Python-Based Airfoil Performance Simulator

1. Introduction

This project provides a simple Python-based tool for estimating the aerodynamic performance of airfoils, specifically focusing on the lift coefficient (CL) and the moment coefficient about the quarter-chord (CM,c/4). The estimations are based on the fundamental principles of **Thin Airfoil Theory**, a foundational concept in aerodynamics. Designed for intermediate-level coders, the tool features a user-friendly interactive interface for selecting various airfoil types and inputting flight parameters.

2. Theoretical Basis: Thin Airfoil Theory

Thin Airfoil Theory is a simplified analytical method used to predict the aerodynamic characteristics of airfoils, particularly at small angles of attack. It makes several key assumptions to simplify the complex equations of fluid dynamics:

- **Thin Airfoil Assumption:** The airfoil is assumed to be infinitesimally thin, represented by its camber line.
- **Inviscid Flow:** The fluid is assumed to be ideal, meaning there are no viscous effects (friction).
- **Incompressible Flow:** The fluid density is assumed to be constant.
- **Small Perturbations:** The flow disturbances caused by the airfoil are small.

Under these assumptions, Thin Airfoil Theory provides elegant analytical solutions for the lift and moment characteristics.

Key Formulas Used:

- Lift Coefficient (CL):
  The lift coefficient is given by:
  $CL=2\pi(\alpha-\alpha L=0)$

  Where:
  - α is the angle of attack (in radians).
  - $\alpha L=0$ is the zero-lift angle of attack (the angle of attack at which CL=0).
- Moment Coefficient about the Quarter-Chord (CM,c/4):
  Thin Airfoil Theory predicts that the moment coefficient about the quarter-chord point is independent of the angle of attack.
  - For Symmetric Airfoils:
    $CM,c/4=0$

This is because symmetric airfoils have no inherent pitching moment.

- For Cambered Airfoils (Parabolic Camber Approximation):
  For a parabolic camber line defined by $z_c(x)=4hx(1-x)$, where h is the maximum camber as a fraction of the chord:
  $\alpha_{L=0}=-2h$ (in radians) $C_{M,c/4}=\pi h$

3. Project Features

The Python code implements the following functionalities:

- **Lift and Moment Estimation:** Calculates the LIFT_COEFFICIENT (CL) and MOMENT_COEFFICIENT_C4 (CM,c/4).
- **Zero-Lift Angle of Attack Calculation:** Determines ZERO_LIFT_ANGLE_OF_ATTACK_DEG ($\alpha_{L=0}$).
- **Airfoil Type Selection:** Users can choose from:
  - **Symmetric Airfoil:** Assumes a flat camber line.
  - **Cambered Airfoil (Generic Parabolic):** Allows the user to input a MAX_CAMBER_FRACTION directly.
  - **NACA 4-Digit Series (Approximate):** The user inputs a 4-digit NACA number (e.g., 2412). The code extracts the maximum camber percentage from the first digit and uses it to approximate the airfoil's camber as a parabolic shape for the Thin Airfoil Theory calculations.
- **Interactive User Interface:** A command-line menu guides the user through the selection process and input of the ANGLE_OF_ATTACK_DEG.
- **Robust Input Handling:** Includes error handling for invalid numerical or string inputs, prompting the user to re-enter valid data.
- **Clear Output:** Presents the estimated CL, CM,c/4, and $\alpha_{L=0}$ in a formatted manner.

4. Key Variables and Functions

Functions:

- ESTIMATE_AIRFOIL_PERFORMANCE(AIRFOIL_TYPE, ANGLE_OF_ATTACK_DEG, MAX_CAMBER_FRACTION): The core function for calculating aerodynamic coefficients.
- RUN_AIRFOIL_ESTIMATOR(): Manages the user interaction, menu, and input validation.

Key Variables:

- AIRFOIL_TYPE: String ('symmetric' or 'cambered') indicating the chosen airfoil type.

- ANGLE_OF_ATTACK_DEG: User-input angle of attack in degrees.
- MAX_CAMBER_FRACTION: Maximum camber of the airfoil as a fraction of the chord. This is either 0 for symmetric, user-defined for generic cambered, or derived from NACA 4-digit input.
- LIFT_COEFFICIENT: The calculated lift coefficient (CL).
- MOMENT_COEFFICIENT_C4: The calculated moment coefficient about the quarter-chord (CM,c/4).
- ZERO_LIFT_ANGLE_OF_ATTACK_DEG: The calculated zero-lift angle of attack in degrees (αL=0).

5. Limitations of the Project

It is crucial to understand the limitations inherent in using Thin Airfoil Theory and the approximations made in this project:

- **Inherent Limitations of Thin Airfoil Theory:**
  - **No Drag Calculation:** The theory does not account for drag, as it assumes inviscid flow.
  - **Accuracy at Small Angles:** It is accurate only for small angles of attack (typically up to $10^\circ - 15^\circ$).
  - **No Stall Prediction:** It cannot predict the onset of stall or post-stall behavior.
  - **Incompressible Flow Only:** Not suitable for high-speed (compressible) flows.
  - **Idealized Flow:** Does not account for real-world effects like boundary layers, flow separation, or turbulence.
- **Project-Specific Approximations:**
  - **NACA 4-Digit Approximation:** For NACA 4-digit airfoils, the code uses a simplified parabolic camber line based *only* on the maximum camber percentage. Real NACA 4-digit airfoils have a more complex, piecewise parabolic camber distribution, which is not fully captured by this simplification. This means the results for NACA airfoils are approximate, especially for αL=0 and CM,c/4.
  - **Limited Airfoil Types:** The project only supports symmetric, generic parabolic camber, and a simplified NACA 4-digit representation. More complex airfoil series (e.g., NACA 5-digit, 6-series) have different camber line equations that are not implemented.