Effect of Wing Aspect Ratio on the Aerodynamic Performance and Stability of a Balsa Wood Glider

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Abstract. This study explores how the shape of a wing, specifically its aspect ratio (AR), affects the performance of a balsa wood glider in both smooth and turbulent air. We conducted a series of controlled flight tests in a closed room to ensure accurate results. By carefully changing the wing's shape and recording each flight with a high-speed camera, we measured key performance metrics such as the lift-to-drag ratio and angular deviation (wobbling). Our data clearly show that wings with higher aspect ratios perform better in calm air. For example, when the AR increased from 5.35 to 10, the lift-to-drag ratio improved significantly from 1.853 to 13.25, and the glide angle decreased from -25.48° to -12.25°, resulting in a flatter flight path. This confirms the classic aerodynamic principle that long; narrow wings are more efficient. However, we found a major drawback: high-AR wings become much less stable in turbulent air. The wobbling increased nearly threefold, as the angular deviation rose from 1.042 to 2.991, leading to a noticeable drop in performance. This suggests that although high-AR wings are efficient, they are more sensitive to air disturbances. In conclusion, our research highlights an important trade-off in glider design: a higher aspect ratio provides better efficiency but worse stability in turbulent conditions. This finding is crucial for future designers, emphasizing that real-world performance must consider turbulence as well as ideal flight conditions.

Keywords: Aspect ratio, Glider performance, Aerodynamic efficiency, Flight stability.

1. Introduction

A glider is an unpowered fixed-wing aircraft that utilizes aerodynamic forces generated by its wings for sustained flight, typically requiring external assistance for launch. The lift-to-drag ratio (L/D), defined as the ratio of lift force to drag force, is a fundamental metric for assessing glide efficiency [1]. Theoretically, a higher L/D enables longer glide distances per unit of altitude loss. This ratio is predominantly governed by aerodynamic design parameters, including wing geometry, aircraft mass distribution, and the operational Reynolds number. An optimized wing design maximizes lift generation while minimizing drag, with the wing aspect ratio (AR), defined as the square of the wingspan divided by the wing area, being a critical determinant of induced drag components [2].

While existing studies have extensively documented that increasing AR enhances L/D under steady-state conditions (for example, by reducing glide angles), the interaction between high-AR designs and unsteady flow environments remains poorly quantified [3]. Specifically, atmospheric turbulence, characterized by stochastic velocity fluctuations, may disrupt the coherent vortex structures essential for high-AR performance [4].

To address this gap, the present study hypothesizes that as the aspect ratio of the glider wing increases, its lift-to-drag ratio improves under steady-state conditions, reducing the glide angle. However, this performance advantage exhibits significant vulnerability in turbulent environments, where higher-AR wings experience disproportionate degradation due to amplified sensitivity to flow separation and induced drag fluctuations.

2. Method

2.1. Materials

The experimental setup utilized the following materials and equipment: A custom-designed wood model plane, specifically engineered to allow for interchangeable main wing parts to achieve varying aspect ratios, served as the primary test subject. A high-speed camera capable of recording video at a minimum of 120 frames per second was employed to capture flight kinematics. A precision balance was used to measure the mass of the glider before each trial to ensure consistent weight distribution. Video analysis was conducted using Tracker, a dedicated motion tracking software, to extract quantitative kinematic data from the recorded footage. Finally, a manual launcher, powered by rubber bands, provided a consistent and repeatable initial thrust for all flight tests, ensuring uniform launch conditions across different wing configurations.

