The comparison of power capability between towed kite and horizontal axis fan

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Abstract: Airborne Wind Energy (AWE) mainly collects wind energy by tethered aircraft at a certain altitude. This paper discusses the recent development of AWE. The actuator disc theory is adopted to consider the influence of kites on wind flow obstruction. The difference of working mode between a horizontal-axis wind turbine (HAWT) and a crosswind kite power systems (CKPS) is compared, the power limit of HAWT and CKPS is calculated, and the reason of the limit power is analyzed. It is pointed out that CKPS has a wider range of flight and should be further analyzed and calculated rather than simply generalized by the system disk theory.

1. the introduction
Airborne Wind Energy (AWE), abundant in the high sky, has been attracting people's attention. [1] As early as 1826, The British George Pocock published the art of Flying in the Air or sailing with Kites or Floating sails, which introduced how to use kites to drag wagons on the ground and lift people into the air. The kite uses a double tether structure to control the kite's crosswind Angle and thus generate lateral traction, similar to the crosswind of a sailboat. But the design was never commercialized because the amount of traction could not be controlled and the brakes were imperfect. In modern times, people have made full research on the rotating horizontal axis fan, so that it has a high power efficiency. At present, most of the wind energy acquisition equipment use horizontal axis fan.

However, with the development of high altitude wind power generation, a new device adapted to high altitude wind energy collection is urgently needed. Makani Power, the representative of high-altitude wind Power generation, has the strongest economic and technological strength. It uses a combination of horizontal axis fans and unmanned aerial vehicles, and flies around the figure“8”in the air with teropes to collect wind energy. In 2020, Google abandoned the seven-year Makani kite power project, saying it would be too difficult to commercialize. China's Zhonglu Joint-stock Company uses wind-powered circular parachutes to generate power, but the project has also been suspended due to funding problems.

Buoyant Airborne Turbine (BAT), invented by Altaeros Energies of MIT, is a combination of fan and turbine-shaped airships that cost up to $1.4 million to make. The comprehensive requirements of the weather resistance layer, helium resistance layer and strength layer of the airship skin make the airship expensive. Compared with the huge shape, the horizontal axis fan hanging by tether in the hollow interior of the airship is relatively small and has limited power capacity. Similarly, The Magenn Air Rotor System (MARS) developed by Magenn Power of Canada uses capsule-shaped airships to fly up. Flexible resistance fan blades are set outside the airships to do work. However, the power coefficient of the resistance type fan is only 3%~5%, and due to the limitation of the wind resistance performance and volume of the aerostat itself, the power generation is also difficult to
improve, so it can only be used in the temporary and rapid construction of wind power system in the field.

The Dutch company Kite Power, Italy's Kite Gen and Germany's Sky Sails Power are using Parafoil, or soft kites, to collect wind energy. Ampyx Power, a Dutch company that produces high-altitude wind Power, and Twingtec, a Swiss technology company, use drones, or rigid kites, to collect wind energy. What are the working mechanisms and energy conversion properties of these kites? How is the efficiency compared with the traditional horizontal axis fan? Is the goal of this paper to explore.

2. Establishment of computational model

The concept of "kite power generation" was first proposed by American scientist Miles L. Loyd in 1980[2], which means that the kite flies in the air, drags the tether, and makes the ground generator generate electricity through the traction effect of the tether. Specifically, when the kite surface is perpendicular to the airflow, the tether pull pulls the winch on the ground to generate power. When the kite is parallel to the current, the tether pull pulls down and the winch reverses to pull the kite back, so the kite does repeated work to generate electricity.

