CyberTruk Dynamic Stability Analysis

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Abstract

The CyberTruk project aims to develop an efficient and cost-effective hybrid flying truck, requiring careful stability analysis to ensure safe flight performance. Canard configurations, while beneficial for certain aerodynamic advantages, introduce complexity and cost, prompting an investigation into their necessity. This study evaluates the longitudinal dynamic stability of the CyberTruk with and without a canard in to determine whether its removal compromises flight stability and handling. The key issue examined is whether the canard's removal leads to unstable flight dynamics, particularly in pitch response. Initial analysis revealed that the original canard design exhibited acceptable stability but with overly sensitive short-period oscillations at 21.53 rad/s. Removing the canard without adjustments resulted in severe instability, with oscillations increasing to 38.84 rad/s, making the aircraft difficult to control. To address this, a modified wing configuration was analyzed, featuring a larger and forward-shifted wing to compensate for the canard's absence. The methodology relied on Athena Vortex Lattice (AVL) for aerodynamic modeling and eigenvalue analysis to assess stability modes. Manual validation was performed to account for AVL's limitations in computing eigenvalues. Assumptions included sea-level flight conditions, rigid-body dynamics, and simplified geometric adjustments, omitting real-world factors like turbulence and structural flexibility. The results demonstrated that the adjusted wing design successfully stabilized the aircraft, reducing short-period oscillations to a manageable 18.70 rad/s while maintaining stable phugoid dynamics. This configuration proved that the canard could be eliminated without sacrificing flight stability, provided proper aerodynamic compensation was implemented. However, the study did not evaluate lateral stability or structural weight implications, which require further investigation. This work significantly impacts the CyberTruk project by validating a simpler, canard-free design that reduces manufacturing complexity and cost while preserving flight stability. The findings provide actionable insights for future design iterations, emphasizing the importance of aerodynamic tuning when modifying control surfaces. Future research should explore lateral stability effects and validate results through flight testing. Overall, this study confirms that canard removal is feasible with careful wing adjustments, contributing to the broader goal of developing practical and economical hybrid flying vehicles.

Contents

1 Introduction

A notable feature of the CyberTruk is the canard at the front of the plane. The canard is an essential component for providing longitudinal stability. In previous stability studies, only static stability was considered. While static stability determines an aircraft's initial tendency to return to equilibrium after a disturbance, dynamic stability characterizes its time-dependent response, revealing whether oscillations will decay, grow, or persist following perturbations like turbulence or controlled inputs.

This report will consist of a comprehensive dynamic stability analysis of the aircraft. To better understand the stabilizing effects of the canard, three separate analyses will be performed. The first will examine the current aircraft model, including the canard. The second analysis will use a modified version of the aircraft with the canard removed. To isolate the canard's influence, the wing and horizontal stabilizer areas as well as their locations—will be adjusted to maintain the same lift and static margin as the first analysis. Finally, a third analysis will be conducted, by adjusting the area and location of the wing to compensate for the removal of the canard, keeping the aircraft's lift and the static margin constant.

The dynamic stability analysis will cover the longitudinal and lateral stability. By analyzing the equations of motion, key aircraft characteristics can be determined. In longitudinal stability, the phugoid and short-period modes will help assess pilot workload and comfort. These modes will return a set of eigenvalues, containing critical parameters such as damping coefficients and natural frequencies, which are key factors in stability and responsiveness. By comparing the eigenvalues between the two analyses, we can directly determine the canard's impact on aircraft stability.

Through this analysis, we will evaluate how the addition of a canard affects the aircraft's responsiveness to disturbances. Our hypothesis is that the canard will improve both responsiveness and stability. By introducing additional lifting surfaces, a larger disturbance would be required to displace the aircraft by a given amount. However, the inclusion of a canard increases research and manufacturing costs. By quantifying its impact on overall stability, this analysis will determine whether the inclusion of the canard is justified. Furthermore, through conducting a static stability analyses, we will be able to compare several important metrics of our aircraft to FAA requirements, ensuring our aircraft is flight worthy.

