Flow Physics behind the Effects of Leading-edge Protuberances on the Airfoil Aerodynamic Performance

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Abstract. This paper presents a numerical investigation of the flow physics behind the effects of leading-edge protuberances on the airfoil aerodynamic performance utilizing vortex dynamic method. An improved delayed detached eddy simulation (IDDES) method was adopted and validated through the comparisons with experimental results. Utilizing the IDDES scheme, together with vortex dynamic analysis, investigations were focused on the attached and post-stall regions, respectively. It was found that, within the attached region, the generation and development of the dominant diffused spanwise vortex rings over tubercled airfoil was responsible for the subsequent airfoil performance; within the post-stall region, the impaired flow detachment around both peak and trough sections of tubercles, due to the enhanced momentum injection by the strong streamwise vortices, resulted in better airfoil aerodynamic performance.

1. Introduction

Rotor blade is the key equipment of wind turbine which provides aerodynamic forces and extracts mechanical energy from atmosphere. Meanwhile, flow separation and gust will have unpredictable influences on aerodynamic performances, including time-averaged and fluctuant ones [1].

To this end, a biomimetic design concept of wind turbine airfoil with leading-edge protuberances is proposed in present study to overcome the shortcomings mentioned above. Actually, based on our previous studies [2, 3], the airfoil with leading-edge protuberances could provide more aerodynamic lift than the smooth one within the post-stall region and the stall process is rather gentle, which bring the benefit of longer fatigue lives. Analogous conclusions could also be reached from investigations of other groups [4, 5].

Despite of above outstanding advantages, flow physics of present biomimetic design concept have to be clarified, which remain unclear till now. Therefore, an IDDES method was utilized to simulate the flow field of airfoil with and without protuberances in present study. After that, the vortex dynamic schemes in terms of boundary vorticity flux (BVF) and vorticity transport quantities, together with pressure and velocity fields, were deployed to depict the complicated formation, evolution and dissipation of the specific vortex system created by the leading-edge protuberances at angles of attack, within attached and post-stall regions, respectively.

2. Numerical Schemes

2.1. Turbulence modeling

As mentioned above, unsteady detached vortex motion was inevitable in the flow field of tubercled airfoil; RANS method was thus not applicable. Considering feasibility and accuracy, an IDDES
method was adopted in present study, which has recently become much favored in the study of the unsteady and geometry-dependent separated flows. In practice, IDDES method based on \( k-\omega \) SST turbulence model was adopted [6], which can be constructed through modifying the dissipation term of the turbulent kinetic energy equation \( (k\text{-equation}) \). After introducing a length scale, \( L_{\text{hybrid}} \), the turbulent kinetic energy and specific dissipative rate equations can be given in tensor form as

\[
\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \mu_l + \sigma_{\mu} \mu_l \right] \frac{\partial k}{\partial x_j} + \tau_{ij} S_{ij} - \frac{\rho k^{3/2}}{L_{\text{hybrid}}} \tag{1}
\]

\[
\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_i \omega)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \mu_l + \sigma_{\omega} \mu_l \right] \frac{\partial \omega}{\partial x_j} + \alpha \frac{\omega}{k} \tau_{ij} S_{ij} \]

Here, \( S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \) is the strain tensor and \( \tau_{ij} = 2 \mu_l S_{ij} - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_j} \delta_{ij} \) is the stress tensor. \( F_i \) is the blending function. The IDDES length-scale can be implemented as

\[
L_{\text{hybrid}} = \frac{1}{\bar{f}_d} (1 + f_r) L_{\text{RANS}} + (1 - \bar{f}_d) L_{\text{LES}} \tag{2}
\]

\[
L_{\text{RANS}} = k^{1/2} / (\beta \omega) \quad , \quad L_{\text{LES}} = C_{\text{DES}} \Delta . \quad \text{Here, } \Delta \text{ is the grid length scale, } \beta ^{'} = 0.09 .
\]

\[
\bar{f}_d = \max \left\{ (1 - \bar{f}_d), f_B \right\} \quad \text{with} \quad f_B = 1 - \tanh \left[ 8 r_d^{-3} \right] .
\]

\[
r_d = \frac{\rho \kappa^2 d^2 \cdot \max \left\{ \sum_j \left( \frac{\partial u_i}{\partial x_j} \right)^2 \right\}^{1/2}}{10^{-10}}
\]

is borrowed from Spalart-Allmaras turbulence model, where \( d \) is the distance to wall surface and \( \kappa = 0.41 \). \( f_B = \min \{ 2 \exp(-9\alpha^2), 1.0 \} \), \( \alpha = 0.25 - d / h_{\text{max}} \), and \( h_{\text{max}} \) is set equal to the maximum local grid spacing.

