Experimental Performance Research of Vertical Axis Wind Turbine with Expandable Airfoil

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Abstract. In order to improve the wind energy utilization of the vertical axis wind turbine (VAWT), a new type of VAWT with expandable NACA0012 airfoil is proposed in this paper. The airfoil has opening and folding state. The airfoil is open in windward which is similar with curved blade in Savonius turbine. And it is folded in leeward which is similar with airfoil in H-type turbine. In this paper, a wind tunnel test system is designed to measure the aerodynamic performance of the new turbine and three main structural parameters of the turbine are analyzed. The structural parameters contain the maximum unilateral open angle which influence the flatten of the blade and the sweep wind area. The revolution angle of the rotor corresponding to the self-rotation open angle which influence the effective working time and the airfoil self-rotation effect on the turbine rotation. And the revolution angle of the rotor corresponding to the self-rotation folded angle of the airfoil which influence the wind resistance and impact on the turbine in rapid folding process. The results show that the maximum wind energy utilization of new turbine with appropriate airfoil structural parameters and tip speed ratio corresponding maximum wind energy utilization is higher than Savonius turbine which means the performance of the new turbine capturing wind power is better than Savonius turbine and can be more suitably used in areas with relatively barren wind resource.

Keywords: Vertical axis wind turbine; Airfoil; Structural parameters; Wind energy utilization.

1. Introduction
In recent years, environmental pollution and traditional energy exhaustion makes the using of renewable energy become national energy development strategy. The research on the aerodynamic performance and power generation efficiency of wind turbines has become focus in the renewable wind energy. In spite of low wind energy utilization, the cost-less blade manufacture, large starting torque, and no additional devices in aligning wind in VAWT makes the improving wind energy utilization of VAWT becomes a research focus.

The blade is the key component of the VAWT, the structure and the operating mode of the blade directly determine the efficiency of the turbine, the starting torque and other performance. The research of the new S-type wind turbine structure has become the focus of the research. Such new configurations of the turbine as the following has achieved good results: the overlap rate of blade and blade shape, the helical angle in helical blade, the layout angle of blades and number of rotor layers, rotor combined with Savonius and Darrieus buckets and VAWT with a tower cowling structure.

At present, the most common experimental methods for analyzing the flow field of the S-type wind turbine are the particle imaging velocimetry, and the wind tunnel experiment. These methods have a good effect on the study performance of VAWT and shorten the study period and so on.
In this paper, wind tunnel experiment is used to study wind energy utilization and the law of variation of the VAWT with expandable airfoil. By comparing the maximum $C_p$ value of each wind turbine to obtain the optimal structural parameters of the new turbine.

2. Physical Model

When the rotor of Savonius turbine is working, the wind resistance in the leeward is very large, which leads to low performance of the turbine. In this paper a new turbine with expandable airfoil is studied. The blade of the turbine is a symmetrical split airfoil which can open and fold during rotating. The airfoil is open in windward which can effectively improve the driving torque. The airfoil is folded in leeward which can effectively reduce the resistance torque. And in folded state the airfoil can produce drive torque at certain rotating angle. So the wind energy utilization of new turbine can be greatly improved. When the open airfoil is facing the flow and the chord of folded airfoil is parallel to the flow in the state of starting, the leeward area is reduced and the starting torque is effectively improved. Considering the symmetry airfoil in the windward, it is reasonable to select the airfoil which can be divided into two symmetrical blades. Considering the airfoil thickness and rotational resistance, NACA0012 symmetrical straight airfoil is selected in this paper. The symmetrical part of the airfoil can rotate to open a certain angle around the axis in vertex of the airfoil. The structure of the airfoil is shown in figure 1.

The airfoil rotate around the main shaft to generate electricity, meanwhile it rotates around the airfoil axis to open and fold, one rotation cycle area is divided into 4 sections: the area in which airfoil is not fully open, the area in which airfoil is fully open, the area in which airfoil is not fully folded and the area in which airfoil is fully folded, as shown in figure 2, in which $\theta'$ is the maximum unilateral open angle of the airfoil, $\gamma$ is the revolution angle of the rotor corresponding to the self-rotation open angle of the airfoil, $\gamma'$ is the revolution angle of the rotor corresponding to the self-rotation folded angle of the airfoil. Such formula can be obtained while turbine rotates constantly in airfoil opening and folding:

\[
\frac{\gamma'}{\omega} = \frac{\theta' + \gamma'}{\omega_c} \quad (1)
\]

\[
\frac{\gamma}{\omega} = \frac{\theta' + \gamma}{\omega_o} \quad (2)
\]

Wherein $\omega_c$ is the angular velocity of rotation during airfoil folding (rad / s)
$\omega_o$ is the angular velocity of rotation during airfoil opening (rad / s)

Figure 1. The structure of the airfoil in new type wind turbine.

