Extended Essay

Physics

Topic:

Aerodynamics

Research question:

How does the shape of an airfoil affect Drag / Lift coefficients in aerodynamic performance, as observed in a wind tunnel experiment?

Word Count: 3474

Contents

1. Introduction

My interest in airfoil design started on a family trip on a plane, where I observed how the wings negotiated through air. The curiosity for understanding the science of flight and how wing shapes affect the lift and movement of an aircraft really developed at that time.

Airfoils are designed to handle lift, that pushes the plane up, and drag, which holds it back. The shape, thickness, and curve of an airfoil influence these forces. For example, curved airfoils speed up airflow over the top, reducing pressure and allowing higher pressure below to lift the wing. This is how the mechanics of flight work and is well-documented in studies about aeronautics. NASA[1] published research on the dynamics of air pressure.

For this extended essay, I will be exploring the research question: How does the shape of an airfoil affect Drag/Lift coefficients in aerodynamic performance, as observed in a wind tunnel experiment? I can control airflow in a wind tunnel to accurately measure how the different shapes of an airfoil affect drag and lift, and thus pinpoint the design features that enhance aerodynamic efficiency. I would like to try out various airfoil (with different shapes) to identify optimal shapes for balancing lift and drag.

The importance of this research pertains to the enhancement of aviation efficiency through better-designed airfoils, which improve aircraft performance, save fuel, and reduce environmental impacts. My project connects my childhood fascination to become an astronaut one day, aiming to uncover airfoil designs that optimally help aviation

2.Theoretical Background

2.1 Airfoil Geometry and Aerodynamic Forces

The aerodynamic performance of an airfoil depends upon many factors, the most important being curvature, shape and thickness. Thickness, curvature etc impact airflow pattern impacting pressure on surface and thus creating lift. In an aircraft, air flows faster over the top part of the wing than under the bottom surface, therefore leading to a lift. Shape of the airfoil determines the resistance offered to air by the object and thus the drag coefficient. Thickness of the airfoil can impact flow separation impacting lift and drag. Having an optimized airfoil design balances various factors to maximize efficiency across various conditions. This was highlighted in various studies for example - Virginia Tech Stability Wind Tunnel[2].

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[1]**NASA Glenn Research Center.** (n.d.). *Beginners Guide to Aeronautics: What is Lift?* Retrieved from https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/what-is-lift/

[2]**Kuester, M. S., Brown, K., Meyers, T., Intaratep, N., Borgoltz, A., & Devenport, W. J.** (2015). Wind tunnel testing of airfoils for wind turbine applications. *Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA*.

2.2 Drag/lift Coefficients

Drag/lift are quantified by coefficients, C_L (lift coefficient) and C_D (drag coefficient), Lift force L generated by an airfoil is given by:

Equation 1: Lift Force

$$L = C_L \cdot \frac{1}{2}\rho V^2 S$$

where:

- C_L is the lift coefficient,
- ρ is the air density,
- V is the velocity of the oncoming flow, and
- S is the surface area of the airfoil.

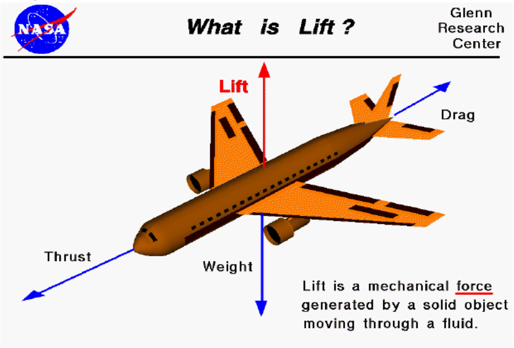
The drag force D is similarly calculated:

Equation 2: Drag Force

$$D = C_D \cdot \frac{1}{2}\rho V^2 S$$

Both lift (CL) and drag (CD) coefficients are influenced by the airfoil's shape, angle of attack, and Reynolds number. Wind tunnel tests[3] reveal that even slight changes in angle of attack significantly alter CL by shifting the flow separation point, which impacts the airfoil's aerodynamic efficiency.

