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Energy extraction from wind shear: Reviews of dynamic soaring

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Abstract

This paper presents a review of research works related to the application of dynamic soaring for extracting and collecting energy from certain structures in the wind using a small unmanned aerial vehicles (UAVs). By dynamic soaring, UAVs can extract energy from wind shear to produce electrical power or conduct a high-speed, long-endurance mission without adding extra weight. Combined with rapid technological development of UAVs, dynamic soaring might become a new way to explore nature's energy; extracted energy from wind shear might become a new source of renewable and sustainable energy. In this paper, we review the dynamic soaring and analyze the energy extraction process of it from the view of energy transformation. We also discuss the rate and efficiency of energy extraction as well as the possible applications, challenges and future of dynamic soaring in UAVs.

Keywords

Dynamic soaring, wind shear, unmanned aerial vehicles, energy extraction process

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Introduction

Background

Currently, unmanned aerial vehicles (UAVs) represent one of the most interesting technologies in aeronautics.[1] They have been increasingly used in more and more applications, especially to replace the human presence in repetitive or dangerous missions,[2] e.g. in environmental monitoring, security, military surveillance, crop and forest assessments, scientific exploration, etc.[3] The trend for UAVs' technological development has been towards versatility, small size, long endurance coupled with high speed.[4]

However, the major handicap associated with UAVs is the limited on-board energy capacity,[5,6] and the energy supplement has already been the crucial constraint for the development of UAVs, because it does affect UAVs' working duration and mission completion. The energy of UAVs is usually supplied by the onboard batteries, these years, although many institutions and scientists have dedicated great efforts to the research of battery technologies, UAVs still suffer from on-board energy storage limited in size and weight.[7] Additionally, the energy stored onboard will decrease the mission payload capabilities further. Thus, a trade-off must be made between increasing the energy storage on a UAV and its range, or carrying ability.[8]

Is there a method for the UAVs that not only can supply energy for long-endurance mission but also need not to affect their carrying ability in the form of extra weight?

Motivation

Albatrosses, as shown in Figure 1, can fly long distances even around the world almost without flapping their wings, which means that they are flying nearly at no mechanical cost.[9] Sachs et al.[10] recently have calculated that an albatross has to develop a power of 81.0 W for flying at 70 km/h, which is equivalent with the power produced by 0.9 L of gasoline per day. The albatross must spend 6.2 days for the typical journeys from South Georgia to the southwest Indian Ocean and 13.2 days to southwest Pacific,[11] which implies that the energy consumed during journey equals to 5.6–11.9 L of gasoline. If it is impossible to generate so much energy from the food, then where does the

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Figure 1. Albatrosses.[13]

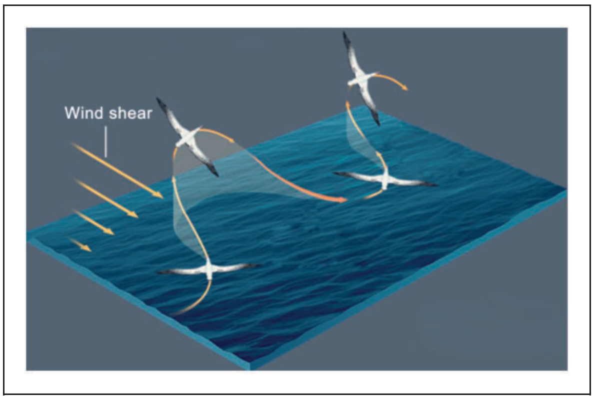

Figure 2. The trajectory of albatross.[14]

energy come from? Many scholars have been intrigued by this question.

After long time observations, researchers gradually find that albatrosses are exploiting a special technique when they are flying in wind shear. The bird firstly pulls up into the wind and becomes exposed to a head wind to gain height, then turns in the other direction with the wind behind it, dives back into the sea to gain speed, as shown in Figure 2. This results in an increase in its air-speed. So by repeating this maneuver, the bird can continue flying almost indefinitely without having to put in much effort, in effect, it is extracting energy from the wind shear. This maneuver is called as dynamic soaring.[12]

The idea of dynamic soaring now is widely accepted by scholars in aviation, especially for UAVs which may be controlled automatically to extract energy from wind shear to greatly extend flight duration and distance.[15] Zhao[16] and Sachs et al.[17] have shown the two patterns of dynamic soaring for UAVs: the one is traveling type (or named as traveling type), the other is oval type (or named as loiter type), the typical behavior of two patterns to perform dynamic soaring can be named as 'belly-to-wind',[18] as shown in Figure 3.

Instead of perusing battery performance, researchers find that UAVs can be conserving battery/mechanical energy by taking advantage of the dynamic soaring, and it is possible to use dynamic soaring to reduce the need of battery/mechanical power during a particular flight. Recently, energy extraction from wind shear has attracted more and more attentions of researchers all around the world.[7,8,19–21] Since wind shear is persistently distributed in the boundary layer above the ocean surface and upper atmosphere from altitude of 15–20 km.[22] Incorporating with the rapid technologies development of UAVs, dynamic soaring may become a new way to explore the energy from nature, and the energy extracting from wind shear possibly becomes a new renewable and sustainable energy source. The motivation of this paper is to review the research development about dynamic soaring, and expect that it may be benefit for the energy exploration of wind shear in nature.

