UNIQUE PERFORMANCE CHARACTERISTICS OF SOLAR AIRCRAFT

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Abstract

Unique flight performance characteristics of solar aircraft are identified. There are substantial differences when compared to aircraft with an air-breathing propulsion system. Characteristic properties of the flight envelope of solar aircraft are determined. It is shown that solar aircraft can achieve a higher ceiling and a greater maximum speed than comparable aircraft with an air-breathing propulsion system. Furthermore, solar aircraft are dealt with which can store energy in batteries. Thus, they offer the possibility of an unlimited endurance performance. As a performance goal case, the minimization of the required battery capacity is considered in order to keep the related weight penalty as small as possible. Results from the trajectory optimization for a solar aircraft with an unlimited endurance capability are presented. They show that the optimal trajectory consists of segments with characteristic properties.

Nomenclature

C_D	drag coefficient
C_L	lift coefficient
D	drag
E	energy
g	acceleration due to gravity
h	altitude
J	performance criterion
L	lift
m	mass
n_ρ	altitude effect on power
P	power
Q	battery capacity
q	battery charging
$\bar{q}$	dynamic pressure, $\bar{q} = (\rho/2)V^2$
S	reference area
T	thrust
t	time
V	speed
γ	flight path angle
δ_P	power setting
ε	drag-to-lift ratio
η	efficiency factor
ρ	density

1 Introduction

Considerable progress in solar technology has contributed to the interest which aircraft using the sun radiation for thrust production have attained in recent years. There are significant research and development efforts in this field (e.g., Refs. 1-8). Various solar aircraft have been built, and their performance capability has been successfully demonstrated.

For the performance issues dealt with in this paper, solar aircraft may be grouped into two categories I and II: Category I concerns solar aircraft which use the sun radiation for thrust production only during daytime and do not store solar energy in batteries for a flight in the night. Category II relates to solar aircraft which possess an ability to store the energy received from the sun so that a flight is possible also in the night when there is no sun radiation. Thus, a performance capability with an unlimited endurance becomes feasible.

It is the purpose of this paper to derive and present results on the flight performance of solar aircraft. It will be shown that there are unique performance characteristics of these types of aircraft when considering comparable vehicles equipped with an air-breathing propulsion system. There are substantial differences as regards the achievable maximum performance in terms of ceiling and top speed as well as in the associated flight conditions. Furthermore, solar powered aircraft offer the possibility of an unlimited endurance performance.

2 Available Solar Power and Engine Power

A mathematical model for describing the sun radiation has been developed, accounting for all dependencies relevant for the flight of solar aircraft. These dependencies are due to the effects of the time of day, altitude, latitude, longitude and season on the solar power that can be received. Effects of the daytime, the altitude and the latitude are graphically illustrated in Figs. 1 and 2.

The power available for propelling the vehicle does not only depend on the solar radiation, but also on the power characteristics of the electrical motor which drives the propeller. For the solar aircraft under consideration, it is assumed that the power of the motor is given by the following relation

$$0 \le P \le P_{\max} \tag{1}$$

where the maximum power output which the electrical motor provides, $P_{\max}$, is regarded as constant for the speed and altitude ranges of interest.

3 Modeling of Solar Aircraft

The solar aircraft is considered to comprise the following main modeling components

– Aircraft dynamics model
– Aerodynamics model
– Engine and energy management models

For describing the dynamics of the vehicle, a mathematical model based on point mass dynamics can be applied, yielding

$$\begin{aligned} \dot{V} &= \frac{T-D}{m} - g\sin\gamma \\ \dot{\gamma} &= \frac{L}{mV} - \frac{g}{V}\cos\gamma \\ \dot{h} &= V\sin\gamma \end{aligned} \tag{2}$$

This model is also used for dealing with the steady-state flight performance (with $\dot{V} = 0$, $\dot{\gamma} = 0$).

