Numerical study on noise reduction of wind turbine blade vortex generator

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Abstract. At present, wind power is widely used, especially in near-residential areas, and blade noise has become an important factor affecting the installation and operation of the unit. Vortex Generator is a new technology that has been used by wind turbine blade manufacturers in recent years. At present, there are few studies on the changes of blade aerodynamic noise after the installation of vortex generators in China. In order to study the influence of vortex generators on aerodynamic noise, the flow field is simulated by numerical calculation method before and after the blade is installed with vortex generators. The visualization results are output and compared, and the parameters such as vorticity and pressure are analyzed. Secondly, based on the detailed parameters of the flow field, FW-H equation is used to calculate the sound source propagation, and the sound pressure level spectrum of the blade before and after the vortex generators added is obtained. The research shows that the vorticity increases in the vicinity of vortex generators and the downstream region, which promotes the mass and energy exchange between the upper fluid and fluid in the boundary layer, so the boundary layer separation is delayed, and the wake vortex subsides. The aerodynamic noise is low frequency noise, and the addition of vortex generators can significantly reduce the aerodynamic noise of the blade.

1. Introduction
As a clean energy source, wind power is getting more and more applications in China. At present, many wind turbines have been installed in the areas not far from the crowd, and wind turbine noise has become an important factor affecting people's living environment. At present, the noise of wind turbine abroad is clearly required. For example, Denmark requires in residential areas: when the wind speed is 8m/s, the noise of the wind turbine should not exceed 44dB; when the wind speed is 6m/s, the noise of the wind turbine should not exceed 42dB. Studies have shown that wind turbine noise also has an adverse effect on the structure and service life of the wind turbine [1].

Wind turbine noise is derived from mechanical and structural noise, aerodynamic noise. Mechanical and structural noise is emitted by the operation of mechanical components such as bearings, gearboxes, and the like. Aerodynamic noise is caused by the interaction between the blade and the air flow. The noise is related to the air flow speed, blade structure and blade rotating speed. Aerodynamic noise is mainly caused by the vortex on the blade surface and the trailing edge [2]. Practice has shown that aerodynamic noise is the main source of wind turbine noise. In recent years, the Vortex Generator (VG) technology has been applied to wind turbine blade [3]. This technology improves the blade performance through improving the flow structure on the blade surface, which will inevitably cause changes in the aerodynamic noise characteristics of the blade. Studying the influence of VG on the aerodynamic performance and noise characteristics has practical significance for
improving the blade shape and VG design, improving the efficiency of the blade and reducing the noise. However, there are few reports on the noise characteristics of VG & blade coupling in China.

In order to grasp the influence of VG on blade aerodynamic noise, this paper will use FLUENT software to numerically calculate the flow characteristics and noise characteristics of wind turbine blade before and after VG installation, and analyze the influence of VG on blade flow field structure and aerodynamic noise.

2. Numerical simulation and analysis of flow field

2.1 Geometric modeling and meshing

The blade and the flow area in three dimensions were shaped. The blade chord length was 885mm, and the calculation area was the space around the blade. In order to save computing resources, the calculation area takes 0.2 times and 5 times chord lengths upstream and downstream, and the airfoil up and down direction was 2 times chord length.

Hexahedral structured mesh was used for the smooth blade area, and the area around the blade was mesh-encrypted. The total number of meshes was 1.8 million, as shown in Figure 1(a).

VG was installed on the pressure surface of the blade. VG was trapezoidal, 12mm high and 130mm pitch, as shown in Figure 1(b). Due to the strong deformation and narrow area after the installation of VG, the calculation area was divided by tetrahedral unstructured mesh, and the mesh around the VG and the blade was encrypted. The total number of meshes was 1.92 million.

![Figure 1. Calculation area and VG](image)

(a) Smooth blade and calculation area  
(b) Blade added VG

2.2 Numerical simulation

The blade was defined as non-slip wall boundary condition, and the inlet air velocity was 16m/s, and the Reynolds number was $0.97 \times 10^6$, the incoming angle of attack $10^\circ$, and the outlet was atmospheric pressure. The fluid was air, and the reference pressure was set as $1.013 \times 10^5$Pa. The momentum equation was an unsteady, second-order implicit equation, and the discrete format was second-order upwind. In this paper, the calculation was converged until the residual to $10^{-4}$. Set the time step size as 0.0001s, and the maximum number of iterations per time step was 10. The calculation was performed using 3D double precision solver. The governing equations for CFD calculation were Flow, Turbulence [4, 5].

