Jet Trainer Aircraft Configuration Project

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MECH-4671: Aerodynamics and Performance

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March 20, 2023

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Abstract

This report outlines the overall stability configuration of a jet trainer aircraft that meets the specified design requirement and constraints. The problem that needs to be addressed is to design an aircraft that satisfies the condition of being statistically stable during cruise, centre of mass must lying ahead of the fixed-stick neutral point, and the aircraft being dynamically stable in all oscillatory modes (phugoid, short-period, spiral, dutch roll and roll-subsidence model), expect the spiral mode, which is allowed to unstable as longas the time constant with the mode is at least 20 seconds. The analytical approach was used by developing the aircraft configuration with AVL software and was compared with the numerical analysis of the overall design. The content of the report includes the problem statement, theories involved in solving the design's parameter, assumptions to be accounted, and tools used to solve the problem. This aircraft is based upon the assumption that the horizontal and vertical tail airfoils are flat and hinged at 50% chord and both control surfaces of tail cover the full length of the span. The report was conducted in three iteration of wing design that increased the efficiency of the aircraft and improved each oscillatory mode significantly. Various graphs, plots and tables are shown in the report to represent the final design of the aircraft.

Introduction

The main purpose of this project is to generate a stable and efficient jet trainer aircraft configuration using the provided set of design requirements and constraints by utilizing analytical modeling methodologies and AVL (Athena Vortex Lattice) software. The aircraft developed must be statically and dynamically stable, and in addition to that, it should also satisfy the requirement of being statically stable during the cruise, with the center of mass lying ahead of the fixed-stick neutral point and exhibiting dynamic stability in all modes except the spiral mode, which is permitted to be unstable if the mode's time constant is no less than 20 seconds. The analysis is based upon the assumption that the horizontal and vertical tail airfoils are flat plates hinged at 50% chord, and the control surfaces, elevator, and rudder, cover the entire span of the respective tails.

The task is to determine the overall design of the wing, locate the center of mass of the aircraft, and have a complete design of the tail. This has been obtained by performing 2D and 3D wing analysis through selection of aspect ratio and taper ratio, determination of lift distribution, wing performance in AVL, and iteration when necessary. It is necessary to select the aspect ratio and taper ratio first as it provides definition to the geometry of the aircraft that will lead to determining the lift distribution. The aircraft stability has been established by determining the wing location, angle of incidence, tail sizing, control surface sizing, and by analytically and numerically assessing each stability condition. Likewise, each constraint was taken in account to ensure that all the requirements were satisfied. Furthermore, various links that have been provided to assisted us in generating the desired outcome, including reporting guidelines, writing tutorials, and YouTube videos. This has created an opportunity for us to present our results in a professional report. This report is further divided into various steps to determine the complete configuration of the jet airplane of our selection. After establishing the problem statement, various ground theories are explained to understand the methodologies used to determine the wing design. The results are discussed and presented by graphs, plots, and tables for visual representation.

Problem Definition

The problem statement is to design an overall configuration of a jet trainer by establishing and iterating wing geometry through defining the aspect ratio, taper ratio, incidence angle, aileron, dihedral, sweep, and locating each parameter relative to the center of mass of the aircraft, and completing design of stabilizers that satisfies the requirement of being statically stable during the cruise, the center of mass lying ahead of the fixed-stick neutral point, and exhibiting dynamic stability in all modes except the spiral mode, which is permitted to be unstable as long as the mode's time constant is no less than 20 seconds, while fulfilling the established design requirements and constraints. The analysis needs to be conducted by numerically modelling and using software such as Aero Console and AVL. It is important to note that this statement is based upon the assumption that the horizontal and vertical tail airfoils are flat plates hinged at 50% chord, and the control surfaces, elevator, and rudder, cover the entire span of the respective tails. We can obtain the location of the wing aerodynamic center by modelling our wing design in AVL.

Aircraft Information

The Aermacchi or Macchi MB-326 is a popular light military jet aircraft designed in Italy, initially for training purposes but also produced as a single or two-seat light attack plane (Wikimedia Foundation). It has been purchased by over 10 countries and has been produced under license in Australia, Brazil, and South Africa. In Australia, the Royal Australian Air Force (RAAF) used MB-326H variant for their tasks. The aircraft has set multiple records, including an altitude record of 56,807 ft on March 18, 1966. Over 600 of these planes have been built. (Pubishing, 1985)

The Aermacchi MB-326 was a low-wing monoplane built with light alloys and designed to serve both as an ab initio and advanced jet trainer. It had a simple design and high-performance capabilities that allowed for efficient training and low maintenance requirements. According to Flight International, it was suitable for teaching most advanced flying techniques. (International, 1961, p.492)

Aircraft Geometry

Dimensions of Macchi MB-326 Jet trainer:

Table 1

Jet Trainer Aircraft Dimension/Geometry

Design Parameter	**Specifications**
Airfoil	NACA 64A114
Incidence Angle	0 degrees
Sweep	No Sweep
Taper Ratio	0.35
Wingspan (b)	10.85 m
Wing Area (S)	19.35 m^2 (208 sq ft)
Length of fuselage (L_{fuse})	10.65 m
Powerplant	Bristol Siddeley Viper 20 Turbojet Engine
Performance Parameter	**Specifications**
Maximum Speed	867 km/hr
Cruise Speed	797 km/hr

Aircraft Mission

This light military jet trainer aircraft was designed as light attack aircraft and used for trainers and in an armed configuration as well. In 1965 AD, Aermacchi MB-326 was selected as RAAF's new training aircraft. (Navy, R. A.)

