Numerical Study on the Relationship between Lift-to-drag Ratio and Airfoil of Gliders in High-speed Cruising Conditions

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Abstract. This research attempts to examine the aerodynamic characteristics of gliders, specifically concentrating on the impact of airfoil configurations and wing designs on the lift-to-drag ratio when operating at high velocities. Amid rising concerns for environmental sustainability and the pursuit of greater aviation efficiency, traditional approaches, including the enhancement of lightweight materials and the adoption of biofuels, encounter limitations. Particularly in extending the range and improving the efficiency of gliders, the advancements in material weight reduction and biofuel efficacy are approaching their limits. This challenges the industry to seek innovative solutions beyond these conventional methods to achieve significant gains in aircraft performance and environmental impact reduction. To tackle such obstacles comprehensively, this study employs a combination of experimental and computational fluid dynamics (CFD) approaches to analyze these crucial aerodynamic variables. This study illustrates that optimizing aspect ratios and airfoil shapes, particularly through the utilization of high aspect ratio cambered airfoils like the NACA 4412, can substantially improve glider performance. By minimizing induced drag and enhancing lift, these design modifications significantly elevate the overall lift-to-drag ratio, offering a pathway to more efficient and environmentally friendly aviation technologies. These developments not only provide a focused remedy for the identified deficiencies but also indicate progress in integrating aircraft design with initiatives for environmental sustainability. This research highlights its potential impact on the broader endeavor to achieve sustainable aviation by offering practical strategies for the development of more efficient and environmentally friendly aircraft, thereby making a substantial contribution to aerospace engineering and environmental science.

Keywords: CFD, Glider airplanes, Aeronautics.

1. Introduction

Amid escalating concerns regarding air pollution and the depletion of fossil fuels, the aviation industry's role in environmental degradation has garnered significant attention. Referencing Hannah Ritchie, aviation is responsible for about 2.5% of worldwide CO_2 emissions [1], and as highlighted by the Total Energies Foundation, it consumes 7.8% of the world's final oil consumption—a figure exceeding maritime shipping's 6.7% [2]. This scenario underscores the urgency for advancements in aircraft efficiency, focusing on fuel efficacy, and the development of composite materials and aerodynamic designs. This essay aims to explore aerodynamic enhancements in aircraft design, especially during the high-speed cruising phase pivotal for commercial flights. By examining gliders—engineless and solely dependent on aerodynamic efficiency—this study aims to illustrate how airfoil and aircraft design critically influence glider performance, offering insights into reducing fuel consumption and advancing environmental sustainability in powered aviation.

The pursuit of aerodynamic optimization is not merely a technical challenge but also a strategic imperative for the aviation industry. The development of advanced airfoils and innovative wing designs could lead to significant improvements in aircraft efficiency, translating into lower operational costs and reduced environmental impact. Such advancements are essential in the context of global efforts to combat climate change and transition towards more sustainable modes of transportation.

Recent advancements in Computational Fluid Dynamics have facilitated a deeper understanding of the flow dynamics around airfoils, crucial for optimizing lift-to-drag ratios—a key determinant in aircraft performance. This study selects two prevalent airfoil designs, NACA 0012 and NACA 4412, to explore their aerodynamic characteristics under high-speed conditions. Despite existing studies, such as the comprehensive analysis by Shahariar et al. [3], which detailed the aerodynamics of these airfoils, a gap persists in applying these findings to practical aviation scenarios, particularly in optimizing glider performance for enhanced range and efficiency.

In examining the structural dynamics of gliders, notable research efforts such as Qu et al.'s study on high-altitude balloon-launched microgliders have significantly contributed to the understanding of glider design and control mechanisms of glider design and control mechanisms [4]. This investigation not only highlighted the potential of microgliders in data collection at high altitudes but also underscored the critical role of precise landing control through CFD analysis. Moreover, the comparative study by Harvey and Inman on the aerodynamic efficiency of gliders versus gliding birds' sheds light on the potential benefits of bio-inspired design principles in enhancing aircraft performance [5]. However, these studies, while pioneering, predominantly focus on control and design aspects without delving into the optimization of glider range under high-speed conditions, an area crucial for extending the applicability of gliders in commercial aviation and environmental research. To address this, the current study employs both experimental methods and CFD analysis to explore the aerodynamic properties of gliding aircraft. By doing so, it aims to establish foundational relationships between airfoil design and wing configuration, with a specific focus on enhancing glider performance and efficiency. Through this approach, this essay aims to propose targeted solutions for aerodynamic improvements, thereby contributing to the broader objective of reducing aviation's environmental impact.

2. Methodology

2.1. Physical Model

To begin with, a glider is an aircraft category that is clearly distinguished by its engine lessness. A glider plane's structure is usually made up of five main parts: the fuselage, the wings, the tail, the landing gear, and the control surfaces. Due to the absence of engines, as shown in Figure 1 [6], gliders are affected by three main forces: lift, weight, and drag.

