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Flight Optimization for Remotely Piloted Aircraft

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Abstract

The research is focused on the development of Remotely Piloted Aircraft Systems **(**RPAS). The design process involves the application of Systems Engineering Approach. The objective is to design a small long endurance unmanned aircraft system. Long endurance also depends considerably on air vehicle gliding quality. This paper describes the calculation of parameters providing the best gliding qualities for the air vehicle being designed. The obtained results will be further used in experimental flight simulations and practical experiments for comparison with the aim that the development reaches design objectives. As shown by the results previously obtained from calculations, they are very close to similar systems currently in use and operation.
KEY WORDS: *aircraft design, engine, matching plot, remotely piloted aircraft system, wing, gliding performance*

1. Introduction

An aircraft without an engine is not able to take off independently, but it is capable of gliding and landing, as performed by sailplanes and gliders.

A typical glide angle for most General Aviation and transport aircraft is about 5–7 deg.

The gliding flight performance during the launch phase, landing and free flight phase depends on many factors: design, weather, wind and other atmospheric phenomena.

Gliding flight parameters will be calculated to analyze flight performance and to get the best possible gliding flight attitude for the air vehicle for maximum endurance. The Drag Polar shown in Fig.1 below demonstrates the difference between parameters in the case of flights for maximum endurance and maximum range. The drag polar is a plot of aircraft drag versus velocity. The velocity is expressed in calibrated airspeed [1, 2, 6].

The aforementioned parameters are very important for a gliding flight. To analyze flight performance, we will use the Drag Polar plots, two of which are shown in Fig. 1 below as an example [3, 5].

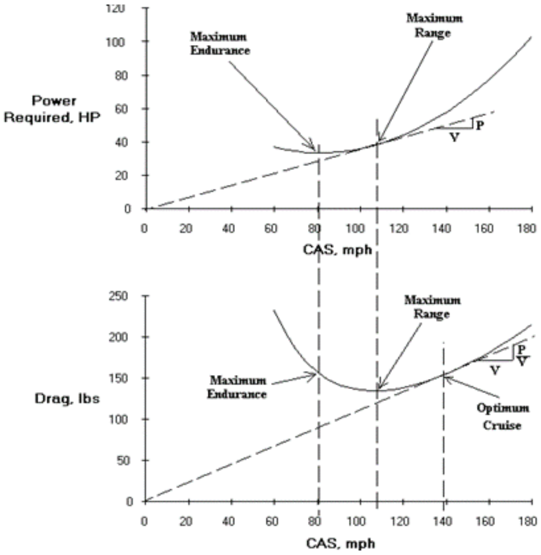

Fig. 1 An example of drag polar plot

2. Glide Flight

When the engine is turned off, ($T = 0$), it is necessary to maintain the airspeed for gliding flight and, the air vehicle should be put at an attitude in which the glide angle is smallest that insures minimum rate of descent [2, 4]. The equations of motion are the following:

$$0 - D - W \times \sin\gamma = m \times \dot{V} = 0\,; \tag{1}$$

$$L - W \times \cos\gamma = m \times V \times \dot{\gamma} = 0\,, \tag{2}$$

where γ is the flight path angle (the angle between the velocity vector and the air vehicle x axe vector on the horizontal).

Dividing one equation by the other, we will get:

$$\tan\gamma = -\frac{D}{L} = -\frac{1}{\frac{L}{D}}\,. \tag{3}$$

We can define the glide angle as the negative of the flight path and obtain the following equation:

$$\tan\gamma_1 = \frac{1}{\left(\frac{L}{D}\right)}\,, \tag{4}$$

where γ_1 is the positive glide angle.

From the above data, we can make the following conclusions:

a) the glide angle depends only on L/D and is independent of the weight of the vehicle;

b) the flattest glide angle occurs at the maximum L/D.

3. Glide Range

The glide range is expressed in distance that an aircraft travels along the ground during the glide descend. It is easy to see from Fig. 2 that:

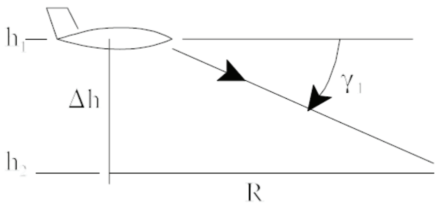

Fig. 2 Gliding flight parameters

$$\tan\gamma_1 = \frac{h_1 - h_2}{R} = \frac{-\Delta h}{R} \tag{5}$$

or

$$R = \frac{h_1 - h_2}{\tan\gamma_1} = \frac{L}{D} \times \left(h_1 - h_2\right). \tag{6}$$

As we can see from the equations above, the gliding flight range depends on *L*/*D* and Δh. Also, the maximum range occurs when *L*/*D* is maximum, that is the maximum range glide is flown at the minimum drag airspeed V_{md} [3, 6].