First, Spalart-Allmaras turbulence model was used to perform the unsteady calculation. The model could shorten the calculation time. Based on the calculation of Spalart-Allmaras turbulence model, we used Large Eddy Simulation (LES) model to perform the calculation, because LES model could capture more subtle vortex motion [6]. We monitored the pressure fluctuations of the calculation area.
when the calculation was performing. Until the iteration was convergence and the monitoring point pressure appeared periodically, the CFD calculation ended.

2.3 Analysis of calculation results

Figure 2. Pressure coefficient of blade surface

Figure 3. Static pressure cloud diagram of the blade surface

Figure 2 and Figure 3 show the pressure coefficient and static pressure distribution of the blade before and after adding VG. It can be seen that pressure fluctuations occur at the VG region, indicating that VG has disturbing action on the incoming flow. And the effect of the action is not only near VG, but also causes a change on the pressure gradient downstream. High pressure peaks and low pressure peaks are formed on both sides of VG wall, respectively, and the presence of the pressure difference will increase the secondary flow perpendicular to the direction of the airflow. Moreover, due to the turbulence effect of VG, the reverse pressure gradient on the blade surface becomes smaller, and the high pressure region on the blade surface migrates to the vicinity of the blade trailing edge, causing the separation-induced transition to move backward and the boundary layer separation to be delayed. At the same time, the pressure value in the trailing edge region is also obviously reduced.
Figure 4. Fluid vorticity of VG downstream

Figure 4 is a vortex diagram of the VG downstream fluid, with two induced vortex downstream of each VG and the two induced vortices facing opposite. Figure 5 is a vortex cloud diagram of the blade surface after adding VG. It can be seen that the vorticity is significantly larger in the vicinity of VG and in the downstream region. The inflow will be affected by VG, and at VG area the flow will curl centered on the vortex core.

Therefore, under the combined influence of vortex and a small amount of secondary flow caused by VG, the fluid in the boundary layer will be transferred and detached from the surface of the blade. The mass and energy of the fluid in the boundary layer and the upper fluid can be exchanged. The kinetic energy of the upper fluid will be delivered to the fluid in the boundary layer, increasing the kinetic energy of the fluid in the boundary layer. As the velocity of the upper fluid decreases, the turbulence intensity decreases. As the velocity of the fluid in the boundary layer increases, the ability to resist the inverse pressure gradient also increases, which helps to delay flow separation.

As shown in Figure 6, the separation of the boundary layer of the blade with VG is delayed, so that the turbulence intensity of the trailing edge and trailing region of the blade is significantly reduced. According to vortex sound theory [7], vortex is the root cause of aerodynamic noise. The trailing edge of the blade is the main position for generating aerodynamic noise [8, 9]. Therefore, it is possible to predict that VG will affect aerodynamic noise of the blade, for that the vortex structure changes on the blade surface region after adding VG [10, 11].
3. Simulation and analysis of aerodynamic noise

On the basis of the above unsteady flow calculation, the aerodynamic noise simulation before and after adding VG was executed. We started FW-H equation, as equation (1), and defined the reference sound pressure value as $2.0 \times 10^{-5}$ Pa, and calculated the sound propagation [10]. Through the calculation of FW-H equation, the relationship between the sound pressure and time of the aerodynamic noise could be obtained. Then, the Fast Fourier Transform (FFT) was applied, and the time information of the sound pressure signal was converted into the frequency information by using equation (2). So we obtained a sound pressure level spectrum map, as shown in Figure 7.

$$
\frac{1}{\rho_0} \frac{\partial^2 p'(x_i, t)}{\partial t^2} - \frac{\partial^2}{\partial x_i^2} \rho u_i (u_n - v_n) \delta(f) + \frac{\partial^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right] \delta(f) - \frac{\partial}{\partial x_i} \left[ -P_{ij} n_j + \rho u_i (u_n - v_n) \right] \delta(f)
$$

$$
P(f) = \int_{-\infty}^{\infty} P(t) e^{-jft} dt
$$

In Figure 7, the green line (up) and the white line (down) respectively indicate the aerodynamic noise generated by the blade before and after adding VG. It can be seen that the blade noise is mainly low frequency noise. As the frequency increases, the sound pressure decreases rapidly and tends to be stable. The maximum noise before adding VG is 107dB, corresponding to a frequency of 41HZ. The
maximum noise after adding VG is 83dB, corresponding to a frequency of 45Hz. The aerodynamic noise of the blades after adding VG is significantly reduced at different frequencies. In the 2000-4000 Hz segment, the human ear has the highest sensitivity and the sound pressure drops by about 20 dB.