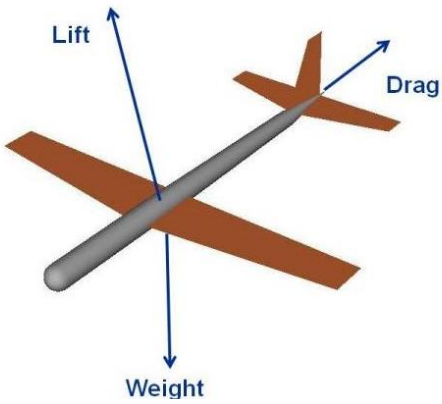


Figure 1. Force diagram of glider [6]

These factors determine the glider's motion. The weight, acting relentlessly downward is a direct consequence of the glider's mass. On the contrary, lift, which functions in the direction perpendicular to the glider motion, is determined by a combination of various elements: the glider's velocity, the angle of attack, the airfoil shape, and the surrounding air density. An additional crucial force, drag, is generated by the air density, surface roughness, and velocity. It operates in opposition to the glider's forward motion.

Due to the absence of an engine-generating component in glider flight dynamics and according to Bernoulli's principle, lift is generated through the relative motion of the glider and the wind. Hence, to enhance the glider's efficiency and range, it is critical to optimize the lift-to-drag ratio. The glider's ability to glide smoothly over long distances and maintain altitude is strictly regulated by this aerodynamic equilibrium.

The lift-to-drag ratio is significantly influenced by factors such as wing design, angle of attack, and airspeed. Given that this essay primarily focuses on high-speed cruising, aspects of wing design, particularly airfoil design and aspect ratio, are of paramount importance.

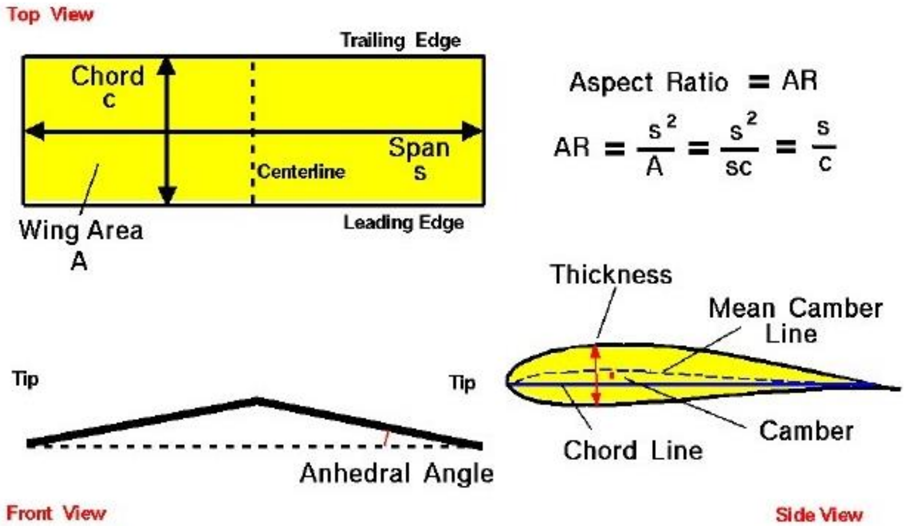


Figure 2. Aspect ratio [7]

As shown in Figure 2, the aspect ratio (AR) of a wing is defined as "the square of the span divided by the wing area" [7]. The aspect ratio is calculated by the formula:

$$AR = \frac{s^2}{A} = \frac{s^2}{sc} = \frac{s}{c} \quad (1)$$

According to the formula, in gliders, the incorporation of long wings serves to enhance the aspect ratio.

2.2. Research Process

The authors have decided to employ CFD simulation to determine the optimal airfoil and conduct an experiment to determine the appropriate aspect ratio of the airfoil designs.

This essay simplifies the glider model into the balsa wood glide plane with a cupboard-made wing, as depicted in Figure 3, to examine the aspect ratio. Glider models include the fuselage, wing, vertical stabilizer, and horizontal stabilizer, which are all fundamental glider components.

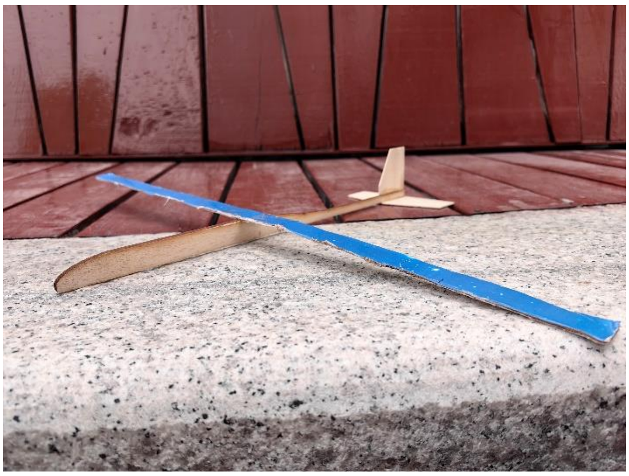
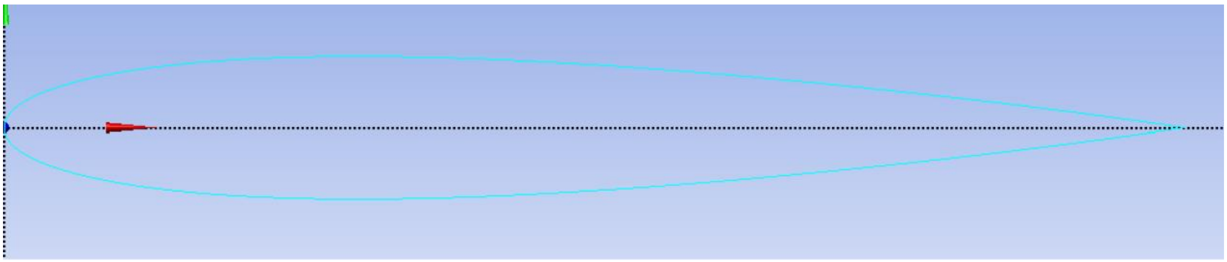