The “+” in formula 1 is the split part of airfoil near the point “O” in figure 2, the “-” is the split part of airfoil away from point “O”. The result of “+” and “-” in formula 2 is just the opposite from formula 1. In figure 2, $\mu$ is the angle of the symmetry axis of airfoil relative to the starting position when the airfoil symmetry axis is parallel to the Y axis and the intersection of the chord and the X axis is 1/4 of the chord length.
Considering that the new turbine is improved based on the S-type turbine, according to the principle of resistance-type turbine, the chord length of airfoil is close to the diameter of the revolution. From the analysis above, the main factors affecting the performance of the turbine with expandable airfoil are $\theta'$, $\gamma$, and $\gamma'$.

3. Experiment Model

In order to study the performance of the new turbine, a prototype and experimental system was developed. According to the structure of symmetrical split airfoil, the thickness of airfoil is thin. Taking the manufacturing cost and other factors into account, epoxy is used to manufacture the airfoil. Servomotor, electric cylinder and linkage mechanism are installed under the airfoil shaft to guide the self-rotation. The laser emitter and the magnetic gate sensor are used to collect the information of spindle angle, spindle speed and number of revolutions in the state of revolution. In contrast to the preset angle information in the ARM microprocessor, servomotor drive pulse signal is sent out respectively in the opening and folding starting position, and the servomotor drives the electric cylinder to open or fold the airfoil in the preset position when the wind turbine rotates. The control system used in the experiment is shown in figure 3.

The installation and the schematic of the model in the wind tunnel is shown in figure 4. The output of turbine is tested by three-phase AC-DC rectifier bridge circuit. Permanent magnet three-phase generator is used to output the electric power, whose rated power is 1000W, rated voltage is 77V and rated speed is 750rpm. The large test section of Wind Tunnel and Water Flume Lab of Harbin Institute of Technology is used in the experiment which can be obtained speed of wind in range from 0 to 50m/s. And the wind speed used in this experiment is ranged from 3m/s to 15m/s. The size of the large test section of the wind tunnel is 3m height and 4m wide. The model of the wind turbine is 1.77m high and 1.72m wide shown as in figure 4.

4. Results

The $C_p$-$\lambda$ curve results of wind tunnel experiment are shown from figure 5 to figure 10, in which the angle of $\theta'$ is 45°, 50°, 55° and 60°, $\gamma$ is 10°, 15°, 20° and 25°, and $\gamma'$ is 15°, 25°, 35° and 45°.

4.1. The Influence of $\theta'$ on the Performance of New Turbine

Figure 5 is the $C_p$-$\lambda$ curve of the turbine while $\gamma' = 15^\circ$. With different value of $\theta'$, the range of $C_{p_{\text{max}}}$ is 0.1328~0.1517 when $\gamma$=10°, the range of $C_{p_{\text{max}}}$ is 0.1299~0.1557 when $\gamma$=15°, the range of $C_{p_{\text{max}}}$ is 0.1559~0.1863 when $\gamma$=20° and the range of $C_{p_{\text{max}}}$ is 0.1381~0.161 when $\gamma$=25°. The tip speed ratio corresponding to $C_{p_{\text{max}}}$ range from 0.8679 to 0.9366 in the curves.

When $\gamma$ and $\gamma'$ are constant, the $C_{p_{\text{max}}}$ in each curve increases and then decreases with the increase of $\theta'$, and $\theta'$ is 55° corresponding to $C_{p_{\text{max}}}$. When the $\gamma'$ is constant, the $C_{p_{\text{max}}}$ increases and then decreases with the increase of $\gamma$ while $\theta'$ remains the same, and $\gamma$ is 20° corresponding to $C_{p_{\text{max}}}$.

