Impact of Taper Ratio on Low-Speed, Flat-Winged Glider Flight Performance

Mitansh Dutta

Abstract

While the influence of taper ratio on wing aerodynamics has been studied extensively in high-speed conditions and theory, its effects on simple, flat wings at low speeds remain less well-characterized, especially in experimental testing. This gap is significant because many small-scale aircraft operate in these low-Reynolds-number conditions. These include gliders, micro air vehicles (MAVs), and hobbyist projects. In this context, low-speed flight refers to flights that operate at approximately 5 m/s, whereas high-speed aircraft operate on the order of hundreds of meters per second. Here, even subtle geometric changes strongly influence flight behavior. Flat wings are important in these applications due to their simplicity, yet their aerodynamic behavior is not well understood through experimentation. Understanding how the taper ratio affects flight in this regime allows us to design efficient low-speed flying vehicles. This study investigates how four taper ratios (0.5, 0.6, 0.8, and 1) in a flat wing impact aerodynamic performance through forty controlled free-flight tests of a balsa-wood glider in an indoor laboratory, where flight distance, horizontal deviation, trajectory, and remaining propeller rotations were measured. Among the tested configurations, moderate taper ratios provided the best balance between aerodynamic efficiency and flight stability for low-speed flat-wing gliders. Thus, these findings provide experimental evidence for the influence of taper ratio on low-Reynolds-number flat-winged gliders' flights. This may help inform the design of small-scale aircraft operating in similar conditions.

Introduction

Gliders are unpowered aircraft that use solely aerodynamic forces to sustain flight. The two aerodynamic forces that drive vertical motion are lift and drag. Lift is the upward force generated as air flows over any body. It is caused by the flow turning in a direction. Due to Newton’s third law of motion, a force is generated opposite to that direction, which is lift. In contrast, drag is the resistive force during the motion of an object through a fluid. It is generated by the difference in velocity of the object and the fluid [1, 2].

For there to be aerodynamic forces, fluid must flow around a surface. For that to occur in a glider, an initial thrust must be provided that allows it to go forward and let air go around it. In powered aircraft, thrust is often produced by engines or propellers. In this study, the gliders were given propulsive force with a rubber band and then launched freehand. Propellers generate thrust by displacing air. The angled blades create a pressure difference when it rotates. Due to this, air pushes the vehicle forward [2].

Wing planform geometry is an important consideration in aircraft design because parameters such as aspect ratio, sweep, and taper influence aerodynamic performance [3, 4]. Among the parameters of a wing, the taper ratio plays a dominant role in aerodynamic performance [4]:

$$\lambda = \frac{c_{tip}}{c_{root}}$$

Taper ratio (λ) is the ratio between the chord at the wing root (c_{tip}) and the chord at the wing tip (c_{root}). For example, a rectangular wing would have a taper ratio of 1:1 [4].

Flight stability is also an important aspect of flight performance. For this study, it refers to the glider's ability to maintain a constant flight path with minimal deviation.

The parameters chosen do not have very obvious effects.

Literature Review

Previous studies have shown that taper ratio can affect aerodynamic performance at low Reynolds numbers, but its role depends on the wing geometry, aspect ratio, and in some cases, the testing method. Ananda et al. (2015) experimentally tested low- to moderate-aspect-ratio wings at low Reynolds numbers, which included taper ratios of 1.0, 0.75, and 0.5 [3]. They found that wing geometry influenced three factors: lift, drag, and Oswald efficiency. This showed that taper ratio can change aerodynamic efficiency by modifying lift distribution and induced drag behavior.

Previous experimental studies have also shown that taper ratio has a considerable effect on the aerodynamics of wings. Anderson (1938) performed experiments using 22 tapered wings with various aspect ratios, including taper ratios, analyzing parameters like lift curve slope, maximum lift coefficient, drag, pitching moment, and aerodynamic center location [5]. These studies thus showed that the taper ratio of a wing affects many aerodynamic parameters.