2.2. Procedure

1. Purchase experimental materials online
2. Find an area that is suitable for the experiment
3. Measure the weight of the glider using a balance
4. Launch the glider, record it with a camera, and repeat this several times to get a consistent result.
5. Analyze the video using Tracker software to obtain the average tangent theta, average theta, and the lift-to-drag ratio
6. Use scissors to alter the glider's wing length and width to change the aspect ratio.
7. Repeat step 3-6 until enough information has been collected

The camera was positioned approximately four meters from the flight trajectory of the wood plane model to capture a clear orthogonal view of the glide path. All experiments were conducted within an enclosed 8 m × 6 m room with no active airflow sources (for example, fans or HVAC systems) to minimize uncontrolled environmental disturbances. The model plane was launched from a consistent height of about 1.5 meters using a rubber-band-powered launcher, ensuring repeatable initial conditions across trials.

Video recordings were acquired at a high frame rate of 120 frames per second (fps) to enable precise motion tracking. After video capture, the footage was imported into Tracker software for processing. A calibration scale was first established using reference markers to determine actual displacement distances, thereby converting pixel-based measurements into real-world units. Subsequently, the glider’s position was manually marked frame by frame throughout each flight sequence, generating raw coordinate data (for example, x–y positions) and orientation angles (for example, pitch or yaw).

From these annotations, Tracker’s built-in algorithms computed velocity magnitude and direction as well as angular velocity (ω) based on frame-to-frame positional and orientational changes. The raw kinematic data (velocity and ω) were then exported to Excel for further processing. The angular deviation amplitude, which quantifies turbulence-induced attitude instability, was derived by integrating ω over time relative to the glider’s longitudinal axis orientation during steady glide phases.

3. Results

3.1. Experimental Data

Note the exceptionally high CL/CD at AR=10 under controlled conditions. This peak performance may be vulnerable to turbulence-induced flow separation, warranting dedicated environmental sensitivity studies.

Table 1. Processed results

	AR = 5.35	AR = 8	AR = 10
Average Theta	-25.48	-24.57	-12.25
Average tan theta	-0.079772	-0.82377	0.0161998
Average CL/CD	1.853	2.743	13.25
Average amplitude	1.042	1.816	2.991

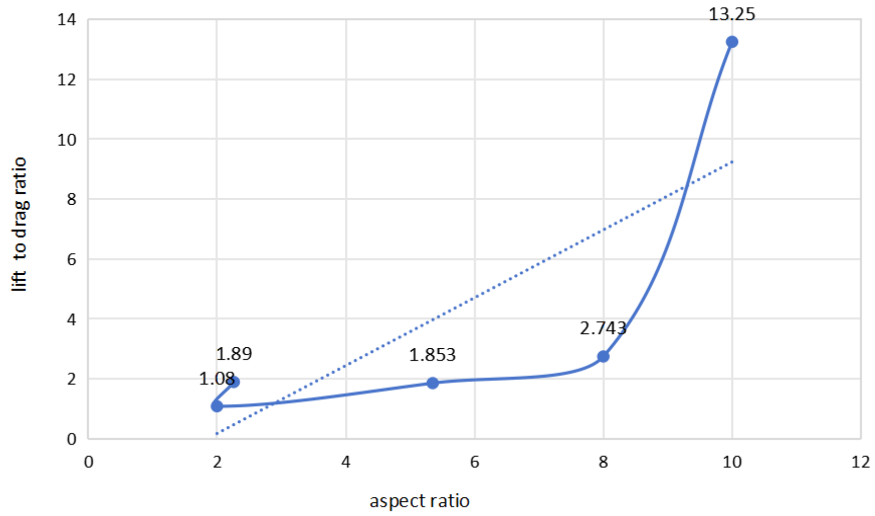

Figure 1. The relationship between aspect ratio and lift-to-drag ratio

3.2. Post-Lab Analysis

Based on experimental data (as shown in Table 1), it can be concluded that when all other conditions remain constant, the lift-to-drag ratio increases as the aspect ratio increases. As shown in Fig. 1, the horizontal axis represents the aspect ratio, while the vertical axis represents the lift-to-drag ratio. As shown in the graph, the lift-to-drag ratio increases with the aspect ratio. However, as the aspect ratio increases, the magnitude of the model aircraft’s angular deviation relative to its direction of motion also becomes larger, with turbulence being the primary factor contributing to this instability. Consequently, the data preliminarily indicates that as the aspect ratio increases, the model aircraft’s susceptibility to turbulence also rises, leading to less stable flight attitudes.

