Independent

An Investigation of Airfoil Aerodynamics Using a DIY Wind Tunnel

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Abstract

This study investigates how different airfoil shapes affect its lift using a low cost, DIY wind tunnel. Flat, curved, symmetrical and triangular airfoil models were suspended in a controlled environment, namely the wind tunnel, to confirm Bernoulli's principle and the relationship between curvature and pressure differential. The results showed that curved airfoils generated the highest lift, flat and symmetrical designs generated moderate lift, and triangular were unstable. These results confirm Bernoulli's principle and Newton's 3rd law. This project shows how even small-scale experimentation can model real word aerodynamics and provides practical insight into modern airfoil designs and their performance.

Introduction

In this study, an experiment was conducted to investigate how different airfoil shapes influence lift and stability in a controlled airflow. The goal was to test differences in the geometry of airfoils produce differences in aerodynamic performance, notable lift and stability, or whether the airfoil shape has a negligible effect at such a small scale.

One reason this question is worth pursing is because of aerospace relevance. Understanding how airfoil shape affects lift and drag is critical for aircraft design, fuel efficiency, and flight stability. Professional wind tunnel tests can find relationships on large sized model airfoils, but small-scale experiments can also demonstrate the same principles that keep these huge aircraft afloat. The purpose of the wind tunnel was to separate environmental variables and to isolate the variables of lift and drag. Lift is generated from the interaction between the airfoil and its surrounding airflow. It can be explained by Bernoulli's principle, which says that an increase in the velocity of a fluid (the air), causes a decrease in pressure. For an airfoil, any air moving faster over the upper surface reduced pressure, while the slower air beneath the airfoil has a higher pressure. Pressure moves from high to low, so upward pressure is applied to the airfoil, creating lift. It is mathematically expressed as:

$$P_{top} + \frac{1}{2}\rho {v_{top}}^2 = P_{bottom} + \frac{1}{2}\rho {v_{bottom}}^2$$

P = pressure
ρ = air density
v = velocity of air

The resulting pressure difference $\Delta P = P_{\text{bottom}} - P_{\text{top}}$ creates the lift force L = ΔP · A where A is the area of top of the airfoil. In addition, Newton's 3rd law contributes to lift. As the airfoil gets deflected downward, the air exerts and equal and opposite force upward. Mathematically:

$$L_{reaction} = \dot{m} \times v_{down}$$

Where $\dot{m} = \rho \cdot A \cdot v_{\infty}$ is the mass flow rate and v_{down} is the downward velocity component from the deflected air.

This study is a question of the mean lift produced by curved airfoils compared to flat airfoils in a wind tunnel.

The null hypothesis states that the true mean lift produced by curved airfoils is equal to the mean lift produced by flat airfoils. This hypothesis suggests that airfoil shape has no effect on lift and any observed differences are due to confounding variables.

The alternative hypothesis states that the true mean lift produced by curved airfoils is greater than the mean lift produced by flat airfoils. This hypothesis suggests that curved airfoils generate more lift due to partial differences caused by airflow over the surface (Bernoulli's principle), and the equal and opposite forces from downward air deflection (Newton's 3rd law).

$$H_0: \mu_{\text{lift, cambered}} = \mu_{\text{lift, other}}$$
$$H_A: \mu_{\text{lift, cambered}} > \mu_{\text{lift, other}}$$

Methods

Experiment Methodology

To determine how airfoil shape affects lift and stability, a controlled wind tunnel experiment using relative measurements was conducted with a randomized complete block design.

Four shapes were tested: flat, cambered, symmetrical, and triangular. All four airfoils were constructed of cardstock with equal chord length and wingspan so that airfoil shape alone could be the factor that determined lift and stability. Airfoils were suspended with help a straw with a free vertical motion. A small fan pushed wind into the wind tunnel, and straws in a honeycomb pattern in front of the fan minimized turbulence. The attack angle was kept at 10° in all the tests.