2 Methods

2.1 Tools and Software

For dynamic stability analysis, two separate programs are utilized. OpenVSP is an open-source aircraft geometric tool developed by NASA. The OpenVSP was the primary program used when creating and modifying the actual design of the aircraft. Additionally, OpenVSP has a Mass Properties tool, which provided useful values such as the aircraft's center of gravity and inertia values. The second program utilized was AVL. AVL is a program for the aerodynamic and flight-dynamic analysis of rigid aircraft developed by MIT. For the purpose of the dynamic analysis, AVL provided essential information on forces of the various lifting surfaces. Additionally, AVL provides stability derivatives, which provide essential stability constants used for dynamic stability calculations, in addition to the neutral point of the aircraft configuration.

2.2 Aircraft Variations

2.2.1 Variation 1: Original Geometry

There are three variations of the Cybertruk that were analyzed. The first variation, acting as the control, is the original Cybertruk model, showcased in the Critical Design Report. This would be the only of the three models to retain the canard. Figures 1 and 2 show the models in OpenVSP and AVL, respectively. Additionally, Table 1 shows the center of gravities and inertia values determined from OpenVSP.

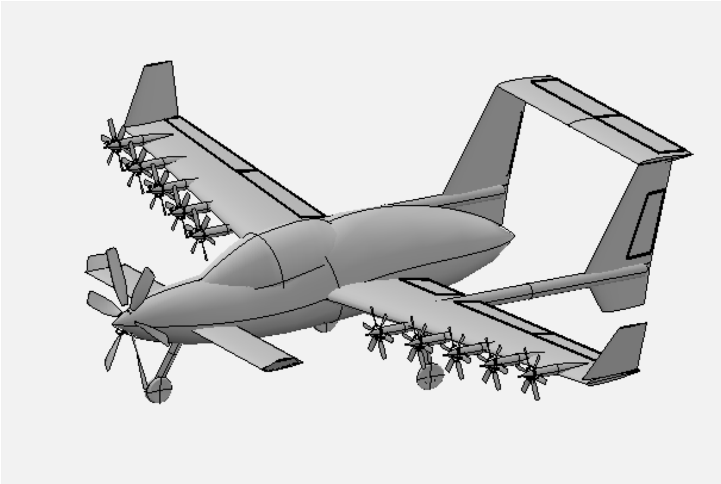

Figure 1: Original Cybertruk Model in OpenVSP

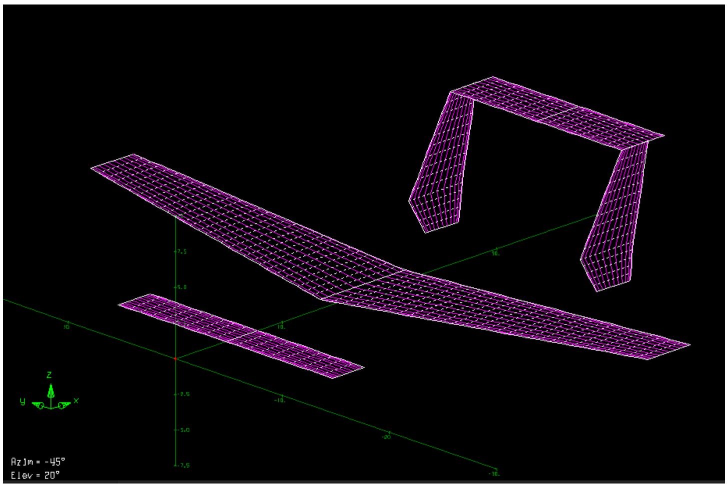

Figure 2: Original Cybertruk Model in AVL

Table 1: Mass Properties for Longitudinal Analysis (Original Configuration)

Parameter	Value
X CG	16.277 ft
Z CG	0.102 ft
I_{xx}	39,628.177 slug-ft^2
I_{yy}	40,840.220 slug-ft^2
I_{xz}	3,997.986 slug-ft^2

2.2.2 Variation 2: Canard-Removed Geometry

The second variation would be an copy of the first variation, but with the exclusion of the canard. This variation would if and how the aircraft would react if the canard was excluded. Due to no other modifications to the aircraft taking place, its likely that the second variation would be highly unstable due to the movement of the neutral point and center of gravity affecting the static stability of the aircraft. Figures 3 and 4 show the second variations in OpenVSP and AVL, with Table 2 showing the Mass Properties for the Canard Removed Variation.

