# ASEN 2004 Aero Lab: Foundations of Aircraft Design (MILESTONE 1)

## Administration

- Milestone 1 Timelines:
  - Assigned: 12 Jan
  - Due: Fri, 28 Jan, 5:00 pm (Mountain Time)
- Collaboration Guidance: Individual Assignment (However, collaboration and discussion among peers is encouraged)
  - Please document any collaboration done in your submission (see requirements guidelines)
- Software Requirement:
  - Any computational/programming tool (MATLAB, Excel, Python, etc). Must provide code or file with submission
  - Any word processing software

## Overall Learning Objectives

1. Demonstrate an adaptive engineering mindset and good engineering judgement towards the open-ended design of a basic aerospace system
   1.1. Engineering Judgement: Be able to explain the advantages and limitations of theoretically and empirically derived first-order aerodynamic models for estimating the lift characteristics, drag polar and performance in the design of new aircraft
   1.2. Adaptive Mindset: Demonstrate the ability to identify assumptions and unknowns and seek out knowledge to apply new and theoretically sound models when needed
2. Practice the application of a structured design methodology towards a complex engineering problem.
3. Reinforce understanding of aerodynamic coefficients (lift, drag, moments) and the underlying impact and inter-related aspects of key aerodynamic parameters and design variables such as:
   3.1. Reynolds Number
   3.2. Wing planform geometry and airfoil
   3.3. Oswalds and span efficiency factor
   3.4. Weight
   3.5. Wing Loading and Thrust-to-Weight Ratios
4. Understand and describe the basic concepts of longitudinal and lateral stability through the design, fabrication, and test flight of a sub-scaled glider.

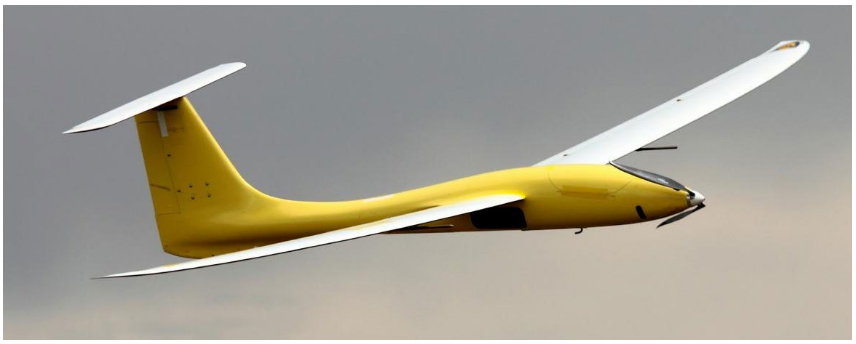
## Required Milestone 1 Deliverables

- **(100 pts) Milestone 1: Drag Polar Benchmarking Analysis (Individual Deliverable)**
  - Written report (results discussion)
    - 2x Lift Curve Plot and associated analysis discussion
    - 2x Drag Polar Plots and associated analysis discussion
  - Upload any MATLAB / Software code used in analysis and development of plots

# MILESTONE 1: DRAG POLAR BENCHMARKING REPORT

## Section 1: Background

The purpose behind benchmarking is to validate / verify your engineering models prior to utilizing them in a blank sheet design. This is a critical step before beginning the aircraft design process. For Milestone 1, you will do this for two aircraft: the Tempest UAS and the Boeing 747-200.



Tempest UAS

Boeing 747-200

### Finite Wing Lift

Through ASEN 2002, you were introduced to airfoil data that represented the lift characteristics of a theoretically "infinite" wing where experimental data for the coefficient of lift were obtained for airfoils using a wing section that spanned the entire width of a wind tunnel test section. In order to begin your analysis you will need to know the characteristics of the airfoils used on both the Tempest UAS and the Boeing 747-200.

The Tempest UAS utilizes the MH 32 airfoil. It is a 8.7% thick airfoil at approximately the 30% chord with 2.3% camber. See the attached Tempest and B747 data file for the 2-D lift characteristics generated via the XFOIL program[1] and Airfoil Tools[2] website.

[1] Drela, Mark, MIT, https://web.mit.edu/drela/Public/web/xfoil/

[2] http://airfoiltools.com/index

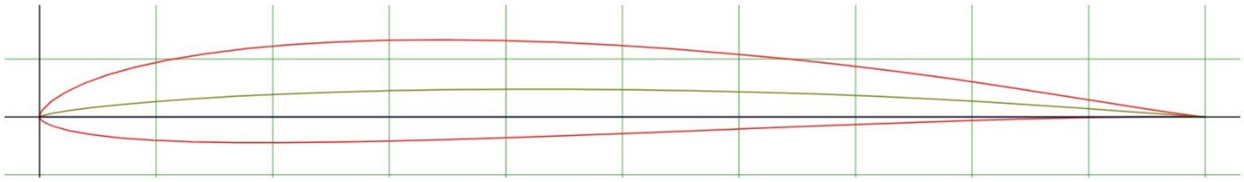


Figure 1: MH-32 Airfoil Profile (Source: UIUC Airfoil Database[1])

The Boeing 747-200 utilizes two different airfoils at the root of the wing vs the tip of the wing (aerodynamic twist); however for the purposes of this analysis, we can assume that the entire wing utilizes the Boeing BACJ supercritical airfoil. See the attached Tempest and B747 data file for the 2-D lift characteristics generated via the XFOIL program[2] and Airfoil Tools[3] website.

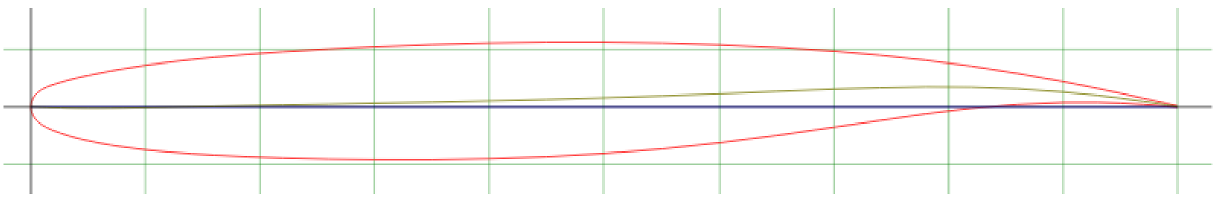


Figure 2: Boeing BACJ Airfoil Profile (Source: UIUC Airfoil Database[4])

Clearly, infinite wings do not exist on real aircraft, and the impacts of having a finite (or 3-D) wing have a significant effect on the performance of a wing in generating lift. The presence of a wingtip results in downwash which reduce the effective angle of attack “seen” by the wing, which in turn reduces the coefficient of lift generated by the wing relative to the 2-D airfoil data.

[1] https://m-selig.ae.illinois.edu/index.html
[2] Drela, Mark, MIT, https://web.mit.edu/drela/Public/web/xfoil/
[3] http://airfoiltools.com/index
[4] https://m-selig.ae.illinois.edu/index.html

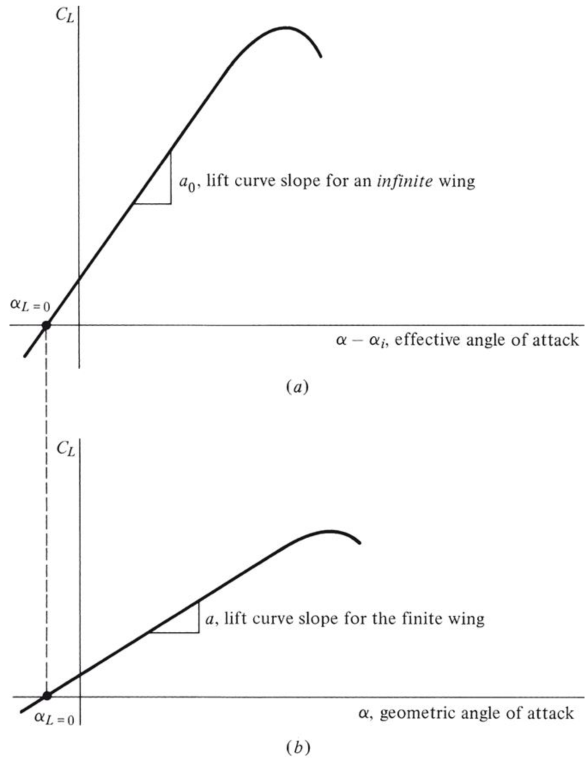



Figure 3: Impacts on lift curve slope for infinite and finite wings from Anderson[1]

Anderson also provides the following formulation of the impacts of downwash on both the lift curve slope ($a$) and coefficient of lift:

$$a = \frac{dC_L}{d\alpha} = \frac{a_o}{1+\frac{57.3 \cdot a_o}{\pi \cdot e \cdot AR}} \qquad (1)$$

$$C_L = a \cdot (\alpha - \alpha_{L=0}) \qquad (2)$$

Where ($a_o$) is the 2-D airfoil lift curve slope in (1/deg) and ($e$) is the span efficiency factor. For whole aircraft, lift is not just generated by the wing along, but can also be generated by the fuselage and tail surfaces; however, for the purposes of this lab, we will be assuming that the Tempest's wing generates significantly more lift relative to the fuselage and tail and treat the finite wing lift as the total aircraft lift. **Additionally, we will assume a span efficiency factor of e = 0.9 for both the Tempest and B747 wings.** Also note that the formulation for the 3-D wing lift coefficient $C_L$ only models the linear portion of the lift curve slope and not the nonlinear behavior near stall.

From this finite wing value of $C_L$, the 3-D wing drag polar can be calculated by adding the induced drag to the profile drag of the 2-D airfoil

$$C_{Dwing} = C_d + \frac{C_L^2}{\pi \cdot e \cdot AR} \qquad (3)$$

[1] Anderson, J. D., Introduction to Flight, 8th Ed., McGraw Hill (2012)

## The Whole Aircraft Drag Polar

An investigation of the aerodynamic performance of a whole aircraft generally begins with determining the relevant aerodynamic coefficients, either in the wind tunnel, in flight tests, or using computational fluid dynamics (CFD). Of the relevant aerodynamic coefficients, an aircraft's drag polar (relationship between and aircraft's $C_D$ vs $C_L$) is especially important as many performance characteristics of an aircraft can be determined from this relationship. Unlike the 3-D wing drag polar, a whole aircraft drag polar must take into account all components of an aircraft which will significantly increase drag as compared to the simple streamlined shape of a wing. Anderson discusses the drag polar of a complete airplane that shows how drag varies with respect to lift, where the most general form is written as:

$$C_D = \underbrace{C_{Do}}_{\text{Parasite Drag}} + \underbrace{k_1 \cdot C_L^2}_{\text{Drag due to Lift}} \qquad (4)$$

$$\text{Where } k_1 = \frac{1}{\pi \cdot e_o \cdot AR} \qquad (5)$$

However, this formulation assumes that an aircraft's minimum drag occurs at zero lift which, for many aircraft, is not true as most have been designed to generate a small value of lift when most streamlined to the relative wind. This can also be seen in the drag polar for cambered airfoils as a shift in the drag polar where the minimum value of drag occurs at a non-zero value of lift. Raymer and Anderson both provide a formulation of the drag polar which accounts for this difference. See Parasite Drag Coefficient discussion below for more expanded discussion on accounting for this.

$$C_D = C_{Dmin} + k_1 \cdot (C_L - C_{LminD})^2 \qquad (6)$$

Another common formulation which is just an expansion of (6) and utilized in many sources is:

$$C_D = C_{Do} + k_1 C_L^2 + k_2 C_L \qquad (7)$$

$$k_2 = -2k_1 C_{LminD} \qquad (8)$$

$$C_{Do} = C_{Dmin} + k_1 C_{LminD}^2 \qquad (9)$$

### *Parasite Drag Coefficient (or Zero-Lift Drag Coefficient)*

The entire parasite drag or zero lift drag coefficient ($C_{Do}$) is typically determined experimentally or via flight test; however, many methods have been developed in support of conceptual aircraft design that can provide an estimation of this value. The problem at this point is the determination of both the minimum drag coefficient ($C_{Dmin}$) and the associated coefficient of lift where the minimum value of drag coefficient occurs ($C_{LminD}$) when you do not yet have what $C_D$ is for the entire aircraft is yet. At the conceptual design stage, it is sufficient to approximate these values by assuming that the aircraft designer would attempt to align the aircraft minimum drag to the angle of attack where the wing has minimum drag. Therefore, $C_{LminD}$ for a whole aircraft can be approximated by finding the coefficient of lift where you have minimum drag for your 3D finite wing drag polar.

The $C_{Dmin}$ coefficient represents the skin friction drag of the entire aircraft. Raymer[1] outlines a very simple empirically-based method utilizing a equivalent skin friction coefficient ($C_{fe}$) based on the type of aircraft and the ratio of wetted area ($S_{wet}$) to the reference wing planform area of the aircraft ($S_{ref}$).

$$C_{Dmin} = C_{fe}\frac{S_{wet}}{S_{ref}} \qquad (10)$$

The equivalent skin friction coefficient is a empirically derived value based on classes of aircraft that has shown to be fairly consistent and accounts for the skin friction drag and the small pressure drag due to separation that occurs when the aircraft is in subsonic cruise conditions. Raymer provides the following equivalent skin friction coefficient relevant for this lab:

| **Aircraft Type** | **Equivalent Skin Friction Coefficient ($C_{fe}$)** |
|---|---|
| Civil Transport / Glider | 0.0030 |
| Light, single engine propeller plane | 0.0055 |

Table 1: Equivalent Skin Friction Coefficients[1]

The wetted area ($S_{wet}$) of an aircraft is the entire exposed surface area of the aircraft (all surface area that touches the air). This is different that the wing planform area (denoted as $S_{ref}$ in equation (10) above) which is the projected area of the wing (shadow of wing) to include the portion hidden by the fuselage.

