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Cable connected active tuned mass dampers for control of in-plane vibrations of wind turbine blades

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ABSTRACT

In-plane vibrations of wind turbine blades are of concern in modern multi-megawatt wind turbines. Today's turbines with capacities of up to 7.5 MW have very large, flexible blades. As blades have grown longer the increasing flexibility has led to vibration problems. Vibration of blades can reduce the power produced by the turbine and decrease the fatigue life of the turbine. In this paper a new active control strategy is designed and implemented to control the in-plane vibration of large wind turbine blades which in general is not aerodynamically damped. A cable connected active tuned mass damper (CCATMD) system is proposed for the mitigation of in-plane blade vibration. An Euler–Lagrangian wind turbine model based on energy formulation has been developed for this purpose which considers the structural dynamics of the system and the interaction between in-plane and out-of-plane vibrations and also the interaction between the blades and the tower including the CCATMDs. The CCATMDs are located inside the blades and are controlled by an LQR controller. The turbine is subject to turbulent aerodynamic loading simulated using a modification to the classic Blade Element Momentum (BEM) theory with turbulence generated from rotationally sampled spectra. The turbine is also subject to gravity loading. The effect of centrifugal stiffening of the rotating blades has also been considered. Results show that the use of the proposed new active control scheme significantly reduces the in-plane vibration of large, flexible wind turbine blades.

1. Introduction

The reduction of vibrations in wind turbine blades is of topical interest. Wind turbine blade lengths have increased exponentially in the past two decades in order to maximize power output under specified atmospheric conditions. Several researchers have attempted to mitigate blade vibrations [1,2]. Uncontrolled vibrations can lead to structural damage which could reduce the life of the blades and increase maintenance costs. Ahlstrøm [3] has also shown that large blade vibrations have a major influence on power production. Therefore the reduction of the vibration of wind turbine blades has become an increasingly important area of research in the wind turbine industry.

The main modes of vibration for wind turbine blades are flapwise and edgewise. In this paper, the control of in-plane blade vibrations (which are predominantly edgewise with some flapwise contribution) is considered, i.e. reducing blade vibrations which occur in the blade rotation plane. It is well known that in the in-plane direction the modal damping is low

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due to low aerodynamic damping. Aerodynamic damping of the blade vibrations in the edgewise direction can become negative and as a result the sum of the structural damping and the aerodynamic damping can be less than zero.

As wind turbines have become larger and more flexible edgewise vibrations have become a serious problem. Moeller [4] has shown that theoretically edgewise vibrations can occur on all rotor blades. It was found that edgewise vibration increases with blade size and wind strength. Therefore, with modern blades of over 60 m length operating in harsh conditions (high wind speeds, high turbulence intensities, offshore, etc.) edgewise blade vibrations have become a real problem for the wind energy industry. Moeller stated that the appearance of edgewise vibration problems: *"can certainly be interpreted as a warning that it is not possible to continuously scale up a design without facing and resolving new vibratory and aeroelastic problems"*. The severity of the edgewise blade vibration is influenced by the structural design of the blade i.e. the blade stiffness and the mass distributions have an influence. Thus, the problem worsens as blades become more flexible, lighter structures.

Aeroelastic stability problems arising from edgewise vibrations were first noticed in the early 1990s and have been studied by several researchers since then. Thomsen et al. [5] investigated the problems caused by edgewise vibrations in stall-regulated wind turbines. Hansen [6] showed that edgewise blade vibration could cause aeroelastic instability in modern commercial wind turbines. Riziotis et al. [7] presented an aeroelastic stability tool to consider the complete wind turbine configuration. The use of stall strips to reduce edgewise blade vibrations has also been investigated by Riziotis et al. [7] and Petersen et al. [8]. Stall strips were shown to increase the aerodynamic damping and therefore reduce edgewise vibrations. However, both studies found that a significant power penalty was incurred when stall strips were mounted on the leading edge of the blades.

Although structural control has been an active area of research for several decades, applying structural control techniques to wind turbines is a new and developing area of research. There are only a few papers published that focus on this area of research. Furthermore, the papers that are published in the literature generally focus on passive structural control techniques [1,2,9,10]. Lackner and Rotea [11] investigated the use of passive and active structural control techniques with mass dampers for floating offshore wind turbines. Stewart and Lackner [12] investigated the causes and effects of control–structure interaction with respect to an active structural controller installed on a large-scale floating wind turbine. Several of the studies recommended further investigations into active control strategies in future studies [9,12,11,10]. Active control of wind turbines has been studied by Staino et al. [13]. The authors developed an active actuator control algorithm to reduce blade vibrations. Active control was shown to perform well at controlling blade vibration. The authors recommended further investigation into the application of active control in wind turbines. Recently Fitzgerald et al. [14] investigated the use of active tuned mass dampers (ATMDs) for the mitigation of in-plane vibrations in rotating wind turbine blades. It was found that an active control strategy achieved greater response reductions than a passive control strategy. The study also showed that an ATMD control strategy is feasible for a wind turbine blade particularly for higher turbulent loadings with enough room for stroke of the ATMD within the blade.

It is clear therefore that there is presently a gap in the literature and studies reported on active control are sparse. This paper aims to address that knowledge gap through investigations carried out into active structural control for vibration control of wind turbine blades. Inspired by the success of Staino et al. [13] in active tendon actuator control and Fitzgerald et al. [14] in ATMD based control, this paper proposes a new control hardware with a cable connected active tuned mass damper (CCATMD) merging the benefits of the two.

In this paper the use of CCATMDs to reduce in-plane vibrations in wind turbine blades is investigated. An active structural control strategy is employed to overcome some of the issues that render traditional passive control of large engineering structures such as wind turbine blades ineffective.

Using a passive controller such as a tuned mass damper (TMD) in large structural systems with complicated system dynamics like wind turbines leads to problems. The mass ratio is the governing parameter that affects the performance of a passive TMD. If the primary structure is very large (e.g. a wind turbine blade) the TMD will inevitably have a small mass ratio. Furthermore, if the mass ratio is small the auxiliary system response may become very large. Therefore, free vibration of the TMD will continue for a long time after the excitation has been removed from the primary structure [15]. Moreover, the main problem with using a passive TMD to damp wind turbine blade vibration is that there is no single appropriate dominant resonant frequency present consistently for the entire time history of the response as they change with rotational frequency or operating conditions. The response is dominated by the rotational frequency of the blades, known as the 1P frequency. It would be ideal to tune the blade dampers to the rotational frequency of the blades. However, tuning a TMD on a rotating blade to the frequency of rotation has been shown to introduce an instability into the system [16], see Eq. (57). These problems can be mitigated by introducing an active control strategy.

ATMDs are well known and have been used classically to reduce the dynamic response of structures [17,18]. In this paper a new variation on the classical ATMD is proposed. The new type of damper is called a CCATMD. The CCATMD consists of a classical ATMD with a cable connection. An optimal LQR controller is used with this CCATMD. The time varying nature of the wind turbine system makes it difficult to control with passive dampers. Although the 1P frequency dominates the response it is not possible to tune a TMD to this frequency. There is also a stochastic component to the loading which is impossible to predict and impossible to tune a passive TMD to. The rotating wind turbine blades with tower interaction represent time varying dynamical systems with periodically varying mass, stiffness and damping matrices. This complex dynamic system is subjected to turbulent aerodynamic loading and periodically varying gravity loading which makes controlling blade vibrations a serious challenge.