The model for the aerodynamic forces, drag and lift, can be expressed as

$$\begin{aligned} D &= C_D(\rho/2)V^2 S \\ L &= C_L(\rho/2)V^2 S \end{aligned} \tag{3}$$

where

$$C_D = C_D(C_L) \tag{4}$$

The model for the propulsion system featuring an electrical motor and a propeller yields the following expression for the thrust

$$T = \eta_P \eta_M \frac{P_{\max}\delta_P}{V} \tag{5}$$

4 Steady-State Flight Performance of Solar Aircraft

4.1 Flight Envelope

The flight envelope of a solar aircraft is shown in Fig. 3. The top and the right part are determined by the maximum available motor power while the left part is due to the maximum lift coefficient. Since the motor power is independent of the altitude, the envelope extends to high values. Thus, there is a comparatively large domain where flights are possible.

For comparison purposes, the flight envelope of a vehicle with an air-breathing propulsion system is presented in Fig. 4 in order to show the unique performance characteristics of solar aircraft. It is assumed that both aircraft have the same aerodynamic characteristics in terms of the drag polar $C_D(C_L)$ and the maximum lift coefficient $C_{L\max}$, the same maximum engine power at sea level ($h=0$), denoted by $P_{\max}$, as well as the same mass.

Comparison of Figs. 3 and 4 basically shows that the flight domain of the solar aircraft is significantly larger, enabling greater altitudes and higher speeds. The left part of the envelope, determined by $C_{L\max}$, is partially the same for both vehicles. This holds until the highest altitude is reached that is possible for a flight of an aircraft with an air-breathing propulsion system at $C_{L\max}$. Thereafter, the envelope of the air-breathing propulsion system aircraft is determined by the engine performance limit given by $P_{\max}$. For the solar aircraft, the limit due to $C_{L\max}$ is still effective concerning higher altitudes. Not until reaching a higher altitude, the flight envelope of the solar aircraft is determined by the motor performance limit $P_{\max}$.

The superiority of the solar aircraft manifests especially in performance quantities such as the ceiling and the maximum speed which are specially marked in Figs. 3 and 4. Analytical relations for these quantities are derived in the following.

4.2 Ceiling

The ceiling of solar aircraft is determined by the power relation

$$P_{\max} = (DV)_{\min} \tag{6a}$$

or by

$$P_{\max} = \sqrt{\frac{(mg)^3}{\bar{C}_L(\rho/2)S}}\,\bar{\varepsilon}_{\min} \tag{6b}$$

where $\bar{C}_L$ is the lift coefficient associated with

$$\left(\frac{C_D}{C_L^{3/2}}\right)_{\min}$$

and $\bar{\varepsilon}_{\min}$ the glide ratio at $\bar{C}_L$

$$\bar{\varepsilon}_{\min} = \frac{C_D(\bar{C}_L)}{\bar{C}_L} \tag{7}$$

Solving Eq. (6) for the maximum altitude in terms of $\rho = \rho_{\min}$ yields the following result for the ceiling

$$\rho_{\min} = 2\frac{\bar{\varepsilon}^2_{\min}}{\bar{C}_L}\frac{(mg)^3}{P^2_{\max}S} \tag{8}$$

4.3 Maximum Speed

Reference is made to the general power relation determinative for the maximum speed

$$P_{\max} = DV \tag{9a}$$

or to

$$P_{\max} = V\frac{C_D}{C_L}mg \tag{9b}$$

Solving for V yields

$$V = \frac{P_{\max}}{(C_D/C_L)mg} \tag{10}$$

From this relation it follows that the maximum speed is obtained as

$$V_{\max} = \frac{P_{\max}}{\varepsilon_{\min}mg} \tag{11}$$

where $\varepsilon_{\min}$ is the minimum glide ratio

$$\varepsilon_{\min} = (C_D/C_L)_{\min} \tag{12}$$

5 Flight Performance of Solar Aircraft with Unlimited Endurance Capability

5.1 Trajectory Optimization Problem

Category II aircraft which can store solar energy in batteries offer the possibility of an unlimited endurance performance. This is because they can use the stored energy for a flight in the night when no sun radiation is available. For such aircraft, a performance goal is to minimize the solar energy which is required for the flight in the night and, hence, to be stored in the batteries. Thus, the weight penalty caused by the batteries can be kept as small as possible. This performance goal can be achieved with a non-stationary flight rather than a steady-state cruise showing constant values of control and state variables. Furthermore, the trajectory yielding an unlimited endurance performance, based on the described performance goal, shows periodic properties. This means that the unlimited endurance trajectory is repeated after a complete day-night cycle in the same manner as before.

