PERFORMANCE ANALYSIS OF A SOLAR POWERED TAIL LESS MOTOR GLIDER

by Giorgio Guglieri and Fulvia Quagliotti
Politecnico di Torino, Torino (Italy)

Abstract

In this paper, the design requirements of a solar powered tail less motor glider are discussed. An introductory comparison with conventional two surface aircraft demonstrates that the all wing configuration is competitive, even if some more typical aspects must be considered in detail. A feasibility study concerning this subject is presented, based on the parametric study of wing characteristics, in which aircraft aerodynamics and general performances are directly evaluated for a complete set of possible configurations.

The conclusions demonstrate that the design of a tail less solar powered motor glider is possible and that the increase of complexity is acceptable.

Introduction

A solar powered flying machine is an extremely attractive challenge for any aircraft designer. Many attempts were made in the past and some of them were very successful (1).

Several limitations - related with the low efficiency of the energy conversion process - restrict the attention only to very light aircrafts, such as motor gliders, designed for low speed flight.

The configurations adopted are generally based on the coupling of two lifting surfaces (e.g. Solair I, Solar Challenger, Sunseeker), both of them covered by solar cells.

This design is selected as a consequence of some typical advantages. The wing is moderately swept, so that the manufacturing is simplified. As the spanwise lift distribution is very close to the elliptic shape, the induced wing drag is minimized. The longitudinal control is obtained with conventional movable surfaces, and the stability margin can be easily modified, after preliminary tests, by changing either the incidence or the location of wing and tailplane (or canard), without any significant configuration change. Furthermore, a moderate excursion of center of gravity is possible, without compromising aircraft stability.

All these relevant arguments can clearly explain the choice of a conventional configuration for a solar powered motor glider, when the primary question for the designer is making it fly.

Differently, if we suppose that the primary aim is the optimization of the performances (such as endurance), the selection of a different configuration may be considered and a possible competitive candidate could be the flying wing.

The primary advantage is the minimization of parasite drag for tail less aircrafts, with the dual impact of increasing aerodynamic efficiency and reducing best endurance power requirements.

Most of wing surface can be easily covered by solar panels and the particular spanwise aerodynamic loading minimizes structural stress and cell damage (note that the compliance of solar cells is limited), reducing the aircraft structural weight fraction. Hence, larger aspect ratios and wing spans are acceptable, with respect to conventional unswept wings.

Nevertheless, some important disadvantages of tail less aircrafts must be discussed (2).

The first critical concern is the possibility of tumbling (i.e. Auto rotation in pitch), due to rapid nose pitch-up applied at low speeds. This behavior is typical of configurations which are statically unstable (particularly at high angle of attack). When the static margin is supposed to be positive, Auto rotation should not occur, but a more detailed analysis is obviously necessary. Anyway, an increase of sweep angle is generally beneficial.

The second bad factor is the lack of pitch and yaw damping, as some pilots have some negative comments to make about handling qualities of tail less designs, due to their tendency to pilot induced oscillations (PIO) under adverse flight conditiolls (rough air). This dangerous tendency can be generally eliminated by increasing wing sweep angle Δ.

The next serious flight concern involves aerolastics. As you increase the wing sweep to improve handling qualities and reduce the possibility of tumbling, the aerolastic coupling between wing flap bending and pitch motion is increased, resulting in reduced pitch stability at high speed. The way to alleviate this problem is a correct dynamic mass balancing of elevons.

Furthermore, the stability requirements are generally satisfied by the designer with a careful selection of wing sweep and twist. Unfortunately, the spanwise lift distribution obtained with this procedure is far from being elliptic, with the related induced drag penalty when a comparison is made with conventional unswept lifting surfaces. Anyway, larger aspect ratios reduce to a minimum this last disadvantage.

Finally, maximum lift coefficient is reduced by increasing Δ (stall speed is increased). Moreover, the sweep back deflects the surface flow and the boundary layer towards the wing tip, affecting stall characteristics and stability around the yaw axis during flight with sideslip (3,4).

