ENDURANCE GLIDER

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ABSTRACT

A hand launched glider is designed for maximum endurance. Governing equations regarding the flight performance, geometry, drag and stability of small gliders are reviewed and developed. A FORTRAN program is given to estimate the sink rate of a glider of given characteristics. The design and iteration process is given. Problems with low Reynolds number flows are discussed. Results show that at low Reynolds number, a conventional configuration monoplane gives better performance than a similar biplane. The optimized monoplane's design process is discussed.

NOMENCLATURE

$\alpha = Angle\ of\ Attack$

$\dot{h} = Sink\ rate$

$AR = Aspect\ Ratio$

$c = Chord$

$c_o = Root\ chord$

$C_D = Drag\ Coefficient\ (3D)$

$C_L = Lift\ Coefficient\ (3D)$

$C_m = Longitudinal\ Moment\ Coefficient\ (3D)$

$C_{m_\alpha} = Slope\ of\ Longitudinal\ Moment\ Coefficient$

$i = incidence\ angle$

$Re = Reynolds\ number$

$S = Wing\ surface\ area$

$W = Weight$

$V = Velocity$

$z = Vertical\ distance$

$\lambda = Taper\ Ratio$

$\rho = Density$

$\nu = Dynamic\ Viscosity$

Subscripts

$ac = Aerodynamic\ center$

$t = Tail$

$cg = Center\ of\ Gravity$

$o = Zero\ condition$

$v = Vertical$

$w = Wing$

$x = Longitudinal\ distance$

INTRODUCTION

The objective of this project is to design a hand launched glider to maximize endurance while satisfying certain physical constraints. Equations governing the flight of a small glider will be reviewed. Experimentation methods are reviewed.

The primary goal is to maximize the endurance of a small hang launched glider. The glider has a maximum wingspan of 18 inches with a payload of one U.S quarter. The glider must be designed within feasible material and construction limitations while still being capable of withstanding both flight and landing loads.

The methodology used in the glider design consisted of both analytical and experimental methods. There are five major parameters of interest in the performance of the glider. These are endurance, wing characteristics, weight, drag and stability. Governing equations are needed to relate these parameters with performance.

The most significant is that for endurance. The endurance depends on the sink rate and initial altitude. From theory,

$$\dot{h} = \sqrt{\frac{2\ W}{\rho S}}\ \frac{C_D}{C_L^{3/2}}$$

That is, the endurance is a function of wing loading and a function of lift to drag.

Wing characteristics include both airfoil characteristics and wing geometry. For thin circular arc cambered sections, the airfoil characteristics are given in McCormick[1].

$$C_l = 2\pi\alpha + 4\pi\ z_{max}$$
$$C_{m_{c/4}} = -\frac{\pi}{2}(\alpha + 4\ z_{max})$$

The wing geometry will be considered to be that of a linearly tapered wing. Thus an expression for the chord width,c , with respect to the distance outboard, y, is,

$$c(y) = \left(1 - (1-\lambda)\left(\frac{2y}{b}\right)\right)$$

Additionally, an important measure of the wing's aerodynamic length is the Reynolds number.

$$Re = \frac{V\ c}{\nu}$$

The weight will need to be determined by calculation and experimentation with the materials used. The weight of components will reduced to weight per unit. Thus weight calculations can be easily introduced into equations.

Drag of the glider consists of induced and profile drag. Because of the low Reynolds number, laminar flow is assumed. From McCormick[1], the friction drag is laminar flow is

$$C_f = 1.328 R^{-1/2} = \frac{D}{QS_w}$$

So per unit width, $C_f = \frac{D}{ql_w}$. Integrating over one linearly tapered wing panel and remembering the wetted area is twice the wing area,

$$D = 2 \cdot 1.328 \; b\rho v \frac{\left(\nu\lambda\sqrt{\frac{c_0^2 \lambda v^2}{\nu^2}} - c_0 v\right)}{3(\lambda - 1)\sqrt{\frac{c_0 v}{\nu}}}$$

Nondimensionalizing the drag yields,

$$C_D = (8/3) \cdot 1.328 \frac{(\lambda^{1.5} - 1)}{(\lambda^2 - 1)} \sqrt{\frac{\nu}{c_o V}}$$

The Induced drag of the wing will be assumed to be equal to that of an elliptical lift distribution. Induced drag for an elliptical lift distribution depends on a function of the lift coefficient squared and the aspect ratio. Finally, the total drag is assumed to occur from the addition of profile drag and induced drag. Thus from theory,

$$C_D = C_{D_0} + \frac{C_L^2}{\pi AR}$$

Additionally, the assumption of an elliptical distribution allows for insight into maximum endurance. Substituting into the and taking the derivative of $\dot{h}$ with respect to C_L yields,

$$C_{L_{\text{endurance}}} = \sqrt{3 \; C_{D_0} \; \pi \; AR}$$

Similarly,

$$\dot{h} = \sqrt{\frac{2W}{\rho S}} \; \frac{4}{3^{3/4}} \frac{C_D^{1/4}}{(\pi AR)^{3/4}}$$