For a solar aircraft of category II, the described optimization problem was subject of a detailed computational treatment. An issue in modeling the vehicle is the energy management system which is more complicated than for solar aircraft of category I. A realistic energy management model was developed which is schematically shown in Fig. 5, together with the propulsion system. It comprises the following elements:

– Solar cells (20 % efficiency)
– MPPT (95 % efficiency)
– Electric lines (99.5 % efficiency)
– Converter (98.5 % efficiency)
– Battery manager (99.5 % efficiency)
– Batteries (96.5 % efficiency)

Concerning the battery model, it is assumed that a remainder of 10 % of the battery capacity cannot be used.

The energy management system provides also power for other electrical components. For this purpose, a constant power consumption is considered to be necessary. This has also to be stored in the battery for the time when there is no sun radiation.

For the trajectory optimization problem, the required capacity of the batteries is selected as the performance criterion which can be formulated as

$$J = Q_{Battery}(t_{cyc}) \tag{13}$$

where t_{cyc} is the time of a day-night cycle.

Because of the periodicity of a day-night cycle, the following boundary conditions hold

$$\begin{aligned} V(0) &= V(t_{cyc}) \\ \gamma(0) &= \gamma(t_{cyc}) \\ h(0) &= h(t_{cyc}) \\ Q(0) &= Q(t_{cyc}) \end{aligned} \tag{14}$$

Control variables are C_L, δ_P and q, subject to the following inequality constraints

$$\begin{aligned} C_{L\min} \le C_L &\le C_{L\max} \\ 0 \le \delta_P &\le 1 \\ 0 \le q &\le q_{\max} \end{aligned} \tag{15}$$

There are also constraints in state variables, yielding

$$\begin{aligned} h_{\min} &\le h \le h_{\max} \\ n_{\min} &\le n \le n_{\max} \\ \bar{q} &\le \bar{q}_{\max} \\ 0 \le Q_{Batterry} &\le Q_{Batterry\max} \end{aligned} \tag{16}$$

The optimal control problem can now be formulated as to determine the controls $C_L(t)$, $\delta_P(t)$ and $q(t)$, the initial states $V(0)$, $\gamma(0)$, $h(0)$ and $Q_{Batterry}(0)$ as well as the cycle time t_{cyc} which minimize the performance criterion $J = Q_{Battery}$. This is subject to the dynamic system Eq. (2), the boundary conditions Eq. (14) and the inequality constraints Eqs. (15) and (16).

The described problem which shows complex relationships requires an efficient optimization method to determine solutions. These complex relationships are due the solar aircraft model which involves the energy management system, the vehicle dynamics, the aerodynamics characteristics and the propulsion system. Furthermore, the kind of unlimited endurance trajectory under consideration shows a complex structure, yielding various segments. Solutions of the described problem were achieved using the optimization technique of Ref. 8 with the graphical environment of Ref. 9.

5.2 Trajectory Optimization Results

Results on the optimization of a periodic trajectory for a complete day-night cycle are presented in Figs 6 to 8. In Fig. 6, the optimal altitude profile is shown. The optimized time for a complete day-night cycle after which a new one starts with the same periodic features of the control and state variables amounts to $t_{cyc} = 23.22\ \mathrm{h}$. This is less than the time of a whole day because the aircraft moves in an eastward direction.

