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Numerical Study on Flow Field Characteristics of Wind Turbine with Double Fork Tip Structure

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Abstract:

Based on the double fork tip structure of wing of Boeing 737MAX, herein, we designed a new type of wind turbine with double fork tip structure blade. By the means of computational fluid dynamics method, fork we simulated wind turbine with original tip structure and two type of double fork tip structures; wind velocity was set at 10 m/s, tip velocity ratio was 4.5, and the effect of wind turbine fluid field from different tip structure were investigated. The results show that double fork tip structure was able to increase the pressure difference between pressure surface and suction surface by 4.3% and 7.7%, comparing with the original tip structure; as a result, the rotor power coefficient was increased. The double fork tip structure increased the linear velocity and velocity gradient of the blade tip, the linear velocity was increased by 3.5% and 4.3% comparing with original tip blade. The wake and tip vortex of double fork tip structure wind turbine tend to move inward, the tendency increases with a smaller angle.

Keywords: *Wind turbine, Double fork tip structure, Pressure difference, Velocity.*

I. INTRODUCTION

As a renewable energy, wind energy has the advantage of abundant and environmentally friendly. Utilizing wind energy will lower carbon emission, relieve the effect of greenhouse effect, and reduce non-renewable energy consuming. Horizontal-axis wind turbine is most widely used tool that transform wind energy to mechanical energy [1,2]. Nowadays, wind tunnel experiment and computational fluid dynamics (CFD) simulation are two main ways to study horizontal-axis wind turbine.

Wind tunnel experiment allows researchers to control the experiment condition precisely, with the limited impact from external factors, wind tunnel experiment is able to simulate rea-world conditions [3]. Particle Image Velocimetry technology is commonly utilized to study

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the flow field. PIV technology is able to capture the velocity distribution of a significant amount of tracer particles, and based on the data from PIV results, researchers are able to analyze characters of flow field [4]. Currently, there are many research groups are focusing on studying wake flow and blade tip vortex through PIV technology. Whale's group [5] has studied wake flow field of wind turbine. With PIV technology, they simulated and studied double blade wind turbine, the tip speed ratio λ was set from 3 to 8, and the Reynolds number was from 6,400 to 16,000. By analyzing vorticity and velocity of the wake flow field, it is found that wake vorticity increases when tip speed ratio increases; PIV technology is good for analyzing shape, expanding, and shrinking of wake flow field of wind turbine. Hiroyuki Hirahara etc. [6] investigated running performance of mini wind turbine with diameter of 500mm through wind tunnel experiments. The results indicate that mini wind turbine with 500mm diameter has the highest efficient when wind speed is between 8 – 12m/s. under the rated speed, the power factor was 0.36, the blade tip ration was 2.7, blade tip vortex is visible. It is also found that the noise from wind turbine come from vortex around the blade, therefore, blade shape of wind turbine and study on blade tip vortex is especially important for reducing noise. Xiao etc. [7] investigated the generation, development, and dissipation of blade tip vortex in a wind tunnel with 3.2m diameter. Under the high wind speed, they revealed that blade tip vortex has a significantly effect; and in the wake area, blade tip vortex would move inward first, then move outward.

Finite element analysis software is often utilized when conducting computational fluid dynamic simulation research. Kimura etc. [8] numerically simulated wake fluid field of wind turbine based on CFD methods. By using Flow-3D simulation software, they observed changing pattern of tip vortex under different speed ratio. They found that tip vortex of wake changes with different turbulence model; and there is strong radial speed around blade tip. Lanzafame etc. [9] simulated and verified SST $k-\varepsilon$ turbulence model and rationality of tetrahedral unstructured mesh of three-dimensional wind turbine with ANSYS software. Bechmann etc. [10] numerically simulated wake fluid field of three-blade wind turbine by applying CFD methods; their calculation was based on Reynolds AverageN-S equation, the SST $k-\varepsilon$ turbulence model was applied in simulation. Rate incoming wind speed were set at 10m/s, 15m/s, and 24m/s. By comparing results from calculation and wind tunnel experiments, it is found that gridding partition and choice of turbulence model can impact calculation results significantly. Carriónf etc. [11] also verified numerical simulation of same experiment, after the convergence of residual variance curve, pressure distribution and speed isogram have a good match with results from wind tunnel experiment. Weng etc. [12] utilized AutoCAD software to build wind turbine two-dimensional models, then structured mesh was constructed by GAMBIT; their numerical calculation was based on Reynold average N-S equation, $k-\varepsilon$ model was chose as turbulence model. By calculating in Fluent, they were able to obtain the changing patterns of fluid field speed of wind turbine, as well as pressure cloud and noise.

