Mechanics of Flight Final Project Technical Report

Alex Ren, Jay Heymann, Xander Song

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Background

In 1903, the Wright brothers became the first to fly a powered, sustained, and controlled aircraft [1]. Their success led to decades of rapid development in aircraft and wing design. In this report, we will discuss the design of the Wright Flyer wing and propose a new design to improve upon the original wing.

Wright Flyer Design

The airfoil design used by the Wright brothers was the Eiffel 10 airfoil [2]. This airfoil has a maximum thickness of 2.7% and a camber of 6.1%. Some key parameters from the Wright brothers' blueprint [Fig. 1] are a 1:20 camber, a 12.89 meter wingspan, a 1.98 meter chord length, a 3.417° angle of incidence, and a 10 inch anhedral (~2.3°) [3]. The Wright brothers used a biplane design with two wings vertically stacked.

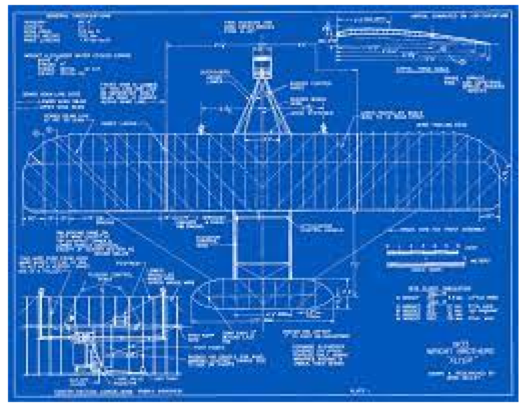

Figure 1. Wright Flyer blueprint

Wright Flyer Aerodynamic Characteristics

XFLR5 software was used to model the aerodynamic characteristics of the Wright Flyer. The airfoil was approximated as a NACA 2404 airfoil with the camber changed to 5% to account for the Wright brothers' 1:20 camber. Interestingly, this resulted in a slightly different airfoil than directly inputting a NACA 5404 airfoil [Fig. 2].

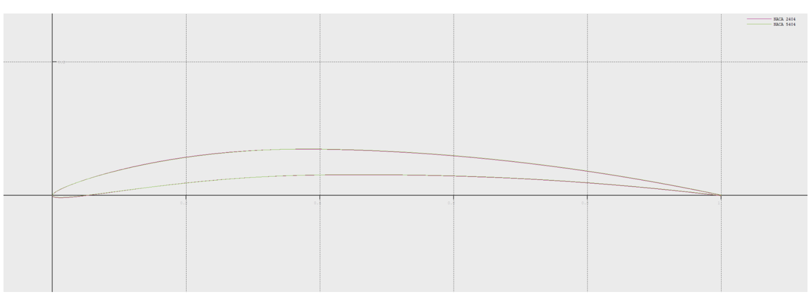

Figure 2. Modified NACA 2404 (red) with 5% camber compared to NACA 5404 (green). Slight differences are observed between the two foils despite all parameters being the same.

The wing was modeled as an approximately rectangular biplane with a taper ratio of one. Inviscid analysis was performed with a Reynolds number of $3x10^6$. Some notable performance features included a slightly concave drag polar [Fig. 3(a)], a coefficient of lift approximately linearly correlated with increasing angle of attack [Fig. 3(b)], a negative moment coefficient with increasing magnitude correlated with increasing angle of attack [Fig. 3(c)], and a lift to drag coefficient ratio decreasing at a decaying rate with increasing angle of attack [Fig. 3(d)].

