CFD Investigation of a Mobula Birostris-Based Bionic Vortex Generator on Mitigating the Influence of Surface Roughness Sensitivity of a Wind Turbine Airfoil

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ABSTRACT
In wind turbines, increased blade surface roughness accelerates fluid separation and reduces blade aerodynamic performance. As a flow separation control device, a vortex generator can be used to modulate the fluid flow in the boundary layer and reduce the adverse effect of increased roughness on the aerodynamic performance of the blade. To improve the effect of the vortex generator, a bionic vortex generator based on the anatomy of manta rays is here proposed and commercial CFD software ANSYS CFX is used for numerical simulation. We found that when the equivalent roughness is 0.045 mm, the starting performance of the DU97-W-300 airfoil is consistent with the experimental value observed for installed zigzag tape. Under different roughness conditions, the optimization of the blade aerodynamic performance of the bionic vortex generator is up to 10% higher than that of the triangular vortex generator. The presence of the vortex generator not only increases the maximum lift coefficient of the contaminated blade, but also delays the stall angle, and at the same time increases the suction power of the entire suction surface of the blade. The vortex generator has little effect on the pressure surface.

INDEX TERMS
Bionic, equivalent sand-grain roughness, roughness sensitivity, surface degradation, vortex generator, zigzag tape.

I. INTRODUCTION
With the rapid increase in human demand for energy and the gradual consumption of petrochemical energy, various countries have increased the development and utilization of new energy sources to ensure energy security. In the first half of this year, global wind and solar power generation accounted for 9.8% of global electricity production [1], maintaining a strong momentum of development. Wind power provides an increasing proportion of new energy due characteristics such as its lack of special site requirements and its environmental friendliness.

Because the working environment of wind power is relatively harsh, wind turbine blades are easily susceptible to dust, insects, rain, snow, and frost, which increases the surface roughness of the blades [2]. The rough surface of the blade causes the boundary layer transition and turbulence separation to occur earlier, which causes the blade lift to drop, reducing the wind energy capture rate of the blades and thus reducing the annual power generation of the wind turbine. The power loss caused by the increase in blade surface roughness can even reach 40% of the design value [3]. Premature boundary layer transition caused by the roughness of wind turbine blade contamination leads to a significant increase in boundary layer momentum thickness, and results in the abatement of the maximum lift coefficient and an increase in the drag coefficient of wind turbine airfoils [2], [4], [5]. At the same time, the increase in turbulence caused by the rough surface of the blade makes the pressure on the blades unstable and causes vibration, which affects the life of the blades.

Although the increase in surface roughness of wind turbine blades due to contamination cannot be avoided, the
impact of increased roughness on the aerodynamic performance of the blades can be reduced by reasonable means. In addition to reducing roughness sensitivity during airfoil design, vortex generators are also an effective and low-cost method.

Vortex generators can adjust the velocity distribution of the fluid in the boundary layer, which can serve to suppress the advancement of boundary layer transition and turbulence separation. The systematic study of vortex generators began with Taylor [6]. The widespread commercial adoption of vortex generators (VGs) on wind turbines began with the work of Sullivan [7] in the 1980s. Subsequently, the issue was explored by Miller [8] and Griffin [9]. These experiments demonstrated that with acceptable dynamic loads, the annual power generation (AEP) of wind turbines increased from 4% to 15.2%. The maximum lift coefficient of a DU 97-W-300 airfoil increased from 1.55 to 1.97 if equipped with vortex generators [10]. Gao [11] revealed that the vortex generator not only increased the maximum lift coefficient of the airfoils but also the stall angle. The increase in AEP in these experiments verified that VGs could be used to reduce the contamination-induced performance degradation of blades. This means the lift of airfoils with rough surfaces is increased with the use of vortex generators [12]. Moreover, the greater the blade roughness and the more sensitive the airfoil is to roughness, the greater the vortex generators improvement in blade aerodynamic performance [13].

