HOW GLIDERS HELPED THE WRIGHT BROTHERS INVENT THE AIRPLANE

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ABSTRACT

Orville and Wilbur Wright integrated and safely flew the first successful, controlled, powered airplane. The process they used was one of progressive design and was successful to a large degree due to their use of gliders. Previous attempts at powered flight were unsuccessful because the inventors tried to fly first with power before the subtleties of control were addressed. The Wrights instead first learned how to fly by using gliders as tools to solve the challenges of adequate control, and then added power to invent the airplane.

Their overall approach and configuration optimization (including wing sizing, airfoil development, 3-axis flight controls) are discussed in this paper. Other elements that were required for a successful airplane, such as development of the propulsion system, and have been chronicled elsewhere. Airfoil, drag, and performance analysis using current techniques are presented to illustrate the Wright's contributions to powered flight.

NOMENCLATURE

α	= Angle of attack, deg.
AR	= Wing aspect ratio = b^2/Sref
b	= Wing span, ft.
C_D	= Total drag coefficient
$C_D$profile	= Airfoil profile drag coefficient
C_L	= Lift coefficient
C_M	= Pitching moment coefficient
Cp	= Pressure coefficient = (p-pinf)/qinf
e	= Lifting surface induced drag factor
L/D	= Lift to drag ratio
p	= Static pressure
q	= Dynamic pressure = 0.5 * ρ * V^2, lb./ft^2
ρ	= Density
Sref	= Wing reference area, ft^2

BACKGROUND

Attempts at piloted, sustained, controlled, and powered flight before the Wright brothers were only partially successful. Usually the activity was an unsustained hop without adequate control. Clement Ader1, Sir Hiram Maxim2, and Samuel Langley3 were unsuccessful when they tried to fly first with power before the subtleties of control were addressed. That said, all of these aviation pioneers still contributed greatly to overall aeronautical knowledge. Other aviation pioneers such as Otto Lilienthal4,5, Percy Pilcher6, and Octave Chanute7 used unpowered hang gliders as tools to address the challenges of adequate lifting surfaces and controls needed to carry a human safely aloft. Their experiments demonstrated to the world that heavier than air human flight was possible. The timing was perfect for someone to work the difficult problems and put all the pieces together. The Wright brothers built on the work of Lilienthal, Pilcher, and Chanute by developing improved gliders, and then adding power to invent the airplane.

THE WRIGHTS ENGINEERING PHILOSOPHY

Orville and Wilbur Wright (Figure 1) working with help from their family and colleagues, learned from their predecessors, and then used a well-disciplined engineering approach to overcome each challenge to achieving flight. Their approach was superb, using engineering, design and testing techniques that would be admired in today's current aerospace industry. Orville and Wilbur Wright came from a close, supportive family and worked well together as a team. They also had a natural curiosity, were hard working, and were mechanically inclined. They also developed a close friendship with Octave Chanute, who was one of the more prominent engineers studying the problem of powered flight in their time. Chanute and the Wrights exchanged several hundred letters from 1900 to 1910, beginning with the famous letter from Wilbur of May 13, 1900, which began with the words, "For some years I have been afflicted with the belief that flight is possible to man." 8 Octave Chanute provided the perfect technical sounding board for the Wrights to discuss many of their ideas.

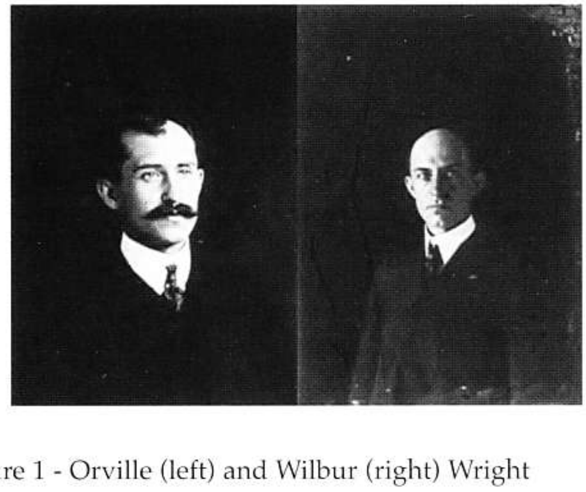

Figure 1 - Orville (left) and Wilbur (right) Wright

Typical of how Orville and Wilbur interacted together was their use of debate or humor to resolve technical issues.9 For example, during the formulation of their propeller theory Orville wrote, "After long arguments, we often found ourselves in the ludicrous position of each having converted to the other's side with no more agreement than when the discussion had begun."10 There are several excellent resources with more information about the Wrights and reasons for their ultimate success.11, 12

The Wrights used the work of previous experimenters as a starting point for their own experiments. They did not invent, but freely used these tools and concepts:

1. The wind tunnel (invented by Francis Wenham in 1870)13
2. Airfoils (patented by Horatio Phillips in 1884)14
3. The multi-plane design concept (used by John Stringfellow in his 1868 triplane)15
4. The structural concept of Octave Chanute and Augustus Herring's successful biplane glider design of 189616, 17.

They were inspired by Otto Lilienthal's successful glider experiments and saddened by his tragic death16. The time was ripe for discovery of an integrated solution as many of the basic building blocks to achieve flight were available when the Wrights began their work.

The Wrights then improved upon this previous work and progressively evolved their glider designs into what became the successful 1903 Flyer powered airplane. They identified and solved the critical problems in the proper order: Creating adequate control, lift, and power. Examples will be outlined in subsequent sections of this paper.

Two additional factors helped ensure the Wright's success and legacy as the inventors of powered flight: Their approach to full-scale flight testing and their commitment to robust documentation.

Orville and Wilbur originally wished to accumulate flight time by flying their gliders tethered from a high tower, but soon settled on manned glides from the sand dunes of Kitty Hawk. They attempted to estimate the characteristics of their gliders prior to flight using the best understood methods at the time, and then used the flight data to update their methods.