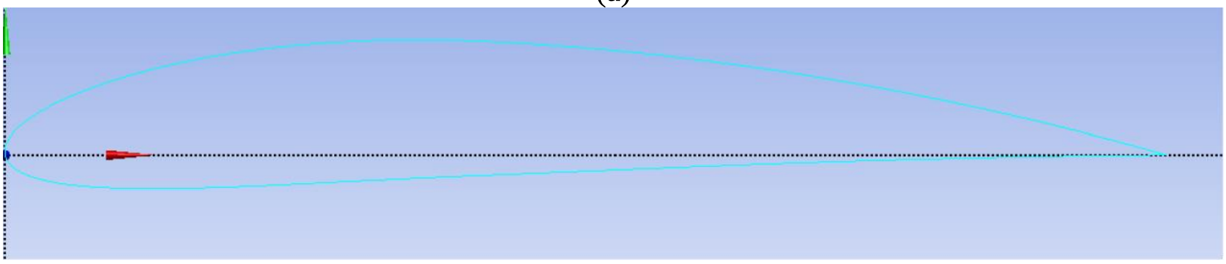
Figure 3. Balsa wood glider

Determine the mass of the wooden glider before commencing the experiment, and then launch the model at a constant velocity while maintaining an incidence angle of zero. Utilize a camera to capture the glider's motion as it is repeated five times; calculate the mean. Subsequently, administer the experiment with an alternate aspect ratio.

The aspect ratios of most modernized glider aircraft range from 10:1 to 30:1, so this essay conducts five experiments at aspect ratios of 10:1, 20:1, and 30:1. Furthermore, the trajectory of the glider is assessed through the utilization of tracking instruments.



(a)



(b)

Figure 4. Shapes of NACA 0012 (a) and NACA 4412 (b)

Regarding CFD analysis, as shown in Figure 4, the airfoil configurations most frequently employed in CFD analyses for gliders are NACA 0012 (National Advisory Committee for Aeronautics), which is a symmetrical airfoil, and NACA 4412, which is a cambered airfoil. The CFD analysis procedure begins with utilizing Fluent's built-in geometry tools and constructing a 2D model of the airfoil shapes. Subsequently, a C-mesh is generated, fluid properties including density and viscosity are specified, and boundary conditions including inlet velocity and angle of attack are specified. Finally, the CFD is implemented.

