Optimal wing configuration for glider flight performance at slow speeds

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Abstract

A propeller or jet engine typically powers modern aircraft. A key difference between the two is that the engines operate at faster flight speeds than propellers. Aircraft wing design becomes more important at slow speeds where propellers are used. The six most common wing configurations are dihedral, anhedral, neutral, neutral swept back, neutral swept forward, and bi-wing designs. All of these designs generate lift using Bernoulli's principle, where faster air underneath the wing creates a pressure differential that pushes the plane upward. This paper has tested the performance of three wing configurations: dihedral, anhedral, and neutral. The wing types were tested with balsa wood gliders, and performance was assessed through the categories of distance traveled, air time, and aerodynamic stability. The dihedral wing design had the best statistics with averages of 46.7ft in distance, 20s in time, and good stability. In most categories, the neutral wing design was close behind with averages of 44.9ft, 18.9s, and good stability. The anhedral wing glider had the worst performance in all categories with averages of: 20.1ft, 9s, and low stability. Dihedral wings are thus the recommended design for low-speed gliders, though a neutral wing may also offer comparable advantages.

Keywords: wing configuration, Bernoulli's principle, dihedral, anhedral, glider, low-speed aerodynamics

Introduction

A glider is an aircraft only powered to help it take off and take off. A glider can be powered in two ways: by a propeller or by a jet engine. Each propulsion system operates differently and has various uses. The primary difference is a jet engine generates more thrust at faster speeds while the propeller-powered planes are normally used for slower speeds. A jet engine works by sucking air in and compressing it down. The compressed air is forced into the combustion chambers where it is mixed with fuel. From there the gas expands quickly out of the exhaust generating thrust [1] (as seen in **Figure 1**). The propeller, on the other hand, works by scooping air behind it. When it spins, air is displaced, pushing the aircraft forward from the resulting pressure difference (as seen in **Figure 2**). The more air the propeller can scoop, the more thrust is generated [2].

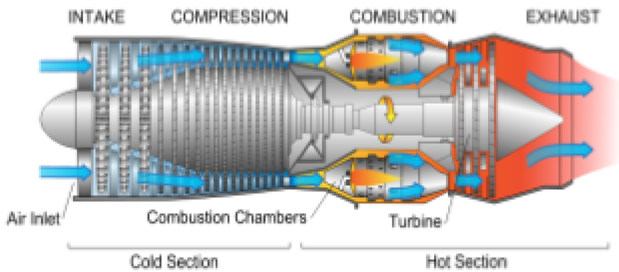


Fig 1

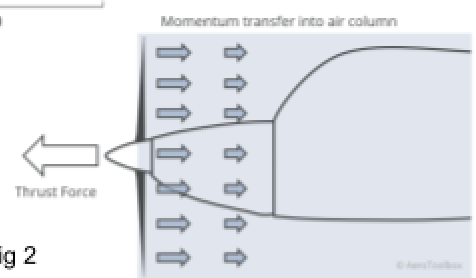
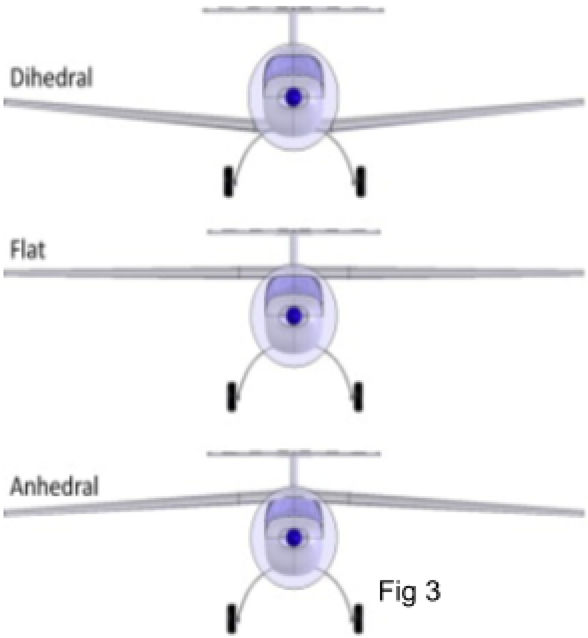
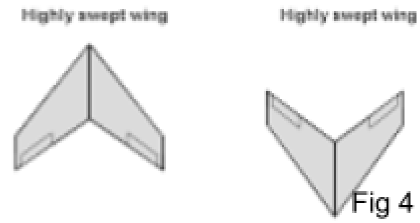