The above discussed disadvantages of the tail less design can be directly eliminated or minimized by means of a detailed preliminary design procedure. A simplified [1] feasibility analysis concerning this subject is given hereafter, where the primary aim is to demonstrate that the design of a tail less solar powered motor glider is possible and the additional complexity introduced is acceptable.

This analysis is based on the parametric study of wing characteristics, in which aircraft aerodynamics and general performances are directly evaluated for a complete set of possible configurations.

2. Aerodynamics

The aerodynamics of flying wings is strictly coupled with the performance evaluation of tail less solar powered aircrafts.

Two significant questions concern the activity of the aerodynamicist: 1) the selection of the wing airfoil, and; 2) the evaluation of the wing characteristics for a given configuration (λ, Λ, ε, ρ).

The selection of a wing airfoil should be the result of a compromise between required aerodynamic characteristics (i.e. E_{max}, $C_{L,max}$) and practical operative prerequisite.

Several high lift airfoils were designed (5,6) for the limited speed range ($Re = 10^6$), in which the solar powered motor gliders can normally fly, due to their limited power-to-weight ratios P_A/W. Anyway, these highly cambered airfoils cannot be adopted for the present application, as solar cells must be fixed on an almost flat surface, in order to obtain a uniform solar irradiation and a higher panel stiffness.

As a consequence, a lower performance airfoil with flat upper surface is chosen: the Lissaman-Hibbs 8025 (7). This airfoil was adopted by MacCready for the design of the Solar Challenger. The results on the flying aircraft were satisfactory, although no wind tunnel data was available. Only recently test have been performed, and the aerodynamic coefficients for this wing section were obtained in the 3m low speed wind tunnel of Politecnico di Torino. The static force and pressure measurements were performed for $Re = 360000 \div 1560000$ and $V = 10 \div 50$ m/s on an unswept wing with end plates ($c = 0.5$ m - $b = 2$ m).

Some general conclusions concerning these experimental data can be summarized: 1) the behavior is critical for lower Reynolds number, 2) the drag decreases moderately with angle of attack, reaching a minimum for positive α,3) the pitching moment coefficient is moderately positive (i.e. stable) for incidence below stall, 4) E_{max} and $(E\sqrt{C_L})_{max}$ occur at the same angle of attack and, 5) the separated flow at wing stall propagates abruptly along the lifting surface.

The evaluation of wing characteristics as a function of design parameters is performed by means of Weissinger method (8,9) - an extension of lifting line theory - which is able to evaluate the effects of sweep in incompressible flow with acceptable precision, when a comparison is made with other methodologies. The other computational methods are obviously much more advanced, but they are generally time consuming. On the contrary, this simplified theory is able to analyze a wide number of configurations using a standard PC, requiring a minimum computational time.

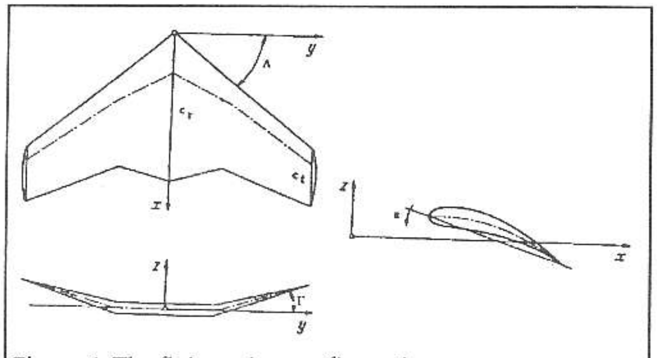

Figure 1. The flying wing configuration.

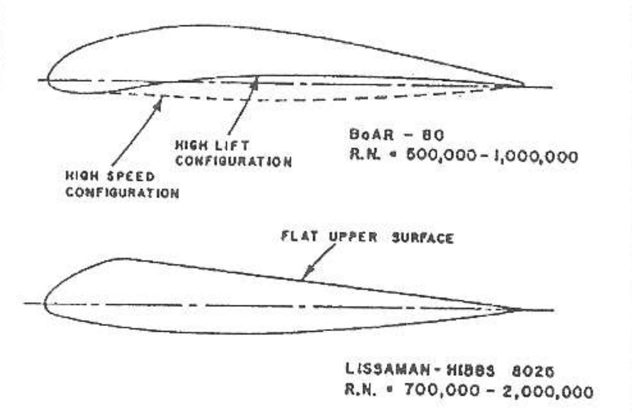

Figure 2. The Lissaman-Hibbs 8025 airfoil (7).

