Haley Bates-Tarasewicz, Sabina Chen, Matthew Luerman, Alan Osmundson

Lab 3: Airplane Optimization and Layout Design

Introduction

The purpose of Lab 3 was to guide students through the process of designing an airplane to fulfil a function and fit design parameters by designing and optimizing their own airplane for the Unified Design Competition.

In the Detailed Wing Optimization section, we were to write a program to optimize several different design variables pertaining to the geometry of the wings and other control surfaces. Suitable taper, washout, and dihedral values for the wing were to be chosen as well as a proper angle of attachment to the fuselage.The function that was to be optimized was equation 1 below.

$$F \equiv \frac{W_{pay}}{t_{rev,\,pay} + t_{rev,\,empty}} \tag{1}$$

In the Airplane Configuration Design section, we were to choose suitable stability and control parameters such as static margin and spiral stability, and then design an aircraft configuration around those.

Lastly, a scale 3D model of our aircraft was to be produced to show our final decisions.

Models Used

All models used to optimize the aircraft performance for were taken from either the Lab 2 Lecture Slides, from the Lab 3 Appendix, or derived from equations taken from these sources.

Parameter	Equation	Citation
Wing weight	$W_{wing} = \frac{4}{5} \rho_{foam} \tau g S \sqrt{\frac{S}{AR}} \cdot \frac{\lambda^2+\lambda+1}{(\lambda+1)^2}$	Integration of wing dependency from Lab 2
Fuse weight	$W_{fuse} = (m_{fuse,0} + m_{fuse,\ell} \frac{b}{b_{pv}} + m_{fuse,S} \frac{S}{S_{pv}}) g$	Appendix C Equation 17
Profile Drag	$c_d = [c_{d_0} + c_{d_1}(c_\ell - c_{\ell_0}) + c_{d_2}(c_\ell - c_{\ell_0})^2 + c_{d_8}(c_\ell - c_{\ell_0})^8] [\frac{Re}{Re_{ref}}]^a$	Appendix B Equation 6
CDA_0	$CDA_0 = CDA_{fuse,0} + CDA_{fuse,S} \cdot \frac{S}{S_{pv}}$	Appendix C Equation 16
Thrust	$T = \frac{1}{2} \rho_{air} V^2 S C_D$	Drag = Thrust + C_D equation Derived
Drag Coefficient	$C_D = \frac{CDA_0}{S} + c_d + \frac{C_L^2}{\pi AR e}$	Lab 2 Lecture Slides
Load Factor	$N = [1 - (\frac{W_{fuse} + W_{wing} + W_{pay}}{\frac{1}{2} \rho g R S C_L})^2]^{-1/2}$	Lab 2 Lecture Slides
Velocity	$V = \sqrt{\frac{2W_{tot}}{C_L \rho A}}$	Derived from C_L Equation
Time of Revolution	$t_{rev} = \frac{2\pi R}{V}$	Lab 2 Lecture Slides
Max Thrust	$T_{max} = T_0 + T_1 V + T_2 V^2$	Appendix A, Equation 1
Tip Deflection/Span Ratio	$\delta/b = 0.018 N \frac{W_{fuse} + W_{pay}}{E\tau(\tau^2+\varepsilon^2)} (1+\lambda)^3 (1+2\lambda) \frac{b^2}{c^4}$	Lab 2 Lecture Slides
Reynold's Number	$Re = \frac{\rho V c}{\mu}$	Lab 3: Improved optimization, Equation 3
Camber/Chord Ratio	$\varepsilon = 0.10 - 0.5\tau$	Appendix B, Equation 5
Nondimensionalized Yaw Rate	$\bar{r} = \frac{b}{2RN}$	Appendix E, Equation 19
Sideslip Angle	$\beta = \frac{C_L}{Y} \cdot \frac{1 + 4/AR}{2\pi} \bar{r}$	Appendix E Equation 21
Span Efficiency	$e = e_0 (1 - 0.5 \bar{r}^2) \cos^2\beta$	Appendix E Equation 20
Objective Function	$F = \frac{W_{pay}}{t_{rev,pay} + t_{rev,empty}}$	Lab 3