Figure 6 is the $C_p$-$\lambda$ curve of the turbine while $\gamma$=20°. With different value of $\theta'$, the range of $C_{p_{\text{max}}}$ is 0.1559~0.1863 when $\gamma'=15^\circ$, the range of $C_{p_{\text{max}}}$ is 0.2006~0.2995 when $\gamma'=25^\circ$, the range of $C_{p_{\text{max}}}$ is 0.1737~0.2238 when $\gamma'=35^\circ$ and the range of $C_{p_{\text{max}}}$ is 0.1537~0.1704 when $\gamma'=45^\circ$. The tip speed ratio corresponding to $C_{p_{\text{max}}}$ range from 0.8679 to 0.9366 in the curves.
When $\gamma$ and $\gamma'$ are constant, the $CP_{\text{max}}$ in each curve increases and then decreases with the increase of $\theta'$, and $\theta'$ is 55° corresponding to $CP_{\text{max}}$ except figure 6 c). In figure 6 c) $\theta'$ is 50°. When the $\gamma$ is constant, the $CP_{\text{max}}$ in each curve increases and then decreases with the increase of $\gamma'$ while $\theta'$ remains the same, and $\gamma'$ is 25° corresponding to $CP_{\text{max}}$.

4.2. The Influence of $\gamma$ on the Performance of New Turbine

Figure 7 is the $CP-\lambda$ curve of the turbine while $\theta'=50°$. With different value of $\gamma$, the range of $CP_{\text{max}}$ is 0.1335~0.1712 when $\gamma'=15°$, the range of $CP_{\text{max}}$ is 0.2049~0.2683 when $\gamma'=25°$, the range of $CP_{\text{max}}$ is 0.1766~0.2238 when $\gamma'=35°$ and the range of $CP_{\text{max}}$ is 0.1213~0.1645 when $\gamma'=45°$. The tip speed ratio corresponding to $CP_{\text{max}}$ range from 0.8875 to 0.8877 in the curves.

When $\gamma'$ and $\theta'$ are constant, the $CP_{\text{max}}$ in each curve increases and then decreases with the increase of $\gamma$, and $\gamma$ is 20° corresponding to $CP_{\text{max}}$. When the $\theta'$ is constant, the $CP_{\text{max}}$ in each curve increases and then decreases with the increase of $\gamma'$ while $\gamma$ remains the same, and $\gamma'$ is 25° corresponding to $CP_{\text{max}}$, which is consistent with the analysis in figure 6.

Figure 8 is the $CP-\lambda$ curve of the turbine while $\gamma'=25°$. With different value of $\gamma$, the range of $CP_{\text{max}}$ is 0.16~0.1366 when $\theta'=45°$, the range of $CP_{\text{max}}$ is 0.2049~0.2683 when $\theta'=50°$, the range of $CP_{\text{max}}$ is
0.2329~0.2995 when $\theta' = 55^\circ$ and the range of $C_{P_{\text{max}}}$ is 0.1771~0.2006 when $\theta' = 65^\circ$. The tip speed ratio corresponding to $C_{P_{\text{max}}}$ range from 0.8679 to 0.9366 in the curves. When $\gamma'$ and $\theta'$ are constant, the $C_{P_{\text{max}}}$ in each curve increases and then decreases with the increase of $\gamma$, and $\gamma$ is 20° corresponding to $C_{P_{\text{max}}}$. When the $\gamma'$ is constant, the $C_{P_{\text{max}}}$ in each curve increases and then decreases with the increase of $\theta'$ while $\gamma$ remains the same, and $\theta'$ is 55° corresponding to $C_{P_{\text{max}}}$.

4.3. The Influence of $\gamma'$ on the Performance of New Turbine

Figure 9 is the $C_P$-$\lambda$ curve of the turbine while $\theta' = 40^\circ$. With different value of $\gamma'$, the range of $C_{P_{\text{max}}}$ is 0.1094~0.1846 when $\gamma' = 10^\circ$, the range of $C_{P_{\text{max}}}$ is 0.1244~0.16 when $\gamma' = 15^\circ$, the range of $C_{P_{\text{max}}}$ is 0.149~0.2366 when $\gamma' = 20^\circ$ and the range of $C_{P_{\text{max}}}$ is 0.1203~0.1819 when $\gamma' = 25^\circ$. The tip speed ratio corresponding to $C_{P_{\text{max}}}$ range from 0.8677 to 0.8679 in the curves.