The link between taper ratio and spanwise loading was further explored by DeYoung (1947). The lifting line method used in this study showed that taper ratio affects the distribution of aerodynamic load on the wing and, in the case of an unswept wing, the span loading is close to elliptic if the taper ratio is 0.45 [6]. Therefore, there is justification for the hypothesis that a wing with moderate taper may have better aerodynamic performance than a regular rectangular one.

In a numerical study by Güzelbey et al. (2019), the effects of taper ratio on high-aspect-ratio wings with taper ratios from 0.2 to 1.2 with constant wing area, aspect ratio, and mean aerodynamic chord were analyzed. The study revealed that taper ratio affects spanwise lift distribution, induced drag, Oswald efficiency, and wingtip vortices, with taper ratio 0.4 showing the lowest induced drag and highest Oswald efficiency [7]. Thus, this study also confirms the theory that moderate taper ratios provide better aerodynamic efficiency than different taper ratios of 0.2, 0.8, and 1.2.

Zhang et al. (2009) investigated the effect of taper ratio on cropped nonslender delta wings and found that taper ratio significantly influenced lift, drag, stall angle, and vortex behavior [4]. The experiments conducted for it showed that changes in the ratio altered the interaction between leading-edge vortices and tip vortices, thereby modifying the wing's aerodynamic characteristics and delaying stall in certain configurations. These results further support the idea that taper ratio affects aerodynamic performance in any type of wing geometry.

Traub et al. (2015) did something similar where they examined wings at Reynolds numbers of 100,000 and 150,000 and found that taper ratio had only a weak effect on overall lift-to-drag ratio [8]. Although moderate taper ratios (0.4-0.6) produced the best aerodynamic efficiency, surface flow visualization showed that reducing taper ratio increased the laminar separation bubbles near the wing tip, creating stronger tip region flow effects. They concluded that while taper can improve aerodynamic efficiency, excessive taper may create unfavorable flow behavior, especially near wing tips.

Numerical studies conducted recently have also shown how taper can greatly affect the performance of wingtips and wakes. For instance, Ribeiro et al. (2023) studied the impact of taper on wingtips with taper ratios between 0.27 and 1.0 and found that reducing the tip chord reduced the strength of tip vortices and changed the downwash and wake structure [9]. Although they mainly studied swept wings operating post-stall regime, this research again shows the direct relation between taper ratio and wingtip flows.

Together, these studies show that taper ratios definitely influence aerodynamic efficiency, lift generation, drag characteristics, and flow behavior. However, most previous work has relied on wind-tunnel testing, force measurements, and flow visualization rather than free-flight performance of simple gliders. As a result, it is still unclear how effects of taper translate into practical flight characteristics in the real world.

As such, there is a clear need for experimental investigation of taper ratio effects on flat-plate wings operating at low Reynolds numbers under controlled, free-flight conditions. This study attempts to bridge this gap by isolating taper ratio as the primary variable and experimentally evaluating its influence on aerodynamic performance based on flight characteristics. Thus, the work aims to clarify the practical role of taper ratio in flat-wing glider design.

Methodology

To study the effect of taper ratio on the low-speed aerodynamic performance of a glider, four flat-wing configurations with taper ratios of 0.5, 0.6, 0.8, and 1.0 were tested. These taper ratios were chosen to span from a rectangular wing to strongly tapered geometries. Previous studies suggest that moderate taper ratios provide optimal performance for flat wings by improving lift distribution and delaying stall [7]. Lower ratios, such as λ = 0.5, on the other hand, may increase tip loading and reduce stability [7]. Testing ratios both within and outside this moderate optimal range would help create greater experimental evaluation.

Each configuration was evaluated using the same glider body and controlled launch conditions in the Boeing Flight Room at Stanford University, an indoor laboratory.

1. *Testing Environment*

The tests were conducted in a room measuring 50 feet in length, 20 feet in width, and 20 feet in height. The larger, open space provided unobstructed flow. All gliders were launched from a height of 5'6" and were released at a 0-degree angle.