2.2. Numerical methods and validations

A symmetric total variation diminishing (STVD) scheme was adopted to discretize the flux of compressible NS equations in present study, which can be written as

\[
F_{i+1/2} = F_{\text{symmetric, i+1/2}} - \phi \times \frac{1}{2} \left| L_{\text{r}} \right| (q^k - q^l)_{i+1/2}
\]

where the inviscid flux is in the sixth-order symmetric scheme. The numerical dissipation is the original Roe’s dissipation with fifth-order WENO interpolation. In detail, \( L_{\text{r}} \) is the matrix of Roe average, \( q^k \) and \( q^l \) are obtained through the fifth-order WENO interpolation. Then, this STVD scheme can be shortened as 56WENO5 and adaptive-\( \Phi \) was adopted in present study, which was closely related to local flow field [7]. The net effect of above formulas is that \( \Phi \) approaches zero in the separation region and it is close to unity in the irrotational region and near the wall to guarantee the robustness of present numerical method.

For the purpose of consistency, the same smooth and tubercled NACA 63\textdegree-021 airfoil with the mean chord length \( c = 100 \text{ mm} \) as those in our previous experimental study at \( Re = 2 \times 10^5 \) [2] were selected as the research subject, and the tubercled leading edge had an amplitude \( A = 24\% c \) and a wavelength \( \lambda = 25\% c \). Free-stream velocity \( U_\infty = 30 \text{m/s} \). Figure 1a indicates the sketch of computational domain. The far-field boundary was placed 20\( c \) upstream and downstream of the airfoil.
To properly resolve the wall boundary layers, mesh nodes were clustered near wing surfaces using a geometric expansion. Eventually, the structured grid system with $\Delta y' \approx 1$, $\Delta x' \approx 20$, $\Delta z' \approx 40$ and growth ratio $\approx 1.12$ was selected, satisfying the minimum requirement recommended in [8], resulting in the overall amounts of grids of $1.08 \times 10^7$ and $8.6 \times 10^6$ for tubercled and smooth airfoils, respectively. The $x$, $y$ and $z$ directions were defined as the streamwise, longitudinal and spanwise coordinates, respectively, with the origin at the smooth airfoil leading edge. Figure 1b illustrates the lateral and streamwise slices of the computational mesh as well as surface mesh. The wall surfaces were regarded as no-slip and adiabatic for viscous simulation, and periodic conditions were set along $z$-direction.

![Sketch of computational domain](image1)

![Illustration of the computational mesh](image2)

**Figure 1.** Sketches of computational mesh system

To validate our developed CFD method, the numerical results were compared with experimental ones [2] at $\alpha = 6\degree$, 12\degree, 18\degree, 21\degree and 45\degree. In addition, the time step was set to be $1.667 \times 10^{-5}$s, and the solution proceeded until 0.3s. To obtain the time-averaged flow properties and prevent any effects of the initial flow conditions, the first 1500 time steps were removed from the results. Figure 2 displayed the variation of lift and drag coefficients with $\alpha$. Here, the lift and drag coefficients were defined as $C_l = 2L/(\rho U_{\infty}^2 sc)$ and $C_d = 2D/(\rho U_{\infty}^2 sc)$, respectively. Clearly, the computational results were in good agreements with experimental ones for both wavy and baseline cases, with an error around 5.0%.

![C_l vs. $\alpha$](image3)

![C_d vs. $\alpha$](image4)

**Figure 2.** Comparisons of aerodynamic forces between numerical and experimental results
3. Results and Discussions

3.1. Attached region
Using developed CFD method, the flow physics within attached region was first studied. Figure 3 indicates the instantaneous flow structures over smooth and tubercled airfoils at $\alpha = 6^\circ$ using $Q$-criterion. Obviously, the spanwise vortices dominated the flow field over the smooth airfoil, while they were characterized by complex 3D vortex motion over the tubercled airfoil, behaving as periodical vortex rings at trough sections and their subsequent dissipation near the airfoil trailing edge.

