A NEW ACTIVE CONTROL STRATEGY FOR WIND-TURBINE BLADES UNDER OFF-DESIGN CONDITIONS

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A new active control strategy for wind-turbine blades under off-design conditions has been investigated in this paper. According to our previous work, in comparison with the traditional straight leading-edge blade, a new kind of bionic blades with a sinusoidal leading edge can significantly enhance the turbine's power output at high speed inflows. However, the wavy leading-edge shape is unfavorable under the design operating conditions since an early boundary-layer separation is inevitable for a wind-turbine blade because of the geometric disturbances of the leading-edge tubercles. But for the present active control, the defect in wavy leading-edge blades can be eliminated by introducing a series of small flat delta wings as the control units, since delta wings can also generate powerful leading-edge vortices. As a preliminary test, our numerical results show that, the shaft-torque fluctuation in the turbine's stall region can be improved from 27.8% for a straight leading-edge blade (no control) to 8.9% for the present active control; and by adjusting the control parameters, the control units nearly have not any negative effect on the blade's shaft torque under the design conditions. We believe that, as an auxiliary tool of the conventional control strategies, the present active control approach may be favorable to generate a more stable and more controllable power output for wind turbines under all operating conditions (even in the yawed inflows).

Keywords: Wind turbine; active control; delta wing.

1. Introduction

Wind turbines are subjected to complicated environmental effects including atmospheric turbulence, ground boundary layer and so on. As a result, severe fluctuations of power output usually occur for modern wind turbines under off-design operating conditions (e.g., high wind-speed inflows), since a strong boundary-layer separation is inevitable at the wind-turbine blade's suction side even if some control strategies (e.g., stall regulation or pitch control) have been performed.

Distinguishing from the traditional control strategies (stall regulation or pitch control), recently Hamilton [1], Peacock and Bradley [2] reported a new kind of wind-turbine blade, in which the blade was designed with a wavy leading-edge shape by mimicking the leading-edge tubercles of a humpback whale's flippers. Fish *et al.*'s experiments [3–7] have revealed that, humpback whale's leading-edge tubercles can significantly increase

its flippers' lift-to-drag ratio in high angle-of-attack inflows. This kind of aerodynamic characteristics is required for a stall-regulated wind turbine, since there is usually a clear reduction in turbine's power output under deep-stall operating conditions.

Fig. 1: (a) A whale-inspired wind-turbine blade with a wavy leading-edge; (b) comparison of shaft torque between the traditional blade and the wave leading-edge blades [8].

The aerodynamic performances of this new-type blade have been investigated numerically in details by Zhang and Wu [8]. As shown in Fig. 1, the numerical result shows that, in comparison with a traditional straight leading-edge blade (e.g., the NREL Phase-VI rotor), the shaft torque of the wavy leading-edge blade have a significant increment under high speed inflows (e.g., 15 ~ 20m/s). A strong suction pressure generated by the localized vortices shedding from the leading-edge tubercles is the physical root to enhance the aerodynamic performances of the new-type blade. The numerical result further reveals that, the outboard segment from the 60% spanwise station to the blade tip is the key region for wavy leading-edge blades to improve the aerodynamic characteristics at high speed inflows. However, the calculation in Fig. 1(b) also indicates that, the wavy leading-edge shape is unfavorable for wind-turbine blades under the design operating conditions (e.g., at the rated speed 10m/s inflows). Under these conditions, the geometric disturbance of the leading-edge tubercles will inevitably result in a visible shaft-torque reduction (Fig. 1(b)) by following an early boundary-layer separation at the blades' suction sides.

In this paper, a new active control strategy is developed for wavy blades, in which the uncontrollable leading-edge tubercles are replaced by a series of small flat delta wings as the control units. Our numerical results will reveal, that the conflict between the design conditions and the higher speed inflows for wavy blades can be resolved by adjusting the control state of the small delta wings. The next section will present the numerical geometric model and the corresponding numerical methodology. The aerodynamic performances of the new-type wind-turbine blade with the active control strategy will be discussed in detail in Sect. 3. At last, some conclusions will be given in Sect. 4.

