Innovative UAVs with Configuration of Liking Both Plane and Kite for Wind Power

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Abstract

The UAV(Unmanned Aerial Vehicle) has a novel configuration of liking both plane and kite for wind power. The fresh wind power UAV comprises two main components of the Kite-plane Integrated Configuration UAV and the Sky-Ground collaborative wind power generation control system, targeting the goal of achieving a 2-kilowatt Airborne Wind Power generation.

Keywords: Innovative UAVs, Plane , Kite , Wind Power

1. Introduction

Recently, with the continuous rise in global energy prices and the cost of carbon emission permits under carbon trading systems, the cost of fossil fuel-based power generation is becoming increasingly expensive. Wind power, as a clean and renewable energy source with vast potential, surpasses the total exploitable hydropower resources on Earth by a factor of ten. Wind power generation does not face fuel-related issues, and its costs are expected to decrease with the expansion of economic scale, without causing radiation or air pollution. However, traditional tower-type wind power generation systems exhibit inherent drawbacks such as being " large size and high cost", being "significantly affected by geographical and seasonal factors" and facing challenges in "grid connection and inconvenient applications". On the other hand, solely kite-based wind power generation systems[1] face limitations including "large-scale systems and high costs", "impacts on civil aviation and restrictions", as well as "fixed facilities and inconvenient assembly and disassembly".

In order to address the aforementioned challenges, a novel concept of Kite-plane Integrated Configuration for airborne wind power Unmanned Aerial Vehicles and systems is proposed herein. This system is anticipated to offer an abundant supply of electricity for populations in regions where providing sufficient power is either impractical or inconvenient, such as residents in deserts, grasslands, plateaus, and mountainous areas, among others. Furthermore, it offers an inexhaustible and renewable energy solution for countries and regions worldwide facing severe electricity shortages.

2. The Novel Wind Power UAVs Concept

2.1 Prototype System

The The standardized "Kite-plane Integrated Configuration Airborne Wind power UAV and System" comprises two main components: the "Kite-plane Integrated Configuration UAV" and the "Sky-Ground Collaborative Wind Power Generation Control System".

The first part, the " Kite-plane Integrated Configuration UAV" consists of four main components[2]: the fuselage component, wing component, tail component, and motor device component. The fuselage component further includes three parts: the front cabin, main fuselage, and rear fuselage. The wing component comprises two symmetrically positioned parts: the inner wing and outer wing. The tail component consists of both a horizontal tail and a vertical tail. The motor device component includes a motor component located in the front cabin, responsible for providing flight pulling force, and two generator components installed symmetrically on the underside of the outer ends of the inner wings on the left and right sides, dedicated to airborne wind power generation.

A novel Wind Power UAV is illustrated in Fig.1.

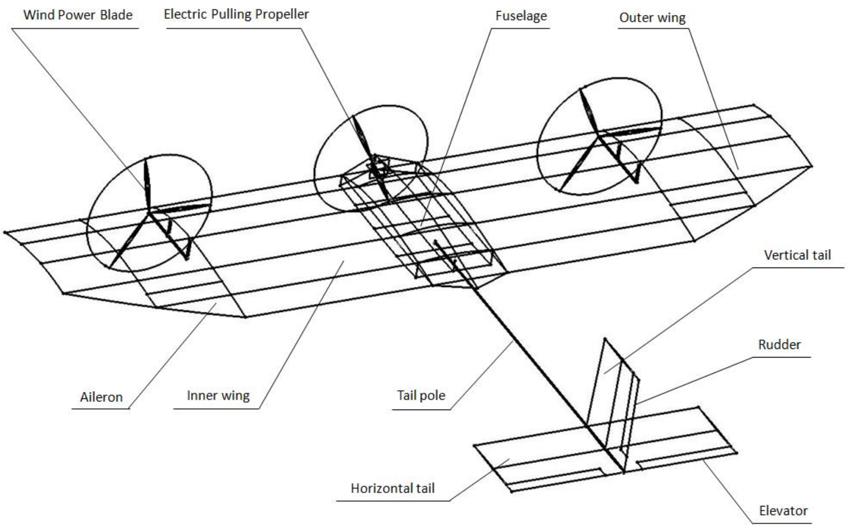


Figure 1 – The drawing of a standardized wind power uav

The second part, the "Sky-Ground Collaborative Wind Power Generation Control System" (shown in Fig.2) comprises the following components: A "tether/transmission" cable fixed at one end to the midsection of the UAV's main fuselage, with the other end connected to a "retractable cable drum" mechanism. A ground-mounted "retractable cable drum" mechanism designed to dynamically control the length of the "tether/transmission" cable between the UAV and ground facilities in real-time. A ground-based "electric power comprehensive processing and storage" facilities[3] designed to convert the electrical energy generated by the airborne UAV's wind power generator component into chemical energy. This energy is transmitted to the ground through the "tether/transmission" cable and stored in dedicated battery units for user consumption. An "Sky-Ground Collaborative Control System" responsible for receiving status information transmitted from the airborne UAV to the ground. It controls the UAV's transition between "aircraft flight" and "kite hovering" modes, as well as the initiation and suppression of airborne wind power generation.