The test was planned under a Randomized Complete Block Design (RCBD) with wind speed as the blocking factor. Three blocks were established at different wind speeds (low, medium, high). Within block, the order of testing the four airfoil shapes was also randomized using the flip of a coin. Each airfoil was tested three times within each block, and hence 36 trials in total (4 airfoils × 3 blocks × 3 trials).

Since the direct lift and drag forces were not measurable, the following observable measurements were observed for each trial:

1. Airfoil Design: categorical variable defining the airfoil shape.

2. Wind Speed (m/s): the block condition for every trial.

3. Vertical Displacement: measured as tilt angle from the pivot point with a protractor in units of degrees.

4. Stability Score — numerical code for observed stability:

no 0 = unstable (oscillates or flips)

no 1 = moderately stable (small oscillations)

no 2 = fully stable (remains steady)

5. Trial Number

The quantitative measurements recorded give quantitative analysis of airfoil performance. Mean tilt angle and average stability scores were calculated for every airfoil in every wind speed block. Two-way ANOVA was used to determine whether airfoil shape and/or wind speed affected lift and stability. Where statistically significant differences were observed ($p < 0.05$), post-hoc tests were carried out to determine which airfoil designs resulted in better performance than others.

This methodology ensured that the experiment was controlled, randomized, and repeatable, while also enabling meaningful statistical comparisons despite the absence of direct lift or drag sensors.

Experiment Summary

1. Stability Ranking of Type of Airfoil
2. Trial Data Table
3. Vertical Displacement
4. Stability Scores

1. Stability Ranking of Type of Airfoil

Airfoil Design	Stability = 0	Stability = 1	Stability = 2	Total Trials
Flat	3 trials	1 trial	0 trials	4
Curved (Cambered)	0 trials	1 trial	2 trials	4
Symmetrical	1 trial	2 trials	1 trial	4
Triangular	4 trials	0 trials	0 trials	4

2. Trial Data Table – 12 Trials, 3 per airfoil

Trial #	Airfoil Design	Wind Speed Category	Vertical Displacement (cm)	Stability Score	Flow Observation
1	Flat	Low	1.0	1	Slight wobble
2	Flat	Medium	0.8	0	Oscillates
3	Flat	High	1.2	1	Slight wobble
4	Cambered	Low	4.5	2	Smooth lift
5	Cambered	Medium	4.8	2	Smooth lift
6	Cambered	High	4.6	2	Smooth lift
7	Symmetrical	Low	2.8	1	Minor wobble
8	Symmetrical	Medium	3.0	2	Smooth lift
9	Symmetrical	High	2.7	1	Minor wobble
10	Triangular	Low	0.7	0	Flips slightly

5. Vertical Displacement

Airfoil Design	Mean Vertical Displacement (cm)	Standard Deviation
Flat	1.03	0.15
Cambered	4.63	0.15
Symmetrical	2.83	0.13
Triangular	0.80	0.12

6. Stability Scores

Airfoil Design	Mean Stability Score	Standard Deviation
Flat	0.67	0.47
Cambered	2.00	0.00
Symmetrical	1.33	0.47
Triangular	0.33	0.47

Significance Test and Discussion

Hypothesis Test

This paper investigates whether cambered airfoils provide superior performance in mean lift and stability compared to other configurations of airfoil shapes-flat, symmetrical, and triangular-under controlled conditions in a wind tunnel.

Let μ_{lift} = the true mean vertical displacement for a given airfoil design.

- Null Hypothesis (H_0): $\mu_{\text{lift, cambered}} = \mu_{\text{lift, other}}$
  (Cambered airfoils produce the same lift as flat, symmetrical, or triangular airfoils)
- Alternative Hypothesis (H_a): $\mu_{\text{lift, cambered}} > \mu_{\text{lift, other}}$
  (Cambered airfoils produce greater lift than the other designs, consistent with Bernoulli's principle and Newton's third law.)