According to the results presented in Fig. 6, there are the following main segments which can be considered as characteristic for the flight of the solar aircraft type under consideration, enabling an unlimited endurance performance:

– Climb to maximum altitude
  In this segment, the aircraft performs a climb until reaching the maximum altitude. The solar energy available from the sun radiation provides the motor with electrical power to generate thrust. Furthermore, the batteries are charged. The maximum altitude is supposed to be limited due to breathing requirements and safety considerations for the pilot wearing a pressure suit.
– Descent to minimum altitude
  After climbing to the maximum altitude, the trajectory is continued as a descent. When the lowest altitude is being reached, the night flight segment starts.
– Flight in the night
  The flight in the night takes place at the lowest altitude which is supposed to be constrained due to the terrain profile. The night segment is basically a steady-state flight. Since there is no sun radiation, the energy necessary for propelling the vehicle is taken from the batteries. After the end of this segment, the next day-night cycle of the periodic trajectory begins.

The time history of the speed is presented in Fig. 7. The speed shows a behavior which corresponds with that of the altitude in the three segments. During the climb to the maximum altitude, the speed continually increases to approach its highest level at the top of the trajectory. In the descent to the minimum altitude, the speed decreases to reach the values of the flight in the night. During the flight in the night, the speed is basically constant, according to the steady-state nature of this segment.

In Fig. 8, the time histories of the power available from the sun and the power used by the motor are presented. The change in the available solar power with the daytime is similar to that shown in Fig. 1, but there is a slight difference because of the eastward motion of the aircraft. From the relationship between the two power curves shown in Fig. 8 it follows that the available solar power is significantly larger than the power required by the motor. The surplus in the available solar power can be used to charge the batteries. Furthermore, Fig. 8 also shows the motor power in the night to propel the vehicle. The motor power is at a constant setting, thus corresponding with the steady-state nature of this flight segment.

5.3 Interpretation of Optimization Results

There are unique characteristics of optimal periodic trajectories of solar aircraft offering an unlimited endurance performance. In the following, an interpretation of optimization results is presented in order to provide an insight in the underlying physical mechanisms.

The first aspect relates to the power detracted from the vehicle due to the aerodynamic drag, P_{Aero}. With reference to the general relation $P_{Aero} = DV$, the minimum can be expressed as

$$P_{Aero,\min} = \bar{\varepsilon}_{\min} mg\bar{V} \tag{17}$$

where $\bar{\varepsilon}_{\min}$ is the glide ratio at $\bar{C}_L$, Eq. (7). This is achieved in steady-state flight at the minimum-power speed denoted by $\bar{V}$ for which the following relation holds

$$\bar{V} = \sqrt{2mg/(\bar{C}_L \rho S)} \tag{18}$$

In Fig. 9, $\bar{V}$ is plotted, with reference made to V of the optimal periodic flight of the solar aircraft. Comparison of both quantities shows that they are close to each other. This means that the flight is practically performed such that the power detracted from the aircraft due to the drag is kept at a minimum.

The relations given in Eqs. (17) and (18) also show why the flight in the night is conducted at the lowest altitude. For this flight segment, the required power is solely taken from the batteries. The goal is to consume as little power as possible in order to minimize the required battery capacity. From Eqs. (17) and (18), it follows that

$$P_{Aero,\min} \sim 1/\sqrt{\rho}$$

As a result, the power detracted from the vehicle due to the drag is the smallest for a flight with $\bar{V}$ at the lowest possible altitude.

The second aspect is related to the energy state of the aircraft and its possible utilization. The fact that the solar aircraft performs a climb to the maximally possible or admissible altitude is due to energy reasons. With a flight to a high altitude, the energy state of the aircraft can be increased. This yields an increase of both the potential and the kinetic energy when compared with the low altitude flight at night. The energy gain at the maximum altitude, E_{Gain}, is given by

$$E_{Gain} = mg(h_{\max} - h_{\min}) + (m/2)(V_{h_{\max}}^2 - V_{h_{\min}}^2) \tag{19}$$

The time history of the energy state of the aircraft is presented in Figs. 10 and 11. The energy gain approaches its greatest level at the highest altitude, with both energy forms increased in a conform manner. Comparison of Fig. 10 and 11 shows that the potential energy increase is significantly larger. Thus, it primarily contributes to the overall energy gain.

