ASEN 2004 Aero Lab Part 2:
Glider Design Lab (100 pts)

Assigned: Monday, 27 Jan 20
Lab Presentations Due: 2, 4 Mar 20 (Times will be scheduled)
Collaboration Guidance: Team Assignment
Software Requirement:

- Any computational/programming tool (MATLAB, Excel, Python, etc). Must provide code or file with submission
- Any presentation software

1. Learning Objectives

- Demonstrate the ability to assess analytical assumptions and develop new models based on benchmarking work done in the Aero Computational Lab #1.
- Demonstrate the ability to utilize analytic aerodynamics and performance concepts to develop an open-ended aircraft design solution to meet requirements.
- Understand and describe the basic concepts of longitudinal and lateral stability in the design of an aircraft.
- Demonstrate the ability to conduct sensitivity analysis of design variables on performance of a glider.
- Demonstrate the ability to obtain experimental flight test data to reconstruct an aircraft's L/D curve and drag polar
- Demonstrate the ability to assess natural longitudinal and lateral stability based on test flight profile observations.
- Understand and describe the differences between experimental flight test results and analytic calculations of aircraft performance

2. Required Deliverables & Design Requirements

2.1 – Glider Design Requirements Table

The following table represents the customer requirements for your glider. Requirements translate the customer's needs into measurable values and are usually given in terms of "must have" or threshold measures and "like to have" or objective measures. The weighting of each requirement by the customer is critical to give the designer a better understanding of what measures are most important and guide the designer in making design tradeoffs. Make sure you read and understand the customer's weighting and be able to discuss how it affected your design choices.

Table 1. Summary of Glider Prototype Requirements
(7 m launch height, 1.5 km Standard Atmosphere)

System Requirements	Threshold	Objective	Min or Max
Max Glide Range (meters)	40 m	70 m	Max
Max Glide Range Velocity (meters/second)	15 m/s	10 m/s	Min
Elevator Pitch Control (degrees)	+/- 8 deg	+/- 10 deg	Max
Longitudinal Stability (x_{cg} location relative to wing LE)	x_{cg} = 0.5c	x_{cg} = 0.25c	-
Longitudinal Stability (Horz Tail Volume)	V_H = 0.3	V_H = 0.6	-
Lateral Stability (Vert Tail Volume / Spiral)	V_V = 0.02 B ≥ 4	V_V = 0.05 B ≥ 5	-
Maximum Wingspan (meters)	1.0 m	0.5 m	Min
Payload Requirement	Must securely & safely transport the payload outlined in Attachment 1. • Camera must be secured where it cannot shift in flight or upon impact with ground. • At least one "lens" must be able to see the ground (both lenses exposed is preferred but not required). • Camera or Lens cover should not be subject to direct impact forces during landing or a crash. • Aircraft must be flight certified with a "dummy payload" before an actual payload is used in flight		-
Unit Cost (Fake dollars) using the formula: Empty Weight (in g) * $1 = Cost	No "limit", but will be used as a discriminator between designs		Min

2.2 – Lab Deliverables

2.2.1 - Attendance at every lab period is required. Instructions for weekly tasks and the group report will be presented during the scheduled lab time.

2.2.2 – (15 pts) **Conceptual Design Tabletop Brief and Down-selection (In class, 10 Feb)**

- All team members must *individually develop* a conceptual design for a glider
- Presentation must answer all the questions & show all the required items listed in section 6.
- 10 min total time (including questions)

2.2.3 – (15 pts) **Flight Test Day (24, 26 Feb during lab section 08:30 am – 3:00 pm)**

- All team members must be present
- Must attempt at least 1x flight (more encouraged)
- Collect data from flight for PDR
- Awards will be presented based on flight test results for the following (**No impact on grade**):
    - Performance Award – Longest ground range measured straight line from launch point to glider
    - Engineering Award – Most accurate analysis of flight max range (calculated vs flight test)
    - Design Innovation Award – Most innovative glider design (Instructor, TA/CA/LA vote)

2.2.4 – (70 pts) **Team Preliminary Design Review (PDR) presentation** **(2, 4 Mar in PILOT Breakout Room during scheduled times)**

- Maximum 10 min + 5 min questions
- Presentation must answer all the questions & show all the required items listed in section 6.
- Every group member is required to brief a portion of the presentation.

2.2.5 -- Upload all presentation and source calculations file (Excel, Matlab, Hand Calcs, etc) to Canvas lab assignment

3. Background

The General Design Process

> *"Those involved in design can never quite agree as to just where the design process begins. The designer thinks it starts with a new airplane concept. The sizing specialist knows that nothing can begin until an initial estimate of the weight is made. The customer, civilian or military, feels that the design begins with the requirements."*
>
> -- Daniel Raymer, Aircraft Design: A Conceptual Approach[1]

This statement by Raymer illustrates concisely the problem that many students have with the design of a complex system such as an aircraft: Where do I start? There are many aircraft design processes, but all are generally similar. The following design process from Brandt[2] is a simple, but effective process that this lab will utilize to help you through this process for your glider design. Note that this process is iterative to both refine and optimize a given design as well as attempt to fully explore the design space. While lab is time limited, each individual on a team should accomplish at least 2 iterations of your conceptual designs which combined with the design iterations of your teammates will expand the level of design iterations per team within a reasonably short period of time to ensure you have reasonably explored your design space. Additionally, once you select a single design to build, you will also repeat this process to further refine the design (specifically in terms of stability). More specifics on what you should be accomplishing relative to your glider design will also be provided in the subsequent sections.

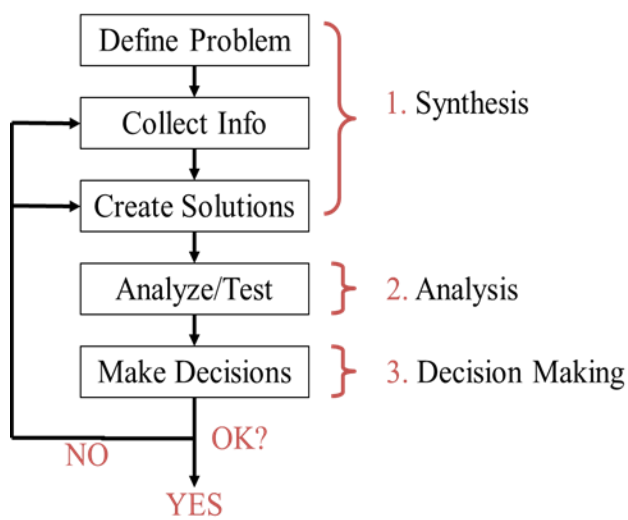


Figure 1: Design Process (Source: Brandt)

[1] Raymer, D. P., Aircraft Design: A Conceptual Approach, 2nd Ed., AIAA Inc., Chap. 12 (2012).
[2] Brandt, S, Introduction to Aeronautics: A Design Perspective, 2nd Ed, AIAA (2004).

Define Problem: Most design processes for any discipline begin with developing an understanding of the problem you are attempting to solve. In the case of this glider design lab, the problem is simple—fly the farthest! Most engineering problems will be more complex than this; however, you will find that even the simplest problem can be overwhelming when your design space is unbounded. This is the purpose of customer requirements. Requirements translate problems into measurable values that you can design towards and bound your design space. Be sure to regularly revisit the requirements listed in Section 2 throughout your design process to ensure you are staying within the bounds of the problem and design space.

