SOUTH DAKOTA MINES
Department of Mechanical Engineering

Fluids Poject

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Summary

In this project, we were tasked with determining the minimum length of a runway and the maximum thrust required for takeoff for a given airplane on an island (sea level). In order to determine this, the Coefficient of Drag (C_D) and Coefficient of Lift (C_L) need to be found for a given wing geometry. The values for the Coefficient of Lift and Drag for a Clark Y-14 Airfoil at different velocities and angles of attack (α) were determined using both a computational fluid dynamics (CFD) simulation and a wind tunnel experiment. This data was used to determine the minimum runway length and maximum thrust required for take-off. As a result, the minimum runway length, with a safety factor of 1.25, was determined to be 4640 m and the maximum thrust was determined to be 113 kN.

Introduction

A Clark Y-14 Airfoil is a standard airfoil that has been well-tested. We investigate the properties of this airfoil for educational advancements and validation of previous results. Using a subsonic wind tunnel and a test model for a Clark Y-14 Airfoil, the Coefficient of Lift and Coefficient of Drag were experimentally determined for different velocities and angles of attack. Each experiment was repeated twice to account for the statistical variances in the results. A CFD simulation was also used to determine the Coefficient of Lift and Coefficient of Drag values. The wind tunnel data was used to validate the CFD data. We will compare our airfoil data against literature data, such as the data repository on Airfoil Tools [1]. We apply this data to the case of a plane landing on an island where the parameters for the plane were given as follows: mass equal to 45,000 kg with a wingspan of 35m and an aspect ratio of 8. The Coefficient of Drag and Coefficient of Lift values were then used to determine the minimum required runway length for safe take-off and landing as well as the maximum thrust required for take-off. This investigation is vital to ensure safe runway construction.

Description of Apparatus

One method used to determine the Coefficient of Lift was pressure data from a wind tunnel experiment utilizing an AeroLab wind tunnel. The Clark Y-14 Airfoil was tested in the wind tunnel for velocities ranging from 40mph to 70mph. Pressure data was taken at angles of attack of 0°, 5°, 10°, 15°, and 20°. The pressure data was taken using 18 small orifices in the airfoil surface connected to an array of manometers. Height differences for each manometer were taken in reference to a manometer connected to the atmosphere. These height differences were used to determine the pressure profile around the airfoil.

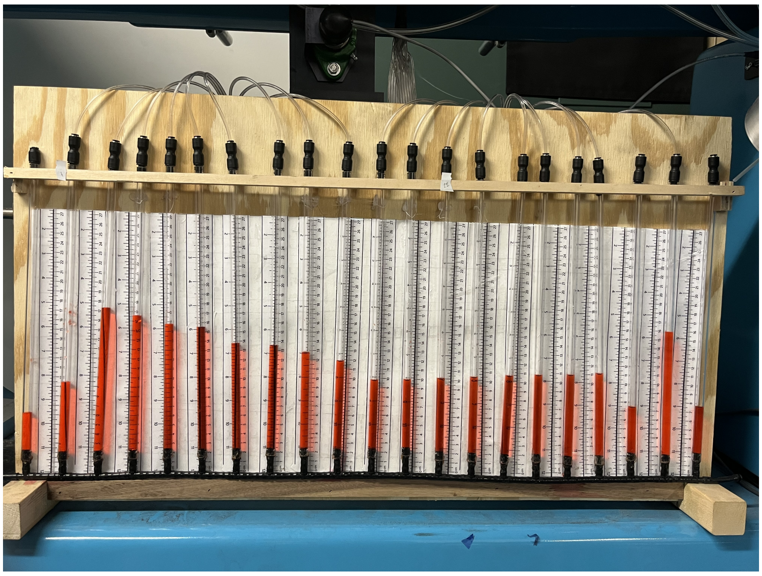

Figure 1: Sample image of the manometer array used to determine the pressure profile around the airfoil.

Description of Numerical Simulation

The CFD simulation was conducted under the assumption that the flow around the airfoil was laminar. Therefore, the K-epsilon Model in Ansys Fluent [2] was used to conduct this simulation. Because this simulation was 2-D, the edges of the geometry were selected to be boundary conditions. The top and bottom edges of the geometry were assigned "symmetry". The left edge was the inlet, the right edge was the outlet, and the airfoil itself was assigned "wall" (see Figure (2)). The mesh consisted of linear elements. As a result, the edges and the surface were assigned a mesh size of $5(10^{-3})$ft. At the boundary of the airfoil, the mesh size was $1(10^{-3})$ft (see Figure (3)).

