Application of magnus effect and lift blade in high altitude wind power

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Abstract: A high-altitude wind power generation system scheme is proposed. The cylindrical airship is surrounded by the lifting blade of H-type vertical axis wind turbine. The blades are used to drive the airship to rotate. The airship rotating under the wind has a magnus effect, and the generated lift maintains the floating state of the airship. The paper establishes its 2D numerical simulation model. The turbulence scheme adopts SST $K-\omega$ and the $y+$ value is controlled between 5~10. The slip grid method is used to calculate the parameters when the model has a Compactness degree of 0.4, and the airship's lift-to-drag ratio is 7 and power coefficient is 13%, the corresponding tip speed ratio is 2.33. Then in this tip speed ratio, the working condition of the wind turbine at 3~24m/s wind speed is analyzed. It is found that the power coefficient increases slowly to 16% and the lift-to-drag ratio is between 4~7. Comparing the torque coefficient difference between the scheme and the H-type wind turbine, it is found that it performs negative work at most moments on the leeward side. The streamline diagram and pressure cloud diagram of the airship blades at different azimuth angles are analyzed, which explains the reason why the airship reduces the thrust and generates lift. It is concluded that the scheme has certain rationality.

1. Preface

High-altitude wind power faces many technical difficulties. The most critical problems are three points: 1. How to upgrade the wind turbine equipment[1]; 2. How to keep the wind power equipment floating in the windy range from the breeze to the strong wind[2]; 3. It is also the most critical One thing, if the fan equipment can maintain a stable attitude in the air, how to capture wind energy with maximum efficiency or maximum capacity[3].

Some people try to use the airship to pull the wind power equipment off, and use the buoyancy of the helium airship to make the power generation equipment floating for a long time[4], but the system has a small lift-to-drag ratio, and the lift height under the wind is limited, limited to the lower The lifting height is used to generate electricity. During the research of the system, it was found that as the rotational speed of the cylindrical airship increased, the lift-to-drag ratio gradually increased[5].
However, since the circumference of the airship is attached to the resistance type blade, the tip speed ratio is harder than 1 Large, thus limiting the speed of the cylindrical airship, but also its lift-to-drag ratio can not be further improved[6].

Therefore, it is further conceived that if the lift type blade is used as the driving blade of the wind turbine and the ratio of the chord to diameter is controlled reasonably, that is, the rotation speed of the "H" type fan is controlled, and the airship is fixedly coupled with the fan, the airship can also obtain a higher rotation speed, thereby An ideal lift-to-drag ratio can be obtained[7], which makes the airship greatly reduce its horizontal thrust in the windy range of breeze, strong wind and squally wind, and multiplies its lift. The remaining question is whether the combination of the hard-shell airship and the "H"-type fan can rotate? Is there a higher wind energy conversion factor? And how much energy does the airship's rotation consume from the fans? With such questions, the design and simulation of high-altitude wind power systems began.

2. Wind turbine design model and calculation model

The fan design has a lifting capacity of 30 Kg. That is to say, the helium capacity of airship should be more than 27 m³. The airship-shaped wind turbine model is shown in Figure 1. The wind turbine center is a huge cylindrical hard-shell airship 5, which is responsible for the whole set of high-altitude wind power equipment can be lifted off smoothly when there is no wind. The four-lift type blade 1 is distributed around the cylinder of the airship and is kept at a certain distance from the airship. The blade is fixedly connected to both end faces of the airship through the four connecting rods 2. In this way, the wind turbine blade can provide torque to drive the airship to rotate under the action of the wind, and the rotating airship can generate electricity and provide lift under the action of the wind, and drive the whole system to rise to a higher altitude.

The rotating airship transmits the kinetic energy to the driving large gears 8 through the transmission shaft 7, and transmits the kinetic energy to the driven pinion 9 and increases the speed. 9 is directly connected to the generator to drive the generator to generate electricity. Electrical energy is transmitted through the wires to the ground electrical equipment. The connection of the wind power system to the ground relies on a cable that is tied to the drawbar 6 and limits the five degrees of freedom of the airship.