Currently, most wind tunnel experiments and CFD simulations focus on the fluid field of original horizontal-axis wind turbine. Many researches have reported that speed and vorticity

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have a significant change at blade tip area, this reveals the source of noise and blade vibration [13]; however, research on numerical simulation of remodeling of horizontal-axis wind turbine is relative rare. Inspired by the double fork structure of airfoil of Boeing 737MAX, this research was focusing on the remodeling of wind turbine blade. Airfoil of Boeing 737MAX comes from fusion structure, fluid dynamics and wind tunnel experiments have proved that such structure is able to reduce the resistance from wind, increase fuel efficiency by 12%, reduce fuel consumption by 2%, and increase the cruising ability of aircraft [14]. Three types of wind turbine were simulated numerically; numerical simulation can provide results with high accuracy and detailed information on fluid field and turbulence model, practical fluid field can be well simulated from such calculation. Hence, in this research, by utilizing finite element analysis software ANSYS, the fluid fields of original structure and remodeled structure of wind turbine were numerical simulated; by focusing on the changing pattern of pressure, speed, and vorticity of fluid field of three types of wind turbine, this research is able to provide theoretical basis for research of future wind turbine tip structure remodeling and aerodynamic performance improving.

II. WIND TURBINE MODEL

300W minitype wind generator was used in this experiment, turbine blade number was 3, and the rate speed was 750r/min, TABLE I listed all blade parameters, and Figure 1 and Figure 2 present the graphic model of blades.

TABLE I. 300W wind generator blade parameters

Parameters	Data	Parameters	Data
Blade Number	3	Wind Tip Chord Length/m	0.048
Blade Length/m	0.6	Maximum Span-chord Ratio	4.14
Wind Wheel Diameter/m	1.2	Relative Thickness	10.26%
Tip Speed Ration	4.5	Blade Airfoil	S-series airfoil

Fig 1: Graphic model of original tip structure blade

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Fig 2: Graphic model of double fork tip structure blade

The double fork tip structure includes tip intersection angle θ, tip length a, and tip width h. Figure 3 presents the structure of double fork tip blade, and the parameters are listed in TABLE II.

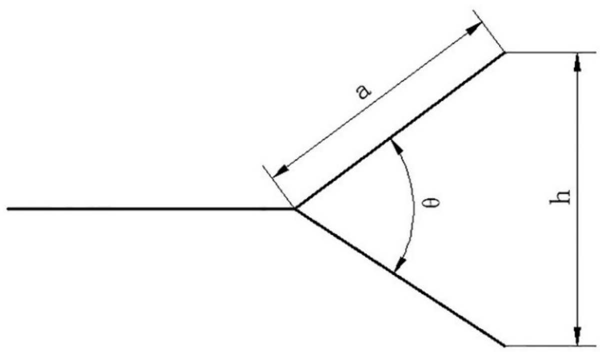

Fig 3: Double fork tip structure

TABLE II. Double fork tip parameters

	Tip length a/mm	Tip width h/mm	Tip Intersection angle θ/º
Structure 1	47	45	30
Structure 2	47	63.5	60

III. GRIDDING PARTITION OF WIND TURBINE

Three dimensional UG model of wind turbine was imported into ICEM CFD and then grid partitioned. Structured grid can provide high quality results and clear data configuration, and hexahedral structure grid has a better fit with the model; also structured grid requires a shorter computing time which is better for convergence. Therefore, in this research, three types of tip structure of wind turbine were partitioned by structured grid. To better simulate the actual situation, the grid was divided into three parts, rotate part, non-rotate part, and wind turbine part. The number of structured grids of original tip structure wind turbine was 1.97 million, the number of structured grids of double fork tip structure with $\theta = 30^o$ wind turbine was 2.12 million, and the number of structured grids of double fork tip structure with $\theta = 60^o$ wind turbine was 2.14 million. Figure 4, 5 and 6 are grid partition diagrams. The mesh file was

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imported into Fluent for numerical simulation, a multi-core server was used for calculation, and internet connection must be established when Fluent started multi-core calculation.