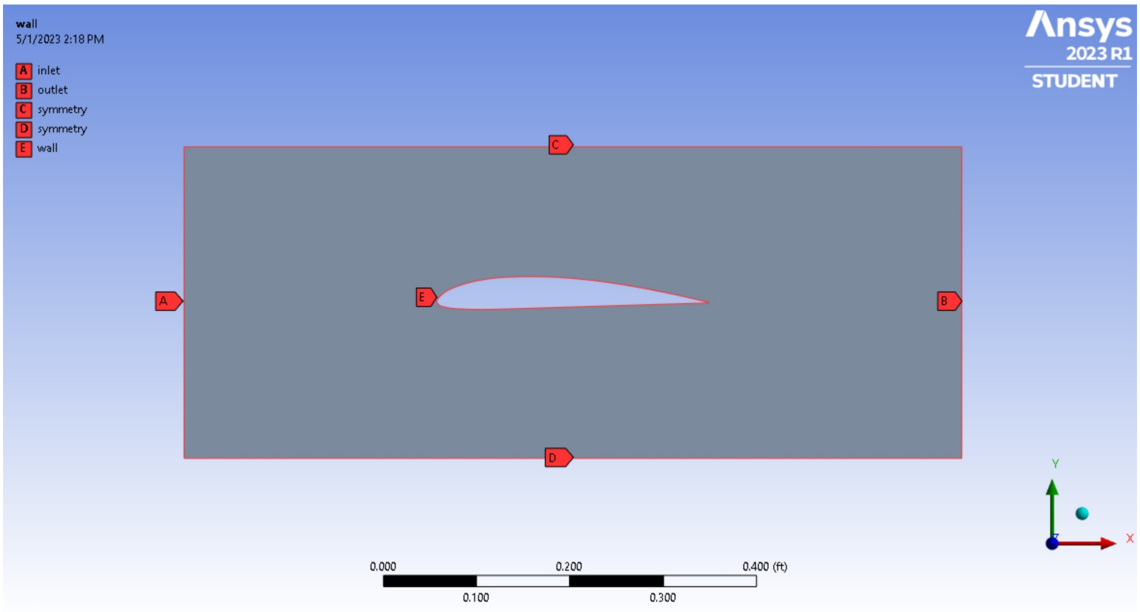

Figure 2: A figure of the Clark Y-14 Airfoil with the associated boundary conditions.