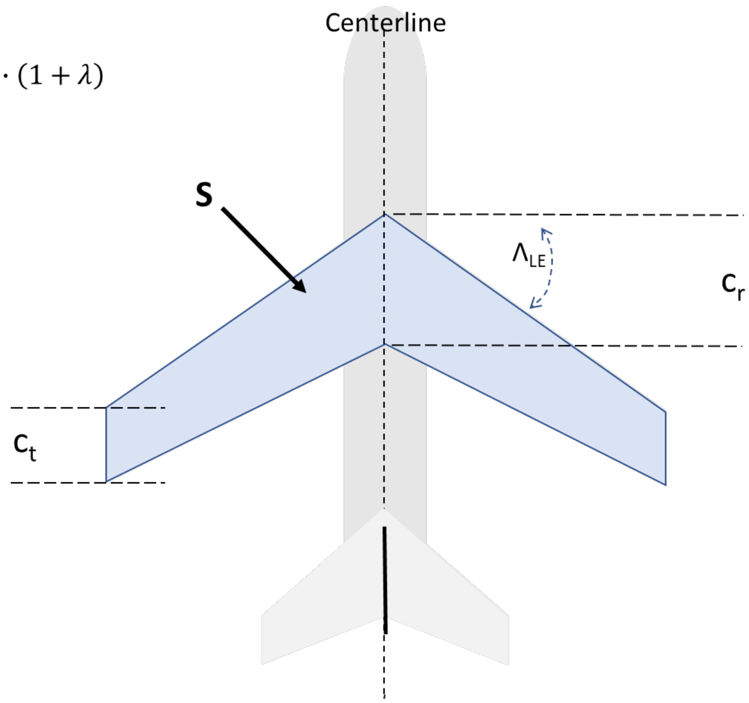
[1] Raymer, D. P., Aircraft Design: A Conceptual Approach, 2nd Ed., AIAA Inc., Chap. 12 (1992).

$$S_{ref} \; or \; S = b \cdot \bar{c} = \frac{b}{2} \cdot c_r \cdot (1 + \lambda)$$

$$\bar{c} = \frac{c_r + c_t}{2}$$

$$AR = \frac{b^2}{S}$$

$$\lambda = \frac{c_t}{c_r}$$




The most accurate method of estimating $S_{wet}$ would be to utilize a CAD model of the aircraft to precisely calculate the wetted area; however, there are also many methods that have been developed over time to more quickly approximate this area. Most of them basically reduce the form of an aircraft to more easily analyzed basic geometric shapes to estimate the wetted area.

Alternatively, you could also treat the aircraft a series of "flat plates" and utilize the flat plate coefficient of friction models from ASEN 2002 (be careful how you do this!). The choice of how you model the skin friction drag coefficient is up to you. It is recommended that you assess different methods to see how they compare. This will enable you to better discuss the effectiveness of different methods on your aerodynamic models in your milestone 1 report discussion.

### *Induced Drag Coefficient (Drag Due to Lift)*

In estimating the component of the drag polar due to lift, one of the key variables is the value of Oswald's efficiency number ($e_o$). Oswalds has many approximated formulations many of which are based on empirical industry data within each aerospace company. As a result, the accuracy of models for estimating Oswalds tend depend upon the body of empirical data the model is based on and how relevant that data is to the type of aircraft being design (for example, it wouldn't be good to use a model for Oswalds that is based on data from supersonic fighters to develop an approximation for low speed UAVs). For the purposes of this lab, you will utilize formula (12) from Raymer that is derived from US Navy research on subsonic drag estimation[1] ; **however, you are also required to compare results using at least 1 additional model for Oswalds via reference[2] below and provided to you in on Canvas (lab materials). This reference will be important for you as you assess and discuss updating your aerodynamic model for the milestone 2 glider design that is part of your milestone 1 report discussion.**

$$e_o = 1.78(1 - 0.045AR^{0.68}) - 0.64 \qquad (12)$$

Aircraft Data

All aircraft data for the analysis of both the Tempest UAS and the Boeing 747-200 is provided in the aircraft data spreadsheet on Canvas under lab materials.

