Research of the leading edge separation vortex characteristics due to the inlet velocity shape

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Abstract: The zero adverse pressure gradient plate is taken as the study object, in order to study the leading edge separation vortex characteristics due to the inlet velocity shape. With the CFD method, we classify the study cases into 6 groups \((h/\delta = 0.1, 0.2, 0.5, 1.0, 1.5, 2.0)\) \((h\) for vortex generator(VG) height, \(\delta\) of inlet boundary layer thickness) to study the inflow boundary layer's influence law to the vortex generator characteristics. Calculation results show that, vortex generator leading separation vortex strength is proportional to fluid average kinetic energy within vortex generator height range. Vortex strength shows essentially inverse relationship with the flow boundary layer thickness, while the vortex generator shape resistance also shows the inverse proportion to the flow boundary layer thickness. Namely, heavier flaw boundary layer thickness leads to lower vortex strength and lower vortex generator shape resistance simultaneously.

1 Introduction
During wind turbine generation system operating, rotor blades occur surface flow separation and effect the wind turbine power generating efficiency. Vortex generator(VG) is one of the effective flow control equipment for flow separation\(^{[1-6]}\). Its control mechanism is right below: when air flows across the vortex generator, downstream of the VG will generate approximate stream vortex, which can strengthen the momentum exchange between the low energy inside the airfoil surface boundary layer and the high energy outside the boundary layer, so air flow with inverse pressure gradient, VG can postpone the airfoil boundary layer flow separation.

Vortex Generator was firstly proposed by Taylor\(^{[7]}\) and initially applied into airplane airfoil. As for the wind turbine, Gyatt\(^{[8]}\) did analysis and experimental study on the small two blade horizontal wind turbine(diameter 9.75m) with inverse rotation vortex generator. According to measurement data shown by the wind farm site, wind turbine with VG could increase the output power under the large wind velocity. While in the low wind velocity, wind turbine would generate less power instead. To learn more about the vortex generator technology applied into the wind turbine, the Dutch Delft university wind energy study center carried out the experiment about the Du series wind turbine airfoil lift and drag characteristic by the vortex generator with the different Reynolds number\(^{[9]}\). The result showed that the vortex generator could postpone the stalled attach angle, and improve the lift and drag ratio. Recently, Zhang Lei\(^{[10]}\) etc. conducted a numerical simulation on the airfoil with the vortex generator installed. They got a good get a good agreement simulation result with the experiment data, what’s more, the result showed that under the condition of the large attach angle, vortex generator was an effective equipment to restrain the boundary flow separation.

The characteristic of the VG includes vortex generator leading edge separation vortex intensity,
vortex core area and vortex dissipation etc. When VG is installed on the solid surface, it can be affected by the wall boundary layer, what’s more, the fluid flow status differs from the different boundary layer height. So, it is very significant to take a study on the vortex characteristic under the different flow boundary layer thickness. Especially, take the wind turbine blade flow control as example, VG is installed inside the turbulent boundary layer, so the paper studies the vortex generator characteristic under different flow boundary layer thickness.

2 Geometry Model and Numeric Method

2.1 Geometry Model

The paper research on the zero pressure gradient plane, and change the boundary layer thickness of inlet turbulent velocity shape (as shown in fig.1) so as to study the vortex generator characteristic by the flow boundary layer thickness. The flow turbulent velocity shape is define as the equation (1):

\[
u = \begin{cases} 
U \left( \frac{y}{\delta} \right)^{7/3} & y < \delta \\
U & y \geq \delta 
\end{cases}
\]  

(1)

Where \(u\) is the current velocity, \(\delta\) is boundary layer thickness, \(U\) is the main stream velocity, and \(y\) is wall normal height.

![Fig.1 Flow and schematic of VG](image)

Table 1 shows the VG geometry parameter, VG is wall without thickness. Let flow velocity \(U\) 82 m/s, and Reynolds number based on the VG height about \(3 \times 10^4\).

| Install angle \(\beta\) (°) | Chord length \(l\) (mm) | Height \(H\) (mm) | The proportion of VG Height \(H\) and boundary layer thickness \(\delta(H / \delta)\) |
|-----------------------------|------------------------|------------------|----------------------------------|
| 20                          | 17                     | 5                | 0.1, 0.2, 0.5, 1.0, 1.5, 2.0      |

2.2 Computational Method

Steady numerical simulation is carried on with Fluent software, and finite volume method is used to discretize the control equation, with two order accuracy central difference scheme for space discretion and pressure-velocity coupling SIMPLE algorithm. The full turbulent Spalart-Allmaras(SA) model is selected as turbulent model.