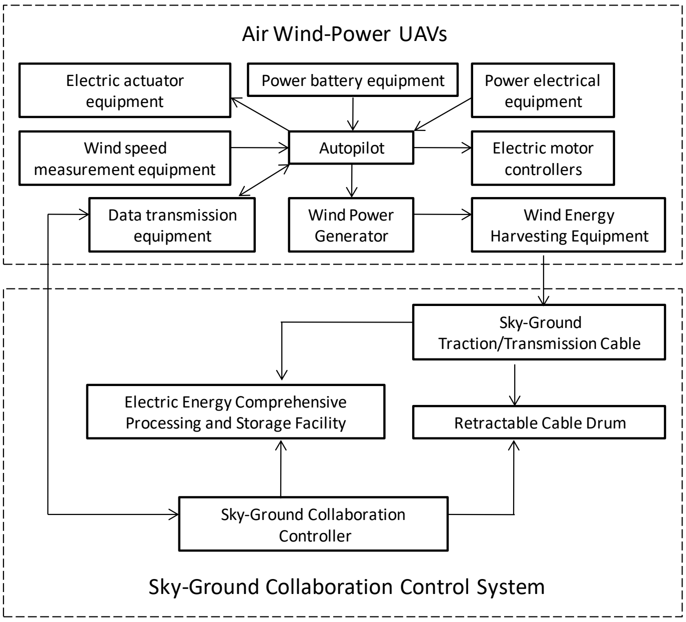


Figure 2 – The flow chart of a wind power uav sky-ground cooperative control system operation

2.2 Product System

2.2.1 Wind Power Target

The airborne wind power generation capability objectives for a Typical Kite-plane Integrated Configuration Airborne Wind power UAV and System are as follows:

- Wind power is 2 kW
- Wind power height is 100m and wind speed is 20m/s
- Maximum distance for air-to-ground transmission of airborne wind power is 300m

2.2.2 UAV Parameter

The specifications for a typical "Kite-plane Integrated Configuration Airborne Wind power UAV and System" are as follows:

- Wing Area is 4 square meters
- Wing Span is 6 meters
- Aspect Ratio is 9
- Total Platform Weight is 80 kilograms
- Motor Weight is 35 kilograms
- Structural Weight is 25 kilograms
- Tether Weight is 15 kilograms
- Equipment Weight is 5 kilograms

2.2.3 Kite-Plane Integrated UAV Configuration

The specifications for a typical "Kite-plane Integrated Configuration Airborne Wind power UAV and System" are as follows:

A basic "Kite-plane Integrated Configuration UAV" design[4], with the following main features:

✧ Blended Configuration

The wings are composed of two straight segments with a low aspect ratio (3-5). Each single wing (left or right) includes an inner wing section and an outer wing section (shown in Fig.3). The inner wing section has a rectangular planform with a low aspect ratio (1-5) and features a large camber (10-25%) and ultra-thin (1-5%) laminar airfoil cross-section. The outer wing section has a trapezoidal planform with a low aspect ratio (1-5) and a low taper ratio (1-3), with a cross-section featuring large camber (10-20%) and ultra-thin (1-5%) laminar airfoil. The wing profile is a "shell" shape with large camber and ultra-thin thickness, forming a blended configuration that integrates the plane and the kite. This design provides the main aerodynamic lift necessary for forward flight in "airplane mode" and the main aerodynamic drag required for hovering in "kite mode".

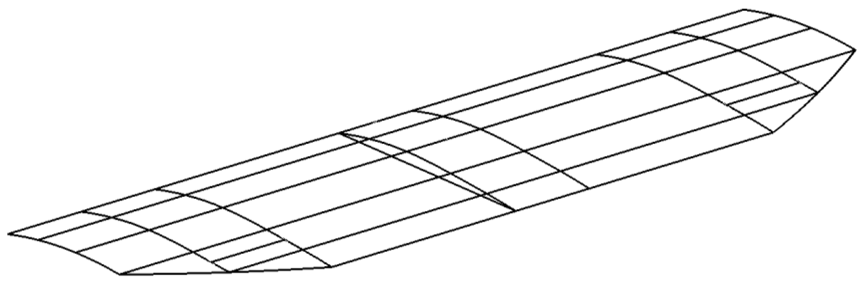


Figure 3 –The wing diagram of a blended kite-plane

✧ Aircraft Characteristics

The UAV achieves "flight mode" at a low angle of attack (2-5 degrees): The UAV utilizes its forward flight speed to generate "maximum possible lift and minimum possible drag" on its wings, while its electric propeller provides thrust. This enables the UAV to take off from the ground, climb to a certain altitude range, transition from the unpowered kite "hovering mode" back to the powered aircraft "flight mode," and descend and land.

In "flight mode," the main forces acting on the UAV's wings are as shown in Fig.4:

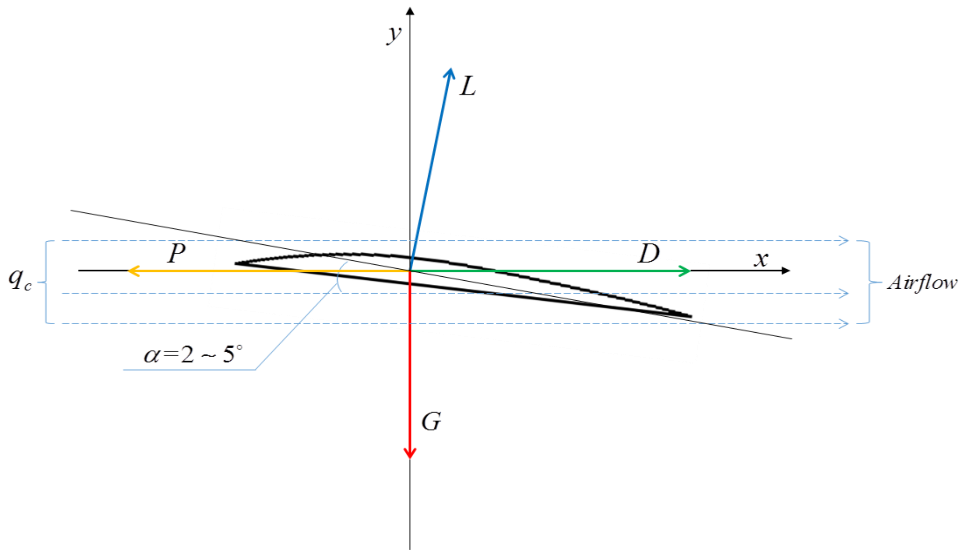


Figure 4 – The wing force diagram in "flight mode"

✧ Kite Characteristics

The UAV achieves "hovering mode" at a high angle of attack (30-60 degrees): The UAV relies on its special configuration (large camber, ultra-thin "shell" wing cross-section) and utilizes wind force to generate "maximum possible drag" on its wings. Additionally, the tether between the UAV and ground facilities provides the necessary tension. This allows the UAV to transition from powered aircraft state to unpowered kite state and maintain long-duration "hovering mode" in the air.