Related works

For centuries, observers have been fascinated by the ability of certain birds, such as albatrosses, falcon and jackdaw,[23–25] to fly with little apparent effort. Numerous observations about birds soaring without flapping their wings have been recorded, ranging from Leonardo da Vinci to Octave Chanute.[21] Rayleigh[26] is known as the first one to propose that dynamic soaring can be done in a horizontal but nonuniform wind field in the year of 1883. Idrac[27] has calculated the energy gained by albatrosses in 1920 from wind shear, and found that dynamic soaring is only possible for very swift birds with a minimum strength of wind shear at 5 m/s. Wilson[28] has suggested another method named sweeping flight to interpret the fight manner of albatrosses, and he thought that the birds could use the updraft above the wave to get energy. However, recently, Philip L. Richardson had pointed out that more than 80–90% of total energy for albatrosses was coming from wind shear soaring, and only a small part of energy was coming from updraft.

The interesting of ornithologists is mainly concentrated on the influences of dynamic soaring on the behaviors of birds. Many researchers pay their attention on how albatrosses fly around the world without flapping their wings[9] and how the changes in wind pattern alter the distribution and lift-history traits of albatross.[29] However, the most interesting topic for the scholars in aviation is which one is the optimum flight path for an UAV to extract the maximum energy from wind shear. Many commercial software are developed to determine trajectories for dynamic

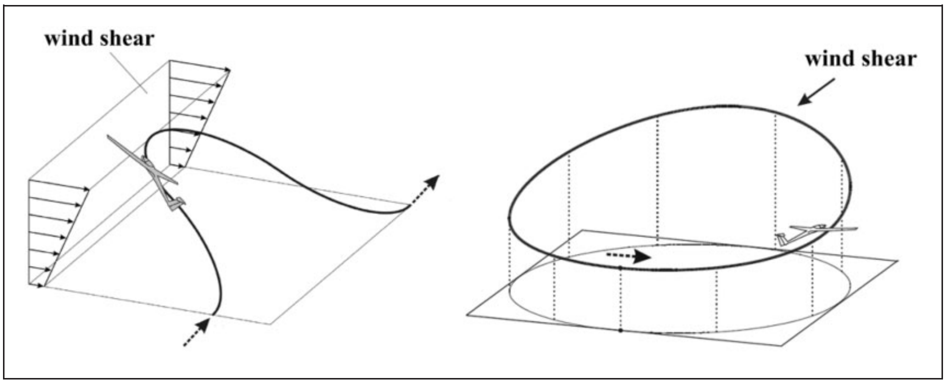

Figure 3. Traveling and oval type of trajectory.[17]

soaring in specific conditions, and lots of valuable results are obtained, such as Zhao and Qi[30] present the minimum fuel powered dynamic soaring of UAVs utilizing wind shear by the software named NPSOL, Sachs analyzes the minimum strength of wind shear required for albatrosses to perform dynamic soaring by the software named ALTOS[31] and Deittert et al.[32] generate the optimal trajectories of UAVs in the condition of the minimal and maximal strength of wind shear for the optimal cross-country travel by the software named AMPL, other examples can be seen in various other references.[17,19,33–37]

Nowadays, dynamic soaring has been used to extend flight duration of small UAVs, and many researchers try to realize the autonomous dynamic soaring of UAVs. Some pioneering works have been done, such as Boslough[38] addressed the feasibility of developing dynamic soaring flight control algorithms to sustain the flight of UAVs; NASA paid great effort to explore the potential to increase range and endurance by extracting energy from the ambient atmospheric velocity field;[39] Barate et al.[40] designed a bio-inspired controller for dynamic soaring in a simulated UAV; Lawrance et al.[41] designed a guidance and control strategy for a gliding UAV to perform the autonomous dynamic soaring; Kahveci et al.[42] developed an adaptive control scheme based on linear quadratic control for UAV in autonomous soaring application; Denny[43] provided an instructive example of fixed-wing aerodynamics suitable for demonstration of dynamic soaring; Lawrance et al.[44,45] and Langelaan et al.[46,47] separately designed the methods to estimate wind field for autonomous dynamic soaring.

Contributions

Great progress has been made over the last 130 years from 1883 in understanding the physics of bird flight. However, the mechanisms of the energy extraction in terms of the energy transformation from the wind shear to the UAV are still not well documented. In order to make it more clearly, in this paper, the models of wind shear and the estimation methods of wind field are reviewed firstly, it shows that a UAV can sense the strength of wind shear under current filter technology. Secondly, the model of UAVs flying in wind shear are summarized, the energy extraction during flying in wind shear is interpreted as the work done by a fictitious force in a noninertial frame. Thirdly, the energy extraction process in dynamic soaring from the view of energy transformation is analyzed, the rate of energy extraction and energy extraction efficiency are discussed separately. Finally, the possible applications, challenges and future of dynamic soaring in UAVs are discussed in this paper. These works can supply some principles in analyzing the energy extraction process of dynamic soaring and may be benefit for energy exploration from wind shear in the future.

The rest of the paper is organized as follows: the models of wind shear and the method for estimation of wind field are introduced in the subsequent section. The model of UAV flying in wind shear is presented later. Next, the rate and efficiency of energy extraction about dynamic soaring is analyzed. The typical applications of dynamic soaring are summarized and the challenges and futures are discussed in later sections. The concluding remarks are made in the last section.