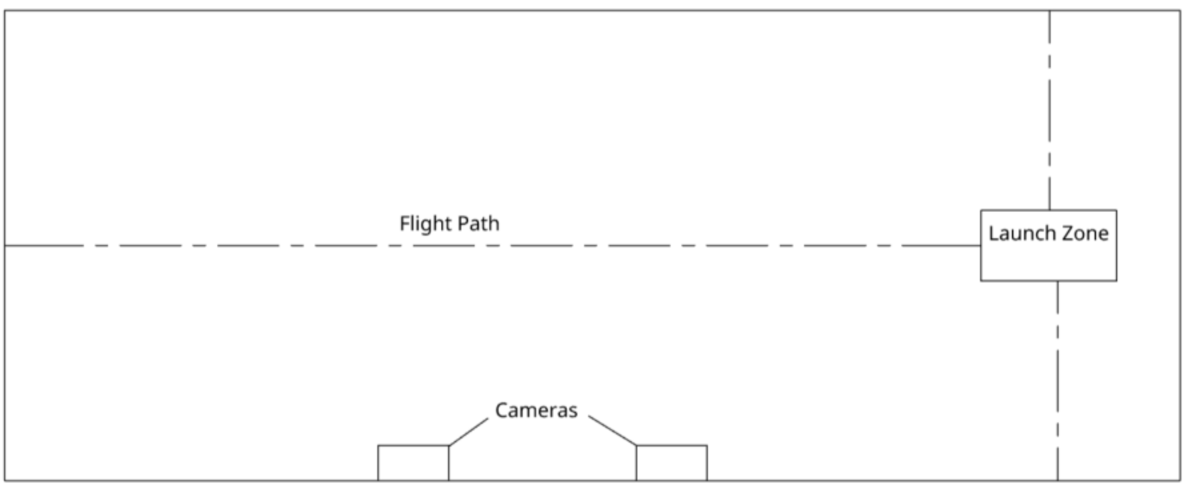


Figure 1. *Top-down view of Boeing Flight Room at Stanford University, showcasing the key features for testing: the launch zone at the front of the room, the projected flight path when straight, and two parallel cameras for recording the flight path and maximum height.*

2. *Glider Design and Preparation*

A single fuselage design was used with a slot for replacing the wings. The wings consisted of a piece of balsa wood centered on the thin fuselage. Flat wings were used, and to control the weight of all wings, different amounts of tape were uniformly layered over the wings.

Table 1*. Wing specifications for gliders tested, including taper ratio, weight, and thickness.*

Taper Ratio	Weight (g)	Thickness (in)
1.0	7.282	0.0370
0.8	7.319	0.0375
0.6	7.200	0.0375
0.5	7.172	0.0385