Key Performance Parameters After Optimization

Parameter	Units	Optimized (with payload)	Optimized (w/out payload)	Nomenclature
V	Meters per Second	5.207	4.071	Flight speed
N	Newtons	1.0253	1.009	Load factor
t_{rev}	Seconds	15.082	19.293	Time to complete a revolution on a circular path
C_L	Unitless	1.22	1.22	Total lift coefficient
C_D	Unitless	0.092	0.092	Total drag coefficient
e	Unitless (less than unity)	0.913	0.913	Span efficiency
T	Newtons	0.507	0.331	Thrust
δ/b	Unitless	0.073	0.037	Tip-deflection/span
W_{pay}	Newtons	2.6	0	Weight of payload
W_{wing}	Newtons	1.281	1.281	Weight of Wing
W_{fuse}	Newtons	2.649	2.649	Weight of Fuse
W_{total}	Newtons	6.53	3.93	Total Weight
Predicted Objective Function	Newtons per Second	0.075	0.076	Score of Unified Design Challenge

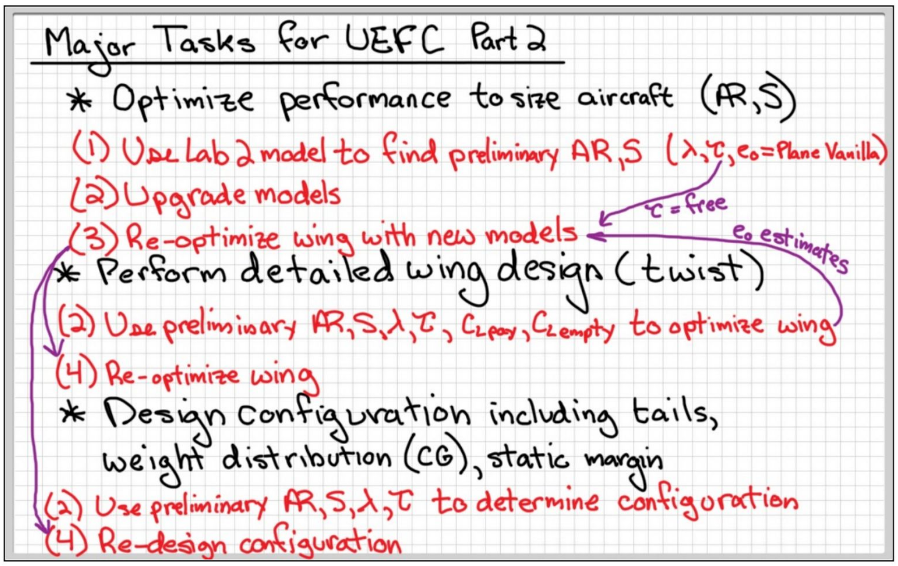
Key Aircraft Parameters

Parameter	**Units**	**Optimized (w/out payload)**	**Nomenclature**
S	Square meters	0.33	Wing Surface Area
b	Meters	1.922	Wing Span
c	Centimeters	17.165	Average Chord
AR	Unitless	11.2	Aspect Ratio
λ	Unitless	0.41	Taper Ratio
SM	Unitless	0.99	Static Margin (normalized distance between center of gravity and neutral point)
α_{geom}	Degrees	-13	Geometric Twist Distribution
AR_h	Unitless	2.75	Horizontal Tail Aspect Ratio
x_{cg}	Centimeters	6.26	Center of Gravity location, measured from leading edge of MAC
x_{np}	Centimeters	7.96	Neutral Point location, measured from leading edge of MAC
c_r	Centimeters	24.3	Root Chord
c_t	Centimeters	9.98	Tip Chord
S_h	Square meters	0.0271	Horizontal Tail Surface Area
S_v	Square meters	0.0236	Vertical Tail Surface Area
l_h	Centimeters	94.1	Horizontal Tail Moment Arm
l_v	Centimeters	94.1	Vertical Tail Moment Arm
Υ	Degrees	20.626	Dihedral
B	Unitless	8.289	Spiral stability
Airfoil	UEW-11-045; Other values describing airfoil can be found in Appendix B		

Design Procedure for Aircraft Performance

<u>General Task Order / Timeline</u>

Our group generally followed the recommended task procedure included in the "Suggestions for UEFC Part 2" PDF document:



First we fixed our Lab 2 model to match the expected results of the Plane Vanilla optimization based on the feedback we received from Lab 2. Then, while two members of our group worked on upgrading the models used to optimize the aircraft performance (1st *), the other two members simultaneously worked on creating a preliminary wing design (2nd *) and design configuration (3rd *).

