AIAA-2002-1134

An Evaluation of the Wright 1901 Glider Using Full Scale Wind Tunnel Data

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Abstract

A reproduction of the Wright 1901 Glider, built by The Wright Experience™ in Warrenton, Virginia, was wind tunnel tested at the Langley Full Scale Tunnel through a range of conditions similar to what was experienced 100 years ago. The testing included a range of dynamic pressures that encompassed the stall and maximum gliding speeds, angles of attack up to 20°, and sideslip angles of up to 15°.

The results of the test were used to determine not only lift, drag and moment coefficients, but also control power from the actuation of the canard and wing warping controls. A glide ratio measurement of 3.9:1 was recorded and compared to the observations of the Wrights. Simulations of longitudinal and lateral dynamics showed that the aircraft was controllable, although adverse yaw from wing warping caused the aircraft to turn opposite of the commanded roll. Longitudinal stability was found to be a function of angle of attack and the condition of the wing covering, resulting in static margins that varied greatly.

The subsequent success in aircraft development by the Wrights was in part due to the questions raised from the 1901 tests. New theories were developed, and observations and intuition lead to improvements that defined them as leaders in aircraft design.

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Nomenclature

α = Angle of attack
β = Sideslip
δ_c = Canard deflection
δ_w = Warp deflection
ζ = Damping ratio, $C/C_{critical}$
ϕ = Roll angle
θ = Pitch angle
b = Wingspan
$\bar{c}$ = Chord
n_z = Vertical load factor
$s.m.$ = Static margin
u, v, w = Aircraft velocities in X, Y, Z
p, q, r = Rotation rates about X, Y, Z
Q = Dynamic pressure
L/D = Lift to drag ratio
x_{C_p} = Center of pressure
x_{NP} = Neutral point
x_{CG} = Center of gravity
$C_{l\delta w}$ or C_{ldw} = Roll coeff. / warp deflection
$C_{l\beta}$ or C_{lbeta} = Roll coeff. / sideslip angle
$C_{m\delta c}$ = Moment coeff. / canard deflection
$C_{n\beta}$ = Yaw coeff. / sideslip angle
C_{lp} = Roll coeff. / roll rate
$C_{L\alpha}, C_{Lo}, C_{m\alpha}$ = Aircraft lift and moment coeff.

Background

In 1899, the Wright brothers began a flight test program to answer questions about the stability and control of aircraft. It was their understanding, and to a degree Chanute's understanding several years earlier, that the most vexing problem in flying machine development was how to regulate the glide path and lateral direction of the machine. Using a box with ends cut out, Wilbur Wright intuitively solved the roll control problem when he applied pressure to the opposite corners of the box, resulting in the warping distortion of the box. This warping subsequently became the first example of an aircraft subsystem (control) being integrated directly into another subsystem (structures) to minimize weight. The Wrights built a five-foot wingspan kite to demonstrate the warping control and found it successful enough to proceed with a full-sized glider[1].

In October of 1900, a biplane glider designed by the Wrights was kited and test flown in Kitty Hawk, North Carolina with limited success. This glider, with its 17-foot, 5-inch wingspan, featured a canard (or horizontal "rudder") for pitch control, and wing warping for lateral control. Extensive testing was performed with the glider tethered, and measurements of lift and drag were made using a spring scale. Despite its wing area of 165 square feet (200 was to be used, but restrictions on available lumber size reduced the span), this glider managed to fly piloted on a slope of 9.5° for an L/D = 6. With "…the hours and hours of practice we had hoped to obtain finally dwindled down to about two minutes…,"[2] the tests of 1900 were complete and the Wrights returned to Dayton to begin work on the 1901 glider.

Although the 1900 machine demonstrated the controllability the Wrights were looking for through the use of the adjustable canard and the wing warping system, they found its lifting performance to be less than predicted. In particular, the angle of attack required for sustained flight was about 6x greater than what they had predicted, either when the glider was kited or flown manned[3]. For this reason, the 1901 glider featured an enlarged 285 sq. ft. wing, with a 22-ft. wing span and a 6.5-ft. mean chord. The canard measured 18.7 square feet, and with a 140 lb. pilot on board, the gross weight was 240 lbs.

The 1901 design retained the wing warping mechanism that functioned exactly as Wilbur had discovered it with the box model in 1899. A foot-operated "T" bar changed the length of the fore-aft diagonal support lines in their modified Pratt truss biplane design (the non-deforming version of which Chanute had used in his glider designs). Manipulation of the diagonal support cable lengths effectively warped the wings by moving the diagonal wing end-points either closer or farther apart. The canard was actuated by two levers pivoted near the leading edge of the bottom main wing, allowing the operator to control the pitch of the canard while at the same time retaining the ability to move slightly forward or backward to adjust the center of gravity. The ash ribs in the canard were bowed under the action of the levers, causing the canard airfoil to change its camber, thus providing additional control power over simply pivoting the non-cambered control surface. Figure 1 shows the glider flying at Kitty Hawk.

Figure 1 – Glider in flight at Kitty Hawk

To compensate for the reduced performance found in the 1900 glider, the camber of the wing was increased from 1/22 to 1/12, similar to Lilienthal's design and the basis for the Duchemin-Lilienthal table relating lift, drift (or drag), and angle of attack. This table was considered the definitive source for sizing wings at the time. However, as the Wrights accumulated flight testing knowledge during their 1900 and 1901 test campaigns, they became convinced that the Duchemin-Lilienthal table was contributing to serious discrepancies between their design estimates and their actual flight results.

Gliding experiments began with the new machine in July, 1901 with limited success. In addition to finding that the aircraft lifted less weight at a given angle of attack than predicted (similar to the previous year), the aircraft was difficult to control longitudinally. Culick[4] has concluded that the Wright brothers were unaware of the moment balance equations that would have greatly facilitated their isolation of the root cause to their glider handling problems. However, they understood intuitively (and from measurements) that a forward shift in the center of pressure as the angle of attack increased would result in the observed longitudinal control problem. This was confirmed in a kiting flight test of a single 1901 glider wing panel, where the center of gravity and the center of pressure were measured as a function of angles of attack. The data supported Wilbur's flight test results that were indicative of a pitch-unstable aircraft[5].

Deducing correctly that the increased camber caused the unwanted pitching moment change, the Wrights reduced their 1901 glider wing camber by trussing down the centers of the wing panels[6]. Not only did this reduce the camber, approximating that used in 1900, but it also added reflex – unknown to the Wrights but very effective in reducing the pitching moment variation. Commonly found on flying-wing aircraft or aircraft with limited tail volume, reflex provides longitudinal stability by negating the camber-induced moment. When this was accomplished, the increased drag of the trussing wires was a minor penalty to the improved longitudinal controllability. Piloted glider flights of well over 300 feet became commonplace, and the 1901 distance record was 389 feet. Wilbur wrote, "the machine with its new curvature never failed to respond promptly to even small movements of the rudder (canard). The operator could cause it to almost skim the ground, following the undulations of the surface, or he could cause it to sail out almost on a level with the starting point, and, passing high above the foot of the hill, gradually settle down to the ground."[7]

Along with about 100 manned flights in the 1901 glider, numerous kite flight tests were conducted to measure lift and drag in various wind speeds. A maximum $L/D = 6$ was again reported in both the manned and kited configurations[8]. Angles of attack were recorded that confirmed their belief that the Lilienthal lift and drift (drag) data were in error. These concerns lead them to embark on a true aeronautical research program in Dayton, starting in late 1901 that utilized wind tunnel testing to optimize the airfoils selected for their wing designs, and subsequently, propellers.[9] In part because of the failures of 1901, the Wrights pursued the science of flight with renewed intensity that led them to the successful first powered flight of 1903.

Overview of Test Configuration

A reproduction of the 1901 Wright glider was fabricated at The Wright Experience™ in Warrenton, Virginia for the purposes of rediscovering the events leading up to the successful first powered flight of 1903. In partnership with the NASA Langley Research Center and the Old Dominion University (ODU), this aircraft was tested at the Langley Full-Scale Tunnel (LFST), operated since 1997 under a memorandum of agreement between ODU and NASA. The building which comprises the LFST measures 132 m long by 70 m wide by 30 m high. This facility (formerly the NASA 30 X 60) is the second largest in the United States in terms of test section size and is the largest university run wind tunnel in the world. During its seventy years of service, a wide variety of aerospace test programs have been undertaken. Sub-scale model testing has included high angle-of-attack testing of current U.S. front-line fighters, high-lift systems on supersonic and subsonic transports, parachutes, an airship, submarine, a building complex, and most recently, automobiles and trucks.

The open jet test section of the LFST (formerly the NASA 30 X 60) is semi-elliptical in cross section with a width of 18.29 m (60 ft) and a height of 9.14 m (30 ft) as shown in Figure 2. The elevated ground board is 13 m (42.5 ft) wide by 16 m (52 ft) long and features a turntable with a diameter of 8.7 m (28.5 ft). Power is supplied by two 3 MW (4000 HP) electric motors driving two 11 m (35.5 ft) diameter four-bladed fans.

Full-scale aircraft are supported on three struts which are shielded from the flow to minimize tare loads and corrections. The two main struts are used as pivots to allow the aircraft to pitch by articulating the third (tail) strut. This entire assembly is mounted to the turntable and can be rotated in yaw. The struts transfer loads to the 6 degree-of-freedom external balance located below the turntable. The balance utilizes load reduction linkages consisting of lever arms and knife-edge pivots ultimately driving balance beam scales with strain gage outputs. The scale voltages are digitized using a 16 bit analog to digital PC based data acquisition system and data is reduced on-line using LabView software, available to the customer at a separate PC via local area network.

Just prior to this test, the external balance was reworked and a full calibration was performed. All knife-edges were examined and sharpened or replaced as necessary. Individual balance beam scale calibrations were established using traceable weight standards. A load frame was installed on the aircraft support struts and the balance was loaded and calibrated including determination of first-order interactions.[10] The one-sigma precision based on deadweight loading and a nominal test dynamic pressure of $Q = 2.0\text{psf}$. was as follows:

$$\sigma_{C_L} = 0.0023$$
$$\sigma_{C_D} = 0.0011$$
$$\sigma_{C_Y} = 0.0032$$
$$\sigma_{C_m} = 0.0016 \quad \sigma_{C_{l,n}} = 0.00048$$

The 1901 glider was mounted to the three-post system via the inboard wing strut attach points on the bottom leading edge spar, and also at the center of the rear spar. Rod end bearings were used on the rear spar attach point to allow for the wing warping action to occur. With free-free boundary conditions, wing warping produces opposite-direction roll between the front and rear spars and opposite direction yaw between the top and bottom wings. Fixing the bottom leading edge spar creates a reference datum which should be noted when converting to the in-flight, free-free condition. Figure 3 shows the glider mounted in the tunnel. All data shown are corrected for support tares (primarily drag). No boundary corrections have been made, since these are extremely small.