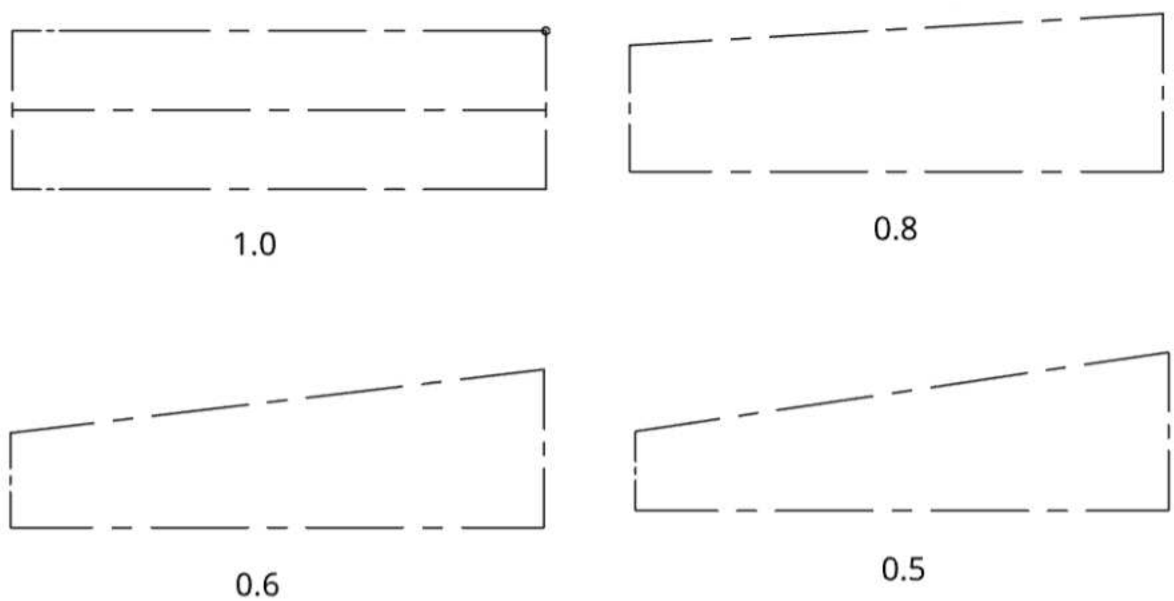


Figure 2. *Different taper ratios tested on the balsa wood glider. Half a wing is shown.*

***Figure 3**. Balsa wood wings (1.0, 0.8, 0.6, 0.5 in order)*

3. Camera Setup and Calibration

Two iPhone 15 cameras were placed at different points along the flight trajectory, at the same height and plane on a vertical surface. Their placement ensured the trajectory of the flights could be recorded, and valuable data, like the position of the glider over time, could be extracted from it using a known correlation between pixel number and physical dimensions (e.g., length).

For the calibration process, a 5 '2'' person held a measuring tape up at 1-foot increments to indicate the height in each camera's frames. From this, we can correlate the number of pixels to known lengths in that camera position.

4. Data Collection

For each taper ratio, ten independent flights were conducted, totaling 40 data points. For each flight, the following information was extracted:

- Maximum height
- Horizontal deviation from the intended straight-line path
- Total flight distance before the glider came to rest
- Trajectory in vertical plane (plotted from frame data)

- Flights with less than 10 inches of horizontal deviation were included as valid flights with reasonable stability

5. Success Criteria

A flight was considered successful and included in our data analysis if it met all of the following:

- Vertical height > 20 feet
- Horizontal deviation ≤ 10 feet
- No collisions with walls, ceiling, or objects before a complete stop

All other tests were discarded from our analysis as not being representative of unhindered, free flight.

6. Reynolds Number

Reynolds number (*Re*) is a dimensionless quantity that describes the relationship between inertial and viscous forces in a fluid flow. It tells us whether fluid flow is laminar or turbulent [11]. It is given by:

$$Re = \frac{\rho V c}{\mu}$$

where *Re* is the Reynolds number, ρ is the density of air in kg/m³, *V* is the velocity of the glider relative to the air in m/s, *c* is the characteristic chord length of the wing in meters, and *μ* is the dynamic viscosity of air in kg/(m·s) [12].

Calculating this for our tests, we find it to be in the range of 15,000–20,000. This places the glider in an extremely low-Reynold’s number territory, indicating that the fluid flow over the wing is mostly laminar.