In "hovering mode," the main forces acting on the UAV's wings are as shown in Fig.5:

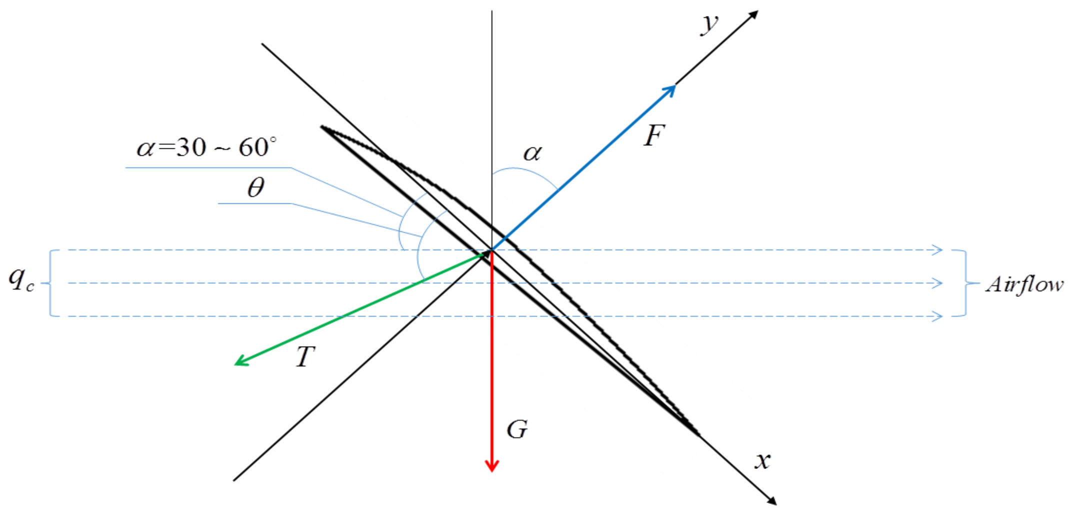


Figure 5 –The wing force diagram in "hovering mode"

$$\begin{cases} G \cdot \sin\alpha - T \cdot \cos\theta = 0 \\ T \cdot \sin\theta + G \cdot \cos\alpha = F \end{cases} \tag{1}$$

$$\begin{cases} T = (G \cdot \sin\alpha)/\cos\theta \\ F = G \cdot \cos\alpha + (G \cdot \sin\alpha \cdot \sin\theta)/\cos\theta \end{cases} \tag{2}$$

The UAV's force acquired from Wind Force is calculated by the following formula:

$$F = 0.5\rho \cdot V^2 \cdot S \cdot C_D^{\alpha} \tag{3}$$

The condition of "Hovering Mode" is calculated by the following formula:

$$F \cdot \cos\alpha > G \tag{4}$$

2.2.4 Wind Turbine Blade and Pulling Force Propeller Integration

✧ Principle Concept

Due to the reversible nature of engines and electric motors in principle, it is proposed to employ a single motor to serve both as the electric motor for wind power generation and as the electric motor to propel the aircraft in flight. The switching and time-sharing utilization between the "power generation" and "motor operation" modes of the motor are achieved through an (electrical-electronic) circuit, significantly enhancing the efficiency of motor utilization. The wind power UAV is equipped with two 1-kilowatt (three-phase AC permanent magnet synchronous) electric motors. Moreover, due to the fact that wind power blades and propellers are based on the same aerodynamic principles (i.e., utilizing the difference in curvature between the upper and lower surfaces of the blades to induce pressure differentials, thereby generating forces acting on the blades). Therefore, it is proposed to use the same set of blades, serving both as the fan blades for wind power generation and as the propellers driving the aircraft in flight, as illustrated in Fig.6.

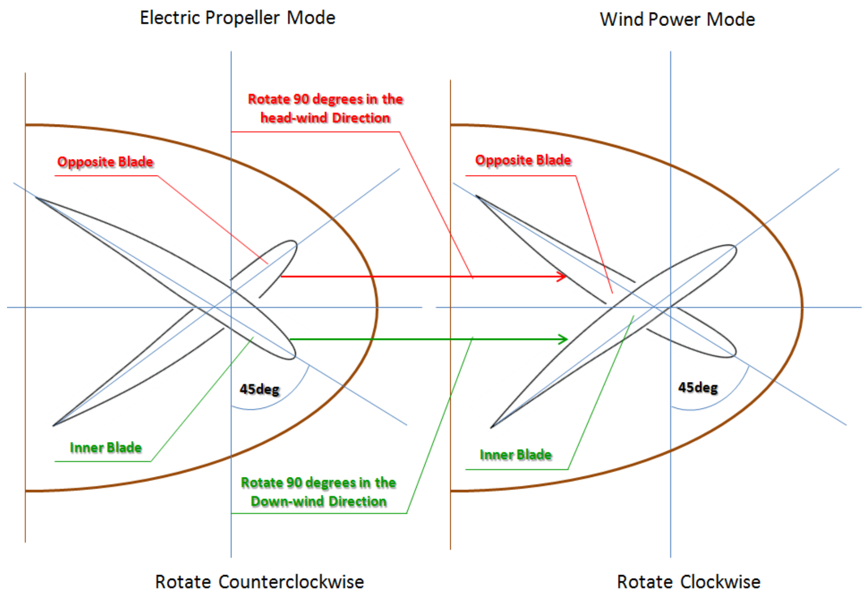


Figure 6 – The principle drawing of wind turbine blade and pulling force propeller Integration

The twist configuration of the fan blade profile to "upward bend" (The profile chord line twists progressively upward from the root to the tip, as illustrated in Fig.7) and the twist configuration of the fan blade profile to the "downward bend " (The profile chord line twists progressively downward from the root to the tip, as illustrated in Fig.8) are achieved through a especial mechanism based smart material (e.g SMA). This significantly enhances the efficiency of blade utilization.

