International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Optimization of Angle of Attack for Maximum Aerodynamic Efficiency on Symmetrical Airfoil

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DOI : https://doi.org/10.55248/gengpi.6.0225.0726

ABSTRACT

This study investigates the aerodynamic performance of a symmetrical airfoil by analyzing the lift, drag, and side force characteristics over a range of angles of attack (α). The primary goal is to identify the angle of attack that optimizes the lift-to-drag (L/D) ratio, which is a key measure of aerodynamic efficiency. The experiment was conducted by varying the angle of attack from -15° to 15° and measuring the corresponding forces acting on the airfoil.

Lift is the force that acts perpendicular to the airflow, while drag is the resistance force acting parallel to the airflow. Side force, though not typically a primary factor, is also measured, as it can influence the overall stability of the airfoil. By varying the angle of attack, the relationship between these forces changes, providing insight into the aerodynamic performance.

The analysis shows that the airfoil's lift increases with the angle of attack up to a certain point before stalling, where the airflow becomes turbulent and detaches from the surface. Drag, on the other hand, tends to increase with higher angles of attack due to greater resistance to airflow. The L/D ratio is critical in this context, as it quantifies how efficiently the airfoil generates lift relative to the drag it experiences.

The study's results indicate that the optimal angle of attack for this particular airfoil is 5°, as this angle corresponds to the maximum L/D ratio, which is approximately 10.34. At this angle, the airfoil achieves the highest efficiency in generating lift with minimal drag. Understanding this optimal angle is crucial for practical applications, such as aircraft design, where maximizing aerodynamic efficiency can lead to improved performance, fuel savings, and overall stability during flight.

1. Introduction

The angle of attack (α) plays a crucial role in determining the aerodynamic performance of airfoils and wings. Understanding the variation in lift and drag forces across different angles is essential for optimizing aircraft efficiency. This study aims to analyze experimental data and identify the angle of attack that yields the best aerodynamic performance. Katz, J., & Plotkin, A. [1] author provides a comprehensive overview of airfoil performance and aerodynamic principles, including lift, drag, and the impact of angle of attack on the L/D ratio. Selig, M. S., & McGranahan, D. A [2] in their paper investigates the aerodynamic characteristics of different airfoils, including lift-to-drag ratios, at various angles of attack, which is closely related to the study we have described.

Kuenzi, R. C., & Jang, L. H [3], article explores the aerodynamic properties of symmetrical airfoils at low Reynolds numbers and examines lift, drag, and side forces over a range of angles of attack, similar to the study outlined here. Anderson, J. D. [4], is a widely recognized resource for understanding the fundamental principles of flight, including airfoil aerodynamics, lift-to-drag ratios, and the effects of varying the angle of attack. Choi, J. H., & Kwon, O. S [5], this paper investigates how the angle of attack influences the aerodynamic performance of symmetrical airfoils, focusing on lift, drag, and the variation of L/D ratios across a range of angles. Ansys (2020) [6], Aerodynamic Performance of Airfoils, A computational study using CFD simulations to analyze the aerodynamic performance of airfoils, including lift-to-drag ratios at varying angles of attack, providing insights into the optimal operating conditions for airfoils.

Maughmer, M. D., & McKinney, R. J. (1993) [7] in their study focuses on the performance of symmetrical airfoils at various angles of attack, similar to present analysis, and examines how changes in angle influence aerodynamic characteristics like lift, drag, and side forces.

1.1 Low Subsonic Wind Tunnel and its Apparatus

The section features an aerodynamically contoured design with a contraction area ratio of 9:1. It begins with an inlet measuring 900mm x 900mm, which is gradually contoured down to 300mm x 300mm. To minimize axial and lateral turbulence and ensure smooth airflow into the section, honeycombs and screens are installed for maximum efficiency. The honeycomb's length-to-cell size ratio is maintained according to recommended standards. Additionally, a wire mesh is fitted to further enhance flow smoothness, aiding in achieving laminar flow. The screen is designed to be removable for easy cleaning. The duct is securely attached to the test section using a flange, with provisions for the effortless removal of the effuser and diffuser, allowing for separation from the test section when necessary. The entire structure is highly smoothened and painted for optimal performance.