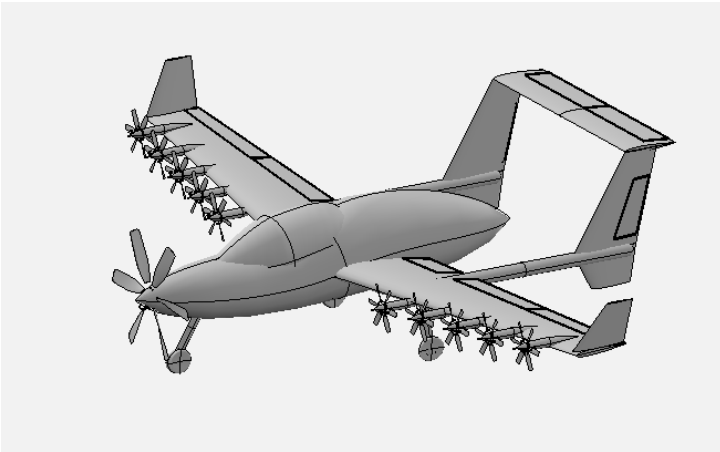

Figure 3: Canard-Removed Cybertruk Model in OpenVSP

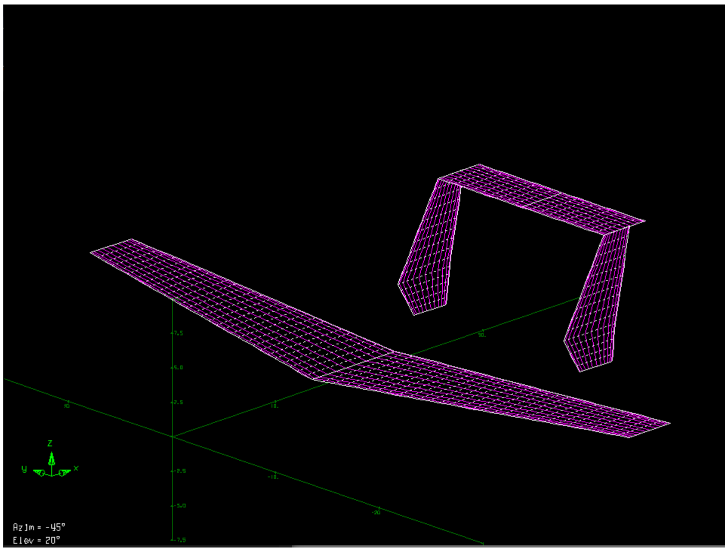

Figure 4: Canard-Removed Cybertruk Model in AVL

Table 2: Mass Properties for Longitudinal Analysis (Canard-Removed Configuration)

Parameter	**Value**
X CG	16.426 ft
Z CG	0.120 ft
I_{xx}	39,187.656 slug-ft^2
I_{yy}	39,595.863 slug-ft^2
I_{xz}	3,841.335 slug-ft^2

2.2.3 Variation 3: Adjusted Geometry

The third variation would act as the primary comparison to the original model. In the Canard-Removed Geometry, no further adjustments to the size and location of the wing were made to offset the removal of the canard. The third variation would attempt to adjust for the removal of the canard in two ways. Firstly, the reference area of the wing is increased to adjust for the lift lost by the canard, keeping the Aspect Ratio of the wing constant. Secondly, the wing would be shifted forward to keep the neutral constant. While not perfect, these methods would attempt to keep the static stability of the aircraft as close as possible to that of the original aircraft. In turn, when analyzing the aircraft's dynamic stability, any discrepancies in values will be easier to attribute towards the removal of the canard.

In order to determine the lift contribution of the canard, an AVL analysis was conducted on the original geometry. The analysis resulted in the lift coefficients by surface, from which the Lift by Surface is determined using the following equations.

$$L = C_l \cdot q \cdot S_{surf} \tag{1}$$

$$q = \frac{1}{2}\rho V^2 \tag{2}$$

This analysis assumes the aircraft velocity to be the cruising speed of 150 knots, or 253.171 ft/s. Furthermore, density is assumed to be at sea level with a value of 0.00237 slugs per cubic feet. This results in a dynamic pressure of roughly 76 pounds per square feet.

$$q = 75.953 lb/ft^2$$

With the dynamic stability determined, the following Lifts can be calculated. The following table shows the lift coefficients and respective lifts for various surfaces of the aircraft. The coefficient values were obtained from AVL. To model trimmed flight, sea level flight conditions were used in addition to the mass and inertia values found through OpenVSP.