1. Small Glide Angle Assumption.

The glide angle is almost always small for an equilibrium glide. Under such circumstances it is possible to make the following approximations ($\gamma_1 << \pi$):

$$\cos\gamma_1 \approx 1 \qquad \sin\gamma_1 \approx \tan\gamma_1 \approx \frac{1}{\left(\frac{L}{D}\right)}\,. \tag{7}$$

The important result of this assumption is that it is possible to make an approximation that:

$$L = W \times \cos\gamma \approx W \rightarrow V = \sqrt{\frac{2 \times W}{\rho \times S \times C_l}} \tag{8}$$

and we can use weight to calculate the airspeed [1, 9].

2. Rate of Climb (Sink)

The rate of climb is given by the following equation:

$$\dot{h} = V \times \sin\gamma \tag{9}$$

From Eq. (9), we can exclude sin γ and get:

$$\dot{h} = -V \times \frac{D}{W} \approx -V \times \frac{D}{L} = -V\frac{C_D}{C_L} = -\sqrt{\frac{2 \times W}{\rho \times S \times C_L}} \times \frac{C_D}{C_L} \tag{10}$$

or

$$\dot{h} = -\sqrt{\frac{2 \times W}{\rho \times S}} \times \frac{C_D}{C_L^{3/2}} \, . \tag{11}$$

The rate of climb is negative (then this is a sink rate) and it is related to the quantity $C_D/C_L^{3/2}$. If we need to minimize the sink rate, we must minimize the ratio $C_D/C_L^{3/2}$. So, we get the following assumptions [5, 6]:

a) to get the maximum range, we must operate at the maximum *L/D* condition (minimum drag);

b) to get the maximum endurance (minimum sink rate), we must operate at the minimum power required condition.

3. Time to Descend

The rate of descend depends on the altitude (through the density – ρ). To get a precise solution for the time to descend, we need to include density variations in calculations. If we assume that the change in altitude is relatively small (in this case it is less than 50 m), and we assume that the density is constant and the angle of attack (AoA) is constant, we will get the following equation:

$$\text{Time of Flight } = TOF = \frac{-\Delta h}{\dot{h}} , \tag{12}$$

where $\dot{h}$ is the assumed constant. The value $\dot{h}$ is that calculated for the altitude half way between the initial and final altitudes. Large altitudes are incremented by several small ones. It is very easy to set theorems, lemmas, definitions, examples and proofs [1, 6].

4. The Best Glide Performance for the UAS Air Vehicle

To get the best glide performance of the UAS air vehicle being designed, at this design stage it is necessary to define a drag polar equation, which is expressed in the following form:

$$C_D = C_{D0} + \frac{C_L^2}{\pi \times AR \times E} \tag{13}$$

or

$$C_D = C_{D0} + K \times C_L \, , \tag{14}$$

where *K* is the induced drag correction factor.

As drag and lift are dependent on the Mach number, Reynolds number and geometric configuration of the wing, which were calculated and determined already in previous design steps, the parameters are taken from those stages and given further [4-6].

4. Gliding Flight Performance

The Table 1 below shows the parameters of the unmanned aircraft system air vehicle used for the calculation.

Table 1

Air vehicle parameters

Air vehicle weight	$m = 7.066$ kg
Wing reference area	$S = 0.98$ m^2
Design glide flight altitudes	$h_1 = 350$ m
	$h_2 = 400$ m
Air density at glide altitude	$\rho = 0.842$ kg/m^3
Gravity acceleration	$g = 9.80665$ m/s^2
Wing leading edge sweep angle	$\Lambda_{LE} = 32.57°$
Wing aspect ratio	$AR = 8$

The gliding flight performance was determined with the help of two methods. One calculation method was based on the maximum L/D value, while the other one on the best glide velocity.

1. Using the above equations, the gliding flight performance calculation based on the maximum *L*/*D* was completed in two ways – for the maximum endurance and for the maximum range.