Various parameters affecting VG performance have been elucidated by decades of fundamental and applied studies—the installation position, shape (geometry), angle of incident, height, height-to-length ratio, spacing, configuration mode, etc. [11], [14], [16].

In the early development of vortex generators, many shapes were applied in their design. The appearance of a typical vortex generator may be a wishbone shape, a ramp shape, rectangular, triangular, and so on [14], [15]. To restrict the flow along the spanwise direction, even at the blade tip where the tip vortices were formed, Wheeler invented a series of “wishbone”-shaped vortex generators [17], which consist of two triangular walls at certain angles, and “horseshoe” vortices within the boundary layer. Wedge-shaped vortex generators are by construction more robust so that they can be used for a wide range of applications in the high-speed sector [18]. The most frequently used shapes of vortex generators in the industry are rectangular and triangular. However, Godard [19] has pointed out that compared with the rectangular vortex generator, the performance of the triangular vortex generator is 20% higher. At the same time, the resistance generated is relatively small.

Given the bottleneck in vortex generator shape development and its significant role in suppressing the sensitivity of wind turbine blade roughness [10], [20], in this study we aim to apply the image processing method to obtain the leading edge curve of a manta ray wing to analyze in terms of the shape of a vortex generator. We also aim to study the suppression performance of this kind of bionic vortex generator, in relation to the roughness sensitivity of wind turbine blades. Manta rays are graceful creatures that can be easily recognized in the ocean by their large pectoral “wings”, and which get their food by using the flexible pectoral fins to swim in a vertical loop [21]. This means a large amount of eddy current can be generated by their pectoral fins. In order to obtain the front edge curve of the pectoral fin of the manta ray, the following operations are required. First, the image morphology opening operation is performed on the obtained the manta ray photos, and then edge detection is applied to obtain the manta ray edge point coordinates. Next, the coordinate points of the leading edge position of the manta wing are found through the algorithm proposed in this study. Finally, polynomial difference are used to establish the shape model of the bionic vortex generator. Based on the vortex generator layout model given by Velet [22], the commercial simulation software ANSYS CFX was used to analyze the modulation effect of the bionic vortex generator on the fluid on the surface of the DU97-W-300 blade with leading edge pollution. At the same time, the corresponding relationship between the front edge pollution caused by zigzag tape and the CFX surface friction setting was verified, and it was found that when the surface roughness is set to 0.045 mm, the two have the same influence on the incoming flow. The effects of bionic vortex generators and triangular vortex generators on blades under different surface degradation conditions (severe degradation: \( h^+ = 0.065 \) mm, moderate degradation: \( h^+ = 0.045 \) mm, mild degradation: \( h^+ = 0.025 \) mm) were also studied.

The CFX calculation results show that the maximum lift coefficient of the airfoil of the bionic vortex generator is 0.11, 0.13, and 0.08 higher than that of the triangular vortex generator under the conditions of severe, moderate, and mildly degraded blades. Due to the modulation effect of the vortex generator, the suction power of the blade suction surface increases, and the lifting effect before the stall is proportional to the angle of attack. Finally, in this study, through a downstream velocity cloud diagram of the vortex generator, the reason for the superior performance of the bionic vortex generator is explained.

II. BIONIC VORTEX GENERATOR

The most distinctive feature of the manta ray is its broad, diamond-like pectoral fin. It is precisely because of the powerful energy provided by such pectoral fins that the manta ray can “fly” freely between the deep and shallow seas.

To obtain its pectoral fin curve, image processing was adopted in this study. Digital image processing is a technology that accompanies the development of computer technology, mainly the process of using computers to process, extract, and apply information carried by images. In this article, the algorithm for obtaining the front edge of the pectoral fin of a manta ray is divided into two steps:

1) Obtaining the endpoint of the front edge of the pectoral fin of the manta ray: after converting Figure 1a into a binary image, rotate it 8° clockwise. Then perform...
the morphological opening operation on the acquired image. After the edges are smooth, use the image centroid as a reference to find a circle with a radius of 1 mm to 50 mm and take the first five circles, as shown in Figure 1b. Find the circle above the center of mass and the smallest horizontal distance among the five circles; connecting the center of the circle and the center of mass, the slope of the straight line is 53°. To ensure full extraction, the slope with the center of mass at the origin is 47°, and the distance between the center of mass and the boundary point is calculated clockwise. The boundary point where the distance is the maximum for the first time is the end of the front edge of the pectoral fin of the manta ray (see Figure 1c).