Drag polar and performance data is provided as "truth data" for both aircraft as a means of comparison for your analysis and to aid in your discussion of your aerodynamic drag polar model validity.

**Section 2: Detailed Required Analysis Discussion Elements**

The following items must be discussed for **both** the Tempest UAS and Boeing 747-200. For all required plots, use a different figure for the elements below for each aircraft (i.e. all Tempest items on one figure, all 747 items on a separate figure):

1. Lift Curve Comparison (CL vs α): Calculate and plot on the same figure the $C_L$ vs. α for the 2-D airfoil vs your approximation for a 3-D finite wing.
   a. Compare and explain the data.
   b. Make sure discuss the validity of your model based on fundamental aerodynamic concepts. For what range of conditions is it valid and why?
2. Drag Polar Comparison ($C_D$ vs. $C_L$): Calculate and plot on the same figure:
   a. 2-D airfoil drag polar (given data) provided in the aircraft data file.
   b. Your 3-D finite wing drag polar model based on your corrections to lift drag curve model
   c. Your whole aircraft drag polar model using Raymer's Oswalds Efficiency Factor Model (Eq 12)
   d. Your whole aircraft drag polar model using a different Oswalds Efficiency Factor Model of your choice (from Nita & Scholz reference)
   e. Whole aircraft drag polar (given truth data) provided in the aircraft data file.
   f. At a minimum, there should be five curves plotted per aircraft analyzed (i.e. two figures, one for the Tempest one for the B747 with five plots on each)

[1] Cavallo, B., 11 Subsonic Drag Estimation Metbods, U.S. Naval Air Development Center, Rept. NADC-AW-6604, 1966;DoD Technical Report Number: AD 376-358L

[2] Nita, M., Scholz, D., *Estimating the Oswald Factor from Basic Aircraft Geometrical Parameters*, Hamburg University of Applied Sciences, 2012.

i **Bonus points if you also analyze different methods for modeling the zero lift parasite drag coefficient than the one provided in this writeup.**

g. Validate your models
   i Compare and explain the data shown by the different drag polar plots.
   ii Quantify the error of your whole aircraft drag polar models vs the provided whole aircraft drag polar truth data. Explain any regions or range of conditions where your model is more or less accurate based on fundamental aerodynamic concepts.
   iii Discuss the validity of your model based on fundamental aerodynamic concepts.

3. Summarize and discuss the overall validity of your aerodynamic models for designing a small UAS vs a large jet airliner
   a. What is the best aerodynamic model for you to use to design your small glider in milestone 2?
   b. Discuss if any additional changes or modifications to your aerodynamic models you might consider before starting your new design.
4. Summarize any collaboration you did in accomplishing your models.
5. Report Formatting Guidelines
   a. Use AIAA report formatting rules (You are basically just writing only a "Results" section of a full AIAA report, but no cover page, abstract, etc required. Just answer the questions directly).
   b. Maximum 4 pages (including figures, but not including collaboration section, title page)
   c. Figures must take up no more than 1/4 a page
   d. Answer all the questions & show all the required figures posed in section 6.
   e. Upload report and source calculations file (Excel, Matlab, Hand Calcs, etc) to the Canvas lab assignment

## References

**Lab derived from:**

Argrow, Brian**, ASEN 2004 Experiment 1 Aero 20180124, Spring 2018.**

**Additional References:**

Anderson, J. D., Introduction to Flight, 8th Ed., McGraw Hill (2012).

Brandt, S, Introduction to Aeronautics: A Design Perspective, 2nd Ed, AIAA (2004).

Cavallo, B., 11 Subsonic Drag Estimation Metbods, U.S. Naval Air Development Center, Rept. NADC-AW-6604, 1966;DoD Technical Report Number: AD 376-358L

Drela, M., XFOIL Program, MIT, https://web.mit.edu/drela/Public/web/xfoil/

Kroo, I., Aircraft Design: Synthesis and Analysis, Stanford University, AA241, 2012.

Nita, M., Scholz, D., Estimating the Oswald Factor from Basic Aircraft Geometrical Parameters, Hamburg University of Applied Sciences, 2012.

Raymer, D. P., Aircraft Design: A Conceptual Approach, 2nd Ed., AIAA Inc., Chap. 12 (2012).

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

Roskam, J., Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust, and Power Characteristics, Chapter 5, DARCorporation (1997).

Roadman, J., Elston, J., Argrow, B., and Frew, E., "Mission Performance of the Tempest Unmanned Aircraft System in Supercell Storms," *Journal of Aircraft*, Vol. 49, No. 6, pp. 18211830 (2012).

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