One key element easy to overlook was the superb piloting skill of the brothers, gained through multiple, brief glides.18 They had the double tasks of not only inventing a practical flying machine, but also learning how to safely pilot it. They were willing to face the risk of personal injury which no doubt motivated them to rapidly resolve the technical issues needed to fly safely. Their flight time increased dramatically as their glider technology improved. They minimized the risk and had a superb safety record while doing their glider experiments.

The Wright's use of photography, notes, and technical presentations preserved a large historical record of their experiments and provided proof that they indeed achieved flight. Though often viewed as an unglamorous task, adequate documentation can become priceless history.

1899-1900 EXPERIMENTS

The first Wright aircraft was an unpiloted kite flown in 1899 to test the wing warping approach to lateral control (Figure 2). Little is known about the kite design details other than a drawing of how it works. One group's interpretation of the kite may be found on the Internet.19 The 1899 Wright kite validated the biplane design philosophy and wing warping using aerodynamic surfaces, all combined in a very simple package.

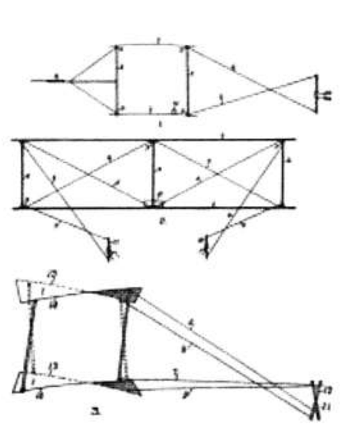

Figure 2 - Wright 1899 kite

The 1900 glider followed this and was an improvement of Chanute and Herring's "Two-surface Machine". Improvements included relocating the wing front spars to the wing leading edges and using wing warping that still preserved the bending strength of the airframe. The pilot flew in a prone position rather than by hanging from the airframe to reduce drag and increase pilot comfort. The Wrights found this position safe because they were flying over sand.20 The glider also had a canard (called a "forward rudder" by the Wrights). The Wrights reasons for choosing a canard rather than tail-aft arrangement are best expressed in a letter from Orville dated April 11, 1924 that describes improved safety due to the canard's ability to prevent "nose dives" such as the incident that killed Lilienthal.21

The 1900 glider (Figure 3) had 165 ft2 of wing area and weighed 52 pounds. It had inadequate wing area to easily allow sustained piloted glides, though the Wrights still recorded several minutes of airtime from multiple flights16. Unfortunately the glider was later heavily damaged when upset by a gust of wind. The 1900 experiments lasted from September 12 to October 23.

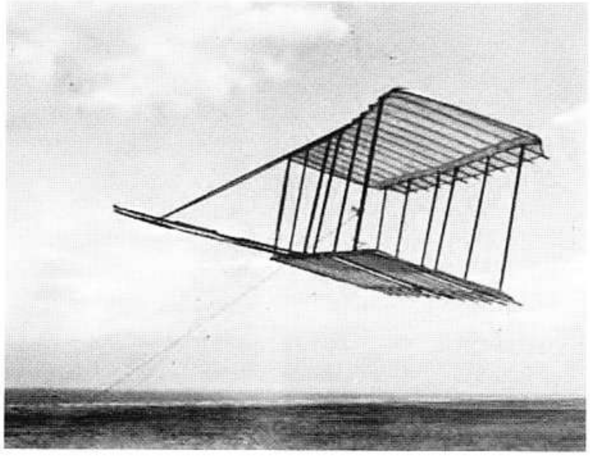

Figure 3 - 1900 Glider in tethered flight

The 1900 glider's deficiencies led the Wrights to ask many questions to find the root problems. The primary design change for 1901 was to significantly increase the wing area relative to the 1900 glider.

THE 1901 EXPERIMENTS

The 1901 glider had almost twice as much wing area as the 1900 glider, 285 ft2, with a wing span of 22 ft. It provided the first sustained glides and yielded a wealth of longitudinal trim and handling qualities data (Figure 4). Summer testing was difficult due to severe storms and subsequent hordes of mosquitoes. Initial flight tests revealed the 1901 glider was more difficult to control than the 1900 glider, with Wilbur's diary of July 30, 1901 saying, "It is true that we have found this machine less manageable than our smaller machine of last year but we are not sure that the increased size is responsible for it. The trouble seems rather in the travel of the center of pressure." 22

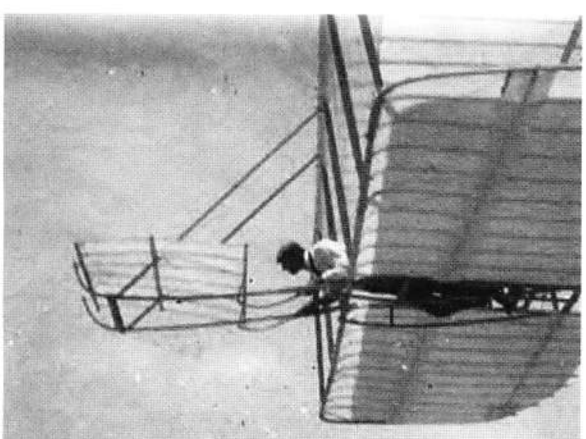

Figure 4 - 1901 Glider in flight

This was further explained in Wilbur's presentation to the Western Society of Engineers16, in which he described having to move his body position further and further aft to trim the glider. The resulting flight characteristics described what appears to be an unstable glider that required much more use of the canard to maintain control, to the point of saying, "there was something radically wrong..."16

The glider design allowed for variations in wing camber, which were done by the addition of an extra spar on the bottom wing coupled with a series of small vertical stays (see Figure 4). Longitudinal cables from the bottom wing front spar to the top of the stays and then to the rear spar were used to force the bottom wing airfoil to reflex in shape. Cables from the stays to the top wing ribs pulled the top wing airfoil into a similar, but slightly different reflexed shape. The positive pitching moment caused by the airfoil reflex allowed Wilbur to shift his weight forward to trim the glider, resulting in a CG located further forward, an increase in pitch stability, and a glider that was much easier to fly. Wilbur said, "The machine with its new curvature never failed to respond promptly to even small movements of the rudder." 16

1901 GLIDER AIRFOIL ANALYSIS

This has been confirmed by 2D airfoil CFD analysis of three different 1901 glider airfoils. No original drawings of the 1901 glider exist, but well-known Wright historian Rick Young was kind enough to provide a rib template from his replica 1901 glider. Additional information was gleaned from Wilbur's airfoil measurements of the 1901 glider.23 All these data with available photographs were then used to generate smoothed airfoil ordinates of the basic jig airfoil shape, a loaded shape with more camber, and a trussed down airfoil with a large amount of reflex. From Figure 4 it should be noted that the top wing had a better airfoil shape than the bottom wing on the bottom surface aft near the leading edge. The CFD modeled the top wing airfoil. Figure 5 compares all three 1901 airfoils and for reference shows (on the jig airfoil) the rear spar and the auxiliary spar used for trussing.

