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Characteristics of Maximum Gliding Endurance Path for High-Altitude Solar UAVs

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***Abstract*—**Gliding during night without electric power is an efficient method to enhance endurance performance of solar aircrafts. The properties of maximum gliding endurance path are studied in this paper. The problem is formulated as an optimization problem about maximum endurance can be sustained by certain potential energy storage with dynamic equations and aerodynamic parameter constrains. The optimal gliding path is generated based on gauss pseudo-spectral method. In order to analyse relationship between altitude, velocity of solar UAVs and its endurance performance, the lift coefficient in interval of [0.4, 1.2] and flight envelopes between 0~30km are investigated. Results show that broad range of lift coefficient can improve solar aircrafts' long endurance performance, and it is possible for a solar aircraft to achieve the aim of long endurance during whole night just by potential energy storage.

***Keywords*—**Solar UAVs; Gliding Endurance; gauss pseudo-spectral method; optimization problem

I. INTRODUCTION

IN recent decades, solar UAVs have drawn greatly attentions to achieve the goal of high-altitude long-endurance (HALE) in many research groups all around world[1-3]. There were mainly two series of HALE UAV projects—ERAST and Zephyr already basically achieving the high-altitude, long-endurance goals. The former one includes Pathfinder, Pathfinder+, Centurion, Helios HP01 and Helios HP03, whose sizes range from 30.2m to 75.3m wingspan. On August 2001, the HP01 prototype reached a record altitude 29.5km, and the flight durations extended to 18 hours, whereas, the HP03, which was designed for long-duration flight, encountered a disturbance in the way of turbulence and morphed into an unexpected configuration, at last, it lost ability to maintain lift and fell into Pacific, one of the root causes was structure significantly reducing design robustness [4]; the later one includes from Zephyr3 to Zephyr7.On July 2010, Zephyr 7 flew for over 336 hours in Yuma, Arizona, reaching an altitude of 21.6km, it flowed on solar power generated by amorphous silicon arrays, but it couldn't supply enough power yet, and must rely on Sion-Power batteries to supply extra-power to maintain level flight during night[5], so it didn't realized long endurance flight authentically yet.

After these pioneer experiments, researchers gradually realized that: the crucial technology to constrain the aim of HALE for solar UAVs are the conflict between weight of aircraft and power requirement[6, 7].

As pointed out by ref.[8]: the weight of the batteries represents around 50% of the total mass of solar aircraft; the density of the batteries is therefore a dominant value concerning feasibility. Nowadays, electric batteries reach around 200 Wh/kg. Though it is expected that this value will double within next decade[9], and the required power consumption allows dimensioning the weight of battery, whereas the additional weight of battery needs more power to sustain continuous flight at the same time [6]. So it can only see that the feasibility of continuous flight is possible at low altitude in nowadays.

The final target of solar aircraft is to achieve the aim of high-altitude long-endurance flight, except waiting for the greatly progress on technologies of ultra-lightweight structure and rechargeable battery, it is also valuable to research on alternative method to enhance endurance performance of solar aircraft solar aircraft by the characteristics of near-space. In order to achieve the goal of attaining a night flight capability requiring as little solar energy as possible, an appropriate trajectory control during gliding in night is considered an efficient method. Thus, an unlimited endurance flight capability becomes feasible with a minimum or even no solar energy to be stored in batteries[10]. As everyone known that, gliding is the solo mode for solar UVAs in night without electric energy storage batteries, in this mode, solar UAVs covers the aerodynamic cost by losing potential energy, thus, it needs a minus path pitch angle to maintain that the projection of gravity on velocity can counteract the force generated by the airflow on the wings[11]. Hence, the main questions for this method are which manner is the best way to get the maximum gliding endurance, and what the main characteristics of maximum gliding endurance path are, and what the influences of velocity and altitude are to gliding endurance performance.

The objective of the paper is to study the characteristic of maximum gliding endurance path. The problem of finding the maximum gliding endurance path is formulated to be one of optimum problem, and the gauss pseudo-spectral method is employed to solve this problem. The remainder of this paper is organized as follows. The aircraft kinematic model and formulation of maximum gliding endurance problem are introduced in section 2. The methods to estimate and analyze aerodynamic parameters are discussed in section 3. Next, the optimal gliding path is generated based on gauss pseudo-spectral method, the difference between optimal gliding path and minimum sinking rate path are analyzed in section 4. The characteristics of maximum gliding endurance path are summarized in section 5. Finally, the conclusions and future works are presented in section 6.