Wind shear

Models of wind shear

Wind shear is the atmospheric phenomenon which occurs on thin layers separating two regions where the predominant airflow vector is different.[48] Wind shear is the necessary condition for dynamic soaring and has a significant impact on the performance of dynamic soaring, so it is crucial to find an accurate model to describe the wind profile.[49] In order to describe the wind shear above the sea surface and at ridges, the exponential model is adopted by Sachs et al.,[17,31] Firtin et al.,[50] Shen et al.,[51] and Bower,[52] since the wind speed increases with a narrow layer before reaching the value of the free air stream. The exponential model is simply formulated as follows

$$V_W(h) = V_R\left(\frac{h}{H_R}\right)^p \tag{1}$$

where h is the altitude, V_W is the velocity of wind which is the function of altitude, H_R is the reference height, V_R is the wind speed at reference height, p denotes the reference value that is used to indicate the strength of wind shear and to take properties of the surface into account.

There is also a greatly persistent wind shear in the upper atmosphere, especially at the altitude of 15 to 20 km. To describe the wind speed varies in altitude with an approximate constant wind gradient in this situation, the linear model is adopted by Grenestedt et al.[22] and Zhao and Qi,[30] which is formulated as follows, where the B is the strength of wind shear.

$$V_W = Bh \tag{2}$$

It is clearly seen that equation (1) equals to equation (2) when the value $p=1$, so, equation (1) is a more general form to model the wind shear. Figure 4 shows the influence of the reference value p on the profile of wind shear.

The reference value p is always calculated by the measurement of wind speed at two or three heights for a period of at least 1 year,[53] and highly depends on atmospheric stability, wind speed, terrain type, and the height interval. In general, higher p values about 0.4 are found in urban areas with tall buildings, 0.3 in small towns or 0.24 in areas with many trees, whereas lowest values about 0.1 occur over smooth, hard ground, lake, or ocean.[54] In fact all the reference in the paper about the exponential model is about the wind profiles over the ocean, such as Sachs et al.,[17,31] Firtin et al.,[50] and Shen et al.[51]

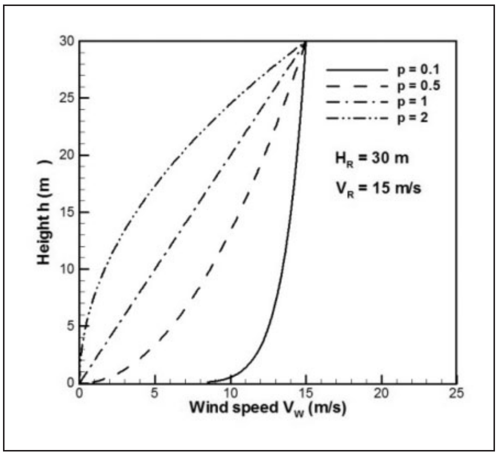

Figure 4. The influence of the reference value p on the profile of wind shear.

In order to analyze the energy extraction process conveniently, the Sachs' model is adopted in this paper and the strength of wind is treated as a linear function with altitude in a short distance, which means that the value p in Sachs' model is assumed to 1. The wind model is expressed as follows, where the β indicates the strength of wind shear.

$$V_W(h) = V_R\left(\frac{h}{H_R}\right)^p = \frac{V_R}{H_R}h = \beta h \tag{3}$$

Estimation of wind field

For the condition in unknown wind fields, some authors recently have developed many methods to estimate the wind field. The principle of estimation of wind field is to compare the differences between the value of state's estimation from dynamic equations and observations collected during the flight to estimate the parameters of wind shear by a kind of filter, such as Kalman filter,[47] extended Kalman filter,[55] particle filter,[48] Gaussian process regression,[45] and others. The adopted model, estimated accuracy, the drawbacks, and merits of some typical filters are listed in Table 1.

Table 1 shows that the estimated accuracy of wind speed is about 0.2–0.5 m/s, this implies that the UAV can sense the strength of wind shear under current filter technology. So it is possible to design an UAV to operate in an unknown wind field and extract energy from it to keep long-endurance flight autonomously.

The model of UAV flying in wind shear

A mathematical model that consists of the equations of motion for three-dimensional flight of UAV is always adopted to analyze the UAV flying in wind shear. There are mainly two types of model to describe a UAV flying in a spatially and temporally varying wind field—the Sachs' equations of motion[17,31,35,57] and the Zhao's equation of motion.[16,30,32,33] Bower[52] has discussed the advantages and disadvantages of the two sets of equations of motion. Zhao's model is considered to be more intuitive by using airspeed, flight path pitch angle, and heading angle as state variables. Based on this reason, the Zhao's model is adopted in this paper, and a linear wind shear is supposed to be always blowing along x-axis. The definitions of forces and angles used in the model are shown in Figure 5.

The differential equations of motion for UAV is given as follows, where the speed of UAV is modeled in a wind relative reference frame and the position of UAV is modeled in an earth fixed frame

$$m\dot{V} = T - D - mg\sin\gamma - m\dot{V}_W\cos\gamma\sin\Psi \tag{4}$$

Table 1. The comparison of filter algorithms in estimation of wind field.