3. Performance Analysis

The configuration selected is that of a flying wing, with a central profiled ogival fuselage along the root chord, in which the pilot is seated in an inclined position.

Aircraft longitudinal and lateral control is performed by means of differential deflections of elevons, while directional control is obtained using conventional rudders, hinged on vertical wing tip fins (10). Observe that, wing tip section must be able to withstand loads induced by both vertical stabilizer and ground handling (highly tapered wings are critical). Spoilers should be provided for speed control during glide or dive.

The landing gear should be designed in a low aerodynamically interfering position, profiled in order to minimize drag in cruise flight. Some shock absorbing device is required with the aim of minimizing cell damage during landing.

The solar cells are fixed on wing upper surface and electrically connected, so that series of panels are obtained (photo voltaic generator). The electrical power supplies a motor, which drives a reduction gearbox and a propeller.

The thrust axis is supposed aligned with the wing root chord, i.e. no pitching moment is generated by thrust setting. Therefore, the static longitudinal stability of the wing is mainly influenced by neutral point and center of gravity locations.

The propeller generates the thrust required for aircraft propulsion. This last unit should be designed for low speed high efficiency in possibly different flight conditions, that means large propeller diameter and low rotation rates, with controllable blade angle. This large propeller should reach good efficiencies ($\eta_P = 0.90$ in level flight), even if several geometrical interference problems are introduced for the designer (for example ground clearance during take off and landing). As a consequence, the possibility of adopting two separate smaller propellers could be considered.

Furthermore, the available energy for take off and climbing from ground to flight altitude (generally lower than 1000 m) obtained from the photo voltaic conversion process is limited. Hence, a second spare voltage supply unit (accumulators) is required, recharged by solar cells during ground stops. Another relevant aircraft weight fraction is introduced due to the presence onboard of batteries.

As a conclusion, two typical flight conditions should be analyzed by the designer: 1) solar powered level flight, and 2) battery powered climbing flight.

The selection of acceptable performances and safety conditions determine the severe constraints for the definition of wing design characteristics.

3.1. Level Flight Conditions

The primary question is the comparison of required power and energy with those ones available from direct solar radiation. This last term is generally small and seriously affected by external factors such as adverse weather, pollution, cell orientation, latitude and local time.

All preliminary calculations are performed considering a conventional reference mean solar irradiation ($I = 500\ W/m^2$).

Energy conversion process (substantially influenced by photo voltaic and mechanical effects) reduces dramatically the available power for aircraft propulsion.

Hence, global efficiency (obtained by multiplying motor, gearbox, propeller and photo voltaic efficiencies) is limited to $\eta = 0.10 \div 0.15$.

We obtain that:

$$P_A = \eta \, \sigma \, S \, I \tag{1}$$

The required power is related with the equilibrium of external loads acting on the aircraft during level flight:

$$\begin{cases} W = L = \frac{1}{2}\rho V_{LF}^2 \, S \, C_L \\ T = D = \frac{1}{2}\rho V_{LF}^2 \, S \, C_D \end{cases} \tag{2}$$

Hence:

$$P_N = T \, V_{LF} = D \, V_{LF} \tag{3}$$

By combining the formulation of aerodynamic efficiency

$$E = \frac{L}{D} = \frac{C_L}{C_D} \tag{4}$$

with the expression of cruise airspeed

$$V_{LF} = \sqrt{\frac{2W}{\rho S C_L}} \tag{5}$$

we find that

$$P_N = \frac{V_{LF} W}{E} = \sqrt{\frac{2}{\rho}} \frac{1}{E\sqrt{C_L}} \sqrt{\frac{W}{S}} W \tag{6}$$