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II. PROBLEM FORMULATION

A. Aircraft Kinematic Mode

The interesting solar UAV in the paper can be described as follow: its main energy comes from solar panels, which are composed of silicon arrays covered on surface of wing or other part of airplane. During daytime, it converts light into electrical energy, which is divided into two parts by energy management system, one part supplies power to motor and other electronics, the other part charges to lithium-sulphur battery with surplus of energy[12]. For describing the motion of the solar UAV, a mathematical model based on point mass dynamics is supposed to be applicable[10], as shown in Fig.1, solar UAV is assumed to fly in still air, the velocity axes[13] is used for the aircraft, and thus the assumption of vertical plane flight induces an assumption of zero yaw angle.

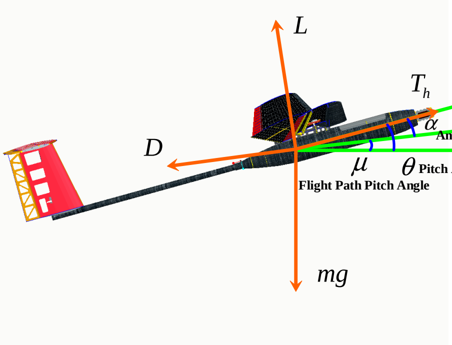

Fig. 1 Scheme of force acted on aircraft

The main aim of this paper is to analyse the gliding endurance of aircraft, so the thrust model will not be considered, and then the kinematic model can be formulated as follows:

$$\begin{cases} m\dot{V} = -D - mg\sin\mu \\ mV\dot{\mu} = L - mg\cos\mu \\ \dot{h} = V\sin\mu \\ \dot{x} = V\cos\mu \end{cases} \tag{1}$$

Where x and h are the Cartesian coordinates of the aircraft, μ is the heading angle, V is the speed, m is the mass of aircraft, L and D are lift force and drag force respectively, they can be obtained by interpolation from a table defined by attack angle, altitude and velocity, and this will be discussed particularly in section 3.

B. Formulation of Maximum Gliding Endurance Problem

The maximum gliding endurance of solar aircraft can be considered as the maximum flight time of solar UAV during unit distance in vertical altitude without thrust, thus, the performance criterion can be formulated as

$$J = \min\left(t_0 - t_f\right) \tag{2}$$

Where t_0 and t_f denote the initial time and final time of the whole process respectively, and the boundary condition can be expressed as

$$\begin{aligned} V(t_0) &= V_0 \\ \mu(t_0) &= \mu_0 \\ h(t_0) &= h_0 \\ h(t_f) &= h_f \end{aligned} \tag{3}$$

Because of Reynolds number is the function of altitude and velocity, which are states variables in Eq.(1), so the attack angle is the sole control variable, and it subjects to the inequality constrain in flight envelope:

$$\alpha_{\min} \le \alpha \le \alpha_{\max} \tag{4}$$

The optimal control problem can now be formulated as to determine attack angle of aircraft under constrain of Eq.(4) as well as dynamic equation of Eq.(1) to minimize the performance criterion of Eq.(2) at the initial and final boundary condition of Eq.(3). For solving the described endurance performance problem, efficient optimization methods and computational techniques capable of coping with complex relationships are required, which will be described in section 4.

III. AERODYNAMIC PARAMETERS ANALYSIS

For estimating the dynamic features of the solar UAVs, it is important to acquire its aerodynamic parameters from sea level to an altitude of 30km. The forces of lift L and the drag D acting on the aircraft during level flight can be defined as Eq.(5) & Eq.(6), where C_L and C_D are respectively the lift and drag coefficients, ρ is the air density, S_w is the wing area and V is the airplane relative speed.