Theory

Athena Vortex Lattice

It is an open-source vortex lattice code by Mark Drela used for aerodynamic and flight-dynamic analysis of rigid aircraft of arbitrary configuration.

Lifting line Theory

It is a model of a finite wing which allows the induced drag generated and the overall lift coefficient to be determined (ANDERSON). Based upon this theory, elliptical lift distribution is the most efficient distribution that provides lowest possible value of induced drag coefficient for a given lift coefficient and wing aspect ratio. This theory can predict lift distribution for higher aspect ratio straight wings and unswept wings. However, different approach was required for lower AR, swept and delta wings.

Vortex Lattice Method

This method was built to remove the limitation of lifting line theory, which was practicable for Low AR wings, swept and delta wings (ANDERSON). This approach was based upon placing horseshoes vortices in a grid of panels over wing surface and can be solved numerically by applying Kutta condition.

Aspect Ratio

Aspect Ratio was first introduced using a wind tunnel constructed by Wright Brothers (ANDERSON). A long, skinny wing (higher AR) generated less drag for a given lift that a short, fat wing (lower AR). Initially, it was defined simply as the span divided by the chord. However, the definition of AR for a tapered and un-tapered wing overall is the wingspan squared by the area. A higher AR can be generated by increasing the wingspan length and decreasing the area of the wing.

$$AR = \frac{b}{c} * \frac{b}{b} = \frac{b^2}{S} \text{ where } b \text{ is the wingspan and } S \text{ is the reference wing area.}$$

Higher AR generates more C_L. Further, effect of changing AR can be seen in the change in stalling angle. As the effective angle of attack reduces at tip, a lower-aspect ratio wing will stall at higher angle of attack than a lower-aspect ratio wing.

Root Chord

The root chord is the total length of airfoil at the centerline attached to the fuselage (Raymer). It is given by, $C_{root} = \frac{b}{AR}$

Taper Ratio

Taper Ratio, λ, is the ratio between the tip chord and the centerline root chord (Raymer). Tapering a wing affects the lift distribution along wingspan. Having un-tapered wing results in heavier loads in wing tip, causing more lift generation towards tip which is not desired. Increasing tapering, brings lift distribution closest to elliptical lift distribution by reducing drag, increasing aspect ratio, reducing load effect in the tip.

$$\lambda = \frac{C_{tip}}{C_{root}}$$

Oswald efficiency factor:

The Oswald efficiency factor is given by, $e_0 = 1.78(1 - 0.045AR^{0.68}) - 0.64$

Static Stability

The aircraft is said to be statically stable if the center of mass is behind the aerodynamic center and the center of mass is ahead of the fixed-stick neutral point (ANDERSON). To be statistically equilibrium point, the aircraft must have restoring force to bring the equilibrium condition.

Condition for static stability:

$C_M = 0, \frac{\partial CM}{\partial \alpha} = C_{M\alpha} < 0$

Dynamic Stability

The pre-requisite condition for an aircraft to be dynamic stability is to be statistically stable (ANDERSON). A statically stable aircraft undergoes oscillatory motion during the flight. Therefore, if the aircraft retain its position after going through the series of decaying oscillations over time, the aircraft is said to be dynamically stable. The dynamic stability consist mode in longitudinal and lateral axis. Longitudinal Mode: Phugoid Mode, and Short-Period Mode

Lateral Mode: Spiral Mode, Dutch Roll, and Roll–subsidence model

These depends upon the stability derivatives. These modes are numerically solved by using the vortex lattice method. All the value of eigenvalues should be negative to make mode's stable. For example,

For Short Period Mode, the eigen values becomes,

$$\lambda 1{,}2 = \sigma SP \pm i\omega \mathrm{SP} = \frac{1}{2}\left[M_q \pm \sqrt{{M_q}^2 + 4\upsilon o Mw}\right], \text{(ANDERSON)}$$

Mw is nearly equal to Cm_α, is negative for stable. Therefore, short period is stable for negative eigenvalue.

Design Requirement

- Cruise Mach: $M_\infty = 0.5$
- Mass of the Aircraft, m = 4000 kg (fuel, pilot, etc. included) (Given)
- Cruise Altitude: 11 km; Wing Airfoil used: NACA 2312; Stall angle of attack: 10 degree
- Aircraft Static thrust at Mach Zero: 1.5 at sea level.

- Mass Distribution are as follows:

    1. The fuselage, engine and tail are single, and masses are distributed as 20-point masses of 120 kg which adds to 60% of total mass.

    2. Each wing will have mass distributed as one point mass of 800 kg which is 20% of total mass.

    3. Point mass's locations are,

       20% in each wing, each point masses located at $z^b = 0$, $y^b = \pm b/6$

- Engine thrust is proportional to free-stream air density.

Constraints

- The plane needs to be a jet trainer.

- The aircraft needs to statically stable at cruise.

- Center of mass must lie ahead of fixed-stick neutral point.

- The aircraft should be dynamically stable in all modes, except the Spiral mode, which is allowed to be unstable if the time constant associated with the mode at least 20 seconds.