Fig 4: Overall computational domain mesh

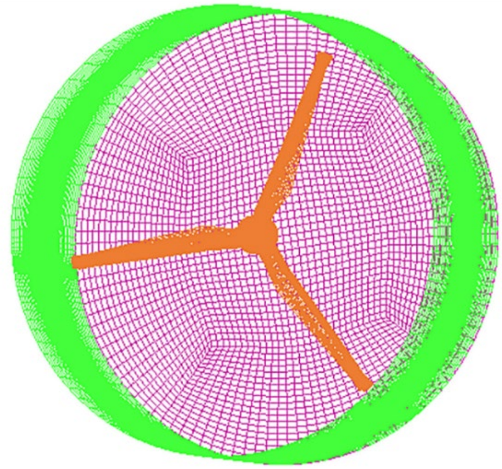

Fig 5: Impeller rotation domain mesh

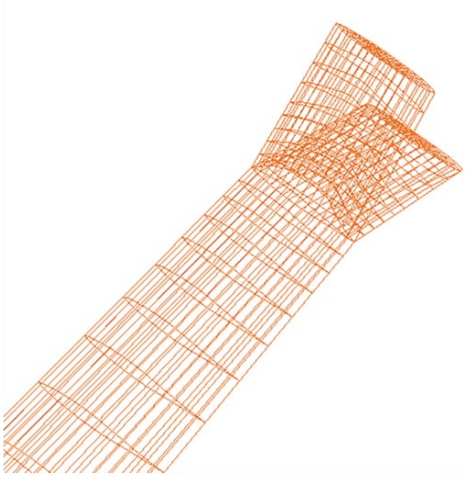

Fig 6: Local enlargement mesh of double fork tip structure

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IV. FLUENT CALCULATION SET

The three-dimensional steady Reynold average Navier-Stokes equation, which is incompressible flow, was used as governing equation, and its vector form is (1)

$$\begin{aligned}\rho\frac{du}{dt}&=-\frac{\partial p}{\partial x}+\rho X+\mu\Delta u\\ \rho\frac{dv}{dt}&=-\frac{\partial p}{\partial y}+\rho Y+\mu\Delta v\\ \rho\frac{dw}{dt}&=-\frac{\partial p}{\partial z}+\rho Z+\mu\Delta w\end{aligned}\tag{1}$$

Where Δ is the Laplace operator; ρ is fluid density; P is pressure; u, v, and w are speed components at point (x, y, z) when time equal to t; X, Y, and Z are components of external force; constant μ is dynamic coefficient of viscosity.

The choice of turbulence model was based on realizable $k-\varepsilon$ model of Reynold average N-S model, it has fairly good performance for rotation, boundary layer separation and circular flow under pressure gradient, as well as circular flow; iterative computation for each step is relatively small. SIMPLEC algorithm was used as pressure-speed coupling method, it is semi-implicit algorithm of pressure-speed coupling equation. Inlet wind speed was 10m/s, outlet was set as free outflow. Air was used as flow media, the tip speed ratio of wind turbine was $\lambda=4.5$, rotate speed was 750r/min, center of rotation was Y axis, interface was applied to process interface between rotate part and non-rotate part, the transient time for each step of this non-stable rotate wake was 0.00022s, which means the impeller needs 0.00022s to rotate 1 degree. To obtain stable and valid wake flow characteristic and pattern, the convergence criteria of continuity residual variance curve was 1×10^{-5}. Each step of calculation would require iteration set up, if number of iterations is too small during Fluent calculation, calculation will forward to next step automatically before reach convergence; therefore, number of iterations was set at 300, and the computer will stop iteration automatically and move on to next step when calculating convergence, this will help with calculation of convergence; and each convergence calculation step has 21 iterations. After impeller rotates 10 circles, the fluid field was stable, data was ready for extraction, the change of pressure, speed, and vorticity was observed, data was analyzed after applying results to post-processing software Tecplot to profile data cloud.

