Iowa State University

LONGITUDINAL STABILITY ANALYSIS

StratoShield

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Glossary

C_{HT} Horizontal tail volume coefficient. *(p. 5–7)*

C_{VT} Vertical tail volume coefficient. *(p. 5–7)*

L_{HT} Length from quarter chord of the primary wing to quarter chord of the horizontal tail. *(p. 5)*

L_{VT} Length from quarter chord of the primary wing to quarter chord of the vertical tail. *(p. 5)*

S_{HT} Horizontal tail planform area. *(p. 5)*

S_{VT} Vertical tail planform area. *(p. 5)*

S_{ref} Main wing planform area. *(p. 5)*

b Wingspan. *(p. 5)*

c Chord length. *(p. 5)*

Acronyms

AoA angle of attack. *(p. ii, 1, 3, 4, 6)*

CAD computer-aided design. *(p. ii, 2, 6)*
CG center of gravity. *(p. ii, 1, 2, 4–7)*

NACA National Advisory Committee for Aeronautics. *(p. 6)*
NP neutral point. *(p. ii, 1, 2, 4)*

SLF steady-level flight. *(p. 1, 4, 6)*

1

Introduction

This report presents the analysis of the longitudinal stability of our aircraft based on the center of gravity (CG) static margin calculations and present design iteration. The objective is to assess the stability characteristics, determine if the static margin is within acceptable limits, and propose potential modifications to improve the aircraft's performance in steady-level flight (SLF).

Important aspects of the analysis include:

- Determining the angle of attack required for SLF, supported by lift vs. angle of attack (AoA) plot.
- Evaluate the center pitching moment across various AoA, focusing on determining the AoA necessary for cruising conditions.
- Reviewing the aircraft's CG and neutral point (NP) through a side view diagram to visualize the relative positions that influence stability.
- Assessing the tail sizing coefficients for this design iteration and determining whether they are appropriately sized for optimal stability and control.

The report provides an in-depth evaluation of the aircraft's static margin and pitching moment characteristics, followed by recommendations for design adjustments based on the results. Additionally, we outline possible changes the team may consider to improve the aircraft's stability and performance in future iterations.

2 Results

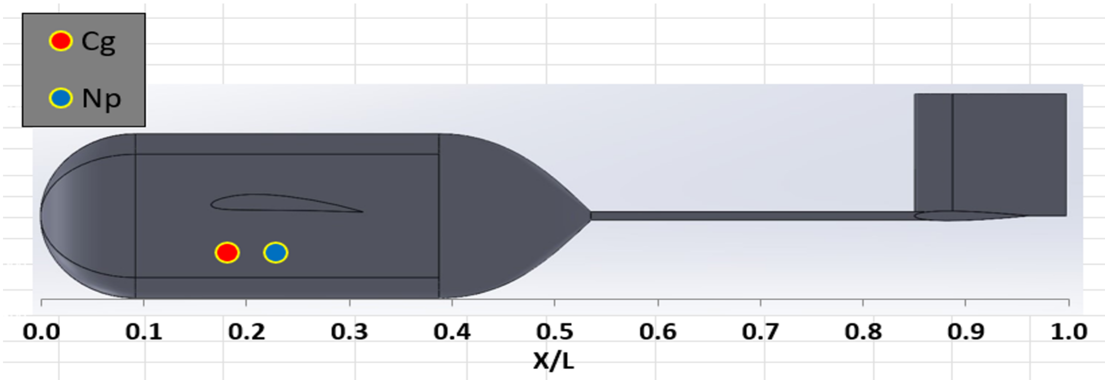

Figure 2.1: *Side profile visualization of the aircraft computer-aided design (CAD) model with estimated center of gravity (CG) and neutral point (NP) locations noted.*