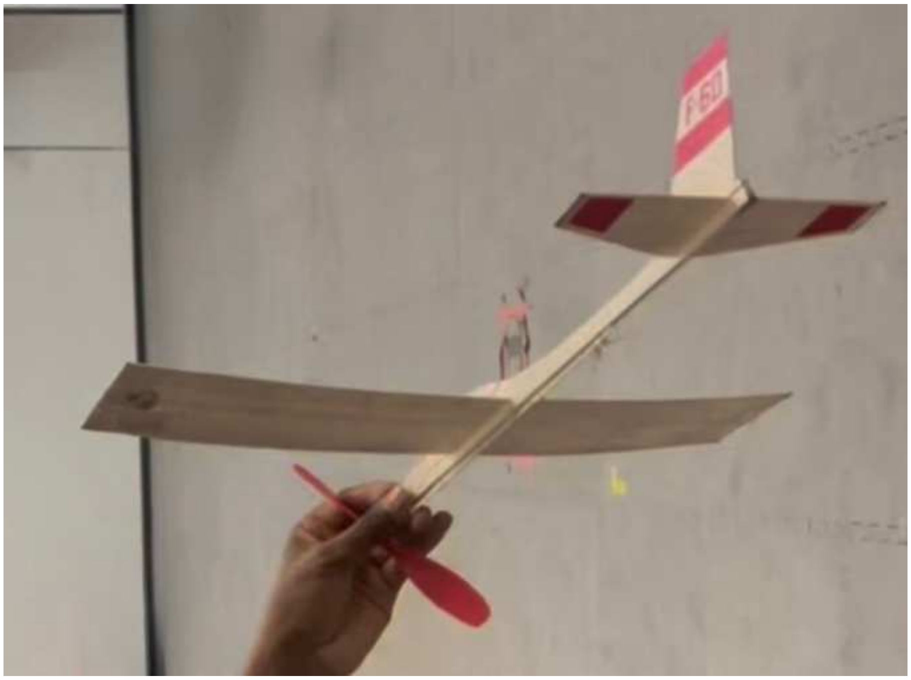


Figure 3. *Example of fully constructed glider used in test flights*

Data

The tables below show all the flight trajectories flown using different wings.

Table 1. *Flight results for 1.0 taper wing*

Flight Number	Max Height	Travel Distance (in)	Horizontal Deviation (in)	Turns Left on Propeller
1	68	338	86.5	11
2	66	392	12.5	4
3	66	363.75	27.5	20
4	70	371.5	28.5	12
5	70	358.6	94	8
6	70	447	0	14
7	66	343.63	9	8

8	66	379.25	52	11
9	68	360	30.5	12
10	68	386.5	58	13

Table 2. *Flight results for 0.8 taper wing*

Flight Number	Max Height	Travel Distance (in)	Horizontal Deviation (in)	Turns Left on Propeller
1	66	465.5	52.5	13
2	66	370	79.5	18
3	66	469.25	11.38	20
4	66	482	54.88	15
5	66	525	9.5	14
6	66	459.25	88	20
7	66	512.25	56	4
8	66	497.63	45.5	12
9	66	477.25	48.5	24
10	66	530.75	78.38	4

Table 3. *Flight results for 0.6 taper wing*

Flight Number	Max Height (in)	Travel Distance (in)	Horizontal Deviation (in)	Turns Left on Propeller
1	66	486.75	63.25	19
2	66	517.83	27	9
3	70	608.5	38.38	3
4	66	585	14.63	6
5	66	607.13	36.5	2

6	66	390.5	87.63	20
7	70	530.25	12	11
8	66	449.5	107	32
9	66	457	108.5	26
10	66	491	79.5	14

Table 4. *Flight results for 0.5 taper wing*

Flight Number	Max Height (in)	Travel Distance (in)	Horizontal Deviation (in)	Turns Left on Propeller
1	66	500	118.5	22
2	66	447.63	81.5	21
3	66	534.4	119.63	14
4	66	487	90	24
5	66	484.25	96.75	17
6	66	470.5	92.75	14
7	66	486	66.5	12
8	66	528	63.25	13
9	66	491	19	14
10	66	480.5	10	15