Fig 2

Figure 1. Jet engines operate by sucking in and compressing air. The compressed air is forced into the combustion chamber where it is mixed with fuel. When burned, the gas expands quickly out of the exhaust, generating thrust [3].
Figure 2. The propeller works by scooping air behind it. When it spins, air is displaced, pushing the aircraft forward from the resulting pressure difference [4].

However, this work focuses on the case when less thrust is generated, as the wings become even more influential in aircraft performance [5]. Since the wings affect performance more, their design becomes more important in this regime. Six main wing configurations can be implemented, each one with different pros and cons. These wing types are dihedral, anhedral, neutral, neutral swept back, neutral swept forward, and bi-wing design [6]. Dihedral wings are pointed up ever so slightly (as seen in **Figure 3**) allowing for more stability; anhedral means the wings are slightly pointed down (as seen in **Figure 3**) allowing for less stability but more maneuverability. Neutral wings are neither dihedral or anhedral (as seen in **Figure 3**) and allow for a mix of the other two's abilities. Both neutral swept forward and neutral swept back have wing tips that point either forward or backward (as seen in **Figure 4**) both make the wings unstable and easier to stall but work better at increased speeds. A bi-wing is two wings stacked on top of each other (as seen in **Figure 5**), giving stability and increased lift.





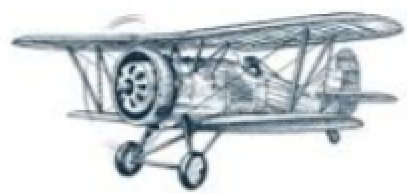


Fig 5

Figure 3. Front views show dihedral, neutral, and anhedral wings on a plane [7].
Figure 4. Top-down views show the neutral swept forward and neutral swept back wings [8].
Figure 5. A side view shows the bi-wing design on a plane [9].

Even though each wing is slightly different, they generate lift similarly. They do this using Bernoulli's principle, which states "an increase in the speed of a fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy" [10]. The wing implements this through its camber, or curve of the wing. Since air is traveling past both sides of the wing, it tends to travel more slowly over the camber and faster under the wing. This fast-moving air creates high pressure that generates an upward force, or lift.