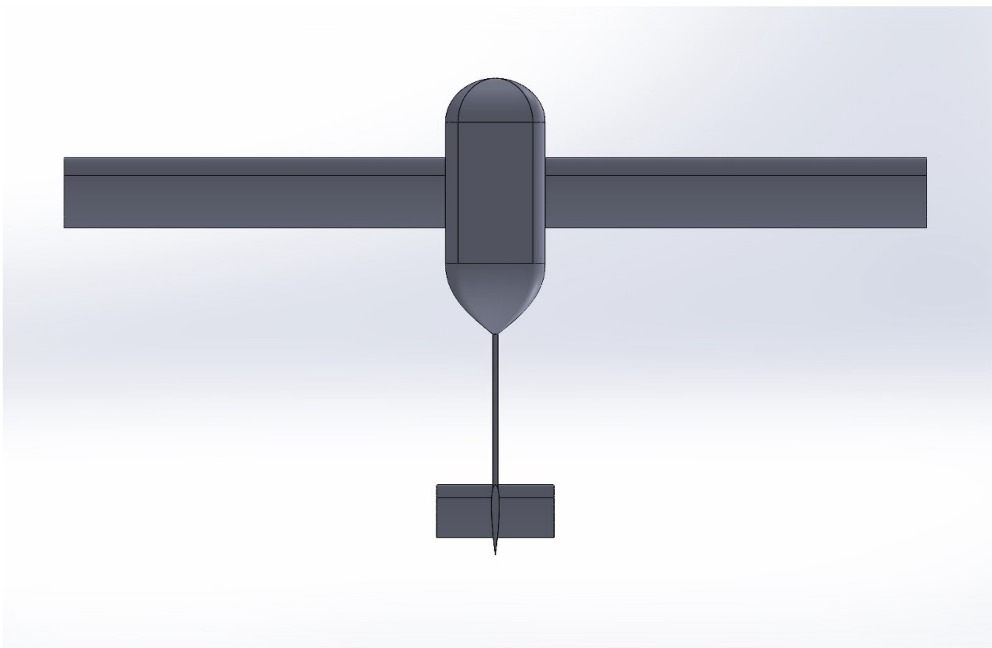

Figure 2.2: *Top view of the aircraft CAD model.*

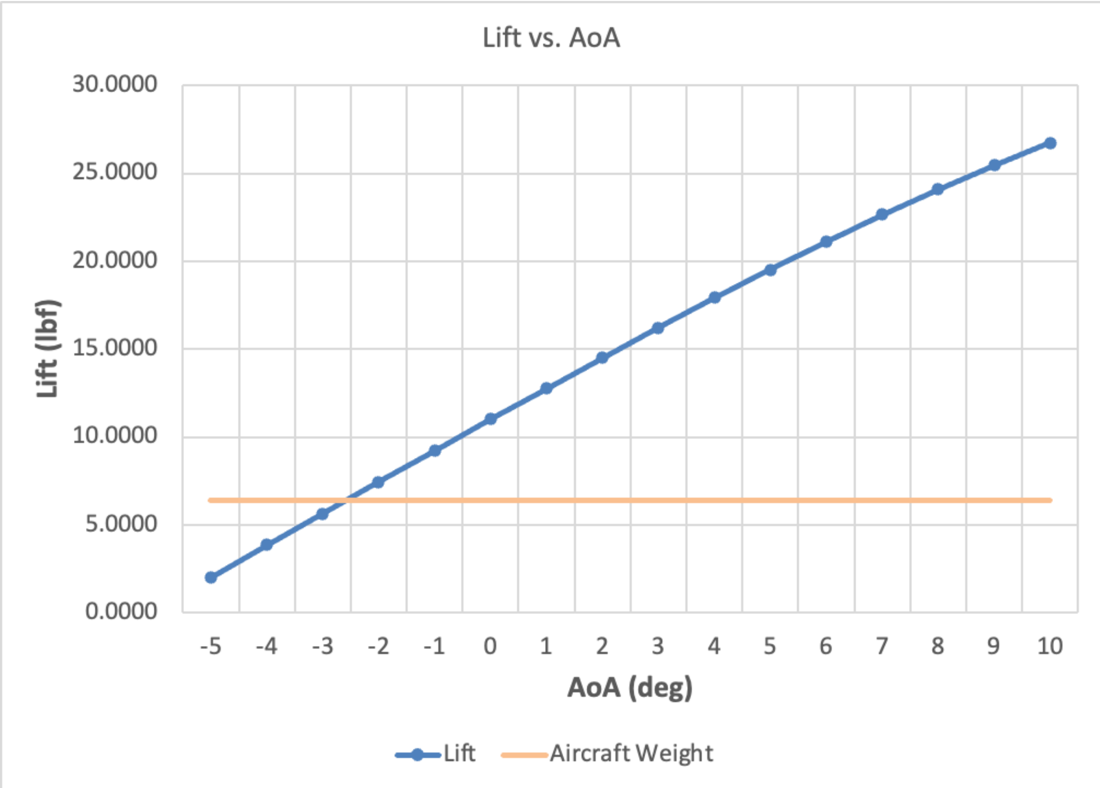

Figure 2.3: *Lift force vs. AoA, as reported by our STAR-CCM+ simulations.*

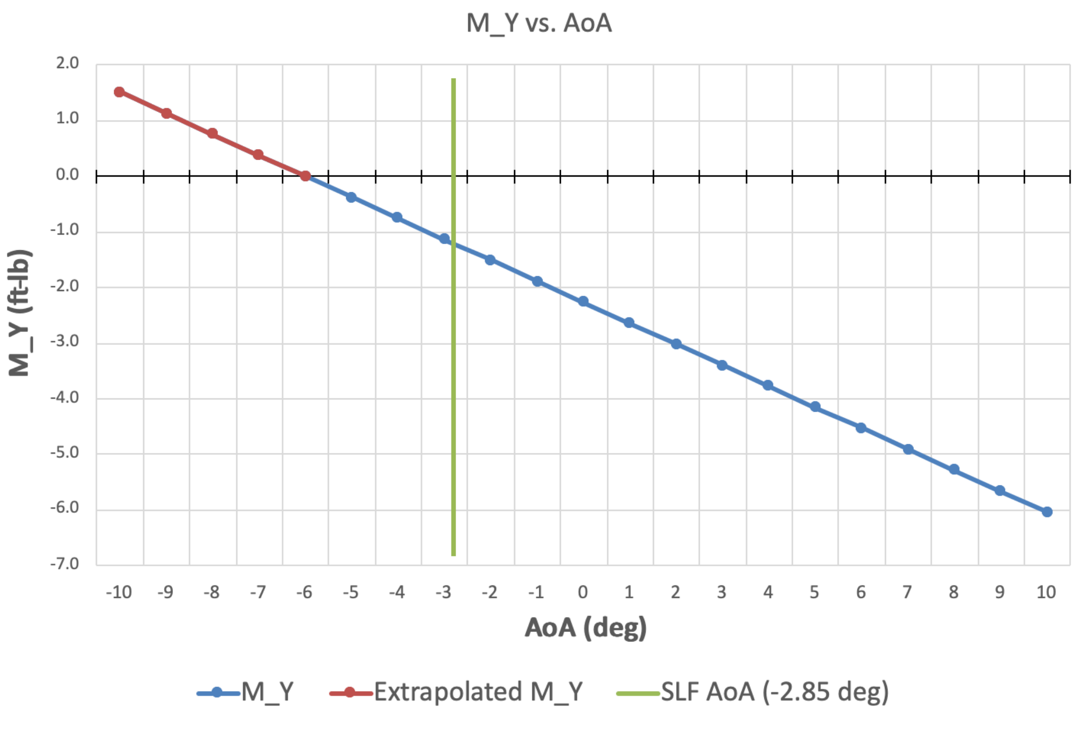

Figure 2.4: *Pitching moment vs. AoA. Data at an AoA less than $-5°$ is extrapolated since our analysis did not include this data, but we thought it would be pertinent to our report.*

3

Analysis

3.1 Static Margin

Our static margin was calculated to be 31.42 %, which is outside of the acceptable range required (5 % to 25 %). This does indicate that this current craft iteration is stable but not optimally stable as the restoring moment around the CG would be too strong.