![Flow structures over smooth and tubercled airfoils](Figure 3)

To understand the vortical flow over the tubercled airfoil, the time-averaged vorticity and its $x$, $y$, and $z$-components were computed in Figure 4. The process of vorticity development could be divided into three phases. In phase I ($x \leq 0.2c$), the streamwise vorticity ($\bar{\omega}_x$) dominated, although the spanwise vorticity ($\bar{\omega}_z$) was also remarkable; In phase II ($0.2c < x \leq 0.35c$), the vortex rings emerged, mainly characterized by $\bar{\omega}_z$; In phase III ($x > 0.35c$), $\bar{\omega}_x$ almost vanished due to flow diffusion.

![Distribution of time-averaged vorticity](a) Distribution of time-averaged vorticity
![Time-averaged $\bar{\omega}_x$](b) Time-averaged $\bar{\omega}_x$
The vortex dynamic method was deployed to further quantitatively describe the generation and evolution of the time-averaged vortex system. To this end, boundary vortex flux (BVF, $\overline{\sigma}$) was first computed at phase I, which could theoretically denote the generation and viscous diffusion flux of vorticity [9].

$\overline{\sigma} = \frac{\partial \overline{\omega}}{\partial n} = \overline{n} \times (\overline{a} - \overline{f} + \frac{1}{\rho} \overline{\nabla p}) + \overline{v} (\overline{n} \times \overline{\nabla}) \times \overline{\omega}$  \hspace{1cm} (4)

Generally speaking, BVF was comprised of four parts, i.e., $\overline{\sigma} = \overline{\sigma}_a + \overline{\sigma}_f + \overline{\sigma}_p + \overline{\sigma}_{\nu}$, where $\overline{\sigma}_a = \overline{n} \times \overline{a}$, $\overline{\sigma}_f = \overline{n} \times \overline{f}$, $\overline{\sigma}_p = \overline{n} \times \frac{1}{\rho} \overline{\nabla p}$ and $\overline{\sigma}_{\nu} = \overline{v} (\overline{n} \times \overline{\nabla}) \times \overline{\omega}$ represented the inducements of fluid acceleration, external body force, pressure gradient, and viscous diffusion, respectively. Under current circumstances ($\overline{a} = 0$ and $\overline{f} = 0$ at $Re = 2 \times 10^5$), $\overline{\sigma}_p$ dominated the process of vorticity generation, since $\overline{\sigma}_p \gg \overline{\sigma}_{\nu}$ when $Re \gg 1$ [9]. Here, $\overline{n}$ is the normal vector of airfoil surface, $\overline{p}$ and $\overline{\rho}$ are the time-averaged non-dimensional static pressure and density. Thus, the dominant streamwise component of $\overline{\sigma}_p$ ($\sigma_{p1} = \frac{\partial \overline{p}}{\partial z} n_x - \frac{\partial \overline{p}}{\partial y} n_y$) was mainly responsible for the generation of $\overline{\omega}_x$ at phase I. Here, $\sigma_{p1} = \frac{\partial \overline{p}}{\partial z} n_x$, and $\sigma_{p2} = -\frac{\partial \overline{p}}{\partial y} n_y$ indicated the contributions of spanwise and lateral pressure gradients, respectively.

Clearly, as shown in Figure 5a, $\sigma_{p2}$ with opposite sign tended to be stronger, suggesting that the generated $\overline{\omega}_x$ around the tip area of the tubercles was primarily due to lateral pressure gradient $\frac{\partial \overline{p}}{\partial y}$, while the magnitude of $\sigma_{p1}$, depending on spanwise pressure gradient $\frac{\partial \overline{p}}{\partial z}$, was larger near the bottom of the trough. Correspondingly, the typical $\frac{\partial \overline{p}}{\partial z}$-distribution and quasi-streamlines were illustrated at $x = 0.13c$ in Figure 5b. It could be observed that the streamlines were distorted due to $\frac{\partial \overline{p}}{\partial z}$, which could...
be recognized as a source of streamwise vorticity generation (see the contour lines of $|\overline{\omega_z}| = 40$), consistent with the observation by Wu et al. [9].

