

Aerodynamic Analysis of NACA Airfoils Using CFD and MATLAB

A NACA Airfoil CFD Study

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ABSTRACT

I present computational analysis of the aerodynamic performance of 2-dimensional NACA airfoils across a range of angles of attack. Using the SimScale platform, alongside the Fusion product development platform, steady-state incompressible computational fluid dynamics (CFD) simulations were conducted to visualize and quantify the airflow behavior around selected airfoils. For each configuration, certain key aerodynamic characteristics, such as stall behavior and efficiency, were evaluated through attaining the lift and drag coefficients. The results were then processed and plotted using MATLAB, producing C_L vs. α , C_D vs. α , and the drag polar (C_L vs. C_D) plots to compare performance across different angles and airfoil geometries. The study demonstrates how airfoil shape and angle of attack influence aerodynamic response, particularly to generate lift and minimize drag. The project displays the effectiveness of combining modern CFD tools with computational analysis to investigate classic airfoil designs and support engineering decision-making in early aerodynamic design stages.

Key words: Computational fluid dynamics (CFD), lift and drag coefficients, pressure and shear stress, SimScale, MATLAB

1. INTRODUCTION

Aircraft and airfoils depend on the behavior of moving air, or airflow, over their surfaces to generate the forces needed for flight. The interactions between fluid flow and solid bodies mark the foundation of aerodynamics. Understanding how these forces arise and change with shape and orientation is crucial in developing models for wings and entire aircraft.

The key to the interaction is the airfoil, a two-dimensional cross section of a wing, whose geometry determines how air flows along its surface, dictating the forces of lift, drag, and induced moment. These forces are often reported with non-dimensional coefficients, allowing engineers to determine the performance of an airfoil purely from its geometry, and independent of scale, speed, and air density. These include the lift coefficient (C_L), drag coefficient (C_D), and the moment coefficient (C_M), among other crucial non-dimensionals.

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S_{ref}}, \quad C_D = \frac{D}{\frac{1}{2}\rho V^2 S_{ref}}, \quad C_M = \frac{M}{\frac{1}{2}\rho V^2 c S_{ref}}.$$

Equation 1. L, D, and M are the lift, drag, and pitching moment, ρ is air density, V is freestream velocity, S is the reference area, and c is the chord length. The freestream velocity refers to the difference between the air velocity and the aircraft's velocity, or the aircraft's velocity relative to the surrounding air.

The pressure and shear viscous force that happen locally on the surface of the airfoil generate the global body forces, known as lift, drag, and pitching moment.

Pressure: $p(x, y)$

Shear Stress: $\tau(x, y)$

Aerodynamic Force

$$A = \iint_{S_{body}} (-p\hat{n} + \tau) dS.$$

Equation 2. The total aerodynamic force over the surface can be found using the surface integral, where $-p\hat{n}$ is the pressure stress normal and downward into the surface, τ is the wall shear stress tangential to the surface, and dS is the infinitesimal surface element.

The lift is characterized as a force normal to the freestream velocity, typically pointing upward on an aircraft airfoil to oppose the force of gravity. The drag force directly opposes the direction of motion, acting as a sort of friction. Finally, the moment, or torque, contributes to the stability of the aircraft. The lift and drag forces acting on the airfoil means that there is rotational force about the aircraft's center of mass, which must be stabilized with another airfoil near the aircraft's tail.

To quantify the effects, engineers keep certain parameters constant, such as the freestream velocity. At a low Mach number, where $M_\infty < 0.3$, the air is virtually incompressible, meaning that its air density is constant, rather than changing with position.

$$M_\infty = \frac{V}{a}.$$

Equation 3. The Mach number is a non-dimensional parameter determining the behavior of flow, giving the ratio of the freestream velocity to a_∞ , the speed of sound in the freestream. While keeping the freestream velocity and airfoil geometry constant, engineers change the angle of attack, or orientation of the airfoil's chord line with respect to the incoming airflow.