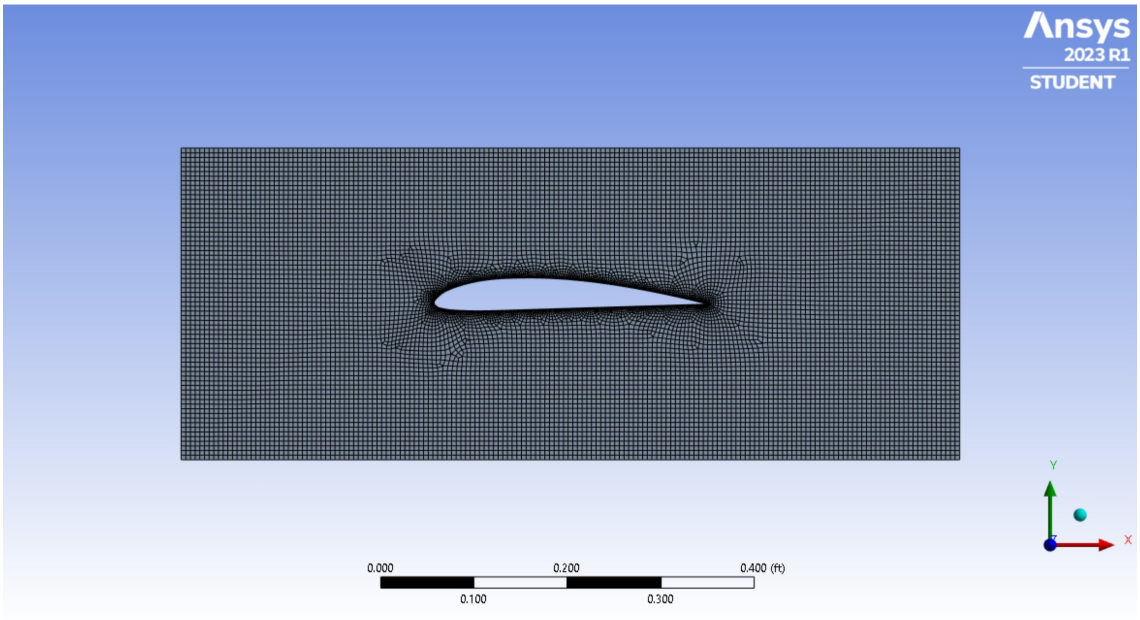

Figure 3: A figure of the mesh for the Clark Y-14 Airfoil.

Once the mesh was generated, the simulation solver was configured. A pressure-based, steady solver, using absolute velocity and planar 2D space was used in this simulation. As previously stated, the K-epsilon model was implemented in this simulation. Air was chosen as the working fluid. The inlet was defined as "velocity inlet" and the velocities were varied between 40 mph and 200 mph. The outlet was defined as a pressure-based outlet at 0 kPa. Under the Solution Methods tab, the Momentum, Turbulent Kinetic Energy, and Turbulent Dissipation Rate were all set to "Second Order Upwind." The pseudo-time method was set to Global Time Step. The simulation was initialized with a standard initialization. Lastly, the number of iterations was set to 500.

Results

Project Objective 1

Data from the wind tunnel experiment was recorded by nine different groups. Each group measured the manometer water height with respect to the atmospheric manometer for two velocities at different angles of attack. Each measurement was repeated by at least two groups. The data was combined into a single file and converted into meters and results for the same experimental conditions were averaged together.

Using the Julia Programming Language [3], an algorithm was written to integrate the pressure with respect to the horizontal distance between ports. This produced the force per unit length of the wing. The ports did not reach to the end of the airfoil so the pressures at the endpoints were estimated using linear extrapolation. Since the experimental data is discrete, the trapezoid rule, Equation (1), was used to numerically approximate this integral. Using the sum of the force on the top and bottom of the airfoil, the net force normal to the top of the airfoil per unit length was determined. Then, using the angle of attack, the force vector was projected onto the vertical axis to determine the lift force.

$$\sum_{n=1}^{n_p} \frac{1}{2}(y(x_{n+1}) + y(x_n))(x_{n+1} - x_n) \tag{1}$$

Since density, velocity, planform area, and the lift force were then known, the coefficient of lift can be found using the following:

$$C_L = \frac{2F_L}{\rho g V^2 A} \tag{2}$$

The Coefficients of Lift calculated from the wind tunnel experiment were plotted over the CFD data for Reynolds numbers of 1.09×10^5 and 1.77×10^5 in Figure (4). The plot of Coefficient of Lift vs the angle of attack for the wind tunnel data is shown in Figure (5). The plots for C_L vs. α, C_D vs. α, $\frac{C_L}{C_D}$ vs. α, and C_L vs. C_D are show in Figures (6), (7), (8), and (9).