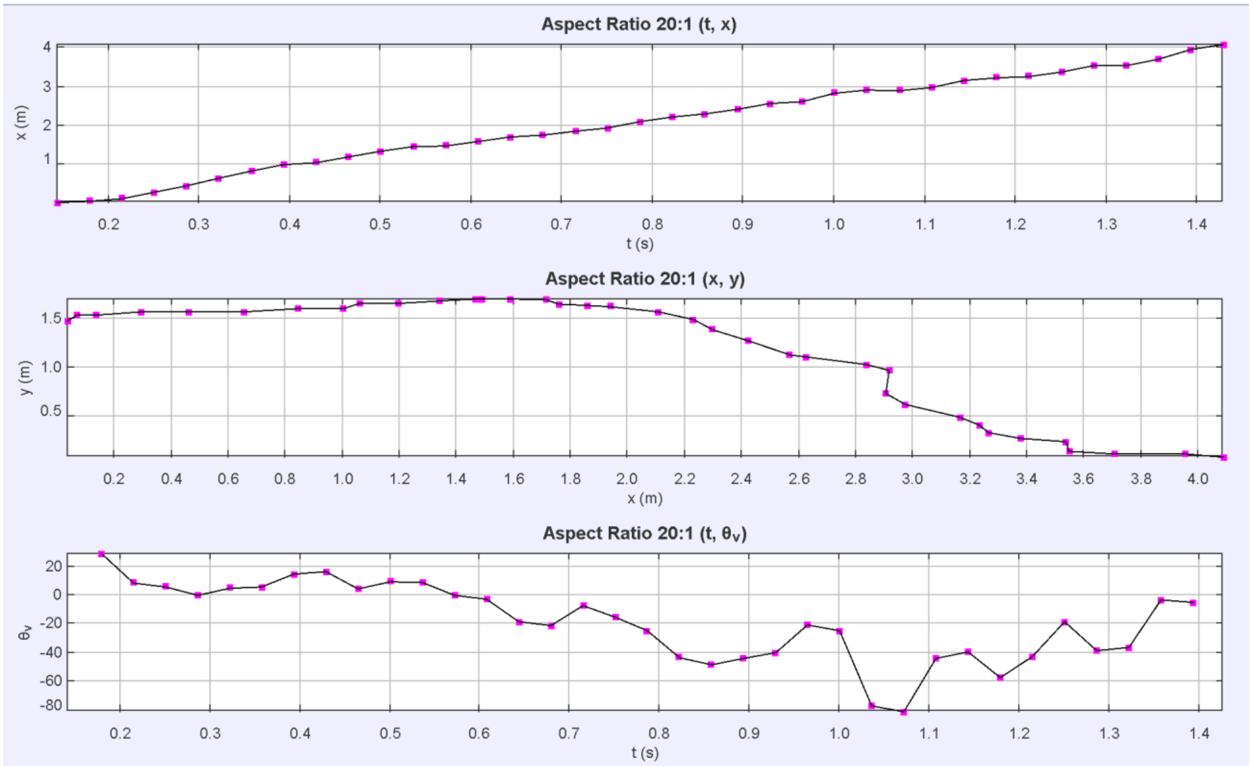
2.3. Experiment Software

The Tracker software, available at https://physlets.org/tracker, is used in this essay to track the motion of the glider and display key parameters, including the glide angle and velocity.

3. Results and Discussion

3.1. Display of the Glider Motion

This essay analyzed glider motions with varying aspect ratios through three distinct graphs. The first graph, plotting horizontal displacement (X) against time (T), elucidates the glider's horizontal movement, allowing insights into its speed and acceleration along the horizontal axis. The second graph contrasts the glider's vertical (Y) position with its horizontal (X) position, mapping out the glider's flight path and offering a visual representation of its aerodynamic path. Lastly, the angle of attack (θ) versus time (T) graph is explored, which sheds light on how the glider's orientation affects lift and drag forces over time, crucial for understanding its aerodynamic performance.


Aspect Ratio 20:1 (t, x)
x (m)
t (s)
Aspect Ratio 20:1 (x, y)
y (m)
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Aspect Ratio 20:1 (t, θ_v)
θ_v
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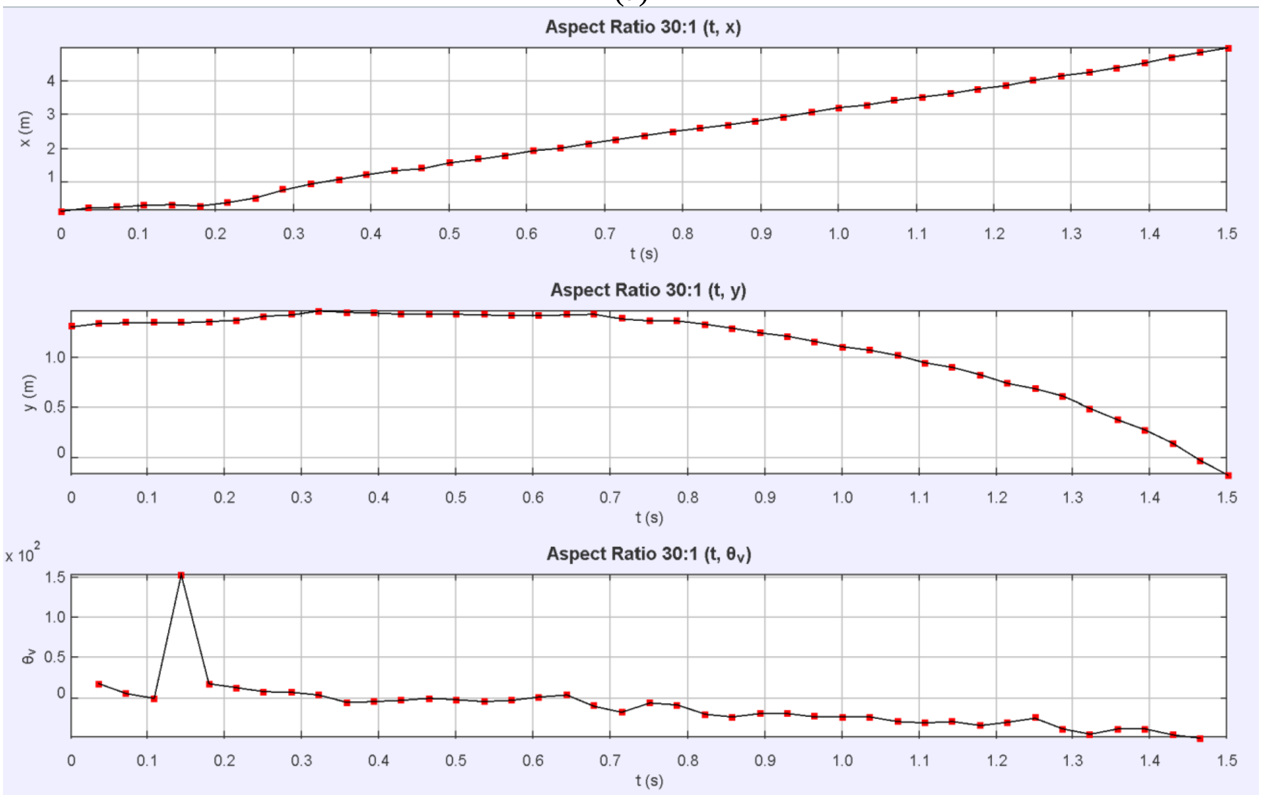
(a)


