Smart Fatigue Load Control on a Large-scale Wind Turbine Based on Different Sensing Strategies

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Introduction

As we know, the recent development of the large-scale offshore wind turbine has been attracted wide attention. Nevertheless, the aerodynamic load of the long flexible blades became much larger due to stronger aero-elastic relations between blades and flow around them, forming a serious thread to the safety of the wind turbine. To improve this, a novel “smart rotor control” concept with local build-in intelligent control system on the blades has shown its superiorities to alleviate the fatigue loads over traditional pitch controls in terms of performance, speed and scale [1]. Many research efforts have been made to develop the actuator in the past. By comparing different schemes, the “deformable trailing edge flap (DTEF)” was found to be the most potential actuator candidate for smart rotor control [2].

On the other hand, the investigations on the sensing signals of the DTEF based smart rotor system have also been active lately. By deploying the signals like acceleration [3], strain [4], inflow velocity and attack angle [5], displacement [6] and surface pressure difference [7], researchers ever studied their number and location influences on control effectiveness. However, the comparisons among representative sensing methods were little reported before. Moreover, the corresponding aero-elastic control physics behind have not been well understood. These unsolved issues might blockage the technique to be applied in the future.

To this end, three typical sensing strategies based on flapwise acceleration ($a$), blade flapwise root moment ($M_y$) and flapwise tip deflection ($D_x$), i.e. $a$--, $M_y$- and $D_x$-strategies, as well as the understanding of the control physics, were presently studied. The control was executed on Upwind/NREL 5MW reference wind turbine under IEC Normal Turbulence Mode wind condition.
Approach

The research was conducted using our newly developed aero-servo-elastic numerical platform [8], consisting of aerodynamic, structural dynamic and control sub-models, which was built by combing the FAST/Aerodyn codes with an edited internal DTEF controller using Matlab/Simulink software.

The aerodynamic model was mainly based on the AeroDyn code [9], with 3D rotational stall delay model, Prandtl tip loss model and shadow effect model, to calculate the aerodynamic forces using the obtained tables of lift, drag and moment coefficients within airfoil attack angle $\alpha$ range of $-180^\circ$ to $+180^\circ$ for each DTEF deflection angle $\varphi$. According to our recent investigation [10], the spanwise length ratio, the chord ratio and the range of $\varphi$ were set to be 0.20, 0.10 and $\pm 15^\circ$, respectively. In addition, as Lackner and Kuik [11] did, a quasi-steady assumption was presumed to neglect the influence of the dynamic stall since the major peak in the $\varphi$-spectrum occurred at a reduced frequency of about 0.02, much less than 0.05, beyond which the aerodynamics of airfoil section could be considered to be unsteady. The structural dynamic model was formed using the FAST code [12], where the turbine multi-body model was deployed to determine the responses to the aerodynamic forces computed by the Aerodyn code.

The control sub-model was composed of original NREL generator torque and pitch controller, and a self-developed DTEF controller, shown in Fig. 1. For DTEF controller, the sensing signal $Q_i (i = 1, 2, 3)$, i.e. $a$, $M_y$ or $D_x$, was first transformed into the fixed reference frame using the inverse Coleman transformation, yielding hub yaw-wise and tilt-wise moments, respectively. Then these two moments were used as inputs to Linear Time Invariant proportional-integral-derivative controllers, and the control actions were exerted through reasonably adjusting the proportional, integration and derivative coefficients within $\varphi$ limit. Finally, the resultant control was transformed back into the rotating frame using the Coleman transformation to assign the proper $\varphi_i$ to each blade for the effective control of $M_{yi}$. 
Main body of abstract

To compare the performances among three sensing strategies, study began with \( a \)-strategy and only the results of blade1 was analysis for simplification. Figure 2 indicates the typical effect of the accelerometer spanwise location, i.e. \( R_u \), on the reduction percentages in the standard deviation and the root damage equivalent load of \( M_{y1} \), i.e. \( \Delta M_{y1,STD} \) and \( \Delta M_{y1,DEL} \) under different hub velocity \( U_{hub} \). Obviously, \( \Delta M_{y1,STD} \) and \( \Delta M_{y1,DEL} \) tended to increase with increasing \( R_u \) and then suddenly decreased near the blade tip for \( U_{hub} = 8.0 \) m/s case (typical region II case) and \( U_{hub} = 11.4 \) m/s case (rated wind speed). This was possibly associated with the flow separations in chordwise and spanwise directions around the blade tip. In contrast, as the turbine was operated into region III \( (U_{hub} > 11.4 \) m/s), the main fatigue load source [13], the performances were greatly improved, especially for \( U_{hub} = 24 \) m/s case, under which the maximum \( \Delta M_{y1,STD} \) and \( \Delta M_{y1,DEL} \) reached 18.1\% and 12.6\%. The significantly impaired tip deflections, and the blade pitching action within region III to reduce \( \alpha \) and thereafter suppressed the uncontrolled flow separation, were believed to be responsible for the reduced \( M_y \).