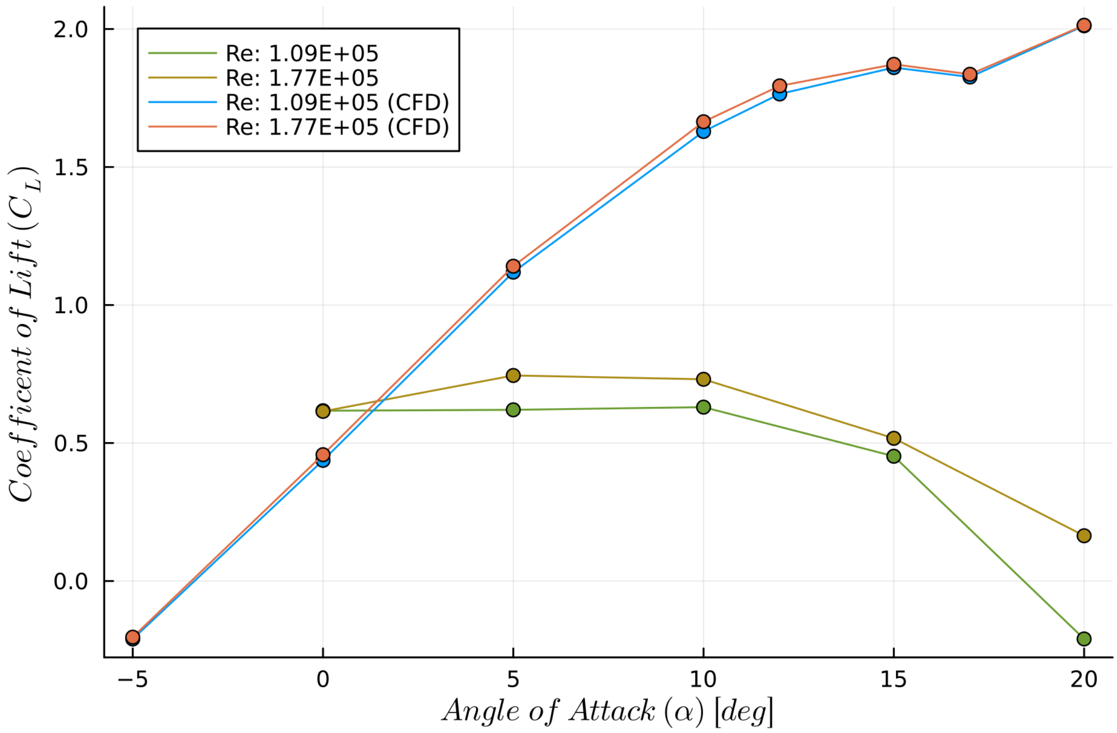

Figure 4: Plot of Coefficient of Lift vs. α data from the wind tunnel experiment and CFD for Reynolds numbers of 1.09E5 and 1.77E5.

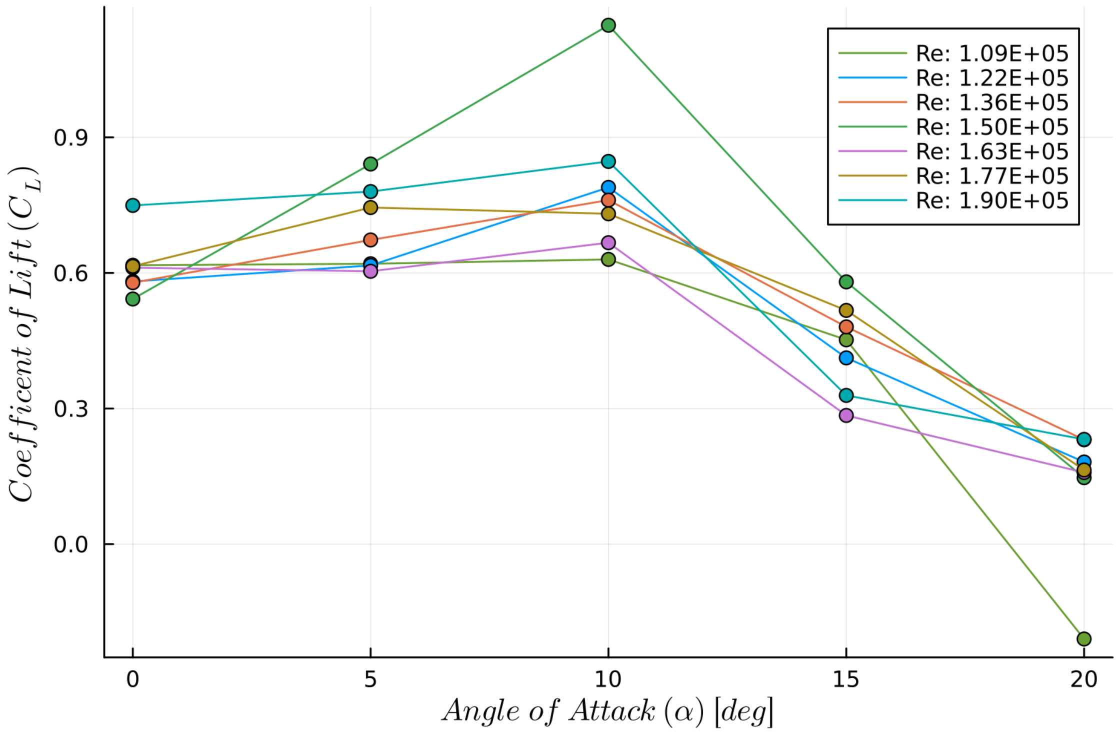

Figure 5: Plot of C_L vs. α data from the wind tunnel experiment.

