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Smart fatigue load control on the large-scale wind turbine blades using different sensing signals

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A B S T R A C T

This paper presented a numerical study on the smart fatigue load control of a large-scale wind turbine blade. Three typical control strategies, with sensing signals from flapwise acceleration, root moment and tip deflection of the blade, respectively, were mainly investigated on our newly developed aero-servo-elastic platform. It was observed that the smart control greatly modified in-phased flow-blade interaction into an anti-phased one at primary 1P mode, significantly enhancing the damping of the fluid-structure system and subsequently contributing to effectively attenuated fatigue loads on the blade, drive-chain components and tower. The aero-elastic physics behind the strategy based on the flapwise root moment, with stronger dominant load information and higher signal-to-noise ratio, was more drastic, and thus outperformed the other two strategies, leading to the maximum reduction percentages of the fatigue load within a range of 12.0–22.5%, in contrast to the collective pitch control method. The finding pointed to a crucial role the sensing signal played in the smart blade control. In addition, the performances within region III were much better than those within region II, exhibiting the benefit of the smart rotor control since most of the fatigue damage was believed to be accumulated beyond the rated wind speed.

1. Introduction

In recent years, with the rapid development of the global offshore wind power, the R&D of the large-scale wind turbine, with a high superiority in cost, has attracted wide attention. Nevertheless, the aerodynamic load status of the corresponding long flexible wind turbine blades becomes much worse due to the influences of wind shear, turbulence, tower shadow and wake from the upstream turbine, etc, forming serious threat to the safety and reliability of the operating turbine [1]. To improve this situation, it is very necessary to develop an available blade load control method, which may also be helpful to reduce the loads on other turbine components as well as to ensure the decreased maintenance requirements and an overall lower cost per kWh for a large-scale offshore wind turbine.

Considering the complicated and changeable aerodynamic load within the rotor plane, a new kind of control concept, i.e. 'smart rotor control', a term used in the rotorcraft research [2], was recently proposed to exert the controllable action for each blade at any azimuthal position and any span-wise station. The essence of the control was to drive the local aerodynamic surfaces through a combination of sensors, actuators and controllers, and thus provid a good load control capacity. This would undoubtedly remedy the drawbacks of the traditional strategy utilizing the integral, low response and excessive wear pitch control method (e.g. collective, cycle or independent pitch control method), mostly applied in current wind turbines. Therefore, the aspect of the smart rotor control has become one of the hot research areas within the wind community for more than one decade.

A large amount of work has been focused on the development of the available actuator/aerodynamic surface in the past. By comparing the different schemes, e.g. micro tab [3], morphing [4], active twist [5], suction/blowing [6] and synthetic jet [7], etc, the "deformable trailing edge flap (DTEF)", a flap that deformed in a flexible shape to generate a substantial change in the lift coefficient of the airfoil by altering the pressure distribution along the chord, characterized by its positive performance, fast response, small size, wide bandwidth and low flow disturbance, had been found to be the most potential actuator candidate for the smart rotor means [8]. Furthermore, many investigations have also been conducted utilizing the DTEFs in terms of DTEF modeling [9–11], controller

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implementation [12–16], load control effectiveness and analysis [17–21], small-scale wind tunnel experiments [22–24] and full-scale field tests [25,26].

On the other hand, the investigations on the sensing signals, equally important to the control performance, of the DTEF based smart rotor system, have been very active lately. Generally speaking, researchers have deployed and collected information on many different sensing signals, including acceleration [27], strain [17,28], inflow velocity and attack angle [28], displacement [14] and surface pressure difference [29], etc, and studied the influences of the number and location of the sensors on the control effectiveness, as well summarized in Ref. [30]. However, the comparison and analysis among representative sensing methods were still little reported before. Moreover, the corresponding aero-elastic control physics behind has not been well understood. These unsolved issues might greatly block the optimal design of the smart rotor system on the large-scale offshore wind turbine in the future engineering applications.

To this end, three types of sensing strategies were mainly studied in this paper based on the flapwise acceleration on the blade surface (a), the blade flapwise root moment (M_y, relative to the strain at the blade root) and the blade flapwise tip deflection (D_x, or displacement), i.e. a-strategy, M_y-strategy and D_x-strategy, and their effects on the fatigue load control on the blades as well as other typical components of the wind turbine, were individually examined and compared. Note these sensing signals could be easily measured using accelerometer, strain gauge and displacement transducer in practice. Like many previous investigations [12–14,16–21,28,33], the variable speed, pitch controlled NREL UpWind/5 MW offshore wind turbine [31], with a 126 m rotor diameter and a 90 m hub height, was selected as a control subject, and the hydrodynamic properties were not considered for simplicity. All this work had been conducted under the Normal Turbulence Mode (NTM) wind condition, followed by the International Electro-technical Commission (IEC) standard [32], using our newly developed aero-servo-elastic numerical platform [33], which was built by improving the FAST/Aerodyn codes with the integration of the internal DTEF controller into the Matlab/Simulink software. In addition, the corresponding modifications in the coupled aero-elastic interactions between flow and blade for the three signal cases were discussed in detail.