Figure1: Visualization of the forces on an airplane



Source: https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/lift1.html

2.3 Angle of Attack and Flow Behavior

The angle of attack (α)—the angle between an airfoil's chord line (straight line which connects front and rear end of the airfoil) and the airflow—is key for lift generation. At low angles, airflow smoothly follows the airfoil, maximizing lift and minimizing drag. As α increases, lift also rises until it reaches a critical point where airflow separates, causing a stall that sharply reduces lift and increases drag. It varies with experimental setup but generally in range of 15 to 20 degrees.

Wind tunnel experiments[3] confirm that the lift curve and maximum CL are highly sensitive to α adjustments, underscoring their importance for optimal aerodynamic performance.

2.4 Wind Tunnel Testing for Airfoil Performance Evaluation

Wind tunnel testing evaluates airfoil designs by measuring drag and lift in controlled conditions, like those seen with the DU96-W-180 model in the Virginia Tech Stability Wind Tunnel. Key findings indicate that surface roughness significantly affects aerodynamic performance, with minor surface defects increasing drag and reducing lift by disrupting airflow.

2.5 Reynolds Number and Flow Characteristics

Reynolds number (Re), defined as

Equation3: Renolds number

$Re=(\rho * V * l)/\mu$

Where:

ρ is fluid density,

V is flow velocity,

l is a characteristic length (such as chord length of the airfoil),

and μ is dynamic viscosity,

Reynolds number indicates the nature of flow around an airfoil—whether it is laminar or turbulent. Higher Reynolds numbers typically induce turbulent flow, affecting drag and lift by changing boundary layer characteristics; wind tunnel studies show this can increase maximum lift coefficients and delay stall, enhancing lift at the possible expense of increased drag.

2.6 Practical Implications of Optimizing Airfoil Design

Optimal airfoil shape is very important in practical situation as it helps to ensure higher efficiency for example in aviation, wind turbines, racing cars etc. Optimal design can help in reducing environmental impacts. Wind tunnel tests help us to refine designs to provide suitable characteristics like high lift with low drag. This study validates theoretical drag/lift models by testing various airfoil shapes, providing data to enhance future aerodynamic designs.

3.Experimental Design

The experimental framework discusses the impact of airfoil shape etc affects its aerodynamic characteristics especially focusing on the coefficients of drag and lift

3.1 Hypothesis: Shape of an airfoil significantly influences its drag and lift coefficients, especially at higher angles of attack due to changes in the boundary layer and increased surface area.

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[3]**Ghosh, P., Dewangan, A. K., Mitra, P., & Rout, A. K.** (2014). Experimental study of Aero Foil with Wind Tunnel Setup. *School of Mechanical Engineering, KIIT University, Bhubaneswar, Odisha-24*