Collect Info: This is an open-ended lab! There are many potential design solutions that could satisfy the customer requirements. Your team is expected to explore the space of current aircraft designs and design features which could support your design. ***You cannot directly copy an existing design holistically***. ***Additionally, any design features you utilize, you are expected to be technically conversant into the fundamental science and engineering that underlie its potential utility to your design requirements***. In addition to researching exiting solutions/designs that may inform your design, you should also identify the design variables within your analytical calculations for determining your glider performance. Knowing the variables can help you identify some of the levers which you can use to adjust the performance of your design, and will be necessary for you to accomplish the sensitivity analysis task of this lab.

Create Solutions: Initial solutions for conceptual design usually take the form of a basic drawing with sizing and dimensions that fall within your design space, but are not likely optimal at this point. The methods you use to develop your design solution are built on the same analytical tools you developed and benchmarked in aero lab 1. Section 4 will expands on the methodology for creating your design solution in more detail.

Analyze and Test: This step is the most time consuming and vital for your process as it will provide you with the data necessary to make informed design decisions to improve your subsequent iterations of the design. Prior to building your glider, your analysis will primarily be analytic using the tools you developed in lab 1 to refine and optimize your design "on paper". As part of the "paper" analysis of your design, you will conduct a sensitivity analysis on at least two design variables of your choice. After you build your glider, you will conduct your final test which will be the flight test to obtain experimental data on your design.

Decision Making: Your "paper" analytical analysis of your design will guide many of your design decision regarding performance; however, in making design decisions, you must also take into account non-performance requirements such as the impact your choices have on manufacturability and resources. You have limited time, budget, and resources to build your glider, so complex design features which may be beneficial to your performance, but add complexity or costs will need to be weighed carefully against the customer requirements. These issues need to be considered when down-selecting your conceptual design and not at the end when you are in the "build" phase of the lab.

4. Developing your Aircraft Design

The following sections outline the general process by which you develop your aircraft design solution. This isn't the only way to approach an aircraft design solution; however, it is provided as a starting point.

4.1 – Overall Aircraft Configuration and Weight Estimation

Based on your understanding of the problem and the information you gathered on both existing aircraft and design elements as well as your analysis of the analytical design variables you can adjust, select design features you deem most beneficial to your requirements. You don't need refined dimensions yet as you will continue to work on those as you iterate your design, but you'll need to have a general sense of the dimensions to aid in your weight estimation.

Determine range of general configurations to explore design space:

In selecting the general configuration of your aircraft, there are endless options; however a few are shown below as examples. Each configuration has advantages and disadvantages, and it will be left to you and your team to research what configuration or combination of configurations best supports your customer requirements.

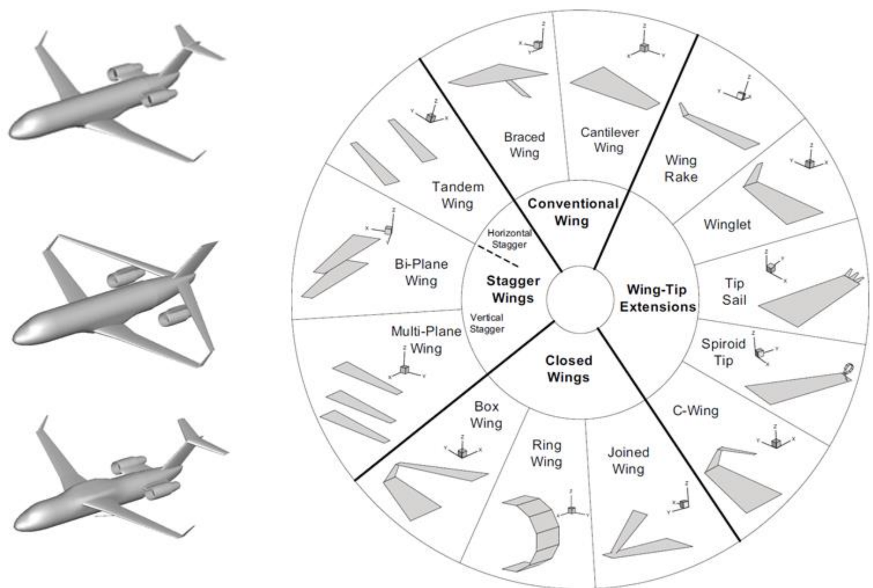


Figure 2: Example Aircraft Configurations (Source: Advanced Aircraft Design Lab Royal Military College of Canada[1])

The choice of overall configuration can be broken down further into the choice of a wing planform shape and control surface configuration. In determining the general wing planform shape, the general parameters which you need to define are:

1) Wing Planform Area (S_{ref} will be used in this lab to distinguish this value from wetted area S_{wet})
2) Aspect Ratio (AR)
3) Taper Ratio (λ)
4) Sweep Angle (Λ)

As well as the positioning of the wing relative to the fuselage:

1) Low wing
2) Mid-wing
3) High-wing

[1] Advanced Aircraft Design Lab Royal Military College of Canada, http://www.aircraftdesign.ca/research/research.html

Choice in your control configuration (horizontal and vertical tail or canards) is vital in that this will have a large impact on your stability as well as your ability to set a trim velocity and angle of attack for your glider. As with your overall consideration, each control configuration has advantages and disadvantages, and it will be left to you and your team to research what configuration or combination of configurations best supports your customer requirements.

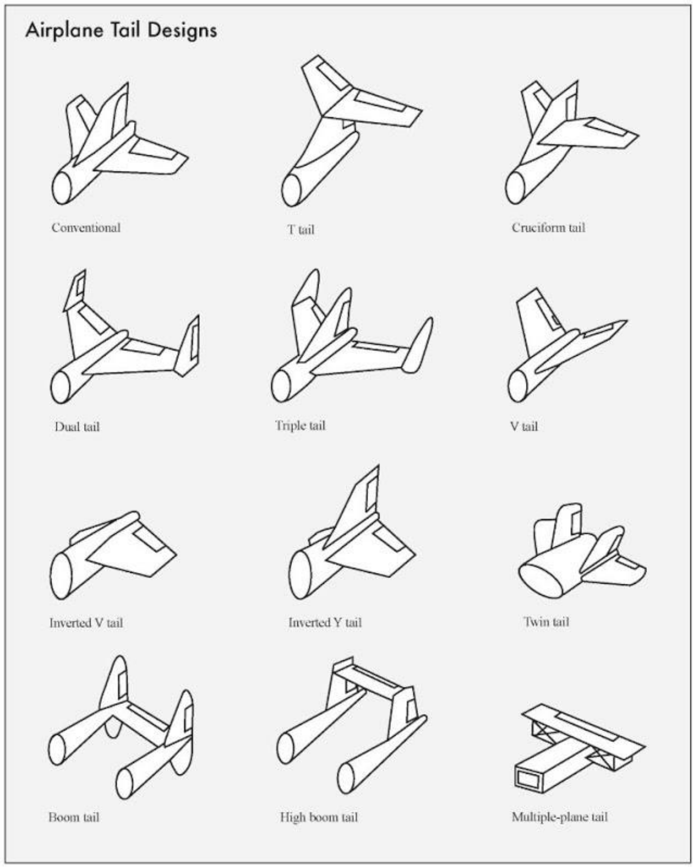


Figure 3: Example Airplane Tail Configurations[1]

At the end of this stage, you should have established an initial estimate for the following:

1) Wing Planform Area (S_{ref})
2) Wing Aspect Ratio (AR)
3) Wing Taper Ratio (λ)
4) Wing Sweep Angle (Λ)
5) Whole Aircraft Wetted Area (S_{wet}) to include control surfaces and fuselage

Weight/Mass Estimation & Initial Sizing:

Based on your initial dimension, estimate your weight using some standard densities of materials you can expect to use. You will be provided both XPS foam and balsa to build at no cost; however, if you want to use other materials you can but you must supply it yourself. Below are some of the more common materials used. Note that densities can vary greatly depending on specifics of each material chosen, but these are good initial approximations. You may need to research others depending on your desired material use.