Assumptions

- Neglect variations in mass during the flight due to fuel burn, etc.

- The horizontal and vertical tail are flat plates, are hinged at 50% chord, and that the elevators and rudder both span the full length of horizontal and vertical tail.

- Assume that the aircraft drag coefficient can be modelled as follows:

$$C_D = C_{D,0} + \frac{{C_L}^2}{\pi e_o AR}$$

$C_{D,0}$= 0.03 is the zero-lift drag coefficient and AR is aspect ratio

$$e_0 = 1.78\left(1 - 0.045AR^{0.68}\right) - 0.64$$

Methodology

2D and 3D wing analysis

By using the knowledge of course, Prandtl Theory and Lifting Line theory insists that an elliptical wing is more stable than a square wing, with higher efficiency according to Oswald's efficiency. However, manufacturing an elliptical wing can be challenging, so modifications such as taper, sweep, and dihedral are often incorporated into square wing designs to approximate the performance of an elliptical wing.

Aspect Ratio and Taper ratio selection

To prevent significant drag increase caused by the formation of shockwaves in areas where the airflow is locally accelerated to speeds above Mach 1, it is essential to perform wing sweeping on airplanes traveling at speeds excess than Mach 0.5 to Mach 0.6.

Lift and Drag coefficient determination.

There are two types of drag that needs *to* be considered for calculations, induced and lift drag.

$C_D = C_{D,O} + \frac{{C_L}^2}{\pi e_0 AR}, where, C_{D,O} = 0.03\ (Given)$

Lift coefficient equation

$$C_L = \frac{2L}{\delta * V^2 * S}$$

At Cruise, L = W, $C_L = \frac{2W}{\delta * V^2 * S} = \frac{2*4000*9.81}{0.3639*147^2*19.35} = 0.5$

Wing Taper and Sweep

In each iteration, the taper is incorporated to assess whether the updated shape is more stable, by analyzing the eigenvalues. The tapered ratio for the final geometry used is 0.35 which is obtained by the graph present in Raymer. The obtained results will be compared to the theoretical outcomes described in the previous section. To prevent significant drag increase caused by the formation of shockwaves in areas where the airflow is locally accelerated to speeds above Mach 1, it is essential to perform wing sweeping on airplanes traveling at speeds excess than Mach 0.5 to Mach 0.6. No sweep is used in the design as the cruise Mach number is less than 1.

Geometry Analysis

The wing design chosen was rectangular along with the rectangular tail. The dimensions of the wing are taken from jet trainer Macchi MB-326, the values are present in the Table 1. Other parameters such as aspect ratio and chord are calculated by the equation mentioned above. The tails areas are calculated by the equation mentioned and the c(HT) and c(VT) values are obtained from Raymer.

Wing performance in AVL

According to the prior knowledge of the coursework the elliptical design of the wing is best for high efficiency. However, it’s difficult and time consuming to build that geometry in AVL. For better performance the wing is tapered by 0.35 from both sides.

Iterations

The three iterations are conducted which will help to determine if the theoretical knowledge is applicable to wing design and the iteration. Best stability derivative will be chosen.

First iteration: In the first iteration, the rectangular wing was used the stability derivatives and geometry is present in the Appendix (2). The efficiency and other parameters are relatively low as compared to other iterations.

Second iteration: In second iteration, the wing was tapered from the trailing edge. The geometry and stability derivative graph are present in Appendix (5).

Third Iteration: In third iteration, the airplane wings are tapered from both sides which is closer to elliptical wing. The geometry performed the best as compared other planes which was expected due to elliptical shape of the wing.

Aircraft stability

Wing location

The fuselage length for the final iteration was 11 m and the leading edge of the wings are starting from the 30% of your fuselage.

Angle of incidence

It is the pitch angle of the wing with respect to fuselage. Angle of incidence is generally used to minimize drag. Angle of incidence is zero for all the geometries.

Dihedral

The iterations do not incorporate dihedral angles in the design, as it is too complicated. However, it is known that dihedral wings provide the best stability. Dihedral refers to the upward angle of an aircraft's wing, which enhances lateral dynamic stability, including roll subsidence, spiral, and Dutch roll. Therefore, if dihedral were included in the iterations, that iteration would likely be the most stable. 2-degree dihedral was used in final iteration as it was performing better.

Tail Sizing Analysis

To determine the size of the vertical and horizontal tails, it is commonly assumed that their chords should be 20% of the wing chord. The areas for both the vertical and horizontal tails are calculated accordingly.

$$S(HT) = \frac{c(HT) * Croot * S}{L_{VT}\ (Fuse)}\ , \qquad S(VT) = \frac{c(VT) * b * S}{L_{HT}\ (Fuse)}\ ; Croot = \frac{b}{AR} = \frac{12}{6.73} = 1.8$$

$$S(HT) = \frac{0.70 * 1.8 * 19.35}{11} = 2.21, \qquad S(VT) = \frac{0.06 * 12 * 19.35}{11} = 1.27$$

