Exploring Aerodynamics: The Impact of Aspect Ratio on Paper Airplane Flight Dynamics

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Abstract. Aspect Ratio significantly influences the aerodynamic performance of aircraft, dictating crucial factors such as lift and glide efficiency. This paper investigates the impact of varying Aspect Ratios on the Gliding Angle of paper airplanes, serving as analogs for larger aircraft. Different models of paper airplanes, each with unique Aspect Ratios, are constructed and tested under controlled conditions to measure their aerodynamic responses. The experiment employs video tracking and statistical analysis to precisely gauge the glide angles and correlate these with Aspect Ratios. Results indicate that an increase in Aspect Ratio generally leads to a decrease in the Gliding Angle, suggesting enhanced aerodynamic performance. However, this relationship exhibits complexity beyond a straightforward linear association, hinting at the nuanced interactions between wing geometry and airflow dynamics. Further, the study explores the Lift to Drag ratio, revealing its dependency on the glide dynamics shaped by Aspect Ratio variations. These findings contribute to a deeper understanding of flight mechanics, potentially guiding the design of more efficient gliders and other aircraft by optimizing Aspect Ratios to suit specific flight requirements.

Keywords: Lift to drag ratio, Aspect ratio, Tracker, airplane performance and design.

1. Introduction

Gliding, an aviation mode devoid of powered mechanisms, leverages aerodynamic principles to sustain flight by converting gravitational potential energy into kinetic energy. This mode of flight does not rely on engine power but on the structural and design efficiency of the aircraft, particularly its wings. The Aspect Ratio (AR), a critical design factor defined as the square of the wing span divided by the wing area, profoundly impacts an aircraft's aerodynamic performance by influencing the lift and glide characteristics [1]. Higher ARs are typically associated with better performance at lower speeds due to increased lift, making them ideal for gliders designed to maximize air time and distance covered from a given altitude [2].

Recent studies have explored various wing geometries to optimize aircraft performance, focusing on enhancing the lift-to-drag ratio—a key determinant of an aircraft's efficiency. This ratio defines how far an aircraft can glide for every unit of altitude lost, which is pivotal for unpowered flight dynamics. Traditional aircraft and gliders typically exhibit ARs ranging from 10 for commercial planes to 20 for high-performance gliders, indicating a trend towards elongated wings to reduce drag at higher speeds [3,4]. These studies have laid the groundwork for understanding how different wing shapes and sizes affect aircraft performance across different flight regimes.

This paper introduces a novel approach by using paper airplanes as analogs to study the impact of varying Aspect Ratios on the Gliding Angle and the Lift to Drag ratio, providing insights into basic aerodynamic principles applicable to larger, more complex aircraft designs. Through controlled experiments using paper airplanes of different ARs, this study aims to explore the nuanced relationship between AR and flight performance, employing video tracking and statistical analysis to accurately measure glide angles and correlate these observations with theoretical aerodynamic models [5, 6]. By examining these relationships, this research contributes to a broader understanding of flight dynamics, potentially guiding future aircraft design to optimize performance based on specific operational requirements.

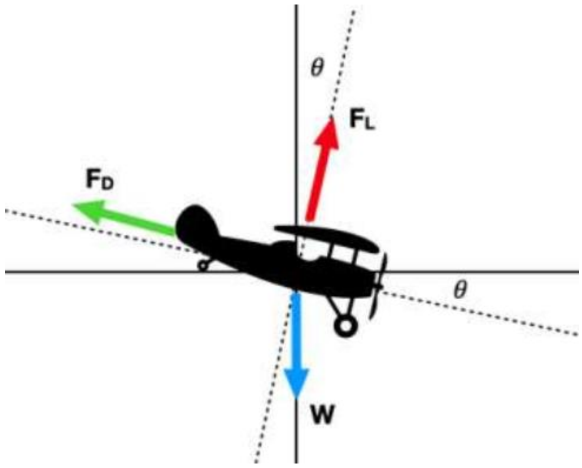

Fig. 1 Where θ is glide angle (Photo credit: Original).

2. Methods

2.1. Flight Dynamics Definitions

Due to free body diagram above (Fig1),
Vertical:

$$-\mathrm{W}+F_{Lift}\cos(\theta)+F_{Drag}\sin(\theta)=0 \tag{1}$$

Horizontal:

$$\mathrm{F_{Lift}}\sin(\theta)=F_{drag}\cos(\theta) \tag{2}$$

Due to newton's third law, the normal and tangential components of the forces canceling each other and align with the same axis, so aircraft can fly and stay in air with no vertical and horizontal accelerations [7,8].

The Lift and Drag of aircraft can be find as:

$$F_L = C_L \cdot \frac{1}{2} \cdot \sigma_{air} \left(U_{aircraft}\right)^2 \cdot A_{wing} \tag{3}$$

$$F_D = C_D \cdot \frac{1}{2} \cdot \sigma_{air} \left(U_{aircraft}\right)^2 \cdot A_{wing} \tag{4}$$

Where $\mathrm{F_L}$ is lift force, $\mathrm{F_D}$ is drag force, σ is air density, U is velocity of aircraft relative to wind, and A is wing area. $\mathrm{C_L}$ and $\mathrm{C_D}$ are lift coefficient and drag coefficient [9].

Rearrange eq3 and eq4 by eq2 and we can get the Lift to Drag ratio:

$$\frac{\mathrm{C_L}}{C_D} = \frac{1}{\tan(\theta)} \tag{5}$$

And continues with:

$$\frac{\mathrm{F}_L}{F_D} = \frac{1}{\tan(\theta)} \tag{6}$$

According eq1, if the weight of paper airplane are known, the lift force and drag force can be calculate with only one variable θ.

$$F_D = \frac{W \cdot \tan(\theta)}{\cos(\theta)+\sin(\theta)\cdot\tan(\theta)} \tag{7}$$

$$F_{\mathrm{L}} = \frac{W}{\cos(\theta) + \sin(\theta) \cdot \tan(\theta)} \tag{8}$$

For each aircraft, Aspect Ratio are define as:

$$\mathrm{AR} = \frac{b}{c} = \frac{b^2}{S} \tag{9}$$

Where AR is Aspect ratio, b is length of wing, c is chord, and S is vertical project wing area.

2.2. Experiment Setup

In this study, five different paper airplanes with varying aspect ratios and wing areas were analyzed. The dimensions were measured using a ruler, and the results were averaged. The figure below shows the five different paper airplanes used in this study. The wing area was calculated using the Decomposition Method, after which the aspect ratio was determined [10]. Aircraft A, B, C, and E exhibit a wide range of aspect ratios, while Aircraft C and D have similar aspect ratios but significantly different wing areas. These variations in characteristics are beneficial for the experiment, helping to obtain valuable results. As show in the fig.2.

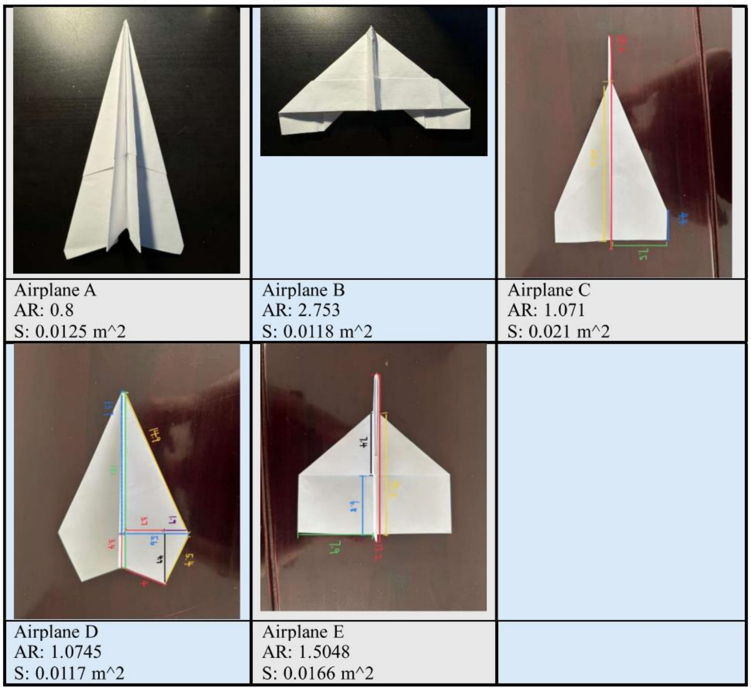

Fig. 2 Paper Airplane Designs and Their Aspect Ratios (Photo credit: Original).

A camera will record each flight, and the glide angle of each aircraft will be determined based on its trajectory, aligned parallel to the aircraft's initial position. To ensure accuracy, the flight tests will be conducted in an indoor, windless environment to minimize the influence of wind. An electronic balance will be used to measure the weight of each aircraft, with the results averaged. The measurements indicate that each aircraft weighs 4.0 grams.

Before the main experiment, multiple practice flights will be conducted to ensure that the initial velocity of the aircraft remains within a consistent range, as the aircraft will be launched manually. The camera will record several flights for each aircraft, and the five with the best launch angles will be selected for analysis. Statistical methods will then be used to calculate the average and variation in the data.

The software Tracker will be used to track the aircraft's trajectory frame by frame in the video. This tool will extract the necessary information to calculate the values of lift coefficient (CL) and drag coefficient (CD) based on the computed glide angle. The glide angle will be calculated using the rise-over-run method, measuring the aircraft's displacement along the x and y axes using Tracker.

To make sure the experimental conditions can be efficiently constrained, there are several assumptions are made in this study:

The mass of each paper airplane remains constant 4 grams, which is the weight of original a4 paper.

There was no wind interference around during the experiment.

The record of flight trajectory in this experiment are in 2-dimansional, and the position of camera are stationary.

The initial speed of aircraft in each test are same.

The angle of attack (AOA) is one of the variables that can affect the lift-to-drag (L/D) ratio in the experiment. Since the calculation of the glide angle is based on the five most stable frames in the recorded trajectory, it is assumed that the AOA is zero during these frames.

The air conditions are 25 degree centigrade (room temperature), 1 atom sphere (sea level pressure) and 1.225 kg/m^3 air density.

2.3. Bird Experiment

For comparison with the aircraft, a video recording of a bird was used as an experimental sample. According to the research, the bird's average weight is approximately 10.1 kilograms, with an average wing area of around 0.24 square meters and an aspect ratio (AR) of 6. All aerodynamic performance, including lift force, drag force, and the lift-to-drag ratio, will be calculated based on the obtained glide angle by tracking its flight trajectory using Tracker software. As show in the fig.3.

Bird:

Trial #	Mass (kg)	Glide Angle (rad)	Glide Angle (deg)	FL (N)	FD (N)	CL/CD	S (m^2)	AR
1	10	0.464	26.565	87.7432965	43.8716756	1.999998753	0.24	6

Fig. 3 Aerodynamic Performance of a Bird in Flight (Photo credit: Original).

3. Results and Discussion

3.1. Glide Angle Variations

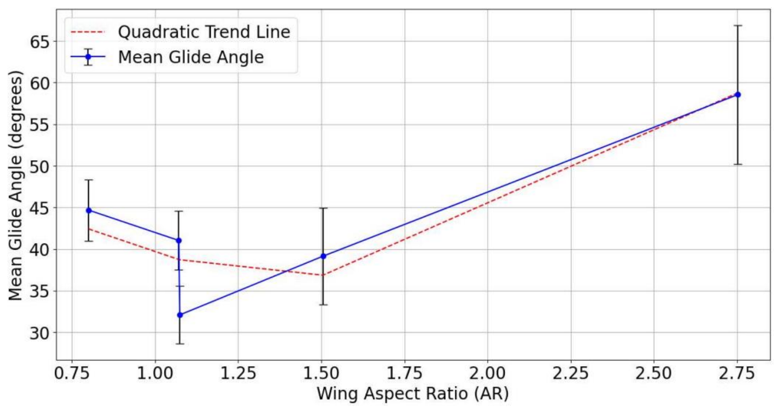

Fig. 4 Relationship Between Wing Aspect Ratio and Mean Glide Angle (Photo credit: Original).

As show in the fig.4. The table below shows the glide angle of aircraft is inversely proportional to the wing aspect ratio. Initially, the glide angle decreases as the AR increases, but after reaching a turning point at AR equal to 1.1, the glide angle increases linearly with the rise in AR. However, it generally shows a upward trend.

3.2. Lift-to-Drag Ratio Analysis

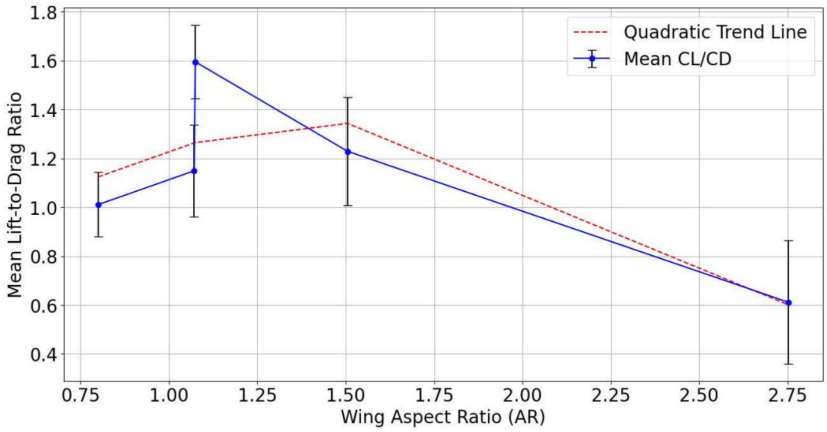

Fig. 5 Trend Analysis of Lift-to-Drag Ratio Across Different Aspect Ratios (Photo credit: Original).

As show in the fig.5. Unlike the previous graph, the lift-to-drag ratio initially increases with the rise in AR. However, after passing the point that AR equal to 1.1, the lift-to-drag ratio decreases linearly as AR continues to increase. Overall, the lift-to-drag ratio decreases with increasing AR.

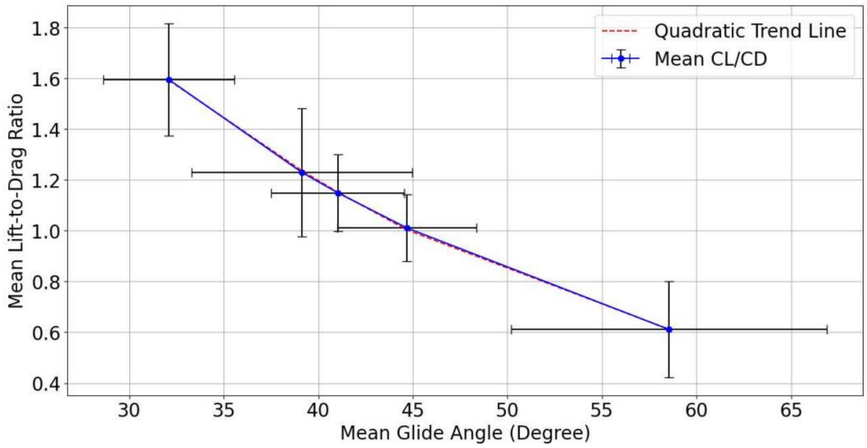

Fig. 6 Correlation Between Glide Angle and Lift-to-Drag Ratio (Photo credit: Original).

As show in the fig.6. This graph shows that the lift-to-drag ratio decreases as the glide angle increases, and it approaches a linear relationship. This relationship demonstrates the possibility predicted in derived eq5 and confirms the accuracy of the experiment.

3.3. Discussion

Table 1. Aerodynamic Performance Metrics of Paper Airplanes

Plane #	A	B	C	D	F
Mass (kg)	0.780	1.022	0.716	0.560	0.683
Mean Glide Angle (rad)	0.780	1.022	0.716	0.560	0.683
Mean Glide Angle (deg)	44.680	58.555	41.027	32.085	39.138
Standard Deviation (deg)	3.677	8.347	3.526	3.462	5.837
FL (N)	0.0279	0.0205	0.0296	0.0332	0.0304
FD (N)	0.0276	0.0335	0.0258	0.0208	0.0248
CL/CD	1.011	0.611	1.149	1.595	1.229
S (m^2)	0.0125	0.0118	0.021	0.0117	0.0166

Table 2. Aspect Ratios and Corresponding Performance Metrics for Paper Airplanes

Aspect Ratio, AR	0.800	2.753	1.0714	1.0745	1.505

As show in the table 1 and 2. The experiment shows that there is a nearly linear relationship between the aircraft's glide angle and lift-to-drag ratio, but the relationship between glide angle and AR is not well demonstrated, it only shows an increasing trend. For aircraft C and D, with nearly identical AR, because larger glide angle lead to a lower lift-to-drag ratio, so that indicating that aircraft C has poorer glide performance compared to aircraft D. Aircraft with the same AR can also have different glide performances. According to the data above, the aircraft with an AR of 1.1 has a smaller glide angle and a larger lift-to-drag ratio (aircraft D), indicating that this aircraft has the best glide performance. Although this aircraft's AR is not the smallest among all samples, it is not the largest either.

3.4. Bird Experiment

Table 3. Aerodynamic Performance Metrics of Bird Experiment

Bird Experiment	
Mass (kg)	10
Mean Glide Angle (rad)	0.464
Mean Glide Angle (deg)	26.565
Standard Deviation (deg)	3.677
F_L(N)	87.743
F_D(N)	43.872
C_L/C_D	2.000
S(M∧2)	0.240
Aspect Ratio, AR	6.000

As show in the Table.3. The table below shows that the lift to drag ratio for a flying bird is 2, while the aspect ratio (AR) is 6. That show the larger different comparing the aircraft test in this study. Birds can adjust their lift-to-drag ratio and other variables during flight by flapping their wings to change their flight performance and generate thrust. Therefore, the data calculated in the table is not precise. It serves only as a reference for aircraft experiments and cannot be considered a result of this study.

4. Challenges

Many aspects of this study are challenging, particularly in controlling the initial velocity when throwing a paper airplane. However, the initial velocity has a significant impact on the experiment. To address this problem, the same airplane is thrown multiple times, and each throw is recorded by a camera. When the trajectory is analyzed by software, the smoothest 5 frames from each throw are used to calculate the glide angle. Statistical methods are then applied to calculate the mean and variance, and these results will be displayed in the final chart.

5. Conclusion

This study systematically explored the influence of Aspect Ratio (AR) on the aerodynamic properties of paper airplanes, serving as simplified models for larger aircraft. Through meticulous experiments involving paper airplanes with varied ARs, this research quantitatively analyzed how changes in AR affect the Gliding Angle and Lift to Drag ratio. The findings reveal that generally, as AR increases, the Gliding Angle decreases, indicating improved aerodynamic efficiency. However, the relationship is not strictly linear, suggesting complex interactions between wing geometry and air flow dynamics which affect flight performance. These observations were substantiated through rigorous video tracking and statistical analysis, ensuring reliable and insightful results that enhance understanding of basic flight mechanics.

While this study provides foundational insights into the impact of AR on gliding performance, it also opens avenues for more extensive research. Future studies could expand the sample size by including a broader variety of paper airplane designs with more diverse wing areas, ARs, and masses. This expansion would allow for a more detailed examination of the nuances in flight dynamics across a wider range of aircraft configurations. Moreover, more controlled experiments should be conducted to isolate and analyze the effects of other influential factors such as the angle of attack and wing twist. Implementing precise control over these variables could significantly refine our understanding of their roles in flight performance. Additionally, integrating computational fluid dynamics (CFD) simulations could complement experimental data, providing deeper insights into the airflow patterns and forces acting on different wing shapes. This comprehensive approach would not only validate experimental findings but also enhance predictive capabilities for aircraft design optimization.

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