The described build-up of potential and kinetic energy can be understood as an energy storage in terms of mechanical energy. Thus, the electrical energy storage in the batteries can be correspondingly reduced. This, in turn, yields a reduction of the weight penalty due to the batteries.

An insight into the magnitude of the reduction of the required battery capacity due to the saving of electrical energy can be obtained when considering the flight phase where the mechanical energy is utilized. This is the descent from the maximum to the minimum altitude, and it pronouncedly manifests in the fact that there is a part where the power setting of the motor is zero. Fig. 12 shows that the addressed flight phase is a significant part in relation to the whole night segment. An estimation of the saving due to the usability of mechanical energy amounts to about 40 % of the entire energy required for the flight in the night.

6 Conclusions

There are unique flight performance characteristics of solar aircraft. Because solar aircraft are propelled by an electrical motor, they have performance characteristics which substantially differ from those of aircraft with an air-breathing propulsion system. For the performance issues dealt with, solar aircraft are grouped into two categories I and II. Category I concerns solar aircraft which use the sun radiation for thrust production only during daytime and do not store solar energy in batteries for a flight in the night. Features of the flight envelope of solar aircraft are determined. It turns out that solar aircraft can reach higher altitude and greater speeds than comparable aircraft with an air-breathing propulsion system when having the same maximum power and weight. Category II relates to solar aircraft which have a possibility to store energy in batteries so that a flight is feasible also in the night when there is no sun radiation. Thus, they can have the capability of a flight without a time limit. As a performance goal for optimizing the trajectory of a solar aircraft, minimization of the battery capacity for storing solar energy is considered. Results on the trajectory optimization of such a solar aircraft are presented. Optimal trajectories of this type of solar aircraft consist of different flight segments showing characteristic features.

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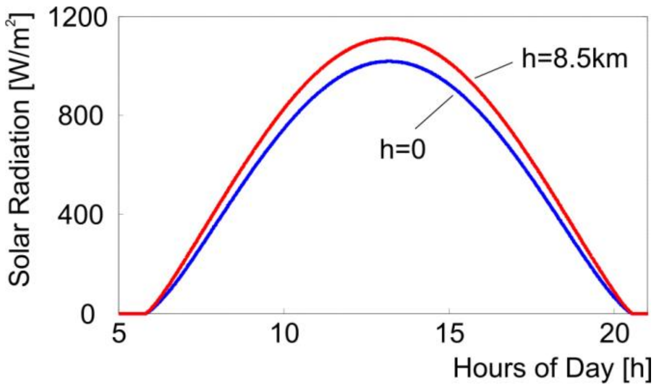