The difference between the two above mentioned ways lies in the fact that the maximum endurance flight occurs in the minimum sink rate condition that occurs at minimum power required flight condition, and the maximum range condition occurs at the minimum drag condition (max *L*/*D*).

The calculation results are summarized in Table 1 below.

2. For the calculation of the gliding flight performance based on the best glide velocity, the MATLAB Aerospace Toolbox™ software was used. In MATLAB, programming is based on C++ programming language.

The advantages of programming in MATLAB are imbedded standard parameter calculation scripts such as ISA atmospheric parameters (*atmosisa*) or value conversion scripts (*correctairspeed*) [4, 6]. The example script is shown in the Fig. 3 below:

```
[T, a, P, rho] = atmosisa(400);
TAS_bg = sqrt((2*W) / (rho*S))*(1./(4*Cd0.^2 +
Cd0.*pi*e*AR*cos(phi)^2)).^(1/4);
CAS_bg = correctairspeed(TAS_bg,a,P,'TAS','CAS')';
gamma_bg_rad = asin( -sqrt((4.*Cd0')./(pi*e*AR*cos(phi)^2 + 4.*Cd0')));
D_bg = -W*sin(gamma_bg_rad);
L_bg =  W*cos(gamma_bg_rad);
Cd_bg = D_bg./(qbar*S);
Cl_bg = L_bg./(qbar*S);
TAS = (5:30)';
qbar = dpressure([TAS zeros(size(TAS,1),2)],rho);
Dp = (1/2)*rho*S*Cd0.*(TAS.^2);
Di = (2*W^2)/(rho*S*pi*e*AR).*(TAS.^-2);
D = Dp + Di;
h1 = figure;
plot(CAS,L./D);
title('L/D vs. CAS');
xlabel('CAS, m/s'); ylabel('L/D');
plot([CAS_bg,CAS_bg],[0,L_bg/D_bg],'LineStyle','--','MarkerFaceColor','k');
legend('L/D','L_{bg}/D_{bg}','Location','Best');
h2 = figure;
plot(CAS,Dp,CAS,Di,CAS,D);
title('Parasite, induced, and total drag curves');
xlabel('CAS, m/s'); ylabel('Drag, N');
plot([CAS_bg,CAS_bg],[0,D_bg],'LineStyle','--','MarkerFaceColor','k');
legend('Parasite, D_p','Induced, D_i','Total,
D','D_{bg}','Location','Best');
```

Fig. 3 An example MATLAB script for the gliding flight performance calculation

The best glide velocity is calculated using the following equation where TAS (true airspeed in meters per second) is the velocity of the aircraft relative to the surrounding air mass:

$$TAS_{bg} = \sqrt{\frac{2\times W}{\rho\times S}} \times \left[\frac{1}{4\times C_{D0}^2 + C_{D0}\times\pi\times e\times AR\times\cos^2\Phi}\right]^{\frac{1}{4}}. \tag{15}$$

The best glide angle is calculated using the equation:

$$sin\,\gamma_{bg} = -\sqrt{\frac{4\times C_{D0}^2}{\pi\times e\times AR\times\cos^2\Phi + 4\times C_{D0}}}. \tag{16}$$

The minimum drag during gliding flight or the best glide drag is calculated using the equation:

$$D_{min} = D_{bg} = \frac{1}{2}\times\rho\times TAS_{bg}^2\times S\times 2\times C_{D0} = -W\times\sin\lambda_{bg}. \tag{17}$$

The best glide lift is calculated using:

$$L_{bg} = L_{max} = W\times\cos\gamma_{bg} = \sqrt{W^2 - D_{bg}^2}. \tag{18}$$

Using the previously obtained results, the drag and lift coefficients are calculated by using the equations:

$$C_{Dbg} = \frac{Dbg}{q \times S} \quad (19)$$

and

$$C_{Lbg} = \frac{Lbg}{\overline{q} \times S} \quad (20)$$

The correctness of the calculations is checked by constructing plots of drag and lift-drag ratio for the air vehicle as a function of CAS.