Method	Model	Estimated accuracy (m/s)	Drawbacks	Merits	Reference works
Particle filter	Model-based estimation requiring few characterization parameters.	0.450 (200 particles)	The prediction accuracy is affected greatly by the gusts.	Estimating the surrounding flow field with a small number of variables and low memory requirements.	Bencatel and Souas[48]
Extended Kalman filter	The nonlinear longitudinal aircraft equations of motion.	0.310	The EKF is sensitive to uncertainty in dynamic model.	Making no assumptions about the structure of the atmosphere disturbance, and providing accurate disturbance estimates in a variety of atmospheric conditions.	Mulgund and Stengel[55]
Linear Kalman filter	Polynomial parameterization.	0.240	May be subject to errors related to both under and over approximation.	Well suited to shear layers in the vicinity of the jet stream and the atmospheric boundary layer.	Langelaan et al.[47] and Stratton and Stengel[56]
Gaussian process regression	Model-free.	0.218	Occasionally causing excessive detours in some of longer loops extending outside the region of interest.	Simultaneous exploration and exploitation of a wind field with limited prior information.	Lawrance and Sukkarieh[45]

$$mV\cos\gamma\dot{\Psi} = L\sin\mu - m\dot{V}_W\cos\Psi \tag{5}$$

$$mV\dot{\gamma} = L\cos\mu - mg\cos\gamma + m\dot{V}_W\sin\gamma\sin\Psi \tag{6}$$

$$\dot{h} = V\sin\gamma \tag{7}$$

$$\dot{x} = V\cos\gamma\sin\Psi + V_W(h) \tag{8}$$

$$\dot{y} = V\cos\gamma\cos\Psi \tag{9}$$

The lift and drag force are expressed as follows

$$L = \frac{1}{2}\rho S_W C_L V^2 \tag{10}$$

$$D = \frac{1}{2}\rho S_W C_D V^2 \tag{11}$$

where the ρ is the air-density, S_W is the reference area of UAV, C_L and C_D are the lift coefficient and drag coefficient, respectively. The drag coefficient C_D depends on the lift coefficient C_L, yielding

$$C_D = C_{D0} + kC_L^2 \tag{12}$$

where C_{D0} is the parasitic drag coefficient and k is the induced drag factor.

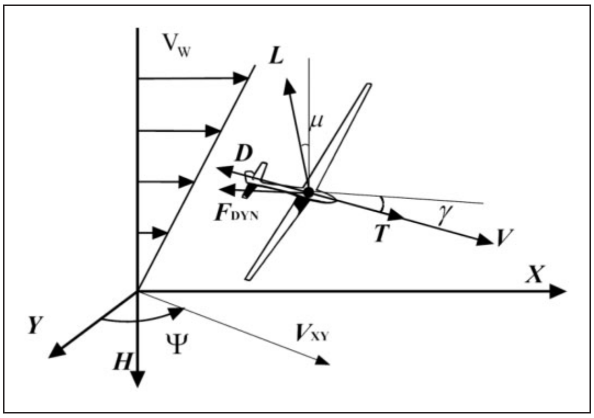

Figure 5. Forces acting on UAV[32,58]: Relative to the wind-frame, the airspeed-frame of UAV is not inertial, so there is a fictitious force F_{DYN} acting on UAV.
Where the V is airspeed, X and Y are positions, μ is bank angle, L is lift force, D is drag force, T is the thrust, F_{DYN} is the dynamic soaring force which will be further interpreted in the following, the V_{XY} represents the projection of velocity on XY-plane, Ψ is the azimuth measured clockwise from the Y-axis and γ is the flight path pitch angle.

For equations(4) to (6), because the airspeed-frame of UAV is a noninertial frame relative to the wind-frame when UAV is flying in wind shear, there is a fictitious force F_{DYN} acted on UAV, as described in Deittert et al.,[32] which is expressed as follows

$$F_{DYN} = -m\dot{V}_W \tag{13}$$

Its projection onto the direction of airspeed can be expressed as follows according to the definition in equations (3) and (7)

$$\begin{aligned}(F_{DYN})_V &= -m\dot{V}_W \cos\gamma \sin\Psi \\ &= -\beta m V \sin\gamma \cos\gamma \sin\Psi\end{aligned} \tag{14}$$

Equation (14) reveals that a UAV can extract energy from wind shear if only the product of sinγ and sinΨ is negative when β is positive or the product of sinγ and sinΨ is positive when β is negative. So a UAV can always extract energy from wind gradient, whatever the gradient of wind shear is positive or negative.

Analysis of energy extraction process in dynamic soaring

By common sense, it is known that the wind gradient is steeper, the UAV is easier to get energy from wind shear, but it is not easy to describe this relationship quantitatively.[59] Furthermore, besides the strength of wind shear, it is also need to know which parameters in environment and UAVs can affect the performance in dynamic soaring. In order to answer this question, the rate of energy extraction and the energy extraction efficiency are discussed in this section.

Rate of energy extraction: Dynamic soaring parameter

Supposing the UAV is flying in a vertical plane, which means that Ψ is a constant and $\mu = 0$. It is known that equation (4) indicates the influences of thrust (the first term), drag (the second term), gravity (the third term), and wind shear (the fourth term) on airspeed, thus, it is reasonable to find the crucial parameters for the UAV flying in the wind shear from equation (4). Substituting equations (3) and (7) into equation (4), yields

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{T}{m} - \frac{D}{m} - g\sin\gamma - \beta V \sin\gamma\cos\gamma\sin\Psi \tag{15}$$

It can be found from equation (15) that the first term presents the velocity generated by thrust. The second term presents the velocity consumed by drag. The third term presents the velocity changed by gravity, it should be also noted that the kinetic energy in velocity will be transferred to the energy in altitude since gravity is the conservative force. The fourth term indicates the influence of wind shear on velocity. In order to add velocity from wind shear on the condition of $\beta > 0$, the $\sin\gamma\sin\Psi < 0$ must be satisfied, i.e. downwind dive or upwind climb.