After successfully upgrading the models (1st *) and getting the initial span efficiency using the preliminary plane vanilla values (2nd *), we inputted this initial span efficiency into the newly upgraded models to get the new dihedral, lambda, S, AR, and CL values, optimizing the productivity. We then inputted these values back into MATLAB to re-optimize the wing design and to get the updated span efficiency. We repeated this process (going back and forth between optimizing the aircraft performance and optimizing the wing) until the dihedral, lambda, S, AR, and CL values started to converge and we got better optimized/higher productivity values.

After repeating this process a few times, we got our final optimized dihedral, lambda, S, AR, and CL, and used these values to re-optimize the wing and re-design the configuration to get our final key performance parameters and key aircraft parameters. We will explain our procedures for each step in more detail below.

Debugging Lab 2 Model

In order to ensure that the Lab 3 optimization algorithm runs correctly, we had to first make sure that the Lab 2 code was also correct, since we will be reusing some of the functions used in the Lab 2 optimization for the Lab 3 optimization. After debugging the Lab 2 model, we were able to use the outputs, AR and S, to begin the preliminary wing design analysis. Furthermore, it also allowed us to have a more solid foundation to begin writing the aircraft performance optimization algorithm.

Aircraft Performance Optimization

Our team used a brute force optimization program to find suitable parameters for our aircraft. While brute force is hardly the most elegant solution, we found with our team’s abilities it produced the most consistent and reliable results that were consistent with debugging values provided.

We used the updated models provided in the Lab 3 notes Appendix A to improve our optimization strategy. We incorporated updated models of T_{max}, ε , cd (profile drag), CDA_0, and W_fuse, along with new functions for calculating various wing design parameters.

Since velocity and W_pay are dependent on each other, we set W_pay as a design variable along with AR, S, and Cl. We iterated through value ranges for each of these variables, and recorded relevant data whenever a new maximum productivity (objective function score) was achieved. After finding locally optimal values for AR, S, Cl, a similar optimization process was run again. However, this time AR, S, and Cl were held constant at their optimized values while iterating through taper, dihedral, and W_pay as design variables to further optimize performance by adjusting the aircraft geometry. Initial aircraft geometry values and span efficiency came from preliminary wing analysis.

After completing the first two series of optimization (one with each foam type), we determined that the HiLoad-60 foam provided the highest productivity for our optimization routine. From here, the optimal AR, S, Cl, Taper, and Dihedral values from the optimization sequence were fed into the wing design analysis program, which then provided a new optimal span efficiency value. The performance optimization process began again, and this sequence was repeated two times to optimize for productivity while also analyzing the resulting wing design to mitigate the risk of wingtip stall.

Wing Design Analysis

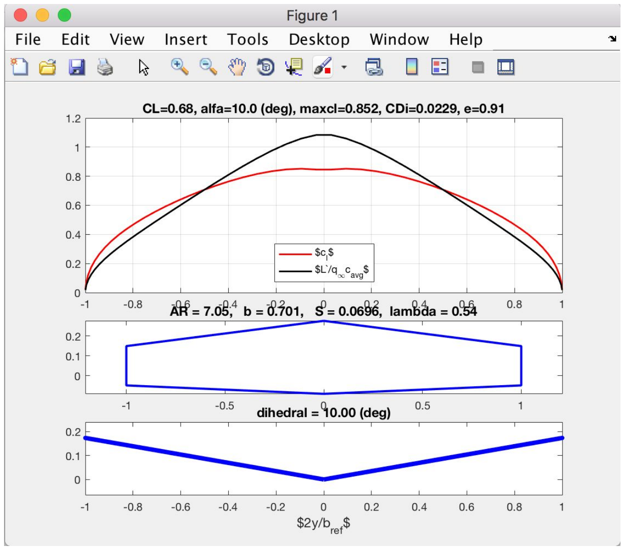
We used the MATLAB function, UEFC_wvl.m (Weissinger Vortex Lattice). The function requires the inputs: dihedral, lambda, S, AR, CL, a0r, a0t, agr, and agt.