As the angle increases, the lift generally increases up to a certain point, known as stall. An even greater angle causes the air to detach from the upper surface of the airfoil, resulting in a stall. Understanding this behavior is key in assessing an airfoil's performance, defining its ability to create lift, minimize drag, and maintain stability throughout flight.

This project uses computational tools to simulate these behaviors numerically. SimScale, a cloud-based CFD platform, is used to solve the flow field around several airfoils at different angles of attack. The resulting lift and drag coefficients are extracted and visualized in MATLAB, providing a quantitative comparison of how airfoil shape influences aerodynamic performance.

2. METHODOLOGY

This study uses computational fluid dynamics (CFD) to analyze aerodynamic performance of two-dimensional airfoils across a range of angles of attack. All simulations were conducted using SimScale, a cloud-based platform capable of solving the Navier-Stokes equations for various airflow regimes. The simulation results were processed using MATLAB, where coefficients and force distributions were visualized and analyzed.

2.1 Airfoil Geometry

A selection of standard NACA 4-digit airfoils was used to compare performance across different shapes. Used throughout aerodynamics, NACA 4-digit airfoils give the maximum camber as a percentage of the chord (first digit), the position of the maximum camber as a tenth of the chord (second digit), and the maximum thickness as a percentage of the chord (final two digits).

The three airfoils to be used in the study will be NACA 0012, 2412, and 4424. Note that NACA 0012 does not have a

maximum camber, therefore it cannot have a position for the maximum camber, meaning that it is symmetrical across its chord line.

SimScale is compatible with Fusion's ability to export CAD models as STEP files, allowing CAD exports of each airfoil to be moved into the simulation easily. The CAD files of each airfoil are taken from the UIUC Airfoil Database as .dat files, converted into SVG files, and extruded manually in fusion.

2.2 Simulation Setup

The simulations were configured as state-ready, incompressible flows, appropriate and accurate for low-speed subsonic conditions, namely $M_\infty < 0.3$ where compressibility is negligible. I selected the $k - \omega$ turbulence model due to its time independence, capturing both attached and detached airflow regions with good near-wall resolution.

The boundary conditions are crucial. There is a velocity inlet with flow directed at varying angles of attack, adjusted by changing the inlet vector. A pressure outlet is set to 0 Pa, and no-slip walls on the surface. A no-slip wall is a boundary condition enforcing a viscous fluid to attain zero flow velocity when adjacent to a solid boundary. Finally, there are slip, or symmetry conditions, at the top and bottom surface.

In the various simulations, the angle of attack is altered by tweaking the inlet vector rather than physically rotating the airfoil within the flow field. This ensures that the mesh along the surface remains consistent throughout trials, reducing variability in results from due to grid formation.

2.3 Mesh Generation

The computation mesh along the airfoil surface was automatically generated using SimScale's SIMPLE meshing algorithm for steady-state time independence. There are local surface refinements so that the mesh density depends on the geometry rather than refining the mesh consistently over the entire airfoil.

Boundary layer inflation is added around the airfoil, simulating thin, inflation layers adjacent to the boundary wall of the airfoil in the mesh. This is done to accurately depict the behavior of the boundary layer, a thin region where shear viscous forces dominate. The combination of these two creates an accurate resolution of pressure stress and near-wall viscous forces which are critical in understanding skin friction and separation behavior.

2.4 Global Forces

The global forces on an airfoil are the lift, drag, and moment forces that are caused from the local pressure stress and viscous shear that happen when the airfoil interacts with airflow. The lift and drag are components of the aerodynamic force, derived from integrating the pressure and viscous shear across the surface of the airfoil. SimScale computes this lift and drag forces, extracting their coefficients. These extracted coefficients, along with their corresponding angles of attack, are exported to MATLAB for further analysis.