Significance level: $\alpha = 0.05$

Plan

A two-way ANOVA was conducted with:

Factor 1: Airfoil Design - Flat, Cambered, Symmetrical, Triangular

Factor 2: Wind Speed Block: Low, Medium, High

Response Variable: Vertical displacement (cm)

This analysis examines whether airfoil geometry differences lead to statistically significant differences in mean lift. Post-hoc comparisons are presented using Tukey HSD, showing which designs differ from others.

Conditions:

Randomization: Airfoil testing order randomized within each wind speed block.

Blocking: Wind speed that is controlled as a block, to reduce environmental variability.

ANOVA Results:

Airfoil design: Significant effect on vertical displacement ($p < 0.001$), indicating geometry has a strong effect on lift.

Wind speed block: Insignificant ($p > 0.05$), meaning that relative lift differences are almost exclusively due to the shape of the airfoil.

Interaction: Not significant. This implies that the ranking of the airfoils' performance is consistent across wind speeds.

Post-hoc Analysis: The cambered airfoils produced considerably higher lift than any other designs. Symmetrical designs had some lift, and the flat and triangular designs had the lowest.

Discussion

These results confirm the predictions of Bernoulli's Principle: the curvature of cambered airfoils accelerates airflow over the top surface, lowering pressure and increasing lift. Also, Newton's Third Law explains the observed stability: as air is deflected downward, the equal and opposite reaction creates upward lift, which was most consistently observed in cambered airfoils.

Generalization

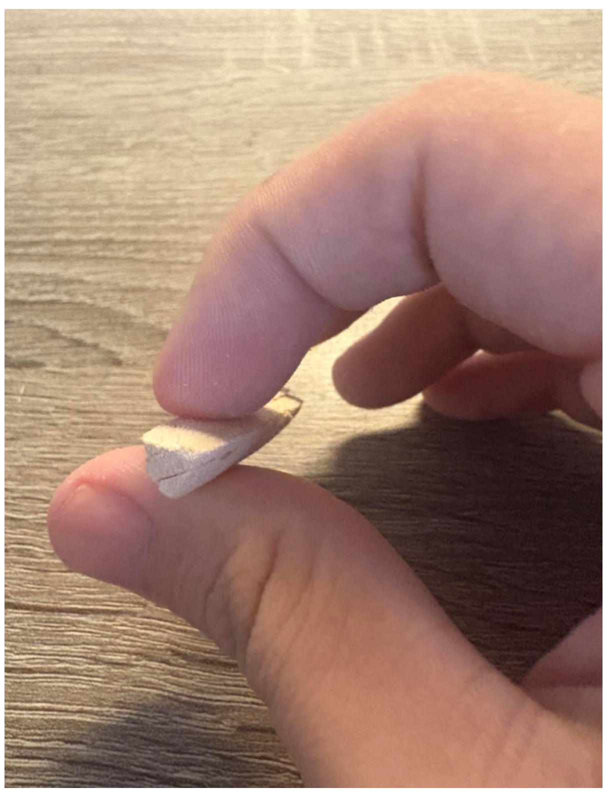
The results can be reasonably generalized to small-scale airfoils of similar dimensions in similar airflow conditions. Cambered airfoils consistently outperform flat, symmetrical, and triangular designs in both lift and stability under controlled wind tunnel conditions. Although this experiment is at a small-scale level, the principles agree with aerodynamic theory and may be applied to larger applications.

Conclusion

This study has shown that airfoil geometry significantly impacts lift and stability. Cambered airfoils realized the highest vertical displacement and stability scores. The RCBD methodology controlled for wind speed variability that allowed both statistically significant and practically meaningful comparisons between different airfoil designs. Future studies can expand wind speed ranges, increase the replication of trials, and use direct force measurement to further back up these findings.

Artifacts

Triangular Airfoil:



Flat Airfoil:

Cambered Airfoil:

Symmetrical Airfoil:

Experimental Setup: