Proceedings of the 4th International Conference on Applied Physics and Mathematical Modeling
DOI: 10.54254/2753-8818/2026.37586

The Influence of Airfoil Geometric Parameters on Lift Generation Mechanisms: An Analysis Based on Aerodynamic Principles

Yuhe Yang

RCF Experimental School, Beijing, China
yangyuhe@rdfzcygj.cn

Abstract. Through geometric optimization, airfoil designs directly affect efficiency, stability, and energy performance in aerospace and wind systems. More specifically, airfoil geometry optimization improves aerodynamic efficiency and reduces energy losses in aircraft and wind turbines, thus supporting technological innovation and cleaner energy utilization. This paper examines the physical mechanisms of lift generation and evaluates the influences of key airfoil geometric parameters, including maximum thickness, maximum camber, their chordwise locations, and trailing-edge configurations, on lift performance. To explain these effects, the analysis examines lift mechanisms from classical inviscid circulation models, including the Kutta-Joukowski theorem and thin-airfoil theory, to viscous-flow frameworks describing boundary-layer transition, shear stress distribution, and vorticity dynamics. At low Reynolds number conditions (0.3×10^5 to 0.8×10^5), viscous effects become significant and produce laminar separation bubbles that reduce aerodynamic efficiency. The results show that airfoil geometric parameters regulate lift generation mainly by reshaping surface pressure distributions and modifying boundary-layer stability, providing a physics-based foundation for optimized lifting surface design.

Keywords: airfoil geometry, lift generation mechanism, pressure distribution, boundary layer, low Reynolds number flow

1. Introduction

The demand for efficient aerodynamic lift has advanced fluid mechanics into a mature engineering discipline, with applications in aviation, wind energy, and turbomachinery. As the primary profile of lifting surfaces, airfoil geometry directly determines the lift-to-drag ratio and operational stability of engineering systems. Thus, airfoil design requires balancing geometric variables, aerodynamic constraints, and operating conditions to improve energy efficiency in aircraft and wind turbines. Traditionally, lift analysis has focused on high Reynolds number flows, where viscous effects are limited to thin boundary layers. With the emergence of new low-speed and small-scale applications, such as small unmanned aerial vehicles, high-altitude long-endurance aircraft, and small-scale wind turbines, airfoils increasingly operate in low to moderate Reynolds number regimes. Under these conditions, viscous effects produce complex flow phenomena, including laminar separation bubbles

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2026.37586

and nonlinear stall behavior, challenging conventional design assumptions and further increasing the difficulty of geometric optimization. Existing studies often emphasize either theoretical analysis or numerical optimization, leaving the influences of geometric parameters on flow fields, pressure distributions, and lift performance insufficiently characterized. This paper examines the relationship between airfoil geometry and lift generation by analyzing the physical origin of lift, the influence of key geometric parameters, and flow responses under different operating conditions. Based on this analysis, geometric design is linked with aerodynamic performance to provide guidance for airfoil optimization.

2. Lift generation mechanisms: pressure distribution and circulation theory

2.1. Pressure distribution as the direct source of lift

From an aerodynamic perspective, lift is generated mainly by the asymmetric pressure distribution over the airfoil surface [1]. To quantify this mechanism, the aerodynamic force on an airfoil can be decomposed into two surface contributions: pressure acting normal to the surface and wall shear stress resulting from viscous friction. Among these contributions, wall shear stress primarily affects skin-friction drag, whereas lift is governed by the imbalance of pressure forces between the upper and lower surfaces. This pressure imbalance is associated with the different flow conditions around the airfoil: accelerated flow along the suction surface reduces the local static pressure, whereas the slower flow near the lower surface maintains a relatively higher pressure. The integration of these pressure differences over the airfoil surface generates the net upward lift force.

2.2. Circulation theory and quantitative lift formulation

In inviscid potential flow, the Kutta–Joukowski theorem states that the lift force per unit span (L) is proportional to the circulation (Γ) around an airfoil:

$$L=\rho U_{\infty}\Gamma \tag{1}$$

where ρ is fluid density and U_{∞} is freestream velocity. This relationship quantitatively connects the aerodynamic lift magnitude to the circulation generated around the airfoil. However, the theorem assumes the existence of circulation and does not describe the physical process responsible for its formation in viscous flows.