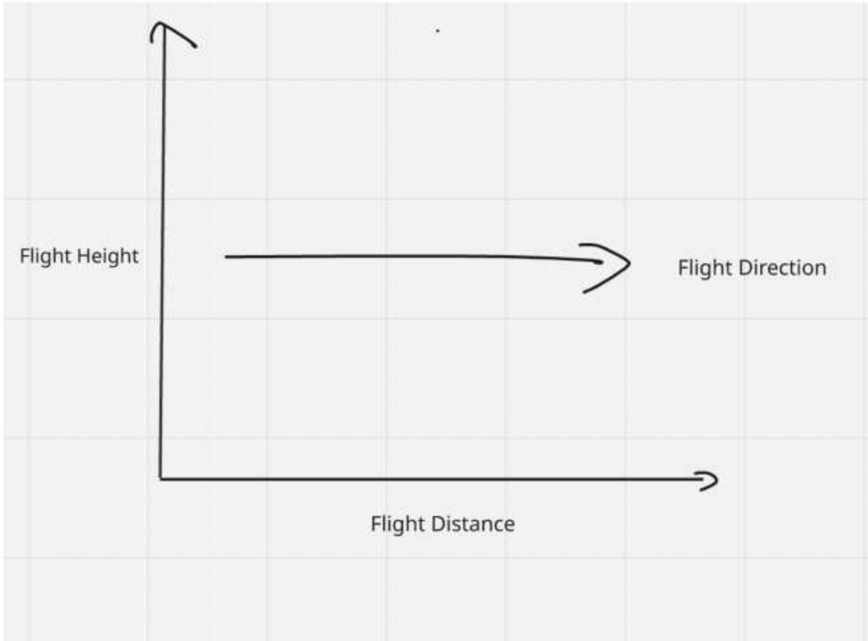
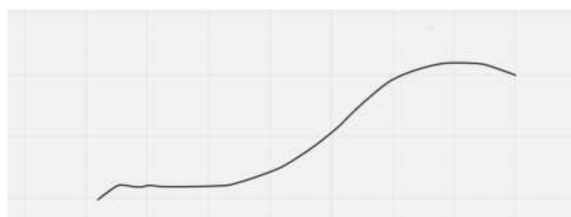
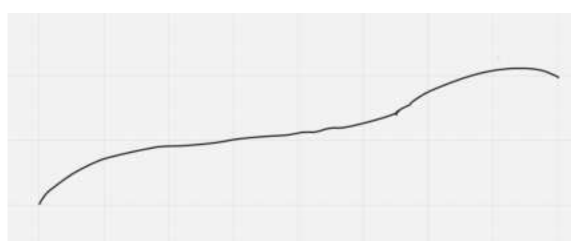
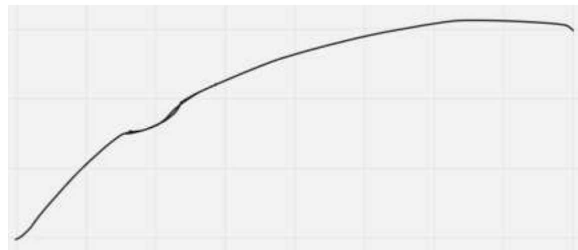


Figure 4. *Flight path axis used in the table below*

Taper Ratio	Trajectory
1.0	
0.8 Most elliptical flight path, with very slight stalls.	
0.6	

0.5	

Results

Table 5. *Average flight results*

Taper Ratio (λ)	Avg. Flight Distance (in)	Avg. Horizontal Deviation (in)	Avg. Propeller Turns
1.0	374.02	39.85	11.2
0.8	478.89	52.41	14.4
0.6	**512.35**	57.44	14.2
0.5	490.94	**84.89**	**16.6**

Across all taper ratios, maximum height remained consistent between trials. The maximum height never exceeded the release height. This is because the flights operated in conditions where the weight exceeded the lift generated over the entire flight profile, resulting in a net descent from the start. Occasional outliers in the maximum height above the release point were observed in the λ = 1.0 configuration, indicating the highest amount of initial lift generated.

The differences between taper ratios became more evident in total flight distance. λ = 0.6 had the highest average total flight distance (512.35 in), and λ = 1.0 had the lowest average total flight distance (374.02 in). This meant that the rectangular wings had the highest induced drag, while moderate tapers from 0.5 to 0.8 performed much better, with 0.6 performing the best. This is likely because the moderate taper ratios balanced induced drag reduction and wingtip effects, allowing the glider to maintain consistent lift throughout the flight. This result also agrees with the findings of Traub et al. (2015), who reported that moderate taper ratios (λ ≈ 0.4–0.6) produced the highest aerodynamic efficiency based on their testing [8].

The horizontal deviation varied significantly across configurations as well, with λ = 1.0 having the lowest (39.85 in) and λ = 0.5 having the highest (84.89 in), while λ = 0.6 and λ = 0.8 were around 50 inches each. This indicates that strong tapers led to reduced directional stability. This is likely due to them being more sensitive to small disturbances and asymmetric generation of lift. This trend is also once may be related to the stronger tip-region flow effects observed by Traub et al. (2015) [8].

