Journal of Wind Engineering & Industrial Aerodynamics 173 (2018) 171–179

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

Enhancement of flutter stability in wind turbines with a new type of passive damper of torsional rotation of blades

Bei Chen [a], Zili Zhang [b], Xugang Hua [a,*], Søren R.K. Nielsen [c], Biswajit Basu [d]

[a] Key Laboratory for Wind and Bridge Engineering, Hunan University, 410082 Changsha, China
[b] Department of Engineering, Aarhus University, 8000 Aarhus, Denmark
[c] Department of Civil Engineering, Aalborg University, 9220 Aalborg, Denmark
[d] Department of Civil, Structural and Environmental Engineering, School of Engineering, Trinity College Dublin, Dublin 2, Ireland

ARTICLE INFO

Keywords:
Horizontal axis wind turbines
Flutter analysis
Viscous dampers
Vibration control

ABSTRACT

Classical flutter of wind turbine blades is defined as an aeroelastic instability where a torsional blade mode couples to a flapwise bending mode to result in a mutual rapid growth of the amplitude of the flapwise and torsional motions beyond certain rotational speed of the rotor. Till date, flutter instability of wind turbine rotor has not been considered to be a serious problem. However, with the advent of larger turbines fitted with relatively softer blades, classical flutter may become a more important design consideration. As an economically viable alternative to increasing the torsional rigidity (which is more expensive), the use of a type of viscous damper mounted inside the wind turbine blades is proposed to promote the flutter critical rotational speed of the rotor. The flutter critical rotational speed is determined by using a time-domain aeroelastic simulation technique based on the quasi-steady aerodynamic forces and also considering turbulence intensity of incoming wind. The optimal damper location and the optimal damping constant values are investigated for the DTU 10 MW wind turbine. It is shown that at an optimal tuning of the damper, the flutter critical rotational speed is only marginally dependent on the turbulence intensity of the incoming wind field, on the mean wind velocity and on the structural damping of the flutter torsional eigenmode. The novel tuned damper device proposed in this paper may increase the flutter critical rotational speed with more than 100%.

1. Introduction

It is known that three typical aeroelastic instabilities may occur in modern commercial wind turbines: divergence, stall-induced vibration and classical flutter. Divergence is a static phenomenon wherein the resulting wind velocity (consist of both the ambient wind speed and the rotational speed of the rotor) becomes large enough so that the load produced for an incremental angle of attack change due to blade twisting is greater than the reaction load produced by the elastic restoring forces for the same amount of twist (Lobitz and Veers, 1998). Stall-induced vibration is a single mode phenomenon characterized by predominantly flapwise blade oscillations, and normally occurs at high angle of attack causing separation of the boundary layer on the backside of the profile. The stall induces negative aerodynamic damping, related to a negative gradient $\frac{\partial c_l}{\partial \alpha}$ of the lift coefficient with the angle of attack (Hansen, 2007). The separation point may be stationary, which is referred to as static stall. At the core of dynamic stall the separation point moves on the backside of the profile, the boundary layer may even vary between fully attached or fully detached during part of the oscillation (Larsen et al., 2007). Pitch-regulated variable speed wind turbines normally do not operate in stall and the risk of stall-induced vibration is not as serious as for stall-regulated wind turbines.

Flutter is a well-known destructive instability from aircraft industry but historically has not been an issue in modern commercial wind turbines' design. Commensurately, among the utility-scale wind turbines that have been built, rarely has classical flutter ever been observed. In short, classical flutter of a beam-like structure such as wind turbine blades is explained as an unfavourable aerodynamic coupling between flapwise and torsional vibrations of blades in the presence of incident aerodynamic forces, and appears in a rapid growth of the amplitudes of the flapwise and torsional motions, which may leads to major structural failure of the blades. In a steady homogeneous wind field the onset of flutter takes place, if the average power supplied to the structure by the self-induced loads exceeds the average power dissipated by the structural

* Corresponding author.
E-mail addresses: chamber@hnu.edu.cn (B. Chen), zili_zhang@eng.au.dk (Z. Zhang), cexghua@hnu.edu.cn (X. Hua), srkn@civil.aau.dk (S.R.K. Nielsen), basub@tcd.ie (B. Basu).

https://doi.org/10.1016/j.jweia.2017.12.011
Received 22 August 2016; Received in revised form 7 December 2017; Accepted 7 December 2017

damping and possibly attached active or passive damping mechanism mounted on the structure (Politakis et al., 2008).