![Figure 1. Airship wind turbine model](image)

The corresponding 2D calculation model is shown in Figure 2. The airship has a diameter of 3 m and the wind turbine blade NACA0012 has a rotation diameter of 4 m. The calculation was performed using the sliding grid method of the commercial software Fluent. The interface slip surface has a diameter of 5 m. The flow field calculation area is 160 m long and 64 m wide. The center of the impeller rotation is the origin, and the impeller is 15 m from the air inlet.
The boundary conditions set the inlet boundary as the velocity inlet, the outlet as the pressure outlet, the upper and lower walls as the symmetry wall, and the airfoil blades and the airship boundary as the wall. The slip zone includes blades that rotate with the airship around the center of the airship with a relative speed of zero. The interface between the sliding zone and the stationary zone is the interface boundary.

3. Geometric model meshing

3.1 Structured grid blocks and grid division

Establish a two-dimensional vertical axis fan flow field as shown in Figure 2.

![Figure 2. Wind turbine calculation model](image)

Figure 2. Wind turbine calculation model

The sliding mesh method is used for simulation. To ensure the mesh quality, the circular sliding area and the peripheral static area are manually divided into structured quadrilateral meshes. As shown in Figure 3(a), the block in the impeller region is divided by ICEM. The circle contains an overall O-grid block, and each wing is separately divided into O-grid blocks to ensure that each wing has sufficient mesh density without excessively affecting the overall mesh count. Figure 3(b) shows the specific meshing around the airfoil. The upper and lower surfaces of the airfoil are divided into 81 nodes, and the front and rear ends are divided into 31 nodes. Radially divided into 61 nodes, the thickness of the first layer is 0.5mm, and the growth ratio is 1.07, which ensures that the y+ value is between 5~10 and 960 nodes on the slip surface under the existing calculation parameters. The same static region also contains an O-grid block, which further enlarges the mesh size, and the maximum mesh size of the flow field is 0.2m.

3.2 Fluent solution settings

The solver uses Fluent to select a pressure-based solver, and the pressure and velocity coupling uses the SIMPLE algorithm. The pressure interpolation method is PRESTO!, the difference method of the kinetic energy, the density and the momentum is the second-order upwind style, and the turbulence model adopts the SST $K-\omega$. The unsteady slip grid method is used to solve the problem. In order to ensure that the sliding domain rotates less than 2° relative to the static domain at each time step, the
time step is selected to be 0.001 seconds, the residual control is less than $10^{-5}$, and the number of iteration steps is 60 steps.

4. CFD results analysis

4.1 Determination of the tip speed ratio

Because the model is based on the H-type vertical axis fan, the airbag for the equipment is added to the shaft part of the H-type vertical axis fan, so the related concept of the lift type fan is applied, and the solidity of the model $\sigma$ is:

$$\sigma = \frac{NC}{D} = \frac{4 \times 0.4}{4} = 0.4 \quad (1)$$

For the number of wind turbine blades is $N$, the blade chord length is $C$, the wind turbine diameter is $D$.

This value is greater than the recommended value of the vertical axis fan (less than 0.3), which is not conducive to the higher tip speed ratio (the tip speed ratio is generally between 3~4 when the power coefficient is large). This is because the blade and the airship are fixedly connected in the system, and the airship obtains a large output torque by means of the lift type blade, and the wind turbine is lifted and suspended at a high altitude by the rotating cylindrical airship, and the rotation of the airship will inevitably consume the output power of the blade, so it is not desirable to rotate the fan too fast, where the solidity is taken as 0.4, and the "best" tip speed ratio is determined below.

The wind speed was 6 m/s and the parameters at different rotate speeds were observed. The torque output is shown in Figure 4(a). It is shown that the torque value fluctuates greatly when the fan speed is low. This is because the NACA0012 blade has a large angle of attack at low speed and generates a large number of stall vortices. It causes the torque fluctuation of the whole wind turbine, and the lift value and the resistance value also change greatly [8]. When the rotational speed is increased, the angle of attack is reduced, the stall phenomenon is reduced, and the torque ripple is reduced. However, the wake of the previous blade affects the pressure difference between the two sides of the next blade, so although the torque ripple value becomes smaller, the output torque value also decreases.