The tail span is calculated as,

C_{HT}= C_{VT}= 0.5*1.8 = 0.9; $\quad b(HT) = \frac{S(HT)}{C(T)},\ b(VT) = \frac{S(VT)}{C(T)}$

$$b(HT) = \frac{2.21}{0.9} =, 2.45\ m\ b(VT) = \frac{1.27}{0.9} = 1.41\ m$$

(Raymer & American Institute of Aeronautics and Astronautics., 1989) The typical value of tail volume coefficient for a jet trainer,

$$c(VT) = 0.6\ , \qquad c(HT) = 0.70$$

Control Surface Sizing

To accommodate the 10% extra control stability mentioned in theory, the control surface for the wings (ailerons) was positioned at 25% of the wing chord and extended to 100% of the span. An aileron is a hinged flight control surface of a fixed-wing aircraft. According to the theory, the ailerons are about 15%-25% of the wing chord and 50%-90% for the span, sometimes 100% of the span. (Raymer & American Institute of Aeronautics and Astronautics., 1989, p. 100). Similarly, the control surfaces for the tails (elevator and rudder) were positioned at 50% of the tail chord and extended up to 90% of the tail span. These control surface locations and percentages remain consistent throughout all iterations. As the wing shape is altered in each iteration, only the wing area and lift coefficient are changed while maintaining a constant aspect ratio and span. The tails of the aircraft do not undergo any geometric modifications, as the mass points are distributed on the fuselage, as explained in theory.

Stability assessment – analytical

The report already mentioned that the Cm(alfa) and the derivative of cm(alfa) should be negative for static stability. And the center of gravity location should be between the aerodynamic center and neutral point. The condition can be observed in the table mentioned below.

Table 2

Stability assessment - analytical

Parameters	Values
Aerodynamic Center	3.6625
Center of Gravity	4.140
Neutral point	4.706
C_M (alfa)	-1.402
C_L (alfa)	4.455
Efficiency	1.000

Stability assessment – numerical

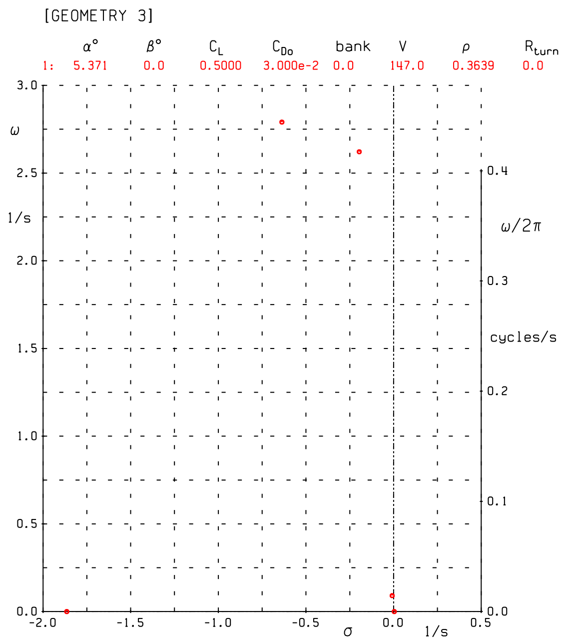
$$e_0 = 1.78\left(1 - 0.045AR^{0.68}\right) - 0.64 = 1.78\left(1 - 0.045 * 6.25^{0.68}\right) - 0.6 = \ 0.86$$

(Aerodynamic Center) $\mathrm{x}_{AC}\ = \mathrm{c}_{ref}\left(\frac{\mathrm{x}_{ref}}{\mathrm{c}_{ref}} - \frac{\mathrm{d}\ \mathrm{C}_m}{d\ \mathrm{C}_L}\right)$ (given) From AVL $= 1.8\ \left(\frac{4.14}{1.8} - \frac{-1.4}{4.45}\right) = 4.706$

Dynamic assessment – Analytical

Figure 1

Eigenmode Stability Graph



All the modes are almost on the negative side of the graph shows the dynamic stability of all the modes the time it takes to get stabilize are mentioned below.

Table 3

Dynamic Stability Assessment

Modes	Time
Phugoid Mode	1085s
Short-Period Mode	10.8s
Spiral Mode	Unstable
Dutch Roll	20s
Roll–subsidence model	4s

Stability assessment comparison – analytical vs. numerical

The efficiency and x_{AC} can be seen higher for analytical value compared to numerical.

Results and Discussions

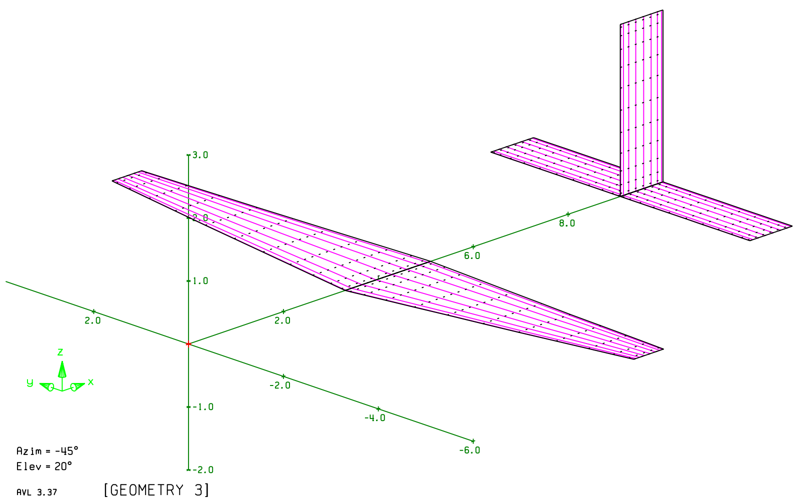
Table 4

Final Dimension of the Aircraft

Component	Dimension
Wingspan	11 m
Wing Area	19.35 m^2
Aspect ratio	6.25 m
Wing Chord	1.80 m
Fuselage Length	11 m
Horizontal Tail Chord	2.73 m
Vertical Tail Chord	1.56 m
Horizontal Tail Area	2.45 m^2
Vertical Tail Area	1.40 m^2

