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Analysis on the Mechanism of Action of Bernoulli's Principle in the Generation of Wing Lift

Zichuan Huang

School of Materials and Metallurgy, University of Science and Technology Liaoning, Anshan, China
16641213727@163.com

Abstract. The generation of lift by wings is a crucial topic in aerospace engineering, and Bernoulli's principle is a classic theory used to explain lift generation, playing a significant role in both education and engineering. This paper introduces the fundamental concept and mathematical formulation of Bernoulli's principle, elaborating in detail on how it explains lift through the difference in pressure caused by varying airflow velocities over the upper and lower surfaces of a wing. The paper analyzes the status and limitations of Bernoulli's principle in explaining lift from perspectives such as wing shape, flow separation, boundary layers, and circulation, demonstrating that Bernoulli's principle alone cannot fully describe the entire process of lift generation and must be complemented by other theories such as Newton's third law and the Kutta–Joukowski theorem. By incorporating experimental data from NACA airfoils, the study examines pressure distribution and velocity variation under different angles of attack and airfoil shapes, verifying the validity of Bernoulli's principle under assumptions of low-speed, incompressible, and ideal fluid flow, while also exploring its modifications and extensions under high-speed, compressible, and viscous flow conditions. The research reveals that Bernoulli's principle provides a foundation for understanding lift mechanisms, but a complete explanation requires integration with other fluid mechanics theories. This study enriches fluid mechanics curricula, enhances students' understanding of aerodynamics, and provides guidance for improving wing design.

Keywords: Bernoulli principle, wing lift, fluid mechanics, Reynolds number, lift mechanism

1. Introduction

The rapid development of the aerospace industry has made aircraft design and performance enhancement one of the key research focuses in modern engineering. According to data from the International Air Transport Association (IATA), the global civil aviation market maintained an average annual growth rate of 4.2% between 2019 and 2023, with commercial aircraft deliveries increasing from 1,645 units in 2019 to 2,094 units in 2023, posing greater challenges for aerodynamics research [1]. The fundamental reason that aircraft can sustain flight lies in the ability of their wings to generate sufficient lift to counteract gravity. The mechanism of lift generation has long been a central topic in aerodynamics and fluid mechanics. How wing lift is produced remains a fundamental issue in aircraft design, directly affecting flight safety and economic efficiency. Among various theoretical explanations, Bernoulli's principle—due to its simplicity, clear physical imagery,

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and extensive experimental validation—has become the most widely adopted theoretical framework. As a fundamental theorem in fluid mechanics, Bernoulli's principle provides significant guidance for understanding wing lift; however, its applicability and limitations remain highly debated [2], requiring further exploration and synthesis with modern fluid mechanics theories. This paper combines theoretical analysis with a comprehensive review of literature, starting from the basic physical meaning of the Bernoulli equation and then systematically examining the complete physical chain: how wing shape modulates flow velocity distribution, how velocity differences create pressure differences, and how these pressure differences combine to generate lift. It further analyzes the effects of flight speed and Reynolds number on lift, as well as the weakening influence of turbulent boundary layers. The findings offer valuable references for both airfoil design and fluid mechanics education.

2. The theoretical basis of bernoulli's theory and the modulation mechanism of airflow velocity by the wing shape

2.1. The core principle of bernoulli and its applicable conditions

Bernoulli's principle, proposed by the Swiss mathematician Daniel Bernoulli in 1738, is a fundamental theorem in fluid mechanics concerning the conservation of energy in fluid flow. It states that for an ideal fluid in steady flow, the sum of pressure energy, kinetic energy, and potential energy remains constant along any streamline. The Bernoulli equation can be expressed as:

$$p + \frac{1}{2}\rho v^2 + \rho g h = C \tag{1}$$

where p is the static pressure, ρ is the fluid density, v is the fluid velocity, g is the gravitational acceleration, h is the height, and C is a constant. This formula illustrates the inverse relationship between fluid pressure and velocity: at the same elevation, neglecting gravitational potential energy, an increase in velocity results in a decrease in pressure, and vice versa.