The airfoil analysis tool, XFOIL24,25, was used to analyze the three airfoils. Inviscid pressure distributions at a CL of 0.5 are shown because the code would not converge when run at full scale Reynolds number. Flow separation always occurred just aft of the leading edge on the bottom surface. Figures 6, 7, and 8 show XFOIL results for the jig, loaded, and trussed airfoils respectively. Note that neither the trussing spar nor the rear spar were modeled in the analysis, which would slightly affect the magnitude of the pitching moments but should still give reasonable incremental differences between the three airfoils. The more negative pitching moment coefficient of the loaded airfoil and the more positive pitching moment coefficient of the reflexed airfoil confirm the stability or lack thereof that Wilbur Wright discovered in flight and wrote about as center of pressure travel. The Wrights are to be commended for their contribution to aeronautical knowledge of the first practical reflexed airfoil.

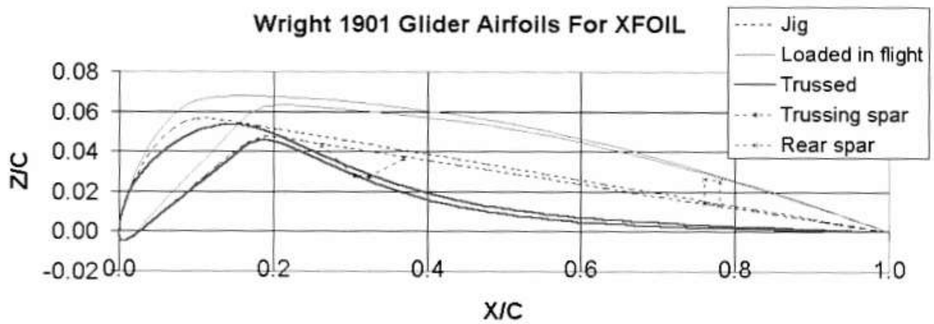

Figure 5 – 1901 Glider airfoils for XFOIL analysis

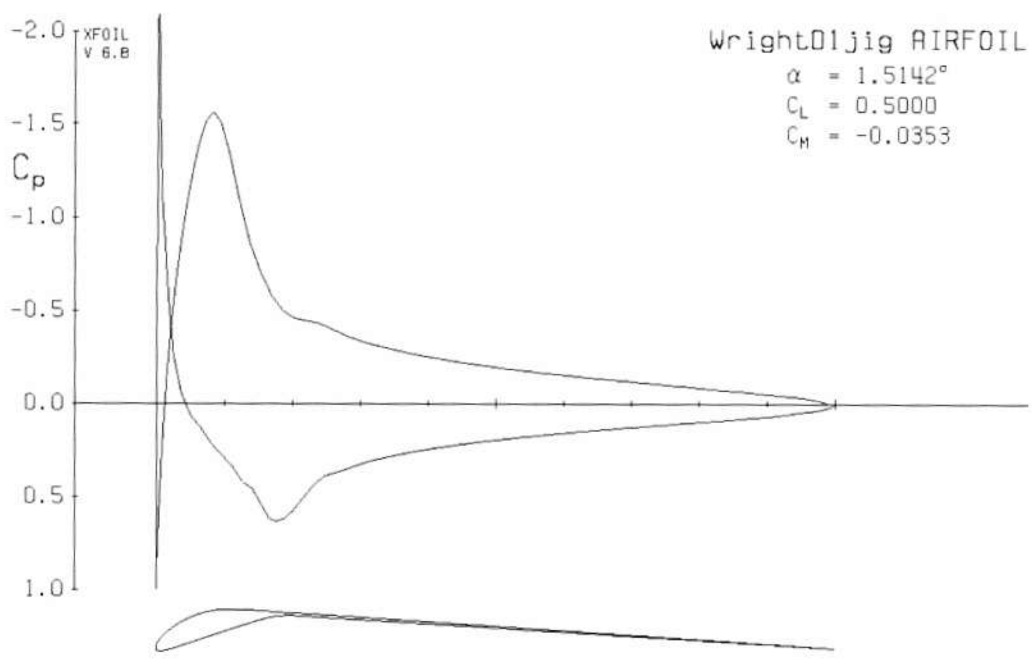

Figure 6 – 1901 Glider unloaded jig airfoil pressure distribution

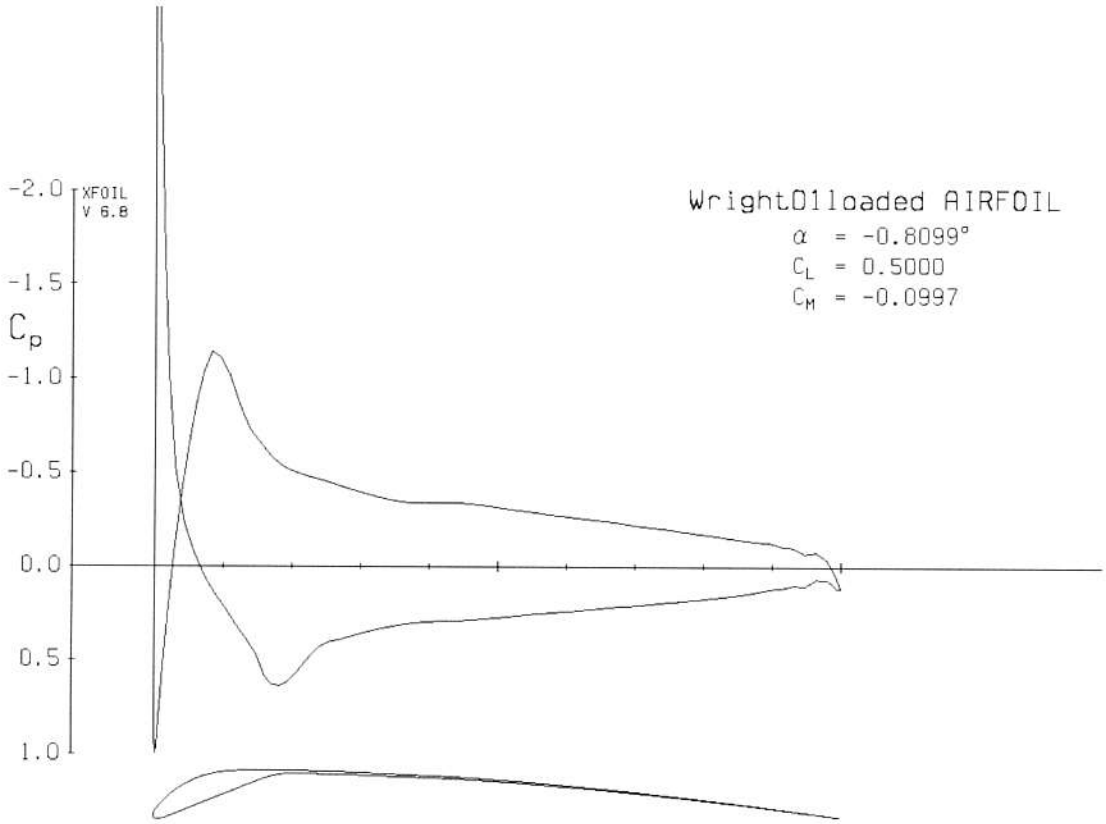

Figure 7 – 1901 Glider loaded airfoil pressure distribution

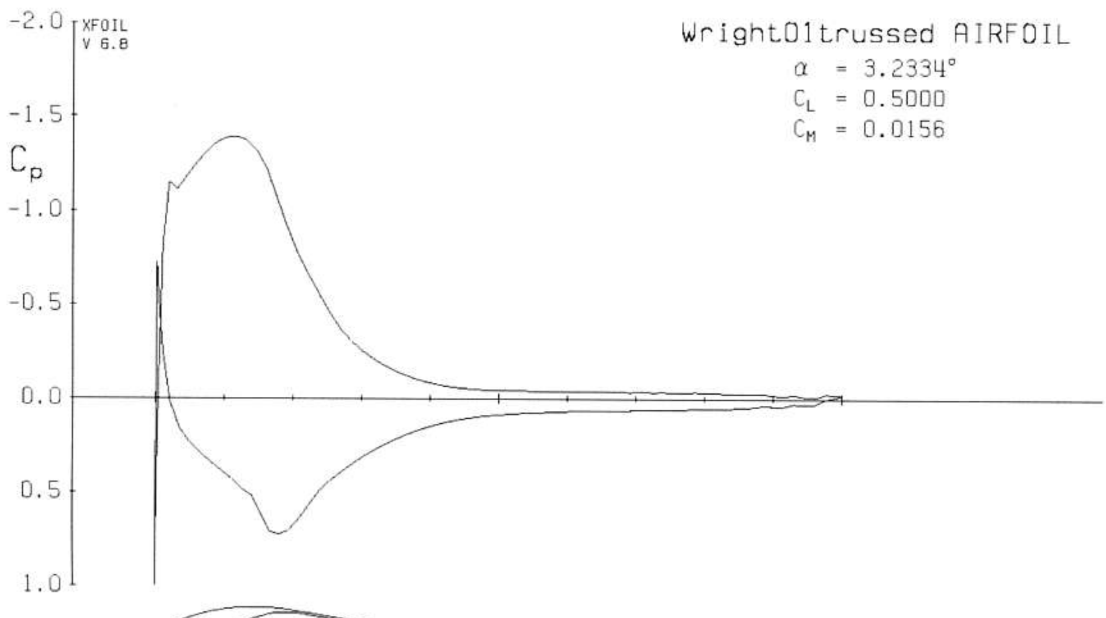

Figure 8 – 1901 Glider trussed, loaded airfoil pressure distribution

STALLS AND ADVERSE YAW

Another type of discovery the Wrights made with the 1900 and 1901 gliders was in the area of handling qualities. In a letter to his sister Katharine dated October 18, 1900, Orville wrote of tethered, unpiloted flights, "it would sometimes turn up a little too much in front, when it would start back, increasing in speed as it came, and whack the side of the hill with terrific force." 