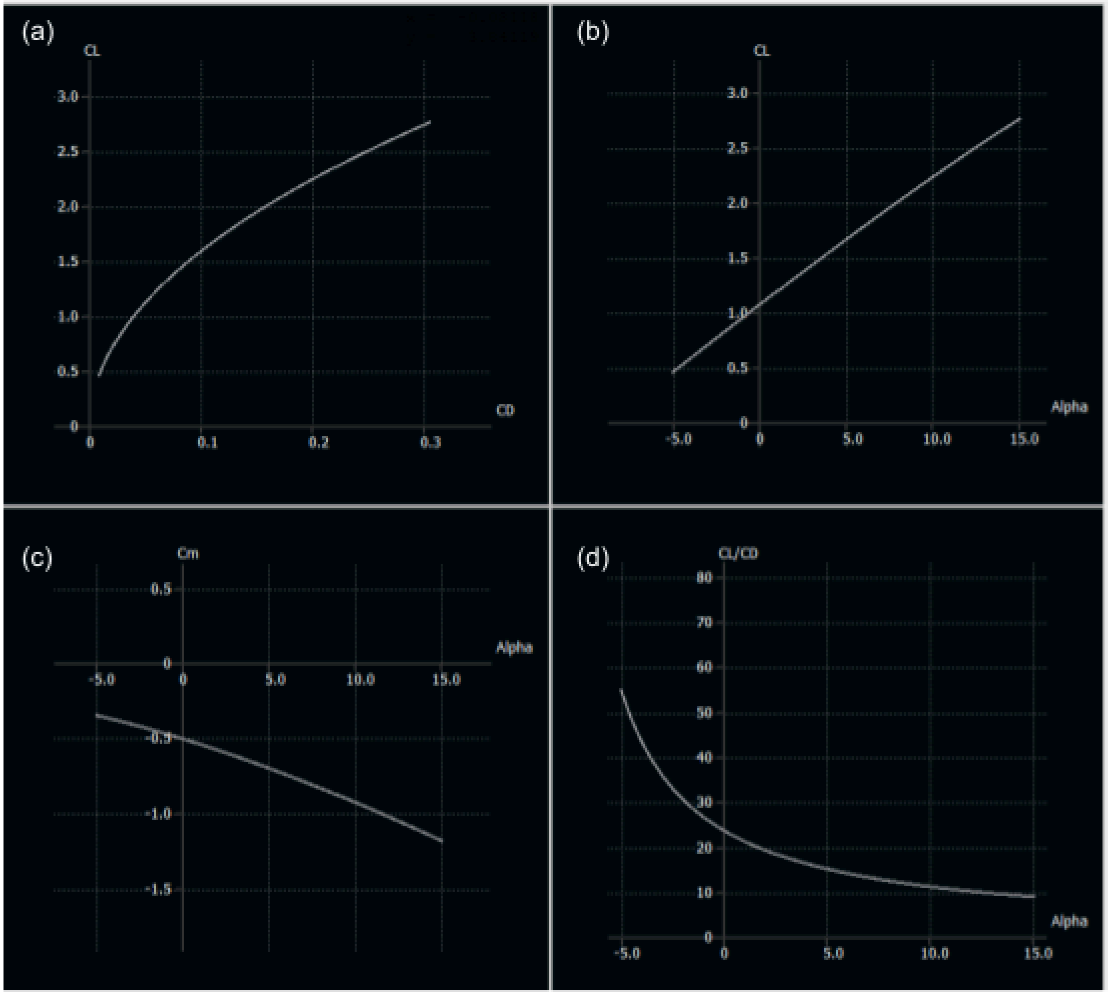

Figure 3. Aerodynamic characteristics of Wright Flyer wing. (a) Drag polar graph, cl vs cd. (b) Coefficient of lift vs. angle of attack. (c) Moment coefficient vs. angle of attack. (d) Coefficient of lift to coefficient of drag ratio vs. angle of attack.

Other performance parameters analyzed were the induced drag, lift distribution, and downwash. We noted that downwash velocity increased and lift decreased near the wingtips [Fig. 4(b)]. The edge of the induced drag distribution formed a parabolic shape, with the most induced drag at the wingtips [Fig. 4(a)].

Improved Wing Design

The main characteristics changed were the dihedral angle, the taper ratio, and the airfoil profile. In the new design, the dihedral angle changed from an anhedral of 2.3 to a dihedral of 2.5, the taper ratio decreased from 1 to 0.25, the airfoil's camber increased from 5% to 8%, and winglets were added at the wingtips. The plane was kept as a biplane.