See Fig. 1. The section of the traction kite is made into a wing shape, with a certain lift force and a good lift-to-drag ratio, under the action of the wind traction rope to do work. Parafoil can be considered as a crosswind kite Power System (CKPS) that captures wind power by intercepting a section of horizontal axis wind turbine (HAWT). CKPS and HAWT are parallel to each other, which has analogicity. Since the work done by the horizontal axis fan mainly depends on the outer edge of the blade with large linear velocity, the work done by 1/3 of the outer edge of the blade accounts for more than half of the work done by the whole fan[3], so the way of work done by the parafoil is reasonable. The parafoil flying around the "O" type is similar to the movement of the fan, so the analysis of the parafoil can borrow the theoretical analysis of the horizontal axis fan, but the movement of the parafoil needs to be considered at the same time. Wing umbrella movement and the work way as shown in Fig. 2. The wing surface of the parafoil is approximately perpendicular to the wind speed of the incoming flow and rotates along the tangent direction with the speed of $V'$, with the speed of $V'$ and the $V'$ overlay, increase the actual effect in the wing of the relative wind, on the umbrella and generates additional lift, the lift force greater than the wind speed $V'$ of thrust, the fan speed $V_d$ of towing rope work.

The flow model of the horizontal axis fan can be simplified into a flow tube, as shown in Fig. 3, and the wind wheel can be simplified into a flat propeller disc, namely the Actuator disc [4]. The difference is that the whole model can move horizontally with $V_d$ speed under wind. $V'$ is the wind
speed at a certain distance from the upstream, \( V \) is the actual wind speed when passing through the impeller, and \( V_2 \) is the wind speed far downstream from the impeller. Assume that the upstream section of the flow through the impeller is \( A_1 \), the downstream section is \( A_2 \), and the impeller section is \( A \). According to theory [5], the rotor is represented by a permeable disk on which the load is evenly distributed. The kinetic energy used by the rotor to extract from the flow. Firstly, consider the situation when the fan is not shifted, and the flow continuity equation is as follows:

\[ A_1 V_1 = A V = A_2 V_2 \]  

(1)

According to the momentum theorem, the axial thrust of wind on the impeller is:

\[ F = \rho A V (V_1 - V_2) \]  

(2)

Where \( \rho \) is the density of air. The power of work done by the wind energy on the impeller, or the power absorbed by the wind wheel, is:

\[ P = F V = \rho A V^2 (V_1 - V_2) \]  

(3)

From the perspective of energy transformation, the change of kinetic energy of airflow before and after the wind wheel is:

\[ \Delta E = \frac{1}{2} \rho A (V_1^2 - V_2^2) \]  

(4)

Since the output power is transformed by kinetic energy, according to the energy conservation theorem: \( P = \Delta E \), So you get:

\[ V = (V_1 + V_2)/2 \]  

(5)

That is, the wind speed \( V \) acting on the wind wheel is the arithmetic average of upstream wind speed \( V_1 \) and downstream wind speed \( V_2 \). The dimensionless number is introduced to measure the rotating power capacity of the wind wheel, and the axial interference coefficient \( a \) is defined as the difference and ratio between the upstream wind speed \( V_1 \) and the ideal wind speed \( V \) on the plane of the wind wheel, i.e. \( a = (V_1 - V)/V_1 \), then:

\[ V = V_1 (1-a) \]  

(6)

\( a \) is an index to measure the ability of the Actuator disc to slow down the wind speed, and it is also used to measure the efficiency of the wind wheel to obtain energy from the airflow. Replace (6) with (5):

\[ V_2 = V_1 (1-2a) \]  

(7)

Therefore, by substituting (5) into (2) and (3) respectively, the axial force and power acting on the impeller can be written as

\[ F = \frac{1}{2} \rho A (V_1^2 - V_2^2) \]  

(8)

\[ P = \frac{1}{4} \rho A (V_1^2 - V_2^2)(V_1 + V_2) \]  

(9)
Substitute (7) into (8) and (9) respectively, get
\[ F = \frac{1}{2} \rho A V_i^2 \cdot 4a(1-a) \] (10)
\[ P = \frac{1}{2} \rho A V_i^3 \cdot 4a(1-a)^2 \] (11)

3. Consider the calculation model after fan movement
Equation (11) is the power expression of HAWT. Considering that the fan moves horizontally with the speed \( V_d \), the dimensionless number is introduced to measure the overall translation power capacity of the wind wheel, and the axial translation coefficient is defined as the ratio between the backward movement speed of the parafoil and the actual wind speed : \( e = V_d / V_i \), is
\[ V_i = V_i e \] (12)