The experimental results, particularly the improvement in the lift-to-drag ratio (CL/CD) with increasing aspect ratio under controlled conditions, support this conclusion. The observed performance peaks (for example, CL/CD increasing from 1.853 at AR = 5.35 to 13.25 at AR = 10) and the associated variances confirm that turbulence sensitivity dependent on aspect ratio is a critical constraint in optimizing glider efficiency.

4. Discussion

This study reveals a fundamental trade-off in glider design through the systematic variation of wing aspect ratio (AR): the pursuit of peak aerodynamic efficiency through high AR comes at the expense of degraded stability in the presence of turbulence. The experimental data robustly demonstrate that while increasing AR from 5.35 to 10 yields a profound 714% enhancement in the lift-to-drag ratio (CL/CD) under steady-state conditions, it concurrently triggers a 187% increase in angular deviation amplitude when ambient disturbances are present. This inverse relationship between efficiency and robustness underscores a critical design constraint that transcends the idealizations of classical aerodynamic theory [5].

The mechanistic underpinnings of this AR-dependent vulnerability are likely trifold. Firstly, the elongated, slender planform of high-AR wings inherently possesses lower torsional and bending stiffness. This structural flexibility amplifies aeroelastic effects, where turbulent gusts induce wing twisting and bending, thereby modulating the instantaneous angle of attack and exacerbating attitude fluctuations (e.g., roll, pitch) [6]. A phenomenon quantified by our angular velocity (ω) data. Secondly, the primary aerodynamic benefit of high AR, which reduced induced drag and intrinsically coupled to lift production. Turbulence-induced fluctuations in effective angle of attack therefore cause commensurate, and potentially large, variations in induced drag. This unstable drag component likely contributes to the accelerated degradation of glide performance observed in unsteady flow. Finally, our findings resonate with the airfoil-level insights of Guo et al., who identified the leading-edge region as supremely sensitive to oncoming turbulence [4]. The elongated leading edge of a high-AR wing presents a larger effective target for turbulent eddies, potentially facilitating more widespread and coherent flow separation along the span, which generates larger destabilizing moments.

The experimental results (as the aspect ratio increases, the magnitude of angular deviation of the model aircraft relative to its direction of motion also grows, with turbulence being the primary cause of its instability) of this study reveal a trade-off. Although increasing the wing aspect ratio (AR) significantly raises the lift-to-drag ratio (CL/CD) and reduces the glide Angle under steady-state conditions, it also introduces a critical vulnerability to atmospheric turbulence. The phenomenon that the observed angular deviation and its rate of change increase with the increase of AR highlights a fact: the performance advantage of high AR wings will disproportionately degrade in a disturbed environment. This discovery strongly supports our initial assumption that the aerodynamic efficiency obtained from the high AR design would be partially offset by its high sensitivity to unsteady flow conditions [7].

The fundamental mechanism of this aspect ratio dependent turbulence sensitivity might be the complex interaction between the aerodynamic characteristics of high AR wings and the nature of turbulent incoming flows. Firstly, the slender planar shape of the high AR wing may exhibit greater structural flexibility, making it more susceptible to the influence of aeroelastic effects. Gusts in turbulence can cause wing bending and twisting, which amplifies the changes in the instantaneous Angle of attack and thereby exacerbates the instability of flight attitude (roll, pitch), a feature quantified by our angular velocity data. Secondly, the main advantage of high AR wings (reducing induced drag) is intrinsically related to lift generation. Turbulence causes rapid fluctuations in the effective Angle of attack and lift, which may in turn trigger significant fluctuations in induced drag. This unstable resistance component is very likely to have led to the accelerated degradation of gliding performance. Finally, by analogy with the research on airfoils in the reference literature (which found that the leading-edge region is the most sensitive to turbulence), the slender leading edge of the high AR wing provides a larger "target" for turbulent vortices. This may make it easier for the wing to undergo consistent flow separation along the entire spread direction, thereby generating a greater instability moment [8].