V. WIND TURBINE: ANALYSIS OF FAN BLADE PRESSURE

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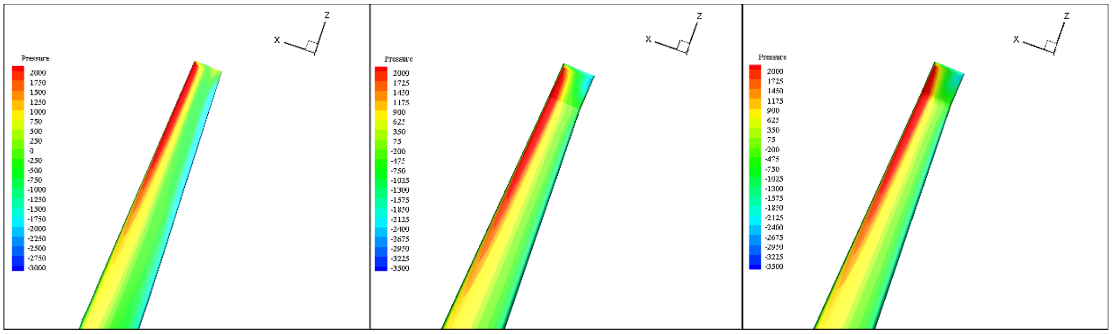
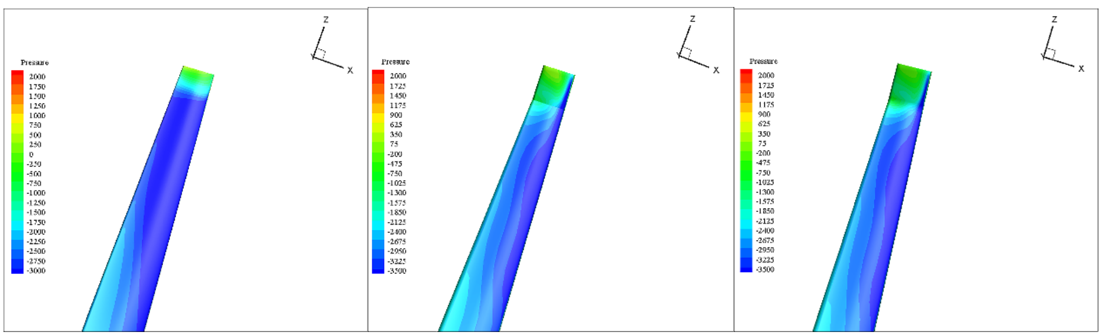


a. Original tip structure b. Double fork tip structure $\theta = 30^o$ c. Double fork tip structure $\theta = 60^o$

Fig 7: Local pressure surface cloud of three tip structures



a. Original tip structure b. Double fork tip structure $\theta = 30^o$ c. Double fork tip structure $\theta = 60^o$

Fig 8: Local suction surface cloud of three tip structures

The pressure difference represents the difference between positive pressure from pressure surface and negative pressure from suction surface. As the pressure different increases, blade tends to gain more wind energy, wind will do more work on blade, and that comes with a higher torque as well as a higher output power of the wind turbine. Herein, by utilizing the probe function of post-analyzing software, Tecplot, the maximum pressure of pressure surface and suction surface were selected. In original tip structure, the maximum pressure of pressure surface is 1975 Pa, and the minimum pressure of suction surface is -3190 Pa, the pressure difference is 5165 Pa; in double fork tip structure with $\theta = 30°$, the maximum pressure of pressure surface is 1998 Pa, and the minimum pressure of suction surface is -3400 Pa, the pressure difference is 5398 Pa; in double fork tip structure with $\theta = 60^o$, the maximum pressure of pressure surface is 2141 Pa, and the minimum pressure of suction surface is -3456 Pa, the pressure difference is 5597 Pa. It is obvious that blade with double fork tip structure with $\theta = 60^o$ possess the highest pressure difference, and the difference increased by 7.7 % comparing with original tip structure, and 4.3 % comparing with the double fork tip structure with $\theta = 30^o$. Therefore, such double fork tip structure increases the pressure difference of the blade as well as utilization factor, and make wind turbine has a higher output power.