[1] http://what-when-how.com/flight/tail-designs/

1) Balsa Wood: 160 kg/m^3
2) XPS Foam: 26 kg/m^3
3) Aircraft grade Ply Wood: 600 kg/m3
4) Wood/White Glue: 1.19 g/ml

The following website provides good descriptions of other material characteristics as you consider you options: http://www.rcplanesguru.org/2015/09/materials-and-hardware-used-for-rc.html

* Note that these materials densities are based on areas, not volumes due to their small thicknesses

The estimated weight of your aircraft will be simply the sum:

$$W_{TO} = W_{fuselage} + W_{wing} + W_{horz\ tail\ or\ canard} + W_{vert\ tail} + W_{ballast} + W_{payload}$$

Breaking this down further into the components:

$$W_{fuselage} = Volume_{fuselage} \cdot \rho_{material}$$

$W_{horz\ tail/canard} = Volume_{horz\ tail/canard} \cdot \rho_{material}$ (use area instead of volume if flat plate material used)

$W_{vert\ tail} = Volume_{vert\ tail} \cdot \rho_{material}$ (use area instead of volume if flat plate material used)

$$W_{wing} = Volume_{structure} \cdot \rho_{structure} + \left[2 \cdot S_{ref} \cdot \left(1 + 0.25\left(\frac{t}{c}\right)_r \left(\frac{1+\tau\cdot\lambda}{1+\lambda}\right)\right)\right] \cdot \rho_{wing\ covering}$$

$\left(\frac{t}{c}\right)_r$ is the thickness to chord ratio at the planform root at the centerline of the aircraft

$\tau = \frac{\left(\frac{t}{c}\right)_r}{\left(\frac{t}{c}\right)_t}$ is the ratio of the thickness to chord ratios at the root and the tip of the planform

$\lambda = \frac{c_t}{c_r}$ is the taper ratio which is the ratio of the root chord to the tip chord of the planform

NOTE: Your material density estimates are in terms of mass and the resulting calculations must be converted to a weight (9.8 N/kg) before doing the following aerodynamic calculations.

The equation for the estimation of the wing weight is more complex than the fuselage and control surfaces and based on the model provided by Roskam[1] used in lab 1. This is because it is expected that the wing of your glider will have an internal structure to define an airfoil shape of your choice and a covering material to serve as the wing skin which may be made of different materials. Additionally, it is important that the calculation of your wing weight be tied specifically to your wing planform area (S_{ref}) as this association will drive much of your optimization and sizing calculations for your design. Based on your constrained weight requirements, the fuselage and control

[1] Roskam, J., "Airplane Design Part II: Preliminary Configuration Design and Integration of the Propulsion System," Chapter 12, DARCorporation, 1997.

surfaces are expected to be simple, single material components. After you calculate your weight estimation, double check to see if your estimates fall within the customer requirements listed in section 2. Provide yourself enough margin from the threshold to account for uncertainty at this stage (generally 10-20%).

The ballast weight ($W_{ballast}$) is weight required (generally on the nose of your glider) to ensure that the center of gravity (cg) of your glider is located in a position for static longitudinal stability (stability in pitch). A good design should require minimal ballast as ballast is “dead weight” that doesn’t contribute to the mission of your aircraft. To determine the amount of ballast weight you need, you will need to calculate the location of your cg based on the configuration of your glider using your weight estimates and an estimate of your cg location for your individual components. For aircraft, the reference origin for longitudinal location is at the leading edge of your wing (x = 0). The following picture and calculations demonstrates how to locate your cg:

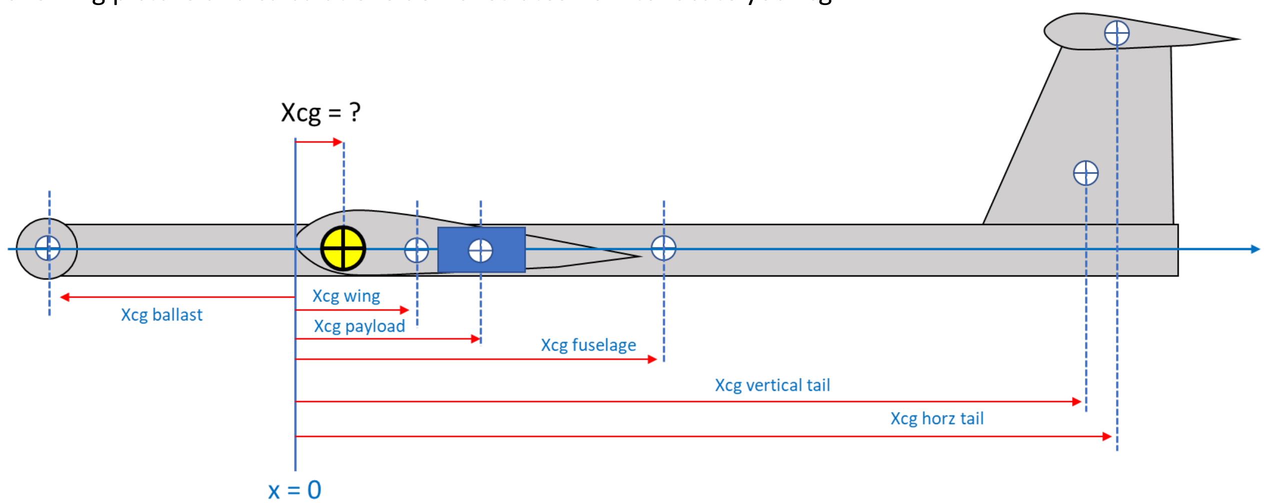


Figure 4: Center of Gravity Determination Reference Geometry

$$\sum M_{cg} = W_{TO}x_{cg} = W_{wing}x_{cg\ wing} + W_{fuse}x_{cg\ fuse} + W_{vert}x_{cg\ vert} + W_{horz}x_{cg\ horz} + W_{ballast}x_{cg\ ballast} + W_{payload}x_{cg\ payload}$$

For symmetric components, assume the cg location is at the middle point of the component. For the wing (airfoil shape), assume that the wing cg is located at 40% of the chord. For other basic geometric shapes, you can calculate the centroid to locate the cg. ***Note that since the distance x is referenced relative to the leading edge of the wing, anything in front of the wing will have a negative value for x.*** To meet basic longitudinal stability requirements, your overall aircraft cg (x_{cg}) should be located between the leading edge of your wing and no further back than the 30% of the chord of your wing (although 25% chord is a safer value to aim for) for conventional configuration aircraft (as shown above). If you have a canard configuration, the location of the aircraft cg to ensure pitch stability is a bit more complex but initial location should generally be forward of the leading edge of your wing (i.e. a negative value).