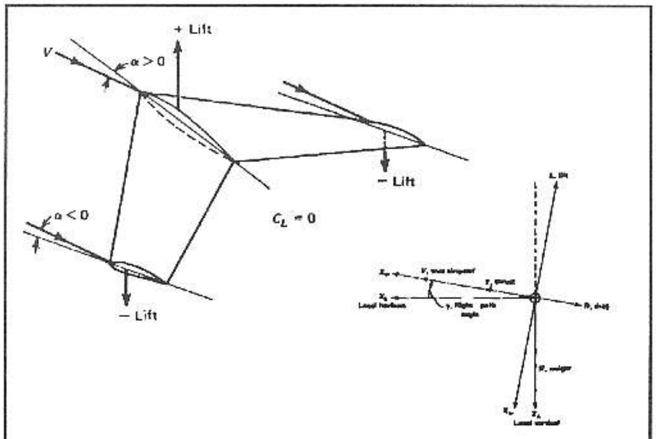

Figure 3. The external forces acting on the aircraft in steady conditions.

3.2. Climbing Flight Conditions

The analysis of climbing flight is performed taking into account the effects of battery powered propulsion only.

The characteristics of batteries are expressed in terms of constant energy output related with a time interval, and usually this energy output decreases as required power increases (or alternatively output time interval decreases).

Several types of accumulators are available but their performances are substantially different. In the present discussion, we suppose that we are using Ni-Zn batteries for the propulsion of the motor glider, and therefore we can assume that the energy output is $\xi \leq 60 Wh/Kg$ as a function of specific power: $\xi = f(P_{CF}, W_B)$. The choice of a different type of accumulator is obviously possible (note that climbing time t_{CF} is generally much lower than 1 h), but lower performances introduce higher battery weight fractions (lead-acid batteries) and low discharge efficiencies ξ/ξ_o while higher performances batteries are not compatible with low energy-to-power rates (i.e. low discharge time intervals), required for reaching the cruise altitude in few minutes.

Within these assumptions, it is possible to evaluate the available energy for climbing flight, using the following simple equation:

$$E_A = \xi \frac{W_B}{g} \tag{7}$$

The energy required for climbing flight from ground to a selected altitude (that we fix at 500 m with constant vertical speed w = 2.5 m/s and t_{CF} = 200s) is obtained through the equilibrium of forces acting on the aircraft in these conditions:

$$\begin{cases} L = W\cos\gamma \\ T = D + W\sin\gamma \end{cases} \tag{8}$$

Introducing the aerodynamic efficiency E in the second of these two equilibrium equations and multiplying by VCF~ we find that

$$P_N = \frac{W\cos\gamma}{E} V_{CF} + W V_{CF} \sin\gamma \tag{9}$$

where $w = V_{CF} \sin\gamma$, and

$$P_N = \frac{W\cos\gamma}{E} V_{CF} + Ww \tag{10}$$

If we consider that usually $\gamma \approx 0$, it is possible to derive that $\cos\gamma \approx 1$ and $L \approx W$. We obtain:

$$P_N \approx \frac{V_{CF} W}{E} + Ww = DV_{CF} + Ww \tag{11}$$

Finally, the formulation of required energy is obtained:

$$E_N = \frac{P_N t_{CF}}{\eta_P} \tag{12}$$

where η_P is the propeller efficiency during climb ($\eta_P \approx 0.60$ in climb conditions).

3.3. Aircraft Weight Fractions

The weight of a flying wing is a linear function of wing surface S:

$$W = W_o + k_1 g S + k_2 g \sigma S + W_B \tag{13}$$

where k_1 is the surface density of a wing built in composite material ($k_1 = 2.5 Kg/m^2$) and $k_2 = 1 Kg/m^2$ is the solar cell surface density (Silicium type). The surface ratio α is fixed at 80 %.

The term W_o = 1420 N is the addition of several constant components:

- Pilot: 900 N
- Fuselage: 200 N
- Motor: 200 N
- Gearbox: 40 N
- Propeller: 80 N

The linear equation $W = f(S, W_B)$ is then directly related with P_A and E_A, as S and W_B increase with the power required for level flight and the energy necessary for climb respectively.