26 Little more was said until July 27, 1901 when Wilbur wrote in his diary of piloted flights, "In two glides lost all headway and sprang forward to regain control. Landed with machine from height of 18 feet practically horizontal." 27 In a letter to Katharine the next day, Orville wrote, "The machine refused to act like our machine last year and at times seemed to be entirely beyond control. On one occasion it began gliding off higher and higher (Will doing the gliding) until it finally came almost to a stop at a height variously estimated by Mr. Spratt and Huffaker at from 18 ft. to forty feet. This wound up in the most encouraging performance of the whole afternoon. This was the very fix Lilienthal got into when he was killed. His machine dropped head first to the ground and his neck was broken. Our machine made a flat descent to the ground with no injury to either operator or machine." 28 Thus we have the first documentation of stalls. The Wrights were beginning to become more skilled pilots and fortunately avoided stalling while turning, which could have easily resulted in tragedy.

Another phenomenon documented by the Wrights was the discovery of adverse yaw. In Wilbur's diary entry of August 15, 1901, he wrote, "Upturned wing seems to fall behind, but at first rises." 29 In an August 22 letter to Octave Chanute he wrote, "The last week was without very great results though we proved that our machine does not turn (i.e. circle) toward the lowest wing under all circumstances, a very unlooked for result and one that completely upsets our theories as to the causes which produce turning to the right or left." 30 The Wrights were very observant engineers and recognized that though they were achieving long glides, it did little good unless they were able to unlock the mysteries of adequate control.