Aspect Ratio 30:1 (t, x)
x (m)
t (s)
Aspect Ratio 30:1 (t, y)
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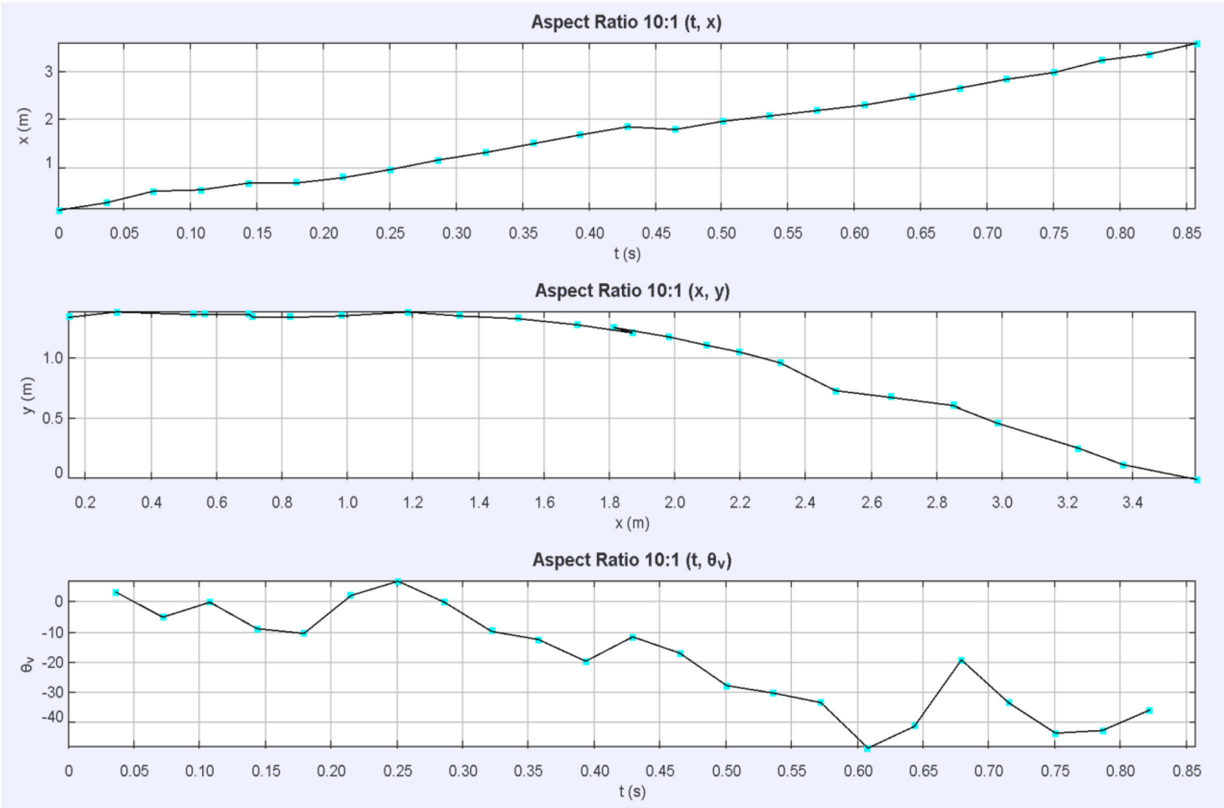
t (s)
x 10^2
Aspect Ratio 30:1 (t, θ_v)
θ_v
t (s)

(b)



(c)

Figure 5. Display of glider motion. (a) Aspect ratio of 30:1; (b) Aspect ratio of 20:1; (c) Aspect ratio of 10:1.

Table 1. Data of glider

Trial	Aspect ratio	Range (m)	Mass (kg)	Length of wing (cm)	Width of wing (cm)	Area (cm^2)
1	30:1	5.6	10.0	45	1.5	67.5
2	20:1	4.2	8.9	30	1.5	45
3	10:1	2.6	7.5	15	1.5	22.5

As Figure 5 and Table 1 show, the aspect ratio decreases from 30:1 to 10:1. The range of the glider decreases from 5.6 to 2.6, which is a percentage difference of 60%. The angle of incidence decreased from around 80 to 0 for all three trials and the motion of gliders in general shows a projectile shape.

3.2. Calculation of Lift and Drag

In terms of a mathematical approach to the glider's motion specifically the drag (F_D) and lift (F_L) forces onto the vertical and horizontal planes, there are two equations:

In vertical direction:

$$cos\,\theta + F_D\,sin\,\theta - W = 0 \tag{2}$$

In horizontal direction:

$$sin\,\theta - F_D\,cos\,\theta = 0 \tag{3}$$

It is possible to derive the ratio of the lift coefficient (C_L) to the drag coefficient (C_D) from the horizontal equation.

$$\frac{F_L}{F_D} = \frac{C_L}{C_D} \tag{4}$$

With the plane's weight W known, the vertical equation can be used to find the drag force (F_D) and the lift force (F_L).

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

$$F_L = \frac{W}{\cos\theta + \sin\theta \tan\theta} \tag{6}$$

Concluding from the graph of θ_v, the average glide angle is around -20° and so the lift and drag force calculations for the three aspect ratios are shown in Table 2.

Table 2. Calculation of the glider's motion

Trial	Aspect ratio	Drag force (N)	Lift force (N)	$\frac{C_L}{C_D}$
1	30:1	3.42×10^{-3}	9.40×10^{-3}	2.75
2	20:1	3.04×10^{-3}	8.36×10^{-3}	2.75
3	10:1	2.57×10^{-3}	7.05×10^{-3}	2.75

From calculation, it is obvious that the difference in mass has nearly no effect on the glider's lift-to-drag ratio since all the lift-to-drag ratios are approximately 2.75 and so the difference in aspect ratio plays a crucial role in the difference in range.