3.4. Parametric Analysis

The comparison of available versus required power and energy in the two flight conditions considered, combined with the weight fractions equation, defines S and W_B so that solar powered level flight and battery powered climb are possible for the specified conditions, where a 20 % margin is introduced. Remind that, one of the important power corrections can be induced by cell heating that could reduce solar cell efficiency (0.5%/°C decrement). Even winds or gusts can affect dramatically aircraft power requirements.

We obtain:

$$\begin{cases} P_A = 1.2\,P_N & \text{(level flight)} \\ E_A = 1.2\,E_N & \text{(climb)} \end{cases} \tag{14}$$

As $\gamma \approx 0$, we remind that

$$V = V_{LF} \approx V_{CF} \tag{15}$$

In order to solve this system of equations, the airspeed V at which cruise and climbing flights are obtained must be specified. This means that the aircraft should fly at a selected angle of attack, with related lift coefficient C_L, aerodynamic efficiency E and optimal factor $E\sqrt{C_L}$, which define together a unique possible airspeed for a given altitude.

Generally, the two angles of attack (or C_L) at which a conventional aircraft with propellers reaches optimal level and climbing flight conditions are substantially different, and usually minimum energy climb attitude (i.e. maximum $E\sqrt{C_L}$) is found at dangerously high α, that means very low speed, in the vicinity of wing stall, which occurs for flight exceeding $C_{L,max}$ (unsafe flight).

Due to the particular aerodynamic behavior of the profile adopted for this solar powered tail less motor glider (LH 8025), the two conditions are almost coincident with stall angle of attack (minimum power level flight and minimum energy for climb occur almost at the same α at $CL \approx C_{L,max}$)

With the aim of ensuring a safe flight, optimal flight attitude cannot be adopted, and a 20% increase in airspeed V (i.e. 70% lift coefficient reduction) is necessary:

$$\begin{cases} V = 1.2\,V_{min} = 1.2\sqrt{\dfrac{2W}{\rho S C_{L,max}}} = \sqrt{\dfrac{2W}{\rho S C_L}} \\ C_L = 0.7\,C_{L,max} \end{cases} \tag{16}$$

Using the Weissinger theory it is possible to evaluate the magnitude of C_L and $E\sqrt{C_L}$ as a function of aspect ratio λ and sweep angle Λ, for given taper ratio (r = 0.7) and twist angle (ε = 3°).

Therefore, for any given $E\sqrt{C_L}$ (i.e. λ, Λ), the variables S and W_B are obtained with the iteration of the following equations:

$$\begin{cases} \eta\,\sigma\,IS = 1.2\sqrt{\dfrac{2}{\rho}}\,\dfrac{1}{E\sqrt{C_L}}\sqrt{\dfrac{W}{S}}\,W \\ \xi\dfrac{W_B}{g} = \dfrac{1.2\,t_{CF}}{0.99\,\eta_P}\{\sqrt{\dfrac{2}{\rho}}\,\dfrac{1}{E\sqrt{C_L}}\sqrt{\dfrac{W}{S}}\,W + Ww\} \end{cases} \tag{17}$$

where a 1% increment is introduced in the second equation taking into account drag and friction during take off run.

By means of the two terms S and W_B, the aircraft weight W, the mean chord c, the span b, the power P_A and the energy E_A are easily derived.

The complete wing geometry is finally defined, as a function of aspect ratio λ and sweep angle Λ. Note that the effect of global efficiency η on the solutions is not marginal.

These solutions are obtained with the above described deterministic procedure, and a unique wing geometry is found for each given $E\sqrt{C_L}$ or (λ,Λ).

All these configurations are compatible with the requirements of P_A for level flight and E_A for climb. Anyway, only a limited subset has a practical interest for the designer.

As an example, when the aspect ratio λ is too small, the wing surface S and the weight W become too large and unacceptable, due to the typical induced drag penalty (i.e. an excessive increase of P_N and E_N), although the aircraft configuration respects the energy requirements for flight.

On the contrary, the benefits on performances for very high aspect ratio wings are negligible, even if the manufacturing and the structural design become extremely complex. Furthermore, the reduction of chord length c and local Reynolds number, particularly in the vicinity of tips, may change abruptly wing stall characteristics and lateral control effectiveness. Finally, the wing loading W/S could increase too much and the power-to-weight ratio P_A/W could become too low.