$$L = C_L S_w \left(\frac{1}{2}\rho V^2\right) \tag{5}$$

$$D = C_D S_w \left(\frac{1}{2}\rho V^2\right) \tag{6}$$

Although C_L and C_D heavily depend on the airfoil, the angle of attack α and the R_e number, for the high aspect ratio wing of HALE UAV, there is just a little difference between complete aircraft and 2-D airfoil in lift efficiency, so it is reasonable to assume lift coefficient C_L of HALE UAV can be approximated by its 2-D airfoil[14]; nevertheless, it is a little complex to estimate drag coefficient, which is the sum of the airfoil drag C_{Da}, the parasitic drag of non-lifting part C_{Dp} and the induced drag C_{Di}. C_{Da} can be estimated by the drag coefficient of 2-D airfoil; C_{Dp} is always very small, because of the interference between fuselage and airfoil is not obvious for the high-aspect ratio wing, for the solar aircraft in this paper, after some flight tests, parasitic drag coefficient can be estimated as C_{Dp}=0.005[1]; The induced drag can be estimated by Eq.(7), where e is the Oswald's efficiency factor and AR is the aspect ratio of the wing.

$$C_{Di} = \frac{C_L^2}{e\pi AR} \tag{7}$$

The method to compute drag coefficient can be summarized as (8).

$$C_D = C_{Da} + C_{Dp} + C_{Di} \tag{8}$$

There are mainly three ways to get aerodynamic parameters: wind tunnel experiment, CFD simulation and engineering estimation, such as Profili or X-foil. Taking FX63-137 airfoil as an example, on the condition of R_e=150000, a comparison about lift coefficient and drag polar among wind tunnel data, CFD simulation by Fluent and estimation by Profili is shown in Fig.2.

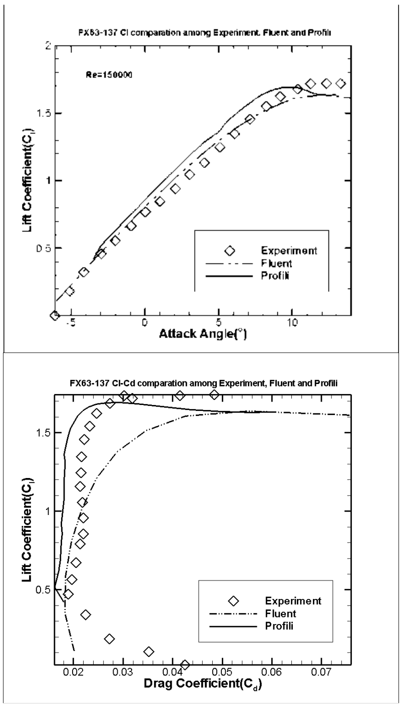

Fig. 2 Comparison of lift coefficient and lift-drag polar among three methods

From Fig.2 we can find that results show good correlation among three methods. The result of Profili is better than Fluent in high lift coefficient, what is more, comparing with Fluent, Profili is convenient to operate, therefore, the following computational analysis in this paper to assess the aerodynamic characteristics of UAV is undertaken by Profili. Supposing the range of lift coefficient is between 0.4 and 1.2, the flight envelope of solar UAV can be shown in Fig.3.

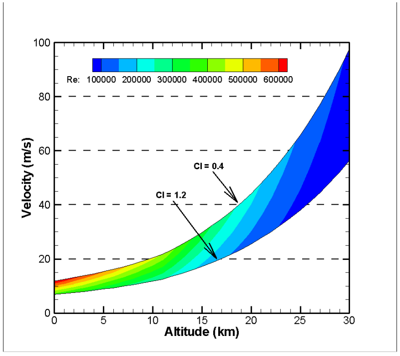

Fig. 3 Flight envelope of solar UAV while C_L is between 0.4 and 1.2

Because the Reynolds number is the function of altitude and velocity, so the lift and drag coefficient of solar UAV can be expressed as a function of attack angle and Reynolds number, i.e.

$$\begin{aligned} C_L &= C_L(\alpha, h, V) = C_L(\alpha, R_e) \\ C_D &= C_D(\alpha, h, V) = C_D(\alpha, R_e) \end{aligned} \tag{9}$$

Then, the interpolation table of lift and drag coefficient can be obtained by discretion of attack angle and Reynolds number. While lift coefficient is between 0.4 and 1.2, the upper and lower bound of attack angle can be determined by one certain Reynolds Number, so the constrain of Eq.(4) can be described in Fig.4.