Bernoulli's principle holds under certain conditions [3]. First, the fluid must be ideal, meaning it is incompressible and inviscid—its density remains constant and there is no friction between fluid particles. Second, the flow must be steady, so that physical quantities such as velocity and pressure at any point in the flow field do not change with time. Third, only flow along streamlines is considered; the equation applies only to different points on the same streamline. Fourth, the fluid system complies with the law of conservation of energy when no external work is done [4]. In aeronautical engineering, when an aircraft flies at low speeds (Mach number < 0.3), air can be treated as an incompressible fluid, and compressibility effects can be neglected. However, when an aircraft flies at high subsonic or supersonic speeds, air compressibility becomes significant, requiring corrections to the Bernoulli equation for compressible flow. Additionally, since real fluids are viscous, energy losses due to viscosity within the boundary layer cause discrepancies between Bernoulli's predictions and actual conditions. Therefore, for accurate calculations, boundary layer theory and boundary layer corrections must also be taken into account.

2.2. Wing shape characteristics and the mechanism of flow velocity difference between upper and lower surfaces

The geometric shape of the wing is one of the key factors affecting lift generation. Typically, the wing cross-section features an asymmetric airfoil with a more curved upper surface and a relatively

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flat lower surface. Due to this structural characteristic, the airflow over the upper and lower surfaces travels along different paths and experiences different curvatures. When a uniform incoming flow reaches the leading edge of the wing, it splits into two streams at the stagnation point—one flowing over the upper surface and the other under the lower surface. The airflow along the upper surface must travel a longer, more curved path, while the airflow on the lower surface follows a shorter, straighter path. According to the continuity equation, for incompressible flow, the cross-sectional area of the streamtube is inversely proportional to the flow velocity. The curved shape of the upper surface reduces the cross-sectional area of the streamtube, thereby accelerating the airflow to maintain mass conservation.

The presence of an angle of attack intensifies the velocity difference between the upper and lower surfaces [5]. The angle of attack is defined as the angle between the chord line of the wing and the direction of the oncoming airflow. At a positive angle of attack, the lower surface faces directly into the incoming flow, creating a high-pressure region that reduces the airspeed, while the upper surface, influenced by both the wing's shape and the angle of attack, features denser streamlines and significantly increased flow velocity. According to the Civil Aviation Administration of China's 2020–2023 Statistical Report on Aviation Industry Development [6], modern commercial airliners typically maintain an angle of attack between 2° and 5° during cruise, and can reach 15° to 20° during takeoff and landing. The pressure differential caused by different angles of attack can reach several thousand pascals. Taking a typical takeoff speed of 280 km/h for a commercial aircraft as an example, the pressure difference between the upper and lower surfaces at a high angle of attack during takeoff can exceed 4,000 Pa, providing sufficient lift for flight. The velocity difference primarily arises from the fluid's response to the geometric boundary conditions of the wing; the wing's shape alters the velocity distribution of the flow field, generating low-pressure suction on the upper surface and high-pressure thrust on the lower surface. However, explaining the velocity difference solely based on path length is problematic, since fluid particles do not reach the wingtips simultaneously. In reality, the velocity difference results from a combination of factors including circulation generation, vortex formation, and the development of viscous boundary layers [7].

3. Analysis of key factors in lift generation

3.1. From velocity difference to pressure difference: quantitative analysis of bernoulli's equation

Figure 1 illustrates the Bernoulli mechanism and flow velocity modulation principle behind wing lift generation. The difference in airspeed between the upper and lower surfaces of the wing results in a pressure differential, which can be described by the Bernoulli equation. Neglecting gravity, during level flight, the Bernoulli equation reduces to a balance between the pressure term and the kinetic energy term.

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{2}$$

The lift is obtained by integrating the pressure difference along the span of the wing. Since the flow velocity on the upper surface is greater than that on the lower surface $v_{up} > v_{down}$, the pressure on the upper surface becomes lower than that on the lower surface, resulting in a net upward pressure difference. The lift per unit span is the integral of the pressure difference across the chord length of the wing. The lift coefficient C_L characterizes the dimensionless lift properties and depends on the airfoil shape, angle of attack, and Reynolds number.

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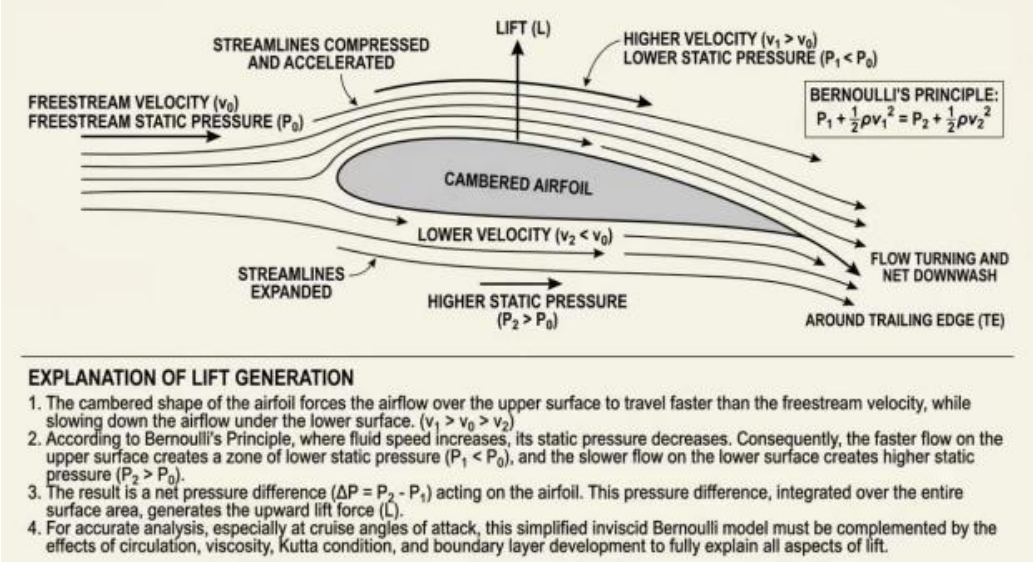


Figure 1. The bernoulli mechanism of wing lift generation and the principle of flow velocity modulation

The pressure distribution in an actual flow field is complex [8]. At the stagnation point at the leading edge of the wing, the flow velocity drops to zero and the pressure reaches its maximum value, approaching the total pressure. At the point of maximum curvature on the upper surface, the flow velocity is highest and the pressure is lowest. At the trailing edge, due to boundary layer separation and wake vortex formation, the pressure partially recovers but not completely. The pressure coefficient C_p, defined as the ratio of local pressure to the freestream dynamic pressure, clearly reveals the variation of pressure along the chord length through its distribution curve [9]. According to NACA airfoil data released by NASA Langley Research Center in 2021, at an angle of attack of 4° and a given Reynolds number 3×10^6, the minimum pressure coefficient on the upper surface of the NACA 2412 airfoil can reach -1.2, while the maximum pressure coefficient on the lower surface is 0.8; the integrated pressure difference between the upper and lower surfaces corresponds to the lift force. It should be noted that Bernoulli's equation applies only to inviscid, incompressible flows relating pressure and velocity. In regions such as the boundary layer, where viscous effects dominate, after shock waves where compression occurs, or in separated flow zones with complex dynamics, the Navier-Stokes equations combined with turbulence models must be used for accurate solutions—this remains the core task of current computational fluid dynamics.

3.2. Quantitative effect of flight speed on lift magnitude

Flight speed is one of the key factors determining lift, and lift is directly proportional to the square of the flight speed. According to the lift formula, the lift acting on the wing is:

$$L = \frac{1}{2}\rho v^2 S C_L \tag{3}$$

In the equation, L represents lift, ρ is air density, V is flight velocity, S is the wing reference area, and C_L is the lift coefficient. This indicates that, with all other factors constant, when the flight velocity doubles, the lift becomes four times its original value. This quadratic relationship significantly affects aircraft takeoff, landing, and cruising performance.

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Commercial airliners typically have a takeoff speed of 250–300 km/h and a cruising speed of 850–900 km/h. Taking the Boeing 737 as an example, its takeoff speed is approximately 270 km/h, at which sufficient lift must be generated to overcome a takeoff weight of around 70 tons. According to the International Standard Atmosphere, during cruise at an altitude of 10,000 meters, although air density is only about 30% of that at ground level, the cruising speed increases to approximately 870 km/h. The increase in the square of velocity compensates for the loss of lift caused by reduced air density [10]. The effect of speed on lift is also evident in stall behavior: if the flight speed falls below the stall speed, no increase in the angle of attack can generate sufficient lift. At this point, flow separation causes a sudden drop in the lift coefficient, placing the aircraft in a stalled condition. Stall speed is inversely proportional to the square root of the maximum lift coefficient; therefore, increasing the maximum lift coefficient reduces the stall speed, which is a primary goal in designing high-lift devices. Modern commercial aircraft use coordinated deployment of leading-edge slats and trailing-edge flaps, enabling the maximum lift coefficient to rise from 1.5 in cruise configuration to 2.8 in takeoff and landing configurations. This reduces the stall speed by approximately 40%, significantly improving low-speed handling and runway adaptability [11].