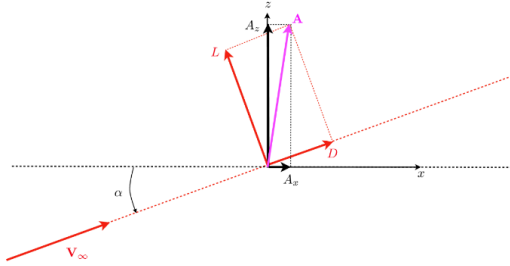


Figure 1. V_∞ refers to the freestream velocity. Note that drag is the component of aerodynamic force in the direction of freestream velocity, and the lift is the component normal to it. Common notation dictates that the airfoil geometry exists in the xz -plane, as the y -axis is reserved as the span-wise direction. Source: MITx 16.101x Introduction to Aerodynamics [1].

2.5 Local Forces

Local pressure and walls stress distributions along the airfoil allow a deeper understanding of the surface forces. Traditionally, data returned by the CFD are discrete values in Cartesian coordinates (x, y) , where $p(x, y)$ and $\tau(x, y)$ are the pressure and shear stress at specific points on the airfoil surface.

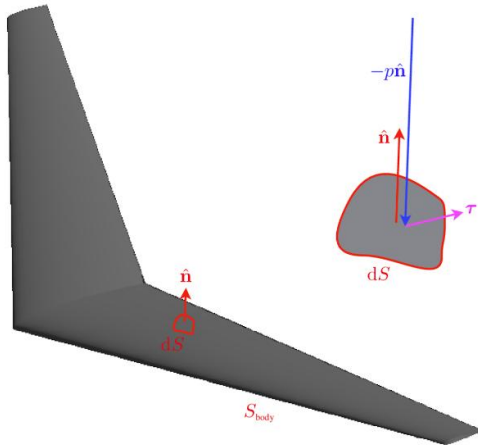


Figure 2. As seen previously, the pressure stress pushing downward and normal to the surface, combined with the shear

stress working tangential to the surface, integrated over the surface, yields the total aerodynamic force that can be separated into lift and drag. Source: MITx 16.101x Introduction to Aerodynamics [2].

For simplicity, engineers often convert stress data from Cartesian coordinates (x, y) into stress data as a function of the arc length s . This technique offers a clearer representation of the forces' effects on the surface as a function of the boundary's length.

In MATLAB, I mapped the data to the arc length parameter s . Definitionally, the pressure stress is resolved as normal, while the viscous shear stress is resolved as tangential to the surface. When local forces are parameterized using s and separated into normal and tangential components, they can be compared to global body forces easily.

3. COMP. FLUID DYNAMICS

Standard NACA airfoil profiles were selected from the UIUC Airfoil Coordinates Database, titled Lockheed L-188/P-3 tip airfoil NACA 0012, NACA 2412 airfoil, and NACA 4412 respectively. The .dat files from this database contain a set of non-dimensional (x, z) coordinate points defining the upper and lower surfaces of the airfoil, where x ranges from 0 to 1, and z defines the camber/thickness. Note that the y -axis is reserved as the span-wise direction, or the direction of extrusion.

The coordinates were redefined from .dat files to .DXF files, then plotted on the xz -plane in Fusion to create a closed 2D airfoil sketch, consistent with conventional notation. Each airfoil is scaled by the standard unit of millimeters, extruded along the y -axis by 10.00 mm, and exported in STEP format, which is widely accepted in professional CFD software.

The resulting solids were then imported into SimScale, where the fluid domain (airflow field) and simulation settings are set up. The airfoils exist as continuous, nearly 2D solids that can be placed into the surrounding flow field.

3.1 Domain Setup

The flow domain, the region where the airflow field exists within the CFD, is created around the airfoil geometry. The domain, in comparison to the airfoil, is large enough in all directions to have negligible boundary effects and replicate the freestream accurately. The airfoil will be oriented at the center, while the inlet and outlet of the fluid will be above and below respectively.