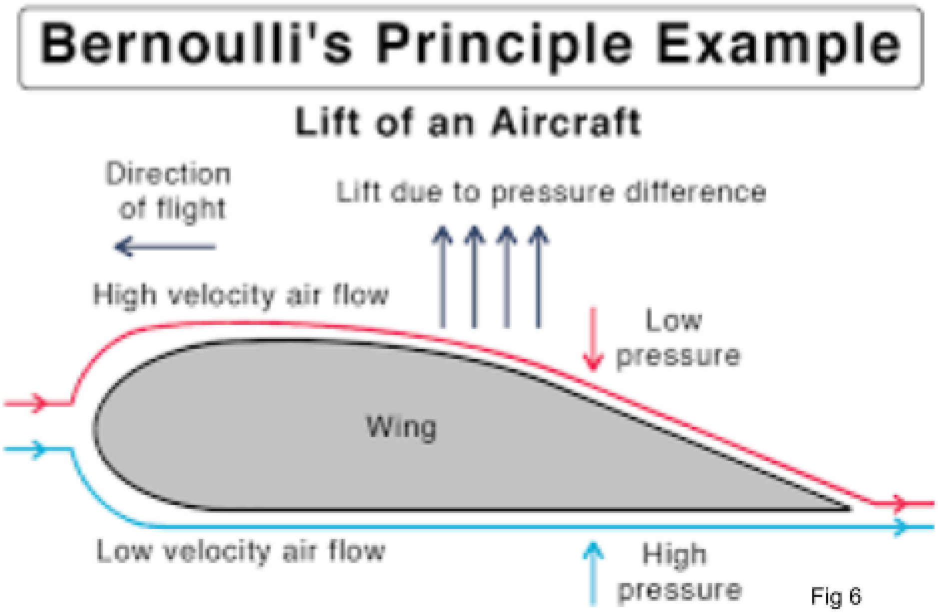


Figure 6. Demonstrates how Bernoulli's principle of “an increase in the speed of a fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy” works on a wing [11].

Literature Review

Prior research on low-speed aerodynamics and glider flight provides an important foundation for this work. In the article, “Designing A Rubber Band-Powered Plane To Uncover Aerodynamics,” by Tommy Gordon published in 2023, Gordon discussed different parts of a rubber band-powered plane and how they work [12]. To prove the main point of the paper–how the wings were the most important part–Gordon used both math and a real glider. He accomplished this by studying how Bernoulli’s principle works on the wing to generate lift and by making a balsa wood glider. This article explored in-depth one of the wing designs that is tested in this work. The wing from Gordon’s work was also tested with a real glider at a similar speed to what this paper is testing at, about two to three ft/s.

Another paper that covers similar topics to this work is, “Design of Glider Wing Shape and Research on its Aerodynamic Characteristics,” written by Ruiwen Kelvin Wang and published in 2024 [13]. The paper focuses on the wing designs for a glider. The gliders talked about in the article are not tested outside like in this research but instead with math and multiple simulate flights of different National Advisory Committee for Aeronautics (NACA) airfoils, such as NACA 4424, NACA 4415, NACA 64A210, and NACA 2412 [14-18]. The gliders, like the aforementioned rubber band-powered planes, both travel at slow speeds, which influences how different wing configurations perform. Similarly, the wing designs tested are the same as the ones in this paper. The authors conclude that the dihedral is the most optimal wing configuration for slow speeds.

Another example of research on low-speed aerodynamics comes from “Aerodynamic Analysis of Low-Speed Wing Design Using Taguchi L9 Orthogonal Array,” written by Kenneth Witcher, Ian McAndrew, and Elena Vishnevskaya and published in 2017 [19]. The article uses a program named the Taguchi L9 orthogonal array to simulate different wing designs in flight. These designs are tested in the program through both an airfoil and matrix system. A few of the designs tested (e.g. neutral, bi-wing) are designs that are tested in this paper as well. This paper alternatively tests both a staggered bi-wing design and a non-staggered version. The paper concludes the staggered design is better than the others since it has an increased lift and increased stability.

Published in 2018 and written by E Amalia, M. A. Moelyadi, R Julistina, and C. A. Putra, “Aerodynamics characteristics of glider GL-1 based on computational fluid dynamics” tackles the problem of thermal updrafts in Indonesia that the GL-1 glider must face [20]. Fluid mechanics is the focus of solving these challenges. Similarly to this paper, the article deals with an aircraft in real flight conditions; still, it is not tested in them. Instead, it is tested through math, simulators, and fluid dynamics. The outcome of the paper is that their glider had the best performance with a dihedral and an angle of attack at 2 degrees.

This work asks the question of which wing configuration—the anhedral, the dihedral, or the neutral—works the best on a slow-moving glider. This work is novel compared to the others in the low-speed aerodynamics community since it relies on hand-made designs and testing in a high-realism environment, rather than testing theories through mathematics and simulations. This research also targets a poorly studied area of low-speed aerodynamics specifically that vehicles like gliders are uniquely situated in. Another aspect that sets this work aside from others in this field is that the aspect ratio (AR) was kept constant compared to wing size and scale. Keeping the AR constant allowed for fair comparison of different wing shapes, such that changes observed could be attributed to the wing shape and not area alone.