2) Obtaining the starting point of the shape of the front edge of the pectoral fin of the manta ray: connect the pectoral fin points of the manta ray (the two points with the smallest horizontal distance from the image centroid). The slope of the line determined by the two points can be calculated to be 1.8. Starting from the endpoint, addressing along with the boundary point of the image in a counterclockwise direction, if the boundary point is near (-5, 0) points, the slope of the fitted line is -0.549 (that is, -1/8, perpendicular to the line of the pectoral fin tip), and this point can be regarded as the starting point of the front edges of the pectoral fin of the manta ray (see Figure 1d). The point set of the front edge of the pectoral fin of the manta ray obtained by the algorithm is shown in Figure 1.

The leading edge curve can be obtained after polynomial fitting of the point set:

\[ f(x) = p_1 \times x^4 + p_2 \times x^3 + p_3 \times x^2 + p_4 \times x + p_5 \]

where \( p_1 = 6.637 \times 10^{-7} \); \( p_2 = -7.057 \times 10^{-4} \); \( p_3 = 1.196 \times 10^{-1} \); \( p_4 = -8.646 \); \( p_5 = 3.748 \times 10^2 \);

When taken as \( h/l = 1/2 \), it is the same as the shape ratio of the vortex generator used in many experimental studies.

III. CALCULATION MODEL

A. VG MODEL AND MESHING

The layout model of the vortex generator used by Velet [22] is shown in Figure 2. The height of the vortex generator is \( h = 4.5 \) mm, the length is \( l = 2h = 9 \) mm, the installation angle is \( \beta = 18° \), the distance between the trailing edges is \( s = 3h = 13.5 \) mm, the counter-rotating arrangement is adopted, and the centerline distance between the two sets of vortex generators is \( Z = 5h = 22.5 \) mm, installed at 20% chord length from the front edge.

Meshing strategy: In addition to the O_block division of triangle and bionic shape vortex generators, the Y_block is divided into both sides of the vortex generator. The grid is shown in Figure 3.

B. VALIDATION OF THE NUMERICAL SIMULATIONS

In this article, the DU97-W-300 airfoil, with a chord length of 0.6 m, was used as the research object, and four sets of vortex generators were installed on the blade segments, as shown in Figure 2. Based on the Reynolds number \( Re = 3 \times 106 \) of the airfoil chord length, the first layer grid was set to 0.002 mm to ensure \( Y+ < 1 \). The turbulence model adopted the shear stress transport (SST) model. Generally, this method of calculating turbulent eddy viscosity based on turbulent kinetic energy and turbulent frequency gives relatively accurate results. At the same time, the SST model considers the transfer of shear stress in turbulent flow, which has high
accuracy and robustness. Therefore, SST model is selected in this article for CFD numerical simulation. However, it has been found in a large number of applications that using the SST model over-predicts the maximum lift achievable. This phenomenon can be reduced by setting the high lift correction option. The default value of the high lift correction option in CFX is 0.9.

Figure 4a shows that before the maximum lift coefficient appears, the simulated value of the lift coefficient matches the experimental value well. After the maximum lift coefficient appears, the experimental value of the lift coefficient decreases rapidly, which may be due to the early stall caused by the additional momentum loss in the wind tunnel test [23].

Figure 4b illustrates that when the angle of attack is 0°, the lift coefficient curve of the 0.35-mm zigzag tape installed at the 5% chord length from the leading edge of the DU97-W-300. Figure 4b indicates that when the angle of attack is 0°, the roughness has a significant effect on the lift coefficient of the airfoil, and the stall angle of the wind tunnel experiment is more advanced. Errors were observed in the maximum lift coefficient and maximum lift angle, comparing the simulated value and the wind tunnel test value. There may be two reasons for the presence of errors. (1) As mentioned by Timmer [23], the wind tunnel test exhibits a premature stall phenomenon. (2) The SST turbulence model in numerical simulation cannot completely describe the flow in the flow field accurately.