Parasite drag is calculated by the following equation:

$$D_p = \frac{1}{2} \times \rho \times S \times C_{D0} \times TAS^2 . \quad (21)$$

Induced drag is calculated using the equation:

$$D_i = \frac{2 \times W^2}{\rho \times S \times \pi \times e \times AR} \times \frac{1}{TAS^2} . \quad (22)$$

Total drag is calculated by the equation:

$$D = D_p \times D_i . \quad (23)$$

As was expected, the maximum *L*/*D* occurs at approximately the best glide velocity calculated and visualized in the plot. In the Fig. 4 below the plotting L/D versus CAS and parasite, induced, and total drag curves are shown:

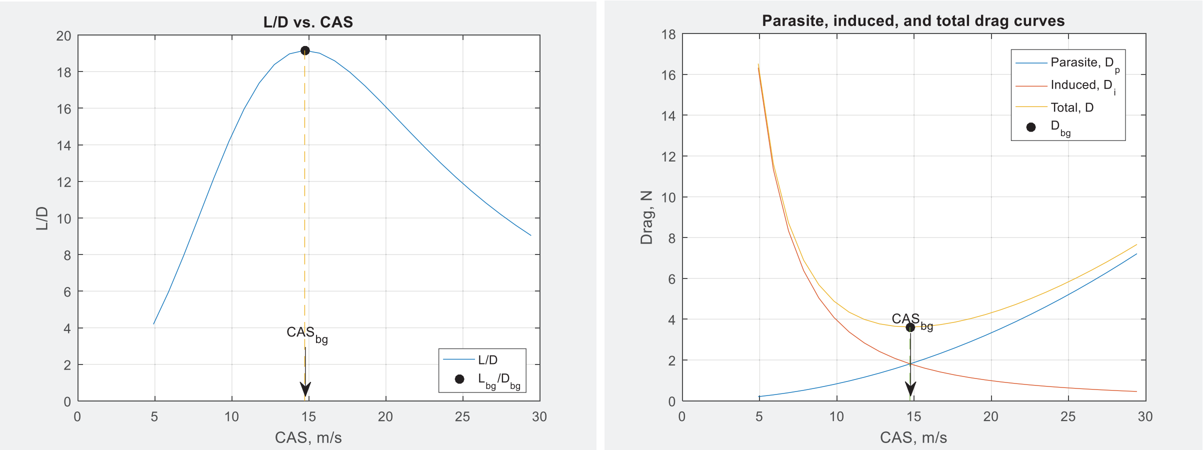

Fig. 4 L/D versus CAS and parasite, induced, and total drag curve plots

The minimum total drag (i.e. D_bg) occurs at approximately the same best glide velocity calculated above.

Table 2

Comparison of calculation results

Flight Condition →	Max Range	Max Endurance	Glide Velocity
Range	957.82 m	829.56 m	-
Endurance (TOF)	53.87 s	61.50 s	-
C_{Lmd}	0.5314	0.92048	0.53157
C_{Dmp}	0.02774	0.05548	0.02774
γ_1	2.9882°	3.45°	2.9873
V_g	17.78 m/s	13.51 m/s	14.7268 m/s
$\left(\frac{L}{D}\right)_{md}$	19.1564	16.5912	19.1625
D_{bg}	-	-	3.6111 N
L_{bg}	-	-	69.1989 N

The results calculated in MATLAB Aerospace Toolbox™ software differ a little from those calculated in the first part, which is possible because of a different mathematical algorithm. In part (7), the calculation was based on the max. L/D value, but in part (8) the mathematical algorithm began with the best glide flight speed calculation and afterwards obtained other values. The result comparison is shown in the Table 2 below.

5. Conclusions

The gliding performance results represent a preliminary evaluation of the performance of the UAS air vehicle being designed. As the main objective of the system is long endurance available airfoils for wing design was very carefully evaluated and two airfoil types selected for construction to obtain the best results, but this is also the reason why the wing structure becomes more complicated (two airfoil types, geometric and aerodynamic twist). The performance of the wing (with the complete design parameters mentioned above) should be tested in CFD program and compared with those obtained in calculations during this stage of design. This will be completed in further design stages.

To completely evaluate air vehicle performance, the gliding flight should be evaluated together with climbing that are exchangeable flight modes in the mode of loitering. During flight performance evaluation the best value of climb (sink) Δh that gives most endurance should be determined.

An experimental examination of the results is also foreseen for further design phases with a live model of the UAS air vehicle that should show difference because of winglets in the design structure, which theoretically will enhance gliding performance reducing drag and augmenting lift. The parameters will be obtained and calculated during the flight of air vehicle live experimental model.

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