The 1901 experiments lasted from the second week of July to August 20. The Wrights returned home to Dayton, Ohio discouraged, but got a lift from their friend Octave Chanute. He invited Wilbur to present their findings at a presentation to the Western Society of Engineers in Chicago,16 which occurred on September 16. This provided the perfect opportunity to take stock in their discoveries and begin to think about their next steps, which included an insightful series of wind tunnel tests over the fall and winter of 1901.

LIFT LOSS EXPLAINED

The Wrights were unsettled that the lift they measured with the 1900 and 1901 gliders appeared to be less than predicted by Otto Lilienthal's table of normal force coefficient versus angle of attack. Wilbur mentioned in his diary on July 29, 1901, "Found lift of machine much less than Lilienthal tables would indicate, reaching only about 1/3 as much." 31 In Wilbur's presentation to the Western Society of Engineers he discussed the lack of lift relative to the Lilienthal tables both in the context of the 1900 and the 1901 gliders. By 1901 the Wrights were well on their way to understanding why,16 mentioning factors (listed in current nomenclature) such as:

1) Instrument error in their anemometer.
2) An overly optimistic value for Smeaton's coefficient, the parameter similar to air density.
3) The Lilienthal tables were incorrect.
4) The biplane wing arrangement caused a lift loss.

In fact, the Lilienthal tables were not necessarily in error. The Wrights incorrectly presumed the data for Lilienthal's aspect ratio 6.48 crescent planform applied directly to their aspect ratio 3.5 biplane gliders.

The recent work by John D. Anderson has done an excellent job of detailing three aerodynamic factors to explain the differences between the wing planform Lilienthal tested and the 1900 and 1901 gliders32, which are as follows:

1) The Wrights used the wrong value for Smeaton's coefficient.
2) They did not correct for the differences in aspect ratio between Lilienthal's wing and the wings of their gliders.
3) They did not account for differences in the location of maximum camber between Lilienthal's circular arc airfoil and their own airfoils with maximum camber near the leading edge.

Figure 9 illustrates how these factors in today's nomenclature combined to explain the apparent reduced lift of the 1900 and 1901 gliders. Later, Anderson mentioned the additional factor of the different Reynolds number between Lilienthal's test apparatus and the higher one of the Wright gliders, which should have helped mitigate the three reasons above.

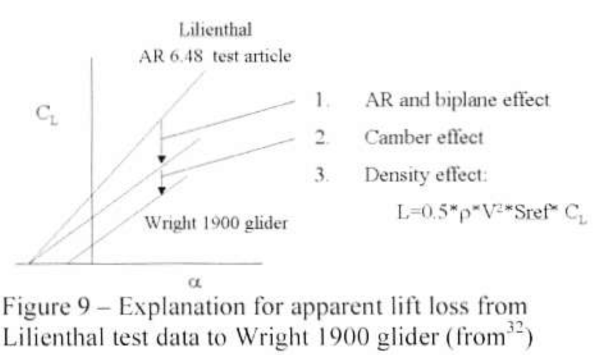

Figure 9 – Explanation for apparent lift loss from Lilienthal test data to Wright 1900 glider (from[32])

WIND TUNNEL TESTING

During October to December of 1901 the Wrights conducted their own series of wind tunnel tests that were key to contributing to the design of the 1902 glider, perhaps the single most important pioneer aircraft next to their 1903 Flyer. Their development of two ingeniously simple balances was just one more example of their admirable engineering technique of quickly finding a way to get just the right information needed to drive to a solution. Their lift balance allowed direct measurement of lift coefficient versus angle of attack. Their drag balance allowed them to measure D/L (not L/D) versus angle of attack and thus, track the most aerodynamically efficient configurations33. Many different wing models were tested of various airfoil shapes, planforms, aspect ratios, and wing arrangements (including monoplane, biplane, triplane, and tandem wings). Geometry and data for 3134 were published, but not until 1953. These tests helped the Wrights choose the best design improvements for their 1902 glider: Increased wing aspect ratio, lower camber, and a high ratio of vertical gap between the wings to wing chord. It should be noted that the final 1902 glider wing geometry was never tested, which could mean the brothers had sufficient confidence to extrapolate beyond their wind tunnel database. 35

THE 1902-1903 EXPERIMENTS

The 1902 glider was the Wright's most successful and highest performing of the three piloted gliders prior to the 1903 powered Flyer. It had a wing span of 32 ft. and a wing area of 305 ft2. The Wrights arrived in Kitty Hawk on August 29 and spent their first few weeks rebuilding their storm damaged buildings and adding another to house the larger glider. As in 1901, they were joined by Octave Chanute and several of his associates for part of their flight testing. The glider was first flown on September 19 with a fixed, double vertical tail. The Wrights were encouraged by the improvement in performance over the 1901 glider, with Wilbur noting in his September 23 letter to Chanute, "The efficiency of the machine is fully 3 deg. better than last year." 36

On occasion the glider still behaved poorly in flight despite the encouraging glide performance. In a lecture to the Western Society of Engineers of June 24, 1903, Wilbur stated, "In several other glides there were disturbances of the lateral equilibrium more marked that we had been accustomed to experience with the former machines.." 37 First they added four inches of anhedral to each wing tip, but the difficulties continued with Wilbur noting, "It had been noticed during the day that when a side gust struck the machine its effect was at first partly counteracted by the vertical tail, but after a time, when the machine had acquired a lateral motion, the tail made matters worse instead of better." 37

Late on October 3 Orville thought of the idea of making the vertical tail movable as a rudder, and Wilbur added the idea of coupling the rudder deflection with the wing warping. In a few short hours the solution to the lateral control problems was found by the unique working partnership of Orville and Wilbur.38 The amount of airtime increased after this improvement, with the brothers starting to make longer flights and coordinated turns (Figures 10 and 11).