3.2 Alternative Hypothesis: Shape of an airfoil does not significantly influence its drag and lift coefficients.

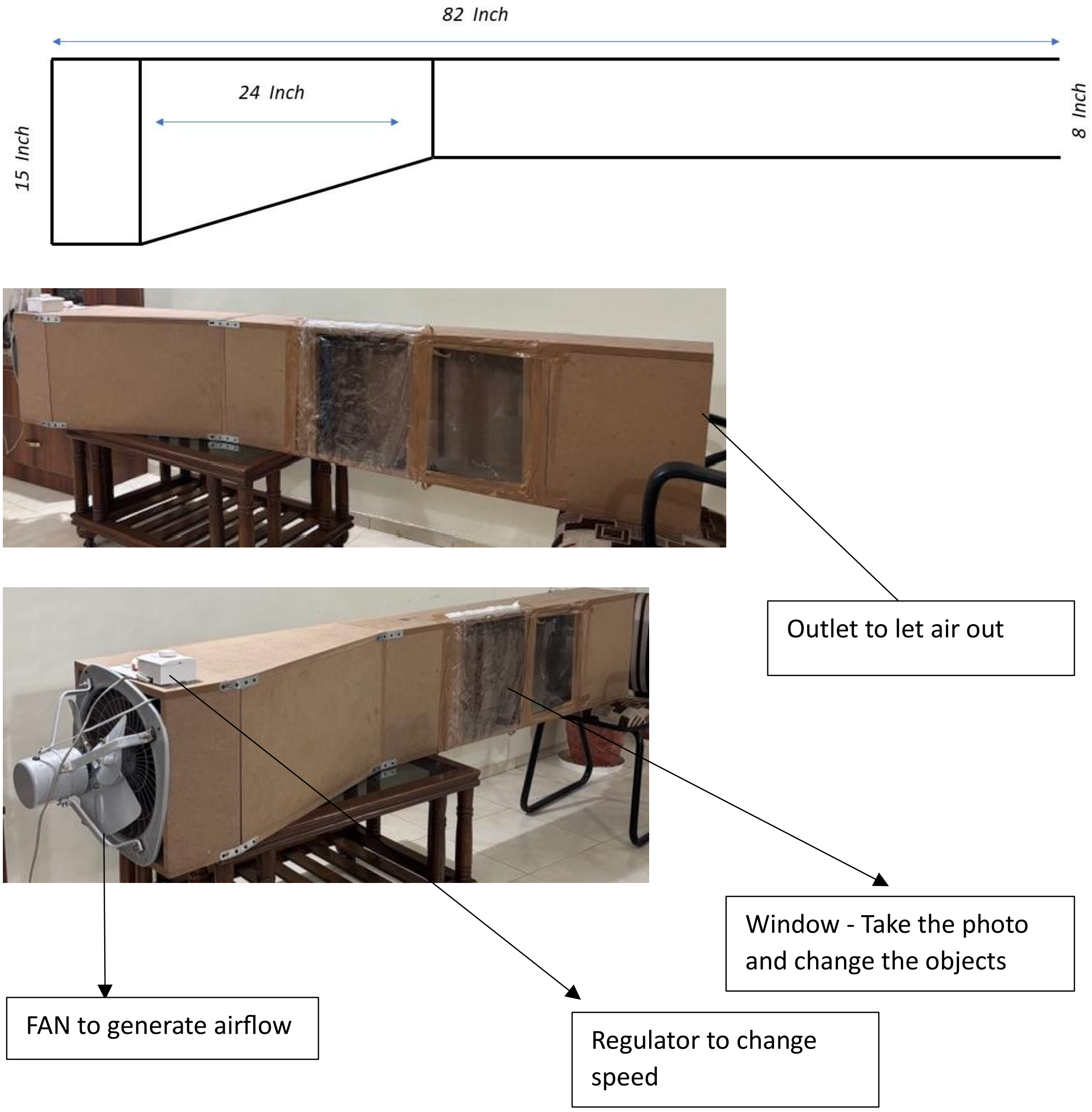
3.3 Materials Required for the Experiment:

Experiment required lot of different kind of materials mainly involving the construction of a wind tunnel. The wind tunnel was designed using online references ([1,4]), with various adjustments made during the experiment to ensure accurate readings. The essential materials included:

1. Wind tunnel
2. Manometer: a device that measures the pressure of a medium
3. Anemometer: an instrument that measures wind speed
4. Camera: for taking photographs
5. Protractor: for measuring angles
6. Weighing scale: highly precise, accurate to two significant digits

3.4 Wind Tunnel Design

Figure 2: Drawings and pictures of the wind tunnel set-up (front-view)



Exact wind tunnel dimensions were mostly based on (https://www.instructables.com/How-to-make-a-wind-tunnel/), with adjustments done to fit the structure at home

Figure 3: Equipment's Pictures

Manometer

Anemometer

Weighing Scale

3.5 Procedure for Wind Tunnel Testing of Airfoils:

1. **Wind Tunnel Setup:**
   - **Design and Assembly:** Initially, the wind tunnel was designed by referencing various models and then constructed with the assistance of a carpenter.
   - **Modifications:** Throughout the experiments, various modifications were made to ensure accurate measurements. These included replacing the fan to achieve higher airflow speeds. The original fan was not sufficient, necessitating an upgrade for better performance.
   - **Window Installation:** Initially, a glass window was used, which caused reflections that interfered with measurement accuracy. It was replaced with a plastic sheet to reduce reflection and improve visibility and measurement accuracy.
2. **Airfoil Models (objects):**
   - Different airfoil models were utilized, each with varying designs and weights, to analyze their aerodynamic properties. These included:
     - A circular sheet.
     - A knife holder modified to mimic the shape of aircraft wings for simulation purposes.