2. Geometry and Numerical Methodology

Following Zhang and Wu [8]'s geometric model for wavy leading-edge blades, in this paper the NREL Phase-VI rotor [9] is also used as a baseline blade to construct a new

geometric model for the active control strategy. Fig. 2 displays the new blade for active control, where a series of small delta wings instead of the stationary wavy tubercles in Fig. 1(a) have been installed at the leading edge of the NREL Phase-VI blade. Here, we choose the delta wing as a control unit for wing-turbine blades because strongly streamwise vortices can be generated from the delta wing's leading edge, which should have the same powerful effects as the tubercles of the wavy blades under high angle-of-attack operating conditions. In Fig. 2, the control fins are located at the blade's outboard segment ($60\%R$ to tip), since Zhang and Wu [8] have shown that the present segment is the key region for wavy leading-edge blades to enhance the aerodynamic performance at high speed inflows. The space between two adjacent fins $l = 0.3c_0$, c_0 is the blade's root chord. Fig. 3(a) further displays that each control unit (delta wing) has two rotational degrees of freedom: one is the roll angle φ and the other is the local pitch angle $\Delta\alpha$.

Fig. 2. Geometric model of wind-turbine blade with a deformable leading-edge.

Fig. 3: (a) Geometric parameters for a leading-edge fin; (b) control state for designing conditions; (c) control state for off-designing conditions.

As shown in Figs. 2 and 3(a), all control fins have the same geometric parameters, i.e., the root chord $\delta = 10\%l$, the sweep angle $\Lambda = 70^\circ$, the thickness-to-chord ratio $t/\delta = 10\%$ and an installation gap $d = 1.5\%\delta$ between a delta wing and the blade's leading edge. The surface area of all control fins is about 0.4% of that of blade. The control state shown in Fig. 3(b) is marked with $\varphi = 0^\circ$, where the action surface of the control fins is in parallel with the flow direction and nearly no visible separated flows can be created by the fins. Therefore, the control state with $\varphi = 0^\circ$ should be suitable to the design operating conditions of wind-turbine blades. As the blade goes into stall at high speed inflows, the control fins can be switched into a new state with $\varphi = 90^\circ$, as shown in Fig. 3(c), where the local angle of attack of a control fin (delta wing) can further be adjusted by a pitch movement with $\Delta\alpha \neq 0$. We denote $\Delta\alpha > 0$ with an upward pitch movement from the installed location.

It should be noted that, as a preliminary test, the geometric parameters of the control units in Figs. 2 and 3 are chosen quite arbitrarily. We only investigate a simplified control strategy in this paper, i.e., all of control units have the same roll angle ϕ and the same local pitch angle $\Delta\alpha$ for one certain controlled case. An optimization about these parameters for each control unit is necessary in an actual wind-turbine design in future.

In this paper, the three-dimensional incompressible flow over wind-turbine blades will be simulated by the commercial code FLUENT, where the steady incompressible Reynolds averaged Navier-Stokes (RANS) equations will be calculated with the Spalart-Allmaras (SA) turbulence model. A second-order upwind scheme has been used to discretize the convective terms and the viscous terms. The semi-implicit method for pressure-linked equations (SIMPLE) is applied to enforce the pressure-velocity coupling.

Fig. 4: (a) Flow field over wind-turbine blade, where the surfaces $S_1S_2S_3$ and $S_4S_5S_6$ are the flow field's inlet and outlet, respectively; (b) volume grid details; (c) surface grid details.

As shown in Fig. 4, an unstructured mesh has been used to discretize the flow field over wind-turbine blade. NREL Phase-VI turbine has two blades, and these two blades' geometry and operating conditions are axial symmetric at the zero-yaw inflows. Therefore, only one blade is explicitly simulated in Fig. 4, and an azimuthally periodic boundary condition is applied at the axially symmetric plane $S_1S_4S_5S_2$. The domain bottom $S_1S_2S_3$ is defined to be the inlet with a prescribed velocity; the top boundary $S_4S_5S_6$ and the side surface $S_1S_4S_5S_6S_2S_3S_1$ are set to be the outlet with a zero gradient condition. An adherence condition (i.e., no-slip and no-through) is applied at the blade's surface. In Fig. 4, the height of the grid's first layer on wall is $8.2 \times 10^{-6}c_0$, corresponding to $y^+ < 1$.

Nine kinds of control states for control fins have been investigated in this paper. The corresponding values for the control parameters ϕ and $\Delta\alpha$ can be found in Tab. 1. Five kinds of wind-speed conditions, i.e., the inflow speeds $W = 7\text{m/s}$, 10m/s , 15m/s , 20m/s and 25m/s with 0° yaw angle, have been calculated for each control case. The numerical

results of all control cases will be compared with that of the baseline blade (i.e., the NREL Phase-VI rotor).

