Comparative Aerodynamic Analysis of Aircraft and Formula 1 Geometries

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Tools used: SolidWorks, MATLAB

Abstract

This project compares the aerodynamic performance of a conventional aircraft wing and Formula 1 front and rear wings using simplified aerodynamic theory and parametric CAD modeling. Wing geometries were created in SolidWorks and analyzed using thin airfoil and lifting-line theory implemented in MATLAB. Results show that aircraft wings achieve significantly higher lift-to-drag ratios due to their high aspect ratios, while Formula 1 wings deliberately sacrifice efficiency to generate downforce. Sensitivity analysis confirms the strong influence of aspect ratio on aerodynamic efficiency.

Introduction and Motivation

Wings are fundamental aerodynamic components used in a wide range of engineering applications, from aircrafts to high-performance race cars. While both aircraft and Formula 1 (F1) cars rely on wings to manipulate airflow and generate aerodynamic forces, their design objectives differ significantly. Aircraft wings are optimized to produce lift with minimal drag in order to maximize range and fuel efficiency, whereas Formula 1 wings are designed to generate downforce to increase tire grip and improve cornering performance, even at the expense of increased drag.

Despite these differing goals, both systems operate under the same aerodynamic principles. This makes a direct comparison between aircraft wings and Formula 1 wings a way to understand how geometry, aspect ratio, and operating conditions influence aerodynamic performance. The purpose of this project is to explore these differences through simplified modeling, highlighting how design priorities shape aerodynamic efficiency and force generation.

Geometry and Modeling

Wing Geometry Overview

Three wing configurations were modeled:

1. A conventional aircraft wing
2. A Formula 1 front wing
3. A Formula 1 rear wing

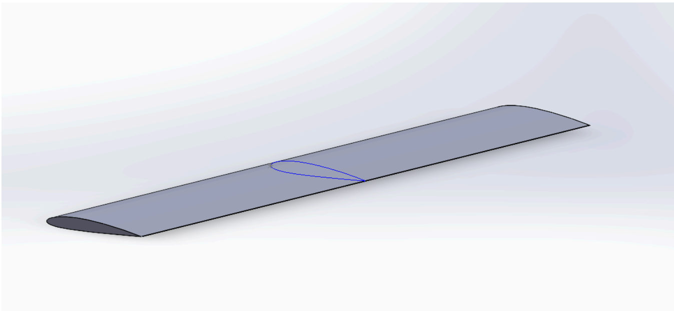
All geometries were created in SolidWorks using simplified, single-element wings to isolate the effects of airfoil shape and planform geometry. Structural features, endplates, and multi-element effects were intentionally omitted to maintain clarity and consistency.

NACA airfoils selected:

- NACA 2412 for the aircraft wing due to its cambered profile and widespread use in subsonic aircraft.
- NACA 0012 for both Formula 1 wings due to its symmetric shape, allowing downforce to be controlled primarily through angle of attack.

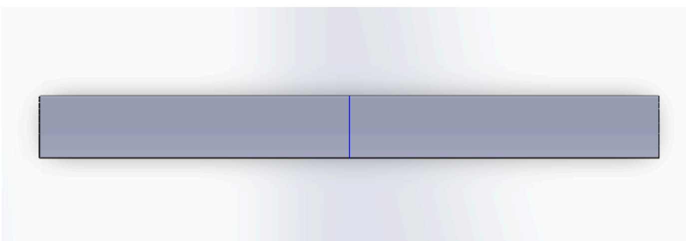
Aircraft wing CAD

- Isometric view



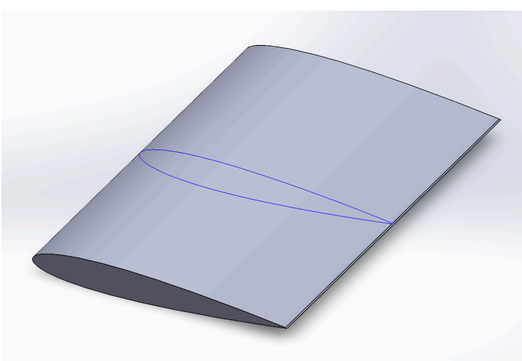
- Side view

- Top view (span visible)



F1 front wing CAD

- Isometric view



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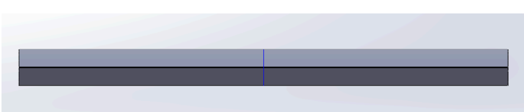