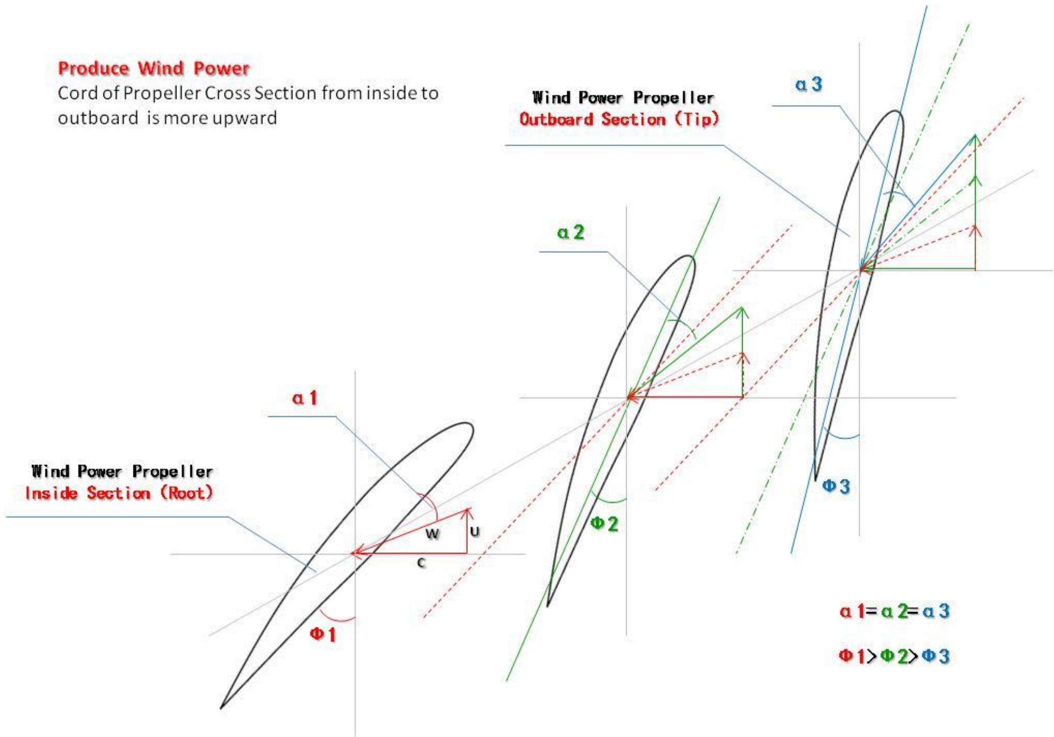


Figure 7 – The profile chord line twists of wind turbine blade

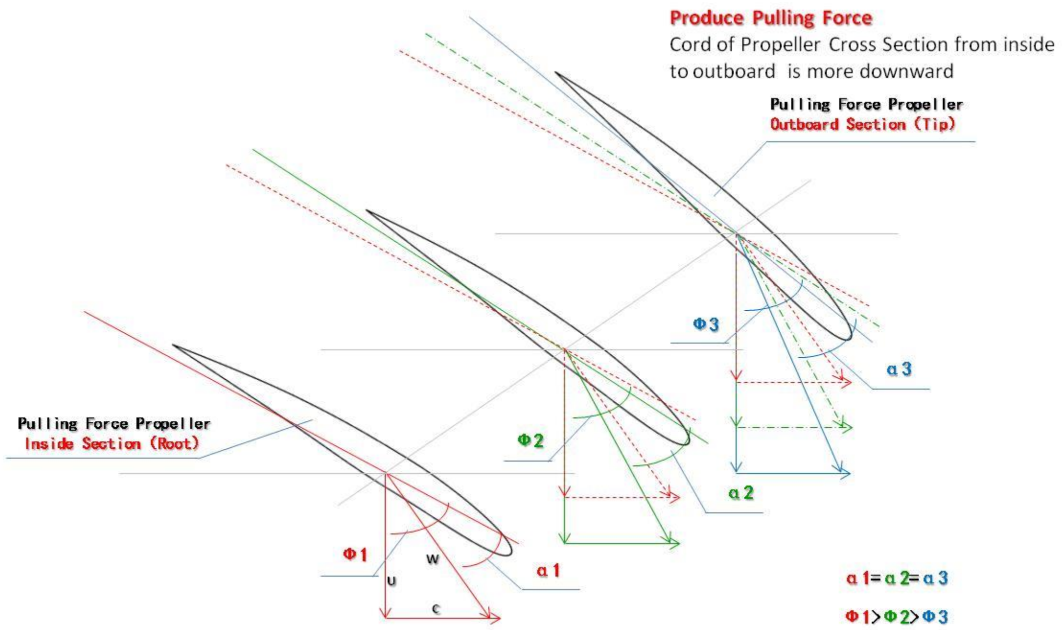


Figure 8 – The profile chord line twists of pulling force propeller

✧ Capability Estimate[5]

According to Betz's theory, the maximum coefficient of wind energy conversion for a wind turbine is:

$$C_{p\max} = \frac{P_{\max}}{E} = \frac{16}{27} \approx 0.593 \tag{5}$$

It can be deduced that the wind energy required to generate a certain amount of electrical power is:

$$E = \frac{P_{\max}}{C_{p\max}} = \frac{27}{16} P_{\max} = 1.6875 P_{\max} \tag{6}$$