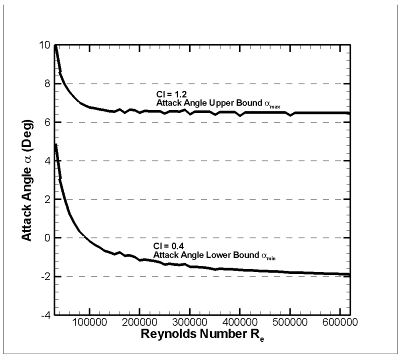

Fig. 4 Upper and Lower Bound of attack angle while C_L is between 0.4 and 1.2

IV. MAXIMUM GLIDING ENDURANCE PATH PLANNING

Because the maximum gliding endurance path planning problem can be converted to the minimum problem of Eq.(2), employing Pontryagin's minimum principle, the necessary conditions for optimality for minimum problem can be applied to the current problem. With states $[V, \mu, h, x]^{\mathrm{T}}$ and control input α, the Hamiltonian function is

$$\begin{aligned} & H(V, \mu, h, x, \lambda_V, \lambda_\mu, \lambda_h, \lambda_x, \alpha) \\ & = -1 + \lambda_V \left(-\frac{D}{m} - g \sin \mu \right) \\ & + \lambda_\mu \left(\frac{L}{mV} - \frac{g \cos \mu}{V} \right) + \lambda_h (V \sin \mu) + \lambda_x (V \cos \mu) \end{aligned} \tag{10}$$

Where $[\lambda_V, \lambda_\mu, \lambda_h, \lambda_x]^{\mathrm{T}}$ is the co-state vector, the state equations derived from (10) are

$$\begin{cases} \dot{V} = \dfrac{\partial H}{\partial \lambda_V} = -\dfrac{D}{m} - g \sin \mu \\ \dot{\mu} = \dfrac{\partial H}{\partial \lambda_\mu} = \dfrac{L}{mV} - \dfrac{g \cos \mu}{V} \\ \dot{h} = \dfrac{\partial H}{\partial \lambda_h} = V \sin \mu \\ \dot{x} = \dfrac{\partial H}{\partial \lambda_x} = V \cos \mu \end{cases} \tag{11}$$

The co-state equations are

$$\begin{cases} \dot{\lambda}_V = -\dfrac{\partial H}{\partial V} = -\dfrac{\lambda_\mu}{mV^2}\left(L - mg\cos\mu\right) \\ \qquad + \lambda_h \sin\mu + \lambda_x \cos\mu \\ \dot{\lambda}_\mu = -\dfrac{\partial H}{\partial \mu} = -\lambda_V g\cos\mu + \dfrac{\lambda_\mu g\sin\mu}{V} \\ \qquad + \lambda_h V\cos\mu - \lambda_x \sin\mu \\ \dot{\lambda}_h = -\dfrac{\partial H}{\partial h} = 0 \\ \dot{x} = -\dfrac{\partial H}{\partial x} = 0 \end{cases} \tag{12}$$

The boundary conditions for the flight are

$$\begin{cases} V(t_0) = V_0 \\ \mu(t_0) = \mu_0 \\ h(t_0) = h_0 \\ h(t_f) = h_f \end{cases} \tag{13}$$

Because the final time is uncertain, in the final time t, the following equations must be satisfied

$$\begin{aligned} &\frac{\partial\left(h(t_f) - h_f\right)}{\partial\left[V_f, \mu_f, h_f, x_f\right]^T}\upsilon - \begin{bmatrix} \lambda_{Vf} \\ \lambda_{\mu f} \\ \lambda_{hf} \\ \lambda_{xf} \end{bmatrix} = 0 \\ &\Rightarrow \boldsymbol{\lambda}_f = \begin{bmatrix} \lambda_{Vf} \\ \lambda_{\mu f} \\ \lambda_{hf} \\ \lambda_{xf} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -\upsilon \\ 0 \end{bmatrix} \end{aligned} \tag{14}$$

$$\begin{aligned} &\left(\frac{\partial\left(h(t_f) - h_f\right)}{\partial t_f}\right)\upsilon \\ &\quad + H\left(V_f, \mu_f, h_f, x_f, \lambda_{Vf}, \lambda_{\mu f}, \lambda_{hf}, \lambda_{xf}, \alpha_f\right) = 0 \\ &\Rightarrow -1 + \frac{\lambda_{Vf}}{m}\left(-D - mg\sin\mu_f\right) + \frac{\lambda_{\mu f}}{mV_f}\left(L - mg\cos\mu_f\right) \\ &\qquad + \lambda_{hf} V_f \sin\mu_f + \lambda_{xf} V_f \cos\mu_f = 0 \\ &\Rightarrow \qquad -1 + \lambda_{hf} V_f \sin\mu_f = 0 \\ &\Rightarrow \qquad \upsilon = -\lambda_{hf} = -\frac{1}{V_f \sin\mu_f} \end{aligned} \tag{15}$$