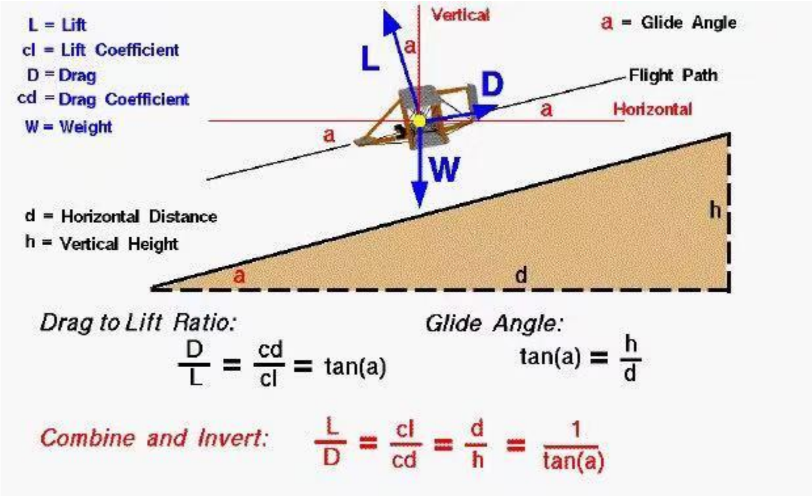
A significant influence on lift generation is exerted by the aspect ratio of a wing. Longer wings (characterized by a higher aspect ratio) possess the capacity to produce more lift than shorter wings (characterized by a lower aspect ratio), all else being equal. This is because the increased surface area of extended wings facilitates greater airflow, for an aspect ratio of 30:1, it has a surface area of $67.5\ \text{cm}^2$ which is three times the surface area of aspect ratio 10:1, which in turn increases lift. However, the process by which this upward force is produced is inextricably linked to the notion of induced drag.

An unavoidable type of aerodynamic drag, induced drag is produced when lift is generated. The formation of vortices at the wingtips, which result from the curvature of airflow from beneath the wing to the top, is especially visible [8]. Forward motion is counteracted by the drag force produced by these vortices. It is imperative to acknowledge that the amount of induced drag is inversely proportional to the aspect ratio of the wing. Lower induced drag is produced by wings with a higher aspect ratio compared to wings that are shorter and wider, due to their longer and narrower profile. The reduction in drag can be attributed to the diminished intensity of wingtip vortices on longer wings, which facilitates the adjustment of the pressure differential between the upper and lower surfaces of the wing throughout its entire extent.

In addition, the lift-to-drag ratio is a critical factor in determining the efficacy of a glider. As shown by the equation:

$$\frac{C_L}{C_D} = \frac{d}{h} = \frac{1}{\tan\theta} \tag{7}$$

The higher the lift-to-drag ratio, the lower the glide angle θ and so the glider can travel a greater distance, as shown in Figure 6 [9].



$$\frac{D}{L} = \frac{cd}{cl} = \tan(a) \qquad \tan(a) = \frac{h}{d}$$

$$\frac{L}{D} = \frac{cl}{cd} = \frac{d}{h} = \frac{1}{\tan(a)}$$

Figure 6. Display of glider motion and lift-to-drag ratio [9]

The assessment compares the glider's capacity to convert generated lift into forward motion, or glide, with the drag forces it experiences. The range of the glider is directly impacted by a higher lift-to-drag ratio, which allows it to progress by one unit for each unit of altitude lost. By increasing the aspect ratio, induced drag is concurrently reduced and lift is maintained, resulting in a natural improvement of the lift-to-drag ratio.

Indicated by the distance a glider can travel without suffering a significant reduction in altitude, its range is directly proportional to its lift-to-drag ratio. Due to an increased aspect ratio, which enhances the lift-to-drag ratio, the glider possesses the capability to descend from its initial altitude and cover greater distances. As a result of the decreased air resistance (drag), the glider attains enhanced gliding efficacy, enabling it to convert an equivalent amount of lift into prolonged horizontal motion.

3.3. Lift-to-drag Ratios of Different Airfoils

The essay uses Ansys Fluent for the CFD analysis of airfoils. To determine the lift and drag coefficient, this essay creates 2D models of NACA 0012 and NACA 4412 airfoils and uses C Mesh as the boundary condition, as shown in Figure 7. The length of the two airfoils is 1m and the C shape has a diameter of 15m and a square of side length of 15m.