The expression for the actual power that ground electrical equipment can obtain is:

$$P = E \times C_p \times \eta_a \times \eta_g \times \eta_c \times \eta_l = E \times 0.40 \times 1 \times 0.80 \times 0.80 \times 0.7 \approx 0.20E \qquad (7)$$

The efficiency of a wind turbine C_p 、Gearbox efficiency η_a 、Generator efficiency η_g 、Power electronic inverter efficiency η_c 、Overhead transmission line efficiency η_l 。

The power generated by the generator is：

$$P_g = E \times C_p \times \eta_g = E \times 0.40 \times 0.80 \approx 0.32E \qquad (8)$$

The wind energy required to drive a certain power generator is：

$$E = 3.125 P_g \qquad (9)$$

According to aerodynamic theory, flowing air possesses energy. The wind power passing through a cross-section perpendicular to the wind speed, also known as wind power, can be expressed as：

$$E = \frac{1}{2} m v^2 = \frac{1}{2} \rho A v^3 \qquad (10)$$

Further derivation yields：

$$E = 3.125 P_g = \frac{1}{2} m v^2 = \frac{1}{2} \rho A v^3 = \frac{1}{2} \rho \pi R^2 v^3 \qquad (11)$$

The length of wind turbine blades required to drive a certain power generator is：

$$R = \sqrt{\frac{6.25 P_g}{\pi \rho v^3}} \qquad (12)$$

E is the wind energy，measured in watt； m is the mass flow rate of air, measured in kilograms per second； v is the wind speed, measured in meters per second； ρ is the air density, measured in kilograms per cubic meter; A is the cross-sectional area perpendicular to the airflow direction, measured in square meters; R is the length of the wind turbine blades, measured in meters.

The low-altitude air density $\rho = 1.225 \times e^{(-h/10.7)}$, where h is measured in kilometers. When h = 0.1, the air density is 1.2136 kilograms per cubic meter; when h = 0.2, the air density is 1.2023 kilograms per cubic meter.

The relationship between wind speed and altitude in different terrain regions is shown in Table 1 below:

Table 1: Wind speed variation with altitude in different terrain regions

Urban Center Area		**Forested Suburbs**		**Plains and Coastal Areas**	
Altitude (meters)	Speed (meters per second)	Altitude (meters)	Speed (meters per second)	Altitude (meters)	Speed (meters per second)
25	10	25	15	25	30
40	12	40	20	40	31
50	14	50	21	50	32
100	**20**	100	25	100	37
140	24	100	29	100	40
150	25	100	30	150	41
210	30	210	35	210	43
275	35	275	40	275	45
400	40	400	45	——	——
530	45	——	——	——	——

Note:

① 10 meters per second is a strong wind of level 6 on the Beaufort scale, characterized by: large branches moving, wires whistling, difficulty in using umbrellas, and tall grass occasionally lying flat.

② 20 meters per second is a gale of level 8 on the Beaufort scale, characterized by: breaking small trees and significant resistance when walking against the wind.

When taking P_g as 1kw and v as 2m/s:

$$R=\sqrt{\frac{6.25P_g}{\pi\rho v^3}}=\sqrt{\frac{6.25\times1000}{3.14\times1.2136\times8\times10^3}}\approx0.453m \tag{13}$$

The length of the wind power generation system's blades is determined to be 0.5meters, concurrently serving as the length for the electric traction system's blades. When blade width of 0.05m, a pitch of 0.3m, a maximum rotational speed of 3000r/min (50r/s), and a maximum horizontal flight speed of 10m/s:

$$T=2R\times h\times d\times n^2\times1\times0.25=6.25kgf \tag{14}$$

Ensuring that a 1kW electric motor drives the propellers to provide 6.25kg of thrust, a UAV equipped with two sets of propellers can achieve a total of 12.5kg of thrust.

The UAVs of this size have a lift-to-drag ratio of not less than 10 and a maximum forward pull of about 8 kg to generate 80 kg of lift; the UAV's electric propellers provide a maximum of 12.5 kg of pull, which is sufficient to meet the flight requirements.

2.2.5 Cooperative Running Between Plane-Flight and Kite-Hovering Mode

✧ System Concept

An improved airborne wind power UAVs, which integrates two systems of wind power generation and electric traction, is used, and its Sky-Ground co-operative control system is operated as shown in Fig.9.

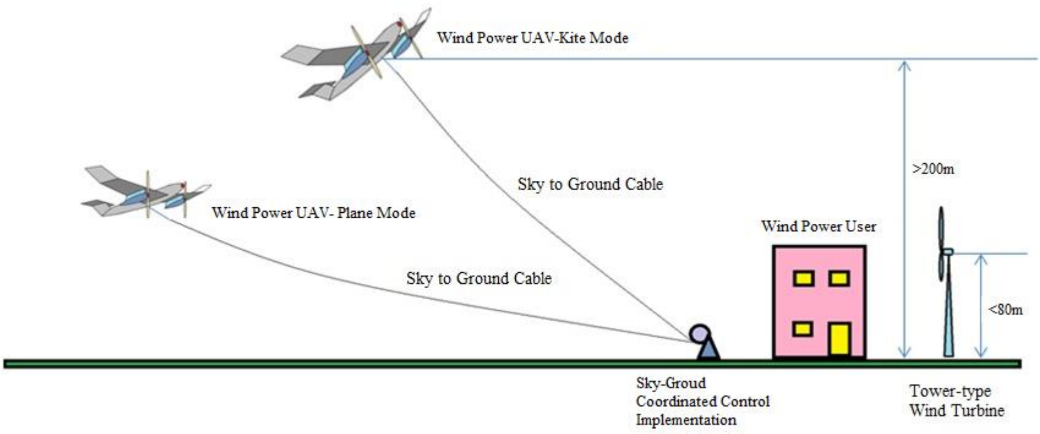


Figure 9 – The schematic drawing of the operation of sky-ground co-operation system for an improved wind power uav