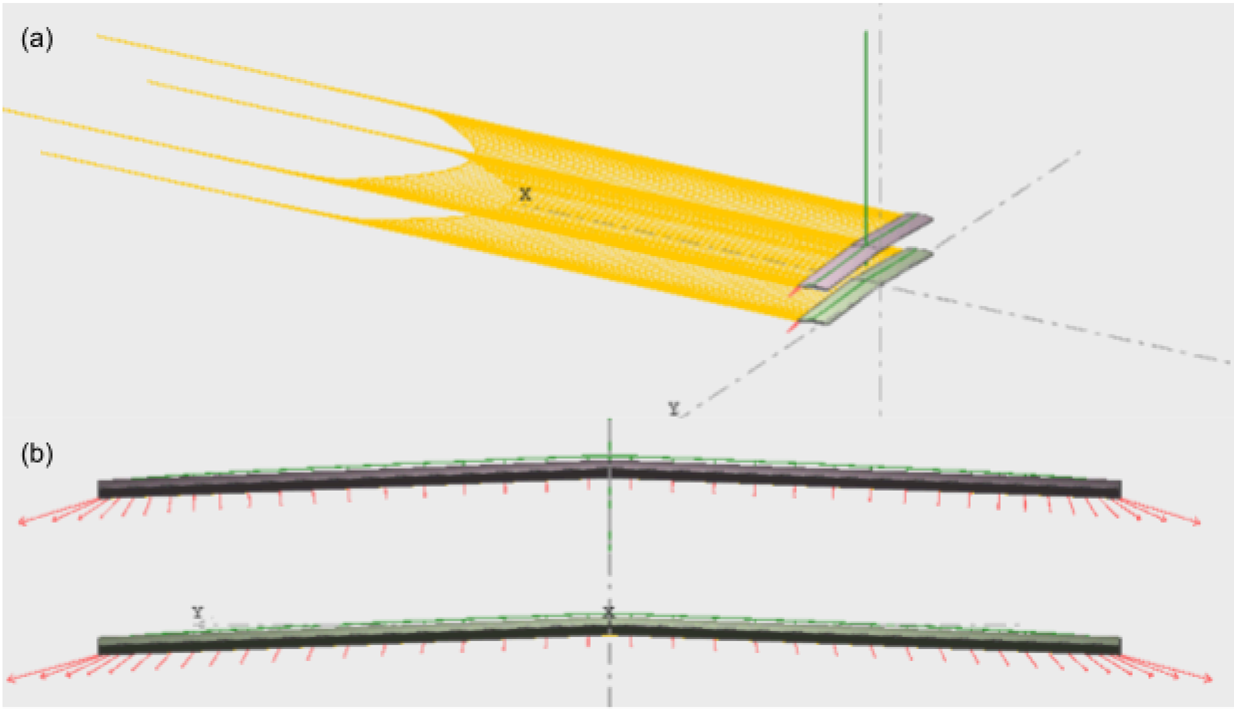

Figure 4. 3D view of Wright Flyer biplane at 0° angle of attack. (a) Induced drag (yellow) and total lift (green) of Wright Flyer. (b) Lift distribution (green) and downwash distribution (red) of Wright Flyer.

Analyzing the effects of wing dihedral revealed that a dihedral angle improved the roll stability of the plane over the original anhedral angle [4]. Improved roll stability improved the control of the plane; however, increasing dihedral decreased the lift and increased induced. Additionally, if the roll stability of the plane is increased too much, the plane will become too stable and thus unmaneuverable. In some cases, the maneuverability of anhedral wings is desirable, such as in large, inherently stable aircraft like the Antonov An-225 Mriya, or in fighter jets like the Grumann F-14 Tomcat. However, one of Wright Flyer's issues was roll stability [5]. The Wright brothers solved this by allowing control of the wings through "wing-warping." By twisting and