In other words, when some pitch disturbance is introduced to the craft, a stabilizing restoring moment about the center of gravity would be applied as desired. However, the applied stabilizing moment would be too large, causing the nose to pitch too much and potentially overshoot the desired AoA for SLF. This restoring moment may continue to overshoot above and below the desired AoA, potentially cascading into oscillations and unstable pitch dynamics.

The high static margin would also make the control response of our aircraft very slow. If we want the autopilot to pitch to a desired angle of attack, this command will be delayed and take longer to complete. This makes it harder to maintain a desired pitch angle and adds to the potential for instability.

To remedy this high static margin, adjustments to the geometry, size, and position of our wing and tail must be made. These changes would bring the NP and CG closer to one another, reducing the static margin to within the acceptable range. Altering the features of our wing and tail through different design iterations will highlight which features contribute more to our static margin and which configuration is more desirable to balance stability and maneuverability.

More specifically, we want to adjust the wing's x-position, as well as the airfoil shapes and chord lengths of the wing and tail. These aspects would be our primary focus when determining how to alter aspects of our designs in subsequent design iterations.

3.2 Tail Sizing Coefficients

3.2.1 Horizontal Tail

The horizontal tail volume coefficient is defined using Equation 3.1 from Grager (2024).

$$C_{HT} = \frac{S_{HT} L_{HT}}{c S_{ref}} \tag{3.1}$$

Where C_{HT} is the horizontal tail volume coefficient, S_{HT} is the planform area of the horizontal tail, L_{HT} is the length from quarter chord of the primary wing to quarter chord of the horizontal tail, c is the chord length of the primary wing, and S_{ref} is the planform area of the primary wing.

The range that most coefficients fall in between given in class was 0.3 to 0.6 (Grager, 2024). Our group chose to take the average and aim for a horizontal sizing coefficient of 0.45. The chord length c for our primary wing is 19.98 cm (7.87 in) and the wingspan b is 216 cm (85 in). The reference surface area is found by multiplying our chord length c by our wingspan b to find $S_{ref} = bc = (19.98\,\text{cm})\,(216\,\text{cm}) = 4316\,\text{cm}^2 = 669\,\text{in}^2$.

Assuming that we will be using a carbon fiber spar length of 91.44 cm (36 in) and assuming that it starts 27.485 cm (10.82 in) from the nose (also the assumed CG), we end up with an L_{HT} of approximately 88 cm (35 in). Solving the horizontal tail volume coefficient equation for S_{HT}, we get a value of $440.935\,\text{cm}^2$ $\left(63.35\,\text{in}^2\right)$. Another assumption that will be made is that the chord length will be 15 cm (5.91 in) on the horizontal tail which results in a horizontal tail span of 29.296 cm (11.53 in).

3.2.2 Vertical Tail

The vertical tail volume coefficient is defined using Equation 3.2 from Grager (2024).

$$C_{VT} = \frac{S_{VT} L_{VT}}{b S_{ref}} \tag{3.2}$$

Where C_{VT} is the vertical tail volume coefficient, S_{VT} is the planform area of the vertical tail, L_{VT} is the length from quarter chord of the primary wing to quarter chord of the vertical tail, c is the chord length of the primary wing, and S_{ref} is the planform area of the primary wing.

The range most coefficients fall in between given in class was between 0.02 to 0.05 (Grager, 2024). Our group chose to once again take the average and chose a vertical tail volume coefficient of 0.035. The chord length c for our primary wing is 19.98 cm (7.87 in) and the wingspan b is 216 cm (85 in). The reference surface area is found by multiplying our chord length c by our wingspan b to find $S_{ref} = bc = (19.98\,\text{cm})\,(216\,\text{cm}) = 4316\,\text{cm}^2 = 669\,\text{in}^2$.