From (10)~(15), it can be confirmed that the maximum gliding endurance problem belongs to the Lagrange form of the optimal control problem, however, it is not easy to find its analytic solution directly by Pontryagin's minimum principle, an alternative method is to discretize state Eq. (11), co-state Eq.(12), as well as control constrain Eq. (4) to an Nonlinear Programming Problem (NLP), many methods including direct collocation Pseudo-spectral methods and spline approximations have been developed to solve similar optimal control problem[15-17], here, the Gauss Pseudo-spectral method is employed, this method is based on approximating the states and control trajectories using interpolating polynomials, and optimal control problems can be carried out by a MATLAB software named Gauss Pseudo-spectral Optimization Software (GPOPS)[18] with some reasonable optimality and feasibility tolerances. To improve the rate of convergence and the probability of accurate result, a good initial guess is required.

For a gliding aircraft, the Sinking Rate V_{SR} can be expressed as $V sin\mu$[19], because the ratio of drag force to lift force is close to $sin\mu$, as shown in Fig.1, so

$$V_{SR} = V\sin\mu = V\frac{C_D}{C_L} \tag{16}$$

During level flight, the lift force equals to weight of aircraft, i.e.

$$mg = C_L S_w\left(\frac{1}{2}\rho V^2\right) \Leftrightarrow V = \sqrt{\frac{2mg}{\rho S_w C_L}} \tag{17}$$

It can be derived from Eq.(16) & Eq.(17) that

$$V_{SR} = \sqrt{\frac{2mg}{\rho S_w C_L}}\frac{C_D}{C_L} = \sqrt{\frac{2}{\rho}\left(\frac{mg}{S_W}\right)}\left(\frac{C_D}{C_L^{3/2}}\right) \tag{18}$$

Because mg/S_W is constant, and ρ is also a constant at certain altitude, so the sinking rate is solely determined by aerodynamic parameters C_L and C_D, the minimum sinking rate can be calculated by Eq.(19)

$$C_d / C_l^{3/2}\left(\alpha^*\right) = \min_{\alpha_{\min} \le \alpha \le \alpha_{\max}}\left(C_d / C_l^{3/2}(\alpha)\right) \tag{19}$$

For lift and drag coefficient C_l and C_d have been determine in Section 3, so, α^* can be obtained and used to be as initial control direction, then, initial guess path is generated by integrating Eq.(11), the final time can be determined by boundary condition Eq.(13). According to Eq.(14)&(15), the end value of co-state can be calculated, therefore, the initial guess co-state can be generated by inversely integrating Eq.(12).

TABLE I
THE BASIC PARAMETERS OF SOLAR UAV AND BOUNDARY CONDITIONS

Name of Parameters	**Value of Parameters**
Aircraft Mass	40 kg
Chord Length	0.8 m
Aspect Ratio	20
Wing Area	12.8m2
Initial Velocity V_0	40 m/s
Initial Flight Path Angle μ_0	0 Rad
Initial Position (x_0, h_0)	(0,20000) m
Final Altitude h_f	19000 m

After these preparation works, it will be very suitable and efficient to solve the proposed path optimization problem by transcribed it into a large-scale NLP problem, the Legendre-Gauss points used in the simulation is 150. The basic parameters of solar UAV and boundary conditions are listed in Table I. Fig.5 shows the path of the four state variables, Fig.6 shows the four co-state variables, Fig.7 shows the value of Hamiltonian and the corresponding control variable α.