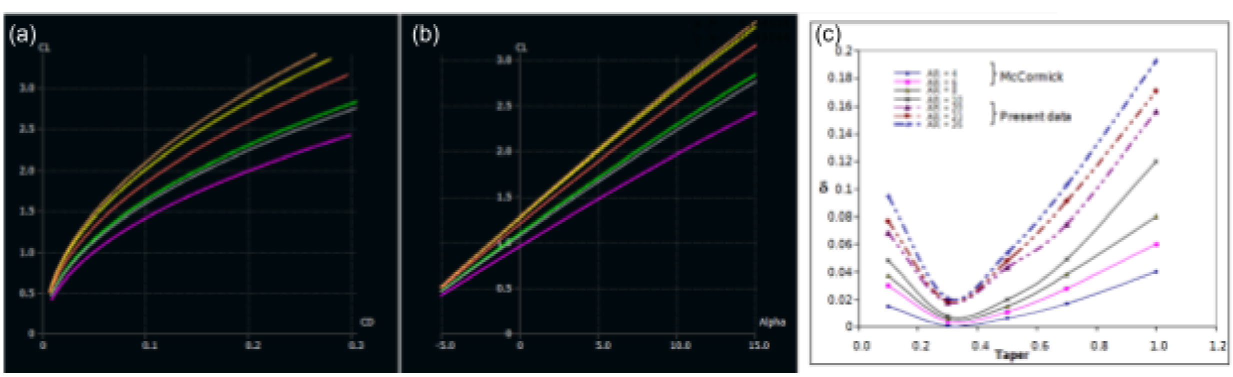

Figure 5. Aerodynamic characteristics at taper ratios of 0 (orange), 0.25 (yellow), 0.5 (red), 0.9 (green), 1 (gray), and 1.5 (magenta). (a) Drag polar graph. (b) Lift coefficient vs angle of attack for various taper ratios. (c) Effect of taper ratio on induced drag for various aspect ratios [6]

warping the wing through, the Wright brothers could adjust the lift generated on each wing and control the plane. However, this meant that the plane could only be flown by a skilled pilot, as the high instability of the plane made flying difficult. As such, the improved design used a small dihedral angle of 2.5 to increase stability without sacrificing too much maneuverability and lift.

Taper ratio describes the ratio of the wing tip chord length to the root chord length. The modeled Wright brother wing used a constant chord length throughout the entire wing. However, in the actual wing, there exists some taper at the wing tips. Decreasing the taper ratio significantly affects the drag polar of the wing [Fig. 5(a)], with the Cl/Cd ratio being much higher at lower taper ratios. Decreasing the taper ratio also significantly increased the coefficient of lift [Fig. 5(b)]. While the best drag polar results from a zero taper ratio, the induced drag increases substantially at taper ratios less than 0.2 and greater than 0.4, with a minimum of ~ 0.3 [Fig. 5(c)]. This is because the taper ratio affects the shape of the wing significantly. The more elliptical a wing, the more efficient it is, resulting in reduced induced drag. Initially, as taper ratio decreases, the wing shape becomes more elliptical, resulting in lower induced drag. However, when the ratio becomes too low, the shape becomes less elliptical again and results in higher induced drag. Due to these factors, the final taper ratio was set at 0.25.

The third characteristic that was changed was the camber of the airfoil. As the camber of the airfoil increased, the lift coefficient also increased [Fig. 6(b)]. Interestingly, the drag polar curves remained about the same for all the modeled cambers. This suggests that while the lift increases with camber, the drag also increases [Fig. 6(a)]. However, this is expected as increasing the camber also increases the frontal area of the wing, which would increase the drag. This results in the lift to drag coefficient ratio being lower at higher cambers [Fig. 6(c)]. As the focus of this change was to increase the lift of the wing, a camber of 8% was chosen: a significant increase compared to the Wright Flyer wing.