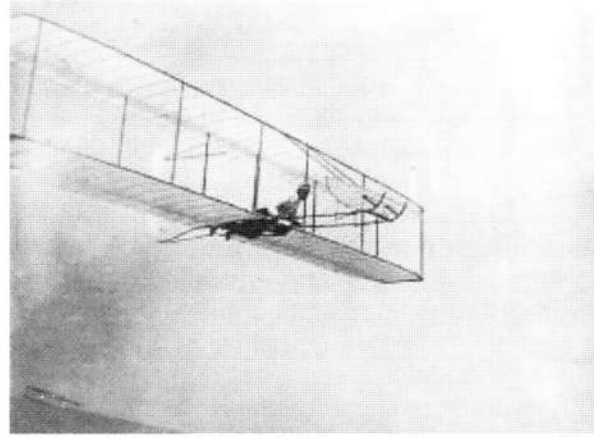

Figure 10 – Wright 1902 glider in flight with the movable rudder that improved lateral control

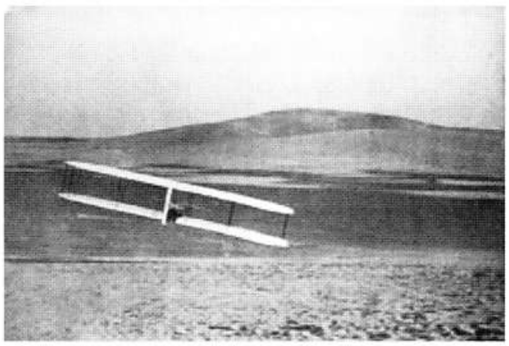

Figure 11 - 1902 Glider turning

One final modification of the 1902 glider was made in 1903 by adding a second rudder surface, which further improved turn coordination (Figure 12). The longest flight of the 1902 glider lasted 73 seconds, and covered a distance of about 450 feet in a wind that ranged from 30 mph at the launch site to 19 mph at the landing site. By this time the Wrights were skilled pilots in a capable glider, able to handle high, gusty winds with confidence.

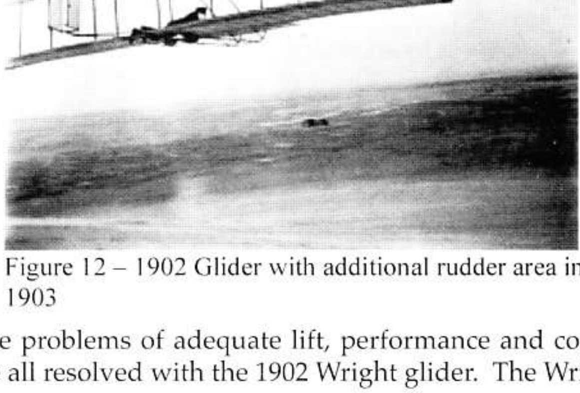

Figure 12 – 1902 Glider with additional rudder area in 1903

The problems of adequate lift, performance and control were all resolved with the 1902 Wright glider. The Wrights could now concentrate on the problems of powerplant and propeller design, which culminated in the historic flights of December 17, 1903.

1902 GLIDER AIRFOIL ANALYSISS

The 1902 glider airfoil geometry was analyzed using XFOIL. The raw ordinates were obtained from 1934 US Army Air Corps drawings combined with guidance from photographs. The fairings around the front and rear spars were modeled but once again XFOIL failed to converge when run with viscosity. Figure 13 shows the resulting inviscid pressure distribution, which indicate a significant local impact on the distribution due to the front and rear spar fairings. These fairings helped provide a drag reduction relative to the exposed spars of the 1901 glider. The airfoil pitching moment coefficient is mildly negative, about half that of the untrussed 1901 glider. Further work is needed to determine the static longitudinal stability level of the Wright 1902 glider. From discussions with Rick Young about flying his 1902 glider replica, the canard had to be adjusted frequently but pitch damping was adequate. This suggests the glider was capable of having nearly neutral static longitudinal stability, depending on pilot position.

PERFORMANCE ESTIMATES

The drag and performance of both the 1901 and 1902 gliders were estimated using a variety of methods. There were three components to the drag build up, including the parasitic drag, the induced drag, and the airfoil profile drag. The parasitic drag was estimated using classical empirical methods,39 accounting for the drag of the pilot, exposed structure, control surfaces, and rigging. The equivalent flat plate drag area of the 1901 and 1902 gliders was estimated to be 8.5 and 8.9 ft2, respectively. The additional drag of the exposed spars of the 1901 glider was book kept as profile drag.

The induced drag included the inviscid drag due to lift of the lifting surfaces, which were modeled using a lifting surface theory method, LINAIR.40 The model accounted for the open gap and pilot between the bottom wings. The induced drag efficiency factor was based on the average aspect ratio of both wings, so differed from how classical aerodynamic methods typically analyze a biplane as an equivalent monoplane. Lifting surface efficiency factors of 0.5 and 0.6 were used for the 1901 and 1902 gliders. The 1902 glider was more efficient due to the smaller gap between the bottom wings as a percentage of span.

A full scale replica of the 1901 glider with untrussed ribs was wind tunnel tested by the Wright Experience, providing valuable aerodynamic data.41 The data plus the author's engineering judgment were used to back out the profile drag of the 1901 glider. Drag at moderate lift coefficients was decreased to create a drag polar with an L/D max of around 4.6 out of ground effect. The Wrights measured an L/D of up to 7 in ground effect at an airspeed of 31 mph, but their measurements included a lot of airspeed variation42. Reference 41 measured a maximum L/D of only 3.9. Drag at low lift coefficients was increased relative to Ref. 41 to yield a more reasonable performance loss at higher airspeed, and to family better with the 1902 glider results. A comparison of the author's drag estimate with Ref. 41 is shown in Figure 14.