Objects

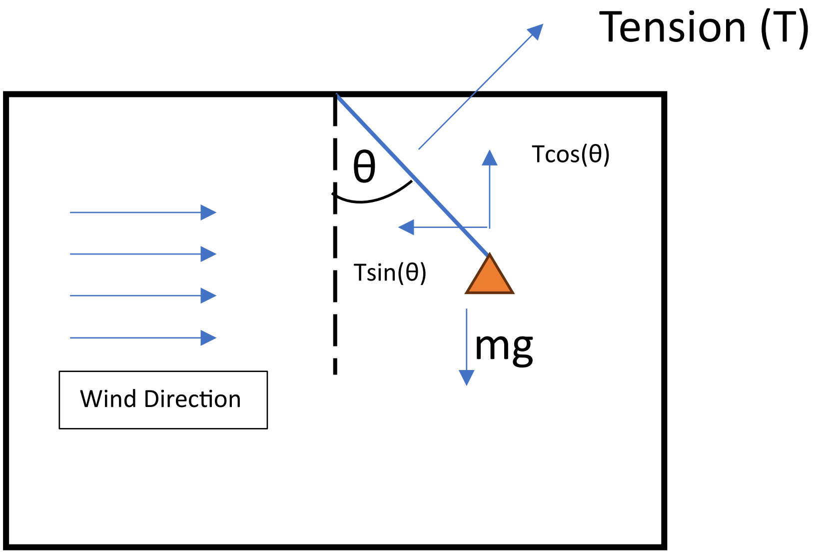
1. Round Object (Circular Disk – 15 cm diameter)
2. Round Object + Weight (Circular Disk – 15 cm diameter)
3. Knife holder to simulate wing (length approx. and max width)

Figure 4: Different airfoil models (objects)

3. **Speed of Wind:**
   - An anemometer was used to measure the airflow speed at the exact location where the airfoil models were positioned, ensuring that the speed readings were accurate for the experimental setup.
4. **Measurement of Aerodynamic Forces:**
   - **Objective:** The primary goal was to measure the velocity and pressure exerted on the airfoil. Direct pressure measurement proved challenging given sensitivity of manometer, so an alternative approach was employed.
   - **Tension Measurement:** The airfoil was suspended using thin wires or strings. As the wind applied force to the airfoil, the resulting tension in the string was measured. This tension correlates with the drag force exerted by the airflow against the airfoil, allowing for indirect assessment of aerodynamic forces.

This procedure outlines the systematic steps taken to set up and conduct aerodynamic testing of airfoils in a wind tunnel, focusing on accurate measurement and analysis of the effects of different airfoil shapes under controlled airflow conditions.

Figure 5: Forces description on an object suspended in a wind-tunnel



- Attach the plane / object to a thin, lightweight string, and suspend it in the center of the wind tunnel.
- Ensure that the string is long enough to allow free movement but short enough to avoid excessive swinging.
- When the airflow is turned on, the drag will cause the string to tilt backward at an angle due to the drag force acting horizontally.
- Measure the Angle- Measure the angle θ, between the string and the vertical when the airflow is applied

Trigonometric Force Balance: T

There are two forces acting on the toy plane:

- Weight of the plane pulling it vertically downward.
- Drag force pulling it horizontally due to the airflow.

Tension T balances the weight of the toy plane (W=mg), and the horizontal component is equal to the drag force F_d

Equation4: Equations – derivations of Drag and Lift Coefficients

- $T*\cos(\theta)=W=mg$
- $T*\sin(\theta)=F_d$
- $F_d=W*\tan(\theta)=mg*\tan(\theta)$

m is the mass of the airfoil.

g is the acceleration due to gravity (approximately 9.81 m/s)

θ is the angle between the string and the vertical

Similarly lift force can be measured

Using the vertical force balance equation:

$F_L = W – T\cos(\theta)$

Given T is not directly measured, T = $\sqrt{F_d^2 + W^2}$

Theoretically once, F_d & F_L is calculated, one can calculate Drag & Lift coefficients

- **Drag Coefficient (CD):** Using the formula $C_d = \frac{D}{\frac{1}{2}\rho v^2 S}$, where D is the drag force.
- **Lift Coefficient (CL):** Using the formula $C_l = \frac{L}{\frac{1}{2}\rho v^2 S}$, where L is the lift force and S is the reference area of the airfoil.