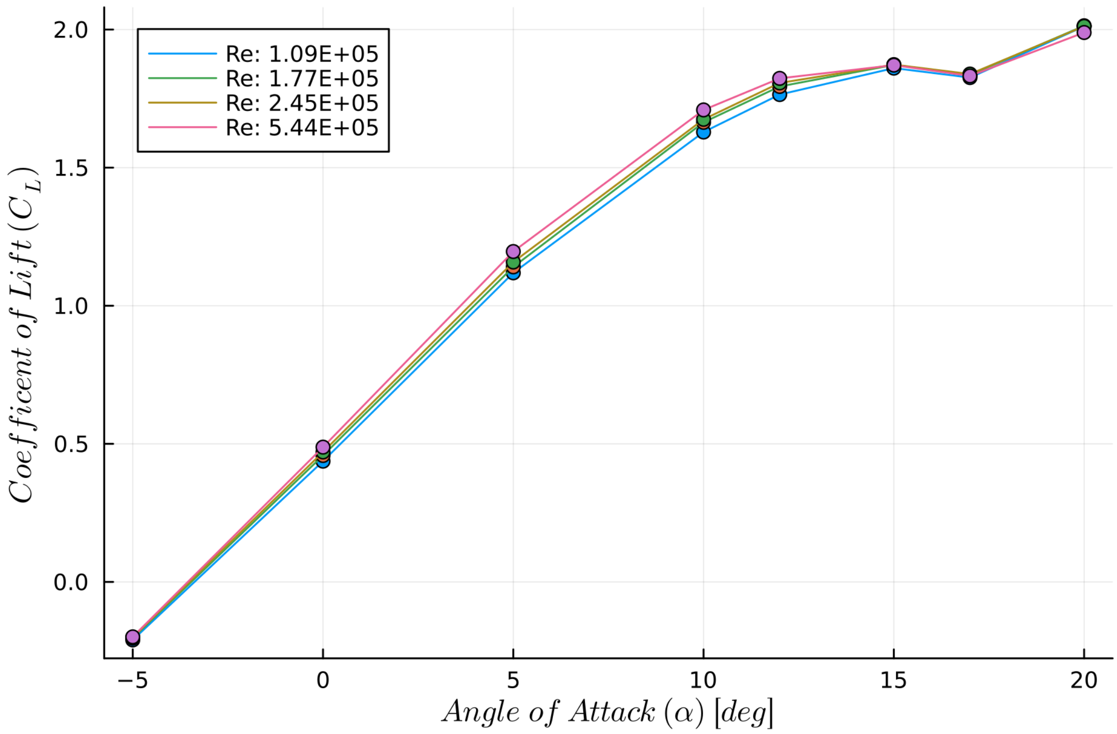

Figure 6: Plot of C_L vs. α data from the CFD simulation.