Method

To assess how wing design affects flight performance, an experiment was created. The experiment tested each configuration under the categories of distance traveled in feet, time in the air in seconds, and stability in the air. The categories were tested 10 times, and then statistics averaged. This was repeated for each configuration. To make the experiment repeatable and consistent, the wing span, the 10.6 wing aspect ratio, wing area, plane body, conditions tested in, 300 propeller spins, and test start point were kept constant.

First, the gliders had to be designed and built. **Table 1** lists the necessary materials for the experiment.

Table 1. This table provides a bill of materials needed for the experiment.

Material	**Amount**	**Specific information**
Basswood	2 sheets	¼” X 8” X 24”
Wax paper	1 roll	24ft x 15in
Exacto knife	1 knife	Any type works
Super glue	2 bottles	Any type works
Sandpaper	2 sheets	1 sheet needs to be 220 and the other needs to be 120
Rubber bands	5 bands	3 must be 3” x 2” while the other 2 must be ½ “ x ½ “
propeller	1 propeller	Any

After acquiring the materials, the first step was to draft a blueprint of the glider and the wing configurations in a 1:1 scale. After this, the main body and vertical and horizontal stabilizers were built. Then, the three saddles that allowed the wings to be changed out were built. The frames for each half of the wings were built with the supports sanded down to ⅛” with 120 sandpaper, then polished until smooth with 120 sandpaper. The first and last support was tilted in or out depending on whether the wing was used for the dihedral or anhedral design. Each half wing was wrapped with wax paper and left to dry for a day. Once the wings were dry, the halves were glued together and left to dry on supports to help the wings dry with a level dihedral, anhedral, or neutral configuration. Once dry, each wing was glued to its saddle.

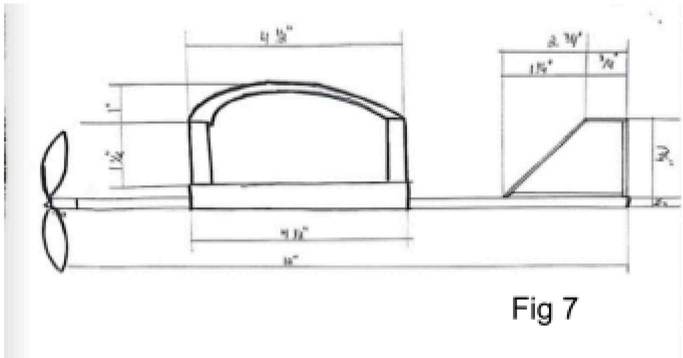


Fig 7

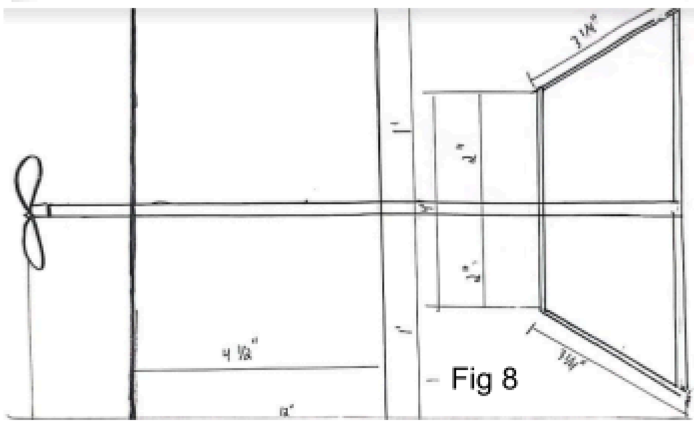


Fig 8

Fig 9

Figure 7. Side view design and dimensions of the plane used in the experiment.
Figure 8. Top view design and dimensions of the plane used in the experiment.
Figure 9. Underneath structure to show the wing was wrapped to sustain flight.