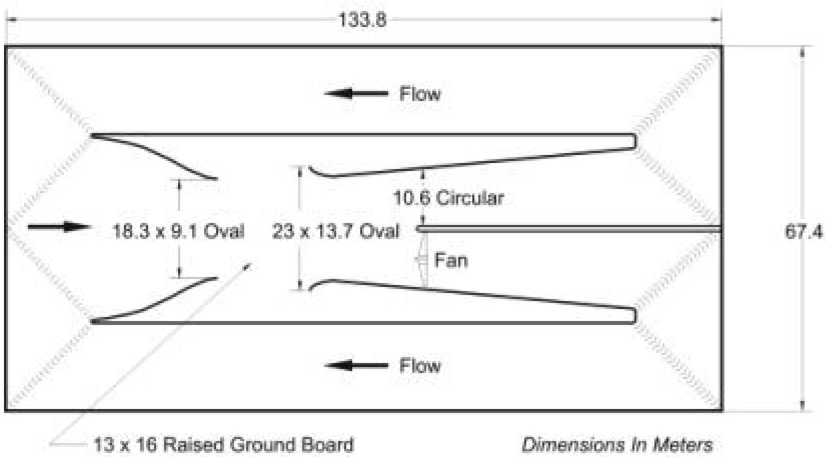


Figure 2 – Langley Full Scale Tunnel

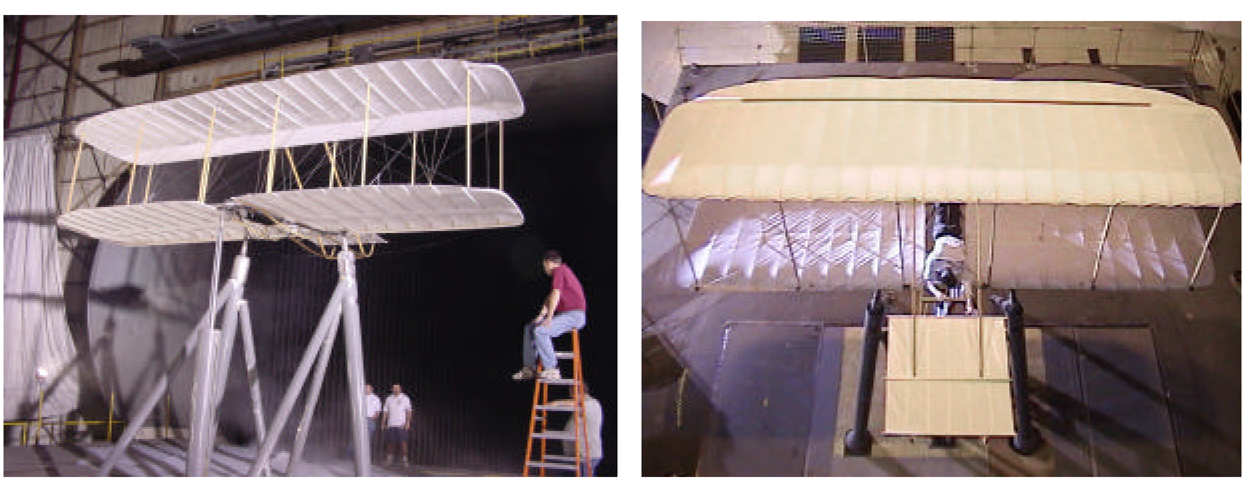


Figure 3 – 1901 Glider installed on three-post balance mount

Test Plan

Originally, 61 runs were mapped to include longitudinal and lateral configurations with angles of attack ranging from $\alpha = -2^\circ$ to $+20^\circ$, sideslip angles of $\beta = \pm 15^\circ$, and canard and warp deflections δ_c and δ_w that covered the control operating range. Dynamic pressures of $.85\text{psf} \le Q \le 2.8\text{psf}$ ($40\text{Pa} \le Q \le 134\text{Pa}$) were used to simulate the range of operating speeds, with the high-end based on Wilbur's report to the Western Society of Engineers.[11] Ultimately, due to time constraints, the test plan was reduced to 31 different parametric runs with five repeat runs for a total of 36 runs. Table I summarizes the runs.

Longitudinal Results and Discussion

Runs 1 – 17 represent the longitudinal runs, from which the baseline lift, drag and pitching moment data were obtained. The basic variation of lift coefficient with angle of attack is plotted in Figure 4, showing only slight influences of dynamic pressure on overall glider lift over the full dynamic pressure range from $Q = 0.85\text{psf}$ to $Q = 2.8\text{psf}$. At high angles of attack, the maximum lift coefficient was reduced slightly at higher dynamic pressures due to leakage through the wing fabric and/or small camber change of the wing.

The zero-lift angle of attack is observed to be -1.2°, and the reference "straight line" lift coefficients are $C_{LO} = 0.06$ and $C_{L\alpha} = 0.045/\text{deg}$. The experimental values were in good agreement with those calculated using a vortex lattice model of the glider, which showed degraded performance due to the slot in the bottom of the wing used to facilitate piloted takeoffs. The slot resulted in the lower wing acting as two smaller wings of aspect ratio 1.5.

The LFST experimental setup could not accommodate test angles of attack greater than 20° and the data in Figure 4 show that the maximum lift coefficient was not yet achieved at 20°. However, it is obvious that the maximum lift coefficient is close to the 20° limit and it was estimated that $C_{LMAX} = 0.85$ at $\alpha = 21^\circ$, corresponding to a theoretical minimum flight speed of 20 MPH (standard atmospheric conditions).

The variation in the overall baseline drag coefficient with angle of attack is shown in Figure 5, over the range of dynamic pressures. Slight increases in drag occur with increases in dynamic pressure over the entire range of angles of attack. This is likely the result of increased leakage rates between the lower and upper surfaces of each wing that would increase turbulent skin friction on both sides of the fabric. In addition, there is likely to be a slight difference in distortion of the wing fabric at increased airspeeds and that too contributes to drag. Overall, drag was significantly higher than predicted using the vortex lattice model and a parasitic drag build-up study that showed an equivalent flat plate drag area, excluding the wings, of 6.5ft.^2 Base drag on the bottom side of the upper and lower wings resulting from the sharp leading edge spars and little or no recovery beyond the 1.5 inch width of the spars was a significant drag contributor. Other contributors included the top-mounted rear spars that are not faired, and the wake caused by the interaction between the pilot (dummy) and the lower wing slot. It should be noted that tufting revealed no attached flow beyond $0.5\bar{c}$ at angles of attack greater than 4°.

Table I – 1901 Glider Test Plan

Runs	Warp	Canard	Beta	AOA Min	AOA Max	Q, psf
1 – 6	0	0	0	-2	20	0.85 – 2.8
7 – 8	0	+1/2, -1/2	0	2	12	1.5
9-17	0	+full, -full	0	0	14	1.0 – 2.8
18 - 19	0	0	+15, -15	2	8	2.0
20 – 21	+1/3, -1/3	0	0	2	6	2.5
22 – 23	+2/3, -2/3	0	0	2	11	1.5
24 – 29	+full, -full	0	0	2	14	1.0 – 2.4
30 – 31	-full	0	+8, -8	2	20	1.0

The variation in pitching moment with lift coefficient is shown in Figure 6. The "hump" shape is partly caused by the biplane / canard configuration, and partly from the center of pressure, x_{C_p}, shift on the relatively inefficient airfoil. Separated flow near the front of the airfoil will cause x_{C_p} to shift aft as the angle of attack is increased, causing a decreasing pitching moment. The static margin, defined by $s.m. = {(x_{NP} - x_{CG})}/{\bar{c}}$, increases from a low of 2.5% at $Q = 2.8\text{psf}$ to a high value of 25% at $Q = 1.1\text{psf}$. Increasing the dynamic pressure shifts the moment curve to the left, and this is probably the result of two factors:

a.) Drag on the trussing lines (that hold the top wing in reflex) will increase top wing reflex as dynamic pressure increases.

b.) Cable tension variations will cause the wings to take on new equilibrium angles of attack as the glider static weight is lifted from the balance with increasing dynamic pressure.