The final parameter needing an analytical governing equation is that for the stability of the glider. Stability of the glider is required. The glider will need to recover from any disturbance naturally. This requires stability in the longitudinal and lateral axes. In the longitudinal axis, the moment coefficient, C_m must have a negative slope with respect to angle of attack. Additionally, C_m must be zero at the trim point. Thus,

$$C_{m_o} = C_{m_{ac_w}} + C_{L_{o_w}} \frac{x_{cg} - x_{ac}}{\bar{c}} + \eta \ V_H \ C_{L_{\alpha_t}} (\epsilon_o + i_w - i_t)$$
$$C_{m_o} = C_{L_{\alpha_w}} \frac{x_{cg} - x_{ac}}{\bar{c}} - \eta \ V_H \ C_{L_{\alpha_t}} (1 - \frac{d\epsilon}{d\alpha})$$

The lateral static stability will be neglected due to the absence of a fuselage. The dynamic lateral stability equations consist of three modes Dutch Roll, Spiral and Roll. The Dutch Roll mode will be neglected due to the absence of humans onboard. The most critical mode is the spiral. For the glider to be spirally stable,

$$L_\beta N_r > L_r N_\beta$$

Estimates for $L_\beta, N_r, L_r \text{and} N_\beta$ are given in Nelson[2].

Experimentation is used to verify the validity of the analytical equations. A FORTRAN program given in Appendix A was created to search combinations of wing geometry and flight conditions to estimate performance. The program outputs the geometries of wings that meet the flight performance, physical size criteria, and the practical considerations found by experimentation. Comparing the flight test results with the analytical results will keep the final design practical.

RESULTS

The glider was designed in accordance with the methodology above and the application of design results. The design was started by applying experience and research to create a list of concepts. Next, a survey of the materials available was made to identify the structural envelope. Finally, A series of analysis and experimentation was performed.

The concept development of high endurance gliders was used to identify possible good designs. First, a series of aircraft books were searched to find major trends in configuration. An initial concept page is given in Appendix E. Because the equations of endurance predicted a high C_L for best performance, especially with high Aspect Ratios, canards were quickly dropped to prevent problems with the main wing stalling first. Triplane and higher numbered configurations were considered but the logistics of rigging the wings was more than justification for rejection. A biplane and a conventional surface monoplane were selected as the contenders.

Next, the structural aspects of the glider design were investigated. Two methods were considered; built-up and sheet. Analysis and experimentation was performed on both methods in the areas of feasibility, strength, weight and availability.

A built-up structure, where each individual surface is composed of a combination of materials joined together, was first considered. This method stands out as an obvious choice due to weight and strength especially when using fiber reinforced composites and thin film covering. However, this method was rejected after constructing a test sample. The method is massively time consuming and messy. Additionally, any covering material which meets the weight criteria is difficult to apply and hard to obtain.

The sheet method consists of cutting thin balsa sheets to the required geometry and gluing whole surfaces together. This method allows any surface geometry to be easily cut out and joined. Additionally the load carrying portions of the structure is easily constructed of relatively few parts. The required camber of the wing is easily created by water forming over a curved surface. This method was selected after thin and inexpensive balsa sheet was found locally.

Finally, an iterative series of analysis and experimentation was done. Center of gravity was first considered. Next, an increasingly comprehensive set criteria was developed and applied to find an ideal geometry. These criteria centered around the wing and tail geometry, weight estimates and low Reynolds number problems.

The Center of Gravity location is critical for the proper performance of the glider. Since the payload, the U.S. Quarter at 0.0125 lbs, is the vast majority of the weight, its location and mounting must be acceptable structurally and aerodynamically. A positive aspect of the Quarter's weight is that the design can concentrate on good aerodynamics and not have to consider aerodynamic surface distance and weight restrictions on cg, since the cg can easily be changed.

Wing geometry and airfoil selection influences performance most severely. Unfortunately, the flight conditions encountered by the glider are outside of the commonly available data. Thus, the wing design required testing the resulting theoretical design for applicability with reality.

The theory supplied a general outlook on the optimization. From theory, the best endurance is with the largest aspect ratio possible. This relationship between AR and endurance for the ideal case is shown in figure 1 (Appendix B). The aspect ratio and the profile drag sets the C_L for minimum sink as shown in figure 2. The best endurance may require a C_L beyond the wings capability. Also resulting from the theoretical analysis is the resulting taper ratio of zero. That is, the pure theory considers a wing ideal if it tapers to zero chord at the tip. This is physically inconsistent with intuition. Also, pure theory favors an infinite number of wings. Increasing the number of wings further decreases the root chord and thus increases the aspect ratio. This already been shown to be physically inconsistent. Pure theory will not result in an optimized glider.

There are several design limitations discovered only through experimentation and investigation. These experiments add the influence of the flight Reynolds number and airfoil characteristics.

From McCormick[1], low Reynolds number flow favors thin curved wing sections. However, the maximum C_L is only 1.0 to 1.2 at Re=42000. An estimated Reynolds number of the glider is less than 10000. Thus, the low Reynolds number flow restricts the maximum C_L and thus increases the sink rate.