Computation mesh: mesh is generated by ICEM, and the domain is divide with structure mesh. Assigning the VG height and chord direction with 80 grid point, VG downstream with 200 grid point, the total mesh quantity is 5 million. The surface and bottom mesh of VG is shown in fig2.
Fig. 2 Grids

Boundary Condition: for the convenience of monitoring the vortex running situation at the downstream of the VG, set the stream-wise length 144H, while VG is installed in the 9H far from inlet, domain width and height are both 20H. Boundary conditions include velocity inlet, pressure outlet, and symmetry condition at the two side of the computational domain. In addition, the upper side is free slip boundary condition, and both VG and downside is no-slip wall boundary condition.

![Computational domain and boundary conditions](image)

Fig. 3 Computational domain and boundary conditions

3 Result

Fig 4 shows the static pressure efficiency curve at the suction surface. We can figure out that the magnitude of $C_p$ increase along with the height of the VG increase no matter the VG installed position along the chord-wise. Especially when $H = 1.0\delta, 1.5\delta, 2.0\delta$, the magnitude of $C_p$ is close to each other, however, the magnitude of $C_p$ has more difference between $H=0.1\delta$ and $H=0.2\delta$. The magnitude of $C_p$ at the height of 0.5$\delta$ is in the middle of the maximum magnitude.

![Cp of the suction surface](image)

Fig. 4 $C_p$ of the suction surface a) $x=0.1l$, b) $x=0.2l$, c) $x=0.4l$, d) $x=0.6l$, e) $x=0.8l$, f) $x=1.0l$

Fig. 5 is the distribution law of the static pressure coefficient and axial velocity along the axial-wise. The magnitude of $C_p$ at the vortex core increase first and then decrease, and get the top value at the half of the chord. The variation of axial velocity at the vortex core is consistent with that of $C_p$, and lower $C_p$ at the vortex core, bigger axial velocity. With the increase of the VG height, $C_p$ at the center of the vortex become higher, and axial velocity become faster, which confirm that the
strength of the vortex core will become stronger with the higher height of the VG. Seen from Fig.5 b), axial velocity at the vortex core all increase first and then decrease in the different height of the VG, which illustrate that vortex core become stable and without the vortex core breakout phenomenon et.

Fig.5 Cp and axial velocity distribution at the center of vortex

Fig.6 shows the variation law of the vortex core area and circulation in the VG airfoil surface along the stream-wise. As shown in the chart, vortex core area has an approximate distribution along the different height of the VG, only some large difference shows at the trailing edge of the airfoil surface. The increase regularity of vortex core area along the stream-wise distance shows approximately linear change distribution, and vortex core circulation increase as the height of the VG increase, especially at the trailing edge of the VG, the difference of the circulation value become bigger.

Fig.6 Vortex core area and vortex strength along with the string

Fig.7 shows the variation law of the vortex core area and vortex circulation at the trailing edge of VG. Seen from Fig.6, vortex core area increase as the flow distance increase, however, vortex circulation inside the VG airfoil surface increase along the stream-wise, and at the downside of VG decrease gradually, namely, the maximum of the circulation exist at the trailing edge of the VG. For the convenience of the comparison, choose the vortex core area and circulation at the trailing edge of the VG. Seen from the below figure, when \( \frac{H}{\delta} < 1 \), vortex core area hit the top, while vortex core area decrease a little when \( \frac{H}{\delta} > 1 \), and vortex core area increase rapidly with the increase of the VG height when \( \frac{H}{\delta} < 1 \). Vortex core circulation is directly proportional to the VG height, namely vortex core strength increase as the height of VG increase. However, vortex core strength is not show the linear change with the VG height. When \( \frac{H}{\delta} < 1 \), the gradient between vortex core strength and VG height is much bigger, but when \( \frac{H}{\delta} > 1 \), the gradient is much smaller.

Fig.7 Vortex core area and vortex strength along with height at trailing edge of VG

Fig.8 a) is the boundary layer velocity shape downside the VG, b) is the fluid average velocity inside the range of VG height. Seen from Fig.8 a), VG is placed in the different boundary layer
thickness, the upstream flow velocity shape is different. And the most intuitive knowledge is that with the increase of the boundary layer height, the boundary layer fluid kinetic energy decrease inside the range of the VG height. Seen from b), as the VGs height increase, namely the boundary layer thickness decrease, the fluid average velocity become higher and higher inside the range of the VG height, and the variation law between the fluid velocity and VG height shows the exponent law distribution. When H/δ<1, the gradient between boundary layer fluid velocity and VG height is a little high. When H/δ>1, gradient become low, and the variation of the velocity show stable.