For a UAV, in order to extract energy from wind shear, the velocity added by wind shear (fourth term) must be greater than or at least even with that consumed by drag (second term), which means that

$$\frac{\beta V \sin\gamma\cos\gamma\sin\Psi}{\frac{D}{m}} \geqslant 1 \tag{16}$$

Here, the lift force L equals to $mg\cos\gamma$, substituting in equation (16), the *dynamic soaring parameter* can be defined as follows

$$D_s = \frac{\beta V \sin\gamma\cos\gamma\sin\Psi}{\frac{Dg\cos\gamma}{L}} = \frac{\beta}{g}\frac{C_L}{C_D} V\sin\gamma\sin\Psi \tag{17}$$

Dynamic soaring parameter D_s reveals the rate of energy extraction from wind shear by UAV. From equations (16) and (17), it can be concluded that if D_s is greater than 1, then the UAV can get extra energy from motion. Otherwise, if D_s is less than 1, then the wind shear is not sufficient to keep UAVs powerless flight. However, the UAVs can still take advantage of the wind shear to reduce energy consumption, Zhao et al. have discussed this case in Sachs.[31]

The parameter D_s also reveals the crucial factors to the performance of dynamic soaring in wind shear, such as strength of gradient wind β, the ratio of lift and drag C_L/C_D, the current air speed of UAV V, the current pitch angle γ and the azimuth Ψ of UAV.

Energy extraction efficiency: Analysis about Rayleigh cycle

It is not easy to analyze the energy transformation process theoretically for dynamic soaring since this process is greatly dependent on the trajectory of UAV in wind shear. Although many software such as NPSOL,[16] ALTOS,[31] and AMPL[32] have been developed to solve the trajectory optimization problem of dynamic soaring, there are still many debates even controversies about how energy is extracted from wind shear by UAV. The reason is rooted in the fact that the airspeed of UAV, not the ground speed, is the quantity relevant to flying, which leads to the kinetic of a UAV in wind shear must be calculated by its airspeed rather than ground speed. So, "this difference complicates interpretations of energy transformation in dynamic soaring and has led to seemingly contradictory conclusions".[9]

In order to interpret this process clearly, Richardson[9,60,61] and Bower[52] have conceived a concept of "step wind shear" to analyze the energy transformation process for dynamic soaring. The so-called "step wind shear" consists of two layers, a lower layer has zero wind speed and an upper layer has a uniform wind speed of ΔV_{wind}, as shown in Figure 6.

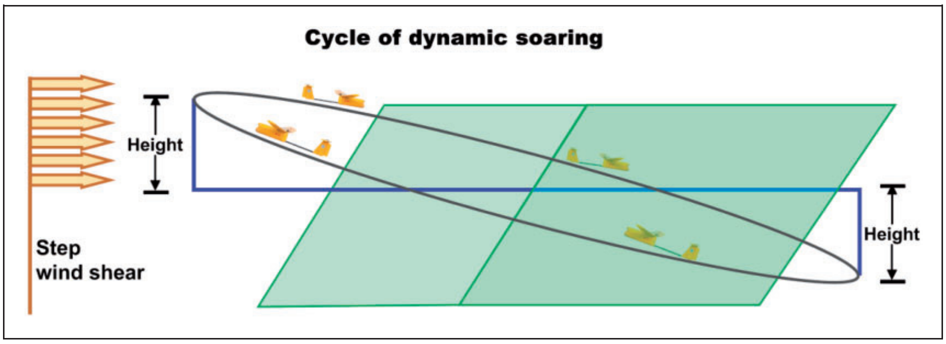

Figure 6. Rayleigh cycle of dynamic soaring in step wind shear.

The nominal dynamic soaring trajectory is supposed as a circle, and consists of only infinitesimal changes in height to traverse the step wind shear between the quiescent air and the moving air (Figure 6 has enlarged the changes in height deliberately, for the aim to understand easily). This cycle is named as Rayleigh cycle which is firstly proposed by Rayleigh.[26] In the Rayleigh cycle, the UAV can be treated as flying at a roughly constant airspeed V, a constant radius R, and a constant bank angle μ when viewed in the local wind reference frame.[52]

In this section, the energy transformation process is analyzed theoretically based on above assumptions, and a more concise conclusion about the energy extraction efficiency is obtained.

The centripetal force F_{cen} for the motion cycle is $F_{\text{cen}} = L \sin\mu$, so the constant radius of the circle is, where μ is the bank angle of UAV

$$R = \frac{mV^2}{L\sin\mu} \tag{18}$$

Meanwhile, if supposing the lift force equals to the gravity force during flight, then

$$L\cos\mu = mg \Rightarrow m = \frac{L\cos\mu}{g} \tag{19}$$

Substituting equation (19) into equation (18), yields

$$R = \frac{mV^2}{L\sin\mu} = \frac{V^2}{g\tan\mu} \tag{20}$$

The time required to turn 360° in this cycle is

$$\Delta t = \frac{2\pi V}{g\tan\mu} \tag{21}$$

So, the energy consumed during one cycle can be calculated by the following equation

$$\Delta E_{drag} = DV\Delta t = \frac{2\pi D V^2}{g\tan\mu} \tag{22}$$

While the energy gained from the wind during the 180° turn in moving air can be calculated by equation (23), the detailed derivation of this equation can be found in Richardson[9] and Bower[52]

$$\Delta E_{gain} = 2mV\Delta V_{wind} \tag{23}$$

Here, the energy extraction efficiency is defined as follows

$$\eta_E = \frac{\Delta E_{gain} - \Delta E_{drag}}{\Delta E_{drag}} = \frac{\Delta E_{gain}}{\Delta E_{drag}} - 1 \tag{24}$$