Canard effectiveness is shown in Figure 7, for only those portions of the test data corresponding to the trim flight speeds at a load factor $n_z = 1$. Using standard atmospheric conditions, trim control is available from 21 MPH to speeds higher than the Wrights recorded (36 MPH). The aircraft cannot be flown without shifting the C.G. at speeds slower than 21 MPH because the canard has reached its full pitch-up travel and the pitch stability has increased to $s.m. = 25\%$. It is certainly likely that the pilot combined canard inputs with a change in his body position to augment longitudinal control, with stability decreasing by ${\Delta\, s.m.}/{\Delta \text{ pilot } c.g.} = {-0.76\%}/{\text{in.}}$, and trim moment coefficient increasing by ${\Delta C_m}/{\Delta \text{ pilot c.g.}} = {0.0056}/{\text{in.}}$ as the pilot moved aft.

Since canard control involves changing the camber, deflection is crudely defined by the angle resulting from a measurement between the trailing edge and the leading edge. Full deflection is $\pm 5.3^\circ$, which results in an average $C_{m\delta c} = 0.0040/\text{deg.}$

The Wrights consistently reported glide ratios and kited L/D measurements of about 6, and Figure 8 shows the measured L/D of the aircraft not including ground effect. An optimal $L/D = 3.9$ was measured at a trim flight speed of 28 MPH ($C_L = 0.42$, $Q = 2.0$ psf under standard conditions), considerably less than what was observed 100 years earlier. When ground effect is included for a flight altitude of 3-ft. above ground level, the *L/D* increases to 4.5. Since much of the gliding performed by the Wrights was on a hill with a 10° slope[12], a combination of slingshot launching, dynamic soaring, vertical wind vector strength and variability in the wing covering could explain their substantially higher lift-to-drag performance.

Figure 8 also shows that the low aspect ratio design provides a reduction in *L/D* at high C_L that will most likely get the pilot on the ground before a stall develops.

Lateral Results and Discussion

Runs 18 - 31 represent the lateral runs including wing warp and sideslip. Figure 9 shows the roll effectiveness $C_{l\delta w}$ for 1/3, 2/3 and full warp deflection of $\delta_w = 4.3^\circ$ (measured at the wing tip) averaged over a range of AOA from 2 to 11 degrees. Roll damping was determined to be $C_{lp} = -0.33$ using a twisted vortex lattice model as well as a straight model that gave spanwise $C_{L\alpha w}$ for a numerical integration scheme. The resulting roll equation for a step input of full warp deflection is:

$$\Delta p = 0.12\left(1 - e^{-8.2t}\right) \tag{1}$$

The theoretical steady-state roll rate is $7^\circ/\text{sec.}$, with $\frac{Pb}{2u} = 0.032$ rad., compared to an "acceptable" range of 0.05 to 0.10 rad.[13] for most aircraft. As will be shown later, adverse yaw prevents a steady roll rate from being developed in this aircraft.

Figure 10 shows the reduction in $C_{l\delta w}$ as a function of dynamic pressure. Since the wing warping lines are not steel but braided cotton cord, the wing tends to untwist under higher loads, effectively decreasing the roll coefficient. Some of this effect can be attributed to flexibility in the ribs as well.

Adverse yaw was determined to be $C_{n\delta w} = -2.8\times10^{-4}$ / deg. at a trim lift coefficient of $C_L = 0.42$, with little effect attributed to dynamic pressure. Additionally, the glider showed only slight yaw stability due to the lack of vertically oriented surfaces. Accurate measurements of yaw moment $C_{n\beta}$

were not possible due to the resolution of the balance instrumentation

The glider demonstrated dihedral stability, as shown in Figure 11. This is most likely caused by the disturbance of flow over the bottom, downwind wing due to an upwash through the central slot. The location of the pilot also would enhance the dihedral effect, increasing the angle of attack on the upwind wing and decreasing the angle on the downwind wing. In 1902, the Wrights identified dihedral stability as a control problem for a ground effect glider, where a side gust would roll the aircraft away from the gust, causing the downwind wingtip to make contact with the ground. As noted in the 1903 Flyer configuration, anhedral was built-into some of the later designs to keep the airplane better aligned with the nominal freestream velocity.