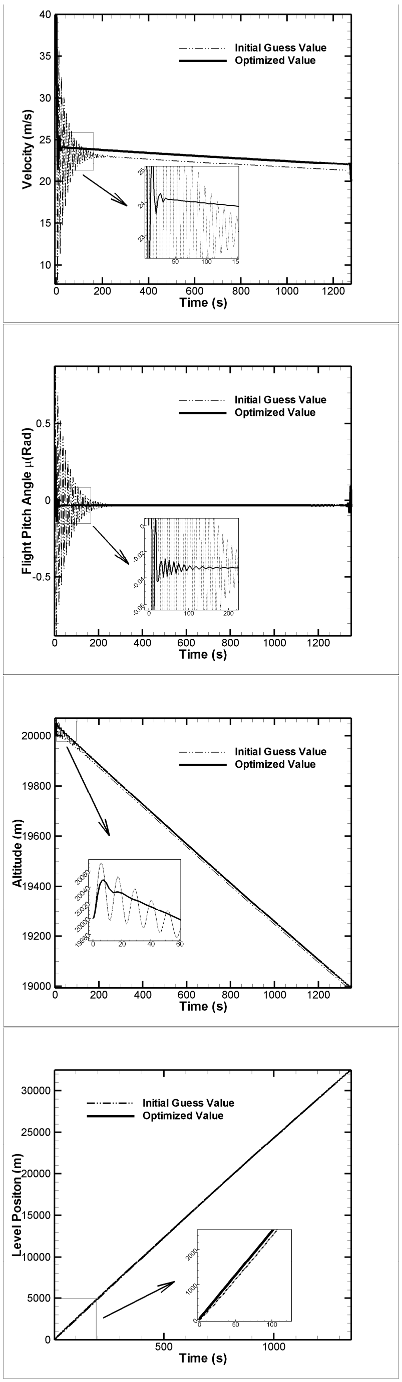

Fig. 5 Comparison about states $[V, \mu, h, x]^T$ between initial guess path and optimized path

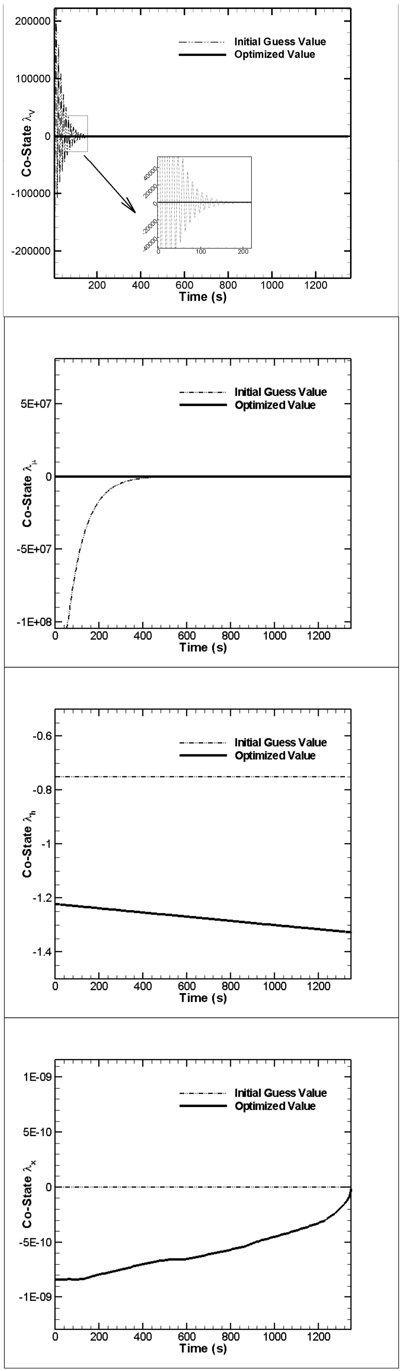

Fig. 6 Comparison about co-states $[\lambda_V, \lambda_\mu, \lambda_h, \lambda_x]^T$ between initial guess path and optimized path

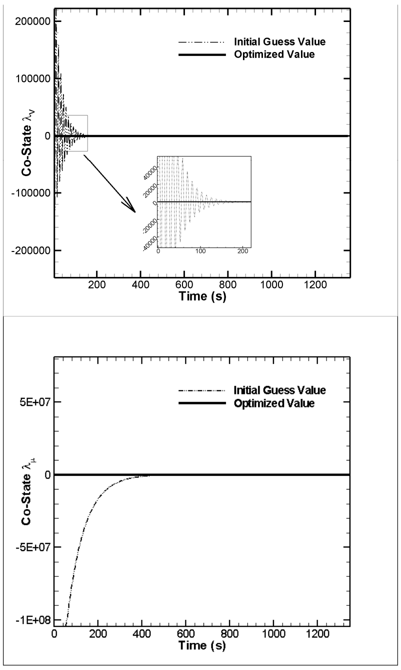

Fig. 7 Comparison about Hamiltonian and control variable α between initial guess path and optimized path

From above figures, it is can be clearly seen that Eq.(19) as well as Eq.(11) and Eq.(12) provide a relatively precise initial guess value for the path optimization problem, and simulation results demonstrates that the Gauss Pseudo-spectral method takes on a fast convergence rate and high optimization precision for this problem.