For the preliminary analysis, the dihedral was set to the plane vanilla value, 10 °. The a0r, a0t, and agr were also kept constant with values, -3, -3, and 0, respectively. The lambda, S, AR, and CL were taken from the preliminary values from the t_{rev} optimization in Lab 2, when δ/b = 0.1:

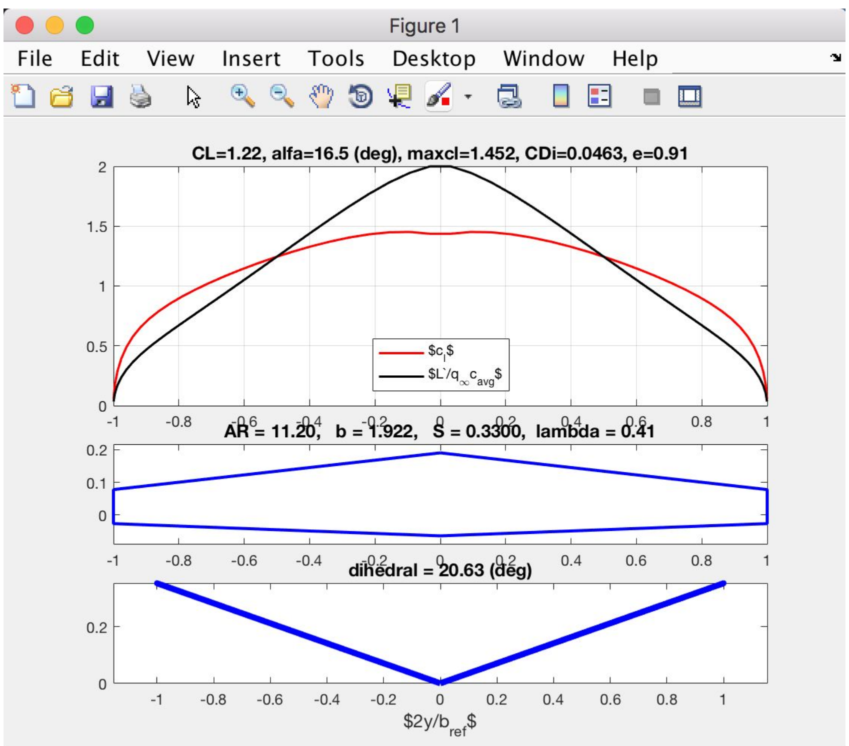
```
delta/b = 0.1000
time for revolution =  6.14
b  = 0.70 cr = 0.13 ct = 0.07
S = 0.0696 AR = 7.052
Wwing = 0.15
N = 1.67 V = 12.80
CL = 0.68 CD = 0.100 L/D = 6.79
Thrust = 0.70 Max Thrust = 0.70
```

For geometric twist angle at the tip, agt, we settled on -10° as the most optimal for preliminary analysis. Values greater than -10 degrees (ie. 0, -5, -8...) would produce a greater span efficiency, *e*, but would also cause the red line on the graph (shown below) to bulge out at the two sides, depicting an increase drag at the wing tips. Values smaller than -10 degrees (ie. -15, -20), would unload the tips, but produce a very low *e*, which will lower the productivity value. Thus, after playing around with some agt values, we decided that agt = -10° was the most ideal value that maximized span efficiency while still keeping the induced drag at the tips as low as possible.

Inputting these preliminary values into MATLAB, we produced a preliminary span efficiency of *e* = 0.9187, which is reasonable because it is within the range 0.85 < *e* < 0.95.



We used the same process described above to determine the final span efficiency, after updating the input variables. The final input variables after optimization were: α_{geom} = 20.626°, λ = 0.41, S = 0.33, AR = 11.2, and CL = 1.22. And the final output for the wing design was: *e* = 0.9136. The graph produced by UEFC_wvl is shown below:



Design Configuration

Using the following values, which were determined by means of the old model:

```
delta/b = 0.1000
time for revolution =  6.14
b  = 0.70 cr = 0.13 ct = 0.07
S = 0.0696 AR = 7.052
Wwing = 0.15
N = 1.67 V = 12.80
CL = 0.68 CD = 0.100 L/D = 6.79
Thrust = 0.70 Max Thrust = 0.70
```

We aimed for well-behaved stability, deriving our configuration based on an optimal static margin of 0.1 and horizontal tail volume coefficient of V_h = 0.45. We set x_{cg} at roughly 36% of the MAC and scaled the remaining lengths based on the wing mass ratio between our preliminarily optimized plane and plane vanilla. This yielded x_{cg} = 3.65 cm and l_h = 19.8 cm.