The central section of the test area, located between the inlet duct (Effuser) and the diffuser, is secured with a flange. It has a cross-sectional dimension of 300mm x 300mm (inner) and a length of 550mm. Transparent windows are installed on both sides, allowing for easy attachment and observation of the models. This section also includes mounting points for the smoke chest. The traversing mechanism for the total pressure probe is mounted on the top. Additionally, holes are provided for securing models for various studies and for positioning the pressure probes.

The diffuser is the downstream section of the tunnel, which connects to an axial flow fan at its end. It begins with a 300mm x 300mm square cross-section at the test section and gradually expands to a 900mm diameter round section at the fan-driven end. The diffuser is flanged and bolted to the test section.

1.2 Wind Tunnel Balance:

The tunnel balance is a three-component system (measuring three forces) designed using electrical strain gauges, which display readings separately on a digital indicator. It is intended to measure Lift, Drag, and Side forces for airfoils, while for bluff bodies such as spherical, hemi-spherical, and flat disc models, it measures only drag force. These models are mounted on a vertical square rod positioned directly beneath the test section. The output signals from the Lift, Drag, and Side force measurements are connected to their respective multi-pin sockets on the control panel.

2. Methodology: Wind Tunnel Experiment

A symmetrical airfoil was analyzed with a velocity of 64.5 m/s in a low subsonic wind tunnel. The aerodynamic forces, including lift, drag, and side force, were recorded for seven different angles of attack. Using the given force values, the lift coefficient (CL), drag coefficient (CD), and side force coefficient (CS) were calculated. The lift-to-drag ratio (L/D) was then computed to determine the optimal operating condition.

Table-1: Lift, Drag Side Force & Moment Readings on Symmetrical Airfoil

Angle of Attack α	**COS α**	**Velocity**	**Lift Force (F_A) Kg**	**Drag Force Kg**	**Side Force Kg**	**A= S*C S=0.295m C=0.1m**	**F_T in Kg**	**C_L**	**C_D**	**C_S**
-15	0.965	64.5	-3.58	1.09	0.03	0.030	7.787	-0.460	0.140	0.004
-10	0.984	64.5	-3.14	0.86	0.04	0.030	7.940	-0.395	0.108	0.005
-5	0.996	64.5	-1.19	0.48	0.06	0.030	8.037	-0.148	0.060	0.007
0	1	64.5	1.03	0.33	0.03	0.030	8.069	0.128	0.041	0.004
5	0.996	64.5	3.66	0.35	-0.09	0.030	8.037	0.455	0.044	-0.011
10	0.984	64.5	3.92	0.85	-0.15	0.030	7.940	0.494	0.107	-0.019
15	0.965	64.5	2.93	1.78	-0.05	0.030	7.787	0.376	0.229	-0.006

3. Results and Discussion

The results of this study provide valuable insights into the aerodynamic performance of the symmetrical airfoil across a range of angles of attack (α). The data was collected for angles between -15° and 15°, and the corresponding lift, drag, and side force characteristics were analyzed to determine the optimal operating conditions for the airfoil.

3.1 Lift and Drag Characteristics:

As expected, the lift coefficient (Cl) increases with the angle of attack up to a certain threshold. At smaller angles, the airflow over the airfoil remains largely attached, resulting in a steady increase in lift. However, as the angle of attack continues to increase beyond a critical point, the airfoil begins to experience greater drag due to the increasing resistance from the airflow. This phenomenon occurs because the boundary layer becomes turbulent, leading to flow separation, which causes an increase in drag and a reduction in lift beyond the critical angle of attack.

3.2 Optimal Angle of Attack (5°):

The most significant observation from the results is the identification of the optimal angle of attack at 5°. At this angle, the airfoil achieves its highest lift-to-drag (L/D) ratio, which is approximately 10.34. This is an ideal condition for maximizing aerodynamic efficiency, as it suggests that the airfoil generates substantial lift while minimizing drag. The L/D ratio is a key parameter in aerodynamic design, and the fact that it peaks at 5° suggests that this is the most efficient operating point for the airfoil in the given range of angles.