4.Risk Assessment

To minimize risks during the experiment, we implemented several safety measures:

1. **Electrical Safety**: A qualified electrician installed and insulated the motors and wiring. Participants also wore rubber shoes to prevent electrical shocks.
2. **Mechanical Stability**: The wind tunnel was made of solid hardboard and placed in a fixed and stable position so that it does not move at all to ensure that the experiment is sound. We tied the airfoil with a string inside the tunnel so that it will not be detached during the high airflow thus avoiding measuring error or mishap during measurement.
3. **Accuracy of Measurements**: We ensured that the object and the string were precisely aligned so that no potential measurement error would be there. We also checked that there were no disturbances due to airflow or any obstructions within the tunnel as such disturbances may cause turbulence and negatively affect the precision of data collected.

5.Key Assumptions

- The tension in the string may not perfectly reflect the aerodynamic forces acting on the objects since various other factors influence how the string operates.
- The impact of rigidity on string computation is that it has almost negligible effects without any change in the results of computation.
- The friction within the suspension setup, for example at contact points, is considered to be negligible and not contribute to a meaningful degree to measurements. Any friction that has not been accounted for may, however, result in an overestimation drag forces on the airfoil and possibly skewing results.

6.Trials

6.1 Preliminary Trials

Many experiments were held to determine the drag coefficient and for this the pressure applied on the object needed to be ascertained first. A manometer was fitted at the base of the wind tunnel for achieving this purpose at first, which failed to work. Even when the fan is replaced to speed up the wind flow, there was no increase in pressure even when detected through the manometer. Given the difficulties and the fact that pressure measurement accuracy was required, it was quite evident that the direction taken required a change. We defined our assumptions and changed the methods accordingly, as noted earlier.

Figure 5: Pictures of original equipment

Original FAN ***Manometer***

6.2 Aerodynamic Analysis of Airfoil Performance

- Drag/Lift Coefficients: Compared drag and lift coefficients across various airfoil shapes at different speed. This analysis helps us understand the relationship between the shape of an airfoil and its aerodynamic performance.
- Performance at Critical Angle of Attack (AoA): We studied how the shape of an airfoil influences stall behavior by observing changes in lift and increases in drag at critical angles of attack.

7.Final Trials

7.1 Experimental Setup and Data Collection Methodology

- **Weight Measurement**: Accurately measured the weight of each object with a precise scale.
- **Velocity Testing**: Using an anemometer, recorded the velocity at four distinct speeds changed by fan regulator.
- **Object Testing**: Suspended the first object and incrementally increased the speed of wind from the lowest setting. We took photos from a fixed position (perpendicular to window) once the object reached a stable state at each speed to document the angle of the object with vertical.
- **Data Compilation**: The results were organized and are presented below.

7.2 Key things to note

In this experiment, there is no lift force generated. The vertical forces are made up of the object's weight (W) and the vertical component of the tension ($T\cos(\theta)$). If the tension only balances the weight, there is no additional force to create lift.