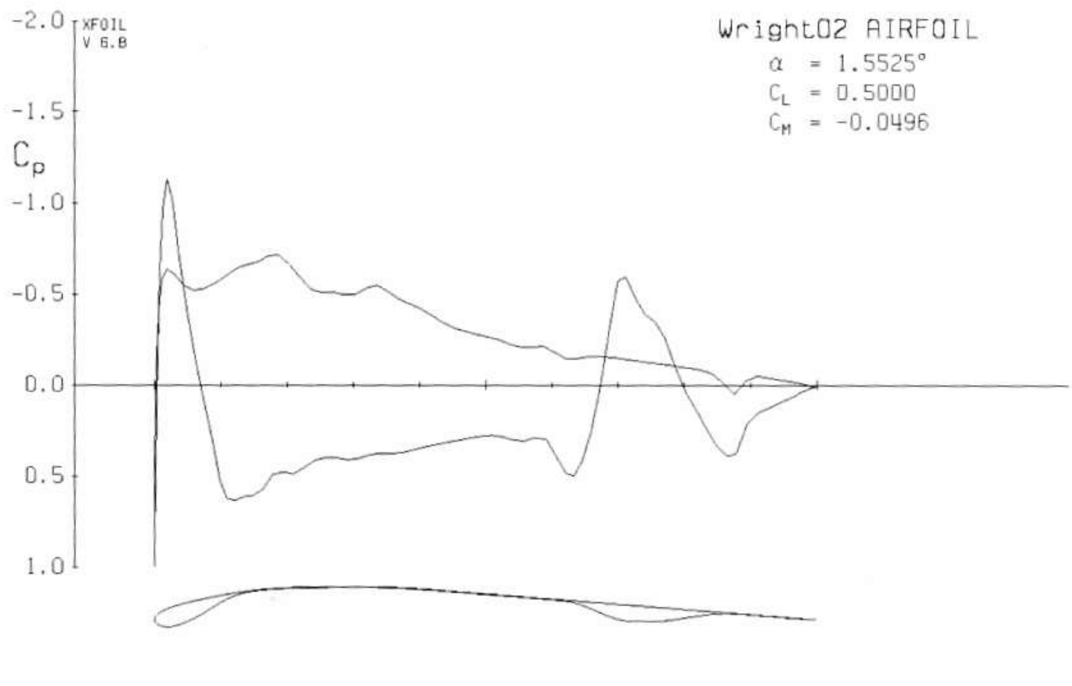

Figure 13 – 1902 Glider pressure distribution

The 1902 glider profile drag was estimated to be similar to the 1901 glider but at a lower level due to the fairings around the 1902 glider wing spars.

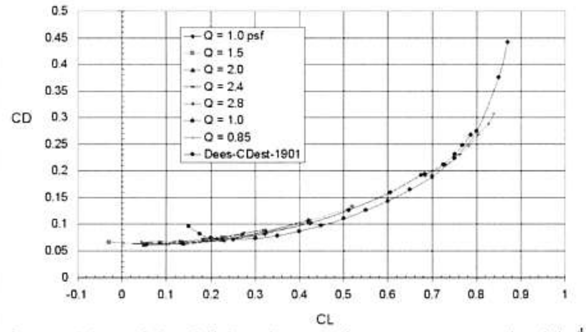

Figure 14 – 1901 Glider drag estimate compared with [41]

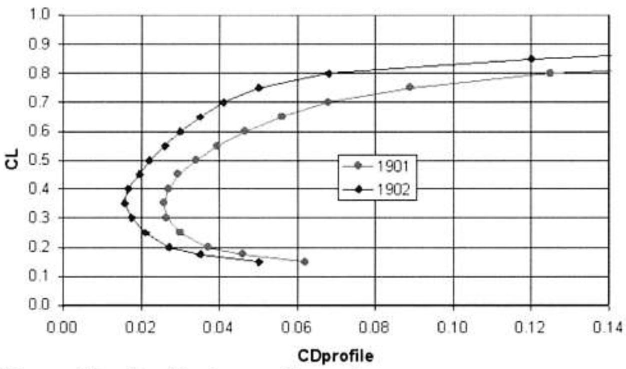

Figure 15 – Profile drag polar estimates

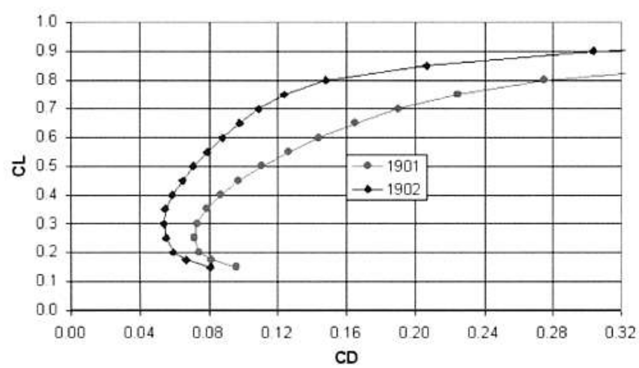

Figure 16 – Total drag polar estimates

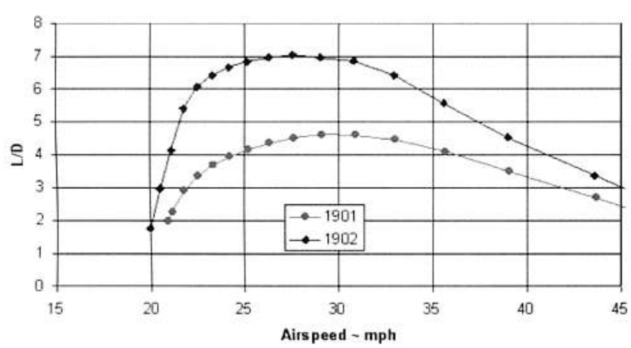

Figure 17 – L/D Estimates (out of ground effect)

A comparison of the profile and total drag polars of both gliders are shown in Figures 15 and 16. The drag was fed into the typical equations to estimate L/D and sink rate versus airspeed, which are shown in Figures 17 and 18. Wind tunnel test results of the 1902 glider43 were not made available in time to compare with the author's estimate.