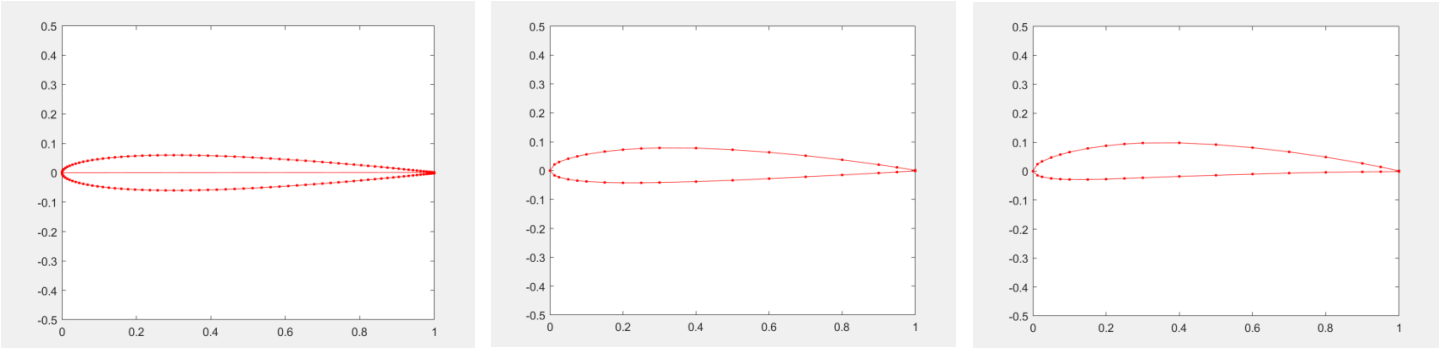


Figure 3. Using MATLAB, airfoil coordinates from the UIUC database are plotted with straight-line connectors, forming the shape of the NACA 0012, 2412, and 4412 airfoils. Note the symmetry of the first airfoil, rightly denoted by its first two digits being 0. The second and third airfoils have their maximum camber occurring at 0.4, or 4/10 of the chord line, denoted by the second digit 4. These coordinates are then opened in Fusion to be extruded.

3.2 Initial Conditions & Solver Settings

The simulations are run using the $k - \omega$ SST turbulence model, a two-equation eddy-viscosity model that is a widely accepted industry standard turbulence model. The model accounts for near-wall effects, determining how the flow interacts with the body. Because the overall flow is subsonic and incompressible, the flow is laminar near the wall, dominated by viscous forces in the viscous sublayer.

The material, of course, will be air, which has a kinematic viscosity $\nu = 1.529 \cdot 10^{-5} \text{ m}^2/\text{s}$, a density $\rho = 1.196 \text{ kg/m}^3$, a velocity inlet $\vec{U} = \langle 0, 0, 0 \rangle \text{ m/s}$, turbulent kinetic energy $k = 3.75 \cdot 10^{-3} \text{ m}^2/\text{s}^2$. There is a global gauge pressure of 0 Pa and specific dissipation rate $\omega = 3.375 \text{ 1/s}$.

For solving the velocity, turbulent kinetic energy, and the dissipation rate, the $k - \omega$ SST turbulence model features the PBICStab solver, a Preconditioned Bi-Conjugate Gradient Stabilized algorithm that solves large systems of linear equations, namely using the form $A\vec{x} = \vec{b}$.

$$\begin{aligned} A \cdot \Psi &= b, \\ (M^{-1} \cdot A) \cdot \Psi &= M^{-1} \cdot b. \end{aligned}$$

The equation uses a matrix M known as a preconditioner, similar to the original matrix A , which can be inverted more easily. The original matrix includes convection, diffusion, and pressure gradient terms among its entries.

The unknowns are denoted with Ψ , and b the knowns. Unknowns include pressure, temperature, components of fluid velocity, and temperature, while the knowns are terms derived from boundary conditions, external forces, and anything not directly related to any unknown variable.

3.3 Output Data & Result Fields

Upon the completion of each run, SimScale will produce outputs: (1) global outputs of lift, drag, and moment, (2) flow field data of pressure, velocity, and turbulence in the domain, and (3) local surface data of wall pressure $p(x, y)$ and wall shear stress $\tau(x, y)$, usually split into its x and y coordinates. Note that the x and y coordinates refer to the x and z coordinates of the traditional orientation of airfoils, as the y direction is reserved for the span-wise direction.

4. POST-PROCESSING

MATLAB

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