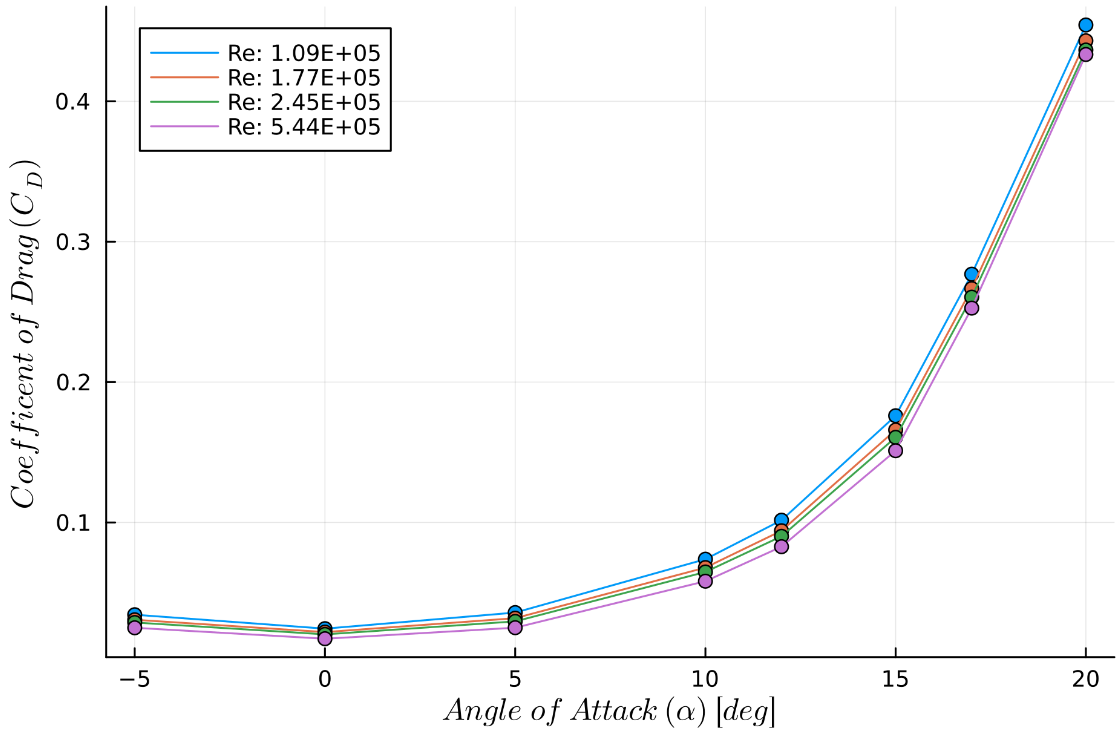

Figure 7: Plot of C_D vs. α data from the CFD simulation.

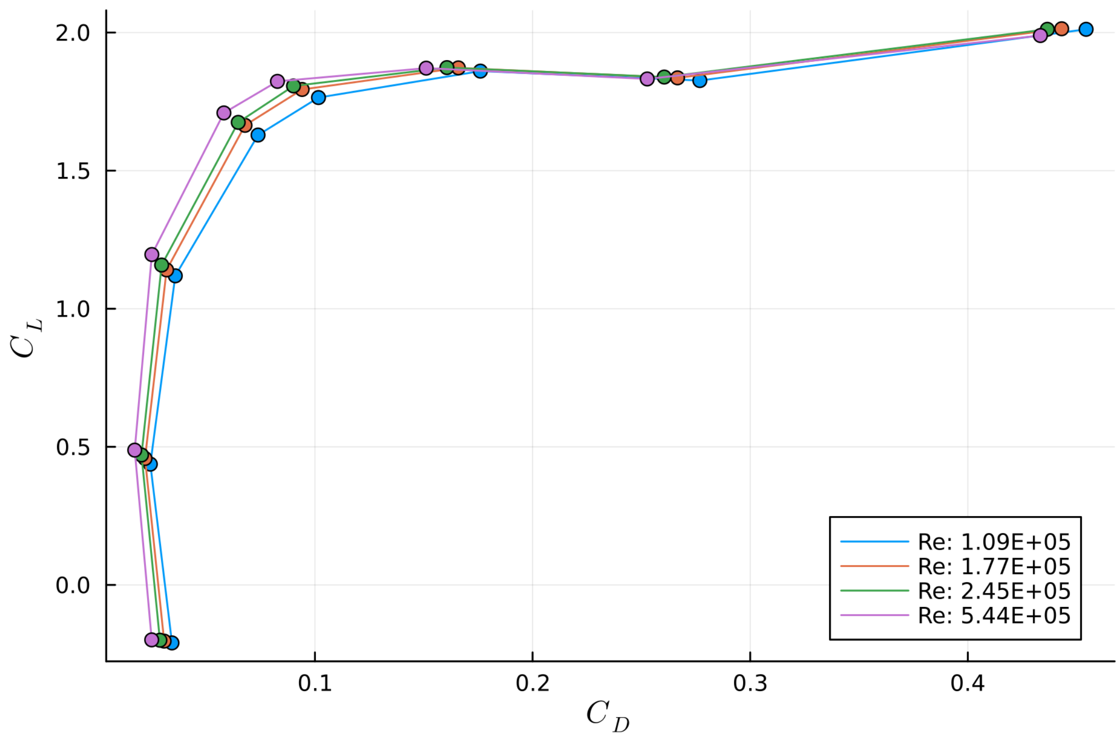

Figure 8: Plot of $\frac{C_L}{C_D}$ vs. α data from the CFD simulation.