Before the parafoil moves back, \( V = V_i (1-a) \). Due to the backward movement of the parafoil with the wind, the actual wind speed of the parafoil changes from \( V \) to \( V - V_d \), and the acting speed of the upstream wind speed \( V_i \) relative to the parafoil moving with the speed \( V_d \) becomes \( V_i - V_d \), so equation (6) becomes
\[ V - V_d = (V_i - V_d) (1-a) \] (13)

Substitute (12) into (13), get
\[ V = V_i [1-a(1-e)] \] (14)

Similarly, Equation (7) can be changed into
\[ V_i - V_d = (V_i - V_d) (1-2a) \] (15)

Substitute (12) into (15), get
\[ V_i = V_i [1-2a(1-e)] \] (16)

Due to the backward movement of the parafoil with the wind, the velocity \( V_i \) becomes \( V_i - V_d \), which is substituted into (10). The net force acting on the parafoil is
\[ F = \frac{1}{2} \rho A V_i^2 \cdot 4a(1-a)(1-e)^2 \] (17)

Because the power is caused by the movement of the parafoil around the "O" shape, that is, the parafoil is relatively stationary horizontally and blocking the wind from passing through, it is called resistance type work, which is distinguished by adding "D" to the subscript, and the power can be rewritten as
\[ P_d = F(V - V_d) \] (18)

Substitute (12) and (13) into (18), and the resistance type power is
\[ P_d = \frac{1}{2} \rho A V_i^3 \cdot 4a(1-a)^2(1-e)^3 \] (19)

\( P_d \) is the power obtained by fan rotation, and the corresponding resistance power coefficient is
\[ C_{RD} = \frac{P_d}{\frac{1}{2} \rho A V_i^3} = 4a(1-a)^2(1-e)^3 \] (20)

Draw the resistance type power coefficient as shown in Figure 4, which is proportional to the cube of \((1-e)\), and will decrease rapidly with the \( V_d \) increase. Therefore, \( C_{RD} \) is only suitable for good performance when there is no translational movement. In fact, basically all horizontal axis fans are fixed on the ground and stationary. When \( e=0 \), that is, when there is no translational movement of the fan, \( C_{RD} = a(1-a)^2 \), take the derivative of that and set it equal to zero.
\[ C_{RD} = (1-4a+3a) = 0 \] Can be solved \( a = 1/3 \)
At this time, it has the largest power coefficient whose value is $C_{P_D} = 16/27 \approx 0.593$, which is exactly the Betz-Joukowsky limit of the horizontal axis fan. That is to say, the horizontal axis fan adopts this kind of output torque form of work, and has a high power conversion coefficient, making it the most widely used wind energy conversion method. It is equivalent to dragging the drag along a circular trajectory to do work when the parafoil is flying around the "O" shape. At this time, the speed at the wind wheel is $V = V_1(1-a) = 2/3$, and the speed $V_2 = V_1(1-2a) = 1/3$ at the leeward side. That is, when the wind turbine outputs the maximum power, the wind speed passing through the wind wheel is $2/3V_1$, and the wind speed downstream is $1/3V_1$. The limit value of wind energy output shows that the energy that a wind turbine can extract from natural wind is limited, and part of its power loss can be explained as the rotational kinetic energy left in the wake.

And the power caused by the horizontal movement of the parafoil at speed $V_d$ is

$$P_d = FV_d$$

Substituting (12) and (17) into equation (21), the lift-type power is

$$P_L = \frac{1}{2} \rho AV_1^3 \cdot 4a(1-a)(1-e)^2 e$$

The corresponding lift coefficient is

$$C_{PL} = \frac{P_L}{\frac{1}{2} \rho AV_1^3} = 4a(1-a)(1-e)^2 e$$

Since the direction of motion is approximately the same as the direction of lift, the traction work is mainly caused by the lift of the parafoil to move upwards obliquely, so the subscript adds "L" to distinguish it, and the lift-type power coefficient is drawn as shown in Figure 5.