Once the wings and the body were built, the configurations were prepared and tested. Ahead of testing, elevators were added to the horizontal stabilizer. Each wing design was tested until it had an approximately straight and level flight. The designs were tested outside on a day with no rain and low wind speeds. The changing variables tested were the three wing designs, but it is also worth noting two other variables—saddle placement and elevator position—changed between gliders so each design could start with a trimmed flight. During the experiment, distance traveled, air time, and flight stability were recorded.

Data

Table 1 shows the 10 test flights for the dihedral wing configuration, assessed for distance traveled in feet, time in air in seconds, and flight stability. From these categories, speed was calculated. The average distance traveled was 46.7ft, and the air time was ~20s. The third column is the stability in flight, which is described in three ways: “stable” for good, “Moderately stable” for acceptable, and “low” for poor. On average. 80% of flights were stable while 20% were moderately stable. The next column focused on speed with the average being 2.43 ft/sec. The last and final column shows any particular notes for each test flight.

Table 1. This table showcases 10 flight logs for the dihedral configuration. The flight logs reveal how the plane did in three categories: distance traveled, air time, and flight stability.

Dihedral wing	Distance Traveled, feet	Air Time, Seconds	Flight Stability	Speed, feet per second	Notes
Flight 1	18	7	stable	2.13	Might have flown longer but drifted to the left and hit a wall
Flight 2	20	8	moderately stable	2.36	Started with a stall but recovered
Flight 3	15	15	stable	2.38	Flight seemed slow
Flight 4	42	20	stable	2.68	Slow gentle glide
Flight 5	98	36	stable	2.80	Did a big circle to the left
Flight 6	43	22	stable	1.72	
Flight 7	42	22	stable	2.47	
Flight 8	106	41	stable	2.53	Hit a nice updraft that helped it
Flight 9	39	13	stable	2.53	The rubber band broke while winding this and was replaced
Flight 10	44	16	moderately stable	2.64	Slight shake in flight from the wing but otherwise good

Average	46.7	20	stable	2.43	

A main finding from these test flights was that the dihedral glider was incredibly stable, even to gusts. If the plane started to become unstable, it would right itself. This occurs because when the plane is unstable, one wing is more upright than the other. The less upright wing has a bigger planar area, which means it has more lift. The wing will then use this increased lift to raise itself slightly higher than the other wing, until the wings are balanced in the level, same planar area position. This process can repeat multiple times until the aircraft is stable in a process referred to as the "rolling effect" [21].

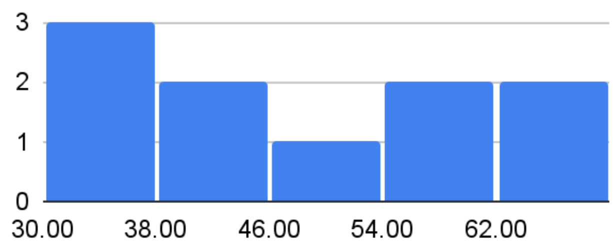


Figure 10. Demonstrates a histogram of distance traveled (ft) in **Table 1**

Table 2 shows 10 test flights for the neutral wing configuration under three performance categories with speed being calculated from that. On average, the neutral glider flew 44.9ft, was in the air 17.9s, and flew stably. More specifically, 60% of flights were stable, 30% were moderately stable and 10% were low. The next column focused on speed with the average being 2.49 ft/sec.

Table 2. This table showcases 10 flight logs for the neutral configuration. The flight logs reveal how the plane did in three categories: distance traveled, air time, and stability.