When $\gamma$ and $\theta'$ are constant, the $C_{P_{\text{max}}}$ in each curve increases and then decreases with the increase of $\gamma'$, and $\gamma'$ is 25° corresponding to $C_{P_{\text{max}}}$. When the $\theta'$ is constant, the $C_{P_{\text{max}}}$ in each curve increases and then decreases with the increase of $\gamma$ while $\gamma'$ remains the same, and $\gamma$ is 20° corresponding to $C_{P_{\text{max}}}$, which is consistent with the analysis in figure 5.
Figure 10 is the $C_P$-$\lambda$ curve of the turbine while $\gamma=10^\circ$. With different value of $\gamma'$, the range of $C_{P_{\text{max}}}$ is 0.1094–0.1846 when $\theta'=45^\circ$, the range of $C_{P_{\text{max}}}$ is 0.1308–0.2117 when $\theta'=50^\circ$, the range of $C_{P_{\text{max}}}$ is 0.1211–0.2329 when $\theta'=55^\circ$ and the range of $C_{P_{\text{max}}}$ is 0.1107–0.1836 when $\theta'=65^\circ$. The tip speed ratio corresponding to $C_{P_{\text{max}}}$ range from 0.8679 to 0.9366 in the curves.

When $\gamma$ and $\theta'$ are constant, the $C_{P_{\text{max}}}$ in each curve increases and then decreases with the increase of $\gamma'$, and $\gamma'$ is 25° corresponding to $C_{P_{\text{max}}}$.

When the $\gamma$ is constant, the $C_{P_{\text{max}}}$ in each curve increases and then decreases with the increase of $\theta'$ while $\gamma'$ remains the same, and $\theta'$ is 55° corresponding to $C_{P_{\text{max}}}$, which is consistent with the analysis in figure 8.

The $C_{P_{\text{max}}}$ of wind turbine under different structural parameters is shown in Table 1.

| $\theta'$ (°) | $\gamma$ (°) | $\gamma'$ (°) | $C_{P_{\text{max}}}$ | $\theta'$ (°) | $\gamma$ (°) | $\gamma'$ (°) | $C_{P_{\text{max}}}$ | $\theta'$ (°) | $\gamma$ (°) | $\gamma'$ (°) | $C_{P_{\text{max}}}$ |
|--------------|--------------|--------------|---------------------|--------------|--------------|--------------|---------------------|--------------|--------------|--------------|---------------------|
| 45           | 10           | 15           | 0.1244              | 55           | 15           | 25           | 0.2409              | 45           | 25           | 35           | 0.1395              |
| 50           | 10           | 15           | 0.1335              | 65           | 15           | 25           | 0.1915              | 50           | 25           | 35           | 0.1766              |
| 55           | 10           | 15           | 0.1517              | 50           | 20           | 25           | 0.2366              | 55           | 25           | 35           | 0.161               |
| 65           | 10           | 15           | 0.1328              | 50           | 20           | 25           | 0.2683              | 65           | 25           | 35           | 0.1485              |
| 45           | 15           | 15           | 0.1299              | 50           | 20           | 25           | 0.2995              | 45           | 10           | 45           | 0.1094              |
| 50           | 15           | 15           | 0.1415              | 65           | 20           | 25           | 0.2006              | 50           | 10           | 45           | 0.1308              |
| 55           | 15           | 15           | 0.1557              | 45           | 25           | 25           | 0.1819              | 55           | 15           | 45           | 0.1211              |
| 65           | 15           | 15           | 0.1498              | 50           | 25           | 25           | 0.2225              | 65           | 10           | 45           | 0.1107              |
| 45           | 20           | 15           | 0.1559              | 55           | 25           | 25           | 0.2556              | 45           | 15           | 45           | 0.1244              |
| 50           | 20           | 15           | 0.1712              | 65           | 25           | 25           | 0.1771              | 50           | 15           | 45           | 0.1375              |
| 55           | 20           | 15           | 0.1863              | 45           | 10           | 35           | 0.1436              | 55           | 15           | 45           | 0.1437              |
| 65           | 20           | 15           | 0.1706              | 50           | 10           | 35           | 0.1766              | 65           | 15           | 45           | 0.1263              |
| 45           | 25           | 15           | 0.1381              | 55           | 10           | 35           | 0.1677              | 45           | 20           | 45           | 0.149               |
| 50           | 25           | 15           | 0.1415              | 65           | 10           | 35           | 0.1367              | 50           | 20           | 45           | 0.1645              |
| 55           | 25           | 15           | 0.161               | 45           | 15           | 35           | 0.1559              | 55           | 20           | 45           | 0.1704              |
| 65           | 25           | 15           | 0.155               | 50           | 15           | 35           | 0.1834              | 65           | 20           | 45           | 0.1537              |
| 45           | 10           | 25           | 0.1846              | 55           | 15           | 35           | 0.1877              | 45           | 25           | 45           | 0.1203              |
| 50           | 10           | 25           | 0.2117              | 65           | 15           | 35           | 0.1576              | 50           | 25           | 45           | 0.1213              |
| 55           | 10           | 25           | 0.2329              | 45           | 20           | 35           | 0.1737              | 55           | 25           | 45           | 0.1304              |
| 65           | 10           | 25           | 0.1836              | 50           | 20           | 35           | 0.2238              | 65           | 25           | 45           | 0.1172              |
| 45           | 15           | 25           | 0.16                 | 55           | 20           | 35           | 0.2036              | 45           | 20           | 45           | 0.1645              |
| 50           | 15           | 25           | 0.2049              | 65           | 20           | 35           | 0.1928              | 50           | 20           | 45           | 0.1645              |