After adding VG, the sound pressure of the blade noise higher than 500Hz is already very low, but there are two sound pressure peaks near 1480Hz and 1800Hz. These two peaks should be generated by VG.

4. Conclusion
(1) VG reduces the reverse pressure gradient at the trailing edge of the blade, and the vorticity increases significantly near and downstream of VG, which enhances the mass and energy exchange between the upper fluid and the boundary layer fluid, and improves the kinetic energy of the boundary layer fluid, thereby delaying flow separation.

(2) After adding VG, the turbulence intensity of the trailing edge and wake area is significantly reduced.

(3) The aerodynamic noise of the blade is low frequency noise, and the sound pressure level decreases as the frequency increases.

(4) VG improves the aerodynamic characteristics of the blade, thus reducing the aerodynamic noise of the blade. The sound pressure drop is different in different frequency bands, and the sound pressure drops about 20dB in the human ear sensitive frequency band.

In this paper, the mechanism of using VG to reduce aerodynamic noise is studied, which provides a basis for noise reduction of wind turbine blade. In terms of the mechanism, VG of other structures can also reduce aerodynamic noise, but the effect is different. We will subsequently continue the study to find the optimal structure for aerodynamic noise reduction and provide experimental data.

References
[1] Eja, P., Persson, W.K. (2004) Perception and annoyance due to wind turbine noise a dose response relationship. Acoustical Society of America, 12: 3460-3470.
[2] Moriarty, P. J., Guidati, G.F., Migliore, P. (2005) Prediction of turbulent inflow and trailing-edge noise for wind turbines. In: Collection of Technical Papers-11th AIAA/CEAS Aeroacoustics Conference. California. pp. 223-228.
[3] LI, X.K., KANG, S., DAI, L.P., JIAO, J.D. (2015) Effects on Airfoil Flow Field by Structure of Vortex Generators. JOURNAL OF ENGINEERING THERMOPHYSICS, 36: 326-329.
[4] ZHAO, Z.Z., LI, T., WANG, T.G. (2016) Numerical Research on Effect of Transition on Aerodynamic Performance of Vortex Generators of Wind Turbine. Proceedings of the CSEE, 36: 1036-1041.
[5] Amith, S., Evan, C., Traub Lance, W. (2009) Effects of vortex generators on an airfoil at low reynolds numbers. Journal of Aircraft, 46: 116-122.
[6] OLIVER, F. (2005) Wind turbine blade flow and noise prediction by large-scale LES. Transactions of the Japan Society of Mechanical Engineers, 71: 184-190.
[7] SUN, X.F., ZHOU, S. (1994) Aerodynamic Acoustics. National Defense Industry Press, Beijing.
[8] Dai, Y.J., Li, B.H., Xu, L.J., Ren, C.Z. (2015) NUMERICAL STUDY ON CHANGE LAW OF AERODYNAMIC NOISE FOR BLADE TIP DOWNSSTREAM OF WIND TURBINE. ACTA ENERGIAE SOLARIS SINICA, 36: 336-340.
[9] Zhang, Z.D., Xu, C. (2016) NOISE ANALYSIS OF TWO-DIMENSIONAL WIND TURBINE AIRFOIL BASED ON CFD. ACTA ENERGIAE SOLARIS SINICA, 37: 2180-2186.
[10] LIU, X.C., MO, Q.Y., LI, S.S., YAN, S.K., SHI, J.J. (2016) Numerical Simulation and Analysis of Aerodynamic Noise Based on Small Vertical Axis Wind Turbine. LIUID MACHINEERY, 44: 11-16.
[11] Tze, P.C., Joseph Phillip, F. (2013) An experimental study of airfoil instability tonal noise with trailing edge serrations. Sound and Vibration, 24: 6335-6358.