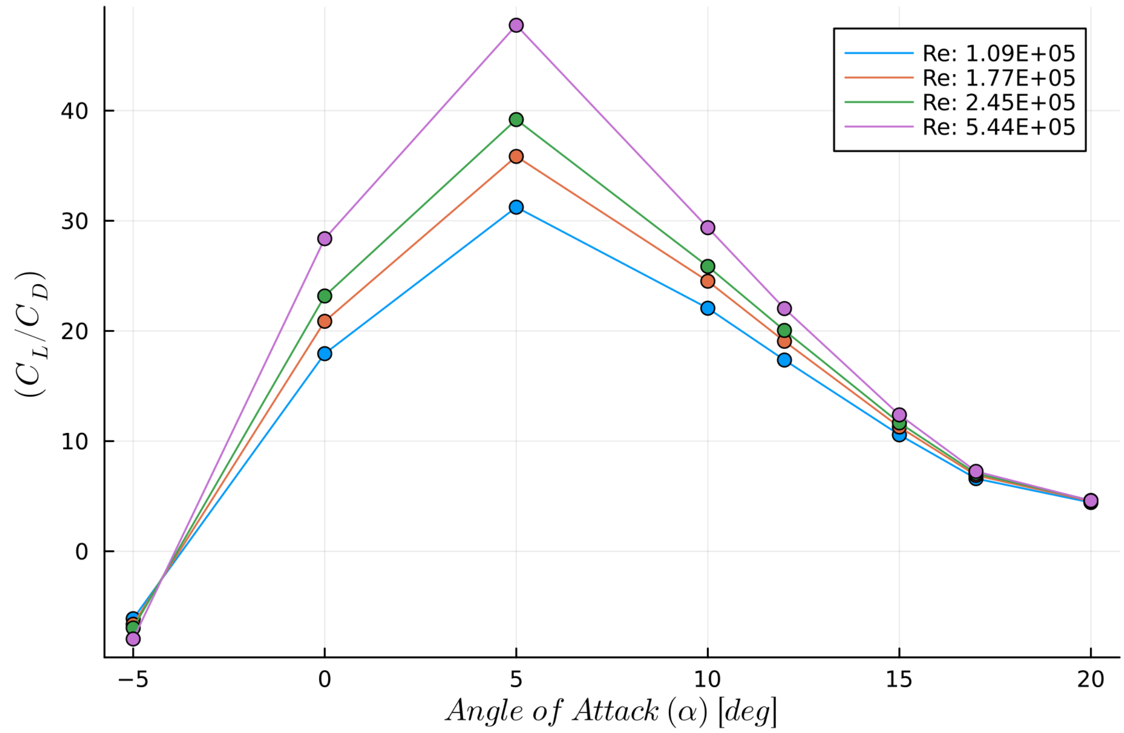

Figure 9: Plot of C_L vs. C_D data from the CFD simulation.

Project Objective 2

In order to determine the minimum runway distance required for the airplane to safely takeoff and land, the distance required for landing was calculated and compared with the minimum distance for take off. This system in the liftoff case can be seen in the following Free Body Diagram:

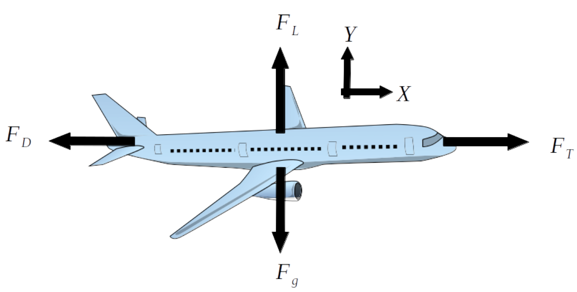

Figure 10: Free Body Diagram of the plane during liftoff.

