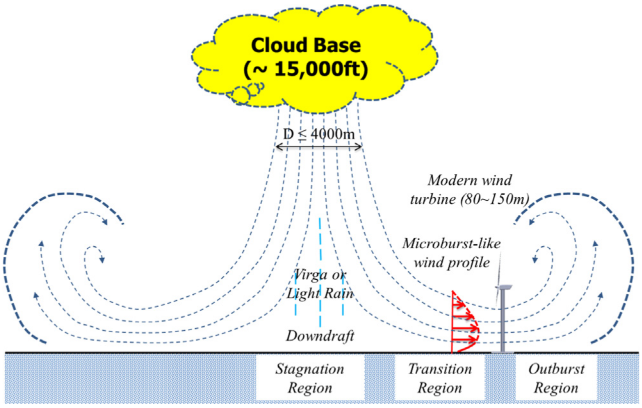

Fig. 1. Schematic of a microburst.

operational safety of wind turbines are receiving more and more attentions. According to the information provided by 2014 Caithness Windfarm Information Forum (2014) available at the website of http://www.caithnesswindfarms.co.uk/accidents.pdf, there were about 1500 wind turbine accidents and incidents in the UK alone in the past 5 years. Among all the turbine safety issues, structural failure, typically caused by extreme winds in thunderstorms, has contributed about one fifth of the total accidents, and resulted in much more property losses than any other types of accidents.

Downburst, as a particular example of the extreme winds, could be a serious wind hazard to the structural safety of wind turbines. Downbursts are quite common in many areas of the world. According to the 2011 Extreme Weather Sourcebook of National Center for Atmospheric Research (NCAR), approximately 5% of thunderstorms would produce downbursts that is one of the primary factors responsible for the estimated $1.4B of insured property loss each year in USA alone (data taken from 1950 to 1997). Fujita (1985) first classified the downbursts into microbursts and macrobursts, based on the horizontal extension of the divergent outburst flows. A microburst, as defined by Fujita (1985), is a strong downburst which produces an intense outburst of damaging wind with the radial extent being less than 4.0 km, or else is defined as a macroburst. Although a “microburst” has a smaller size than its counterpart, “macroburst”, it could produce a much stronger outflow with the maximum wind speed up to 270 km/h.

The flow characteristics of a microburst are dramatically different from those of conventional atmospheric boundary layer (ABL) winds and other wind hazards of wide concerns, e.g., tornadoes. As shown schematically in Fig. 1, a microburst can produce an impinging-jet-like outflow profile diverging from its center with the maximum velocity occurring at an altitude of less than 50 m above ground (Hjelmfelt, 1988). Such extreme high wind speed and wind shear (i.e., velocity gradient) near the ground could produce a significantly greater damaging potential to built structures. Furthermore, a microburst would also produce strong vertical velocity component in both the core region and the leading edge of the outburst, which is very different from conventional ABL winds. Therefore, microburst-induced wind loading pattern is quite different from what is usually expected with conventional ABL winds. Due to the extreme damaging potential of microbursts to built structures, a number of experimental and numerical simulation studies have been conducted in recent years to quantify the flow characteristics of the microburst-like winds and to assess the effects of the microburst-induced wind loading on various built structures on the ground, such as transmission towers, grain bins, low-rise residential houses and high-rise buildings (Savory et al., 2001; Chay and Letchford, 2002; Sarkar et al., 2006; Sengupta and Sarkar, 2008; Zhang et al., 2013a,b, 2014a,b).

Generally, wind turbines are designed to operate in conventional ABL winds. The wake characteristics and resultant wind loads acting on horizontal-axis wind turbines sited in conventional ABL winds have been studied extensively over the past years (Vermeer et al., 2003; Cal et al., 2010; Chamorro and Porte-Agel, 2010, 2011; Lebron et al., 2012; Yang et al., 2012; Hu et al., 2012; Zhang et al., 2012; Tian et al., 2014; Jeong et al., 2014). A number of numerical simulations have also been conducted by coupling stochastic or CFD turbulence models with aeroelastic models (e.g., FAST Jonkman and Buhl, 2005) to investigate the wind turbine loads subject to turbulent atmospheric boundary layer winds (Moriarty et al., 2004; Lee et al., 2011). Although extreme situations, such as Extreme Coherent Gust with Direction Change (ECD) and Extreme Direction Change (EDC), have already been considered in the IEC standards for wind turbine design (International Standard, 2005), such standards are not applicable for non-conventional ABL wind conditions. While microburst-like winds have been shown to generate significantly different fluid–structure interaction characteristics and wind loading effects on both low-rise and high-rise structures (Savory et al., 2001; Chay and Letchford, 2002; Sengupta and Sarkar, 2008; Zhang et al., 2014a,b), only few analytical studies can be found in literature to investigate microburst-induced wind loads acting on wind turbines. For example, Nguyen et al. (2011) studied the wind loads acting on a wind turbine sited in a simulated translational microburst wind by using an analytical model as suggested by Chay et al. (2006). They found that the simulated microburst would impose 86% higher out-of-plane bending moment on turbine blades than a typical EDC load case defined in IEC standards (International Standard, 2005), and 20% higher bending moment than that of an ECD load case when there was no yaw control applied. Kwon et al. (2012) introduced a concept of gust loading factors into the analysis of the wind loads acting on