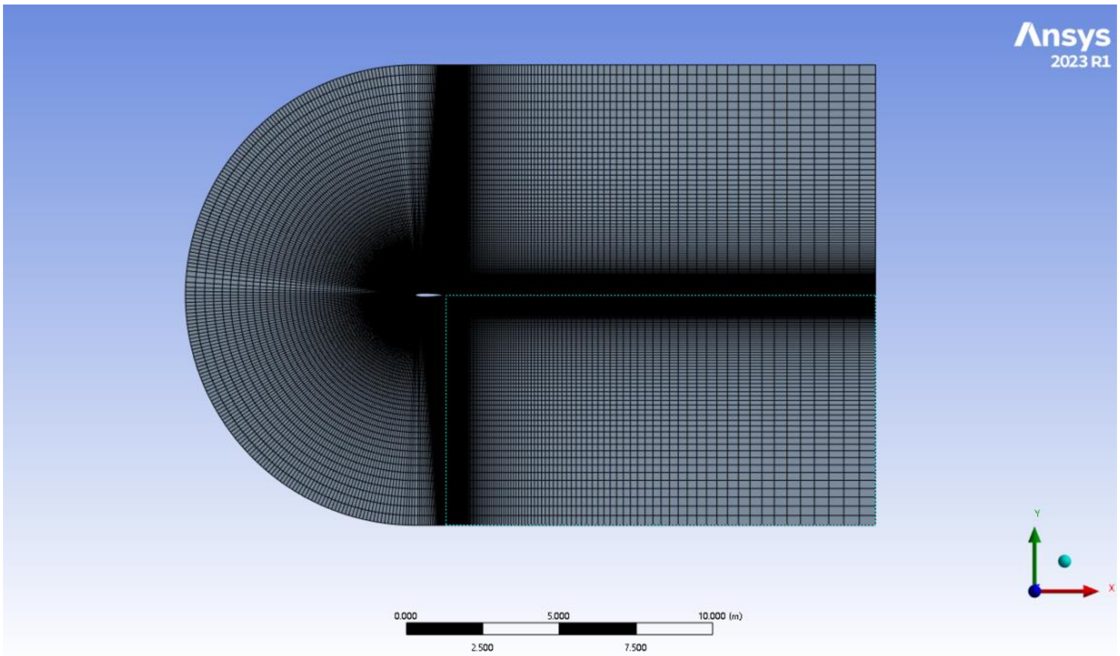
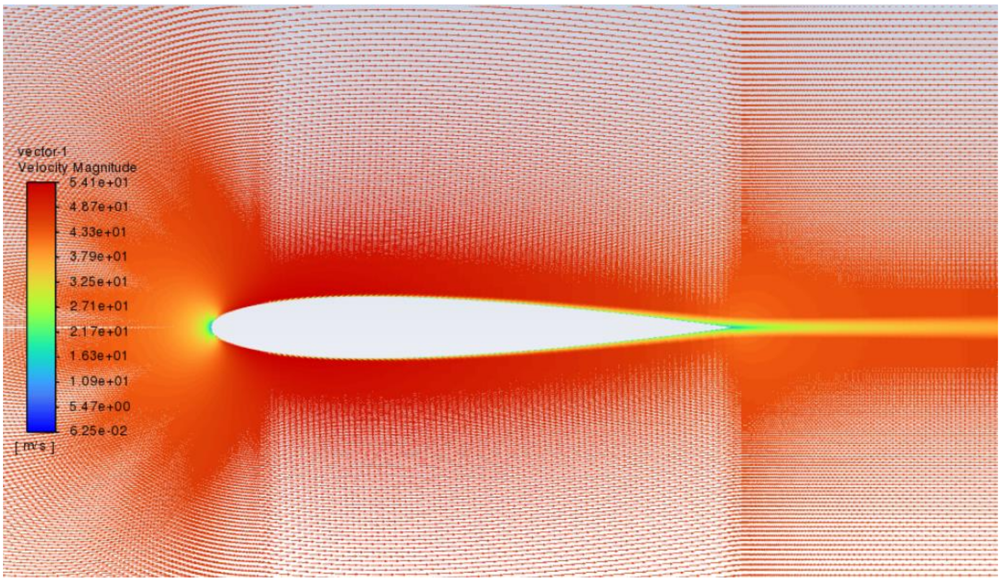
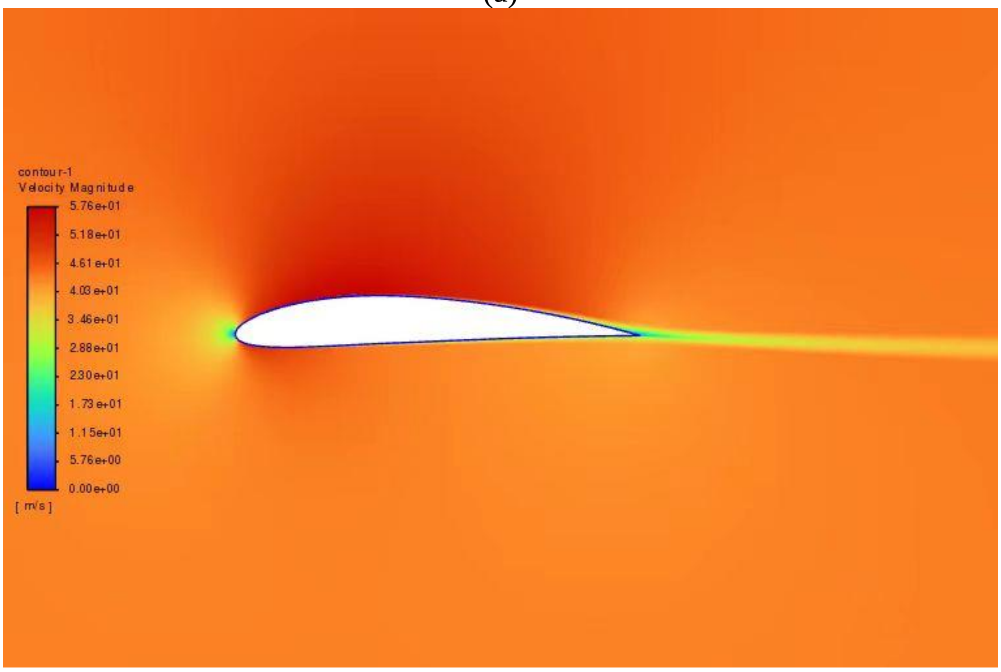