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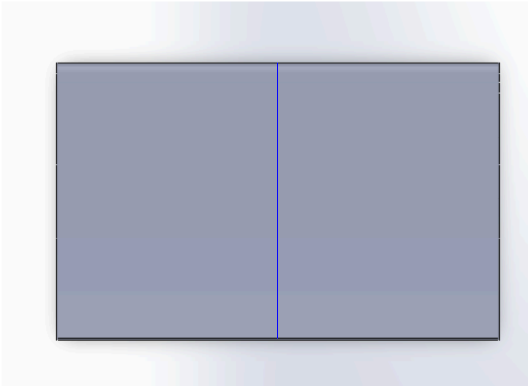
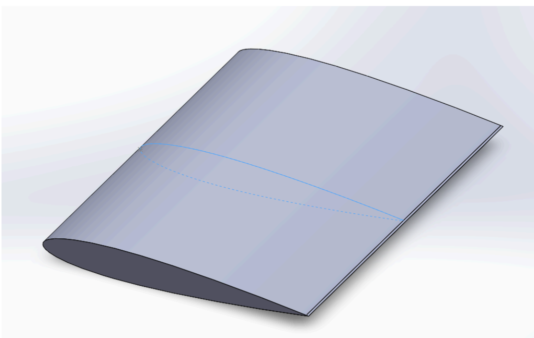
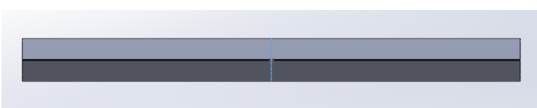


F1 rear wing CAD

- Isometric view



- Side view



- Top view (span visible)

Aircraft Wing Geometry Table

Parameter	Value
Airfoil	NACA 2412

Chord (m)	1.5
Span (m)	10.0
Aspect Ratio	6.7
Purpose	Lift efficiency

F1 Front Wing Geometry Table

Parameter	Value
Airfoil	NACA 0012
Chord (m)	0.8
Span (m)	1.6
Aspect Ratio	2.0
Purpose	Downforce (front balance)

F1 Rear Wing Geometry Table

Parameter	Value
Airfoil	NACA 0012
Chord (m)	1.2
Span (m)	1.4
Aspect Ratio	1.17
Purpose	Maximum downforce and stability

Aerodynamic Theory

The aerodynamic analysis was performed using MATLAB and is based on simplified, low-order aerodynamic theory suitable for conceptual comparison.

Thin Airfoil Theory

For two-dimensional flow and small angles of attack, thin airfoil theory provides a linear relationship between lift coefficient and angle of attack:

$$C_{L,2D} = 2\pi\alpha$$

where α is the angle of attack in radians. This theory assumes inviscid, incompressible flow and attached streamlines, making it valid only in the pre-stall regime.

Finite Wing Correction

Real wings have finite span, which introduces induced drag and reduces lift efficiency. A simplified lifting-line correction was applied:

$$C_{L,3D} = \frac{C_{L,2D}}{1 + \frac{C_{L,2D}}{\pi AR}}$$

where AR is the aspect ratio of the wing. This correction captures the primary influence of wing planform on lift generation.

Drag Model

Drag was modeled using a simple parabolic drag polar:

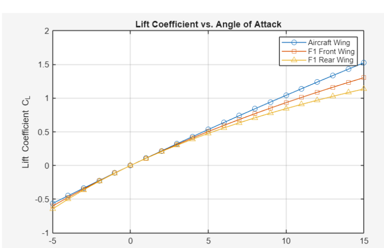
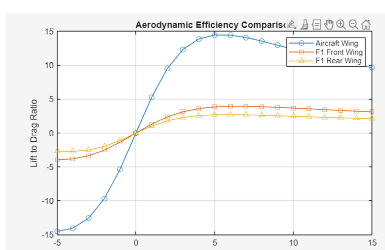
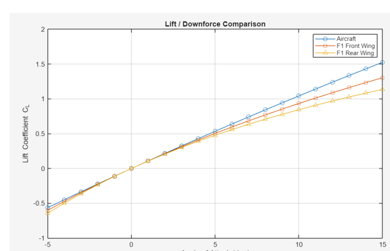
$$C_D = C_{D0} + \frac{C_L^2}{\pi ARe}$$

where CD0 represents parasitic drag and e is the Oswald efficiency factor. While simplified, this formulation captures the dominant relationship between lift and induced drag.

Results and Discussion

This section presents and interprets the aerodynamic performance results obtained from the MATLAB analysis. Each plot is discussed in terms of observed trends, underlying aerodynamic principles, and the influence of wing geometry.

Graphs

<table>
<tr><td>a) Lift Coefficient vs. Angle of Attack</td><td>b) Aerodynamic Efficiency Comparison</td><td>c) Lift/Downforce Comparison</td></tr>
<tr><td>
</td><td>
</td><td>
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<tr><td>d) Downforce Efficiency Comparison</td><td>e) Aircraft vs. F1 Aerodynamic Efficiency</td><td>f) Aircraft Wing Aspect Ratio Sensitivity</td></tr>
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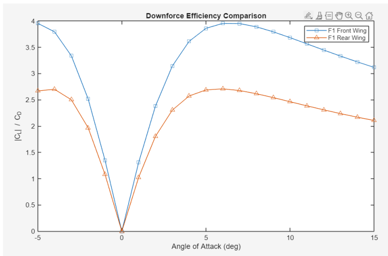

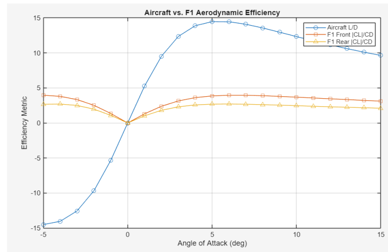

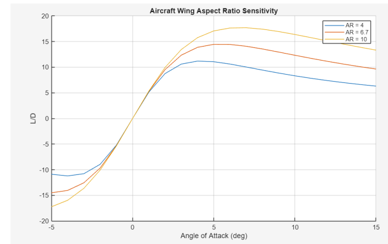

a) Lift Coefficient vs. Angle of Attack

This plot shows the variation of lift coefficient CL with angle of attack for the aircraft wing and the Formula 1 front and rear wings. The aircraft wing shows positive lift that increases approximately linearly with angle of attack, while the Formula 1 wings generate negative lift (downforce) when operated at negative angles of attack.