You’ll find that in many of your calculations later, wing loading (W_{TO}/S_{ref}) will appear. This ratio is an important one when it comes to correctly sizing your aircraft. From your weight estimation equation, wing loading is simply:

$$\frac{W_{TO}}{S_{ref}} = \frac{W_{fuselage} + W_{wing} + W_{horz\ tail/canard} + W_{vert\ tail} + W_{ballast} + W_{payload}}{S_{ref}}$$

Where:

- Wing Planform Area: $S_{ref} = b \cdot \bar{c}$
- Mean Aerodynamic Chord: $\bar{c} = \frac{c_r + c_t}{2}$ (for a simple tapered rectangular wing)

It is important to note that your wing weight (W_{wing}) is also a function of your S_{ref}! Therefore, any adjustment to your wing size will impact weight as well. Taking your geometry and weight estimations from the prior stages, you can now "size" your aircraft based on your range and velocity requirements. Set a goal for your desired max glide range (R). Knowing this range as well as the height (h) from which you will be launching your glider, you can calculate a desired L/D_{max}.

$$\left(\frac{L}{D}\right)_{max} = \left(\frac{C_L}{C_D}\right)_{max} = \frac{R_{max}}{h}$$

Recall that for L/D_{max}, an aircraft's zero-lift drag coefficient is equal to it's induced drag, therefore, you can derive the following relationship to solve for the required C_L to obtain L/D_{max} and your glider design's AR:

$$C_D = C_{D_O} + kC_L^2$$

$$C_{D_O} = kC_L^2$$

$$C_D = 2C_{D_O}$$

$$C_L = \left(\frac{C_L}{C_D}\right)_{max} \cdot C_D$$

$$C_L = \left(\frac{C_L}{C_D}\right)_{max} \cdot 2C_{D_O}$$

As in lab 1, you will need to estimate your glider's zero-lift drag coefficient (C_{Do}); however in this case, since we don't know the airfoil yet, we'll be estimating it without taking into account that minimum drag occurs at zero lift:

$$C_{D_O} = C_{fe} \frac{S_{wet}}{S_{ref}}$$

The equivalent skin friction coefficient is an unknown since it depends on both the material you select and your build quality. For the purposes of this lab, we'll assume that the equivalent skin friction coefficient is equal to the flat plate skin friction coefficient for fully turbulent flow and using the full length of your glider as the characteristic length and the maximum allowable glide velocity via the customer requirements (6 m/s):

$$C_{fe} = C_{f\,turb} = \frac{0.074}{Re^{0.2}}$$

$$Re = \frac{\rho_\infty V_\infty l_{fuselage}}{\mu_\infty}$$

Now that you have an estimated required C_L, you can do an initial sizing of your wing by determining the required wing loading to achieve that value of C_L assuming L=W (small glide angle):

$$C_L = \frac{W_{TO}}{q_\infty S_{ref}}$$

$$\frac{W_{TO}}{S_{ref}} = C_L q_\infty$$

Plot the variation of wing loading vs. velocity for the range of glide velocities allowed for by your customer requirements (and utilizing standard atmosphere 1.5 km altitude properties). Compare the resulting range of wing loading to the one for your design. If your design's wing loading not in the range required of your customer velocity limitations, you'll need to either adjust your design to reduce weight (different materials) or more likely, change your wing planform area (S_{ref}), but remember, your weight is a also a function of your S_{ref}, so any changes to the size of your wing will also affect your weight. Note that you can also vary your aspect ratio (AR) which will have a significant impact on your wing loading both in terms of weight and planform area.

This initial sizing will get you in the right ballpark for your design, but now that you have an initial aircraft configuration and wing sizing, you can refine your design using the tools you developed in lab 1. Before moving on from this stage, you should have:

1) Desired value for L/D_{max} based on your goal range
2) Required value for C_L to achieve L/D_{max}
3) An initial wing loading that meets C_L requirements (W_{TO}/S_{ref})
4) An initially sized wing planform area (S_{ref})
5) An initial total weight estimate (W_{TO}) and component weights
6) An initial estimate of your aircraft cg location (x_{cg})
7) An initial estimation of your required ballast weight to be stable in pitch ($W_{ballast}$)
8) An initial estimate of zero-lift drag coefficient (C_{Do})
9) An initial estimate of your glide velocity for L/D_{max} ($V_{L/Dmax}$)

4.2 – Airfoil Selection & Refining Your Design

Now that you have a configuration and a weight/mass estimate, you can begin refining your wing planform design and selecting an airfoil. Based on the required C_L calculated from your desired L/D_{max}, research airfoils which can achieve the necessary C_L at a low angle of attack and a low value of profile drag (C_d). Remember that lift curves and drag polar vary based on Reynolds number. Do not use the Reynolds number you calculated for your coefficient of friction for selecting your airfoil! You must recalculate it based on the characteristic length of your airfoil chord length rather than the fuselage length (again using the 1.5 km altitude standard atmosphere properties and either your calculated glide velocity from the prior step or 6 m/s from the requirements):

$$Re = \frac{\rho_\infty V_\infty c}{\mu_\infty}$$

It can be very difficult to find airfoil data for the low Reynolds numbers your glider will experience; however, here are some resources which can help you with your search. Start with researching airfoils at the University of Illinois at Urbana-Champaign Applied Aerodynamics Group webpage[1] (https://m-selig.ae.illinois.edu/index.html). This group has compiled a large database and resources on airfoils and has a lot of information and data on low-speed airfoils. Once you have found the airfoil you want, go to the Airfoil Tools Website (http://airfoiltools.com/index). This site leverages MIT's XFOIL[2] program an provide an online calculation of airfoil lift and drag curves over a wide range of airfoils. It will even allow you to adjust the Reynolds numbers for your calculations. Additionally, I have two copies of the book "Model Aircraft Aerodynamics" by Martin Simons which had low Reynolds number data for a number of airfoils for use in small scale aircraft that will be available for your use during your lab sections (must stay in the lab).

Once you've selected your airfoil, you can now analyze your glider design following the same process you used in lab 1 to verify that you can still meet your L/Dmax, range, and velocity requirements.

You may find that your results vary from your initial sizing study and you will need to further iterate on your design. ***As you do, make sure you are updating your weight and aircraft cg estimations every time you change your design!***

4.3 – Control Surface Sizing and Location (Horizontal and Vertical Tails)

The tail surfaces of an aircraft have two main purposes 1) enable stability and 2) provide enough control authority to fly throughout the required operating flight envelope of the aircraft. For your glider, this translates to having good longitudinal (pitch) and lateral-directional (roll and yaw) stability so it can fly straight and maximize its range. For stability, our main concern at this point is static stability. Static stability is the initial tendency of your aircraft to return to equilibrium—which for an aircraft is straight and level flight. We will not be concerned too much with dynamic stability which is the behavior of the aircraft over time (does it converge on an equilibrium state?). The terminology we will use to indicate our equilibrium point is "trimmed" flight. In terms of control, the only focus of your glider will be to have pitch authority. Therefore, you will need elevators, but no alerions or rudder are required. Your glider will required the ability to stabilize (trim) the glider at different angles of attack in order for you to test the variation of your L/D and range with different trim velocities to attempt to find the maximum L/D and range experimentally. Per the requirements in section 2, at a minimum, your elevator should be designed to provide -10 deg to 10 deg of travel to support controlling the glider in pitch. How you will ensure your tail surfaces are large enough and positioned correctly to provide both stability and control is the subject of the following sections.

[1] Selig, M., University of Illinois at Urbana-Champaign Applied Aerodynamics Group, https://m-selig.ae.illinois.edu/index.html
[2] Drela, M., XFOIL Program, MIT, https://web.mit.edu/drela/Public/web/xfoil/

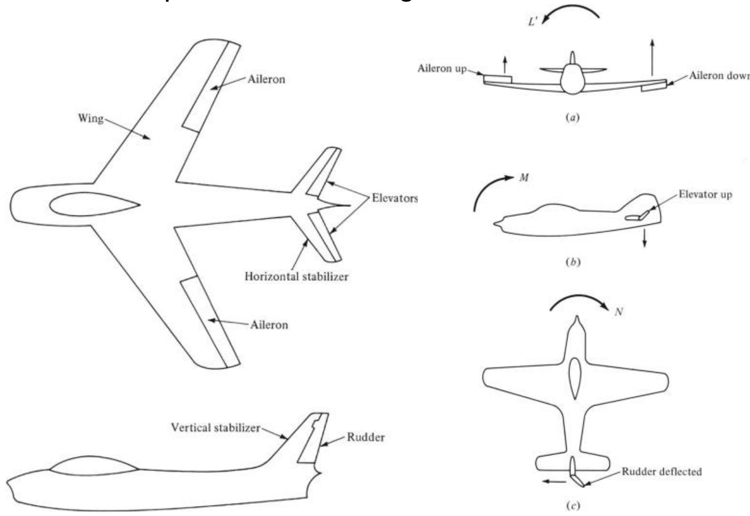


Figure 5: Control Surfaces (Source: Anderson)

4.3.1 – Longitudinal Static Stability and Trim

The design fundamentals behind longitudinal stability have already been discussed in the prior sections on determining the location of your aircraft's center of gravity; however, the other major component to longitudinal stability is the size and location of your horizontal control surfaces. For this requirements, we're going to use some basic rules of thumb compiled by Drela[1] at MIT using a parameter called the horizontal tail volume coefficient (V_H):

$$V_H = \frac{S_h \cdot (x_{ac_{ht}} - x_{cg})}{S_{ref} \cdot c}$$

Where:

- S_h= Planform Area of your horizontal tail
- $(x_{ac_{ht}} - x_{cg})$= distance between your aircraft cg and the horizontal tail aerodynamic center
- c = chord of the wing

The criteria for basic sizing of V_H is:

$$0.30 \leq V_H \leq 0.60$$

You should aim to bias towards the higher end of this scale to ensure you also have enough pitch control authority for your glider to trim at different angles of attack and velocities. The tradeoff is a larger horizontal tail surface (or increased length of your glider to expand the moment arm) which increase your weight and drag. Meeting this horizontal tail volume coefficient criteria while keeping your aircraft cg location (x_{cg}) located between your leading edge of your wing and the quarter chord of your wing should keep you in safe territory with regards to longitudinal stability.

In order to determine your required elevator deflection to trim your aircraft at the appropriate speed to maximize your L/D, you will need to conduct a moment balance of your glider's aerodynamic forces. For these calculations, we'll

[1] Mark Drela, Steven Hall, Paul Lagace, Ingrid Lundqvist, Gustaf Naeser, Heidi Perry, Raúl Radovitzky, Ian Waitz, Peter Young, and Jennifer Craig. 16.01 Unified Engineering I, II, III, & IV. Fall 2005 - Spring 2006. Massachusetts Institute of Technology: MIT OpenCourseWare, https://ocw.mit.edu. License: Creative Commons BY-NC-SA.

assume the only forces contributing to the pitching moment of your glider are the lift generated by the wing (L_w) and the lift generated by your horizontal tail (L_{ht}). If you recall from ASEN 2002, the location of our lift forces for an airfoil was located at the aerodynamic center (ac) of the airfoil because at this point, the moment generated by the pressure and shear distributions around the airfoil was constant as you varied the angle of attack. From our airfoil data, we know that for much of the linear range of an airfoil's lift curve, the location of the aerodynamic center can be approximated by the quarter chord (0.25c) of the airfoil. Below is the simplified force and moment diagram for a conventionally configured aircraft:

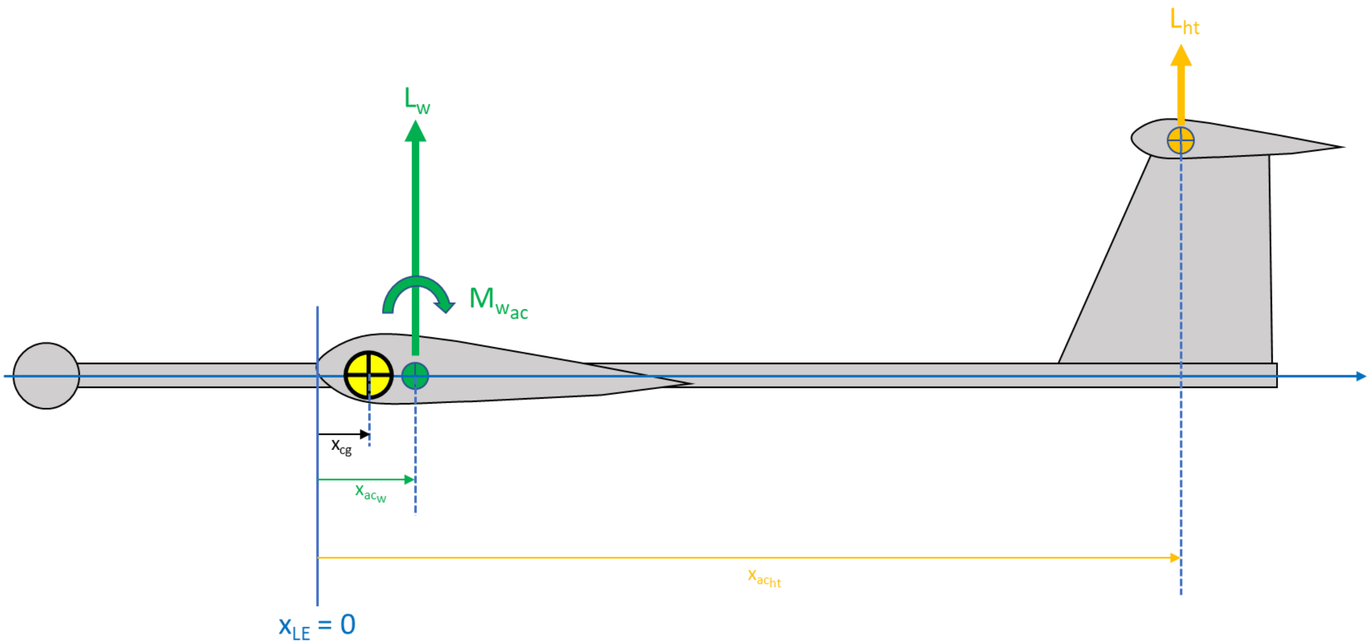


Figure 6: Simplified Longitudinal Force & Moment Diagram

When the moments due to both the wing lift and horizontal tail lift about the center of gravity of the glider are equal to zero, we can say that the aircraft is trimmed in pitch. Notice that the horizontal tail does not produce a moment about its aerodynamic center. This is because most control surfaces are built with symmetric airfoils which do not produce moments when lift is located at the aerodynamic center. From Anderson, the general formula for the coefficient of total pitching moment about an aircraft's cg is:

$$C_{m_{cg}} = C_{m_{ac,w}} + C_{L_w}\left(\frac{x_{cg}}{c} - \frac{x_{ac_w}}{c}\right) - V_H C_{L_{ht}}$$

Where:

- $C_{m_{cg}}$ = coefficient of moment about the cg; this will be equal to zero for trimmed flight
- $C_{m_{ac,w}}$ = coefficient of moment about the aerodynamic center for your wing; approximate with your 2D airfoil value
- C_{L_w} = coefficient of lift for your wing (per our assumptions, equal to our whole aircraft C_L)
- $\left(\frac{x_{cg}}{c} - \frac{x_{ac_w}}{c}\right)$ = distance between your aircraft cg and the wing aerodynamic center (0.25c) in percent chord.
- V_H = horizontal tail volume coefficient
- $C_{L_{ht}}$ = coefficient of lift for your horizontal tail (flat plate approximation)

Where $C_{m_{ac,w}}$ can be approximated using your 2-D airfoil data, the lift from your wing can be determined from your L/D calculations and your tail volume coefficient V_H is determined via your geometry. For simplicity of design at smaller scales, you will only use flap plate control surfaces (not airfoils) for your glider design. From experimental data via Ananda[1], the lift curve for a rectangular flat plate surface with an aspect ratio = 3 at representative Reynolds Number for our small scale glider (~10^4 - 10^5) is as follows:

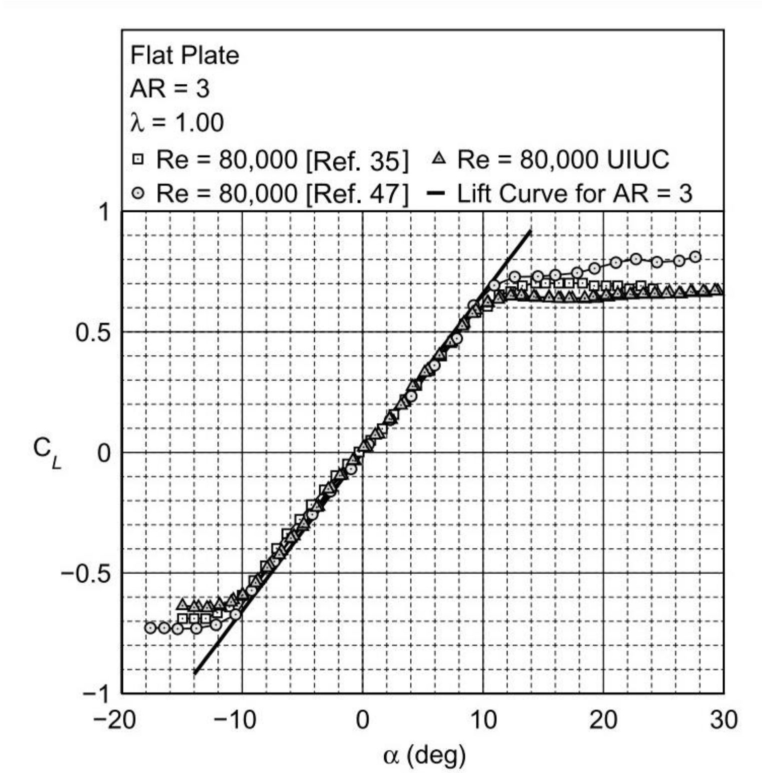
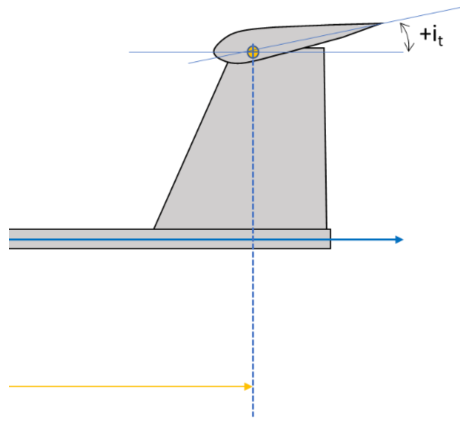


Figure 7: Rectangular Flat Plate Coefficient of Lift vs Angle of Attack, Re = 80,000, AR=3 (Source: Ananda)

Utilizing this information, you can calculate the required lift coefficient for your horizontal tail to trim your glider at the desired C_L to obtain L/D_{max} by setting your coefficient of total pitching moment equal to zero and solving for $C_{L_{ht}}$. From there, utilize the lift curve plot from Ananda (Figure 7) to determine the tail angle of attack ($\propto_{tail}$) and calculate the required tail incident angle (i_t) using the equation from Anderson below:

[1] G.K. Ananda, P.P. Sukumar, M.S. Selig, *Measured aerodynamic characteristics of wings at low Reynolds numbers*, Aerospace Science and Technology, Volume 42, 2015



$$\propto_{tail} = \propto_w - i_t - \varepsilon_o$$

Where:

- $\propto_w$ is the angle of attack required to get the C_L required for your wing for L/D_{max}
- i_t is your horizontal tail incident angle (positive trailing edge up)
- ε_o is the downwash on your tail when your wing is at zero lift (we will assume this value is zero for this lab)

NOTE: The tail incident angle is measure as ***positive with trailing edge up*** from a line parallel to the centerline of your glider. If you cannot achieve the desired $C_{L_{ht}}$ with your tail or it requires too high of an tail angle of attack (you should aim to for as low a trim angle of attack as possible), you will need to either resize your tail or move the moment arm further back. ***Note that like any other change to your aircraft design, this will require you to update your weight, drag, and lift calculations!***

4.3.2 – Lateral Directional Stability

The primary mechanism to ensure directional stability (sometimes also referred to as yaw stability or weather-vane stability) is your vertical tail. The desired behavior for an aircraft is to track back "into the wind" similar to a weather-vane in response to any disturbance that results in a yaw to the aircraft. To ensure basic directional stability, we'll utilize some rules of thumb based on vertical tail volume coefficient (V_v). From Drela, the formulation for the vertical tail volume coefficient and general stability criteria are:

$$V_v = \frac{S_v \cdot (x_{ac_v} - x_{cg})}{S_{ref} \cdot b}$$

Where:

- S_v= Planform Area of your vertical tail
- $(x_{ac_v} - x_{cg})$= distance between your aircraft cg and the vertical tail aerodynamic center
- b = span of the wing

The criteria for basic sizing of V_v is:

$$0.02 \le V_v \le 0.05$$

Unlike V_H, it can be dangerous for a glider to have too large of a vertical tail as this can contribute to “death spirals” as the aircraft continually attempts to chase the wind like a weather vane and any directional disturbance of gust will cause the glider to spiral to its demise. With this in mind, you should aim for a “middle” ground V_v between the values shown above.

Our final concern in terms of stability is lateral stability (or sometimes referred to as roll stability). The desired behavior for an aircraft is to return to “wings level” in response to any disturbance that causes the aircraft to roll. Although there are many ways to impact lateral stability, the primary method is called dihedral (Γ). Dihedral angle is the angle the wing is canted in the y-z plane (looking nose on of an aircraft) relative to horizontal.

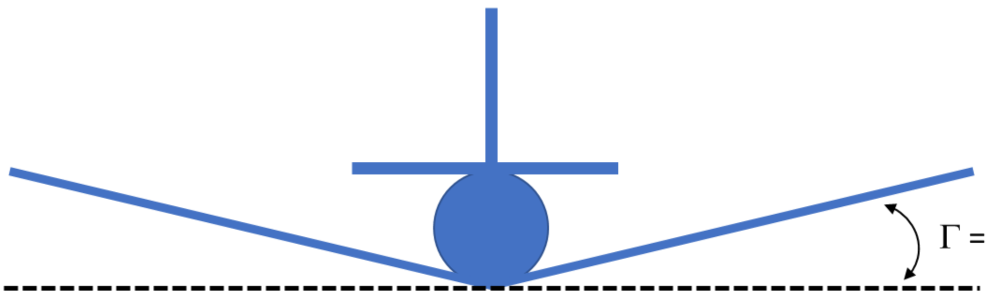


Figure 8: Dihedral Angle

Again, a basic rule of thumb will be provided via Drela using the spiral parameter (B):

$$B = \frac{(x_{ac_v} - x_{cg})}{b}\frac{\Gamma}{C_L}$$

Where:

- $(x_{ac_v} - x_{cg})$= distance between your aircraft cg and the vertical tail aerodynamic center
- Γ = Dihedral Angle (in degrees)
- b = span of the wing
- C_L= desired coefficient of lift for your airplane

The criteria for basic sizing of B is:

Stable Spiral: B > 5
Neutral Spiral: B = 5
Unstable Spiral: B < 5

Although aircraft with marginal lateral stability can be flown without major difficulties, any aircraft (such as your glider) which must be stable without a pilot in the loop must be naturally stable. It is also important to note that dihedral will not impact your measurement of wing planform area (S_{ref}) which is sometimes referred to as the area of the “shadow” of the wing. Dihedral would effect this measurement if that statement was taken literally; however, the determination of your wing planform area S_{ref} is not impacted by the dihedral you choose.

4.4 – Sensitivity Analysis (Optional Bonus Section)

Sensitivity analysis the process by which you can determine how sensitive your customer requirements are to the design variables in order to identify changes that will result in the most value to your design. Sensitivity analysis enables you to more rapidly optimize your design by helping you understand what design variables give you the most "bang for the buck". For this lab, your team will be required to conduct a sensitivity analysis for a minimum of two of your design variables. To do this, you will need to systematically vary a design variable while holding the rest of the design constant and observe the result on your ability to satisfy your customer requirements. For example, you could analyze the impact of aspect ratio (AR) on your range requirement by altering your design for AR and then plotting the impact on range. Select a second design variable and do the same, compare the results and be prepared to discuss them in your final brief.

5. Flight Test Day

One of the major objectives of the aero glider design lab is to expose you to another form of experimental testing other than the wind tunnel—actual flight tests. Flight testing is often the source of the most accurate "truth data" when it comes to the aerodynamic characteristics and performance of an aircraft. Flight testing is generally accomplished as designs become near final and only after multiple design iterations and rigorous analytic and computational analysis. This is because flight test generally holds the most risk in terms of time and cost (especially if there is a failure). However, flight testing is a spectrum, and it can also be used earlier during conceptual design with more basic, often sub-scale, aircraft as a risk reduction method for evaluating general flight characteristics of a design. In this lab, your flight tests are more in line with this latter reason for conducting a flight test. The objective of your flight test is to provide data that will allow you to discuss how well your analytic calculations for your design match your real-world flight performance when it comes to range and L/D_{max}.

5.1 – Flight Test Techniques

While you are only required to attempt one flight to be considered successful for lab grading, more flights are required to validate your engineering analysis of the flight performance of your aircraft. In your flight tests, you will attempt to experimentally determine your L/D_{max} (and thus max range), by flying your glider multiple times (minimum 3, goal of 5) trimmed at different airspeeds (and thus different C_L and angle of attack). You will do this by varying your horizontal tail incident angle (i_t) for each flight, then measuring the range (R) it flies.

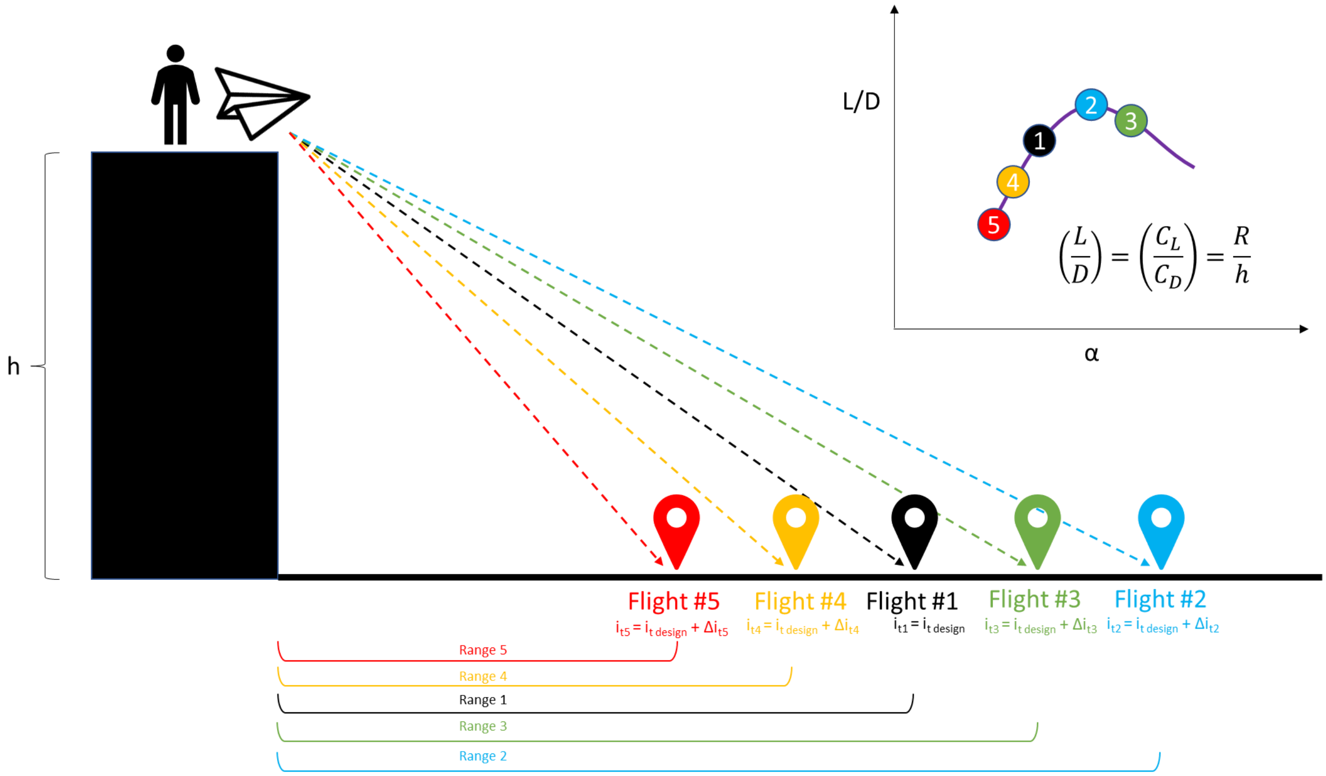


Figure 9: Flight Test Overview

To setup your flight test card, vary your elevator trim angles centered around the elevator angle you calculated to achieve your L/D_{max}. for example, your test card for your flight should look something like this:

Flight Number	**Tail Incident Angle (deg)**	**Pre-Flight Glider Weight (g)**	**Ground Range (m)**	**Flight Time (s)**	**Flight L/D**	**Flight V_{trim} (m/s)**	**Flight C_L**	**Flight α (deg)**
	Set Parameter	Measured	Measured	Measured	Calculated	Calculated	Calculated	Calculated
1	$i_{t1} = i_{t\ design}$ for your calculated L/D_{max}							
2	$i_{t2} = i_{t\ design} + \Delta i_{t2}$ (in deg)							
3	$i_{t3} = i_{t\ design} + \Delta i_{t3}$ (in deg)							
4	$i_{t4} = i_{t\ design} + \Delta i_{t4}$ (in deg)							
5	$i_{t5} = i_{t\ design} + \Delta i_{t5}$ (in deg)							

Table 2: Sample Flight Test Card

The increment you choose to adjust each of your flight's tail incident angles will depend on your design and the results of your flights. For example, if you find that in flight #2, your range increased, you may choose to continue to increase your tail incident angle for subsequent flights until the range drops. If in flight #2, your range decreased, in your subsequent flights, you should choose to decrease your tail incident and see if you see either an increase or decrease in the range. The goal of these flights is to discover the maximum point of your L/D curve per the equations of motion for gliding flight by finding the tail incident angle that gets you the maximum range:

$$\left(\frac{L}{D}\right)_{max} = \left(\frac{C_L}{C_D}\right)_{max} = \frac{R_{max}}{h}$$

Since the height of our launches is known, we can solve for the L/D. Timing the duration of our flight will allow us to calculate the trim velocity for our flight using some basic geometry.

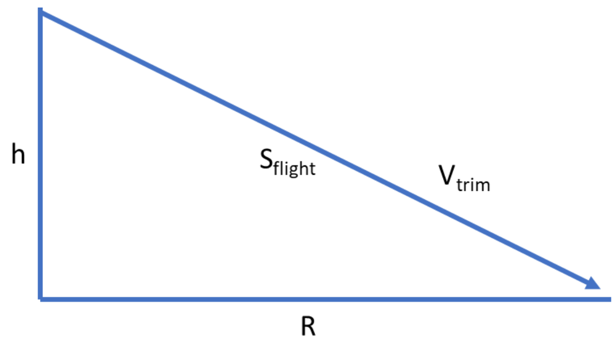


Figure 10: Calculating V_{trim} during flight tests

$$V_{trim} = \frac{S_{flight}}{t_{flight}}$$

$$V_{trim} = \frac{\sqrt{h^2 + R^2}}{t_{flight}}$$

From there you solve for the coefficient of lift of the wing using the measured weight of your glider pre-flight and assuming L = W. The weight will be measured prior to every flight to ensure any on the spot modifications will be accounted for in the weight of the glider. Again, ensure you convert your weights to consistent units (Newtons) before utilizing in your calculations.

$$C_L = \frac{W_{measured}}{\frac{1}{2} \cdot \rho \cdot V_{trim}^2 \cdot S_{ref}}$$

The local air density will be calculated utilizing pressure and temperature measurements outside and the ideal gas law. And finally, you can find the angle of attack from your 3D wing lift curve slope:

$$C_L = a \cdot (\alpha - \alpha_{L=0})$$

With that data, you will be able to fill out Table 2, plot your experimental L/D vs angle of attack (α), and compare your flight test results from those predicted in your design calculations.

5.2 -- Test Range and Flyoff Procedures

Flight tests will take place behind the Aerospace Building on 24 and 26 Feb during your lab section with a potential weather cancellation makeup day on 3 March. You will have the opportunity to launch during lab sections other than your own, but you will be a lower priority than those who current section is flying. The certification launch point will be off the roof of the Aerospace Building garages (7 m height) with the "dummy payload". Once a team has successfully conducted a stable flight off the Engine Test Cell roof, it can now fly with the actual camera payload off the Aerospace Building Annex roof (22 m height). Details on flight procedures and timeframes for each lab section will be provided in a lab section prior. Additionally, safety procedures will be briefed on the day of the flight test for each lab section. Full participation by all team members is expected to enable rapid flight testing and measurements (as well as any repairs as required in-between flights). There are a lot of teams to get through for flight test and there will be limited time to complete all flights so full participation is required in order to ensure we maximize our time.

6. Required Discussion & Tasks

Table Top Conceptual Design Brief

1. Single slide for each design (one per team member)
    a. Tri-View of your final design with appropriate dimensions and predicted performance characterization (see Tempest example from Aero Lab 1)
    b. Discuss main design features and your rationale for choosing them
2. Single slide comparing all designs based on your down-selection criteria & scoring methodology
    a. Criteria and scoring method is your choice, but should be logical relative to your requirements
3. Single slide discussing your winning design
    a. Identify areas of risk in both performance (aerodynamic & stability) and construction
    b. Discuss how you will further optimize the design before build

Final Presentation

1. Figure 1: Tri-View of your final design with appropriate dimensions and performance characterization (see Tempest example from Aero Lab 1)
2. Plot 1: Lift curve slope (CL vs α) for your glider design and your 2D selected airfoil (same plot)
3. Plot 2: Drag Polar (CL vs CD) for your glider design
4. Plot 3: L/D curve (L/D vs α) for your glider design (calculated) and your flight test determined L/D
5. Table 1: Comparison between your calculated glider design performance vs your flight test performance
    a. Max Range
    b. L/D max
    c. Velocity for L/D max
    d. Stall Velocity (calculated only)
6. Discussion #1: Performance
    a. Discuss the predicted performance of your glider based on your calculations
    b. Discuss the actual performance of your glider based on flight tests
    c. Compare the calculations vs the flight tests
        i. Discuss possible sources of error in predicted performance based on analytic calculations
        ii. Discuss possible sources of error in the flight test data
7. Discussion #2: What did you learn?

a. If you could continue to iterate on your glider design, what would you change about it based on how it performed in flight test?
b. What did you learn about the value of flight test vs purely doing a "paper" design?

7. References

Lab derived from:

Brandt, S**.,** Mah, J., Jodeh, N.**, US Air Force Academy, Aero 315 RASP Project**, Summer 2010**.**

Additional References:

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Roskam, J., **Airplane Design Part II: Preliminary Configuration Design and Integration of the Propulsion System**, Chapter 12, DARCorporation (1997).

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Selig, M., **University of Illinois at Urbana-Champaign Applied Aerodynamics Group**, https://m-selig.ae.illinois.edu/index.html

Attachment 1: Glider Payload Information


SEE ASEN 2004 CANVAS PAGE FOR CAD FILE OF THE PAYLOAD

DIMENSIONS	
Weight	133 g without battery; 160 g with battery
Unit size (HxWxD)	39.0 x 59.3 x 69.8 mm
Temperature range	0 to 40^{o} C (32 to 104^{o} F), operating; 0 to 45^{o} C (32 to 113^{o} F), charging; -40 to 85^{o} C (-40 to 185^{o} F), storage
Battery life	up to 1 hour 5 minutes
VIDEO	
Video resolution	5.7K/30FPS, unstitched; 5K/30 FPS, unstiched; 4K/30FPS, stitched; 3K/60FPS, unstitched
Spherical stabilization (up to 4K)[1]	3 modes: stabilize, lock, follow
G-METRIX	
Augmented reality data(G-Metrix)[2]	yes
GPS/GLONASS	10 Hz location capture
Accelerometer	yes
Barometer	yes
Gyroscope	yes
Compass	yes