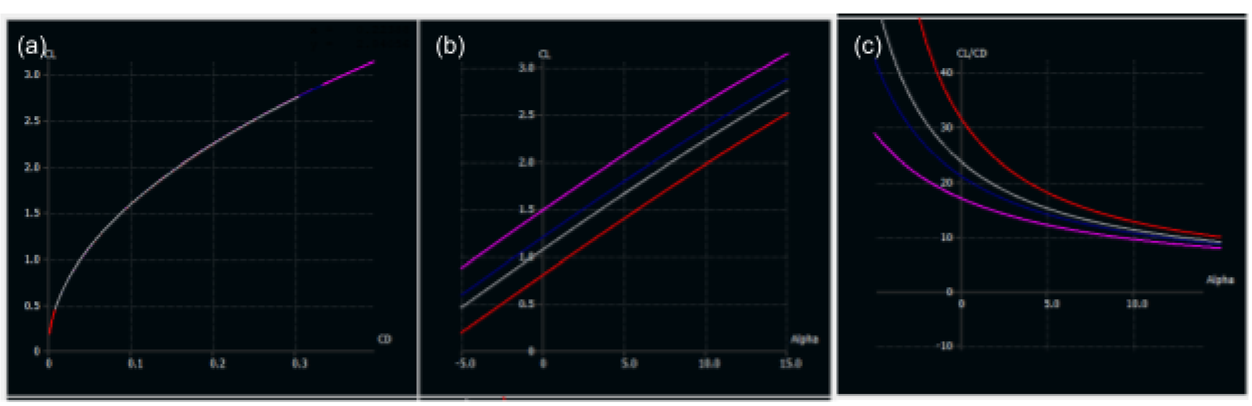

Figure 6. Aerodynamic characteristics at cambers of 3% (red), 5% (gray), 6% (blue), and 8% (magenta). (a) Drag polar graph. (b) Coefficient of lift vs angle of attack. (c) Lift to drag coefficient ratio vs. angle of attack

Many modern commercial airplanes like the Airbus A330 and the Boeing 747-400 include winglets in their wing designs. This is due to the reduction in induced drag at the wingtips that the winglets cause, resulting in increased operating efficiency of the plane [7]. These effects are especially pronounced at lower speeds, and are thus extremely important for our wing design, as the Wright Flyer operated at a slow 20 m/s. As air passes over a wing, unequal pressure is generated by the shape of the airfoil. This causes air to flow spanwise at the wingtips and curl around, forming wingtip vortices. These wingtip vortices increase the wing's drag and decrease its lift. By adding winglets, the strength of the vortices are reduced, as winglets produce a thrust in the circulation field of the vortices. This leads to a reduced induced drag. Another reason that the induced drag is reduced is because the induced drag is related to the downwash [8]. More downwash leads to more induced drag. This is because the downwash induces a decreased effective angle of attack, increasing the effect of the tip vortices and increasing induced drag. The winglets redirect the downwash [Fig. 7(a) and Fig. 7(b)] so there is less of it, leading to a reduction in induced drag at the wingtips [Fig. 7(c) and Fig. 7(d)].

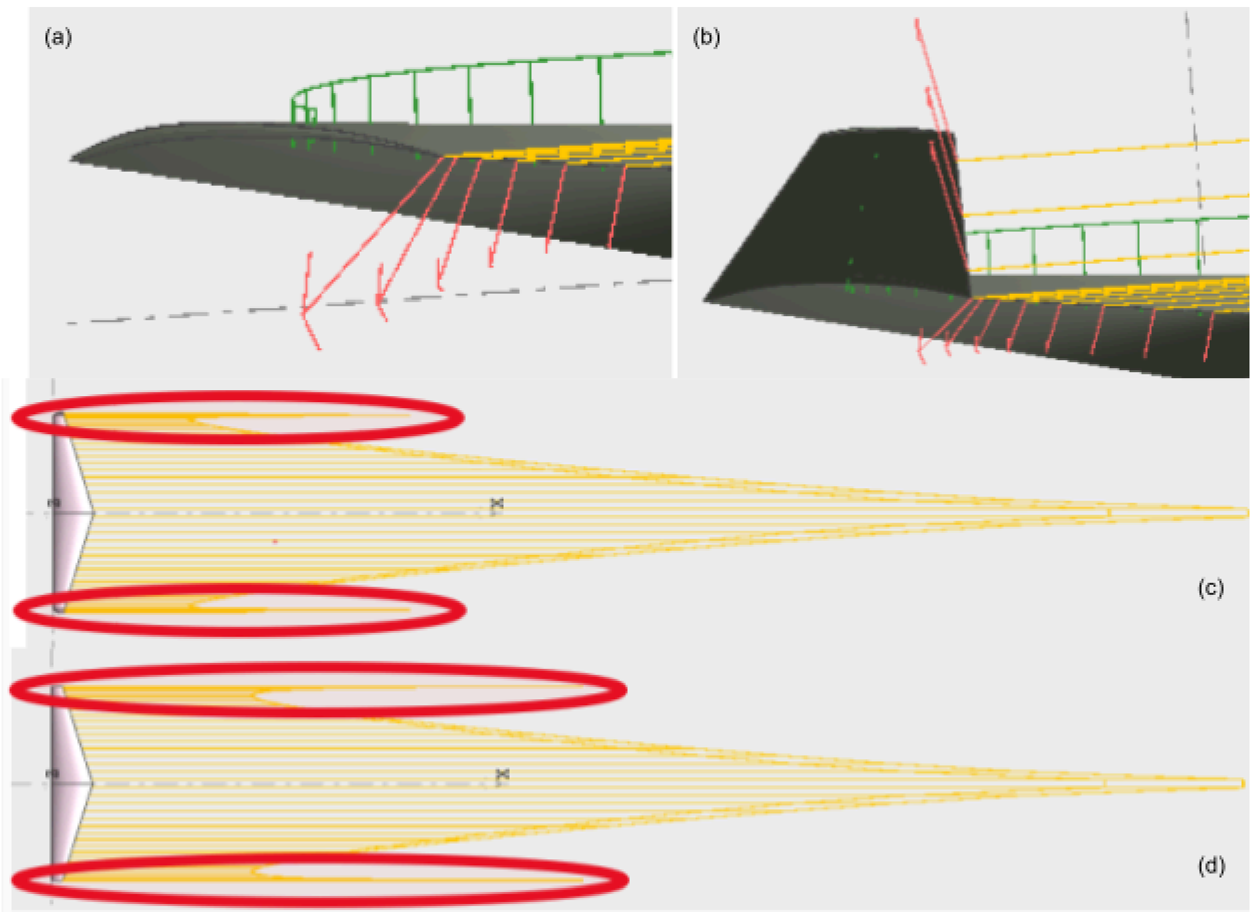

Figure 7. Wings shown at 0° angle of attack. (a) Downwash at wingtip without winglet. (b) Downwash at wingtip with winglet. (c) Induced drag with winglets. (d) Induced drag without winglets.

Changes to the root-to-tip sweep of the wing were considered, but were not implemented. Initially, the consideration was that adding sweep to the wing would lead to a reduction in the drag at the cost of some lift. However, this effect is only significant at the higher speed. Early research in the 1930s by Adolf Busemann and Albert Bertz showed that swept wings had an effect in drag reduction at speeds of Mach 0.7 and Mach 0.9 [9]. At low speeds however, the flow is pushed spanwise and leads to a decrease in stability while the drag reduction is insignificant [10]. Because of this, sweep was eliminated from our changes to the wing.

With all the new changes [Fig. 8(a)] implemented, the drag polar is significantly higher than before [Fig. 8(b)]. This suggests a more efficient design, as the lift to drag ratio is higher. Additionally, the lift coefficient is much higher [Fig. 8(c)]. The moment coefficient [Fig. 8(d)] is about the same as with the Wright brothers, but is slightly more negative. This indicates a better longitudinal stability for the design. An interesting result was that the lift to drag ratio [Fig. 8(e)] was higher at positive angles of attack, but was lower for negative angles of attack. The slope is flatter than the Wright Flyer design. Other notable changes are that lift is increased in the new design with a 3% increase despite planform area decreasing by 37%. This indicates a much more efficient wing design compared to the Wright Flyer. Additionally, induced drag at the wingtips is significantly reduced. The shape of the induced drag is also different [Fig. 4(a) and Fig. 7(c)], as most of the drag occurs at the center of the wing instead of the wingtips. This is due to the taper of the wings. The overall wing is greatly improved in its efficiency, lift, and drag polar.