The UAV is released from the ground and flies automatically to the wind power generation altitude (typically around 200 meters, depending on airspace conditions) by means of its motor-driven propellers. Subsequently, the electric motor driving the propellers is gradually deactivate and the UAV remains suspended in sky, supported by the high-altitude wind and the traction tether connected to the ground. The propellers connected to the UAV's generator are blown by the wind at high altitude to generate electricity in the air, and the electricity obtained is transferred to the power storage/conversion/transmission system on the ground through the wires in the tow rope between the UAV and the ground. Compared to ground-based wind power generation, in the high-altitude (e.g., 200 meters) UAV benefits from higher wind speeds and can adjust its flight altitude to adapt to different seasons and regions. The system incurs relatively lower overall costs by eliminating extensive underground cables and large ground support structures, along with the associated maintenance expenses. In contrast to conventional kite-based power generation, the UAV system operates in a controlled manner, allowing for controlled ascent, altitude maintenance, attitude adjustment, and recovery in aircraft mode, resulting in more precise and reliable system operation.

✧ System Running

The airborne-ground cooperative wind power generation control system includes:

① A "towing/transmission" cable, with one end fixedly installed on the central part of the UAV main body and the other end connected to a " retractable cable drum" mechanism.

② A " retractable cable drum " mechanism fixedly installed on the ground, used for real-time control of the length of the "towing/transmission" cable between the UAV and ground facilities.

③ A ground "electricity comprehensive processing and storage" facility, used to convert the electrical energy generated by the wind turbine components on the airborne UAV into chemical energy, store it in dedicated battery packs, and provide it for user consumption.

④ An "airborne-ground cooperative control system" for receiving status information transmitted from the airborne UAV to the ground and controlling the UAV's transition between "airplane flight" and "kite hovering" modes, as well as initiating and inhibiting airborne wind power generation.

The "Airborne-Ground Cooperative Wind Power Generation Control System" section encompasses the full-cycle operational control characteristics of the entire system, including two modes: "airplane flight" and "kite hovering," as illustrated in Fig.10.

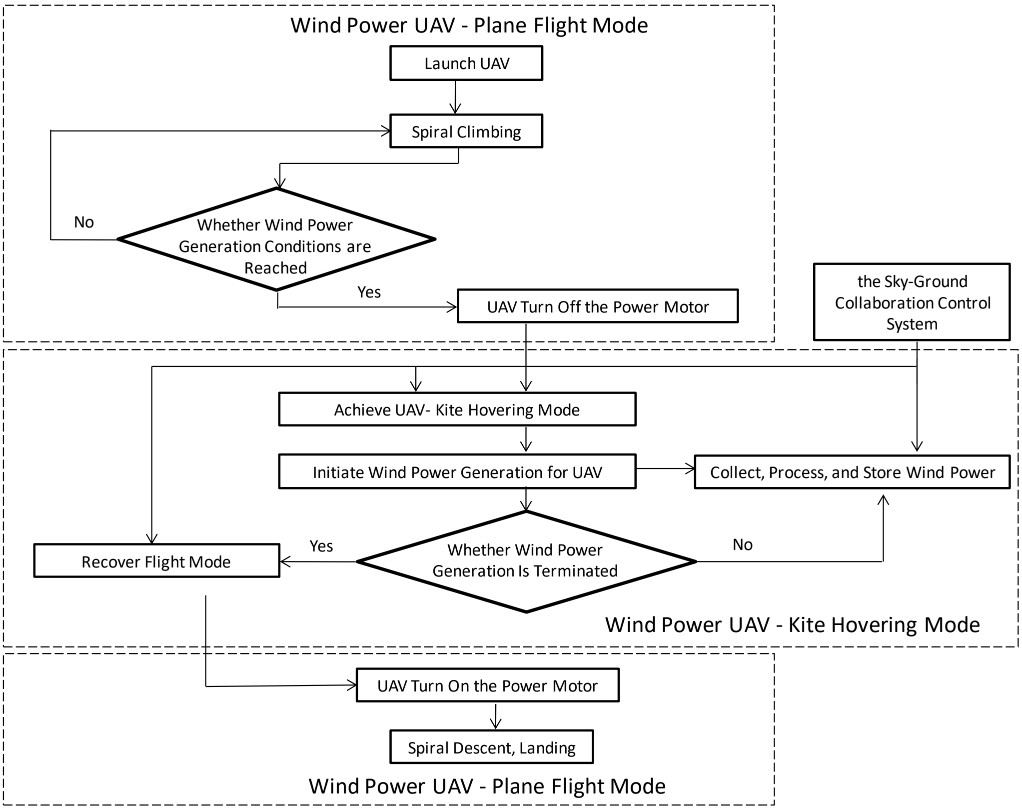


Figure 10 – The flow chart of cooperative running between plane-flight and kite-hovering mode for wind power

Firstly, the "airplane flight" mode includes the following steps:

Step 1, Takeoff and Climb Process:

a. UAV onboard systems power up, towing motor starts, and the "power generation" switch of the airborne wind turbine is turned off (suppressing power generation function);

b. With two people assisting, the UAV is thrown into the air at an angle of approximately 30 degrees upwards;

c. The UAV ascends in a spiral pattern according to the pre-planned route under the control of the autopilot;

d. When the UAV reaches the predetermined lower altitude limit, the current wind speed information at that altitude is detected by the onboard anemometer. This information is transmitted via a data link to the airborne-ground cooperative control system, which calculates whether the conditions for kite mode hovering are met. If yes, it switches to kite mode; otherwise, it returns to step c, and the UAV continues climbing until the conditions for kite mode hovering are met.