To describe how airfoil geometry affects circulation, thin airfoil theory provides an analytical formulation for thin, moderately cambered profiles. By representing the airfoil as a vortex sheet distributed along its mean camber line, the theory derives the lift coefficient as a function of angle of attack (α). For a symmetric airfoil operating within the linear attached-flow regime:

$$C_L=2\pi\alpha \tag{2}$$

For a cambered airfoil, the mean camber line introduces a zero-lift angle of attack (α_0), giving:

$$C_L=2\pi(\alpha-\alpha_0) \tag{3}$$

This formulation shows that airfoil camber modifies the circulation distribution and shifts the lift curve by changing the zero-lift angle [2].

DOI: 10.54254/2753-8818/2026.37586

2.3. Viscous effects and circulation establishment

In real flows, viscosity establishes the circulation required for lift generation by enforcing the Kutta condition at the airfoil trailing edge. This process begins when an airfoil accelerates from rest: the inviscid flow solution places the rear stagnation point away from the sharp trailing edge, resulting in unrealistically large velocity gradients near the trailing edge. In contrast, viscous effects prevent this singular behavior by producing a finite boundary-layer response and forming a trailing-edge shear layer.

The separated shear layer rolls up into a starting vortex that is shed into the wake, while an equal and opposite bound circulation develops around the airfoil to satisfy Kelvin's circulation theorem. As a result, the steady circulation required by the Kutta condition is established. After the transient vortex shedding decays, the upper and lower surface flows leave the trailing edge smoothly, hence allowing inviscid circulation theory to describe the lift produced by the viscous flow.

Using a vorticity-based approach, vortex-force theory further relates aerodynamic forces to the distribution and transport of vorticity in the flow field. It indicates that lift is associated with the circulation generated around the airfoil and the resulting transfer of downward momentum to the wake. In this framework, the bound circulation around the airfoil corresponds to a net deflection of the surrounding flow, producing an opposite reaction force on the airfoil. This vorticity-based view links pressure, circulation, and wake momentum in lift generation.

3. Impact of airfoil geometric parameters on pressure distribution and lift generation

Through geometric changes, airfoil shape alters the flow field, pressure distribution, and boundary-layer behavior, thus determining lift performance. The effects of individual geometric parameters and their interactions are central to physics-based aerodynamic optimization.

3.1. Thickness distribution and leading-edge geometry

Through thickness variation, airfoil geometry controls the pressure distribution and boundary-layer response along the surface. Maximum airfoil thickness, typically expressed as a percentage of chord length (t/c), determines the strength of the pressure gradients near the leading edge. As thickness increases, the larger flow displacement around the stagnation region produces stronger acceleration and expansion over the upper surface. This increases the suction peak and lift potential at moderate angles of attack, but also intensifies the adverse pressure gradient during downstream pressure recovery. Under low Reynolds number conditions, these stronger gradients can exceed the available boundary-layer momentum, thus leading to early flow separation and increased drag [3]. In contrast, thinner airfoils reduce pressure drag but generate sharper leading-edge curvature and concentrated suction peaks, which promote localized separation bubbles and earlier stall.

Beyond thickness distribution, leading-edge geometry governs the initial flow acceleration and the development of the suction peak. A larger leading-edge radius spreads acceleration over a wider region, reducing the peak suction intensity and weakening the following adverse pressure gradient. As a result, flow separation is delayed and stall occurs more gradually. However, an excessively large radius increases frontal area and profile drag under cruise conditions. Conversely, a smaller leading-edge radius produces stronger suction peaks but reduces stall tolerance, making the airfoil more sensitive to angle-of-attack variations.

DOI: 10.54254/2753-8818/2026.37586

3.2. Camber distribution and lift capacity

Through camber variation, airfoil geometry modifies pressure distribution and circulation, thereby affecting lift capacity. In this context, camber is defined by the deviation of the mean camber line from the chord line, with maximum camber representing the largest offset between these two lines. As maximum camber increases, the aerodynamic asymmetry between the upper and lower surfaces becomes stronger, producing a larger pressure difference and higher circulation even at zero angle of attack. This shifts the lift coefficient curve upward and increases the achievable lift coefficient.