The linear behavior reflects the pre-stall assumptions of thin airfoil theory, in which lift varies linearly with angle of attack. The rear wing produces a larger magnitude of lift coefficient than the front wing, indicating stronger force generation.

Geometry strongly influences these trends. The aircraft wing's high aspect ratio improves lift efficiency, while the Formula 1 wings' lower aspect ratios reduce efficiency but allow compact geometries. The larger chord of the rear wing increases its effective lifting area, resulting in greater downforce.

b) Aerodynamic Efficiency Comparison (Lift-to-Drag Ratio)

This plot compares the lift-to-drag ratio L/D of the aircraft wing with the corresponding efficiency metrics of the Formula 1 wings. The aircraft wing achieves significantly higher efficiency across the angle-of-attack range.

This behavior occurs because induced drag decreases with increasing aspect ratio. The aircraft wing's long span and slender planform minimize induced drag, whereas the Formula 1 wings operate at low aspect ratios and higher effective angles of attack, significantly increasing drag.

The geometry reflects design intent: aircraft wings prioritize efficiency for sustained flight, while Formula 1 wings prioritize force generation over efficiency.

c) Lift / Downforce Comparison

This plot directly compares upward lift generated by the aircraft wing with downward force (downforce) generated by the Formula 1 wings over their respective angle-of-attack ranges.

Both lift and downforce arise from the same aerodynamic principles, with the difference stemming from operating conditions. Aircraft wings operate at positive angles of attack to generate lift, while Formula 1 wings operate at negative angles of attack to generate downforce. The rear wing produces more downforce than the front wing due to its larger chord and lower aspect ratio.

The aircraft wing's geometry spreads lift over a large span, reducing induced losses. The Formula 1 rear wing's larger chord increases the reference area, directly increasing force magnitude. The lower aspect ratio of Formula 1 wings amplifies induced drag but does not prevent large force generation.

d) Downforce Efficiency Comparison
This plot presents the downforce efficiency metric ∣CL∣/CD for the Formula 1 front and rear wings as a function of angle of attack.

Downforce efficiency reflects how much usable force is generated for a given drag penalty. As angle of attack increases, downforce increases, but drag increases more rapidly due to induced drag. This leads to a peak efficiency point beyond which additional angle of attack yields diminishing returns.

The rear wing exhibits lower efficiency than the front wing despite producing more downforce. This is due to its lower aspect ratio and larger chord, which increase induced drag. This behavior reflects real Formula 1 design trade-offs, where rear-wing downforce is prioritized for stability rather than efficiency.

e) Aircraft vs. Formula 1 Aerodynamic Efficiency
This combined plot compares the aircraft wing's lift-to-drag ratio with the Formula 1 wings' downforce efficiency on a single graph, emphasizing the stark contrast between the two design philosophies.

Aircraft wings are optimized for sustained, efficient lift, while Formula 1 wings are optimized for transient, high-force conditions. As a result, aircraft wings exhibit far greater efficiency, while Formula 1 wings generate much larger forces relative to their size.

f) Aircraft Wing Aspect Ratio Sensitivity
This plot shows how varying the aircraft wing aspect ratio affects lift-to-drag ratio as a function of angle of attack.

Increasing aspect ratio reduces induced drag, leading to higher peak L/DL/DL/D values and improved aerodynamic efficiency. This sensitivity analysis confirms that aspect ratio is one of the most influential geometric parameters in wing design and validates the trends predicted by aerodynamic theory.

Limitations and Future Work

This study is subject to several important limitations:

- Thin airfoil theory assumes inviscid, attached flow and does not capture stall behavior.
- Viscous effects, Reynolds number dependence, and compressibility were neglected.
- Wings were modeled as single-element surfaces without endplates or ground effect.
- Interaction between front and rear wings was not considered.

Future work could extend this analysis by incorporating ground effect modeling for Formula 1 wings, multi-element airfoil theory, Reynolds number effects, or computational fluid dynamics (CFD) simulations for higher-fidelity results.

Conclusion

This project demonstrates how the same aerodynamic principles can lead to fundamentally different wing designs when performance objectives change. Aircraft wings prioritize efficiency through high aspect ratios and gentle camber, achieving high lift-to-drag ratios. Formula 1 wings, in contrast, deliberately sacrifice efficiency to maximize downforce, enhancing vehicle grip and stability. Simplified aerodynamic modeling successfully captures these trends, showing the strong influence of geometry and aspect ratio on aerodynamic performance.