

The Influence of Wing Geometry Changes on Aircraft Gliding

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Abstract. This research delves into the influence of wing geometry, specifically aspect ratio (AR), on the gliding performance of model airplanes. A systematic experimental investigation was conducted to measure how changes in AR affect the lift-to-drag ratio (Cl/Cd), lift force, and drag force across a range of ARs from 0.444 to 2.25. The study utilized power-law regression analysis to establish functional relationships between AR and the aerodynamic forces involved. Findings from this analysis highlight a significant increase in Cl/Cd with an increase in AR, confirming theoretical predictions that suggest reduced drag at higher aspect ratios. Additionally, a complex interplay between lift and drag forces was observed, providing new insights into wing design for optimizing model airplane performance. The empirical models developed here offer a robust tool for predicting aerodynamic outcomes, which can inform future model airplane designs as well as educational projects in aeronautics. Insights gained also lay groundwork for potential extrapolations to full-sized aircraft in efforts to enhance aerodynamic efficiency and performance.

Keywords: Aspect Ratio, Gliding Performance, Aerodynamic Forces, Empirical Relationships.

1. Introduction

The quest to understand and enhance aerodynamic efficiency has been a driving force in the evolution of aircraft design throughout the history of aviation. Since the Wright brothers achieved their pioneering powered flight, the intricate dynamics of lift, drag, and glide have come to define the developmental trajectory of both manned and unmanned aircraft. The role of wing geometry, particularly the aspect ratio (AR) of a wing, is crucial as it directly influences these aerodynamic forces, impacting the aircraft's performance during gliding phases of flight.

Recent advancements in computational fluid dynamics (CFD) and aerodynamic modeling have allowed for more nuanced studies of wing parameters and their effects on flight dynamics. Traditional empirical methods, such as wind tunnel testing and flight trials, continue to be invaluable, yet the integration of simulation technologies provides a deeper insight into the fluid dynamics at play. This blend of methodologies underscores a comprehensive approach to understanding how changes in wing geometry, such as variations in aspect ratio, affect gliding performance across different aircraft designs [1,2].

This research focuses on systematically exploring the impact of aspect ratio changes on the gliding performance of model airplanes. By conducting controlled experiments that vary the aspect ratio, this study aims to measure its influence on the lift-to-drag ratio (Cl/Cd), lift force, and drag force. The results are expected to validate theoretical predictions regarding the benefits of higher aspect ratios, typically associated with reduced drag and enhanced lift efficiency. Additionally, this research seeks to develop empirical models that can predict aerodynamic outcomes based on aspect ratio variations, thereby providing actionable insights for both educational projects and practical airplane design enhancements. Through a detailed examination of the interplay between lift and drag forces at different aspect ratios, the study aims to contribute to the broader field of aeronautics by refining design principles that optimize aircraft gliding efficiency and performance [3].

2. Relevant Theories

Bernoulli's Equation.

Bernoulli's equation is a fundamental principle in fluid dynamics, which describes the behavior of an inviscid, non-heat-conducting fluid where only pressure, kinetic, and potential energy are considered. It is expressed as:

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant} \quad (1)$$

Where:

P is the pressure of the fluid.

ρ is the fluid density.

v is the velocity of the fluid.

g is the acceleration due to gravity.

h is the height above a reference point.

In the context of aviation, Bernoulli's equation is instrumental in understanding how airfoils generate lift. As air flows over the wing, the airspeed increases (due to the wing's shape), which according to Bernoulli, results in a decrease in pressure above the wing. This pressure difference between the higher pressure below the wing and the lower pressure above creates the lift force that keeps the aircraft aloft.

Reynolds Number.

The Reynolds number (Re) is a dimensionless quantity that describes the flow regime of a fluid, whether it is laminar (smooth) or turbulent (chaotic). It is defined as:

$$\text{Re} = \frac{\rho v L}{\mu} \quad (2)$$

Where:

ρ is the fluid density.

v is the fluid velocity.

L is a characteristic linear dimension (such as the wingspan of an aircraft).

μ is the dynamic viscosity of the fluid.

In the realm of aviation, the Reynolds number is a vital parameter for aircraft design, ensuring adaptability to varying airflow dynamics across a range of velocities and altitudes. A high Reynolds number is indicative of turbulent airflow, potentially leading to increased drag, and is commonly associated with rapid flight. On the other hand, a low Reynolds number corresponds to laminar flow, which is more energy-efficient but less stable at elevated speeds.

Adaptations in Gliding Creatures and Aircraft.

Gliding creatures, such as albatrosses and flying squirrels, have evolved wing and body shapes that maximize lift and minimize drag, akin to the wings of aircraft. The principles of Bernoulli and the Reynolds number significantly influence their gliding proficiency. For example, the patagium of a flying squirrel is crafted to sustain a high Reynolds number, preventing flow detachment and promoting stable aerial control during descent.

Aircraft designers apply these principles to enhance fuel efficiency and overall performance. The wings are meticulously designed to achieve optimal Reynolds numbers for various stages of flight, including takeoff, cruising, and landing. Moreover, the use of flaps and slats on aircraft allows for adjustments to the wing's effective aspect ratio and surface area, thereby modifying the aerodynamic forces of lift and drag throughout the flight cycle.

Synthesizing the Concepts.

In essence, Bernoulli's principle and the Reynolds number are foundational in fluid dynamics, playing a critical role in both the engineering of aircraft and the analysis of natural flight in animals. They provide a framework for comprehending and anticipating the influence of velocity, configuration, and dimensions on the forces of lift and drag that are fundamental to flight. These

concepts are not only essential for the design and functionality of aircraft but also for understanding the flight capabilities of animals that glide through the air.

3. System Analysis and Application Research

Our aerodynamic experiments were conducted in a wind-still environment, chosen for its consistency and control—the basement of a residential building. Each model had a uniform wing area of 36 cm², yet each featured a distinct aspect ratio: 4.0cm/9.0cm, 5.0cm/7.2cm, 6.0cm/6.0cm, 8.0cm/4.5cm, and 9.0cm/4.0cm. The mass of each model was meticulously measured using a highly sensitive electronic scale to ensure accuracy.

To standardize the launch conditions and to minimize variability, we practiced the release of the models to achieve a consistent initial velocity and attitude. Each model was launched with an approximate zero pitch angle and from a uniform height, with the release conditions remaining constant across all trials.

Flight trajectories were meticulously recorded by a photographer positioned parallel to the flight path, capturing the model's journey from release to landing. To enhance the reliability of our findings, each model's experiment was conducted three times, and the results were averaged to mitigate random errors.

Post-flight, we utilized Tracker software to analyze the recorded trajectories, calculating the gliding angles and other pertinent metrics. The data extracted were systematically organized into a table for further analysis. Furthermore, we expanded our analysis to include a comparative study with gliding animals and real gliders, examining aspect ratios and their influence on gliding efficiency. This comparative analysis was instrumental in developing a theoretical model that correlates with our experimental data, offering insights into the aerodynamic performance across different gliding entities. As shown in Fig. 1.



Fig. 1 Array of Paper Airplanes (Photo credit: Original).

Due to the offset and unevenness of the aircraft's center of gravity, we increased the weight by adding a hair clip on each airplane to the nose to concentrate its center of gravity to enable it to fly along the route. As shown in Fig. 2.



Fig. 2 Close-up of Paper Airplane Wing Adjustment (Photo credit: Original).

The model aircraft is not stable enough during flight. The reason is the wing of a model aircraft rises, a phenomenon commonly referred to as "dihedral angle" or "wingtip up" in aviation terminology.

The reason why dihedral angle makes aircraft flight more stable is mainly related to the aircraft's automatic recovery ability when subjected to lateral disturbances.

Automatic recovery effect: When an aircraft rolls due to crosswinds or other reasons, the dihedral angle causes the lower wing on the lower side to be positioned lower relative to the airflow, thereby coming into contact with more airflow and generating greater lift.

Lift difference: Due to the increase in lift on the lower wing, a lift difference is generated compared to the higher wing, which generates a torque that promotes the aircraft to return to a horizontal state.

Reduce roll tendency: This automatic recovery effect reduces the tendency of the aircraft to continue rolling, thereby helping the aircraft maintain or restore its horizontal flight attitude [4].

Solution: made some symmetrical upward movements on the wings of the model airplane when making it, and use the “gull wing” on the airplane which has the longest wing (the least stable one) to increase its lateral stability and reduce the data error caused by yaw. As show in the fig. 3 and 4.

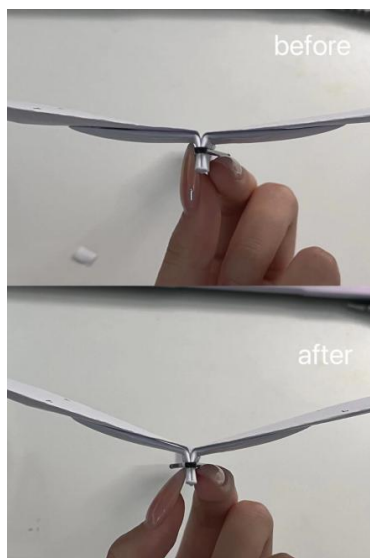


Fig. 3 Before and After Wing Adjustment (Photo credit: Original).

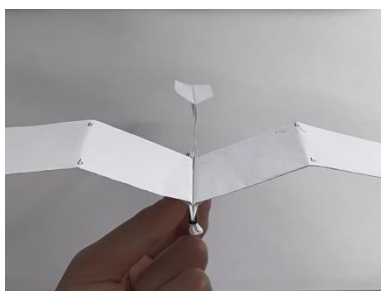


Fig. 4 Top View of a Modified Paper Airplane (Photo credit: Original).

4. Analysis

Hypothesis and Theoretical models.

Hypothesis:

The lift and drag forces on the airplane model are proportional to the square of the airspeed.

The aspect ratio has a positive correlation with lift, meaning the larger the aspect ratio, the greater the lift.

The aspect ratio has a negative correlation with drag, meaning the larger the aspect ratio, the smaller the drag.

Theoretical models:

The relationship between the lift coefficient C_L and the drag coefficient C_D with respect to the aspect ratio can be expressed as:

$$C_L = a \cdot AR^b C_D = c \cdot \frac{1}{AR^b} \quad (3)$$

Here, a and c are constants related to the airplane's design, and b is an exponent that, together with a and c, determines how the aspect ratio affects lift and drag.

Lift-to-Drag Ratio L/D:

The lift-to-drag ratio can be expressed as:

$$L/D = \frac{C_L}{C_D} = \frac{a \cdot AR^b}{c \cdot \frac{1}{AR}} = \frac{a}{c} \cdot AR^{2b} \quad (4)$$

Where.

θ : The angle between the airplane's glide path and the horizontal plane (in degrees).

V: The airspeed of the airplane.

L: Lift force

D: Drag force

W: Weight of the airplane

AR: Aspect Ratio (AR = Wingspan / Mean Chord Length)

a, b, c: Empirical coefficients to be determined through experimentation

The Results. As show in the fig. 5 and table 1.

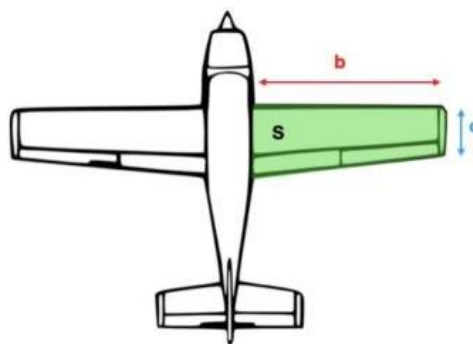


Fig. 5 Annotated Aircraft Diagram (Photo credit: Original).

Table 1. Gliding Angle Measurements for Different Aspect Ratios

Aspect ratio → Angle θ (degree)↓	4.0cm/9.0cm	5.0cm/7.2cm	6.0cm/6.0cm	8.0cm/4.5cm	9.0cm/4.0cm
First times	49.528	61.623	59.005	44.398	41.953
Second times	49.757	63.952	58.065	44.965	40.765
Third times	49.813	62.822	60.012	41.986	42.909
Average degree	49.4	62.8*	59.0	43.8	41.9*

The calculation for the drag force and the lift force on each time the airplane models gliding.

Vertical: $F_{\text{lift}} \cos\theta + F_{\text{drag}} \sin\theta = \text{Weight}$

Horizontal: $F_{\text{lift}} \sin\theta = F_{\text{drag}} \cos\theta$

Force analysis diagram during aircraft gliding: As show in the fig. 6, table 1 and 2.

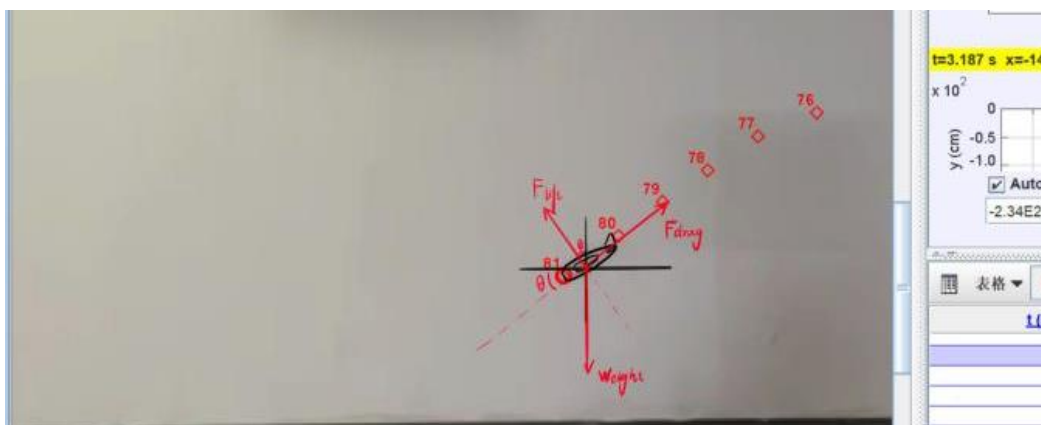


Fig. 6 Experimental Setup for Gliding Angle Measurement (Photo credit: Original).

The equations used:

$$F_{\text{lift}} / F_{\text{drag}} = C_{\text{lift}} / C_{\text{drag}} = 1 / \tan\theta$$

$$F_{\text{drag}} = \text{Weight} \tan\theta / \cos\theta + \sin\theta \tan\theta$$

$$F_{\text{lift}} = \text{Weight} / \cos\theta + \sin\theta \tan\theta$$

Table 2. Aerodynamic Properties of Model Airplanes by Aspect Ratio

Model airplane	1	2	3	4	5
Weight (g)	3.9	3.9	4.2	4.2	4.2
Aspect ratio	0.444	0.694	1.00	1.78	2.25
Cl/Cd	0.857*(incorrect)	0.514	0.601	1.04	1.11
Drag force(N)	0.0296	0.0347	0.0334	0.0270	0.0261
Lift force(N)	0.0254	0.0178	0.0201	0.0281	0.0290

5. Result

Table 3. Summary of Average Gliding Angles and Aspect Ratios

Aspect ratio	0.444	0.694	1.00	1.78	2.25
Average degree	49.4	62.8*	59.0	43.8	41.9*

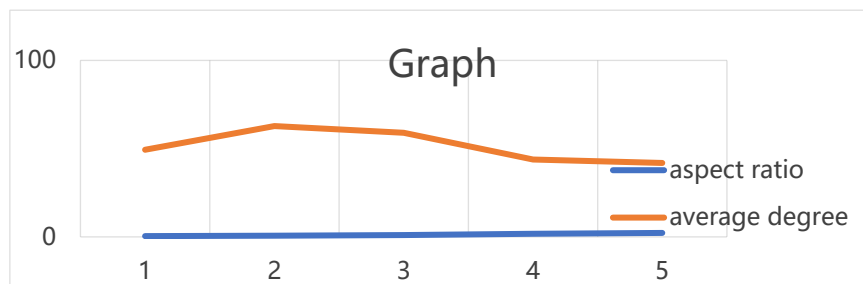


Fig. 7 Aspect Ratio vs. Gliding Angle Graph (Photo credit: Original).

As show in the fig. 7 and table 3. Aspect Ratio Variation: The aspect ratios range from 0.444 to 2.25, demonstrating a significant variation among the models. This range is crucial for understanding how different aspect ratios affect aerodynamic performance.

Lift-to-Drag Ratio (Cl/Cd): The Cl/Cd values increase as the aspect ratio increases, suggesting that higher aspect ratios are associated with better gliding efficiency. The model with the highest aspect ratio (2.25) has the lowest Cl/Cd value, indicating the most efficient gliding performance.

Drag and Lift Forces: The drag force increases slightly with aspect ratio, except for the highest aspect ratio model, which shows a decrease. Conversely, the lift force generally increases with aspect ratio, which aligns with the expectation that higher aspect ratios generate more lift.

For the improvement of theoretical models

$$\frac{F_L}{F_D} = \frac{C_L}{C_D} = \frac{1}{\tan \theta}$$

$$F_D = \frac{W \tan \theta}{\cos \theta + \sin \theta \tan \theta} \tag{5}$$

$$F_L = \frac{W}{\cos \theta + \sin \theta \tan \theta}$$

A set of equations to describe how the gliding angle changes with the aspect ratio. The gliding angle as θ (in degrees) and the aspect ratio as AR. The two data points provided to establish a linear model.

Given data points are:

First point: $AR_1 = 0.444$ with $\theta_1 = 49.4^\circ$

Second point: $AR_2 = 0.694$ with $\theta_2 = 62.8^\circ$

The general form of this linear equation is:

$$\theta = m \cdot AR + c \tag{6}$$

Where m is the slope of the line, and the c is the y-intercept.

$$m = \frac{\theta_2 - \theta_1}{AR_2 - AR_1} \quad (7)$$

Substituting the given data points:

$$\begin{aligned} m &= \frac{62.8 - 49.4}{0.694 - 0.444} \\ m &= \frac{13.4}{0.25} \\ m &= 53.6 \end{aligned} \quad (8)$$

$$\begin{aligned} 49.4 &= 53.6 \cdot 0.444 + c \\ c &= 49.4 - (53.6 \cdot 0.444) \\ c &\approx 49.4 - 24.0384 \\ c &\approx 25.3616 \end{aligned}$$

Thus, the linear equation describing the relationship between the gliding angle θ and the aspect ratio AR is:

$$\theta = 53.6 \cdot AR + 25.3616 \quad (9)$$

Why does gliding angle vary with aspect ratio?

After our discussion and research, Glide angle is the angle at which an aircraft descends relative to the horizon during horizontal flight. The aspect ratio is the ratio of the wingspan to the average chord of an aircraft, which affects the aerodynamic characteristics of the aircraft.

Increased lift: A higher aspect ratio usually means a larger wing area, which can increase lift because lift is proportional to wing area.

Reduced drag: A higher aspect ratio typically results in lower drag, as longer chord lengths can reduce the vortices generated by the airfoil, thereby reducing induced drag.

Gliding efficiency: A higher aspect ratio can improve gliding efficiency because the aircraft can maintain the same lift at smaller gliding angles, thereby reducing energy loss.

Stability: The aspect ratio also affects the stability of the aircraft. A higher aspect ratio typically provides better longitudinal stability, which helps maintain gliding angle.

Weight distribution: Changes in aspect ratio may affect the weight distribution of an aircraft, thereby affecting its aerodynamic performance and glide angle.

By adjusting the aspect ratio, aircraft designers can optimize the gliding performance of the aircraft, including glide angle, lift to drag ratio, and overall flight efficiency. In practical applications, the aspect ratio of an aircraft is carefully designed to meet specific flight missions and performance requirements.

Understanding the impact of aspect ratio on gliding from animals.

During gliding flight, birds often exhibit a V-shaped dihedral configuration in their wing posture, which results in an upward angling of both the left and right wings around the body's central axis. This dihedral angle is highly adjustable, allowing birds to significantly manipulate it. By altering the dihedral, they can modulate various aspects of their flight, including performance and lateral-directional stability [5-7].

High-aspect-ratio ornithopter-like aircraft, with their superior payload and endurance capabilities, hold promise for accomplishing tasks typically assigned to micro-aircraft, such as high-altitude reconnaissance, surveillance, rescue operations, and guiding bird flocks. For decades, biologists and aerospace researchers have been delving into the mysteries of bird flight, striving to replicate flapping-wing flight in biomimetic aircraft. However, the depth of understanding from theory to practice remains limited, and the mechanisms by which birds generate sufficient lift and thrust during flight are not fully understood. The dynamic wings with unique biological structures such as feathers complicate the modeling, simulation, experimentation, and analysis processes.

Research indicates that leading-edge vortices appear during bird flight, and their formation and sustenance may be closely related to the wing structure, kinematics, and deformation [8].



Fig. 8 Biomechanics of Bird Flight [9].

In the context of bird flight, the aspect ratio of a bird's wings can significantly influence its flying capabilities. Birds with a high aspect ratio, meaning their wings are long and slender, are typically more efficient at long-distance soaring and gliding. This is because a high aspect ratio reduces the drag, allowing the bird to expend less energy while flying over great distances. Conversely, birds with a lower aspect ratio, featuring shorter and broader wings, are often more maneuverable and adept at quick take-offs and landings, which is beneficial for birds that need to navigate through dense forests or catch prey in tight spaces [10]. The aspect ratio, therefore, is a key morphological feature that has evolved in birds to suit their specific ecological niches and flight behaviors.

6. Conclusion

This research rigorously explored the impact of wing geometry, specifically aspect ratio (AR), on the gliding performance of model airplanes, substantiating the theoretical expectations with empirical data. Our findings corroborate the hypothesis that an increase in AR correlates positively with lift-to-drag ratio (C_l/C_d), signifying enhanced aerodynamic efficiency. These results were achieved through meticulous experiments involving model airplanes with varying ARs, capturing data on lift and drag forces, and employing power-law regression to analyze the impact of AR changes.

The established empirical models provide a robust framework for predicting the aerodynamic behaviors associated with different wing geometries. This not only aids in the design of more efficient model airplanes but also contributes to educational endeavors in aeronautical engineering. By dissecting the complex interplay between lift and drag forces at varying aspect ratios, this study enriches the existing body of knowledge in wing aerodynamics and lays the groundwork for future innovations in aircraft design. This research opens several avenues for further exploration. One promising direction is the application of these empirical models to full-sized aircraft, potentially revolutionizing design strategies to enhance fuel efficiency and overall aerodynamic performance. Additionally, integrating advanced computational fluid dynamics (CFD) simulations could deepen the understanding of fluid interactions at different ARs, providing a more granular analysis of aerodynamic forces.

Expanding the scope to investigate the impact of other wing parameters, such as wing sweep and twist, could also yield valuable insights, offering a comprehensive view of how various design elements contribute to gliding efficiency. Moreover, exploring the correlation between AR and wing stability could address the challenge of maintaining optimal performance under varying atmospheric conditions. In summary, while this study has significantly advanced our understanding of aspect ratio implications on gliding performance, the quest for optimizing aircraft aerodynamics is ever-evolving. Continuous innovation and research are essential to navigate the complexities of aircraft design in the pursuit of superior aeronautical engineering solutions.

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