Vertical axis wind turbine angle of attack $\alpha$ is:

$$\alpha = -\arctan \frac{\sin \theta}{\cos \theta + \lambda} \quad (2)$$

Where $\theta$ is the blade azimuth, which $\lambda$ is the tip speed ratio.

It is known from Figure 4(b) that as the fan speed increases, the horizontal thrust of the fan is gradually increased, which is undesirable, and the increase in horizontal thrust affects the lifting height of the airship. Therefore, the speed is too large, and the sharp speed ratio is too large to facilitate the airship to take off. And as the same speed increases, the thrust value fluctuates less.

It is known from Fig. 4(c) that under this special structure, the lift generated by the cylindrical airship has
Figure 4. Wind speed 6 m/s, parameters at different rotation speeds

(a maximum value. The reason for the magnus effect is that the two opposite directions of the airflow collide, resulting in a lift perpendicular to the direction of the airflow, and the magnitude of this lift is related to the ratio of the velocity of the two streams, a certain inflow wind speed corresponds to a certain cylindrical rotational linear speed to obtain the maximum lift value, so this maximum lift is actually related to the rotational speed of the cylindrical airship. The lift type work blade and the airship are integrated, so the position of the maximum lift is related to the blade tip speed ratio. It is known from the figure that the maximum lift value occurs when the tip speed ratio is 2.33.

Airship output power is:

\[ P = \omega T \]  

(3)

Where \( \omega \) is the angular velocity of the airship, which \( T \) is the output torque of the airship.

It is known from Figure 4(d) that the airship has reached a maximum value of 13.2% at a rotational speed of 7.8 rad/s. This value is much smaller than the 25~31% of the vertical axis fan power factor, which is only about half of its value. This is because the presence of the airship hinders the smooth passage of wind through the blades, causing a drop in power.

Introducing the concept of lift-to-drag ratio:

\[ \zeta = \frac{C_l}{C_d} \]  

(4)

Where \( C_l \) is the lift coefficient, which \( C_d \) is the drag coefficient. Dividing the vertical lift generated by the rotation of the entire airship by the horizontal thrust it receives, the lift-to-drag ratio is obtained, and the angle between the rope of the airship and the ground is:

\[ \alpha = \arctan \zeta \]  

(5)

Therefore, the lift-to-drag ratio directly determines the liftability of the airship and is a key parameter in the design of high-altitude wind power. At a speed of 7 rad/s, the lift-to-drag ratio is 7.5, which translates to an angle of 82.4° between the traction rope and the ground. These two values prove that the system can be lifted into high air to capture wind energy.

It is known from Fig. 4(e) that due to the viscosity of the air, the huge airship generates a lot of lift when it rotates, but it also consumes a certain amount of energy, and the consumed torque basically increases with the increase of the rotational speed. Therefore, the higher speed of the airship is uneconomical. Introducing the concept of rotational duty ratio:

\[ \xi = \frac{C_t}{C_m} \]  

(6)

In the formula, \( C_t \) is the drag torque coefficient when the airship rotates, \( C_m \) is the dynamic torque coefficient generated by the fan blades. It is known from Fig. 4(f) that as the speed of the airship rises, the airship's rotation-to-power ratio rises sharply. Therefore, it is necessary to control the tip speed ratio when the blade is working, and it cannot be too high.

The tip speed ratio of the blade is related to the chord-diameter ratio and the solidity, that is, the larger the chord length of the blade, the smaller the tip speed ratio when the maximum power occurs. At this time, we need to weigh the three parameters of maximum power, lift-to-drag ratio, and
rotational duty ratio. Although the output power coefficient is higher at 8 rad/s, the lift-to-drag ratio is less than the value at 7 rad/s, and the rotation-to-power ratio is 19%. The power loss is severe. Therefore, the tip speed ratio is 2.33 as the parameter used for further calculation. It can also be seen that the blade chord length can also be made longer, that is, when the solidity is greater than 0.4, the power coefficient and the lift-to-drag ratio can be simultaneously reached the maximum value, and the parameter optimization is achieved.

4.2 Analysis of parameters at fixed tip speed ratios at different wind speeds

After determining the optimal tip speed ratio, the simulation is further carried out to test the parameter changes at different wind speeds when the tip speed ratio is about 2.33, and the performance of the fan under the model is detected. The test results are shown in Figure 5.

Figure 5(a) shows the overall output torque coefficient of the fan. The torque coefficient shown in the figure is:

\[ C_m = \frac{T}{\frac{1}{2} \rho A V^2 R} \]  

(7)

Where \( \rho \) is the air density, \( A \) is the blade swept area, \( V \) is the inflow wind speed, and the blade rotation radius is \( R \).

In theory, the value \( C_m \) should be less than 1, but in the software fluent, the default value of Reference Values \( A, V, R \) is 1, so the measured value is greater than 1. It is shown that when the wind speed is less than 6m/s, the torque output of the airship is small, and when the wind speed is greater than 6m/s, the output torque of the airship is increasing rapidly. In fact, high-altitude wind power is valued by the abundant wind energy stored in the high air. The larger the lifting height is, the more favorable it is to capture the wind energy. Therefore, the output torque of strong wind and squally level is tested. It can also be seen from Figure 5(a) that the torque coefficient value fluctuates more as the wind increases, and this torque value is the result of the superposition of the power torque of the four blades and the airship resistance torque. It is generally stable and there is no torque value in the opposite direction.

Figure 5(b) is a graph showing the change in power coefficient, the value of which is:

\[ C_p = \frac{\omega T}{\frac{1}{2} \rho A V^3} = \frac{\omega C_l}{A V^3} = \frac{\omega C_m}{DV^3} \] 

(8)

Where \( l \) is the length of the airship, which \( D \) is the rotation diameter of the blade. It can be seen from the figure that when the wind speed is changed from 3 to 10 m/s, the power factor is gradually increased from 10% to 15%. After this, in the range of wind speeds of 10 to 24 m/s, the power factor value varies up to 15%. This value has a significant advantage over the 8% power coefficient value of the resistance fan[9], which also proves that the lift fan is more suitable for operation at high wind speeds.

Figure 5 (c), (d) are the thrust and lift values received by the airship when it rotates. It is known that both of them increase rapidly with the increase of wind force, However, it is clear that the lift value rises faster, the value is larger, and the numerical fluctuations are relatively smaller and smoother. 5(e) For the ratio of the vertical lift to the horizontal thrust of the airship, the airship can maintain a lift-to-drag ratio of 7.5 even in the case of a breeze with a wind speed of 5 m/s, it created good conditions for the smooth lifting of the airship on the ground. As the wind speed increases, the lift-to-drag ratio tends to decrease overall, but it can still maintain a lift-to-drag ratio of about 5 in the wind speed of the wind. This means that the fan can rise to a very high altitude, forming a vertically aligned mesh wind farm that captures wind energy over a large area. 5(f) is the ratio of the power consumed by the rotation of the airship to the output power of the blade, that is, the rotation-to-power ratio. It is known from the figure that the value generally shows a downward trend and then stabilizes at around 9%.
The tip speed ratio is about 2.33, and the airship parameters at different wind speeds are compared with the "H" vertical axis turbine. The fan model was converted from an "H" vertical axis fan, and the slim shaft of the "H" vertical axis fan was replaced by a huge airship. Because the existence of the cylindrical airship hinders the smooth passage of the wind through the fan blade, the lift of the fan blade is reduced, and the pressure difference of the fan blade is reduced, which inevitably reduces the work efficiency of the fan. A brief comparison of the work of the two is now made.

On the basis of the original model, the airship wall and internal circle were converted into internal flow field, and the working condition of the wind speed of 6 m/s and the speed of 7 rad/s was tested. When the impeller was rotated 8 times, the flow field was fully developed and the torque was obtained. The torque coefficient diagram is shown in Figure 6(a), and Figure 6(b) is the output torque coefficient diagram under the same parameters of the airship.

![Figure 6](image_url)

Figure 6. Torque coefficient output waveform when the wind speed is 6 m/s and the rotating speed is 7 rad/s

It can be seen from Figure 6 that although the period of the two torque waveforms is the same, the torque coefficient of the "H" type fan is much larger than the output torque of the airship. The reason is two: 1. The work efficiency of the fan blade becomes low; 2. The rotation of the airship consumes a
portion of the torque. This makes the power coefficient of the "H" type fan up to 26~31%, and the airship's work efficiency is only about half of it.

The single blade torque coefficient of a fan with and without an airship is shown in Figure 7. It is known from the figure that both are doing positive work on the windward side, that is, in the range of 90° to 270°, and doing negative work on the downwind side, that is, in the range of 0° to 90° and 270° to 360°. The torque reaches a maximum near the 180° angle, the blades are parallel to the wind at 90° and 270°, and the torque output is zero, but the above values are delayed due to the action of the previous blade wake[10]. It can be seen from Figure 7 that the output torque values of the model at each azimuth angle are substantially smaller than the case where no airship hinders the wind flow, And the "H" type fan does positive work at most angles[11], and the model is mostly doing negative work on the leeward side.

Figure 7. shows the single blade torque coefficient of an airship and no airship.

6. Airship fan streamline diagram analysis
Further investigate the velocity streamlines when the blades are in different orientations. Take the clockwise direction as the positive direction of the azimuth. As shown in Figure 8, at an azimuth of 45°, the blade is mainly driven by the rotating wind direction of the airship. At this time, the wind speed is blocked by the airship, the resistance torque of the blade is greater than the lift torque generated by the blade, and the blade performs negative work. At 135° azimuth, the blade is in the upwind zone and is in a headwind, with a relatively high wind speed and a small angle of attack. The blade produces a large lift, is in the work state and the torque is in the ascending state, and the generated torque gradually becomes larger and reaches a peak before 180°. However, the angle of attack gradually became larger and then stalled. At 225° azimuth, the blade is still in the upwind zone, and different pressures appear on the upper and lower sides of the blade, generating torque, but the torque value is gradually decreasing. At 315° azimuth, the blade is in the downwind zone, and the direction of the incoming air is approximately the same as the direction of the airflow driven by the airship. At this time, the blade performs negative work.

Figure 8. Pressure cloud diagram and velocity streamline diagram of the blade at different azimuth angles
It is known from Figure 9 that when the wind blows over the airship, the rotated cylindrical airship divides the airflow into two parts, and most of the airflow bypasses the upper part of the airship due to the adhesion to the airship, and rotates with the cylinder. The airflow passes through the lower part of the airship, below the airship, the two airflows meet, creating a vortex and creating a large pressure. The upper part of the airship also generates certain suction due to the high speed of air flow. The pressure difference between the upper and lower parts of the airship causes the airship to produce a larger lift. At the same time, the rotating airship directs the airflow on the windward side to the leeward side, so that the pressure difference between the front and rear sides of the airship is greatly reduced, the horizontal thrust value is reduced, and the airship has a high lift-to-drag ratio.

![Pressure cloud map and streamline diagram around the airship](image)

It can also be seen from the streamline diagram that as the airship shell rotates under the blade, the air in a certain range around the airship is also driven to rotate, thereby generating the magnus effect, which makes the airship produce a great lift, while the horizontal thrust is greatly reduced. And at the same time, the airship can remain floating under different wind blows, which is the advantage of this design.

7. Conclusion
The number of nodes of the airfoil blade and the sliding interface is increased later. The operating parameters of the thin blade, the thick blade and the curved blade are compared and analyzed. Although the variation characteristics of the parameters are different, the overall parameters are roughly the same as the variation trend, which is:

1. The airship guides the wind due to the rotary motion, deflecting the wind direction to the upper end of the airship, and greatly reducing the horizontal thrust it receives.

2. The rotation of the airship drives the surrounding airflow to rotate, and superimposes with the incoming wind speed, so that the wind speed at the upper end of the airship is multiplied and the wind speed at the lower end is reduced and a vortex is generated, thus generating a lift-to-drag ratio of 4~7, so that the airship can remain buoyant under the wind force.

3. Due to the presence of the airship, the power coefficient is greatly reduced compared to the H-type vertical axis wind turbine, which can only be maintained between 12%~16%. However, as a scheme to maintain the floating state under the wind, this design has certain rationality.

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