Trajectory analysis in the vertical plane also highlighted differences. The λ = 0.8 configuration produced the most elliptical and smooth paths. λ = 0.6 showed slightly less smooth trajectories with minor slope changes during descent, followed by λ = 0.5, which displayed more pronounced dips. The rectangular configuration exhibited the least elliptical path of all. Altogether, these trajectory characteristics suggest that λ = 0.8 provided the most stable flight behavior. This result supports the conclusion of Ananda, Sukumar, and Selig (2015), who found that taper ratio influences aerodynamic efficiency through changes in lift distribution and drag [3].

Additionally, propeller spin behavior after launch showed that the λ = 0.5 configuration exhibited the highest average number of propeller turns (16.6), followed by λ = 0.8 (≈14.4) and λ = 0.6 (≈14.2), while the rectangular wing (λ = 1.0) showed the fewest rotations left (≈11.2). This trend suggests that stronger taper ratios had more remaining rotational energy of the propeller after flight. This could be due to reduced flight stability in these flights, shortening the flight duration.

Conclusion

This study investigated the effect of taper ratio on the performance of flat-wing gliders at low Reynolds numbers through real flights in a controlled environment. Among the four configurations tested, λ = 0.6 achieved the greatest aerodynamic efficiency based on flight distance, while λ = 0.8 produced the most stable and smooth trajectories. While, λ = 0.5 exhibited the largest horizontal deviation, indicating the worst directional stability, and λ = 1.0 produced the shortest flight distances.

The results suggest that moderate taper ratios provide the best balance between efficiency and stability for low-speed flat-wing gliders, which is consistent with previous studies. These findings may be useful in the design of gliders, micro air vehicles, and other low-speed aircraft where flight efficiency is important.

Future work could investigate more taper ratios, paired with varying wing geometries. Use of better motion-tracking methods, such as high-frame-rate cameras, would also be ideal to better quantify flight behavior for aerodynamic performance.

Acknowledgements
I would like to thank Lauren Simitz for her help in advising and testing for this study. I would also like to thank Polygence for their resources that aided me in this process.

References

1. NASA. (2024, July 19). *Three forces on a glider*. NASA. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/three-forces-on-a-glider/
2. Anderson, J. D., & Cadou, C. P. (2024). *Fundamentals of aerodynamics* (Seventh edition, International Student Edition). McGraw Hill.
3. Ananda, G. K., Sukumar, P. P., & Selig, M. S. (2015). Measured aerodynamic characteristics of wings at low Reynolds numbers. *Aerospace Science and Technology*, *42*, 392–406. https://doi.org/10.1016/j.ast.2014.11.016
4. Zhang, P. F., Wang, J. J., Liu, Y., & Wu, Z. (2009). Effect of taper ratio on aerodynamic performance of cropped nonslender delta wings. *Journal of Aircraft*, *46*(1), 320–325. https://doi.org/10.2514/1.32130
5. R. F. Anderson, The experimental and calculated characteristics of 22 tapered wings, NACA-TR-627, 1938.
6. J. DeYoung, Theoretical additional span loading characteristics of wings with arbitrary sweep, aspect ratio, and taper ratio, NACA-TN-1491, 1947.
7. Güzelbey, İ. H., Eraslan, Y., & Doğru, M. H. (2019). Effects of taper ratio on aircraft wing aerodynamic parameters: A comparative study. *European Mechanical Science*, *3*(1), 18–23. https://doi.org/10.26701/ems.487516
8. Traub, L. W., Botero, E., Waghela, R., Callahan, R., & Watson, A. (2015). Effect of taper ratio at low Reynolds number. *Journal of Aircraft*, *52*(3), 734–747. https://doi.org/10.2514/1.C032559

9. J.H.M. Ribeiro, J. Neal, A. Burtsev, M. Amitay, V. Theofilis, K. Taira, Laminar post-stall wakes of tapered swept wings, *Journal of Fluid Mechanics* 976, A6 (2023).

10. D. Raymer, Aircraft Design: A Conceptual Approach. American Institute of Aeronautics and Astronautics, Inc, 2016.

11. *Simscale documentation*. SimScale RSS2. (n.d.). https://www.simscale.com/docs/simwiki/numerics-background/what-is-the-reynolds-number

12. NASA. (n.d.). *Reynolds number*. NASA. https://www.grc.nasa.gov/www/k-12/airplane/reynolds.html