We combined the following equations to determine the horizontal tail configuration:

$$S.M. \equiv \frac{x_{\mathrm{np}} - x_{\mathrm{cg}}}{c}$$

$$\frac{x_{\mathrm{np}}}{c} \simeq \frac{1}{4} + \frac{1 + 2/AR}{1 + 2/AR_{\mathrm{h}}} \left(1 - \frac{4}{AR + 2}\right) \mathrm{V_h}$$

This yielded AR_h = 3.95 and x_{np} = 4.64 cm. Then by the following definition:

$$\mathrm{V_h} \equiv \frac{S_{\mathrm{h}}\, \ell_{\mathrm{h}}}{S\, c}$$

We have S_h = 0.0158 m^2 = 24.5 in^2.

Setting l_h = l_v, i.e. placing all tail fins at the same x location on the fuselage, yielded a spiral satisfactory stability of B = 4.169. Then, setting the vertical tail volume coefficient to a well-behaved value of V_v = 0.035, we used the following:

$$\mathrm{V_v} \equiv \frac{S_{\mathrm{v}}\, \ell_{\mathrm{v}}}{S\, b}$$

To find that S_v = 0.0086 m^2 = 13.3 in^2.

Preliminary design configuration parameters:

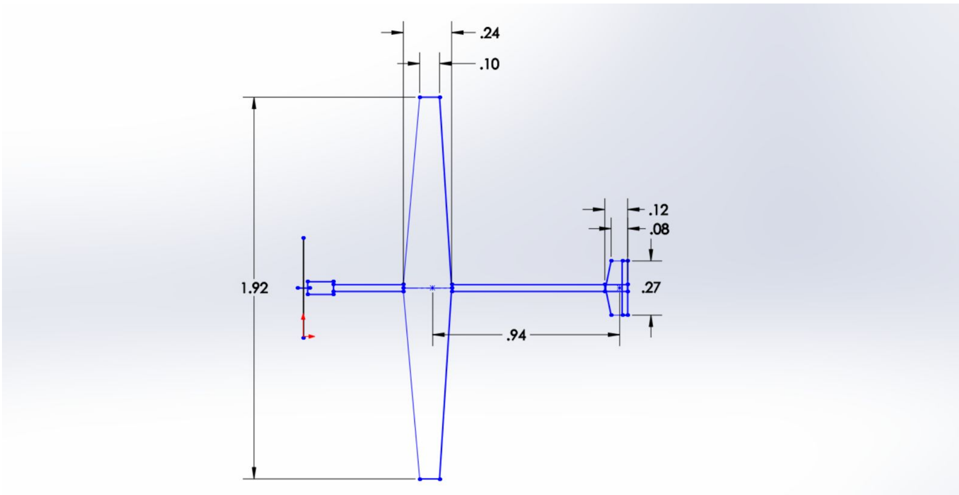
Parameter	**Units**	**Value**
x_{cg}	Centimeters	3.65
x_{np}	Centimeters	4.64
SM	Unitless	0.99
l_h	Centimeters	19.8
S_h	Square meters	0.0158
AR_h	Unitless	3.95
l_v	Centimeters	19.8
S_v	Square meters	0.0086
B	Unitless	4.169

The same code was used to determine the final configuration, after updating the input variables. The final configuration is as follows:

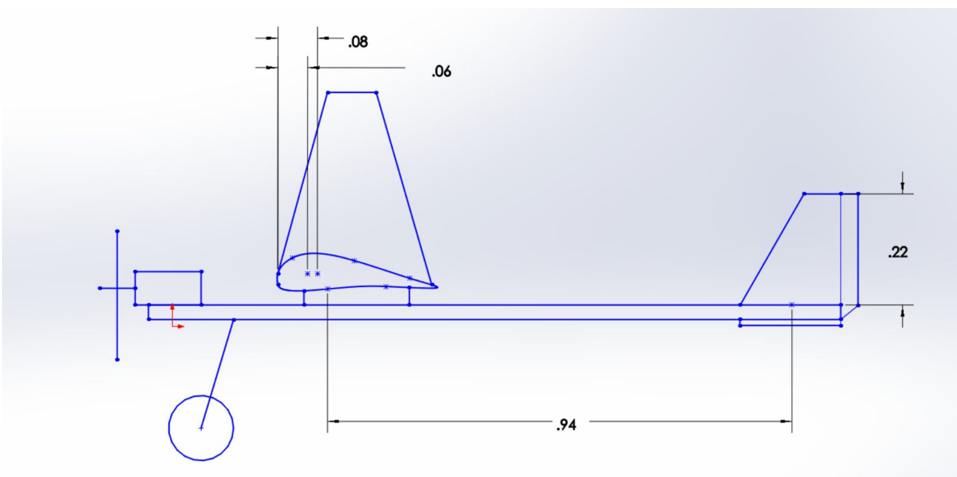
Parameter	**Units**	**Value**
x_{cg}	Centimeters	6.26
x_{np}	Centimeters	7.96
SM	Unitless	0.99
l_h	Centimeters	94.1
S_h	Square meters	0.0271
AR_h	Unitless	2.75
l_v	Centimeters	94.1
S_v	Square meters	0.0236
B	Unitless	8.289

3-View Drawing of Airplane (all units are in meters)

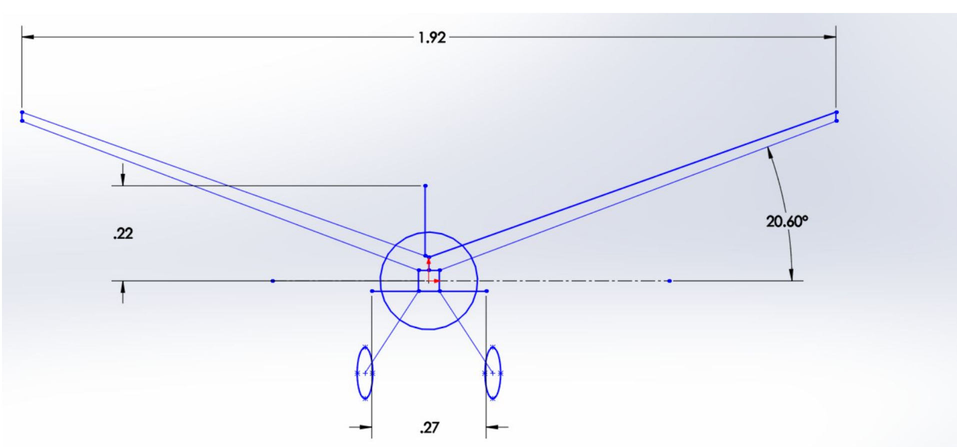
Top View



Front View



Side View



Member Contribution

Haley Bates-Tarasewicz

- Debugged the old functions from Lab 2 (fixed the coding errors we had from Lab 2)
- Upgraded the models for Lab 3
- Optimized aircraft performance values (wrote/debugged new optimization algorithm)
- Report Write-Up

Sabina Chen

- Debugged the old functions from Lab 2 (fixed the coding errors we had from Lab 2)
- Performed preliminary detailed wing analysis using values from Lab 2
- Re-optimized the wing with upgraded values from aircraft performance optimization
- Report Write-Up

Matthew Luerman

- Upgraded the models for Lab 3
- Optimized aircraft performance values (wrote/debugged new optimization algorithm)
- CAD the 3-View Drawing of Airplane
- Report Write-Up

Alan Osmundson

- Calculated design configuration(including tails, weight distribution CG, static margin, etc.) using the preliminary values from Lab 2
- Re-optimized design configuration with the upgraded values from the aircraft performance optimization
- Report Write-Up

The list of significant contributions provided in this report is an accurate representation of each team member's role in UEFC Lab 3: Airplane Optimization and Layout Design:

Haley Bates

Matthew Luerman

Sabina Chen