Based on the studies of Bisplinghoff, Fung and Hansen (Hansen, 2004a, 2007; Bisplinghoff et al., 2013; Fung, 2004), the risk of classical flutter of wind turbine blades with attached boundary layer may rise if the following three main criteria are satisfied: the frequency ratio between a flapwise bending mode and a torsional mode is close to one, the rotational speed of the rotor is sufficiently high and the position of the shear center of the airfoil is placed between the center of mass and aerodynamic center. Considering the first criterion, the risk of flutter increases as the ratio between the first torsional mode and one of the lower flapwise modes approaches one, such that they can couple in a flutter mode. As a reference point, for the 1.5 MW Horizontal Axis Wind Turbine (HAWT) with 35 m blades, it was the second flapwise bending mode and the first torsional blade mode which are coupled in flutter (Lobitz, 2004). For the 5 MW National Renewable Energy Laboratory (NREL) turbine, used as a benchmark in numerous analyses of wind turbines, the flutter instability took place between the third flapwise bending mode and the first torsional blade mode (Hansen, 2007). Similar result has also been found by Bir for a 5 MW NREL wind turbine (Bir and Jonkman, 2007). For the second criterion, the rotational speed of the rotor Ω must be sufficiently high, resulting in higher energy in the aerodynamic forces which 'feed' the flutter mode. Finally, the onset of flutter requires that the shear center is placed between the aerodynamic center and the center of mass. The inertial load is acting at the center of mass, whereas the aerodynamic load is acting at the aerodynamic center. Since the aerodynamic and the inertial loads approximately are in counter phase, they provide a maximum of elastic torsion with the indicated position of the shear center. Lobitz's work shown the flutter speed limit decreases when the center of mass is moved towards the trailing edge of the blade. Furthermore, when the center of mass is ahead of the shear center of the blade profile, flutter is unlikely at any rotational speed of the rotor (Lobitz, 2005).

Since the flutter mode is not known beforehand, thus the flutter can only be predicted by aeroelastic eigenvalue analysis or time domain simulation. Several studies have been carried out on wind turbine stability analysis, especially for flutter. Hansen (2003; 2004a; 2004b) proposed a multi-blade coordinate transformation (MBC, (Bir, 2008)) based eigenvalue analysis. Firstly the time-independent aeroelastic motion equations which couple the structural motion with the dynamics of the aerodynamic forces were derived using Lagrange's equations and MBC transformation. Then the eigenvalue problem which is ill-conditioned based on these autonomous equations was solved by using a modal expansion of the structural DOFs based on the undamped modes of the turbine at standstill. This enabled the computation of the natural frequencies, logarithmic decrements, and mode shapes of the aeroelastic turbine modes. The lowest nominal rotational speed of the rotor which corresponding to a negative damping coefficient exhibits in eigenmode is designated as the flutter critical rotational speed. Similar method has been used by Lobitz (2004). Alternatively, the aeroelastic stability may be checked by a pure mathematical approach of using Floquet theory on the non-transformed linearized equations (Nayfeh and Mook, 1995). However, this approach should be avoided since it doesn't have any physical meaning (Hansen, 2003). Furthermore, the stability analysis may also be performed by observing a certain envelope of the flapwise or torsional motions, indicating the evolution with time of the amplitude of the involved response quantities. Flutter is defined to take place, where the envelope of the torsional angle exceeds a certain critical value θ_{max}. This approach is useful if the instability is dominated by nonlinear mechanisms, either structural or aeroelastic (Chen et al., 2017a).