Neutral wing	**Distance Traveled, feet**	**Air Time, seconds**	**Flight Stability**	**Speed, feet per second**	**Notes**
Flight 1	34	16	Mostly stable moderate	2.16	Mostly stable until it hit an updraft causing a stall slight breeze affected this flight
Flight 2	66	28	Stable stable	2.36	When it hit

					the ground a wing support had to be fixed Nice slow gentle glide
Flight 3	38	16	moderate	2.38	Support broke and had to be repaired from the crash
Flight 4	67	25	stable	2.68	A slight turn to the left
Flight 5	56	20	stable	2.8	A slight turn to the left
Flight 6	31	18	moderate	2.2	
Flight 7	47	19	stable	2.47	
Flight 8	43	17	stable	2.52	The breeze caused the glider to shake slightly
Flight 9	31	12	moderate	2.58	The rubber band broke and had to be replaced
Flight 10	58	22	stable	2.63	Nice gentle glide
Averages	44.9	18.9	stable	2.49	

In comparison to the dihedral and anhedral gliders, this plane had better structural integrity due to a tendency to land on the main body and propeller rather than on the wings. Also, the plane flew quite stably in the air but had a difficult time fixing itself once unstable since the plane was unable to counter a change in center of pressure with the rolling effect.

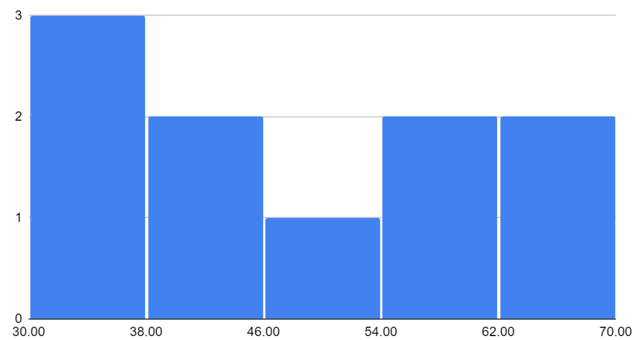


Figure 11. Demonstrates distance traveled (ft) in **Table 2.**

Table 3 shows 10 test flights for the anhedral wing configuration. The glider averaged 20.1ft of distance flown, 9 seconds of air time, and unstable flight. In fact, 50% of flights were low while 30% were moderately stable and 20% were stable. With a calculated average speed of 2.26 ft/sec.

Table 3. This table showcases 10 flight logs for the anhedral configuration. The flight logs reveal how the plane did in three categories: distance traveled, air time, and stability.

Anhedral wing	**Distance Traveled, feet**	**Air Time, seconds**	**Flight Stability**	**Speed, feet per second**	**Notes**
Flight 1	8	4	Low	2	Instantly went into a stall then a slow descent
Flight 2	23	14	moderately	1.64	Kinda shook a little in flight
Flight 3	21	10	moderately	2.1	Wing support broke and had to be fixed
Flight 4	19	8	low	2.3	
Flight 5	33	15	moderately	2.2	Small turn to the left

Flight 6	14	5	low	2.8	Breeze affected flight
Flight 7	46	18	stable	2.56	Wing support broke and had to be fixed
Flight 8	40	16	stable	2.5	Wing support broke and had to be fixed
Flight 9	4	2	low	2	A small breeze started which instantly flipped the plane
Flight 10	5	2	low	2.5	The breeze was still going and flipped the plane
Averages	20.1	9	low	2.26	

In contrast to the other gliders, this version was stable only if nothing acted on the plane. If a light breeze hit the plane, it would quickly flip over and crash on the wings. Since it would crash in this way, many parts of the wing were broken from impact. This lack of stability arises for a positive feedback loop of lift generation on the wings that amplifies disturbances. Once a wing is higher than the other, it has a higher decreased roll stability and no way to recover once it starts to tip [22]. As a result, the anhedral glider flipped a lot during flight.

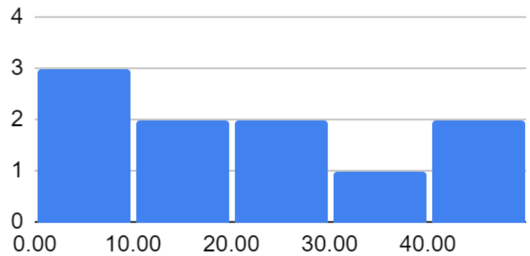


Figure 12. Demonstrates a histogram of distance traveled (ft) in **Table 3.**

Overall, in the first category of distance traveled, the dihedral configuration had the best average with a 46.7ft. The neutral also had a close average in this category with a 44.9ft. In the next category, air time, the dihedral has the highest average with 18.9s. In the last category, stability, the dihedral had the best average here as well with 80% of flights being stable and 20% being moderately stable. Considering these stats, the dihedral glider appears to have the best performance at low speeds with the neutral being close behind. The anhedral design has a much lower performance rate than the other configurations.