Table 1. Values of the parameters ϕ and $\Delta\alpha$ for each control case

Case No.	CS - 1	CS - 2	CS - 3	CS - 4	CS - 5
ϕ	0	90°	90°	90°	90°
$\Delta\alpha$	0	-20°	-15°	-10°	-5°
Case No.	CS - 6	CS - 7	CS - 8	CS - 9	
ϕ	90°	90°	90°	90°	
$\Delta\alpha$	0	5°	10°	15°	

3. Results and Discussion

3.1. Aerodynamic characteristics under designing conditions

When wind-turbine blades run in a designing operating condition, any leading-edge disturbance should be avoided to evoke a severe flow separation. The reason is that the boundary layer attached at the blades' upper side is very sensitive to the leading-edge disturbances under this situation [8]. Therefore, as mentioned above, we designed a special control status for the control fins shown in Fig. 3(b) (i.e., CS - 1), where the angle of attach is close to 0° for the leading-edge fins without yawed inflows.

Fig. 5 Calculated shaft torque (M_z) and root flap moment (M_x) of the baseline blade [8] and CS - 1.

As plotted in Fig. 5, both the shaft-torque value M_z and the root flap moment M_x of CS - 1 are very consistent with that of the baseline blade (i.e., NREL Phase-VI) at each simulated wind-speed inflow. In fact, even under high speed inflows (e.g., 20m/s), the maximal deviation of shaft torque between CS - 1 and the baseline blade is also less than 2.3%. Particularly, we note that the aerodynamic moments (M_z and M_x) contributed by the control fins themselves is less than 1% for CS - 1. Therefore, the results in Fig. 5 indicate that, the leading-edge fins in CS - 1 should have not any negative effect on the blade's aerodynamic performances under the designing operating conditions (e.g., 7m/s - 10m/s). It can further be checked by the following near-wall flow characteristics, i.e., the distributions of skin-friction lines and BVF (boundary-vorticity flux [10]) lines on body surface. Here the BVF denotes the viscous diffusion flux of vorticity ω from a body surface [10], i.e.,

$$\sigma = \nu \mathbf{n} \cdot \nabla \omega, \quad (1)$$

$\mathbf{n}$ is the normal vector. As pointed by Lighthill [11], the BVF measures how much new vorticity is produced from body surface and then sent into the flow field by diffusion at per unit area in per unit time, i.e., BVF is the physical root of all near-wall vortical structures. Wu *et al.*, [10, 12] show that, in a three-dimensional steady boundary-layer separation zone, the BVF lines are turned to be nearly aligned to the separation line (a special friction line). As shown in Fig. 6(b), the separation line marked by the skin-friction lines and the BVF lines in the case CS – 1 is nearly the same as that of the baseline case (Fig. 6(a)), which reveals that there is no apparent interaction between the wake of the leading-edge fins and the downstream boundary layer attached at the blade's upper side for CS – 1.

Fig. 6. Distribution of skin-friction lines and BVF lines on the blade's upper side at 10m/s: (a) the baseline blade; (b) CS – 1.

3.2. Aerodynamic characteristics under off-designing conditions

The numerical results in Fig. 5(a) have shown that, as the inflow exceeds the rated wind speed (e.g., 15m/s), the power output (shaft torque) will decrease significantly for a stall-regulated wind turbine, since the stalled flow will inevitably result in a nonlinear drop of the blade's aerodynamic performances. Pitch control with variable rotating speed is popular for modern wind turbines to enhance the blade's performances under off-designing conditions. As a passive control method distinguishing from the pitch control, Zhang and Wu [8] numerically shows that, by inducing a series of powerfully localized vortices, a wavy leading edge can also alleviate the boundary-layer separation on blade's upper side and then improve the power output. Fig. 7(a) reveals that, as an active control strategy is applied, the present delta-wing fins have the same control abilities as the wavy leading-edge design for wind-turbine blades. In comparison with the baseline blade (i.e., NREL Phase-VI), a great improvement in shaft torque has been displayed in Fig. 1(a) for all controlled cases under the high-speed operating conditions ($W > 10\text{m/s}$). For example, the shaft torque in CS – 6 has a 25.8% increment at the

inflow speed $W = 15\text{ m/s}$. Fig. 7(a) also shows that, by adjusting the local angle of attack of the control units (see Fig. 3(c)), a different increment of shaft-torque value can be obtained. But in contrast with the shaft-torque curves in Fig. 7(a), the root flap moment is insensitive to the attitude of the leading-edge control fins. As shown in Fig. 7(b), the maximal variation in root flap moment M_x is less than 3% among all of the controlled cases under any calculated wind-speed inflow.