Table 3: Lift Distribution by Surface

Surface	S_{surf} (ft^2)	c_{ave} (ft)	C_l	**L** (lbf)
Canard	60.0	3.0	0.3771	1718.5
Main Wing	312.4	6.0	0.2505	5943.8
Vertical Tail	71.6	3.8	0.0	0.0
Horizontal Stab	64.0	4.0	0.1232	598.9

A second analysis was conducted on the Canard-Removed Configuration to check if the component lift coefficient changed from the removal of the canard. Based on the values found in Table 3 and 4, we can assume the lift coefficient stays relatively constant.

Table 4: Lift Distribution (Canard-Removed Configuration)

Surface	S_{surf} (ft^2)	c_{ave} (ft)	C_l	**L** (lbf)
Main Wing	312.4	6.0	0.2505	5943.8
Vertical Tail	71.6	3.8	0.0000	0.0
Horizontal Stab	64.0	4.0	0.1232	598.9

To offset the 1718 pounds of Lift lost through the removal of the canard, the wing will increase its area to have a new lift. With the new lift, Equation 1 can be used to determine the new required wing area. The new Lift and surface area are shown as follows:

$$L_2 = L_c + L_w = 7662.3lbf$$

$$S_{ref,2} = 402.723ft^2$$

There are many ways of increasing the area of the wing. One method is solely increasing the wingspan. Another is increasing the chord. The method I settled on is keeping the Aspect Ratio constant. The formula for Aspect Ratio is as follows:

$$AR = \frac{b^2}{S_{ref}} \tag{3}$$

The Aspect Ratio of the main wing is 8.67 with a 52ft wingspan a 6ft mean chord length. Keeping the ratio constant, the new wingspan and mean aerodynamic chord are determined to be as follows.

$$b = 59.08ft$$

$$c_{ave} = 6.817ft$$

Using OpenVSP's Center of Mass and AVL's stability tool, in order to keep the neutral relatively unchanged, the wing needs to be shifted forward by 2.2 ft through trial and error. Once again, the following figures show the Model in OpenVSP and AVL.

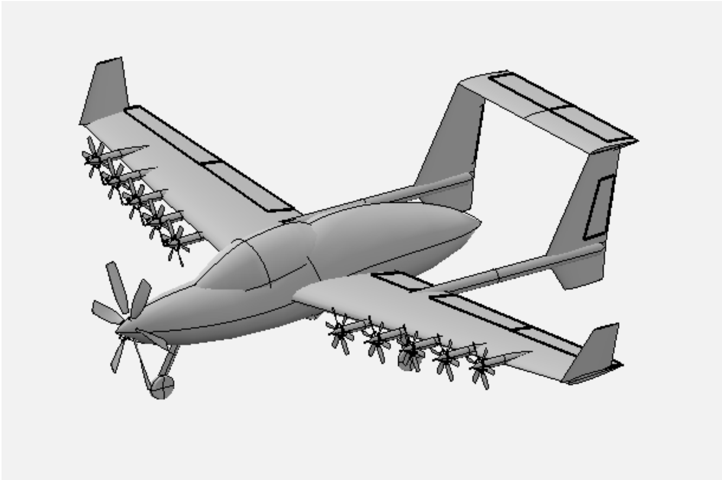

Figure 5: Adjusted Cybertruk Model in OpenVSP

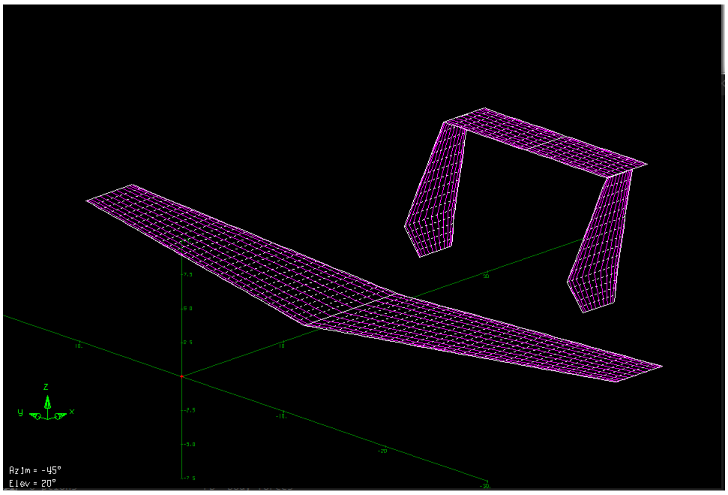

Figure 6: Adjusted Cybertruk Model in AVL

Table 5: Mass Properties for Longitudinal Analysis (Modified Configuration)