In addition to camber magnitude, the chordwise position of maximum camber determines how lift is generated and maintained. Locating maximum camber near the leading edge (30%–40% chord) promotes strong front-section acceleration and increases lift production, which is beneficial for short takeoff and landing applications [4]. However, the resulting rapid pressure recovery over the aft section can generate a stronger adverse pressure gradient and trigger trailing-edge separation. By contrast, rearward camber placement distributes pressure recovery more gradually and maintains boundary-layer stability over a larger portion of the chord. This method forms the basis of laminar-flow airfoils, which reduce cruise drag at the expense of lower maximum lift capability.

3.3. Trailing-edge geometry and aerodynamic moments

Through trailing-edge modification, airfoil geometry can alter the aerodynamic moment distribution and trim requirements. For a conventional cambered airfoil, the asymmetric pressure distribution along the chord generates a negative (nose-down) pitching moment. This moment produces wing torsional loads and requires a horizontal tail to generate a balancing force, resulting in additional trim drag. The nose-down moment is offset through a reflexed trailing-edge design that curves the mean camber line upward near the trailing edge. The upward curvature generates a local downward force at the rear section, which acts through a longer moment arm to offset the nose-down pitching moment. However, though reflexed trailing edges can reduce or eliminate the net pitching moment, particularly for tailless flying-wing configurations, they also weaken overall circulation and reduce the lift coefficient at a given angle of attack.

To quantify these geometric effects, airfoil shapes are represented by mathematical parameters that link geometry variations with aerodynamic performance. Methods including the NACA 4-digit series, PARSEC, Bézier curves, and Class Shape Transformation (CST) provide different levels of geometric control for quantitative aerodynamic optimization [5]. Among these approaches, CST is widely used because it preserves smooth surface geometry while enabling efficient exploration of complex design spaces.

4. Flow regimes and separation behaviors

The aerodynamic performance of a given airfoil geometry is not static; it varies significantly with angle of attack and Reynolds number. Therefore, the interaction between geometric design and flow conditions defines three distinct operational regimes with different lift generation characteristics.

4.1. Angle of attack and stall progression

At low to moderate angles of attack, flow remains attached over both airfoil surfaces. In this regime, the lift coefficient increases linearly with angle of attack, consistent with thin airfoil theory, which predicts a slope of approximately 2π per radian. The lift-to-drag ratio increases across this range and

DOI: 10.54254/2753-8818/2026.37586

reaches its maximum near the design cruise condition. Cambered airfoils generate positive lift at lower angles of attack than symmetric profiles, enabling more efficient cruise operation.

With increasing angle of attack, the adverse pressure gradient on the aft suction surface becomes stronger. Boundary-layer fluid loses momentum through viscous dissipation and can no longer overcome the increasing pressure, causing partial flow separation that often develops near the trailing edge and progresses upstream. This separation reduces the effective aerodynamic camber of the airfoil by modifying the pressure distribution, causing the lift curve to deviate from linearity. Lift growth decreases while drag increases due to the increasing contribution of pressure drag.

At the critical stall angle, the boundary layer can no longer sustain the adverse pressure gradient over the suction surface. The separation region rapidly expands toward the leading edge, covering a large portion of the upper surface with separated flow. This destroys the suction peak, reduces circulation, and produces a sharp decrease in lift coefficient accompanied by a rapid increase in drag. The resulting stall behavior is strongly influenced by leading-edge geometry, with different airfoil profiles exhibiting distinct separation patterns [6]. Accordingly, thick airfoils with rounded leading edges generally experience gradual trailing-edge stall, while thin airfoils with sharp leading edges tend to undergo abrupt leading-edge stall.

4.2. Low reynolds number flows and laminar separation bubbles

At low Reynolds numbers (0.3×10^5 to 0.8×10^5), viscous effects dominate over inertial effects, and the boundary layer over the forward airfoil remains laminar. Laminar boundary layers contain limited cross-stream momentum exchange and therefore have weak resistance to adverse pressure gradients, thereby making separation likely downstream of the maximum thickness or maximum camber location.