5. Limiatations and Future Work

This study acknowledges inherent limitations in experimental control. Despite efforts to minimize disturbances, complete isolation from ambient airflow perturbations was unattainable during flight tests, as noted in the error analysis ("environmental factors... particularly turbulence intensity and gust frequency"). Additionally, imperfections in wing surface treatment (e.g., minor balsa wood irregularities or adhesive residues) may have inadvertently influenced local airflow patterns, potentially amplified unintended turbulence generation and contributing to data scatter. These factors likely introduced measurable deviations in glide performance metrics, particularly for high-AR configurations where sensitivity to disturbances was preliminarily observed [9].

A further methodological limitation concerns the manual data extraction process. The frame-by-frame tracking of the glider's position, while necessary for obtaining orientation data, is inherently subject to human error and temporal resolution constraints of the camera system (120 fps), potentially smoothing over the highest-frequency turbulent fluctuations. Moreover, the study's scope was limited to three discrete aspect ratios; a more continuous exploration of AR values might reveal non-linearities or more precise thresholds in the performance stability trade-off. The use of a rubber-band launcher, though ensuring consistent initial thrust, imparted a slight rotational moment and yaw upon release, the effects of which were not fully quantified and may have interacted with the wing's inherent stability [10].

Methodological refinement: Implement active turbulence suppression (e.g., wind tunnel enclosures with flow conditioners) and standardized wing surface polishing protocols to isolate AR effects. Beyond these steps, future work should employ active turbulence generation grids within a wind tunnel to precisely control intensity and length scales, moving beyond dependence on ambient conditions. The integration of onboard micro-inertial measurement units (IMUs) could complement optical tracking, providing direct high-frequency measurements of angular accelerations to validate and enhance the Tracker software's kinematic calculations.

Advanced dynamics quantification: Extend analysis beyond steady-state glide ratios to directly correlate turbulence intensity with real-time aircraft attitude changes. High-resolution tracking of pitch/yaw oscillations could reveal:

1. Critical AR thresholds for aerodynamic instability
2. Phase relationships between turbulence impulses and attitude-correction cycles as visually suggested by trajectory fluctuations in the original video data.

Furthermore, subsequent research should explore a broader aerodynamic parameter space. This includes testing a wider range of AR values (e.g., from 4 to 12) to map the sensitivity gradient in finer detail and to identify a potential optimal AR that balances efficiency and stability for a given operational environment. Investigating the influence of wing airfoil profile (e.g., cambered vs. symmetric) and weight distribution could disentangle pure aspect ratio effects from other confounding design factors, offering a more holistic understanding of glider robustness. Finally, translating these findings into practical design guidelines or even simple control algorithms for micro-drones that can adapt wing configuration or flight control responses in real-time to measured turbulence levels represents a promising long-term application [11].

6. Conclusion

This study experimentally confirms the dual effect of wing aspect ratio (AR) on glider performance. Increasing AR from 5.35 to 10 significantly enhances the lift-to-drag ratio (CL/CD) from 1.853 to 13.25 and concurrently reduces the glide angle from -25.48° to -12.25°, validating the theoretical aerodynamic superiority of high-AR designs under controlled conditions. However, high-AR wings (for example, AR = 10) exhibit disproportionate degradation in stability, as evidenced by a threefold increase in angular deviation amplitude (from 1.042 to 2.991) under ambient disturbances. This result demonstrates their amplified sensitivity to flow separation and induced drag fluctuations. Overall, these findings establish AR-dependent turbulence sensitivity as a critical trade-off in glider optimization: while a higher aspect ratio maximizes steady glide efficiency, it simultaneously increases susceptibility to aerodynamic instability in unsteady environments.

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