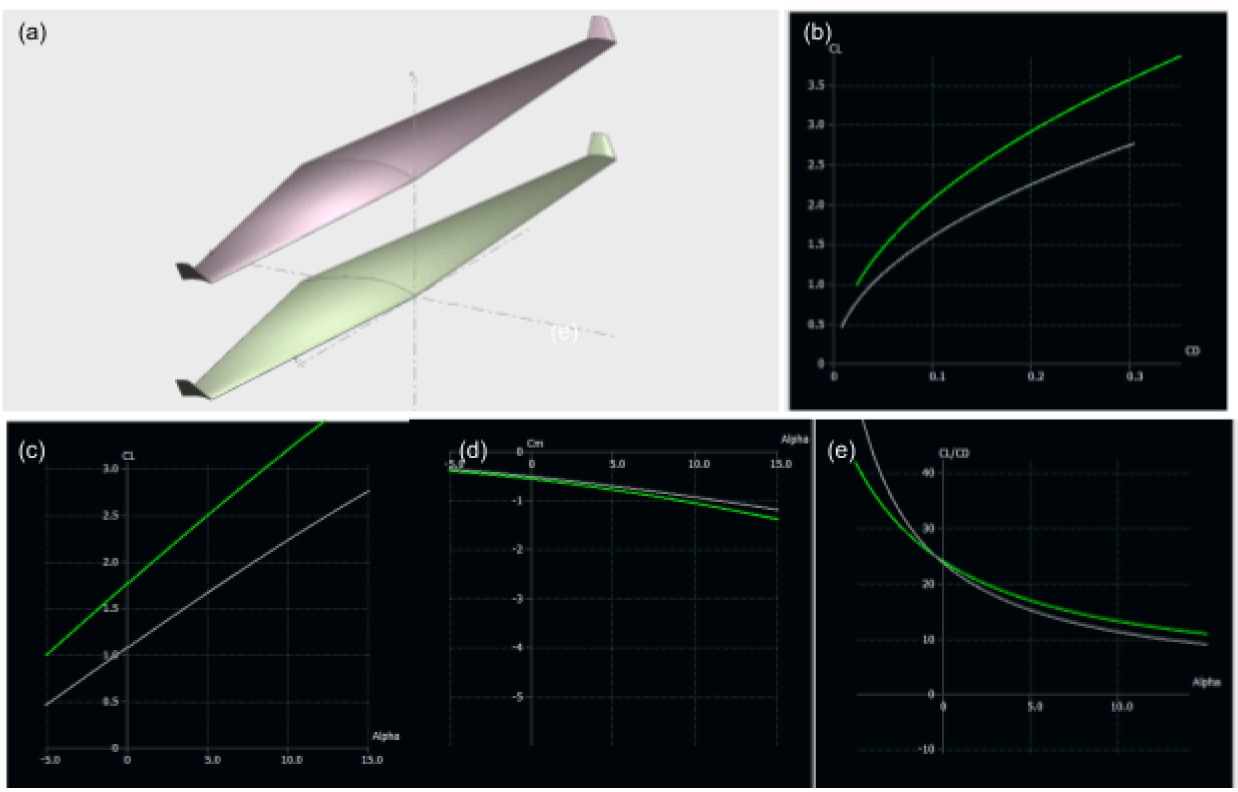

Figure 8. New wing design and aerodynamic characteristics. New design is in green and Wright Flyer is in gray. (a) 3D view of new wing at 0° angle of attack. (b) Drag polar graph. (c) Coefficient of lift vs. angle of attack. (d) Moment coefficient vs. angle of attack. (e) Lift to drag coefficient ratio vs. angle of attack.

References:

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[9] Critical Mach Number Prediction on Swept Wings (asu.edu)