Substituting equations (19), (22), and (23) into equation (24), yields

$$\begin{aligned}\eta_E &= \frac{\Delta E_{gain}}{\Delta E_{drag}} - 1 = \frac{2mV\Delta V_{wind}}{\frac{2\pi D V^2}{g\tan\mu}} - 1 \\ &= \frac{1}{\pi}\frac{C_L}{C_D}\frac{\Delta V_{wind}}{V}\sin\mu - 1\end{aligned} \tag{25}$$

It can be seen from equation (25) that the energy extraction efficiency η_E is determined by the cruise airspeed V, the ratio of lift to drag C_L/C_D (the value $V/C_L/C_D$ is defined as sinking speed in Richardson[9]), the strength of step wind shear ΔV_{wind} and the bank angle of UAV μ. Moreover it reveals clearly that the most important parameter for energy extraction in Rayleigh cycle is not the strength of wind shear ΔV_{wind}, but rather the change in wind speed ΔV_{wind} compared to the UAV's cruise airspeed V. The UAV can extract energy from the Rayleigh cycle when $\eta_E > 0$, whereas, extra energy must be output by UAV to maintain this cycle when $\eta_E < 0$. The Rayleigh cycle is the energy-neutral trajectory when the $\eta_E = 0$. The result of equation (25) is coincident with Lissaman et al.[62] who consider that an energy neutral cycle depends upon the maximum lift/drag ratio of the vehicle and the wind speed variation.

Here it should also be mentioned that equation (25) ignores the effect of shock waves and Raynolds number effect. Because the speed of UAVs always cannot exceed sound, the the phenomenon of shock wave is hardly appear in the flight of UAVs. However, if the speed of UAVs exceeds sound at some times in dynamic soaring, then equation (25) cannot be used to describe the behavior of UAVs.

Typical applications

Dynamic soaring is widely used by big birds in nature. After ornithologists proposed the theory of dynamic soaring, many scholars research how to utilize this method properly to extract energy from wind shear. The typical applications consist of long-endurance unpowered flights, high-speed unpowered flights and possibly extracting energy from wind shear for power production. It can be expected that the D_s parameter and the efficiency of energy extraction derived in this paper can be widely used to analyze the energy transformation process of dynamic soaring, and provide some insights to design a more efficient aerial vehicle to extract energy from wind shear.

High-speed unpowered flights

An exciting application for the dynamic soaring is high-speed unpowered flights. Radio controlled model UAV routinely can reach speeds in excess of 700–800 km/h in the steep wind gradients on the leeward side of mountain ridges.[63,64] These exceedingly fast speeds demonstrate clearly that the UAV can extract a lot of energy from wind shear by an appropriate flight manner.

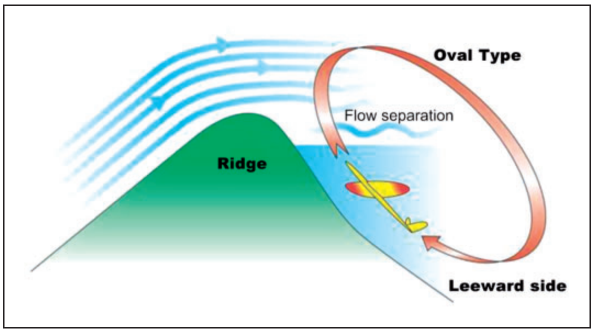

Figure 7. The high-speed dynamic soaring.[65]

The suitable trajectory for high-speed unpowered flight is oval type. The ideal place is on the leeward side of a ridge or saddle, as shown in Figure 7. If the ridge or saddle face the wind, and has a steep back (leeward) side, a flow separation will be caused off the top of the hill and a layer of fast air moving will be resulted in.

Currently, the achievable dynamic soaring speeds are listed in Table 2, the data come from RCSpeeds.[68] So far, the record dynamic soaring speed is 222.7 m/s. There is always a question for the people to perform high-speed unpowered flights: What is upper limit of the speed in dynamic soaring, and how can an UAV to get this value? In fact, equation (25) reveals the maximum velocity can be achieved in dynamic soaring.

The oval type of trajectory can be treated as a Rayleigh cycle, as discussed in section ''Energy extraction efficiency: Analysis about Rayleigh cycle''. The velocity will be increased during each cycle and the velocity achieves the maximum value $V_{\max}$ when the energy extraction efficiency equals to zero, i.e.

$$V_{\max} = \frac{1}{\pi}\frac{C_L}{C_D}\Delta V_{wind}\sin\mu \tag{26}$$

The ΔV_{wind} in the step wind model is approximate to the reference velocity of wind at the top of ridge, since the UAV is flying very fast at this circumstance and the wind velocity is changed rapidly from the free air velocity at the top of hill to zero at the bottom of hill.

As described in equation (26), the maximum velocity can be achieved is the function of the ratio of lift to drag C_L/C_D and the reference velocity of wind shear ΔV_{wind}. Figure 8 shows the maximum velocity of UAV in dynamic soaring. Because the ratio of lift

Table 2. The achievable dynamic soaring speeds.