For the initial guess control variable α^*, the gliding endurance is 1250s, while for the optimum control variable α^{opt}, the gliding endurance is 1289s. There is just a slight difference on gliding performance between guess and optimum control variable, the value of Hamiltonian show that, they have greatly different property during initial process, which may cause considerable diversity in different condition.

The characteristics of velocity and attack angles in optimum gliding path can be found by comparing the velocity profiles on the supposed condition with the corresponding velocity profiles of minimum sinking rate defined by Eq.(19). As shown in Fig.5 and Fig 7, during the steady gliding process on the condition of supposed initial velocity and altitude, their velocity profiles and attack angle profiles almost superposed with that generated by minimum sinking rate.

This phenomenon shows that the optimum gliding path is also defined by minimum sinking rate in steady gliding process. It also gives a reasonable interpretation about why initial guess can make Gauss Pseudo-spectral methods work efficiently. Accounting for the initial conditions cannot always satisfy the requirement of minimum sinking rate, optimal control method computed one path which can transfer the initial states of solar aircraft to one state fulfilled with requirement of minimum sinking rate, meanwhile, the gliding endurance can be maximized.

V. CHARACTERISTICS OF MAXIMUM GLIDING ENDURANCE PATH

According to the method described in above sections, the properties of maximum gliding endurance path will be analyzed in this section. In order to find the optimum style for a solar aircraft to gliding, the influence of initial velocity to gliding endurance at the same altitude must be researched firstly, and then the influence of initial altitude to gliding endurance during unit distance will be analyzed.

A. The influence of initial velocity to gliding endurance

Taking the same parameters and boundary conditions as Table I, except initial velocity will be changed from 25.5 m/s to 44.1m/s, which is determined by the lift coefficient and altitude of aircraft in flight envelope, the step is chosen as 1m/s, then the relationship between initial velocity and gliding endurance can be shown in Fig.8. From this figure, it is can be found that, the gliding endurance is approximately in proportion with initial velocity, but when velocity is changed from 25.5 to 44.1 m/s, which means kinetic energy of aircraft greater nearly one times, whereas the gliding endurance time is just varied from 1224s to 1297s, this data reveals the influent of velocity to gliding endurance is more and more weak. Setting out from this insight, let T and V represent gliding endurance time and initial velocity respectively, for $0.5m^2V$ represents kinetic energy of aircraft, so it is reasonable to define velocity factor K_V as follows:

$$K_V = \frac{T}{V^2} \tag{20}$$

The relationship of velocity factor to initial velocity is depicted by light line in Fig.8.

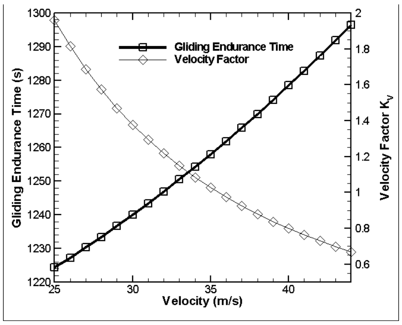

Fig. 8 The relationship of gliding endurance time and velocity factor to initial velocity

Fig. 8 shows that, the less initial velocity the greater velocity factor can be achieved, the relationship of lift coefficient and level flight velocity in flight envelope is

$$V_{lev} = \sqrt{\frac{2mg}{C_l S_w \rho}} \tag{21}$$

Above equation reveals that the large lift coefficient is propitious to get good velocity factor, while, the dark line in Fig.8 also shows that, the more initial velocity, the longer gliding endurance time can be obtain, according to (21), small lift coefficient can deprive better gliding performance. So, it is advantage for solar aircraft to be designed as broad range of lift coefficient as possible to get good gliding performance.