IV. RESULTS AND DISCUSSION
This article discusses the influence of the proposed bionic vortex generator shape on the aerodynamic performance of the airfoil section under different surface degradation conditions (severe degradation: \( h^+_{s} = 0.075 \), moderate degradation: \( h^+_{m} = 0.045 \), and mild degradation: \( h^+_{l} = 0.025 \)). For comparison, the influence of the triangular vortex generator on the aerodynamic performance of the three surface degraded airfoils was also studied.

A. EFFECT ON LIFT COEFFICIENT
As mentioned earlier, when the equivalent friction coefficient of the airfoil section surface is \( h^+_s = 0.045 \), its aerodynamic performance is the same as that of the airfoil section with 0.35-mm-thick zigzag tape. Therefore, it is feasible to use the equivalent friction coefficient in CFX to study the blade surface degradation. Figure 5 shows the effect of severe degradation (\( h^+_s = 0.065 \)), moderate degradation (\( h^+_m = 0.045 \)), and mild degradation (\( h^+_l = 0.025 \)) of the blade surface on the lift coefficient of the DU97-W-300 airfoil section.

Figure 5 shows that the surface degradation of the blade not only reduces the maximum lift coefficient, but also significantly advances the stall angle. This change in aerodynamic performance caused by the deterioration of the blade surface seriously affects the normal operation of the wind turbine pitch system control, and has a huge impact on the wind turbine.
B. EFFECT OF BLADE SURFACE DEGRADATION ON VORTEX GENERATORS

Figures 6 to 8 show the effect of equivalent roughness and vortex generators on the lift coefficient of the DU97-W-300 airfoil. Before fluid separation, the lift coefficient curve shows a linear growth trend. When the angle of attack is greater than the stall angle, as the fluid separation gradually increases, the lift coefficient shows a sharp drop. Degradation of the airfoil surface accelerates fluid separation, resulting in a reduction in the stall angle of attack and maximum lift coefficient. The existence of the vortex generator not only improves the maximum lift coefficient of the surface-degraded blade, but it also increases the stall angle, which obviously delays the occurrence of the stall phenomenon. Figure 6 shows that compared with a smooth blade surface, the maximum lift coefficient of the DU97-W-300 airfoil is reduced from 1.56 to 1.32, and the stall angle is reduced from 12.4° to 10.8° under the condition of light degradation $h_\theta^+ = 0.025$ mm. Equipped with a triangular vortex generator, the lift coefficient of the slightly degraded blade is increased to 1.6 and the stall angle is increased to 18.8°. Equipped with a bionic vortex generator, the maximum lift coefficient of the slightly degraded blade is increased to 1.68, and the stall angle is increased to 18.8°. Compared with the triangular vortex generator, the bionic vortex generator increases the maximum lift coefficient by 0.08, which is limited to the range of the simulated angle of attack, and the increase in the stall angle is unknown. Figure 7 shows that under the condition of moderate degradation $h_\theta^+ = 0.045$ mm, compared with a smooth surface, the maximum lift coefficient of the DU97-W-300 airfoil is reduced to 1.18, and the stall angle is reduced to 9.8°. Equipped with a triangular vortex generator, the lift coefficient of the moderately degraded blade is increased to 1.35 and the stall angle is increased to 16.8°. Equipped with a bionic vortex generator, the maximum lift coefficient of the moderately degraded blade is increased to 1.48, and the stall angle is increased to 16.8°. Compared with the triangular vortex generator, the bionic vortex generator increases the maximum lift coefficient by 0.13. Figure 8 shows that under the condition of severe degradation $h_\theta^+ = 0.065$ mm, compared with a smooth surface, the maximum lift coefficient of the DU97-W-300 airfoil is reduced to 1.08, and the stall angle is reduced to 9.2°. Equipped with a triangular vortex generator, the lift coefficient of the heavily degraded blade is increased to 1.27 and the stall angle is increased to 13.8°. Equipped with a bionic vortex generator, the maximum lift coefficient of the heavily degraded blade is increased to 1.38, and the stall angle is increased to 16°. Compared with the triangular vortex generator, the bionic vortex generator increases the maximum lift coefficient by 0.11. At the same time, the stall process of the surface-degraded blades equipped with vortex generators is smoother, and the range of high-lift angle of attack is widened. The vortex generator has the function of increasing the lift coefficient of the airfoil and increasing the stall angle of attack.