**Fig.8** The velocity shape at VG upstream and average velocity within the height of VG

Fig.9 is the variation rule of VG lift coefficient, drag coefficient and lift-drag ratio inside the different boundary layer height. Seen from a), the lift coefficient gradually increases with the VG height increases, especially the maximum lift coefficient is about 0.65 when H/δ=2. Seen from b), the drag coefficient also increases as the height of VG increases and the maximum drag coefficient is 0.25 when H/δ=2. To a great extent, the lift of VG originates in the vortex induced lift from the delta wing. So if the vortex strength of the concentrated vortex induced by the delta wing become stronger, then the VG lift will become stronger. And drag force is pressure drag, namely VG shape resistance. Take Fig.9 a) and Fig.9 b) into comparison, found that the variant law of the lift and drag coefficient along the have consistent distribution. Seen from Fig.7 b) and Fig.8 b), there are consistent variant law among the fluid kinetic energy, VG vortex strength and lift drag coefficient along the different height of VG. So the VG induced vortex strength and shape resistance have close relation with the VG height H/δ ,and show the direct proportional relation but not linear change, instead the exponent distribution. Namely the effect is less obvious with the bigger VG H/δ. Seen from fig.9 c) the lift-drag ratio hit the top when H/δ=0.5. From a theoretical view of point, when H/δ=0.5, it not only can generate certain vortex strength to conduct flow control, but also the shape resistance is not so big, but whether the ratio of the height and boundary layer thickness is the best or not, the deep analysis should be conducted from the point of the boundary layer fluid kinetic energy.

**Fig.9** C_l, C_d and C_l/C_d of VG

Fig.10 is the distribution of the axis velocity along the normal height at the position of vortex core in the downsize of VG. The line in the figure is about the center of the vortex core. Seen from fig.6 a), with the increase of the flow distance, different height of the VG has the different vortex core area and the bigger the vortex core area is, the higher the normal height is. So the vortex core height noted in the figure is the vortex height when H=1.0δ. Firstly, as shown in the figure, as the increase of the flow distance, vortex core height will become higher. Then the velocity shape inside the boundary layer is basically changed with S distribution. Energy conservation can be confirmed by that the increase of fluid kinetic energy inside the vortex core is equal to the decrease of the energy outside of the vortex.
core. Take comparison with fluid kinetic energy at the different boundary layer height, the boundary layer fluid kinetic energy hit the bottom when $H=0.1\delta$, $0.2\delta$, and both of them have little difference. When $H=0.5\delta$, boundary layer fluid energy have the medium order, namely the value is greater than the energy at $H=0.1\delta$, $0.2\delta$, simultaneously lower than the energy at $H=1.0\delta$, $1.5\delta$, $2.0\delta$, the boundary layer kinetic energy have the approximately same distribution, which means that the boundary layer energy will not increase with the height of the VG increase. While seen from the fig.9, the shape resistance will increase with the increase of the height of the VG. So, the flow control get the best optimal effect at $H=1.0\delta$ for the view of the boundary layer fluid energy, with the much more stronger concentrated vortex strength and less shape resistance.

![Fig.10 The velocity shape at VG downstream](image)

4 Conclusion

The paper research on the VG vortex characteristic by flow boundary layer height with the numerical method, the main conclusion can be shown below:

(1) The VG leading edge separation vortex strength has a direct proportional relation with the average fluid kinetic energy inside the range of the VG height. Vortex strength and shape resistance induced by VG has inversely proportional relation with the flow boundary layer height. Namely, with the increase of the boundary layer, vortex strength induced by VG become smaller, also the shape resistance.

(2) When $H/\delta=0.1$, $0.2$, boundary layer fluid kinetic energy hit the bottom, and both of them have almost not difference. When $H/\delta=0.5$, the fluid energy is at the middle, the VG lift-drag hit the top. When $H/\delta=1.0$, $1.5$, $2.0$, the boundary layer fluid energy is basically the same, but lower the flow boundary layer height is, bigger the VG shape resistance. So when $H/\delta=1.0$, vortex generator flow control can get the best optimal effect.

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