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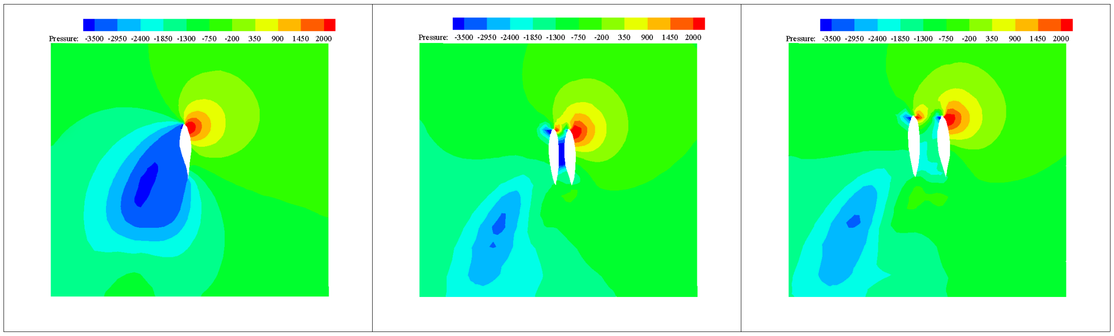
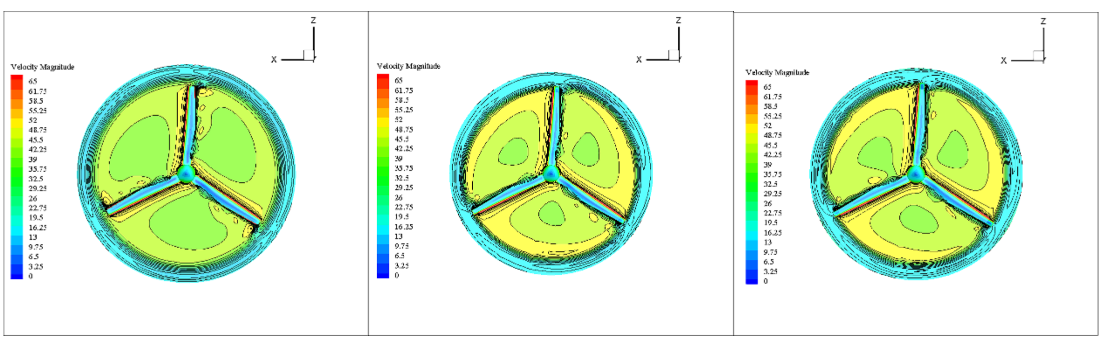


a. Original tip structure — b. Double fork tip structure $\theta = 30^o$ — c. Double fork tip structure $\theta = 60^o$

Fig 9: Isobaric profile of Z = 0.55 cross section of three tip structures

Figure 9 is the isobaric profile of cross section of original tip structure and double fork tip structure, all three cross sections were intercepted 0.55 m from blade root. By comparison, wind would have a better effect on the blade tip with double fork structure. The double fork will form two pressure difference area, and the positive pressure and negative pressure of leeside has a lower value than these of windward side due to energy loss. The double fork tip structure has one more pressure difference area than original tip structure, and this can make double fork tip structure be able to absorb more wind energy. Under the same interception height in double fork tip structure, the smaller fork angle would lead to a larger negative pressure between two fork tips. When intercepted at 0.55m, double fork tip structure with $\theta = 30^o$ has the smallest negative pressure between two fork tips of -3294 Pa, and double fork tip structure with $\theta = 60^\circ$ has the smallest negative pressure between two fork tips of -2376 Pa.

VI. ANALYSIS OF IMPELLER VELOCITY

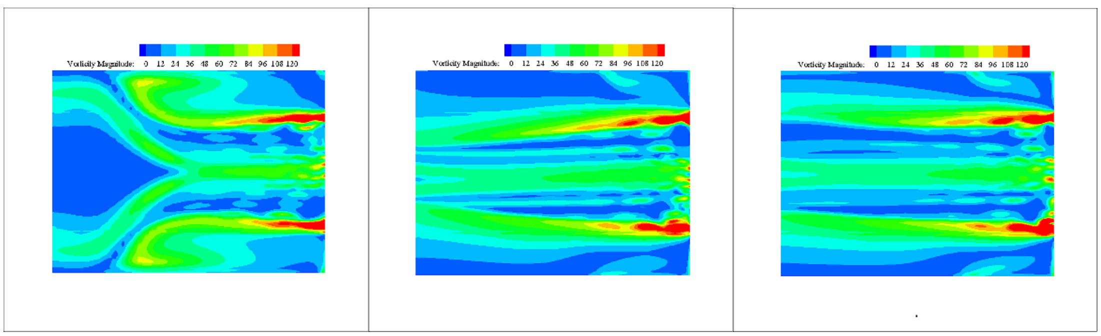


a. Original tip structure — b. Double fork tip structure $\theta = 30^o$ — c. Double fork tip structure $\theta = 60^o$