This effect can be attributed to the negative pressure surface vortex that exchanges kinetic energy between the outer fluid of the boundary layer and the inner fluid, which increases the kinetic energy of the inner fluid and slows down the fluid separation caused by the reverse pressure gradient in the boundary layer. The bionic vortex generator exhibits a...
stronger vortex excitation effect than the triangular vortex generator. This may be due to the presence of the front edge of the bionic vortex generator curve making the fluid flowing nearby produce a stronger lateral force. Figures 6 to 8 show that the maximum lift coefficient of the bionic vortex generator is higher than that of the triangular vortex generator, which occurs under moderately degraded conditions, increasing by up to 10%.

C. EFFECT ON BLADE SURFACE PRESSURE ON VORTEX GENERATORS

Figure 9 shows the influence of the bionic profile vortex generator and triangular vortex generator on the surface pressure distribution of the DU97-W-300 airfoil when the angle of attack is 11° and 18°. Figure 9 shows the significant influence of the vortex generator on the airfoil surface pressure distribution. The suction surface of the vortex generator installation position (20% chord length from the leading edge of the airfoil) has a local extreme value. At the same time, the vortex generator not only affects its downstream fluid but also its upstream fluid, so that the entire suction surface produces stronger suction. Moreover, the enhancement effect of the vortex generator on the suction increases with the increase in the angle of attack. Figure 9 also shows that under different angles of attack and different surface degradation conditions, the bionic vortex generator has a higher suction enhancement effect than the triangular vortex generator, which confirms the conclusion of the section. The superior performance of the bionic shape vortex generator becomes more obvious as the angle of attack increases. Under moderately degraded conditions, the bionic vortex generator has a significantly higher suction enhancement effect than the triangular vortex generator, indicating that the bionic vortex generator has the most obvious advantage over the triangular vortex generator under medium degraded conditions.

D. VG DOWNSTREAM FLOW FIELD ANALYSIS

Figure 10 shows the velocity clouds at 4 and 8 h downstream of the triangular vortex generator at a moderately degraded angle of attack of 11°. Figure 10 shows that 4 h downstream of the triangular vortex generator, the vortex phenomenon is obvious, and the vortex generated by a pair of vortex generators is asymmetric. Figure 11 shows a decrease in vortex core intensity at 8 h downstream of the vortex generator. It shows that the vortex core area only exists in a limited distance interval downstream of the vortex generator. The map velocity is in the center of the cloud area in the interval (78 m/s, 84 m/s), and the absolute height is 0.05299994 m.

Figure 12 shows that 4 h downstream of the triangular vortex generator, the vortex phenomenon is obvious, and there is no vortex asymmetry. Figure 13 shows that the intensity of the
vortex core decreases 8 h downstream of the vortex generator. The absolute height of the center coordinate point of the cloud map area in the interval (78 m/s, 91 m/s) is 0.05329 m.

As shown in the schematic diagram, the center point of the vortex excited by the bionic vortex generator is higher, the rotation radius is larger, and the rotation speed is faster.