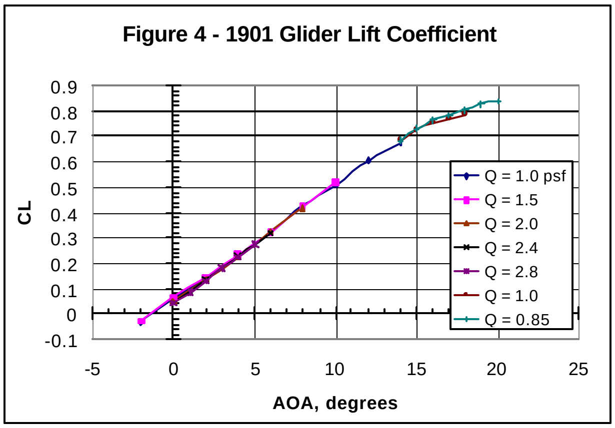


Figure 4 - 1901 Glider Lift Coefficient

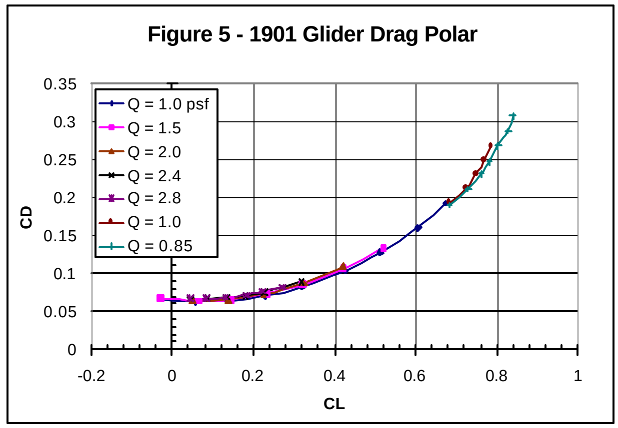


Figure 5 - 1901 Glider Drag Polar

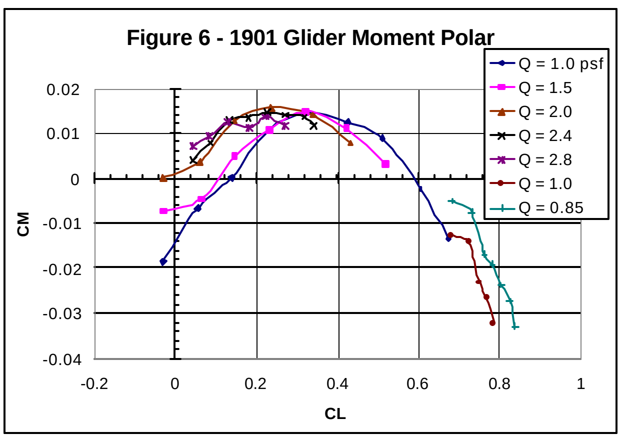


Figure 6 - 1901 Glider Moment Polar

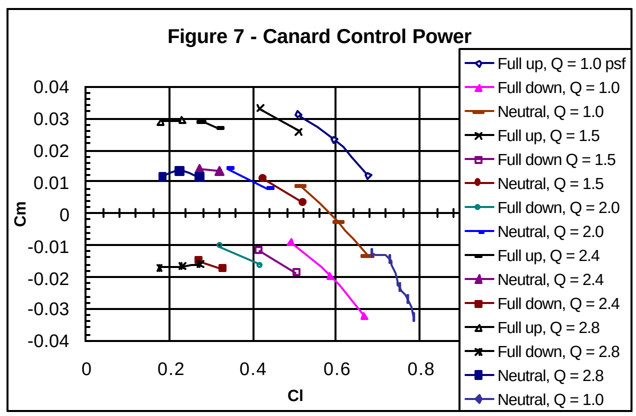


Figure 7 - Canard Control Power

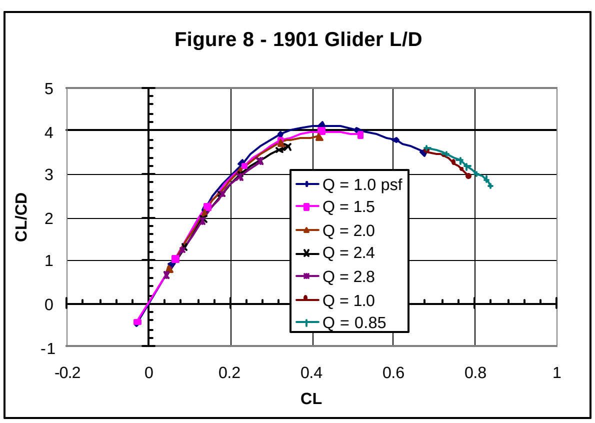


Figure 8 - 1901 Glider L/D

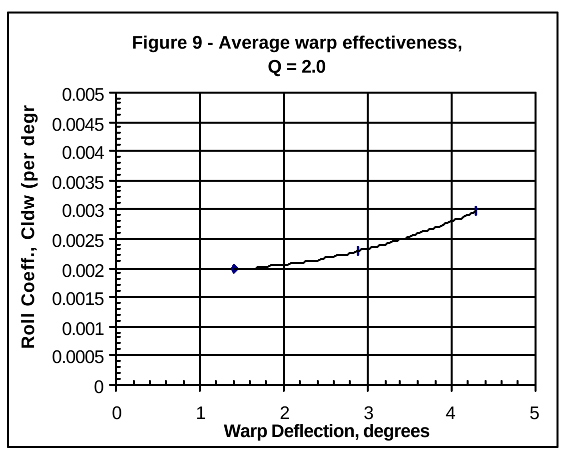


Figure 9 - Average warp effectiveness, Q = 2.0

Figure 10
Reduction in Average Roll Coeffient as a function of Q

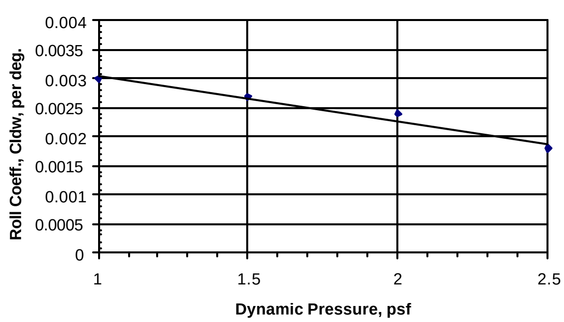
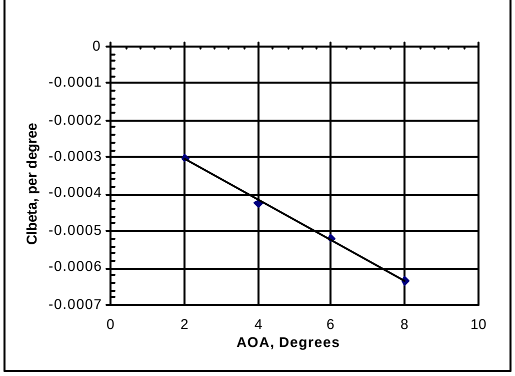


Figure 11 - Dihedral Effect, Q = 2.0



Simulation – Longitudinal Motion

A dynamic simulation using Simulink™ was performed in order to examine the flight handling qualities of the 1901 glider. This information is useful in understanding how the Wright brothers' subsequent designs evolved as a result of their test program. Two cases were examined: one based on the "as built wing" data above, and one based on "humid weather wing" data. Although not part of the original test plan, the wings of the glider were modified to simulate a tighter, less porous covering which may have been a condition experienced during flights in drizzling rain conditions.

The dynamic model is based on linear derivatives for u, w, q, and θ around the best *L/D* speed of 28 MPH, corresponding to $Q = 2.0\text{psf}$ (standard conditions). Figure 12 shows the stick-fixed gust response of the unmodified glider when subjected to a half-sine vertical pulse of magnitude 1 ft./sec. The phugoid mode is evident in the figure, with a period of $T = 8.4\text{sec.}$ and a damping ratio of $\zeta = 0.096$. The short period mode has a period of $T = 1.4\text{sec.}$, and a damping ratio of $\zeta = 0.67$.

When the wings were modified, the moment coefficient became more positive and the curve in Figure 6 shifted to the right, causing the trim moment coefficient $C_{m\alpha}$ to become positive and leading to an unstable condition. Any simulation must now include the pilot in the loop. Using a canard response of $\delta_c = -0.22\theta - 0.10q$ with a 0.2-second delay, a 95% settling time of 4 seconds was achieved for the same 1 ft/sec. gust. As an option and described in Longitudinal Results, the pilot could always move forward to increase stability and shift the moment curve downward.