To calculate the liftoff distance, the forces in the y-direction, as seen in Figure (10), were equated:

$$F_L = mg \tag{3}$$

Substituting Equation (4) into Equation (3) and solving for velocity results in the following:

$$F_L = \frac{1}{2} C_L \rho g V^2 A \tag{4}$$

$$V = \sqrt{\frac{2mg}{C_L \rho A}} \tag{5}$$

Because velocity and the Coefficient of Lift are dependent on each other, a recursive algorithm was used to find the velocity at which the wheels lift off of the ground. This algorithm was executed as follows: given an α, pick a C_L. Find the velocity, V_{guess}, associated with this C_L. Substitute C_L into Equation (5) and return V_{check}. If $V_{check} = V_{guess}$, return V_{guess}, C_L, and C_D. If $V_{check} \neq V_{guess}$, pick a new C_L and restart the loop. In the case that none of the values for C_L and V_{guess} meet the return condition, use linear interpolation to find C_L, V_{guess}, and C_D in between the CFD values.

Once C_D and V_L were found, we can create another Free Body Diagram considering the landing case.

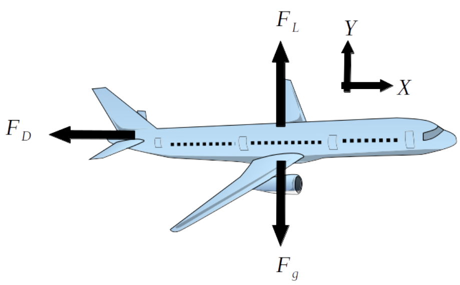

Figure 11: Free Body Diagram of the plane during landing.

The forces in the x-direction as seen in Figure (11) were summed as follows:

$$F_D = ma_x \tag{6}$$

Substituting $\frac{1}{2} C_D \rho V^2 A$ for F_D and solving for a_x yields:

$$a_x = \frac{C_D \rho V^2 A}{2m}. \tag{7}$$

Assuming that the drag force is constant during the whole landing, constant acceleration kinematic equations may be used.

$$t = \frac{V_f - V_i}{a_x}. \tag{8}$$

Once the time it takes to land is calculated, Δx can be found:

$$\Delta x = V_i t + \frac{1}{2} a t^2 v \tag{9}$$

In order to verify that the airplane can take off within this distance, the following calculations were done. First, the algorithm outlined above was used to find $C_{L,max}$, V_{guess}, and C_D. Using C_D, F_D was solved for. Assuming it takes 30s to take off, a_x was as follows:

$$a_x = v_f / t \tag{10}$$

The distance required for take off was found using Equation (9). Lastly, summing the forces in the x-direction and solving for thrust yields:

$$F_t = m a_x + F_D \tag{11}$$

Upon the completion of this process, we determined that the minimum runway length, with a safety factor of 1.25 applied, is 4640 m and the maximum thrust is 113 kN.

Discussion

The wind tunnel and CFD data were similar in terms of the trends that they showed. The obsereved discrepancies can be attributed to many disperate factors. For example, it is possible that some groups may have misinterpreted their manometer readings and provided inaccurate data. Also, the wind tunnel data may be inconsistent because the data points had to be interpolated due to some manometer ports being incorrectly configured. Finally, error also resulted from the inability of the manometer to capture the effects of shear forces on the wind tunnel model. The Coefficient of Lift vs. α plot shows that the angle with the maximum Coefficient of Lift is 10° for the wind tunnel and 15° for the CFD. These values for α seem reasonable when compared with other airfoils. For example, the Clark Y airfoil has its maximum coefficient of lift at the α of 15° [1].

The maximum thrust and minimum runway length results seem reasonable, given the assumptions, when compared with real-world examples. The Fokker 100 is similar in size to the one analyzed in the project, with a maximum takeoff mass of 45, 810 kg, a wingspan of 28.1 m, and a wing area of 93.5 m^2. The calculated maximum takeoff thrust was 112 kN, whereas the thrust of the Fokker 100 engines can produce is 134 kN. The calculated minimum runway length was 4640m and the runway length for the Fokker 100 is $1,350$ m [4]. Considering that these two planes are not identical, this error is within the bounds of reason. The error could also stem from all the assumptions and simplifications that were made. For example, one assumption is that the deceleration when landing is only affected by drag and is assumed to be constant. This assumption was used to simplify calculations and does not accurately represent what would happen in reality. Another simplification that does not reflect reality would be the Coefficient of Lift and the Coefficient of Drag being constant. These Coefficients would change as a function of the velocity. Finally, the plane is not utilizing landing gear brakes or brake flaps which would significantly impact the force of drag. This no doubt results in a longer runway. With this in mind, this project provides an initial approximation for a potential runway design.

Acknowledgements

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References

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