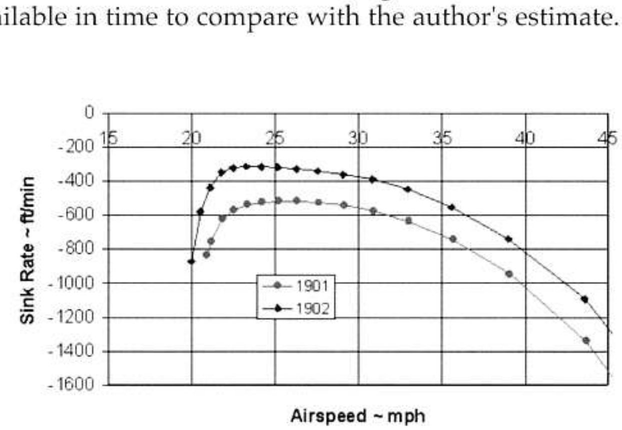

Figure 18 – Sink rate estimates (out of ground effect)

The Wrights' measured better performance than these estimates since their flights were usually in ground effect and over a very dynamic flight path. Further study is required to resolve the differences between these estimates, the Wrights' observations, and the data from Refs. 41 and 43

CONCLUSIONS

1. The Wright brothers were successful because of a combination of fortunate timing, positive personal traits, and a textbook engineering and experimental approach.
2. The 1899 Wright kite validated a biplane design philosophy and the use of wing warping for control.
3. The 1900 glider was the Wright's first piloted glider and further validated wing warping. It also led to questions about wing sizing.
4. The 1901 glider provided the first consistent airtime and contributed to the understanding of center of pressure travel. It also uncovered unpleasant handling qualities such as stalls and adverse yaw.
5. Estimates of airfoil pitching moment coefficient confirm the Wright's in-flight stability observations of several airfoil geometries.
6. The 1901 wind tunnel tests provided design refinement trade study data such as the optimum wing planform, aspect ratio, and vertical gap between the wings. These results drove the 1902 glider design.
7. The Wrights used the 1902 glider flight tests to develop the movable rudder coupled with wing warping, which enabled controlled, coordinated turns.
8. Performance estimates of the 1901 and 1902 gliders vary from the Wright's measurements because of ground effect and other factors that require more study to resolve.

ACKNOWLEDGEMENTS

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REFERENCES

1) Chanute, O., Progress in Flying Machines, Lorenz and Herwig, originally published in 1894, republished in 1976, p. 213.

2) Chanute, O., Progress in Flying Machines , Lorenz and Herwig, originally published in 1894, republished in 1976, p. 232.

3) Crouch, T., A Dream of Wings: Americans and the Airplane, 1875-1905, Smithsonian Institution Press, 1989, p. 127

4) Chanute, O., Progress in Flying Machines, Lorenz and Herwig, originally published in 1894, republished in 1976, p. 204.

5) Nitsch, S., Vom Sprung zum Flug, Brandenburgisches Verlagshaus, 1991.

6) Jarrett, P., Another Icarus: Percy Pilcher and the Quest for Flight, Smithsonian Institution Press, 1987.

7) Means, J., The Aeronautical Annual, 1897, W. B. Clarke and Co., 1897, pp. 30-53

8) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.15.

9) Crouch, T., The Bishop's Boys, W.W. Norton & Co., New York, 1989, p. 103.

10) Wright, Orville, "The Wright Brothers Aeroplane", Century Magazine, September, 1908.

11) Crouch, T., The Bishop's Boys, W.W. Norton & Co., New York, 1989.

12) Jakab, P.L., Visions of a Flying Machine, The Wright Brothers and the Process of Invention, Smithsonian Institution Press, Washington, D.C., 1990, chapter 1.

13) Anderson, John D., A History of Aerodynamics and Its Impact on Flying Machines, Cambridge University Press, 1997, p. 127.

14) Anderson, John D., A History of Aerodynamics and Its Impact on Flying Machines, Cambridge University Press, 1997, p. 122.

15) Penrose, Harald, An Ancient Air, Airlife Publishing Ltd., 1988, pp 109-110.

16) Wright, W., "Some Aeronautical Experiments," A paper read before the Western Society of Engineers, September 18, 1901, reprinted in McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, pp.99-118.

17) Dees, P. W., "The 100-Year Chanute Glider Replica, An Adventure in Education", presented at the 1997 World Aviation Congress, Anaheim, CA, October, 1997, AIAA Paper No. 1997-5573.

18) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.280.

19) http://www.wright-brothers.org/Adventure/Workshop/1899_wright_kite.htm

20) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.45.

21) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.44.

22) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.78.

23) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, pp. 78-83.

24) Drela, Mark, "XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils", presented at the Conference on Low Reynolds Number Airfoil Aerodynamics, University of Notre Dame, June, 1989.

25) Drela, Mark, "XFOIL 6.5 User Primer", MIT Aero and Astro Engineering, September, 5, 1986.

26) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.38.

27) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.71.

28) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.75.

29) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.82.

30) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.84.

31) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p.76.

32) Anderson, J., A History of Aerodynamics and its Impact on Flying Machines, Cambridge University Press, 1997, pp. 149-150, 214.

33) Jakab, P.L., Visions of a Flying Machine, The Wright Brothers and the Process of Invention, Smithsonian Institution Press, Washington, D.C., 1990, chapter 6.

34) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, pp. 558-573, pp. 578-593.

35) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p. 352.

36) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p. 261.

37) Wright, W., "Experiments and Observations in Soaring Flight," A paper read before the Western Society of Engineers, June 24, 1903, reprinted in McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, pp.318-337.

38) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p. 269.

39) Hoerner, S., Fluid Dynamic Drag, Hoerner Fluid Dynamics, Bricktown, NJ, 1965.

40) Linair 1.46 (computer program), Desktop Aeronautics, Stanford, CA.

41) Kochersberger, K., Ash, A., Sandusky, R., Hyde, K., "An Evaluation of the Wright 1901 Glider Using Full Scale Wind Tunnel Data", presented at the 40th AIAA Aerospace Sciences Meeting, Reno, NV, January, 2002, AIAA Paper No. 2002-1134.

42) McFarland, M.W., The Papers of Wilbur and Orville Wright, Vol I, Ayer Company Reprint, Salem, NH, 1990, p. 89.

43) Kochersberger, K., Player, J., Ash, A., "Performance Analysis of the Wright 1902 Glider Using Full Scale Wind Tunnel Data", presented at the 41st AIAA Aerospace Sciences Meeting, Reno, NV, January, 2003, AIAA Paper No. 2003-0096.