Conclusion

In this work, I assessed the low-speed aerodynamic performance of gliders, or aircraft only powered during take-off with three different wing configurations. Wing configuration served as a focus, as prior work had found this design choice to be particularly influential in low-speed aerodynamics. In over 30 test flights, three common configurations were tested on handmade, small-scale, canvas, and balsa wood gliders: dihedral, neutral, and anhedral. All three were evaluated under four categories of air time, flight speed, flight distance, and aerodynamic stability. The dihedral wing glider performed best in all categories. In most categories, the neutral wing design was close behind. The anhedral wing glider ended up far behind in all categories. I would recommend using the dihedral for long stable flights with little turns. The anhedral I recommend for flights that require the plane to be maneuverable. Finally, I would recommend the neutral if the flight requires a good middle ground between the two extremes.

This work could be improved and expanded upon in the future to build even more confidence in what we know about glider low-speed aerodynamics and enhance repeatability. First, since the flights were tested in a real environment, they were affected by different wind patterns and other obstacles, which added variation to the results that would not have been seen in a controlled environment, like a wind tunnel. Outdoor flights were prioritized to capture real conditions though. Notably, weather both hurt and helped test flights observed. An example of a flight that was helped by the wind is dihedral test flight #8. In test flight #8, the glider was hit by an updraft that allowed the plane to gain more height and last longer in the air. In contrast, an example where the wind adversely affected the outcome is in anhedral test flight #2. In this flight, the glider was hit by a wind from the side right after launch that flipped the plane.

Controlling the test environment while retaining realistic conditions would help remedy these situations and their impact on the results seen.

Secondly, the planes were made with heavier materials to keep costs low and due to availability. They could be remade better with lighter materials to help keep them in the air longer. Lastly, the materials were cut by hand since precise tools were not available. Enhanced accuracy in fabrication from better tools may improve the results, cutting out human error.

Despite these areas of improvement, the research outlined in this paper holds tremendous possible impact. Although these experiments were conducted at smaller scales, similitude requirements and scaling laws in aerodynamics allow trends observed to be meaningfully extended to real-size aircraft [23]. In this way, this research provides guidance on how to design higher performing and safer (e.g. more stable) gliders. Not only can these results help gliders, but as the same principles apply in most low-speed aircraft, they can be broadly extended to other machines in similar regimes. Lastly, this work demonstrates a low-cost and accessible experiment, which makes it a great aid for teaching aerodynamics and student research.

Acknowledgments

I would like to thank the learnSTEM program for giving me this opportunity to work on and write this paper. I would also like to thank my mentor Lauren Simitz for helping me understand these topics, answering my many questions, and helping me edit this work.

References

1. Stanford University. (n.d.). *How jet engines work*. Retrieved August 26, 2024, from https://cs.stanford.edu/people/eroberts/courses/ww2/projects/jet-airplanes/how.html#:~:text=In%20the%20basic%20jet%20engine,rear%20of%20the%20combustion%20chambers
2. How Things Fly. (n.d.). *How propellers work*. Retrieved August 26, 2024, from https://howthingsfly.si.edu/propulsion/propellers#:~:text=A%20Propeller%20%E2%80%9CLifts%E2%80%9D%20an%20Airplane,back%20surfaces%20of%20its%20blades.
3. AeroToolbox. (n.d.). *Propeller*. Retrieved August 26, 2024, from https://aerotoolbox.com/propeller/#google_vignette
4. Aerospace Engineering Blog. (n.d.). *Jet engine design*. Retrieved August 26, 2024, from https://aerospaceengineeringblog.com/jet-engine-design/
5. RCCAD2VR. (n.d.). *Dihedral vs. anhedral wings*. Retrieved August 26, 2024, from https://www.rccad2vr.com/aeronautics/dihedral-vs-anhedral-wings
6. ScienceDirect. (n.d.). *Dihedral effect*. Retrieved August 26, 2024, from https://www.sciencedirect.com/topics/engineering/dihedral-effect