7.3 Data Collection & Results

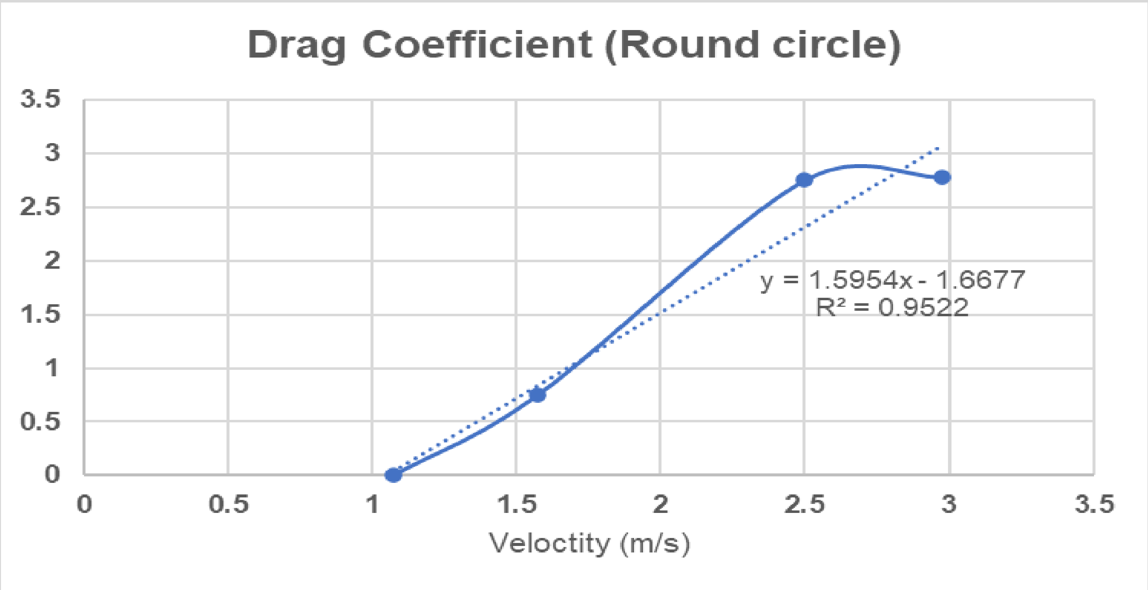
Table 1: Final trial data collection

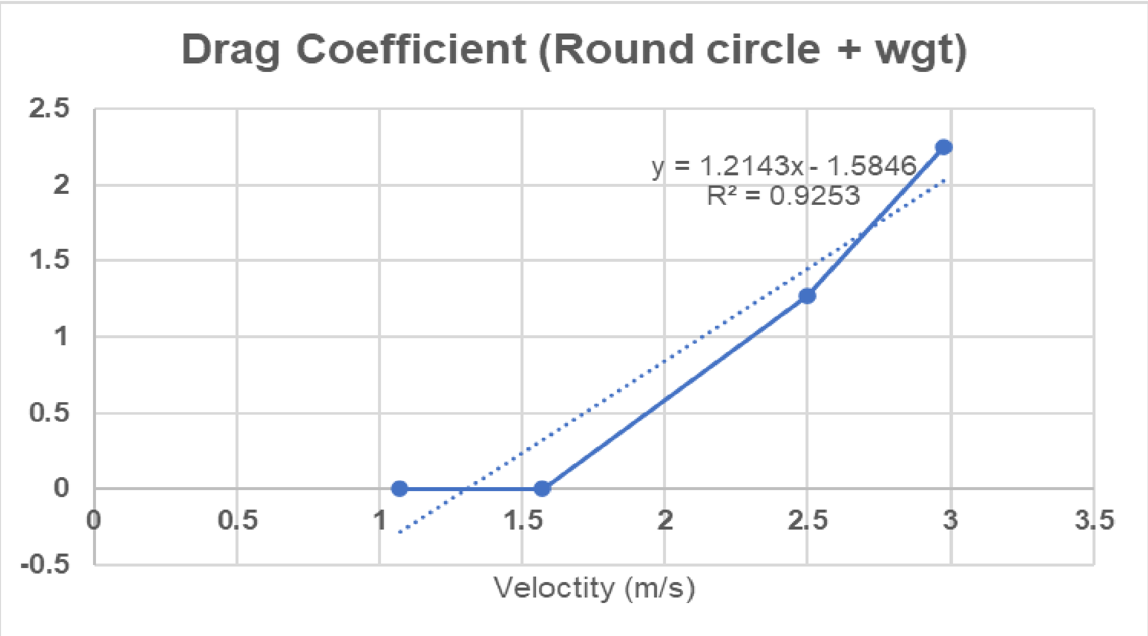
S.No	Objects	Weight (gms)	Veloctity (m/s)	Area (cm2)	Angle (degree)	W (N)	Drag Force	T (Tension)	Lift Force	Drag Coefficient
1	Round Circle	57.29	2.976	176.79	25	0.562	0.26	0.62	0	2.780
2	Round Circle	57.29	2.498	176.79	18	0.562	0.18	0.59	0	2.750
3	Round Circle	57.29	1.571	176.79	2	0.562	0.02	0.56	0	0.747
4	Round Circle	57.29	1.071	176.79	0	0.562	-	0.56	0	0.000
1	Round Circle + wgt	122.63	2.976	176.79	10	1.203	0.21	1.22	0	2.250
2	Round Circle + wgt	122.63	2.498	176.79	4	1.203	0.08	1.21	0	1.267
3	Round Circle + wgt	122.63	1.571	176.79	0	1.203	-	1.20	0	0.000
4	Round Circle + wgt	122.63	1.071	176.79	0	1.203	-	1.20	0	0.000
1	Knife Folder	86.41	2.976	136.00	1	0.848	0.01	0.85	0	0.204
2	Knife Folder	86.41	2.498	136.00	0	0.848	-	0.85	0	0.000
3	Knife Folder	86.41	1.571	136.00	0	0.848	-	0.85	0	0.000
4	Knife Folder	86.41	1.071	136.00	0	0.848	-	0.85	0	0.000