Another problem influenced by Reynolds number is the minimum Re to maintain flow tangency at the trailing edge. A simple experiment was created to test for tangency by attaching small tufts to a wing section and testing a different Reynolds number. Above a Reynolds number of about 4000, the flow was reasonably tangent, the Kutta condition, at the trailing edge. Additionally, a test glider with the appropriately sized tip chord ($Re_{tip} \approx 4000$) was used to verify the experiment. The result was a much better fit with the predicted sink rate than the small chord gliders developed by theory. This change in analysis based on the Reynolds number also prevented the zero taper ratio problem in the theoretical calculations.

Two configurations were tested in detail. These were the conventional-tailed biplane and the conventional-tailed monoplane.

The biplane configuration which was initially favored. After modification of the endurance theory to include wing chord width, the biplane because less desirable. While multiple wings did increase the wing area, the biplane configuration caused problems due to the low Reynolds number flight. The primary theoretical advantage of the biplane was the ability to increase the surface area without decreasing the aspect ratio. However, high aspect ratio wings, which have small tip chords, in low Reynolds number regions are a actually a disadvantage due to the flow not obeying the Kutta condition. Additionally, the spacing of the wing caused problems with drag. Spacing the wings vertically makes assuming that the drag acts through the center of gravity difficult to justify or satisfy. Worse still, the rigging of a biplane is complex. Imperfections in wing mounting will destroy any advantage over the simple monoplane.

The final design is a conventional-tailed monoplane. There are three phases of the design. The first is performance and geometry. Next, stability analysis is performed. Finally, structural design is performed.

Performance of the monoplane is to be maximized with the proper limitations and constraints. The criteria for the design included a minimum Reynolds number at the wing tip. Geometries resulting from the FORTRAN program are given in Figures 3 and 4. The global minimum estimate for sink rate is just under a half foot drop per second. The global minimum has a 1.8 inch root chord (Figure 3) and a taper ratio of 0.44. This yields a tip chord of 0.8 inches for a tip Reynolds number of 4200 at the best velocity of 9.1 ft/s.

Stability analysis was performed as given in theory. Two types of stability are considered; longitudinal and lateral stability. An Excel spreadsheet given in Appendix C was used to calculate the needed stability parameters.

The objective of calculating longitudinal stability was to prevent the glider from being either too stable or unstable. A test airplane was made to compare stability curves. To keep the glider from overreacting to sudden gusts or too fast launches, the stability curve needs to be relatively flat. That is, the moment due to a disturbance should be small. The test airplane supplied the initial Vh and St/S values. A short tail was chosen to keep the C_{m_α} curve flat. A C_{m_α} curve is given in Figure 5. A C_m versus C_L curve is given in Figure 6. From the zero intercept, the trim C_L of 1.2 is found. The A long tail has the unwanted tendencies of flexing or breaking. Additionally, a long tail would result in a stabilizer with a small chord. This would once again cause problems with low Reynolds number flow. No dynamic longitudinal stability calculations were performed. It is assumed that atmosphere relative to the glider is so unsteady that first order dynamic stability equations are useless.

Dynamic lateral stability was analyzed to keep the spiral and roll modes stable. Stable lateral modes are important due to the absence of any human control after launch. The roll mode was stable when dihedral was added. The spiral mode is more complicated. It was noticed that the ratio of I_x to I_z directly affects the stability. Since the glider's weight is dominated by the quarter, I_z is much larger than I_x. Thus with the current geometry, the spiral mode is stable.

Finally, the actual aircraft structure was designed. The wing panels are sufficiently stiff due to the camber even though they are 1/32 inch balsa. The test airplanes had problems with breaking fuselages in hard landings. To increase the stiffness and prevent breakage, a "T" beam fuselage was constructed out of 1/32 inch sheet. The empennage is similarly constructed of 1/32 inch sheet balsa. The cost of the 1/32 inch sheet was $1.50 for a 3x36 inch sheet. The constructed plane uses approximately one half of a sheet. Thus the cost of a completed glider is $1 when including the required quarter. A picture of the completed glider is given in Appendix D.

CONCLUSIONS

A conventional monoplane has been selected for best endurance. While in theory the biplane offers more advantages, the monoplane offers better aerodynamics in real flows and is easier to construct and optimize. The low Reynolds number flow causes problems with theoretically more efficient geometries. The glider was designed with natural stability in both the longitudinal and lateral axes.

REFERENCES

[1] McCormick, B. W., *Aerodynamics, Aeronautics, and Flight Mechanics*, 2nd ed., Wiley, New York, 1995, p. 152, pp. 139-146.

[2] Nelson, R. C., *Flight Stability and Automatic Control*, 2nd ed., McGraw-Hill, Boston, 1998, pp. 121, 123

APPENDIX A:
FORTRAN PROGRAM

APPENDIX B:

Figures

APPENDIX C:

Stability

APPENDIX D:

Picture

APPENDIX E:

Initial Concepts