Hence, in order to distinguish the acceptable configurations, some selection criteria must be adopted for the analysis of the results:

- a) $W < W_{max}$ (e g W_{max} = 3000 N)
- b) $Re > Re_{min}$ (e.g. Re_{min} = 775000 for LH8025)
- c) the minimum sink rate w in power off flight must be limited
- d) the maximum efficiency $E > E_{min}$ (e.g. E_{min} = 20)
- e) the stall airspeed V_{min} must be minimized
- f) the span b must be limited for wing transport
- g) $\lambda > \lambda_{min}$ (e g λ_{min} = 5)

Some of these constraints are generally more effective in selecting the set of acceptable solutions: for the initial conditions considered, the limitations on weight and Reynolds number exclude the lower and the higher aspect ratio wings respectively, while the other controls are almost ineffective.

A final selection is required in order to discard statically unstable flying wings. The criterion for stability is a positive static margin, i.e. the center of gravity must be located forward of neutral point. This last control typically eliminates low sweep angle wings, as the increase of Λ has a stabilizing effect, due to the rearward shift of neutral point.

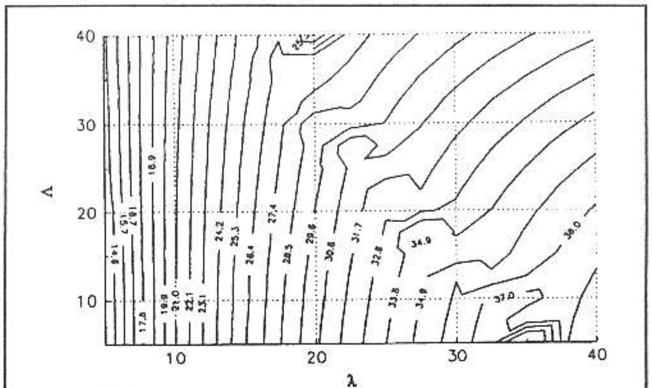

Figure 4. The parameter $E\sqrt{CL}$ as a function of aspect ratio λ and sweep angle Λ.

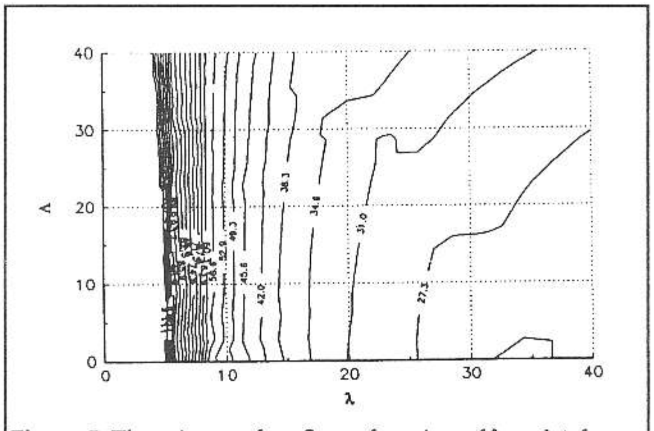

Figure 5. The wing surface S as a function of λ and Λ for $\eta = 0.10$.

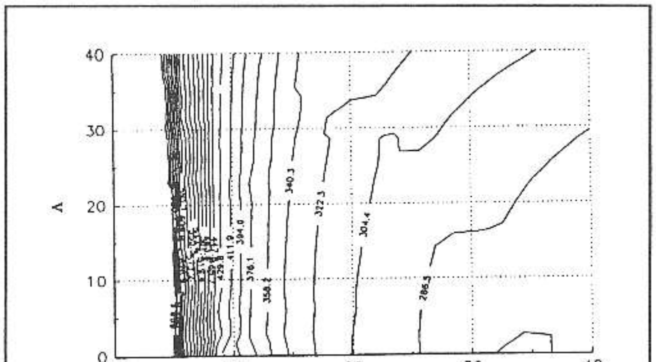

Figure 6. The weight of batteries WB as a function of λ and Λ for $\eta = 0.10$.