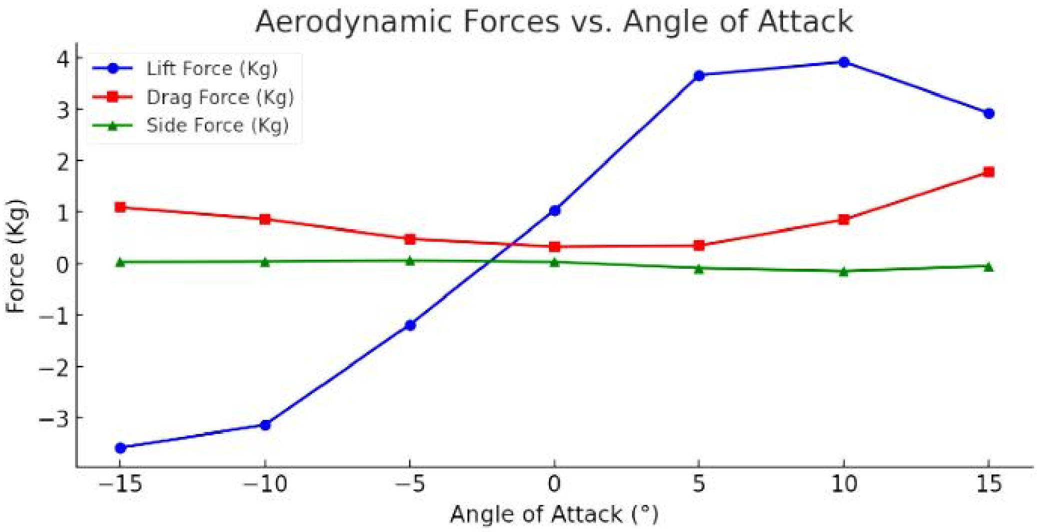
3.3 Effect of Higher Angles of Attack:

For angles beyond 5°, particularly at 10° and 15°, the L/D ratio begins to decline, indicating diminishing returns in terms of aerodynamic efficiency. As the angle of attack increases, the drag rises significantly due to the growing separation of the airflow, while lift continues to rise more slowly or plateaus. This effect highlights the importance of avoiding excessively high angles of attack in aerodynamic applications, as they lead to higher drag and reduced overall performance.

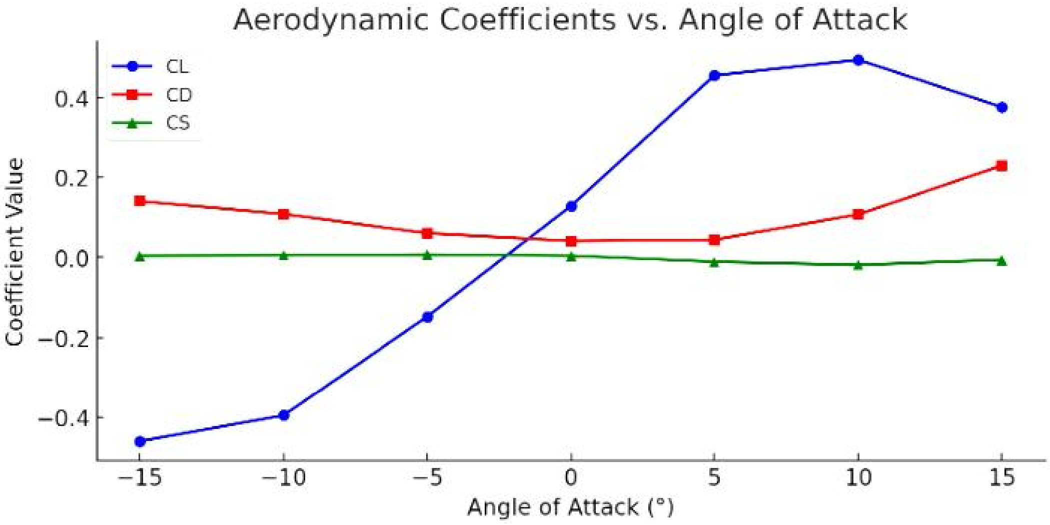
3.4 Side Forces:

The side force data collected during the study, while secondary to lift and drag, showed a consistent and predictable trend, aligning with the expected aerodynamic behavior. The side forces remained relatively small across the angle of attack range, indicating that the symmetrical airfoil did not experience significant lateral forces under the test conditions. This further emphasizes that the primary aerodynamic effects were dominated by lift and drag.

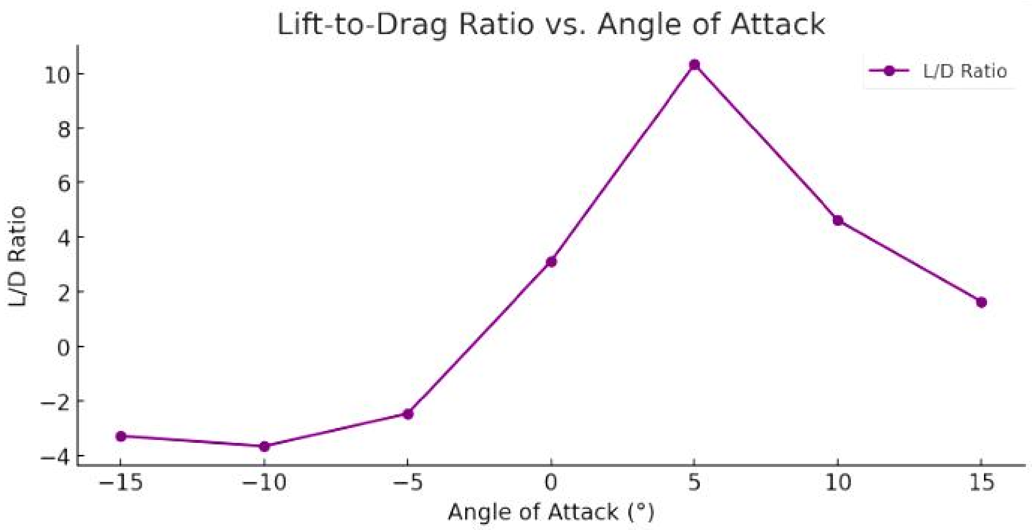
Three key plots were generated:



From the above plot, Aerodynamic Forces vs. Angle of Attack: Lift force increases with α, peaking at 10°, while drag force remains relatively low up to 5°.



From the above plot, Aerodynamic Coefficients vs. Angle of Attack: C_L shows a steady increase, while C_D remains minimal around α = 5° before rising significantly.



From the above plot, Lift-to-Drag Ratio vs. Angle of Attack: The L/D ratio reaches a maximum value of 10.34 at α = 5°, indicating the most efficient aerodynamic performance.

The results suggest that maintaining an angle of attack around 5° ensures an optimal balance between lift generation and drag minimization. Beyond this angle, increased drag reduces overall aerodynamic efficiency.

4. Conclusion & Future Scope

This analysis identifies α = 5° as the optimal angle of attack for maximum aerodynamic efficiency, achieving the highest L/D ratio of 10.34. This finding is critical for applications in aviation and aerodynamic design, where energy efficiency and performance are paramount. Further studies could incorporate flow visualization and computational fluid dynamics (CFD) simulations to validate and extend these results.

The results of this study have practical implications for the design of airfoils and their application in aircraft or other aerodynamic systems. By determining the optimal angle of attack for maximum L/D ratio (5°), engineers can enhance the efficiency of wing designs, ensuring that aircraft or other vehicles operate at their peak aerodynamic performance in various flight conditions. Additionally, the data from this study can serve as a reference point for the further optimization of airfoil shapes and materials, aiming to achieve even higher levels of efficiency.

5. References

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