Assuming that we will be using a carbon fiber spar length of 91.44 cm (36 in) and assuming that it starts 27.485 cm (10.82 in) from the nose (also the assumed center of gravity). This results in a L_{VT} of 88 cm (34.65 in). Solving the vertical tail volume coefficient equation for the platform area of the vertical tail, we find S_{VT} is $370.756\,\text{cm}^2$ $\left(57.47\,\text{in}^2\right)$. Assuming that we would like a chord length of 19.98 cm (7.87 in), we calculated a vertical tail wingspan of 18.556 cm (7.31 in).

3.2.3 Tail Sizing Summary

We believe that the general tail sizing coefficients C_{HT} and C_{VT} that we selected to be 0.45 and 0.035 respectively are relatively small for our mission. Our team came to this consensus after receiving feedback that—even before analysis—the wings appeared visually small. This is most evident when viewed in the top-down view, shown in Figure 2.2. We acknowledge that at this time these numbers are just a starting point and are subject to change later on. After further stability testing, our team will most likely choose to increase the coefficients.

3.3 Pitching Moment

At a cruise speed of $17.88\,\frac{\mathrm{m}}{\mathrm{s}}$ (40 MPH), our desired angle of attack is $-2.85°$, as shown in Figure 2.3. At this angle, our pitching moment about the center of gravity is $-1.54\,\mathrm{N\,m}$ ($-1.1357\,\mathrm{ft \cdot lbf}$), as can be seen in Figure 2.4. This pitching moment is too large for the SLF AoA and will lead to unstable pitch dynamics as mentioned in Section 3.1. We believe this is largely due to a combination of our wing's high-lift production and our high static margin. Regardless, this pitching moment is too high, so another main focus for future improvements must be on reducing this moment to improve longitudinal stability.

3.4 Future Improvements

In subsequent design iterations, we will experiment with increasing the chord length and thickness of the aircraft's wing and tail. This may include running a design iteration with a NACA 0012 airfoil for the tail as opposed to the current NACA 0010. This is primarily for manufacturing reasons; too thin a a wing or tail may not bond to the spars properly or may not handle the aerodynamic loads of the aircraft in flight.

We also plan to change the wing location and sizing in future designs. By moving the wing forward, we may be able to decrease our static margin, bringing us closer to proper stability. We also may have to increase the primary wing's chord length once we have run wing loading calculations.

If our aircraft's pitching moment at the SLF AoA is still too large, we may have to consider changing our wing airfoil to a thinner one, *e.g.*, the NACA 2412. With this airfoil, our wing will produce less lift but will generate lower pitching moments and may increase our pitch stability. This change will be analyzed in future design iterations.

All these improvements will be performed with a more refined CG calculation. During each design iteration, we will add more detail to the CAD model, increasing the accuracy and location of our CG.

4

Conclusion

In this report, we analyzed the static margin, pitching moments, and tail sizing coefficients as they relate to the longitudinal stability of our aircraft.

Currently, the static margin is approximately 31.42 %—above the ideal range. This indicates excessive stability, which could cause poor control response. For the tail sizing coefficients, the values we assumed for C_{HT} and C_{VT} are relatively small and they are subject to change in the future. Lastly, the pitching moment is currently too high at our desired angle of attack of $-2.85°$.

For our future iterations, we will make adjustments to the wing and tail configurations to reduce the static margin. We also need to test the possibility of changing the airfoil shape due to manufacturability and to address the pitching moment. We will refine our CG position to perform more accurate aerodynamic and structural analyses.

This report concludes our first official design iteration. Following this initial design, we will refine our system requirements to create a formal system requirement scorecard that we will use to grade each subsequent design iteration until we have arrived at a suitable design.

Bibliography

Grager, Travis (2024). "Stability and Control". Lecture slides. URL: https://canvas.iastate.edu/courses/112913/files/28358353?module_item_id=6671950 (visited on 10/15/2024).