Step 2, Transition from Airborne Flight to Kite Hovering Mode:

a. The towing motor speed of the UAV is gradually reduced, and the rate of change of UAV altitude is continuously monitored in real-time. This information is transmitted via a data link to the airborne-ground cooperative control system;

b. If the rate of change of altitude is negative, the UAV temporarily stops reducing the motor speed. Meanwhile, the airborne-ground cooperative control system adjusts the tension of the "towing cable" between the UAV and the ground facilities to raise the UAV and compensate for the descent height until the rate of change of altitude becomes non-negative, then the cable retraction is paused;

c. It is determined whether the UAV motor is completely off. If not, return to step a; if yes, transition to "kite hovering" mode.

Step 3, Resumption of Airborne Flight:

a. When the UAV is in "kite hovering" mode and receives the "resume airborne flight" command transmitted by the airborne-ground cooperative control system via the data link, the UAV suppresses the airborne wind power generation function;

b. The UAV starts its towing motor and gradually increases its speed. Under the control of the autopilot, it adjusts its attitude, speed, and altitude until the UAV is completely in a controllable level flight state, gradually transitioning from kite mode to airplane mode.

Step 4, Descent and Landing Process:

a. The UAV descends and circles down along a pre-planned spiral descent route;

b. When the altitude, speed, and heading reach the landing conditions, the UAV shuts down its motor and enters the powerless gliding phase;

c. Under the control of the autopilot, the UAV aligns with the runway, gradually reduces speed and altitude until the UAV lands on the ground;

d. The UAV relies on its own simple landing device to taxi on the ground until it comes to a complete stop.

Secondly, the "kite hovering" mode includes the following steps:

Step 1, Air-Ground Cooperative Powerless Altitude Adjustment Process:

a. While gradually reducing the towing motor speed of the UAV in the air, if the altitude decreases, the ground cable retraction facility is controlled to quickly shorten the airborne-ground connection cable, causing the UAV to rise in altitude and compensate for the height decrease caused by the motor slowdown, until the UAV's motor is completely shut down and maintained at a certain altitude;

b. During the airborne wind power generation phase, if the wind speed at the current altitude of the UAV does not meet the power generation requirements, the ground cable retraction facility is controlled to slowly lengthen the airborne-ground connection cable, allowing the UAV to ascend in kite mode under the action of wind force until the wind speed requirements for airborne wind power generation are met, and maintaining a certain altitude;

c. During the airborne wind power generation phase, if the wind speed at the current altitude of the UAV exceeds the maximum requirement for power generation and threatens the safe operation of the UAV system (such as potential UAV damage or airborne-ground connection cable breakage), the ground cable retraction facility is controlled to slowly retract the airborne-ground connection cable, forcing the UAV to descend until the wind speed at the current altitude meets the safety requirements for UAV system operation and maintaining a certain altitude.

Step 2, Long-term Hovering Airborne Wind Power Generation Process:

a. During the airborne wind power generation phase, the UAV is in kite mode, balancing against the resistance generated by the high-altitude wind, overcoming gravity, and balancing the tension borne by the airborne-ground connection cable, thus hovering in the air;

b. The UAV turns on the "power generation" switch of the airborne wind power generator, triggering the airborne wind power generation function;

c. The UAV transmits the electrical energy generated by its wind power generator to the ground facilities via the airborne-ground connection cable after processing through "conversion";

d. The received electrical energy in the ground facilities is converted and stored in battery packs for flexible user consumption.

Step 3, Air-Ground Cooperative Power Flight Recovery Process:

a. When the UAV needs to terminate the airborne wind power generation task due to various reasons (including reaching the normal working cycle, UAV malfunction requiring repair, encountering thunderstorms or severe weather requiring evasion, etc.), the UAV first cuts off the "power generation" switch to suppress the wind power generation function;

b. The UAV is controlled by its autopilot to gradually transition from powerless kite mode to powered airplane mode.

3. The Small-Scale Wind Power UAVs

3.1 UAV Model

3.1.1 Parameter

In order to verify the principle feasibility of the Kite-plane Integrated Configuration Airborne Wind power UAV and System, a small UAV was developed with the following parameters and specifications:

- Gross aircraft weight is 2.5kg
- Wing wingspan is 2 meters
- Fuselage length is 1.85 meters
- Wing area is 0.96 square meters
- Rally propeller is 14" diameter
- Wind turbine propeller is 14" diameter;
- Electric motor power is 500w;
- Generator power around is 10w;
- On-board battery weight 220g;
- Estimated aerial power generation height is 50-100 meters
- Length of tow rope is 120 meters
- Weight of tow rope is 300g
- Specification of rechargeable batteries on the ground (using mobile phone batteries and their chargers);
- Electrical appliances (LED light-emitting diodes);
- Charging takes no more than 1 minute to light the LEDs.

3.1.2 Practicality

The small-scale wind power UAV has embodied the idea of the Kite-plane Integrated Configuration, But the actual configuration has been essentially simplified for employing aeromodelling technology in consideration of the schedule and budget, as depicted in Fig.11.