Figure 2

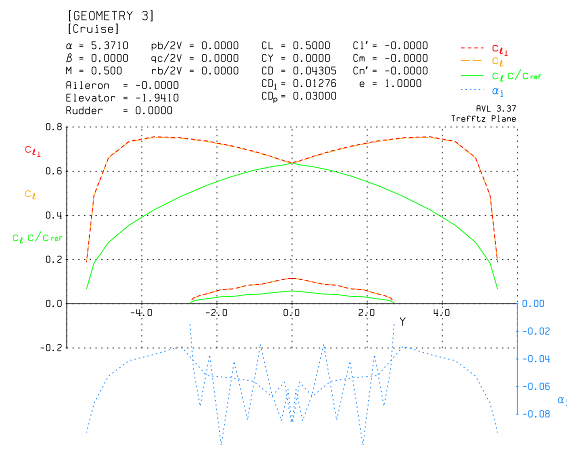
Final Geometry of the Aircraft



Figure

3

Reffz Plane Plot of the Final Aircraft



Using lifting line theory and various theories as explained above, a simple rectangular-shaped wing was built. After analyzing this first iteration, we found out that the efficiency very low, undesired stability derivatives and phugoid mode was taking longer time to converge. For that, we decided to taper the wing from the trailing edge as increasing tapering, brings lift distribution closest to elliptical lift distribution by reducing drag, increasing aspect ratio, reducing load effect in the tip. The result showed better lift distribution, efficiency increased, stability derivatives were showing more stable values. However, the phugoid mode was taking longer to converge. Therefore, 3rd iteration was conducted to improve the phugoid mode stability. It was improved by the concept of lowering the natural frequency by increasing the horizontal size. Furthermore, the tapering was done from both sides to increase the efficiency and have better stability of the aircraft. The aircraft performed exceptionally by 3rd iteration. This result fulfilled the design requirement and was stable in all the modes except spiral, which was not needed.

Conclusion

Overall, the project to learn about the AVL programming and the practical implementation of it. This project provided practical approach to understand the concept of static and dynamic stability of an aircraft. Static stability was obtained by achieving the Condition for static stability: $C_M = 0$, $\frac{\partial CM}{\partial \alpha} = C_{M\alpha} < 0$,

By understanding the concept of all five modes of oscillation and evaluating them in AVL eigenvalue stability graph, the dynamic stability was achieved. Jet trainer was selected, and the geometry was created in the AVL to get the best static and dynamically stable plane. Many iterations were performed by changing the geometry, mass and run file. It was found that the wing design closer to elliptical shape is more efficient and stable as well. The possibility of improving to construct elliptical wings, taper the tails, add dihedral and give the angle of incidence negative.