![Contour of $\sigma_{\mu}$](image1)

![Contour of $\overline{\sigma}_p$ ($x = 0.13c$)](image2)

**Figure 5.** Sketches of $\overline{\omega}_z$-generation at phase I ($\alpha = 6^\circ$)

Analyses were also conducted at phase II to illuminate the formation of vortex rings. To do this, the superior spanwise component of BVF, i.e. $\sigma_{pc} = \frac{\partial \overline{p}}{\partial x} n_z - \frac{\partial \overline{p}}{\partial y} n_x$, was then calculated in Figure 6a since vortex rings mainly took the form of $\overline{\omega}_z$. It was found that the vortex rings emerged around $x = 0.2c$ after the peak of $\sigma_{pc}$ as indicated by dash line. To reveal this, the contour of the non-dimensional pressure ($\overline{p}$) and streamlines at trough section in Figure 6b indicated that the streamwise adverse pressure gradient $\frac{\partial \overline{p}}{\partial x}$ triggered the emergence of vortex ring structures and flow separation at $x = 0.2c$.

In fact, the magnitude of $\frac{\partial \overline{p}}{\partial x}$ was also to be much larger than that of $\frac{\partial \overline{p}}{\partial y}$.

![Contour of $\sigma_{pc}$](image3)

![Contour of $\overline{p}$](image4)

**Figure 6.** Sketches of vortex ring formation ($\alpha = 6^\circ$)

The aforementioned development of the vortex system would undoubtedly influence the flow field near airfoil surface. To clarify this, Figure 7 displays the contours of static pressure over smooth and tubercled airfoils, with separation border denoted by blue dash lines. Obviously, flow separation took place around $x = 0.58c$ for smooth airfoil case (Figure 7a). In contrast, from Figure 7b, flow
detachment was first triggered by the adverse pressure gradient at \( x = 0.18c \) in trough section as denoted by node (N), corresponding to the emergence of vortex rings. Then the spanwise range of flow separation slightly reduced till \( x = 0.35c \) (denoted by saddles, S), coincident with the mutual approach of vortex ring roots within phase II. Afterwards, since the streamwise vorticity almost vanished at phase III, spiral-point separation occurred (denoted by foci, F) and the spanwise range of flow separation was gradually enlarged, corresponding to the “tornado-like vortices” in previous study [10]. For peak sections, the separation was delayed to \( x = 0.82c \). The general feature of flow evolution in Figure 7 might imply the comparable airfoil aerodynamics in the attached region for both cases.

\[ \text{(a) Contour of static pressure (smooth airfoil)} \quad \text{(b) Contour of static pressure (tubercled airfoil)} \]

**Figure 7.** Contours of static pressure of smooth and tubercled airfoils (\( \alpha = 6^\circ \))

### 3.2. Post-stall region

The flow field was also investigated within post-stall regime to interpret the flow physics behind the enhanced performances. To do so, the flow situation at \( \alpha = 45^\circ \) was selected as a typical example. Figure 8 displayed the instantaneous flow structures over smooth and tubercled airfoils. The flow separation was very significant for smooth airfoil case so that the shear layer detached even from the airfoil leading edge. On the contrary, for tubercled airfoil case, the separation phenomenon with single periodical vortex structures became weaker, suggesting the improvement in the airfoil performances.
(a) Flow structures above smooth airfoil  
(b) Flow structures above tubercled airfoil

**Figure 8.** Instantaneous $Q$-criterion flow structures over smooth and tubercled airfoils ($\alpha = 45^\circ$)

To further identify the dominant flow structure within post-stall region, the time-averaged vorticity and its 3D decompositions over tubercled airfoil were shown in Figure 9. Evidently, the strong streamwise vortices ($\bar{\omega}_x$) dominated and mainly influenced the flow characteristics above suction surface. In addition, some secondary vortices and shear layers were also discernible, but the successive vortex rings did not appear.