When $a = 1/2$, $4a(1-a)$ the maximum value is 1; when $e = 1/3$, and $(1-e)^2 e$ the maximum value is $4/27$. If $a$ and $e$ do not affect each other, the maximum value of the lift-type power coefficient is $C_{PL} = 4/27$. At this time, the parafoil moving speed is $V = V_1(1-a) = 1/2V'_1$, and the wind speed on the downwind side is $V_2 = V_1(1-2a) = 0$, a limit value and cannot be reached. $4a(1-a)$ means that the wind energy contained in the actuator disc, $4a(1-a)$ is the wind energy extracted when the parafoil moves and does work [6].

4. Analysis of calculation results

Compare the limit values of the two forms of work. $C_{P_D}, C_{PL}$ and the wind energy in Betz’s theory is
shown in Figure 6, the power coefficient of the horizontal-axis fan is always 4 times the power coefficient of the towed kite in the most ideal situation. This situation occurs when the horizontal-axis fan is stationary and the flying kite is blocked when flying on a circular orbit. In the case of half of the wind, the overall function of the parafoil seems to be poor. However, the CKPS parafoil only simulates a small part of the HAWT system wing tip, not the entire blade, and the trajectory of the flight sweep is only a ring, not the entire circle, and the blocking effect on the incoming wind speed is very limited [7]. Therefore, it is biased to use the Actuator disc theory to find its limit. For example, in order to pursue high wind energy conversion efficiency, the parafoil should be reduced in area, and the swept annular area should be enlarged to contact the wind that has not slowed down the speed, and also reduce the interference effect of its own wake on itself, but in fact, the wind energy conversion coefficient at that time is not high, on the contrary, the wind energy conversion efficiency at this time is only a few percentage points. In order to capture more wind energy, the parafoil should be made larger [8]. Therefore, a more accurate calculation should consider the parafoil area and lift-to-drag ratio, but such calculations cannot be compared with HAWT.

![Fig. 6. Comparison of the limit values of three-dimensional graphs the two power coefficients](image1)

![Fig. 7. Ct](image2)

Fig. 6 is a three-dimensional comparison of the two power coefficients. Which can be seen from the figure, the power coefficient of the lift type depends on the movement of the fan, while the work of the resistance type fan depends on the movement of the fan and depends on the blades to rotate and drag to do work. Overall, the resistance-type work method is much better than the lift-type work method [9]. But the parafoil does not require fixed basic equipment, can sweep a larger area of space, and can rise to higher heights, where the wind is stronger and the wind energy is greater. At the same time, the parafoil itself is lighter than the wind turbine blades, and only requires a lightweight tether (for example, made of ultra-high molecular weight polyethylene). These characteristics make CKPS very attractive in terms of low-cost energy production [10]. Therefore, this form of work is necessary for in-depth research.

In the case of a kite flying with cut wind, in fact, the functional power of a towed kite depends heavily on its aerodynamic performance, such as lift-to-drag ratio, tip speed ratio, solidity, etc. This requires further research in the future.

The total power is the sum of resistance power and lift power, namely

\[ P_{tot} = FV = P_D + P_L = F(V - V_2) + FV_2 \]

(24)

Substituting (13) into equation (24), we have

\[ P_{tot} = FV_1[1 - a(1 - e)] \]

(25)
Substituting (17) into equation (25), we have

\[ P_{tot} = FV = \frac{1}{2} \rho AV_0^3 \cdot 4a(1-a)(1-e)^2 [1-a(1-e)] \]  

(26)

This is the situation when the kite spirals and outputs power in two forms of work at the same time. Obviously, the power after superposition is still mainly resistance type, and the total power has not been substantially improved.

5. Conclusion

The reason why the kite needs to fly at high speed is that it relies on the high lift-to-drag ratio of the kite to produce a high relative wind speed on the kite. Relying on the high-speed flight of the kite, the thrust can be increased in drag mode (if it is a fan blade, the torque can be increased); in lift mode, the lift can be increased to improve the efficiency of towing work, that is, the efficiency of work. This phenomenon can also be called an aerodynamic transmission device, which objectively increases the driving force of the aerodynamic system. At the same time, a flying kite can extract wind energy in a large area on a closed path in the sky to generate electricity. This paper considers the flow-blocking effect of the kite, extends the HAWT brake disc analysis model, and obtains the power limit consistent with Loyd, which proves the feasibility of the classical flow tube analysis of CKPS.

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