Rank	Pilot	Location	Date	Ref. velocity of wind shear (s^{-1})	Maximum Lift/ Drag of UAV	Speed (m/s)
1	Spencer Lisenby	Bird Springs	6 Mar 2012		Kinetic 100 DP	222.7
2	Gery Mazzola	Mount Kumeta	27 Oct 2012		Kumeta DS	211.5
3	Spencer Lisenby	Norco	2 Feb 2011	30.4[66]	Kinetic 100 DP	209.3
4	Bruce Tebo	Weldon	24 Apr 2011		Kinetic 100 DP	204.8
5	John Buxton	Weldon	21 May 2010	22.4[67]	Kinetic 100 DP	199.0
6	Joe Manor	Mars Hill	23 May 2012		Dynamic 130	199.0
7	Jason Lilly	Weldon	7 Mar 2011		Kinetic 100 DP	191.0
8	Chris Bosley	Norco	2 Feb 2011	30.4[66]	Kinetic 100 DP	181.1
9	Marlan Muir	Weldon	12 May 2010		Kinetic 100 DP	179.8
10	Sean Moloney	Weldon	13 Apr 2011		Deepend	177.5

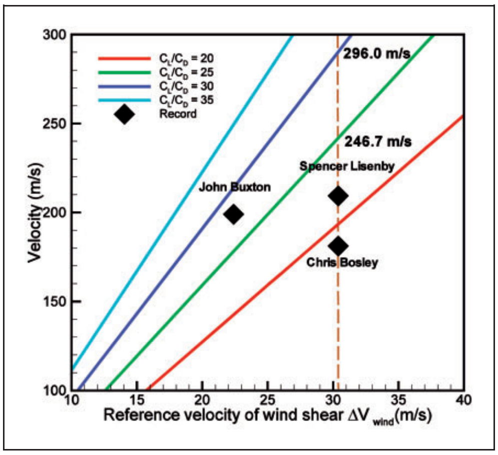

Figure 8. The possible maximum velocity of UAV in dynamic soaring.

to drag of Kinetic 100 DP cannot be found in open literatures, it is hard to estimate what the maximum velocity for this kind of gilder is in dynamic soaring. But it can be asserted that the maximum velocity of dynamic is 296.0 m/s if the maximum of C_L/C_D is 30, or 246.7 m/s if the maximum of C_L/C_D is 25 and when the $\Delta V_{wind} = 30.4$ m/s.

Long-endurance unpowered flights

The most common phenomenon of dynamic soaring in nature is long-endurance unpowered flight, whose trajectory is travelling type. The numerical method to investigate the minimum shear wind strength required for this type can be seen in Zhao,[16] Deittert et al.,[32] and Sachs.[69] Figure 9 provides a perspective view of the long-endurance unpowered flight.

Figure 9(a) shows the flight path of albatross during 6 days, the whole path is consisted of curved trajectory segments that are continuously repeated close to the water surface, as shown in Figure 9(b). The data of both Figure 9(a) and (b) are recorded by the GPS on the coarse 1 Hz online solution. Figure 9(c) is calculated using fine-scale 10 Hz position fixes derived from a GPS post-processing software, which shows that the maneuver in long-endurance unpowered flight is composed of four phases: (1) a windward climb, (2) the upper curve from wind to leeward flight direction, (3) a leeward descent, and (4) a lower curve from lee to windward flight.[10] This kind of fight manner in wind shear may be used in small UAV to enhance its endurance ability in carrying out surveillance missions.

Extracting energy from wind shear for electrical power production

Since the UAV can extract energy from wind shear to increase its altitude or airspeed, it is possible to use the adding energy for power production. Barnes and MacCready[70] have outlined one of this UAV,

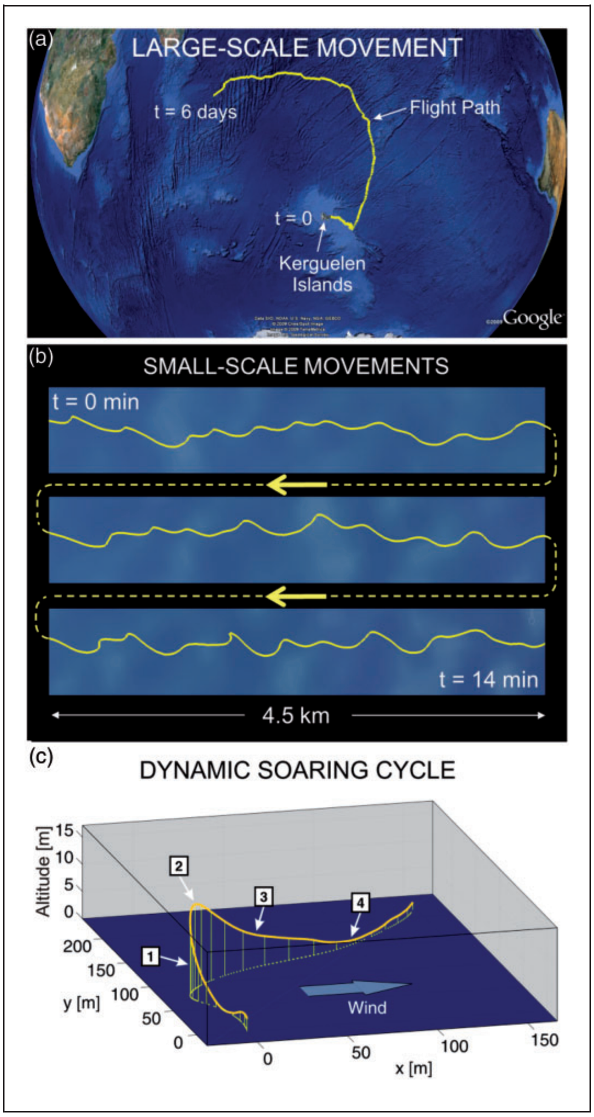

Figure 9. The long-endurance unpowered flights.[10]

which incorporates a wind turbine and an energy storage system, as shown in Figure 10. The wind turbine is a dual-role machine, which can be used for electrical power production when the strength of wind shear is great enough and to propel the UAV when the wind is lull. The energy storage system is used to store the electrical energy when the wind turbine works in the power mode and to supply the electrical energy when the wind turbine in the thrust mode.