Fig 10: Y=0 section velocity isograms of three structures

Figure 10 presents velocity isograms of Y=0 section of original tip structure and double fork tip structures. By comparing results, three structures have similar distribution of velocity, linear velocity reaches maximum value at tip and area that tip swept from impeller surface, and the linear velocity decreases toward blade root due to energy loss and wake effect, noticeable tip vortices exist in tip area. Comparing with the original tip structure, double fork tip structures have a more distinguishable increase of linear velocity, the maximum linear velocity of original structure at the tip area was 49.12m/s, the maximum linear velocity of double fork tip structure with $\theta = 30^{\circ}$ at the tip area was 50.88m/s, the maximum linear velocity of double fork tip structure with $\theta = 60^{o}$ at the tip area was 51.37m/s, such maximum value of the linear velocity of double fork tip structures with $\theta = 30^{o}$ and $\theta = 60^{o}$ increased 3.5% and 4.3, respectively. The minimum velocity value of original tip structure was close to blade root, while the minimum velocity value of double fork tip structures was located at the center of sector area. The rotate velocity of impeller was low- velocity rotation, thus the compressibility of air in Fluent was negligible.

VII. ANALYSIS OF WAKE VORTICITY



a. Original tip structure　　b. Double fork tip structure $\theta = 30^{o}$　　c. Double fork tip structure $\theta = 60^{o}$

Fig 11: Wake vorticity cloud of three structures

Figure 11 presents the wake vorticity cloud of original tip structure and double fork tip structures. Figure 11(a) indicates that wake vorticity would expand, vorticity was strong at tip area, the maximum value was $118s^{-1}$, the vorticity decreases as the distance to impeller increases, and vortices tend to move inward during formation initial stage. The tip vortices decrease when away from impeller, however, new vortices would form after certain distance, the largest vorticity of that was $81s^{-1}$ due to energy loss, such value is the 68% of maximum vorticity. Figure 11(b) and (c) shows that double fork tip structures was able to change the shape of tip vortices at far wake area, there were no strong tip vortices in far wake area.

The vorticity from wake mostly came from tip and back of wheel hub, and vorticity at tip was much greater than vorticity at back of wheel hub, which matches the Blade Element Momentum Theory. By comparing Figure 11(b) and (c), it is found that wake vorticity decreases when the vorticity decreases as the distance to impeller increases, and tip vortices move inward during the initial stage, double fork tip structure with $\theta = 30^{\circ}$ had a stronger tendency than double fork tip structure with $\theta = 60^{\circ}$, this indicates that double fork tip structure is able to change the position of tip vortices. Double fork tip structure decreased the vortex shedding frequency and increased the distance between two tip vortices; double fork tip structure with $\theta = 30^{\circ}$ had a lower vortex shedding frequency comparing with double fork tip structure with $\theta = 60^{\circ}$.

VIII. SUMMARY

Through Fluent numerical simulation, it is found that blade tip had the largest load fluctuation, and double fork tip structures with $\theta = 30^{\circ}$ and $\theta = 60^{\circ}$ increased the pressure difference by 4.3% and 7.7%, respectively, comparing with original tip structure, with such structure, wind turbine is able to utilize wind energy more efficient, the torque and output power can also be increased. The tow fork tip from double fork tip structure would form two pressure difference area, the positive and negative pressure of leeside was smaller than these of upwind area due to energy loss. The double fork tip structure was able to increase the linear speed of blade tip of wind turbine, the linear speed of tip was increased by 3.5% and 4.3%, respect to two different tip Intersection angle, comparing with original tip structure; the speed gradient also increases, and the minimum speed was located at the center of sector area. The tip vortices from wake area of double fork tip structure tend to move inward, and double fork tip structure with $\theta = 30^{\circ}$ had a stronger tendency than double fork tip structure with $\theta = 60^{\circ}$; double fork tip structure was also able to decrease the vortex shedding frequency. The results show that wind turbine with double fork tip structure with $\theta = 60^{o}$ has a better aerodynamic performance, this numerical simulation research would be able to provide theoretical basis for future wind turbine tip structure modification research.

In this numerical simulation, the pressure difference, velocity and vorticity are analyzed visually. The influence of double-forked blade tip structure on the generation and shedding of blade tip vortexes of wind turbines needs further study, and the optimal Angle of the fork can also be found through numerical simulation. At the same time, it is hoped that the double-forked blade tip structure wind turbine can be put into use as soon as possible.

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