Parameter	Value
X CG	15.948 ft
Z CG	0.132 ft
I_{xx}	6,5039 slug-ft^2
I_{yy}	39,837 slug-ft^2
I_{xz}	100,100 slug-ft^2

2.3 Dynamic Analysis Methodology

With the three aircraft configurations ready, the Stability Derivatives function in AVL is utilized to obtained many important values. One such value is the neutral point which, when paired with the center of gravity location, is extremely useful in determining. Additionally, AVL would return the value of important stability values such as the lift slope (C_{la}), the pitch stiffness (C_{ma}), the pitch damping (C_mq),and the lift due to pitch rate (C_lq). Using these values, the Longitudinal Equation of Motion can be used to perform future dynamic stability analysis. Due to the elevator being unused in the analysis, the elevator effectiveness section of the equation is unnecessary. The longitudinal state-space representation is given by:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g\cos\theta_0 \\ Z_u & Z_w & V_0 & -g\sin\theta_0 \\ M_u + M_{\dot{w}} Z_u & M_w + M_{\dot{w}} Z_w & M_q + M_{\dot{w}} V_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} \tag{4}$$

Where:

- u, w: Perturbation velocities in body axes (m/s)
- q: Pitch rate (rad/s)
- θ: Pitch angle (rad)
- V_0: Trim velocity (m/s)
- g: Gravitational acceleration (m/s^2)
- Subscripts denote dimensional derivatives:
  - $X_u \equiv \frac{\partial X}{\partial u}$ (drag speed damping)
  - $Z_w \equiv \frac{\partial Z}{\partial w}$ (lift due to vertical velocity)
  - $M_q \equiv \frac{\partial M}{\partial q}$ (pitch damping)
- $M_{\dot{w}}$: Downwash lag term (m^{-1})

  The moment derivatives will be determined in the Results section of the report. Equations are shown in the Appendix Section of the Report

2.4 Assumptions and Data Management

Overall, this procedure is complex with many assumptions being made. Firstly, there are an infinite number of ways of adjusting the aircraft for the removal of the canard. Not one way is correct, but for this procedure, only the wing was expanded. Additionally, this procedure was assumed to be at cruise flight conditions at 150 knots in sea level atmosphere. Actual conditions may differ with the inclusion of wind and turbulence. Furthermore, the Cybertruk is a complex aircraft, with several parts just on the wing. For the purpose of the experiment, all internal components remained identical and in the same location. Finally, this analysis was computed using the help of AVL. AVL has an eigenvalue feature, but unfortunately produced incorrect results. As a result, eigenvalue values were calculated manually.

3 Results

3.1 Static Stability

One of the first things to be determined through the stability derivatives is the static margin. Table 6 Shows the neutral point, center of gravity, and static margin of all three configurations.

As shown in Table 6, all configurations show a positive static margin, indicating a statically stable aircraft. However, both the modified configuration shows a very high static margin. Removing the canard results in

Table 6: Longitudinal Stability Comparison of Aircraft Configurations

Configuration	X_{CG} (ft)	X_{NP} (ft)	**Static Margin**
Original (With Canard)	16.277	16.753	0.476
Modified (No Canard)	16.426	18.954	2.528
Adjusted (No Canard)	16.048	16.550	0.502

a much greater lifting force in the aft part of the aircraft. This would make the plane too unstable, due to a large moment generated from the aft side of the aircraft.

3.2 Dynamic Stability

In addition to the Neutral Point and Static Margin, AVL returns several coefficients used in the Longitudinal Equation of Motion.

Table 7: Complete Longitudinal Stability Derivatives

Config	C_{L_0}	C_{D_0}	C_{L_α}	C_{m_α}	C_{L_q}	C_{m_q}
Original	0.029 18	0.000 27	5.967 976	−0.513 920	11.373 473	−23.977 654
No Canard	0.020 28	0.005 05	5.484 681	−1.671 824	10.878 815	−16.924 927
Adjusted	0.017 25	0.000 17	4.606 694	−0.264 146	6.792 386	−10.848 510

Where:

C_{L_0} (Zero-angle lift coefficient)

C_{D_0} (Zero-lift drag coefficient)

C_{L_α} (Lift curve slope)

C_{m_α} (Pitch stiffness derivative)

C_{L_q} (Lift due to pitch rate)

C_{m_q} (Pitch damping derivative)

These are all the necessary coefficients to create the longitudinal state matrix. However, there are a few constants necessary to determine first. They can be shown in the list as follows.