2. Sensing and control schemes

The purpose of the present smart rotor control was to effectively suppress the fluctuating magnitude of the sensing signals (i.e. a, M_y and D_x) and thus the primary fatigue loading source, i.e. M_y, on the UpWind/5 MW wind turbine blade, using the controllable DTEF actuation by an internal controller. This was realized by an aero-servo-elastic numerical platform, consisting of aerodynamic, structural dynamic and control sub-models, and one might go through our recent published paper [32] for more information. Moreover, without loss of generality, the incoming wind was set to be the medium wind class (IIB) with the reference speed V_{ref} and the turbulence intensity I_{ref} of 42.5 m/s and 0.14, followed by the IEC NTM standard [31]. Wind data was generated using NREL Turbsim code [34], with 3D turbulent wind formed using a von Kármán spectrum and a wind shear power law exponent of 0.2.

The aerodynamic sub-model was mainly built on the NREL AeroDyn code [35], combining the Blade Element Momentum (BEM) and the Generalized Dynamic Wake (GDW) theories, to calculate the lift, drag and pitching moment forces at any attack angle α from the corresponding lookup tables. Specifically, the lift coefficient (C_l), drag coefficient (C_d) and moment coefficient (C_m) as a function of $\alpha = -20^\circ$~$^\circ 23^\circ$, were first computed by RFOIL code [36] for each DTEF deflection angle φ in 1° increments. After that, these coefficient tables were pre-processed using the Viterna method to expand to the α range of -180°~ $+180^\circ$. The camber curve of the DTEF was generated by fitting a cubic spline through the mean camber line of the baseline airfoil and the new trailing edge point, and a group of DTEF parameters, i.e. the spanwise length L_f, normalized by the rotor radius R, the central chordwise length c_f, normalized by the averaged chord length c at the DTEF location, and the deflection angle range $|\varphi|$, were set to be 0.20, 0.10 and ±15°, respectively, where very good performance had been confirmed in our recent investigation [21]. Furthermore, four other built-in models, including the 3D rotational stall delay model, the Prandtl tip and hub loss model, and the tower shadow effect model, were also used in the AeroDyn code to further improve the accuracy.

In addition, as Lackner and Kuik [13] did, a quasi-steady assumption was presumed to neglect the influence of the unsteady dynamic stall. Correspondingly, the averaged magnitude of the major peak in the PSD of the DTEF angle (or the majority of energy) was computed to occur at a reduced frequency k, *i.e.*, $k = c\omega/U$, representing the degree of unsteadiness of an airfoil section subject to external disturbance, of about 0.02 (not shown), much less than 0.05, beyond which the aerodynamics of the airfoil section could be considered to be unsteady. Based on this, we had confirmed that even though the aerodynamics of DTEF sections, were not entirely quasi-steady, which might influence the smart rotor simulations to some degree, it was indeed a safe assumption to do so. Here c, U and ω stood for the mean chord length of the section with the installment of DTEFs, the sectional relative velocity and the frequency of the disturbance in units of radians per second, respectively.

The structural dynamic sub-model was based on the NREL FAST code [37], where a combined modal and multi-body representation of the turbine was built to determine its response to the applied force. By doing so, the structural dynamic might be aero-elastically coupled to its aerodynamic counterpart by means of the structural deformation velocities and the aerodynamic forces. As a result, the time histories of the fatigue load on the blades were generated with the input aerodynamic forces calculated by the Aerodyn code.

The control sub-model incorporated internal and external parts. Consuming no noise and time delay or lag interferences, the former mainly focused on how to reasonably manipulate the DTEFs for good control performance on the fatigue load, shown in Fig. 1. For each sensing strategy, the signals Q_i ($i = 1, 2, 3$), i.e. a_i, M_{yi} or D_{xi}, originated from three rotational turbine blades, was separately transformed into the fixed nacelle/yaw frame of reference using the inverse Coleman transformation to remove the periodic coefficients in the equations of motion. The coordinate system was defined in Fig. 1, where x, y, z axes and origin was orthogonal with y and z axes, pointing towards the trailing edge of blade and parallel with the chord line at the zero-twist blade station, pointing along the pitch axis towards the tip of blade, and intersection of the blade's pitch axis and the blade root, respectively. The transformed variables were then assumed to be time-invariant and the typical linear time invariant control technique, e.g. proportional-integral-derivative (PID) control, could be used, which was based on the error input between the reference and the actual feedback input. Furthermore, since the goal of the flap controller was to minimize the fluctuating a_i, M_{yi} and D_{xi}, the corresponding referenced variations were set to be zero. The governing equations were:

$$\theta_s(t) = k_P(0 - Q_s(t)) + \frac{1}{T_I}\int_0^t (0 - Q_s(t))\mathrm{d}t + \frac{T_D \mathrm{d}(0 - Q_s(t))}{\mathrm{d}t} \quad (1)$$