Fig. 7. Calculated shaft torque (M_z) and root flap moment (M_x) of the baseline blade and the CS - 1.

Fig. 8. Distribution of skin-friction lines and BVF lines on the blade's upper side at 15 m/s : (a) the baseline blade; (b) CS - 6.

As mentioned above, the change of the boundary-layer flows at the blade's suction side can be tracked by the distribution of the skin-friction lines and the BVF lines. As shown in Fig. 8(a), the baseline blade presents a severe boundary-layer separation at $W = 15\text{ m/s}$, where a separation line originating at the blade's leading edge indicates that the baseline blade has gone into a deep stall. In Fig. 8(b), although a strong boundary-layer separation still exists at the blade's inboard segment ($y/R < 60\%$) for CS - 6 as an example of the controlled cases, the near-wall flows downstream the leading-edge delta wings have a clear change compared with the baseline blade, where some complicated roots of flow separation and reattachment have been presented.

Fig. 9. Near-wall vortical structures ($Q = 50000$) over blade's suction side at 15m/s: (a) baseline blade; (b) CS – 6; (c) a wavy leading-edge case in Zhang and Wu [8].

Further, Fig. 9 draws a comparison of near-wall flow structures at 15m/s among the baseline blade, CS – 6 and a wavy leading-edge case calculated by Zhang and Wu [8], where the Q -criterion [13] has been used to visualize a vortex. It is clear that, compared with the baseline blade, a more organized vortical system is presented downstream the control fins in CS-6 as the result of the interaction between the leading-edge vortices of the control fins and the boundary layer over blade's suction side. By contrast with the wavy leading-edge in Fig. 9(c) case calculated by Zhang and Wu [8], Fig. 9(b) shows that, as the control units, the delta wings can play the role of vortex generator the same as the leading-edge tubercles in wavy blades. Zhang and Wu [8] have proved that, the localized vortices shedding from the leading-edge tubercles are the physical root for the wavy blades to improve the aerodynamic performances at high wind-speed inflows, where a much greater peak of the leading-edge suction pressure can be generated by these vortices in comparison with that of the baseline blade; and the stronger the leading-edge vortices are, the greater increment of shaft torque the wavy-blade cases can be obtained. Therefore, the new streamwise vortices generated by the leading-edge jets of the control fins should also be the origin of the present active control strategy to enhance the localized aerodynamic characteristics under the same operating conditions. In Fig. 9(a), although some streamwise vortices also come into being at the 80% R station of the baseline blade, the effect on the leading-edge suction pressure is very limited because these vortices in the stalled region are away from the boundary layer at the blade's upper side [8]. Particularly, the vortices close to the blade tip are very weak and disordered. As a result, Fig. 7(a) presents a clear reduction in shaft torque for the baseline blade at $W = 15\text{m/s}$.

3.3. Final results for active control

Based on the numerical results above, we can obtain an optimal distribution of shaft torque at all calculated wind-speed inflows for the present active control strategy, as shown in Fig. 10(a), where the fluctuation of shaft torque within the wind-speed range $7\text{ m/s} - 25\text{ m/s}$ has been reduced from 27.8% for the baseline blade (i.e., the NREL Phase-VI rotor) to 8.9% after control. Fig. 10(b) displays the variation of the parameters φ and $\Delta\alpha$ during the whole control period.

Fig. 10. Controlled shaft-torque curve (a) and the corresponding control parameters, (b) depending on the wind speed.

4. Conclusions

In this paper, a new active control strategy for wind-turbine blades has been investigated in detail based on a three-dimensional RANS simulation. The numerical results show that, by adjusting the attitude of the leading-edge control units (i.e., the roll angle φ and the local pitch angle $\Delta\alpha$), the wind-turbine blades can obtain a more stable power output than the baseline case under off-design operating conditions (e.g., high-speed inflows). For example, the shaft-torque fluctuation in the stall region can be reduced from 27.8% for a straight leading-edge blade (no control) to 8.9% after control. The strongly streamwise vortices induced by the leading-edge vortices shedding from the control units (i.e., delta-wing fins), which will eventually result in a great increment of the blade's leading-edge suction pressure, are the physical origin to enhance the blade's aerodynamic performances as it goes into a deep stall. Particularly, the power output can be hold under the designing conditions (e.g., the rated wind-speed inflows) for the present active control strategy, which is difficult for the stationary wavy leading-edge blades since these fixed leading-edge tubercles will inevitably result in an early boundary-layer separation at the blade's suction side even under designing conditions.

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