B. The influence of initial altitude to gliding endurance

The method to analyze influence of initial altitude to gliding endurance is the same as above, Taking the aircraft parameters as Table I too, taking $\Delta H = 1km$ as unit altitude, the boundary condition are changed to initial altitude $h_0 = [30,29,\cdots,2,1]km$, the final altitude is chosen as $h_f = [29,28,\cdots,1,0]km$ correspondingly; according to analysis in above subsection, it is better to chose a low initial velocity in flight envelope, so initial velocity is the lower line in Fig.3.Defining altitude factor K_h as follows:

$$K_h = \frac{T}{g\Delta H} \qquad (22)$$

The relationship of gliding endurance time and altitude factor to initial altitude can be shown in Fig.9.

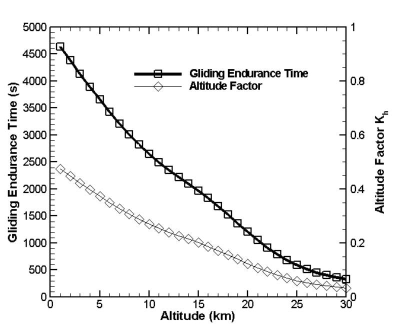

Fig. 9 The relationship of gliding endurance time and altitude factor to initial altitude

Above figure shows that the lower initial altitude, the longer gliding endurance can be sustained by unit altitude, below 4 km, aircraft can glide more than 3600 second, i.e. 1 hour, during vertical altitude of descending 1km, while, during the same vertical distance, aircraft can only glide fewer than 1000 second above 22km.

C. Feasibility Analysis of Unlimited Endurance with Zero Electric Energy Storage

As discussed in Section I, comparing to electric energy storage, the potential energy storage has great merits, but it is can be seen clearly from above subsection, with the increasing of initial altitude, altitude factor decreases dramatically, so, it is less efficient for potential energy storage in high altitude, but what the appropriate interval is for potential energy storage is needed to be analyzed. Here, without loss generality, supposing the night time in one day is 12 hours, Fig.10 shows the feasible altitude interval for potential energy storage.

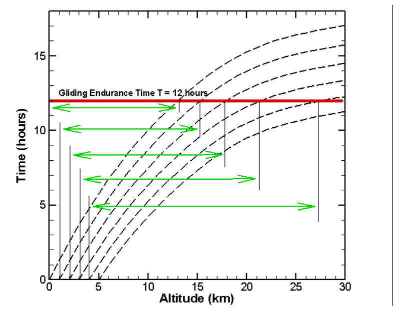

Fig. 10 Feasible altitude interval for potential energy storage

Fig. 10 shows abundant information for us to choose a feasible altitude interval to take measure of potential energy storage, the long dash line presents cumulative time during the each altitude intervals stepped by 1 km, the red line represents that cumulative time equals to 12 hours, and the green bi-arrow line indicates the feasible altitude interval for potential energy storage. From this figure we can see, if we required potential energy storage must sustain 12 hours gliding endurance during night, aircraft must flight to at least 13km, and then glide to the ground, or flight to 27km, and glide to 4km. Although it is seem possible for an aircraft to achieve unlimited endurance without electric energy storage in above analysis, however, it is not safe and reality for a solar aircraft to glide too low during night, because there always is great wind between altitude of 8 and 12 km, so potential energy storage can only partly instead of electric energy storage in application now, it is still a long way to go to achieve unlimited endurance performance of solar aircraft with zero electric energy storage.

VI. CONCLUSIONS AND FUTURE WORKS

The properties of maximum gliding endurance path are systemically studied in this paper. The results of this preliminary study can be concluded as follows:

The large lift coefficient is propitious to get good velocity factor. The larger initial velocity, the longer gliding endurance time can be obtain, So, it is advantage for solar aircraft to be designed as broad range of lift coefficient as possible to get good gliding performance. The lower initial altitude, the longer gliding endurance can be sustained by unit altitude. Below 4 km, aircraft can glide more than 3600 second during vertical altitude of descending 1km, while, during the same vertical distance, aircraft can only glide fewer than 1000 second above 22km. It could be possible for a solar aircraft to sustain 12 hours gliding endurance without supplement of electric power during night, although aircraft must flight to a high altitude more than 13 km, and then glide to a relatively very low altitude.The future works to study the method of enhancing performance of solar aircraft are planned to consider the complete day-night cycle of solar aircraft, and find the optimal trajectory to achieve the aim of high-altitude flight, and find the relationship between the mass of rechargeable electric batteries and altitude ceiling bound of solar aircraft.

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