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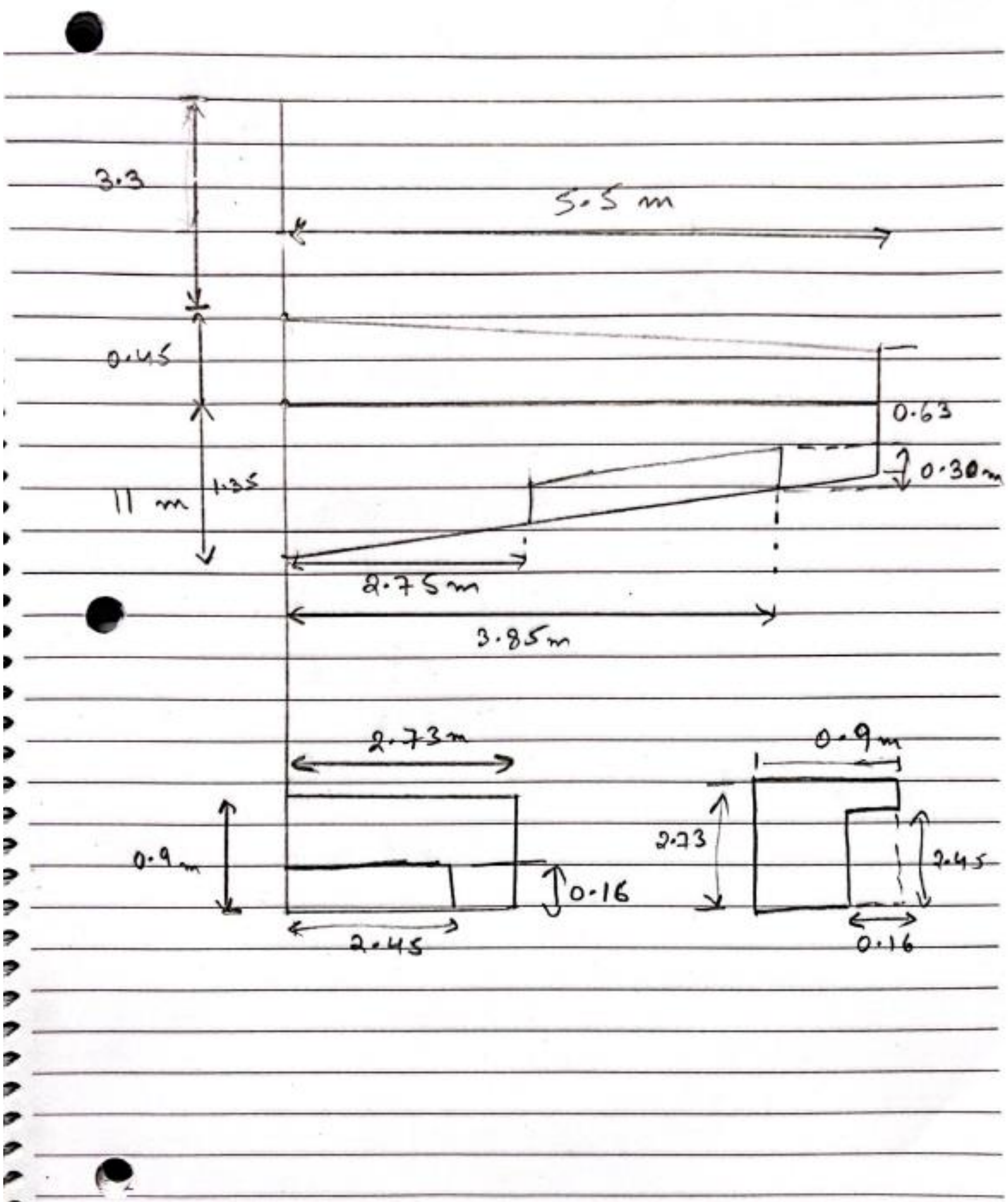
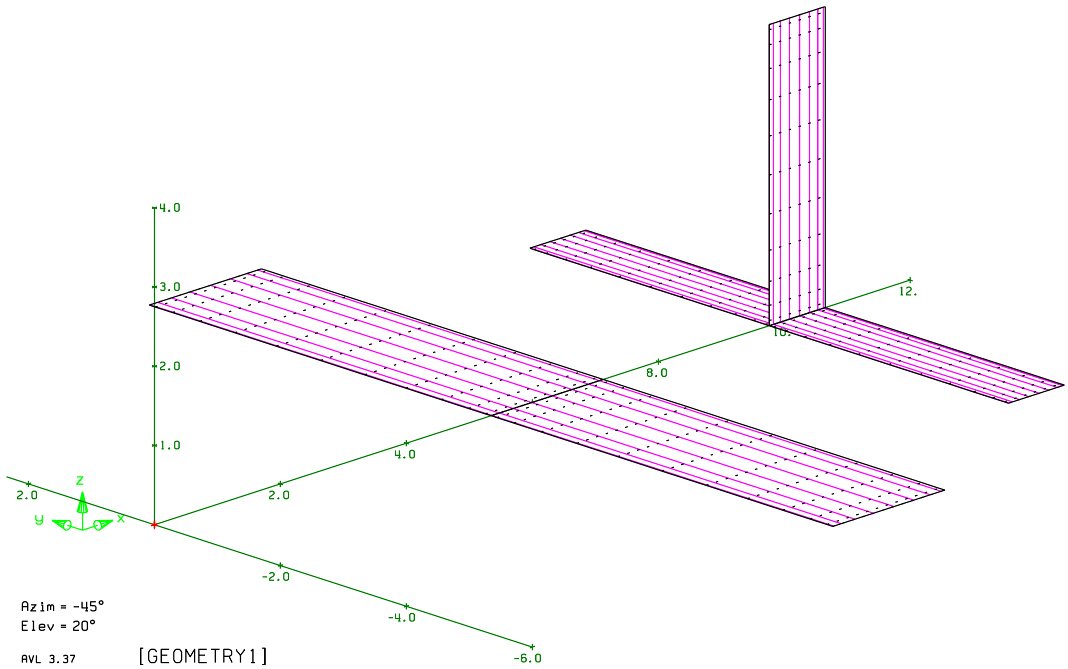
Appendices

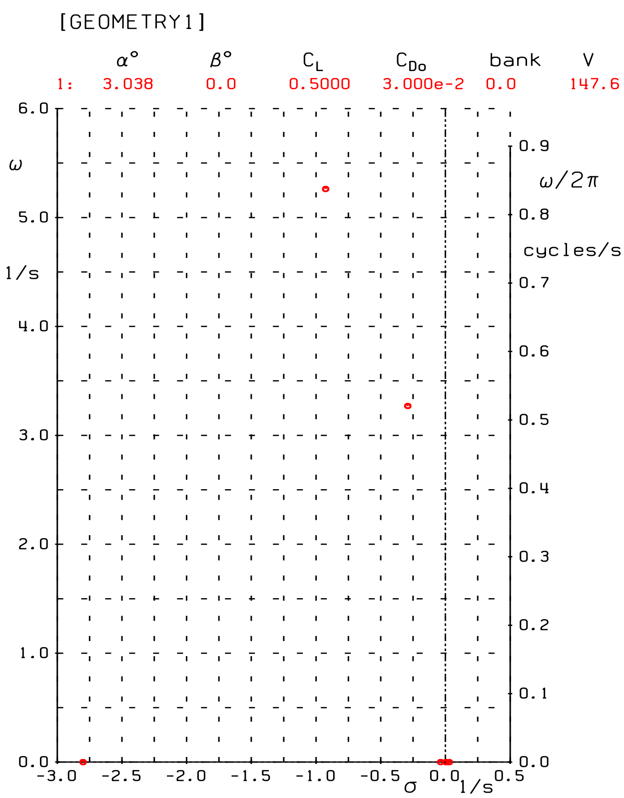
Appendix 1) Hand-sketch drawing of Aircraft Geometry