- Reference Areas:
  - Case 1 & 2: $S = 312\,\text{ft}^2$
  - Case 3: $S = 402.7\,\text{ft}^2$
- Mean Aerodynamic Chord:
  - Case 1 & 2: $\bar{c} = 6\,\text{ft}$
  - Case 3: $\bar{c} = 6.82\,\text{ft}$
- Trim Velocity: $V_0 = 253.171\,\text{ft/s}$
- Mass: $m = 7460\,\text{lb}$
- Pitch Moment of Inertia: $I_{yy} = 40\,000\,\text{slug}\,\text{ft}^2$ (assuming imperial standard units)
- Dynamic Pressure: $q = 75.953\,\text{lb/ft}^2$

Based on the variables found above, the State Matrix for each configuration can be determined. Using the equations found in the Appendix, the following will show the Longitudinal Equation of Motion for the three configurations.

3.3 Longitudinal State Matrices

Original Configuration (With Canard)

$$A_{\text{original}} = \begin{bmatrix} -6.796\times10^{-6} & -7.510\times10^{-2} & 0 & -3.217\times10^{+1} \\ -7.344\times10^{-4} & -7.510\times10^{-2} & 2.532\times10^{+2} & 0 \\ -3.347\times10^{-8} & 9.737\times10^{-1} & -9.411\times10^{-1} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

No Canard Configuration

$$A_{\text{no canard}} = \begin{bmatrix} -5.034\times10^{-6} & -6.902\times10^{-2} & 0 & -3.217\times10^{+1} \\ -5.104\times10^{-4} & -6.902\times10^{-2} & 2.532\times10^{+2} & 0 \\ 1.424\times10^{-7} & -5.960\times10^{+0} & -7.856\times10^{-1} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Adjusted Configuration

$$A_{\text{adjusted}} = \begin{bmatrix} -5.522\times10^{-6} & -7.482\times10^{-2} & 0 & -3.217\times10^{+1} \\ -5.604\times10^{-4} & -7.482\times10^{-2} & 2.532\times10^{+2} & 0 \\ 4.119\times10^{-8} & -1.382\times10^{+0} & -7.829\times10^{-1} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

3.4 Eigenvalues and Phugoid vs Short Period Mode

Table 8: Eigenvalues for Different Longitudinal Configurations

Configuration	Eigenvalues (Short-period/Phugoid)
Original	Short-period: $-0.5549 \pm 21.53j$ Phugoid: $-3.228\times10^{-6} \pm 0.009662j$
No Canard	Short-period: $-0.4273 \pm 38.84j$ Phugoid: $-2.492\times10^{-6} \pm 0.008053j$
Adjusted	Short-period: $-0.4288 \pm 18.70j$ Phugoid: $-2.630\times10^{-6} \pm 0.008438j$

The eigenvalue data reveals critical differences in aircraft dynamic stability across the three configurations. The original configuration's short-period mode (-0.5549 $\pm$ 21.53j) combines moderate damping with extremely high-frequency oscillations (21.53 rad/s), suggesting an aircraft that would feel "jumpy" and over-responsive in pitch. The no-canard configuration shows even higher short-period frequency (38.84 rad/s) with slightly reduced damping, which would produce uncomfortably rapid oscillations. In contrast, the adjusted configuration demonstrates better-balanced handling characteristics with its short-period mode (-0.4288 $\pm$ 18.70j) maintaining similar damping while reducing the oscillation frequency to a more manageable 18.70 rad/s.

All three configurations exhibit essentially identical phugoid behavior, with oscillation frequencies near 0.009 rad/s and negligible damping. This indicates the phugoid mode remains virtually unaffected by these configuration changes, which is typical for conventional aircraft designs. The adjusted configuration emerges as clearly superior - its short-period damping ratio (ξ = 0.023) is slightly better than no-canard's (ξ = 0.011), while its natural frequency sits in the ideal range for pilot control. The original configuration's intermediate characteristics might offer acceptable handling for experienced pilots, while the no-canard version would likely feel excessively sensitive. These results demonstrate how small changes in aircraft configuration can significantly impact dynamic stability while leaving the phugoid mode essentially unchanged. These results can be shown in graphical from, with the following figure showing the eigenvalues in a root locus graph.