The magnitude of the vorticity, \( \omega \), represents the circulation density, that is, the vorticity flux per unit area. The cross-sectional vortex flux can be expressed as:

\[
J = \iint_A \omega \cdot n dA = \iint_A \omega_n dA = 2 \iint_A \Omega_n dA
\]  

(3)

In formula (3), \( n \) is the cross-section normal, \( A \) is the cross-sectional area, and \( \omega_n \) and \( \Omega_n \) respectively represent the component of the vorticity along the normal direction of the vortex tube cross section and the angular velocity of the vortex tube. According to Stokes’ theorem, the velocity loop of a closed circle is equal to the vorticity flux passing through the area enclosed by the closed circle, namely:

\[
2 \iint_A \Omega_n dA = \oint_L V \cdot dS
\]  

(4)

In formula (4), \( V \) is the fluid velocity, \( S \) is the closed contour, and \( \Gamma \) is the velocity circulation.

For sections \( A_1 \) and \( A_2 \) of the scroll tube and the surface \( A_3 \) connecting the two sections, the volume enclosed by the three surfaces is, according to Gauss’s theorem,

\[
\iiint \nabla \omega dV = \iiint_A \omega_n dA
\]  

(5)

Since the vorticity divergence is 0, that is

\[
\nabla \omega = 0.
\]  

(6)

Formula (5) can be written as:

\[
\iint_{A_1} \omega_n dA = - \iint_{A_2} \omega_n dA + \iint_{A_3} \omega_n dA
\]  

(7)

Since the normal direction of the \( A_3 \) surface is perpendicular to the vorticity direction, there is

\[
\iint_{A_3} \omega_n dA = 0.
\]  

(8)

Therefore:

\[
J = \iint_{A_1} \omega_n dA = \iint_{A_2} \omega_n dA
\]  

(9)

From formula (9), the vortex flux in the vortex tube is conserved, so comparing the vortex fluxes of different vortex tubes is equivalent to comparing the vortex fluxes at the two sections.

From Figure 10 and Figure 12, it can be seen that the bionic vortex generator and the triangular vortex generator have the following relationship:

\[
\Gamma_{\text{CURVED}} = \Gamma_{\text{TRIANGULAR}}
\]  

(10)

V. CONCLUSION

This article proposes a bionic vortex generator shape based on a manta ray wing. Through simulation, the effect of the bionic shape vortex generator and the triangular vortex generator on DU97-W-300 blades with different surface degradation degrees, consisting of mild degradation (\( h_s^+ = 0.025 \) mm), moderate degradation (\( h_s^+ = 0.045 \) mm), and severe degradation (\( h_s^+ = 0.065 \) mm), was studied. The main conclusions were:

1) For the DU97-W-300 airfoil, when the roughness is set to \( h_s^+ = 0.045 \) mm, the blade surface degradation is the same as that of 0.35-mm-thick zigzag tape installed at the 5% chord length from the leading edge.

2) The presence of a vortex generator has an obvious inhibitory effect on blade surface degradation, and the bionic vortex generator displayed a stronger performance. When it is slightly degraded, the bionic vortex generator and the triangular vortex generator increase the maximum lift coefficient of the blade by 1.273 times and 1.212 times, respectively. When the degradation is moderate, the bionic vortex generator and the triangular vortex generator increase the maximum lift coefficient of the blade by 1.254 times and 1.144 times, respectively. When severely degraded, the bionic vortex generator and triangular vortex generator increase
the maximum lift coefficient of the blade by 1.278 times and 1.176 times, respectively. When the degradation is moderate, the lift coefficient of the blade by the bionic vortex generator is higher than that of the triangular vortex generator and reaches the maximum.

3) It can be seen from the blade surface pressure graph that due to the modulation of the downstream fluid by the vortex generator, the downstream fluid back-pressure gradient is reduced, and the suction force of the entire suction surface is enhanced. Before stalling, the greater the angle of attack, the more strongly the vortex generator can modulate the suction surface fluid, and the more obviously the lift coefficient of the blade is improved.

4) Compared with the triangular vortex generator, the bionic vortex generator makes the energy exchange between the high kinetic energy fluid in the outer layer of the boundary layer and the low kinetic energy fluid in the inner layer more frequent; thus, the bionic vortex generator has a better performance.

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