7.4 Impact of Velocity & Weight

- When the cross-sectional area remains constant, a decrease in speed leads to a reduction in the drag coefficient, as indicated by the Blue Line and Orange Line.
- With the same cross-sectional area and speed, an increase in weight results in lower drag.

Figure 7: Graph showing the relationship between drag coefficient and the velocity in the experimental trials





7.4.1 Detailed Regression Analysis Including R^2 Calculation for "Round Circle" and "Round Circle + wgt" Groups

For "Round Circle" Group:

$y = 1.5954x - 1.6677$

- **Slope (β_1):** 1.5954
- **Intercept (β_0):** −1.6677
- **Coefficient of Determination (R^2):** 0.9522
- **Standard Error of the Slope:** 0.2527
- **T-statistic for the Slope**: 6.3128
- **P-value for the Slope:** 0.0242

Detailed Calculations:

- **Total Sum of Squares (SS_tot):** SS_tot = sum from i=1 to n of $(y_i - y^{bar})^2$, here, n=4, y^{bar} is the mean value of drag coefficient values y_i
- **Residual Sum of Squares (SS_res):** SS_res = sum from i=1 to n of $(y_i - y^{hat}\_i)^2$, y^{hat}_i are predicted drag coefficient values
- **Coefficient of Determination (R^2):** R^2 = 1 - (SS_res / SS_tot)

Calculating the P-value:

- **T-statistic for Slope:** T = (Slope - 0) / Standard Error of the Slope
- **Degrees of Freedom (df):** n - 2 (n :- number of observations)
- **P-value:** Calculated using a t-distribution table, based on the T-statistic and df

For "Round Circle + wgt" Group:

$y = 1.2143x - 1.5846$

- **Slope (β_1): 1.2143**
- **Intercept (β_0): −1.5846**
- **Coefficient of Determination (R^2): 0.9253**
- **Standard Error of the Slope: 0.2440**
- **T-statistic for the Slope: 4.9772**
- **P-value for the Slope: 0.0381**

7.4.2 Interpretation: Both regression analyses produce statistically significant negative correlations between velocity and drag coefficient. The small p-values and excellent R^2 values of almost 0.9 reflect strong evidence of a significant influence of velocity on the drag coefficient as well as good model fit.

7.4.3 Conclusion:
Regression analyses show significant and substantial effects of velocity on the drag coefficient for both configurations. This underlines the association between velocity and aerodynamic forces, which implies that velocity plays a crucial role in determining aerodynamic performance.

7.5 Impact of Shape
Despite its heavier weight compared to the round object, the knife holder exhibited almost no drag force. This result underlines its impressive aerodynamic efficiency. The streamlined configuration of the knife holder considerably reduces resistance and, thus, shows shape of the object help to reduce drag for improved performance.

8.conclusion
Experiments in the wind tunnel with strong statistical evidence proves that the shape of an airfoil impacts its drag coefficient which has impact on aerodynamic performance. Key observations include:

- **Impact of Shape:** Curved shapes had a higher coefficient of drag than designed-to-streamline shapes such as the knife holder. This confirms that aerodynamic shape is the biggest factor in resisting drag.
- **Velocity Influence:** The drag coefficient decreased as the weight increased at a constant speed, thus bringing out the effect of mass and shape on aerodynamic efficiency.
- **Aerodynamic Forces:** Even though aerodynamic shapes help minimize forces of drag, there is an innate friction due to the skin and pressure differences which cannot be avoided.