According to previous studies, the critical rotational speed for flutter turns out to be higher than the nominal rotor speed. Smaller wind turbines do not experience flutter due to their high torsional angular frequency in comparison to the angular eigen frequency in the critical flapwise bending mode of the blades (Lobitz, 2004; Hansen, 2008). In earlier work on a 20 KW HAWT with stiff, aeroelastically tailored 5 m blades, Lobitz and Veers (1998) predicted flutter critical rotational speed that were six times the nominal rotor speed ($\frac{\Omega_{cr}}{\Omega} = 6$), rendering flutter a moot issue. The predicted flutter limits of a SNL 9-meter CX-100 experimental blade were shown to be four times higher than the nominal rotor speed ($\frac{\Omega_{cr}}{\Omega} = 5$) (Resor and Paquette, 2011). Study on 1.5 MW-sized WindPACT wind turbine with 34 m blades has a safety margin of 2–2.5 ($\frac{\Omega_{cr}}{\Omega} = 2.0 - 2.5$) (Lobitz, 2004). Similar result has also been found by Hansen for a 5 MW NREL wind turbine (Hansen, 2007). Further, for the 10 MW NOWITECH wind turbine with 89 m blades, the critical rotational speed for flutter is found to be about 1.6 times the nominal rotor speed ($\frac{\Omega_{cr}}{\Omega} = 1.6$) (Vatne, 2011). However, result from a 13.2 MW wind turbine with 100 m blades in length showed that there is little or no margin on flutter speed ($\frac{\Omega_{cr}}{\Omega} = 1.0 - 1.1$) reported by Griffith and Resor (Griffith and Ashwill; Resor et al., 2012). The trend shows that the ratio of critical rotational speed for flutter to the nominal rotor speed $\frac{\Omega_{cr}}{\Omega}$ drops significantly as the blades grows in length from 5 m to 100 m. Therefore, it is believed that with a likely reducing blade torsional stiffness with increasing blade radius (considering current design trends) the critical rotational speed for flutter Ω_{cr} will be approach the nominal rotational speed Ω of the rotor (Politakis et al., 2008). This also means that aeroelastic instabilities, especially flutter, would then become one of the principal design drivers (Hansen, 2007).

Great efforts have been devoted to mitigating loads and improving the aeroelastic stability of wind turbines (Belamadi et al., 2016; Bottasso et al., 2016; Moshfeghi et al., 2017; Bernhammer et al., 2016). Due to the limitation of space in wind turbine blades, few works have been carried out on suppressing flutter of wind turbine blade, especially using mechanical countermeasures, such as tuned mass damper (TMD). Hence, the adaptive blades that involving the use of aeroelastic tailoring (also known as bend-twist coupling (BTC)), wherein the blade twists as it bends under the action of aerodynamic loads to shed wind-induced loads and increase the aeroelastic stability of wind turbine has been investigated by a lot of researchers (De Goeij et al., 1999; Veers et al., 1998; Rafiee et al., 2016). Even though the BTC proved to be effective in mitigating the fatigue loads for large-scale wind turbine blades, it may increases the blades proclivity for flutter at the same time (Bottasso et al., 2013; Hayat and Ha, 2015; Hayat et al., 2016). Lobitz's (Lobitz and Veers, 1998) research shown that the flutter speed of the rotor can be increased by around 11% at the optimal values of the coupling coefficient for 20 kW HAWT, since the blade is less stable as the extreme values of the coupling coefficient are approached due to the divergency limit. Further, Hayat (Hayat et al., 2016) extended Lobitz's study using a beam element model to simulate the composite laminate material structure. Results shown the flutter speed of the rotor can be increased by about $7.6 - 9.5\%$ using lighter and stiffer carbon fibers.

As mentioned above, there have been several researches reported on increasing flutter limits using BTC. However, their effectiveness is very limited. Inspired from this, a new 'electromagnetic' type of linear viscous damping device is proposed in this paper in order to mitigate the torsional and flapwise vibration of the blades, hence increasing the flutter critical rotational speed of the rotor. Firstly, a wind turbine model is presented, which considers the coupling between aerodynamic, elastic and inertial loads of the blades. The parameters of the model have been calibrated to the DTU 10 MW wind turbine (Bak et al., 2013; Bak et al.,). The elastic deformations of the blades are coupled via the tower motion, which is modeled by a reduced five degree-of-freedom model, and via the drive train, which is modeled by a two degree-of-freedom model. The pitch of the blades are controlled by a collective PI controller with feedback from the rotor speed. Furthermore, a linear viscous damper model is provided. The optimal parameters of the viscous damper are calculated. Finally, the sensitivity study of this damping system to the turbulence, the mean wind velocity, the structural damping and the parameters of this damper is performed.