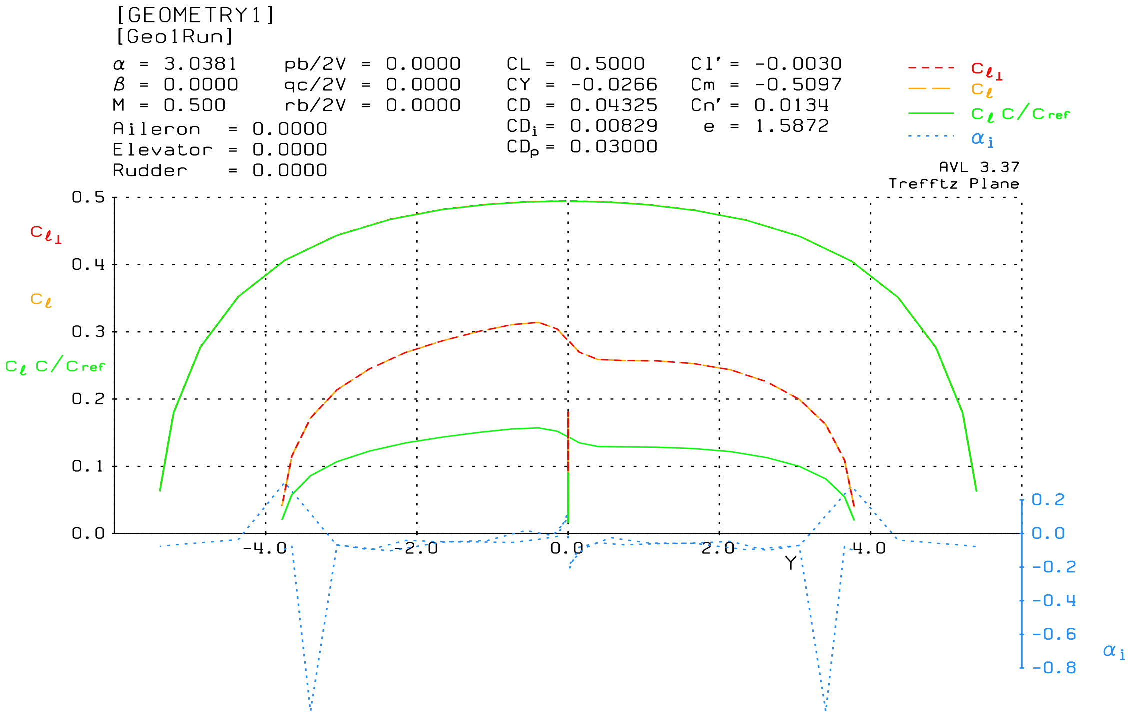
Appendix 2) Geometry 1 (Iteration 1)



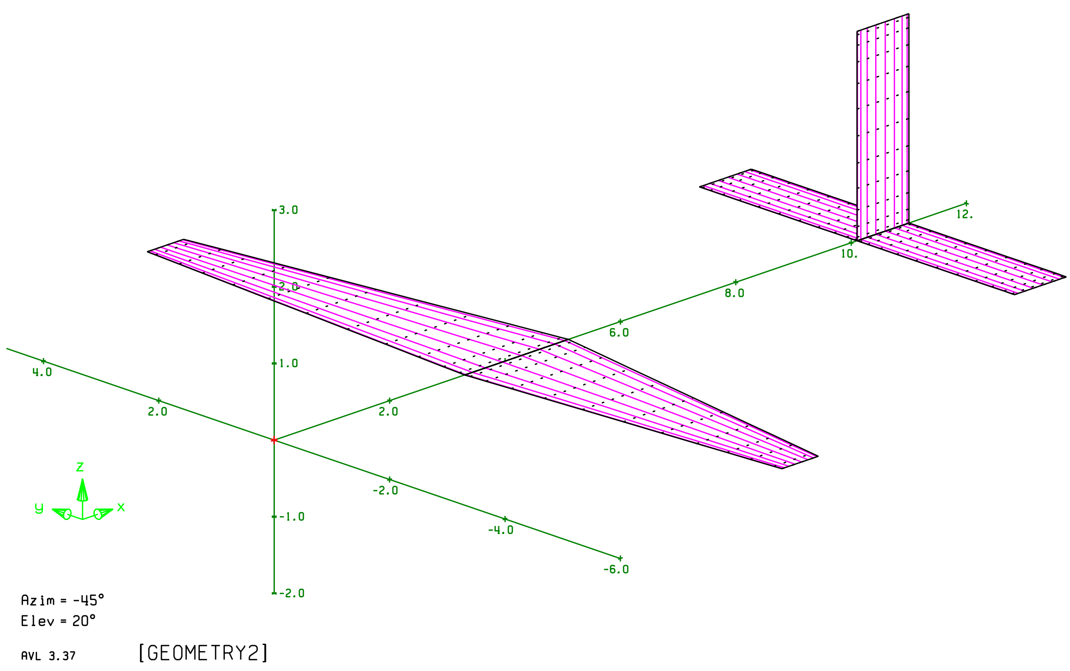
Appendix 3) Eigen Mode Stability Graph of Geometry 1