3.3. The influence of reynolds number variation on lift characteristics

The Reynolds number is a dimensionless quantity that represents the ratio of inertial forces to viscous forces in a fluid, defined as follows:

$$\mathrm{Re} = \frac{\rho v L}{\mu} \tag{4}$$

Here, ρ is the fluid density, V is the characteristic velocity, L is the characteristic length (typically the wing chord), and μ is the dynamic viscosity. The magnitude of the Reynolds number determines the development of the boundary layer, the location of flow separation, and the onset of turbulent transition, thereby influencing properties such as lift and drag.

Different ranges of Reynolds numbers correspond to different flow conditions and patterns of lift variation. Low Reynolds number flows typically occur in small drones or model aircraft ($\mathrm{Re} < 10^5$), where viscous forces dominate, the boundary layer is thick and prone to separation, resulting in a low lift coefficient and a high drag coefficient [12]. Moderate Reynolds number flows ($10^5 < \mathrm{Re} < 10^7$) are characteristic of most general aviation aircraft and light transport planes, in which the boundary layer transitions from laminar to turbulent flow; turbulent boundary layers exhibit better resistance to separation, significantly increasing the maximum lift coefficient. High Reynolds number flows ($\mathrm{Re} > 10^7$) apply to large commercial passenger aircraft or military transport planes, where boundary layer transition occurs earlier and fully developed turbulence results in relatively constant lift but with high sensitivity to surface roughness or contamination.

Table 1. Typical application scenarios and lift characteristics across different Reynolds number ranges

Reynolds number range	Typical aircraft types	Boundary layer state	Boundary layer state	Lift-drag ratio
10^4–10^5	Micro drone	Fully laminar flow Easy to separate	0.8 - 1.2	8 - 12

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Table 1. (continued)

10^5–10^6	Glider, ultra-light aircraft	Laminar- turbulent transition	1.2 - 1.6	12 - 25
10^6–10^7	General aviation aircraft	Turbulent boundary layer development	1.5 - 2.0	15 - 20
10^7–10^8	Large commercial airliner	Fully developed turbulence	1.8 - 2.5	18 - 22

Table 1 presents examples of various aircraft. The influence of Reynolds number on the lift coefficient is primarily reflected in changes in the boundary layer separation point and differences in turbulence intensity. As the Reynolds number increases, the momentum transfer capability of the turbulent boundary layer strengthens, enabling it to withstand greater adverse pressure gradients without separation. This delays the separation point further downstream, increasing the effective area and thus enhancing the lift coefficient. According to test results from the European Wind Tunnel Association in 2023, for the NACA 0012 symmetric airfoil, as the Reynolds number increased from 10^5 to 10^7, the stall angle of attack was delayed from 8° to 15°, and the maximum lift coefficient rose from 1.1 to 1.5—an improvement of 36% [13]. In engineering design, the effect of Reynolds number must be considered. During wind tunnel testing, efforts should be made to match the Reynolds number as closely as possible to actual flight conditions. When necessary, Reynolds number correction formulas or computational fluid dynamics methods can be employed for supplementary analysis, ensuring that the designed lift performance meets requirements across the entire flight envelope.

4. The weakening effect of turbulent boundary layers on wing lift and its physical causes

4.1. Boundary layer transition and formation of turbulent boundary layers

During flow over a wing, changes in the boundary layer state are a key factor determining lift magnitude. When airflow passes over the wing surface, due to fluid viscosity, a thin region forms adjacent to the surface where the velocity is very low—this is known as the boundary layer. Near the leading edge of the wing, the flow within the boundary layer is typically laminar, with fluid particles moving along smooth streamlines and no macroscopic mixing between layers. However, as the airflow progresses along the wing surface, the boundary layer gradually thickens. When the Reynolds number exceeds a critical value or when disturbances such as surface roughness (edge dip method) or pressure gradient occur, the laminar boundary layer becomes unstable and transitions into a turbulent boundary layer [14]. According to wind tunnel test results from the aviation industry for 2019–2023, for civil passenger aircraft under cruise conditions, the chord-based Reynolds number generally ranges from 10^6 to 10^7. Within this range, the boundary layer transition typically occurs at 20% to 40% of the chord length from the leading edge.