Note that tail less aircrafts are extremely sensitive to the shift of the center of gravity location, due to the uncommon concentration of mass in the vicinity of pitch axis.

The final set of acceptable solutions is given in Figure 7, in which the characteristics of several all wing aircrafts (gliders and motor gliders) are compared (see also References (11) and (12)). Note that most of these configurations fall in the acceptable field for solar powered

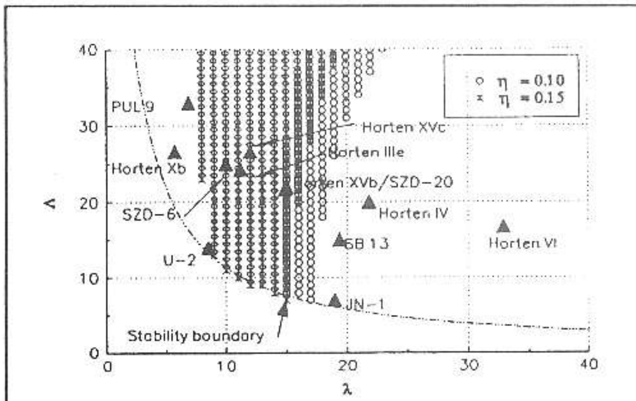

Figure 7. Comparison of compatible solutions for $\eta = 0.10 + 0.15$ with several conventional all wing gliders and motorgliders.

flight for $\eta = 0.10 \div 0.15$.

4. Conclusions

The design of solar powered flying machines is limited to low speed light motorgliders, due to the penalized efficiency of the photovoltaic conversion process, even though many practical applications could be considered if more reliable sun powered aircrafts were available.

Anyway a significant progress in this field of research will be possible only with advances both in solar energy conversion technology and specific aeronautical applied research.

With the aim of giving a contribution concerning this last subject, the present paper deals with the proposal for an all wing motorglider. The feasibility of a tail less aircraft design is discussed and confirmed by means of a simplified analysis of flight performances and aerodynamics, which could be easily extended, even for conventional configurations.

1. *Some restrictions apply to the present analysis: 1) low altitude flight is assumed, 2) lateral and directional stability characteristics are not considered, 3) the effects of wing geometry on aerodynamic damping are neglected, and 4) control surfaces are supposed to be effective in the airspeed range considered.*

Nomenclature

b	Wing span	(m)
c	Wing chord	(m)
cr	Wing root chord	(m)
ct	Wing tip chord	(m)
CD	Drag coefficient ($C_D = D/(^1/_2\rho V^2 S)$)	
C_L	Lift coefficient ($C_L = L/(^1/_2\rho V^2 S)$)	
D	Aerodynamic drag force	(N)
E	Aerodynamic efficiency ($L/D = C_L/C_D$)	
E_A	Available energy for climbing flight	(J)
E_N	Required energy for climbing flight	(J)
g	Gravitational acceleration	(m/s^2)
I	Solar irradiation	(W/m^2)
L	Aerodynamic lift force	(N)
P_A	Available power for level flight	(W)
P_N	Required power for level flight	(W)
r	Taper ratio (c_t/c_r)	
Re	Reynolds number ($\rho Vc/\mu$)	
S	Wing surface	(m^2)

Sc	Surface covered by solar cells	(m^2)
t	Time	(s or h)
T	Thrust	N)
V	Flight airspeed	((m/s)
w	Vertical speed	(m/s)
W	Aircraft weight	(N)
W_B	Weight of batteries	(N)
α	Angle of attack	(deg)
γ	Climb angle	(deg)
Γ	Dihedral angle	(deg)
ε	Wing tip twist angle	(deg)
η	Global efficiency	
η_p	Propeller efficiency	
λ	Aspect ratio (b^2/S)	
Λ	Sweep back angle	(deg)
μ	Air viscosity	(Kg/m/s)
ρ	Air density	Kg/m^3
σ	Surface ratio (Sc/S)	
ξ	Battery energy rate	(Wh/Kg)

Subscripts

CF	Climbing flight condition
LF	Level flight condition
max	Maximum
min	Minimum

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