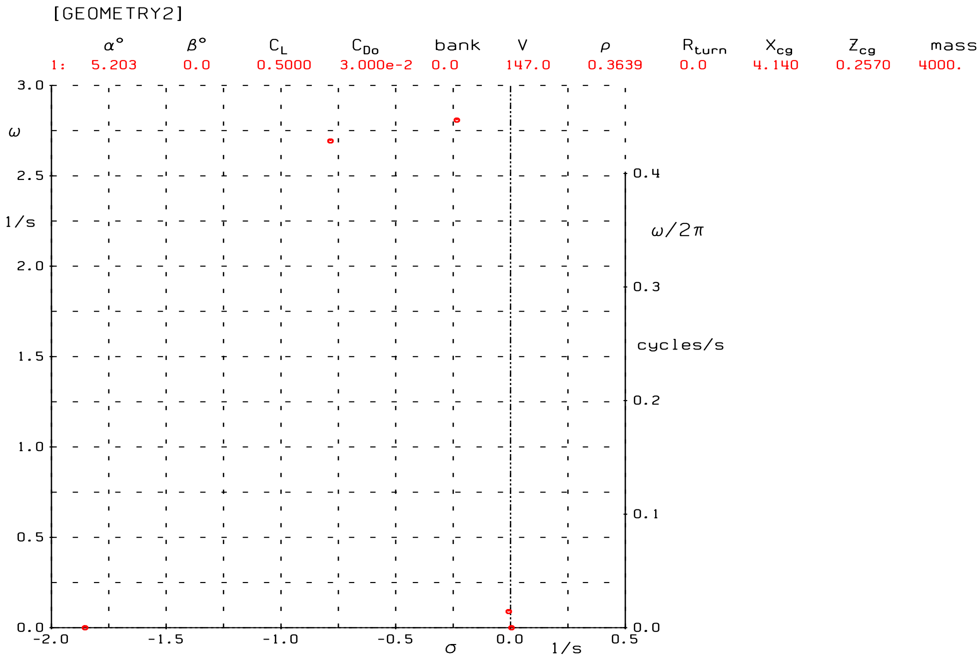
Appendix 4) Refftz Plane Plot of Geometry 1



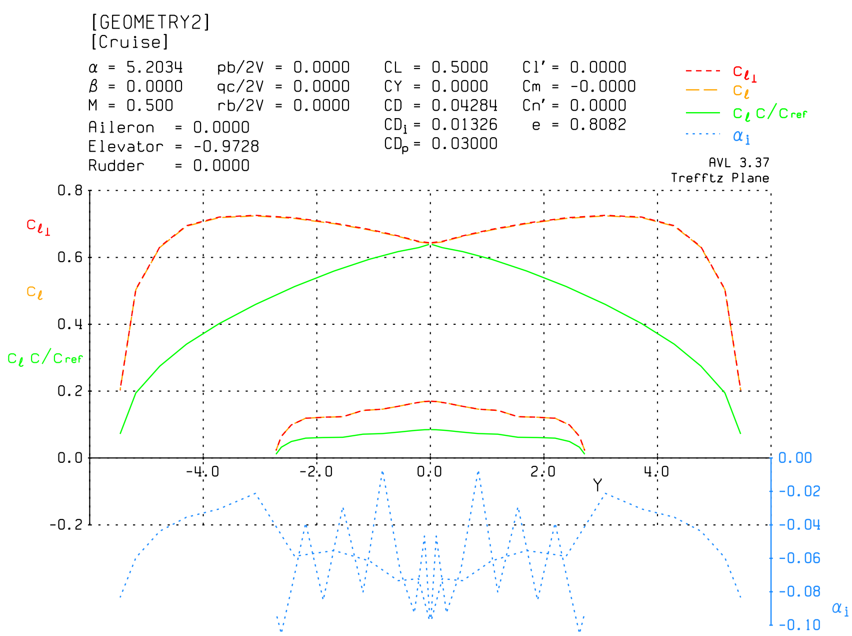
Appendix 5) Geometry 2 (Iteration 2)



Appendix 6) Eigen Mode Stability Graph of Geometry 2



Appendix 7) Refftz Plane Plot of Geometry 2



Appendix 9) Jet Trainer Aircraft Research

Plane Name	Dimensions	Images

DIAMOND – DA42-V	Length: 8.56 m Height : 2.49 m Wing Span: 13.55 m	
CIRRUS – SR20	Length: 7.92 m Height : 2.7 m Wing Span: 11.68 m	
CESSNA – SKYHAWK	Length: 8.28 m Height : 2.72 m Wing Span: 11 m	
PIPER – ARROW	Length: 7.5 m Height : 2.4 m Wing Span: 10.8 m