Boundary layer transition is a complex flow instability phenomenon. After transition, the flow in a turbulent boundary layer exhibits significant disorder and three-dimensionality. Fluid particles not only move along the mainstream direction but also experience substantial lateral and normal fluctuations, greatly accelerating the exchange of momentum, energy, and mass. The velocity profile of a turbulent boundary layer is much fuller, with a very steep velocity gradient near the wall, resulting in significantly enhanced wall shear stress [15]. According to the 2021 aerodynamic research report on Commercial Aircraft Corporation of China (COMAC)'s C919 large passenger

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aircraft, the friction drag coefficient of a turbulent boundary layer is approximately 3 to 5 times that of a laminar boundary layer under similar conditions. This additional friction drag not only requires greater thrust to overcome but also alters the pressure distribution over the wing surface, but also alters the pressure distribution over the wing surface, thereby reducing lift.

4.2. Physical reasons for turbulent boundary layer reducing lift

The reduction in wing lift caused by turbulent boundary layers mainly results from two factors: first, the additional energy dissipation due to turbulent fluctuations alters the pressure field distribution; second, changes in the turbulent boundary layer's ability to resist adverse pressure gradients affect flow separation. On the upstream portion of the upper surface of a wing, after regions of accelerated airflow, an adverse pressure gradient typically occurs—where pressure increases in the direction of the flow [16]. Although turbulent boundary layers possess greater momentum transfer capability and theoretically can delay flow separation, turbulent fluctuations also consume significant flow kinetic energy. According to high Reynolds number airfoil experimental data released in 2022 by NASA's Langley Research Center, under the same angle of attack, the average lift coefficient of an airfoil with fully turbulent boundary layers is approximately 5%–8% lower than that of an airfoil with mixed laminar–turbulent boundary layers. This is because the higher Reynolds stresses within turbulent boundary layers suppress effective pressure recovery near the wall, reducing the peak suction pressure on the upstream portion of the wing's upper surface and thereby decreasing the pressure difference between the upper and lower surfaces.

A more pronounced weakening effect is observed in the influence of incoming flow turbulence on lift [17]. If the incoming flow contains a high level of turbulence, the boundary layer transition point occurs significantly earlier, resulting in turbulent boundary layers near the leading edge of the wing and causing nearly the entire wing to be in a turbulent state.

Table 2. Effect of different incoming flow turbulence intensities on the lift characteristics of the NACA0012 airfoil (Re=3×10^6,)

Incoming flow turbulence intensity (%)	Transition position (x/c)	Maximum lift coefficient C_Lmax	Lift coefficient slope (1/degree)	Stall angle of attack (degree)
0.1	0.35	1.52	0.108	14.2
0.5	0.22	1.47	0.104	13.8
1.0	0.15	1.41	0.099	13.2
2.0	0.08	1.33	0.092	12.5
5.0	0.02	1.21	0.083	11.6

Data Source: European Wind Tunnel Association Standard Test, 2023

Table 2 illustrates the effects of incoming flow turbulence intensity on other parameters. As the incoming turbulence intensity increases from 0.1% to 5.0%, the maximum lift coefficient decreases by approximately 20.4%, the lift slope decreases by about 23.1%, and the stall angle of attack reduces by roughly 2.6 degrees. The primary reason for these phenomena is that higher turbulence intensity accelerates boundary layer transition, increasing the proportion of turbulent boundary layer and enhancing turbulent dissipation. At larger angles of attack, although a turbulent boundary layer

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can delay separation, its inherent turbulent kinetic energy is insufficient to counteract strong adverse pressure gradients. Instead, premature transition results in reduced overall boundary layer kinetic energy, leading to earlier stall and a significant drop in the maximum lift coefficient. This poses a major limitation for commercial passenger aircraft, which require maximum lift during takeoff and landing.

5. Conclusion

This study systematically analyzes the role of Bernoulli's principle in the mechanism of lift generation by airfoils. The results indicate that Bernoulli's principle effectively explains the pressure difference caused by velocity variation and its contribution to lift under assumptions of low-speed, incompressible, and ideal fluid flow. However, a complete physical picture of lift requires integration of multiple theoretical perspectives, including Newton's third law, circulation theory, and viscous flow effects. The research also reveals significant influences of flight speed, Reynolds number, and incoming flow turbulence on lift characteristics. Nevertheless, this study has certain limitations: first, it primarily relies on the steady-state flow assumption, without adequately accounting for unsteady aerodynamic effects; second, its applicability under complex conditions such as high Mach numbers or strong flow separation remains insufficiently discussed. Future research could focus on lift generation mechanisms under multiphysics coupling, dynamic stall behavior in realistic atmospheric turbulent environments, and the development of high-accuracy lift prediction models integrating data-driven approaches with CFD, thereby advancing lift theory from idealized models toward practical engineering applications.

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