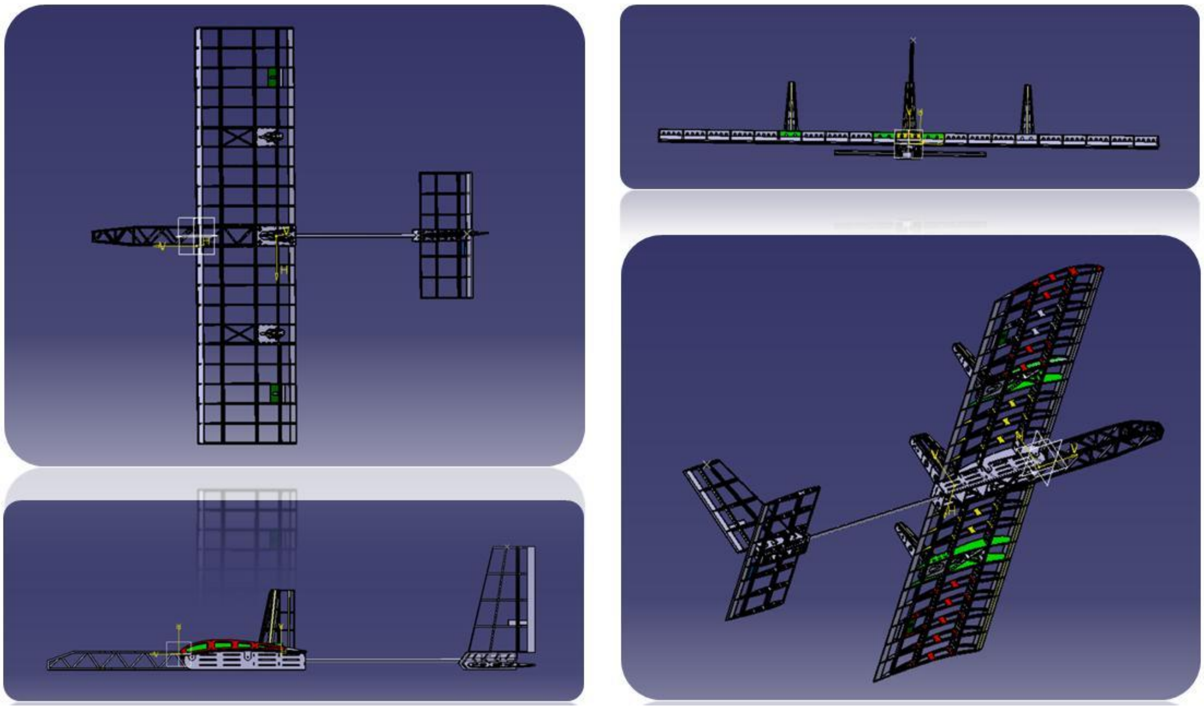
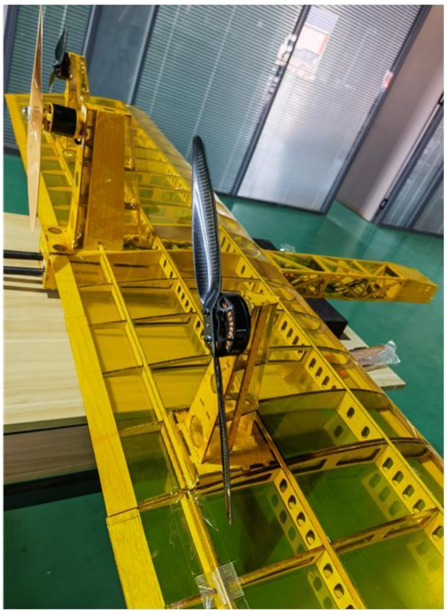


Figure 11 – A computerized model picture of a small-scale conceptual airborne wind power uav

To emphasize principle validation and simplify the system, the small-scale wind power UAV still employs standard wind power generation and traction electric systems, consisting of one set of electric propellers and two sets of wind power generation blades.
During the flight test, the actual position was altered from above wing to at the fore of body for eliminating adverse downward torque, as depicted in Fig.12,13.

(a) An uavs full view (b) A pull wire particulars view

Figure 12 –An entity picture of a small-scale conceptual airborne wind power uav



(a) A pulling force propeller view

(b) A pulling force propeller view

Figure 13 – An entity picture of the separated wind power propeller(left) and pulling force propeller(right)

3.1.3 Estimate

The small-scale wind power unmanned aerial vehicle has a wing area of 0.96 square meters and an AoA of 45deg in Kite Mode. At an altitude of 50 meters, with a minimum wind speed of 14 meters per second and an atmospheric density exceeding 1.2136 kilograms per cubic meter (at 100 meters altitude), the calculated wind drag force (i.e., the vertical force required for hovering) is as follows:

$$F = 0.5\rho \cdot V^2 \cdot S \cdot C_D^{\alpha} = 113.836 \times 0.35 = 39.8kgf \tag{15}$$

$$F \cdot \cos\alpha = 39.8 \times \cos 45^{\circ} = 28.2kgf > G = 25kgf \tag{16}$$

The vertical force of the UAV is acquired from the wind force exceeding the total weight of the UAV which is 2.5 kilograms. The kite mode is feasible because of satisfying the condition of "Hovering Mode".

3.2 Flight Test

The small-scale wind power unmanned aerial vehicle has completed flight tests by human teleoperation, as shown in Fig.14.

Figure 14 – The flight test photograph of a small-scale conceptual airborne wind power uav

During the flight test, the UAV exhibited stable flight, the traction electric system performed adequately, and the aircraft mode proved feasible.

Through the additional test, it is shown that the wind power system operated normally, generating current to power electrical devices (in this case is a lamp).

At present, it is not actualized owing to time that the flight test of the whole procedure for UAV's airborne wind power. Nevertheless, the technology and project have been prepared for the future work.

4. Conclusions

This paper introduces the innovative concept of "Kite-plane Integrated Configuration Airborne Wind power UAV and System", and elucidating the technical solutions for both the "Kite-plane Integrated Configuration UAV" and the "Sky-Ground Collaborative Wind Power Generation Control System". Targeting the goal of achieving a 2-kilowatt airborne wind power generation, a conceptual framework for the integration of wind power blades and traction propellers is proposed, and parameters and metrics for an improved airborne wind power UAV system are designed. A small-scale UAV has been developed and successfully finish flight tests, providing preliminary validation of the feasibility of the "Kite-plane Integrated Configuration Airborne Wind power UAV and System" and fundamental technology for the subsequent work which will focus on the comprehensive development of the entire system and wind power test.

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