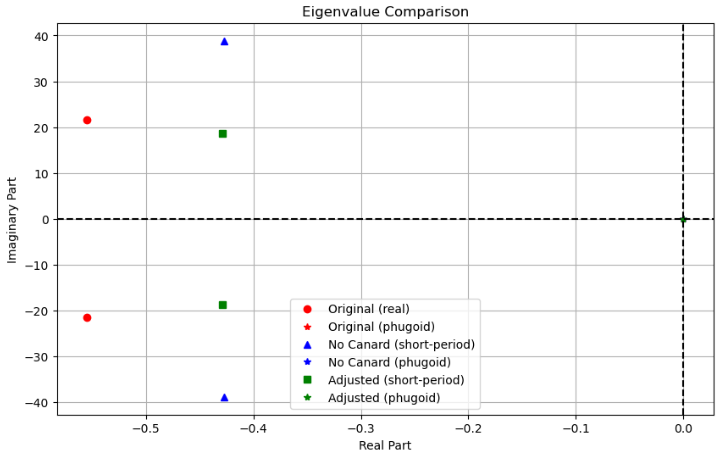

Figure 7: Root Locus Plot of Three Configurations

4 Conclusion

This analysis of the CyberTruk's longitudinal stability shows the trade offs of using a canard setup. The main finding is that the original canard design has stable flight but its high frequency pitch oscillations, at 21.53 rad/s, mean the pitch response is too sensitive. Taking out the canard without other changes made things worse, causing unstable flight and extreme oscillations at 38.84 rad/s. However, the modified design, with a bigger and more forward shifted wing, gave the best results. It had stable dynamics, a more reasonable pitch oscillation frequency at 18.70 rad/s, and kept the phugoid mode stable. This proves that with the right wing adjustments, the canard can be removed while keeping the plane flyable.

The study used many simplifications, such as sea level conditions, rigid body assumptions, and basic geometry changes. Real world factors like turbulence, wing flexibility, and control system effects were not considered. AVL's limitations for eigenvalue calculations meant manual checks were needed, which could introduce errors. Also, the impact of the new wing design on lateral stability and structural weight was not studied, which could affect the real world use.

These results can help guide the team's design choices by showing how the canard affects stability. The modified design proved that a canard free setup can work well, supporting the goal of a simpler and cheaper design. By focusing on the canard's role, this analysis gave clear data for making decisions, ensuring the final design balances performance, stability, and ease of building. Future work should look at lateral stability and test flights.

In summary, this study shows that canard removal can be feasible with careful aerodynamic tuning, offering a simpler design without compromising dynamic stability, a valuable essential to the CyberTruk's iterative development.

A Appendix

A.1 Dimensional Derivatives

The dimensional derivatives are calculated from AVL's non-dimensional coefficients:

A.2 State-Space Representation

The complete longitudinal state-space system:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g\cos\theta_0 \\ Z_u & Z_w & V_0 & -g\sin\theta_0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}V_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} \tag{5}$$

$$X_u = -\frac{q_\infty S}{mV_0}(C_{D_u} + 2C_{D_0}) \approx -\frac{q_\infty S}{mV_0} \cdot 2C_{D_0} \tag{6}$$

$$Z_u = -\frac{q_\infty S}{mV_0}(C_{L_u} + 2C_{L_0}) \approx -\frac{q_\infty S}{mV_0} \cdot 2C_{L_0} \tag{7}$$

$$M_u = \frac{q_\infty S\bar{c}}{I_{yy}V_0} C_{m_u} \quad \text{(Typically negligible at low Mach)} \tag{8}$$

$$Z_w = -\frac{q_\infty S}{mV_0} C_{L_\alpha} \tag{9}$$

$$M_w = \frac{q_\infty S\bar{c}}{I_{yy}} C_{m_\alpha} \tag{10}$$

$$Z_q = -\frac{q_\infty S\bar{c}}{2mV_0} C_{L_q} \tag{11}$$

$$M_q = \frac{q_\infty S\bar{c}^2}{2I_{yy}V_0} C_{m_q} \tag{12}$$

$$M_{\dot{w}} = \frac{q_\infty S\bar{c}^2}{2I_{yy}V_0^2} C_{m_\alpha} \quad \text{(Downwash lag term)} \tag{13}$$