Figure 7. C Mesh used in CFD

And since the essay focuses on the cruising condition, the angle of attack is not within the scope of this article. To simulate the high-speed condition, the speed of flow was set to 45.6m/s, and the velocity magnitude graph is shown in Figure 8.



(a)



(b)

Figure 8. Velocity magnitude of NACA 0012(a) and NACA 4412(b)

The NACA 0012 and NACA 4412 airfoils exhibit discernible aerodynamic characteristics as a result of their structural variations, as determined by a comprehensive analysis tailored to gliders. Due to the identical upper and lower surfaces, the NACA 0012, which is a symmetric airfoil, has zero camber. At an angle of attack of zero, this symmetry prevents the airfoil from producing lift. It provides stability and predictability, particularly at higher velocities, as its lift increases linearly with the angle of attack. Such as specific varieties of aircraft wings and tail surfaces, the NACA 0012 is therefore suitable for applications requiring aerodynamic efficiency and stability at high speeds.

A cambered airfoil, on the other hand, denotes that the upper surface of the NACA 4412 is more curved than its lower surface. As suggested by the NACA four digits series, type 4412 indicated that the camber is 4% of the chord and the maximum camber is at 40% of the chord [10]. The NACA 4412 is capable of producing lift at zero angle of attack on account of this asymmetry; lift increases as the angle of attack increases. Gliders, which function at reduced velocities and necessitate effective lift production, find this characteristic especially beneficial. Higher angles of attack, in particular, result in an increase in drag, which is a consequence of the increased lift.

When contrasting the NACA 0012 and the NACA 4412 at lower angles of attack, the former generally demonstrates superior lift-to-drag performance. For gliders, where generating lift is more important than minimizing drag, this enhanced lift-to-drag ratio makes the NACA 4412 more efficient. Higher speeds are more favorable for the NACA 0012, whose reduced drag characteristics contribute to its lower lift-to-drag ratio at these angles.

Particular aerodynamic requirements dictate which of these airfoils is utilized on gliders. Slaliers find the NACA 4412 to be an ideal companion due to its favored lift efficacy at lower speeds. In contrast, although stability and performance at elevated velocities are not ordinarily the principal considerations for gliders, the NACA 0012 could be selected in such circumstances.

An aspect ratio, wing loading, and overall airfoil shape are all optimized for optimal glide performance in the design of gliders, which is a balance of these aerodynamic factors. By prioritizing efficient, sustained lift in lower-speed regimes, the cambered design of the NACA 4412 is well-suited to the typical operational profiles of gliders. Nevertheless, structural factors must also be taken into account by the designer, given that the cambered configuration may require alternative building methods or materials to effectively withstand aerodynamic forces.

4. Conclusion

This study aimed to investigate the aerodynamic efficacy of gliders. To achieve this, a combination of experimental and CFD methods was utilized to examine the effect of airfoil and wing configuration on lift-to-drag ratios at high speeds. By conducting an exhaustive quantitative analysis, this essay has discovered that the aspect ratio of glider wings has a direct impact on their range and efficacy, thereby significantly enhancing their aerodynamic performance.

The findings of the research demonstrate that by optimizing airfoil configurations and wing architectures, glider performance is substantially enhanced. This essay observed that elevated aspect ratios significantly enhance lift and decrease induced drag, thus optimizing the lift-to-drag ratio that is critical for prolonged range and optimal performance during flight.

The principles outlined in this essay have substantial consequences for a broad spectrum of researchers, specifically regarding aerodynamic optimization as it pertains to glider design and performance. While the study has made a few developments, it is important to acknowledge its limitations. One such limitation is the absence of variable angles of attack during cruising, which have the potential to greatly impact aerodynamic performance. Furthermore, the experimental design employed in this study exclusively simulates rectangular airfoil shapes, neglecting the intricate profiles of NACA airfoils. As a result, the detailed aerodynamic behaviors of more intricate designs might not be comprehensively captured. Additional constraints encompass the experimental models' scale, which might not precisely replicate the operational characteristics of full-scale aircraft; furthermore, the flight conditions were oversimplified to exclude variables such as turbulence and weather, both of which have the potential to impact performance in real-world scenarios.

Subsequent investigations should look into the variation in angles of attack throughout the phases of flight, utilize intricate airfoil models such as NACA shapes to conduct comprehensive aerodynamic analyses, and contemplate conducting full-scale and real-world condition testing to replicate the effects of environmental factors on aircraft performance. Exploring innovative materials and structural designs has the potential to significantly transform the efficacy of aircraft. In addition, by incorporating bio-inspired designs and advanced material sciences, an interdisciplinary approach has the potential to generate novel solutions for aircraft that are both environmentally friendly and highly effective, thereby tackling the urgent challenges faced by the aviation sector.

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