Fig. 1 Effects of daytime and altitude on solar radiation

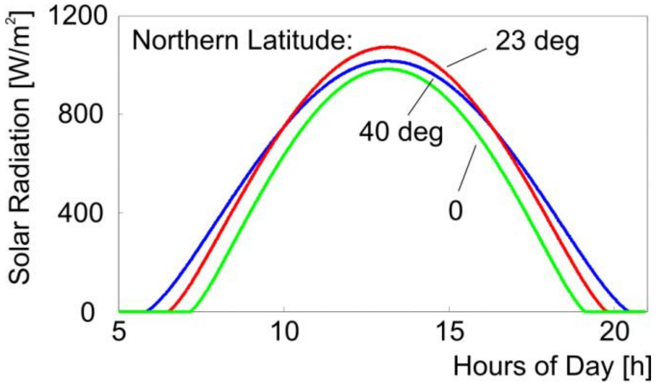

Fig. 2 Effects of daytime and latitude on solar radiation

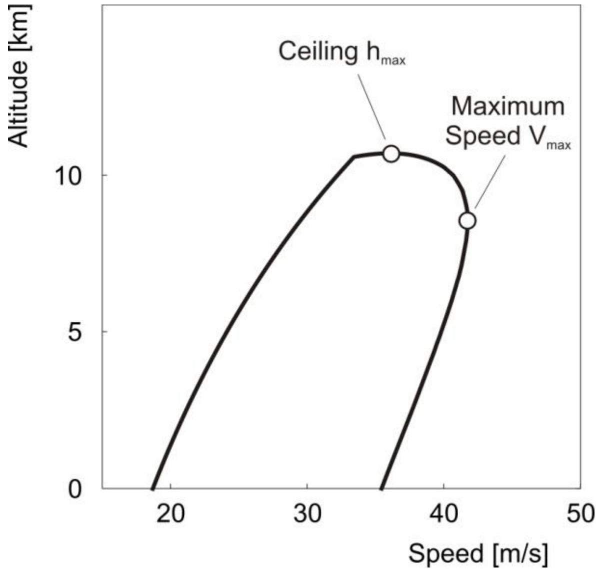

Fig. 3 Flight envelope of a solar aircraft

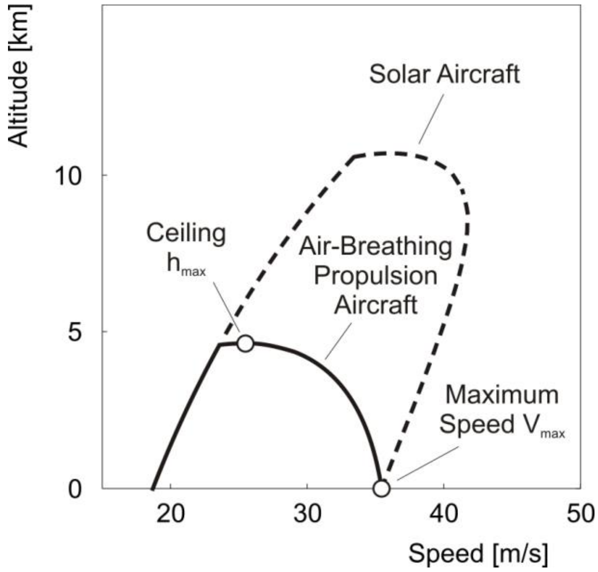

Fig. 4 Flight envelope of an aircraft with an air-breathing propulsion system

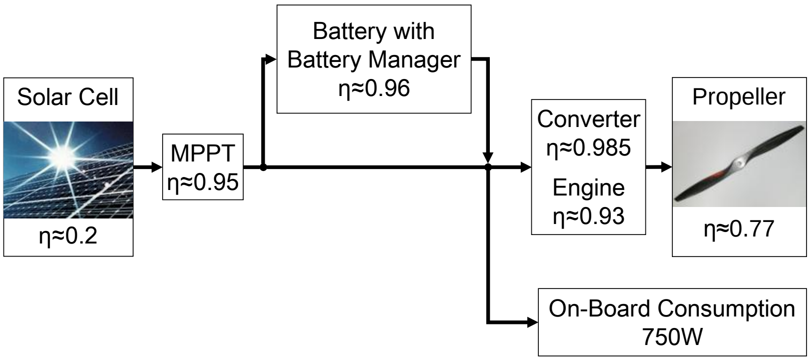

Fig. 5 Energy management and propulsion systems

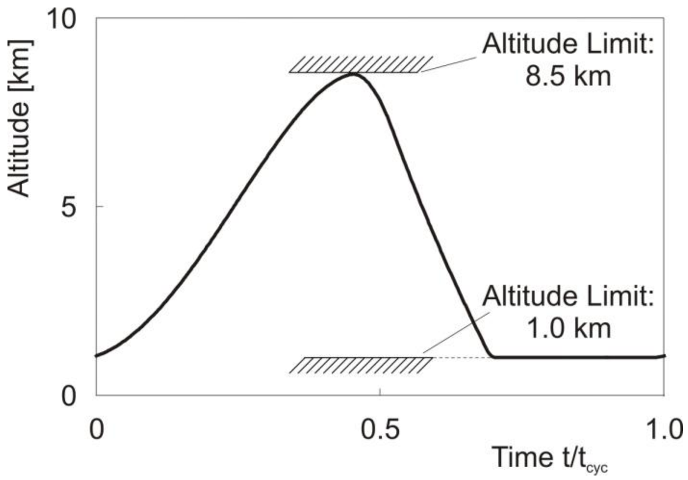

Fig. 6 Optimal altitude time history for battery energy storage minimization
(Curve begin: 7.45 h , $t_{cyc} = 23.22$ h)