The equation of motion for the energy stored in the on-board battery is given by the following equation

$$m\dot{V} = -D - \eta_{gen} D_{gen} - mg \sin\gamma - m\dot{V}_W \cos\gamma \sin\Psi \tag{27}$$

where D_{gen} is the drag of wind turbine working in the power mode, and η_{gen} is the energy conversion coefficient of wind turbine.

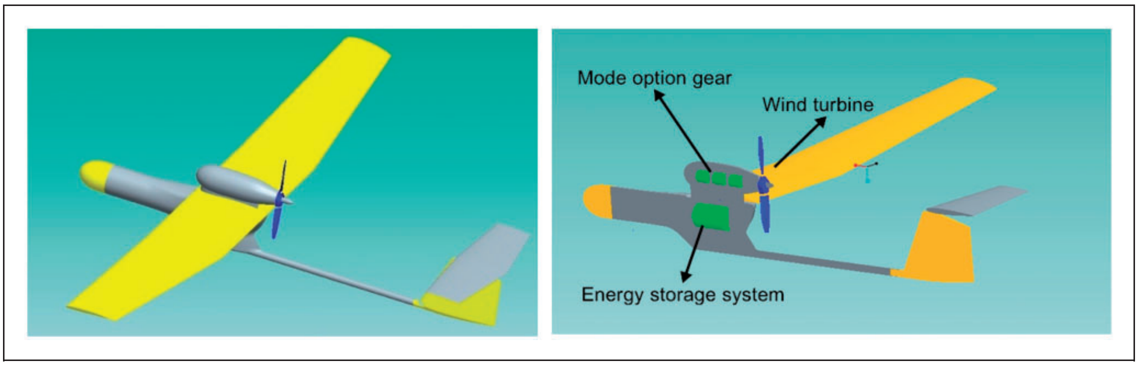

Figure 10. The concept of regenerative soaring UAV.

Challenges

Generally speaking, although the phenomenon of dynamic soaring has been observed and researched nearly 130 years from Rayleigh[26] in 1883 to now, the application of energy extraction from wind shear is immature yet. The immaturities are embodied in two aspects: the first is the structure materials of UAV for dynamic soaring; the second is the autonomous navigation and control system of UAV.

Structure materials

The lift force acting on UAV is about 30–50 times more than gravity during high-speed unpowered dynamic soaring,[9] thus the significant structural reinforcement in the fuselage and wing is important and the models are commonly built using composite materials.[71] However, Lentink et al.[72] has shown that the birds change the shape and size of their wings continually in dynamic soaring to exploit the profound effect of wing morphology on aerodynamic performance and choosing the most suitable sweep can halve sink speed or triple turning rate, which means that it is advantageous for UAV to have a morph wing. Finding a balance between the strength of structure and the efficiency of aerodynamic is still a problem for the designers of UAV used for dynamic soaring.

Autonomous navigation and control

Many researchers have proposed that one effective method to extend range and speed in autonomously guided UAVs is to incorporate dynamic soaring techniques within the navigation algorithm.[4,73] The numerical simulation results about high-speed and long-endurance unpowered flights are encouraging for this idea.[31,33] However, the optimal solutions may not be achievable in practice yet, since the autonomous pilot about the UAV for dynamic soaring have not been developed until now. More works are needed to determine the closed-loop navigation and control law to perform dynamic soaring.[39,74–77]

Future

Although there are many challenges for UAVs to extract energy from wind shear autonomously now, dynamic soaring is considered as one the most promising choice to supply power for the small UAVs. Especially in the long-endurance mission on Mars[78,79] and other emergent circumstances. The wind shear is widely distributed on the earth and Mars, the energy in wind shear is giant and regenerative compared with the onboard fuel or battery. It can be expected that to extract energy from wind shear has a bright future. The UAV incorporated with dynamic soaring will become a powerful land or oceanographic tool to do the works such as long-endurance surveillance, closer measurements of wave patterns, surface temperatures, oil slicks, and others.[80]

Conclusions

The research development and the energy extraction process in dynamic soaring from the view of energy transformation are reviewed and analyzed in this paper. The conclusions of this paper can be summarized as follows:

1. The estimated accuracy of wind speed is about 0.2–0.5 m/s under current filter technology. So, it is possible to design a UAV to operate in an unknown wind field and extract energy from it to keep long-endurance flight autonomously.
2. A UAV can extract energy from wind shear if only the product of $\sin\gamma$ and $\sin\Psi$ is negative when β is positive or the product of $\sin\gamma$ and $\sin\Psi$ is positive when β is negative. So a UAV can always extract energy from wind gradient, whatever the gradient of wind shear is positive or negative.
3. The crucial parameters to the performance of dynamic soaring in wind shear are strength of gradient wind, the ratio of lift and drag, the current air speed of UAV, the current pitch angle, and the azimuth of UAV.
4. The energy extraction efficiency is determined by the cruise airspeed, the ratio of lift to drag, the

strength of step wind shear, and the bank angle of UAV. It also reveals that the important parameter for energy extraction in Rayleigh cycle is not the strength of wind shear, but rather the change in wind speed compared to the UAV's cruise airspeed.

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Conflict of interest

None declared.

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