7. EaglePubs. (n.d.). *Wing shapes and nomenclature*. In *Introduction to Aerospace Flight Vehicles*. Retrieved August 26, 2024, from https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/wing-shapes-and-nomenclature/
8. Smithsonian National Air and Space Museum. (n.d.). *Biplane*. Retrieved August 26, 8 2024, from https://airandspace.si.edu/whats-on/soar-together-air-and-space/biplane
9. Scholz, H. (n.d.). *Aircraft design: Wing design* (7th ed.). Retrieved September 9, 2024, from https://www.fzt.haw-hamburg.de/pers/Scholz/HOOU/AircraftDesign_7_WingDesign.pdfHow Things Fly. (n.d.). *How propellers work*. Retrieved August 26, 2024, from https://howthingsfly.si.edu/propulsion/propellers#:~:text=A%20Propeller%20%E2%80%9CLifts%E2%80%9D%20an%20Airplane,back%20surfaces%20of%20its%20blades.
10. Skybrary. (n.d.). *Bernoulli's principle*. Retrieved August 26, 2024, from https://skybrary.aero/articles/bernoullis-principle
11. Valispace. (n.d.). *What's that formula? Bernoulli's principle*. Retrieved August 26, 2024, 9 from https://www.valispace.com/whats-that-formula-bernoullis-principle/
12. Winchester Thurston. (n.d.). *Sigma volume 5*. Retrieved August 26, 2024, from https://issuu.com/winchesterthurston/docs/sigmavolume5/s/16060863
13. Dr. Press. (n.d.). *Article view*. Retrieved August 26, 2024, from https://drpress.org/ojs/index.php/HSET/article/view/20102
14. Airfoil Tools. (n.d.). *Airfoil details: NACA 4424*. Retrieved August 26, 2024, from http://airfoiltools.com/airfoil/details?airfoil=naca4424-il
15. Airfoil Tools. (n.d.). *Airfoil details: NACA 4415*. Retrieved August 26, 2024, from http://airfoiltools.com/airfoil/details?airfoil=naca4415-il
16. Airfoil Tools. (n.d.). *Airfoil details: NACA 64A210*. Retrieved August 26, 2024, from http://airfoiltools.com/airfoil/details?airfoil=naca64a210-il
17. Airfoil Tools. (n.d.). *Airfoil details: NACA 2412*. Retrieved August 26, 2024, from http://airfoiltools.com/airfoil/details?airfoil=naca2412-il
18. NASA. (n.d.). *FoilSim student*. Retrieved August 26, 2024, from https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/foilsimstudent/
19. Embry-Riddle Aeronautical University. (n.d.). *Research publication*. Retrieved August 26, 2024, from https://commons.erau.edu/cgi/viewcontent.cgi?article=1847&context=publication
20. IOPscience. (n.d.). *Article 012006*. Retrieved August 26, 2024, from https://iopscience.iop.org/article/10.1088/1742-6596/1130/1/012006/pdf
21. Boldmethod. (n.d.). *Dihedral keeps your wings level during flight*. Retrieved August 26, 2024, from https://www.boldmethod.com/learn-to-fly/aerodynamics/dihedral-keeps-your-wings-level-during-flight/

22. WhiteBox Learning. (n.d.). *Glider*. Retrieved August 26, 2024, from https://www.whiteboxlearning.com/c/application/glider/g1l0305.html
23. NASA. (1979). *Space Shuttle and Space Transportation System 1979* (NASA Technical Report No. 19790022005). National Technical Information Service. https://ntrs.nasa.gov/api/citations/19790022005/downloads/19790022005.pdf