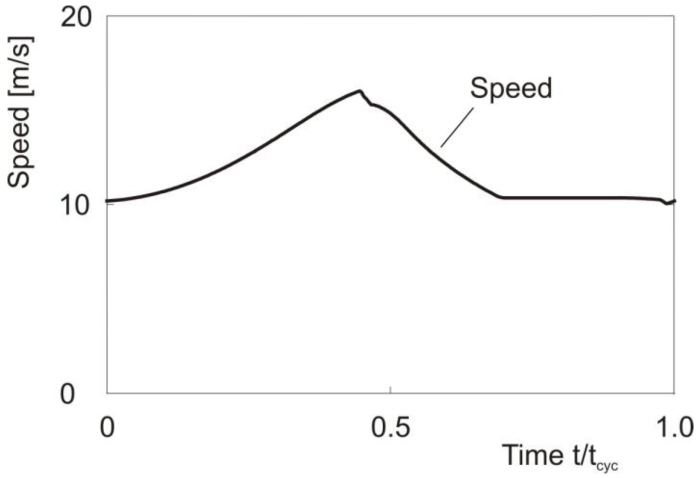

Fig. 7 Optimal speed time history for minimizing required battery capacity

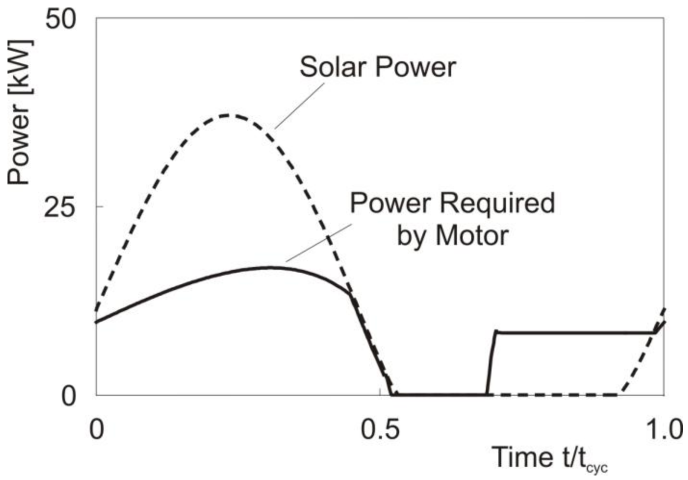

Fig. 8 Solar and engine power for battery energy storage minimization

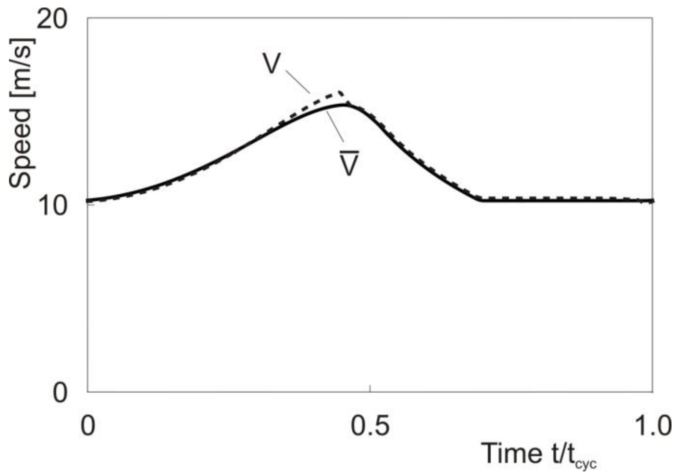

Fig. 9 Optimal speed from trajectory optimization (V)
and speed for minimum power required in steady-state flight ($\overline{V}$)