(a) Distribution of time-averaged vorticity  
(b) Time-averaged $\bar{\omega}_x$

(c) Time-averaged $\bar{\omega}_y$  
(d) Time-averaged $\bar{\omega}_z$

**Figure 9.** The time-averaged vorticity and its 3D decompositions over tubercled airfoil ($\alpha = 45^\circ$)

Similarly, the formation of the main $x$-component vorticity ($\bar{\omega}_x$) was analyzed using the streamwise BVF distributions, as illustrated in Figure 10. Apparently, the contours of $\sigma_{p1} = \frac{\partial p}{\partial z} n_x - \frac{\partial p}{\partial y} n_x$ and $\sigma_{p2} = \frac{\partial p}{\partial z} n_z$ looked very analogous, suggesting the major origin of primary vortices and even secondary vortices and shear layer from the spanwise pressure gradient.
To further investigate the effects of the dominant primary streamwise vortices on flow separation at trough section, the streamlines colored by Mach number and a streamwise slice (x=0.2c) of Mach number contour are described in Figure 11a. It was found that the high-momentum flow induced by $\omega_x$ was injected towards the airfoil surface. As a result, flow became attached, as denoted by red dash line, right after the flow separation near the airfoil leading-edge. This was also quantitatively proved by the streamwise velocity ($\overline{U}$) in x-y plane at trough section in Figure 11b that flow became reattached at $x \approx 0.157c$ under the effect of the transport of high-momentum fluids to the airfoil suction side, which might equivalently contribute the improved aerodynamic performance as peak section.

In addition, Figure 12 displayed the general distributions of static pressure and streamlines at $\alpha = 45^\circ$. Clearly, the flow separation occurred almost at the smooth airfoil leading-edge (Figure 12a). In contrast, for tubercled airfoil case (Figure 12b), the vortical flow at trough sections was subject to initial flow separation near the tip of the protuberance, reattachment at $x \approx 0.157c$, and detachment again beyond $x = 0.4c$, while the flow attachment was maintained until $x = 0.5c$ around peak sections.
4. Conclusions
An IDDES method was adopted to simulate the flow field of NACA 634-021 airfoil with and without protuberances at $Re = 2\times10^5$ within attached, stall and post-stall regions, respectively. Specifically, deploying the vortex dynamics methods, together with three dimensional velocity and pressure data, the flow physics behind the novel biomimetic technique were analyzed in detail, leading to the following conclusions:

1. Within attached region, the vortex stretching and diffusion dominated the evolution of spanwise vortex rings at trough section over the tubercled airfoil, determining the formation and evolution of the corresponding vortex system and the resultant airfoil aerodynamic performance.

2. Within post-stall region, the original detached post-stall flow over the smooth airfoil was effectively weakened by the superior streamwise vortices generated by the leading-edge protuberances due to effectively strengthened momentum transport at both peak and tough sections, leading to the greatly enhanced airfoil performances.

Consequently, this biomimetic design concept of wind turbine airfoil with leading-edge protuberances could overcome the shortcomings of unpredictable influences on aerodynamic performances.

References
[1] Wright A K and Wood D H Journal of Wind Engineering and Industrial Aerodynamics 2004 92 1265-79.
[2] Zhang M M, Wang G F and Xu J Z Experiments in Fluids 2014 55 1710.
[3] Zhao M, Zhang M M and Xu J Z Engineering Applications of Computational Fluid Mechanics 2017 193-209.
[4] Dropkin A, Custodio D, Henoch C W and Johari H Journal of Aircraft 2012 49 5:1345-55.
[5] Bolzon M D, Kelso R M and Arjomandi M Journal of Aerospace Engineering 2015 04015013.
[6] Shur M L, Spalart P R, Strelets M K and Travin A K International Journal of Heat and Fluid Flow 2008 29 1638-49.
[7] Xiao Z, Jian L, Luo K, Huang J and Fu S AIAA Journal 2013 51 1:107-25.
[8] Spalart P R NASA/CR-2001-211032 2001.
[9] Wu J Z, Ma H Y and Zhou M D 2006 Vorticity and vortex dynamics Springer.
[10] Rostamzadeh N, Hansen K L, Kelso R M and Dally B B 2014 Physics of Fluids, 26(107101) 1-22.

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