Similarly, the investigations using \( D_x \) - and \( M_y \)-strategies, with the same spanwise location (90\% of blade radius) as \( a \)-strategy, were examined in Fig. 3. Evidently, irrespective of strategies,
Fig. 2. Effect of the accelerometer spanwise location on the reduction percentages in $\Delta M_{y,\text{STD}}$ (a) and $\Delta M_{y,\text{DEL}}$ (b) at various hub velocities.

Fig. 3. The reduction percentages in $\Delta M_{y,\text{STD}}$ and $\Delta M_{y,\text{DEL}}$ at various $U_{\text{hub}}$: (a) $D_z$-strategy, $\Delta M_{y,\text{STD}}$; (b) $D_z$-strategy, $\Delta M_{y,\text{DEL}}$; (c) $M_y$-strategy, $\Delta M_{y,\text{STD}}$; (d) $M_y$-strategy, $\Delta M_{y,\text{DEL}}$.

Control became more effective when $U_{\text{hub}}$ increased. The best performances were acquired using $M_y$-strategy at $U_{\text{hub}} = 24$ m/s, with the maximum $\Delta M_{y,\text{STD}}$ and $\Delta M_{y,\text{DEL}}$ up to 22.5% and 14.7%.

Furthermore, the typical time and frequency domain results were proposed in Fig. 4. Clearly, the fluctuating magnitude in $M_{yi}$ was effectively decreased. Correspondingly, the dominant 1P spectral
Fig. 4. Typical time domain (a) and frequency domain (b) results of $M_{y1}$ using different control strategies.

peaks at the frequency $f_{1p} = 0.20$ Hz, were significantly reduced, showing the great impairment in the energies of $M_{y1}$. Additionally, the DTEF control of the fatigue loads on other representative turbine components (e.g. low-speed shaft and tower) was also very effective. From these results, the performances using $M_y$-strategy tended to much more outperform than the other two strategies, which lied in the less interference noises contained in $M_y$ signal (besides 1P mode) at the blade root with a relatively higher stiffness than $D_x$ and $a$ signal cases near the blade tip (not shown).

To understand the control physics behind, the spectral phase and coherence [14,15] among $\phi_l$, the local flapwise aerodynamic force $F_n$, and the local $a$, were computed. Figure 5 proposed the typical spectral phase shifts $\phi_{F_n}$ between $\phi_l$ and $F_n$ at $U_{hub} = 24$ m/s. Obviously, $\phi_{F_n}$ at primary frequency $f_{1p}$ was close to $\pi$, suggesting that DTEF excitation and nearby aerodynamic sectional force was in anti-phase. Furthermore, the uncontrolled spectral phase $\phi_{F_n,a}$ of $F_n$ and $a$ in Fig. 6 was around zero over a small frequency range near $f_{1p}$, corresponding to the strong synchronizing flow and structural vibration. Once controlled, $\phi_{F_n,a}$ at $f_{1p}$ was changed from 0 to $\pi$, that is, the synchronizing $F_n$ and $a$ turned into collided interactions against each other. Note the phenomena happened over a wide range of frequencies around $f_{1p}$ for $M_y$-strategy, resulting in more impaired fluid-structure interaction than $D_x$- and $a$-strategies.
Fig. 5. Typical spectral phase $\phi_{\omega F_1}$ for different sensing strategies: (a) $D_x$-strategy; (b) $a$-strategy; (c) $M_y$-strategy.

Fig. 6. Typical spectral phase $\phi_{\omega F_3}$ for different sensing strategies.

On the other hand, the spectral coherence $Coh_{F_1}$ at $f_{1p}$ in Fig. 7 obviously decreased. Moreover, similar observations were also found at other two representative spanwise locations (not shown) and the control using $M_y$-strategy performed the best, meaning the decoupled aero-elastic correlation between flow and the whole blade vibration.
Fig. 7. Typical spectral coherence $Coh_{F,\alpha}$ for different sensing strategies.

Conclusion

(1) The smart control using three sensing strategies greatly suppressed the fatigue loads on blades and turbine components. The best performance was obtained using $M_y$-strategy, leading to the maximum reduction of 12.0 ~ 22.5%.

(2) The performances within region III, main fatigue damage source, were much better than region II, exhibiting the great advantage of the smart rotor control on blade fatigue load.

(3) The smart control greatly modified in-phased flow-blade interaction into anti-phased one at primary 1P mode, significantly enhancing the damping of fluid-structure system and subsequently contributing to effectively attenuated fatigue loads on blade and turbine components. The aero-elastic physics for $M_y$-strategy, more reflected dominant 1P flapwise load, was more drastic, and thus outperformed the other two strategies.

Learning objectives

This work presented our recent progresses on the smart rotor control using representative sensing strategies in terms of fatigue load suppression on blades and turbine components as well as potential aero-elastic physics behind. The outcomes would be helpful to provide some guideline for the optimal design of the smart rotor system on the large-scale offshore wind turbine in the future.
References


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