5. Discussion

The $C_{P_{\text{max}}}$ of the new turbine is 29.95% (higher than Savonius turbine which is 15.1%) while $\theta'=55^\circ$, $\gamma=20^\circ$ and $\gamma'=25^\circ$. It means that the performance of the new turbine capturing wind power is better than the Savonius turbine. The tip speed ratio corresponding $C_{P_{\text{max}}}$ is 0.9056 (higher than the Savonius turbine which is 0.53). It means that the wind speed required by new turbine to achieve the best output conditions is higher than the Savonius turbine, and the new turbine is more suitable for used in areas with relatively barren wind resource.

By the data of the results, the angle of $\theta'$, $\gamma$ and $\gamma'$ can greatly influence the performance of the turbine. The angle of $\theta'$ should ensure that the windward side of the blade to be smooth curve, too large angle will flatten the blade, and too small angle will greatly reduce the sweep wind area.

The angle of $\gamma$ should be small to reduce the airfoil self-rotation effect on the turbine rotation. A small angle of $\gamma$ can make the airfoil into the working state as soon as possible in the windward region, but too small angle of $\gamma$ will shorten the opening process time which leads to impact on the turbine in rapid opening process.

The angle of $\gamma'$ should be small to make the airfoil to maintain a large open angle in the effective work area which can improve the energy conversion rate. In the second half of the airfoil folding process, the open angle is large and proportional to the wind resistance. But too small angle of $\gamma'$ will shorten the folding process time which leads to impact on the turbine in rapid folding process.
The reason of data error in experimental results can be concluded as follows: The linkage mechanism which guides the airfoil open and fold is arranged unilateral in the airfoil height direction, so that the airfoil has certain vibration during the opening and folding process, especially under the high speed rotating condition. The opening and folding of the airfoil will lead to great changes of the air flow resistance which decreases the stability of the rotation and increases the energy loss. The turbine spindle is similar to the cantilever beam structure. Instability of turbine rotating leads to certain vibration in rotating of spindle, which increases the energy loss.

6. Conclusion
In this paper, experimental VAWT with expandable airfoil prototype is developed. The aerodynamic performance of the turbine is tested by wind tunnel experiment. The results show that the $C_{p_{max}}$ of the turbine is 29.95% while $\theta'=55^\circ$, $\gamma=20^\circ$ and $\gamma'=25^\circ$. The tip speed ratio corresponding $C_{p_{max}}$ is 0.9056. According to the experimental results, the influence of parameters on the performance of turbine is analyzed, and the reason of data error is analyzed. The future research will be as follows:

Improve the mechanical structure of the wind turbine to reduce the vibration during the unfolding and folding of the airfoil, especially the vibration at high rotating speed.

Analysis the form of energy loss during the operation of the airfoil by numerical simulation of the wind turbine flow field, and improve the motion mode, the airfoil structure and motion parameters to reduce the energy loss during the operation in order to enhance the wind energy utilization.

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