Once separated, the laminar shear layer becomes unstable and rapidly transitions to turbulent flow. Through enhanced turbulent mixing, the shear layer gains cross-stream momentum transport, replenishes near-wall kinetic energy, and enables reattachment further downstream. This sequence of laminar separation, transition, and turbulent reattachment forms a laminar separation bubble (LSB). The resulting bubble increases pressure drag and may introduce unsteady variations in lift and pitching moment. Its size and stability are governed by Reynolds number and surface pressure gradients. Under very low Reynolds number conditions, delayed transition allows the bubble to expand and significantly modify the effective airfoil shape. If reattachment fails, bubble bursting occurs, causing premature stall at angles of attack below the expected stall limit. To control this behavior, aerodynamic designers modify the upper-surface contour to introduce a transition ramp, creating a mild and controlled adverse pressure gradient that promotes gradual laminar-to-turbulent transition before large-scale separation develops.

4.3. Computational tools for aerodynamic analysis

To analyze flow separation, lift variation, and low-Reynolds-number effects, computational tools are required to resolve aerodynamic behaviors beyond analytical models. The coupling between airfoil geometry and flow development involves pressure distribution, boundary-layer evolution, and separation processes that cannot be fully captured by theoretical formulations alone. Numerical approaches provide detailed predictions of aerodynamic characteristics, including surface pressure distribution, boundary-layer behavior, and stall progression.

For airfoil-level analysis, XFOIL, developed by Drela, combines an inviscid panel method with a boundary-layer model to provide efficient aerodynamic predictions [7]. It is widely used for rapid

DOI: 10.54254/2753-8818/2026.37586

airfoil design and parameter screening, particularly for attached flows and mild separation at low Reynolds numbers. For more complex flow conditions, such as deep stall and large-scale separation, computational fluid dynamics (CFD) solvers with turbulence models provide higher-fidelity flow-field information by resolving detailed velocity, pressure, and vorticity distributions, although at significantly higher computational cost.

These methods quantify the aerodynamic effects of design changes [8]. By predicting variations in pressure distribution, boundary-layer development, and lift performance, they support physics-based airfoil optimization and help evaluate design trade-offs. They complement physical analysis by providing quantitative evaluations of lift generation.

5. Conclusion

This paper analyzes the physical mechanisms of lift generation and the effects of airfoil geometric parameters on aerodynamic performance. The analysis indicates that classical inviscid circulation theory provides the mathematical framework for lift calculation, while viscosity enables circulation establishment through the Kutta condition at the trailing edge. Accordingly, thickness distribution, leading-edge radius, camber magnitude and position, and trailing-edge configuration regulate lift characteristics by modifying pressure distribution, circulation, and boundary-layer stability. Under low Reynolds number conditions, laminar separation bubbles introduce additional constraints on airfoil design, requiring careful geometric control. To address these challenges, computational tools and optimization algorithms, including the GEO-DSGA framework, provide efficient approaches for exploring geometric design spaces. However, their accuracy relies on proper aerodynamic and geometric representation. Therefore, future studies should integrate aerodynamic theory, geometric parameterization, and computational optimization for improved lifting-surface design and analysis.

References

[1] Liu, T. (2021). Evolutionary understanding of airfoil lift. *Advances in Aerodynamics, 3*, Article 37, 1–45.
[2] Anderson, J. D. Jr. (2016). *Fundamentals of aerodynamics* (6th ed.). McGraw-Hill Education. New York.
[3] Alsahlani, A. A., Al-Saad, M., & Al-Mosallam, M. (2023, March). A study of impacts of airfoil geometry on the aerodynamic performance at low Reynolds number. *International Journal of Mechanical Engineering and Robotics Research, 12*(2), 146–155.
[4] Wozniak, J. (2021, April). Research and analysis of optimizing airfoil geometry and angle of attack to maximize short takeoff and landing capabilities. *International Journal of Engineering Research & Technology (IJERT), 10*(4), 289–297.
[5] Abbott, I. H., & von Doenhoff, A. E. (1959). *Theory of wing sections*. Dover Publications. New York.
[6] Kasthuriarachchi, K. V. (2026, March). *Theoretical analysis of the effect of angle of attack on lift and drag of a generic wing*. *Preprints.org*. https://doi.org/10.20944/preprints202603.0665.v1
[7] Drela, M. (1989). *XFOIL: An analysis and design system for low Reynolds number airfoils*. MIT Department of Aeronautics and Astronautics. Cambridge, MA.
[8] Dinler, Ö. B. (2025, October). Enhanced airfoil design optimization using hybrid geometric neural networks and deep symbiotic genetic algorithms. *Applied Sciences, 15*(20), 10882.