The results shows that theoretical predictions and have practical implications for the optimization of airfoil designs that are aimed at reducing drag and improving efficiency. Moreover, these findings point to possible applications in the development of more efficient systems.

9.Evaluation
9.1 Random and Systematic Errors
In any experimental work, both random and systematic types of uncertainties need to be understood and quantified to ensure that the results obtained are reliable. We re-evaluate drag coefficients taking into account systematic errors such as anemometer calibration, while addressing random uncertainties through statistical analysis.

9.1.1 Systematic Uncertainties
Instrument Calibration:
- Error Source: Anemometer calibration error reading higher than actual values.

- Impact on Drag Coefficient Calculation: Systematic error affects all velocity readings, which directly impacts drag force calculations

Misalignment of Airfoil:

- Error Source: String position with the airfoil object
- Effects: Changes the effective angle of attack, which can impact lift and drag measurements.

9.1.2 Random Uncertainties:

Measurement Variability:

- Source: Variation in conditions and resolution of measuring devices.
- Procedure to Estimate Random Uncertainty: Conduct repeated experiments under the same conditions to get variability.

9.1.3 Conclusion:

Systematic and random uncertainties heavily impact experimental results. Reduction of calibration errors and noise improves data accuracy However, in the present set-up, all these could not be fully solved due to limitations in calibration resources and measurement devices. This shows that better conditions are required in future research works.

9.2. Propagation of uncertainty:

Drag Coefficient

$$C_D = \frac{mg\tan(\theta)}{0.5\rho v^2 S}$$

Using, general formula for uncertainty propagation in a function of multiple variables, uncertainty in drag coefficient will be

Equation5: Uncertainity

$$\frac{\delta C_D}{C_D} = \sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta\tan(\theta)}{\tan(\theta)}\right)^2 + \left(2\frac{\delta v}{v}\right)^2 + \left(\frac{\delta S}{S}\right)^2}$$

$\delta = \text{deltavalues(absolute uncertainty)}$

$\frac{\delta C_D}{C_D} = \text{Relative uncertainty}$

Example:

Round Circle	Values	Absolute Uncertainity	Comments
Weight (gms)	57.29	0.01	Measures till two scientific
Veloctity (m/s)	2.976	0.05	Assumed 2%
Area (cm2)	176.79	0.000314	Error of 1 mm in radius calculation
Angle (degree)	25	1	Error of 1 degree

Given

$$\frac{d}{d\theta}\tan(\theta) = \sec^2(\theta)$$

Thus, $\left(\frac{\delta \tan(\theta)}{\tan(\theta)}\right) = \sec^2(\theta) \cdot \delta\theta / \tan(\theta)$

	Values	Absolute Uncertainity	Relative uncertainty
Weight (gms)	57.29	0.01	0.000
Veloctity (m/s)	2.976	0.05	0.017
Area (cm2)	176.79	0.000314	0.000
Angle (degree)	25	1	0.046
		Relative Uncertainty	0.049

δC_D=0.049×2.780= 0.13620

Thus, absolute uncertainty = 0.13620 and relative = 4.9%

9.3 Limitations & Next steps

- **Sophisticated Instruments Needed:** We need more advanced instruments to make our research more meaningful and to know the effects of shape, mass, etc. on drag coefficients.

- **Measurement of Lift Coefficient:** We cannot position objects at an angle with our present setup. This facility has to be included in our setup to make the aerodynamic analysis complete.

- **Diverse Airfoil Designs:** We should investigate more airfoil geometries, such as asymmetrical shapes and non-uniform thicknesses, to explore a greater spectrum of aerodynamic profiles and characteristics.

- **Flow Visualization Techniques:** Smoke trails can be used to significantly enhance the flow visualization capabilities of flow separation locations and even boundary layer transitions, giving much more detailed understanding.

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11.Appendix

Figure 6: Pictures of Objects with different velocities

Velocity - 4

Velocity - 3

Velocity - 2

Velocity -1

Round Object with weight

 Velocity 4	 Velocity 3
 Velocity 2	 Velocity 1

Knife Holder

 Velocity 4	 Velocity 3
 Velocity 2	 Velocity 1

Figure 7: Surface Area Calculation of Knife holder

Total Area will twice (Holder + Scissor)