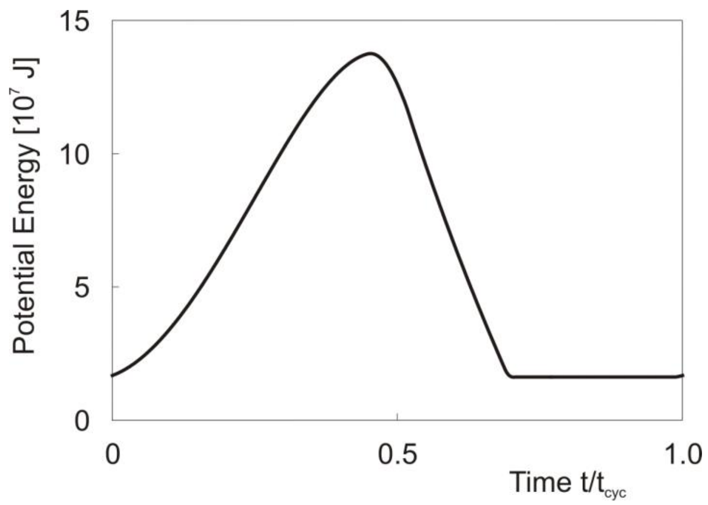

Fig. 10 Potential energy during optimal trajectory

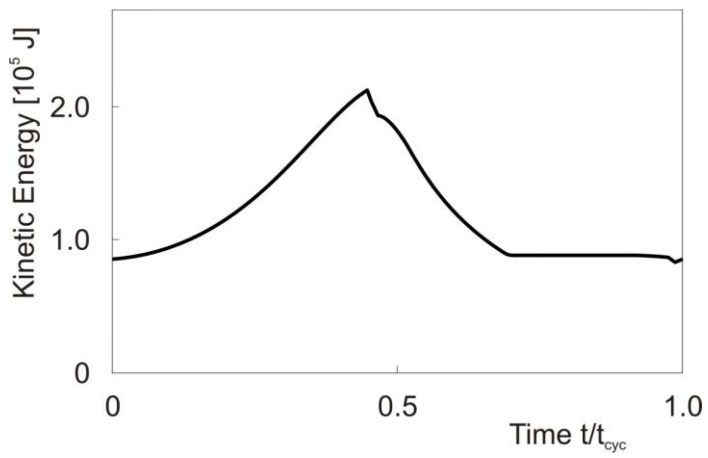

Fig. 11 Kinetic energy during optimal trajectory

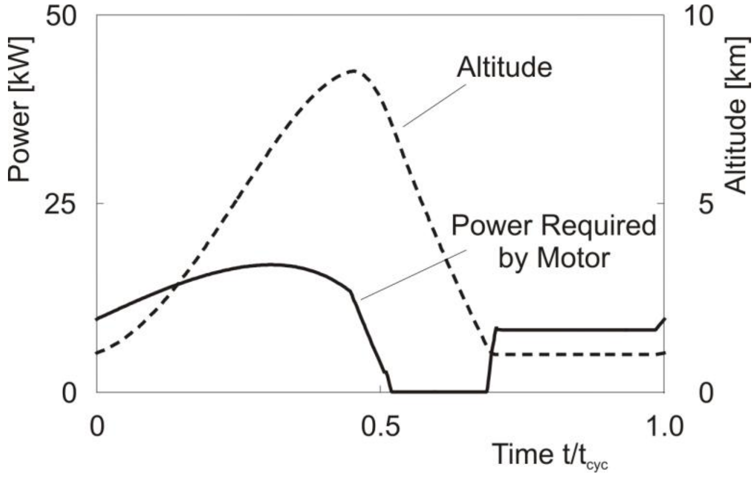

Fig. 12 Relationship between optimal altitude and motor power time histories