Simulation – Lateral Motion

In this simulation a linear model was again used based on the derivatives measured about the trim flight speed of 28 MPH, and state variables β, p, r, and ϕ were chosen to describe the motion. The Wright 1901 glider lacked any vertical surfaces, resulting in limited yaw stability that gave the operator a unique experience in roll control. Figure 13 shows a full deflection, half-sine pulse of right warp to initiate a right-hand turn. However, soon after the glider begins a turn to the right, adverse yaw steers the glider to the left and the dihedral effect combined with roll due to yaw places the aircraft into a steady left-hand turn. It appears from these results that the warping control worked effectively in *reverse*, where a warp to the right resulted in a left-hand turn, and warp to the left resulted in a right-hand turn. The warping system was effective in turning the glider, but only from the standpoint that it functioned as a differential drag device.

The Wrights recognized this incongruity and wrote about it: "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 which completely upsets our theories as to the causes which produce the turning to right or left.[14] Jakab notes that in initial tests of the 1901 glider's lateral control, a left-hand turn would begin normally (roll in the direction of warp) , "but partway into the turn, the glider reversed direction and began to turn about the high wing, to the right."[15] The lateral control conundrum was solved in 1902 when a movable rudder was added their machine, resulting in a modern, three-axis control system.

The poles of this system consist of a fast roll mode pole, $p_1 = -8.24$, a slow unstable divergent pole, $p_2 = 0.060$, and the oscillatory poles described by $p_{3,4} = -0.11 \pm 0.65i$.

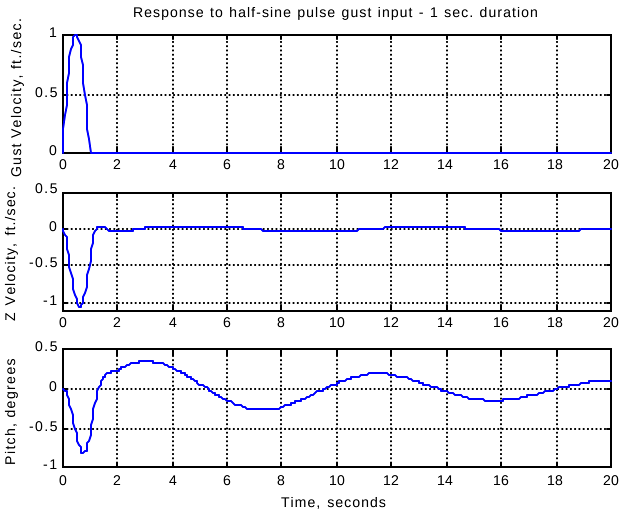


Figure 12 – Longitudinal Simulation

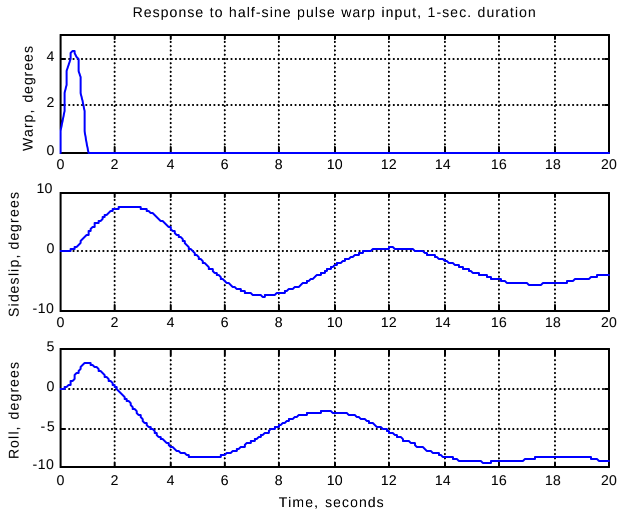


Figure 13 – Lateral Simulation

Conclusions

Many authorities have referred to the Wright 1901 gliding experiments as marginally successful, but the lessons learned from these flights became the impetus to address the problems of flight with renewed vigor. Upon returning to Dayton, they constructed a wind tunnel and systematically tested airfoils to determine corrections to the Lilienthal tables that would resolve the discrepancies observed in flight test. The lateral handling problems were solved with the addition of a rudder to the 1902 machine. Finally, measured drag on the 1901 glider was higher than they desired, and so subsequent aircraft were "cleaned up" to improve the glide ratio.

The test results from this program showed that the Wright 1901 glider had significant drag, and despite a low L/D of 3.9:1, was still able to complete many successful glides. Some advantage in performance was gained in ground effect, and the use of slingshot launching, dynamic soaring and variability in the wing covering gave the Wrights a measured L/D of 6:1. The glider was longitudinally stable, although in a test with modified fabric, it was shown to be unstable due to a shift in the moment curve. This did not present a problem in simulations because the slow unstable pole gives the pilot time to react.

The use of wing warping to effect lateral control was effective, although not in the way the Wrights intended. Both in test and documentation from the flights 100 years ago, the 1901 glider experienced significant adverse yaw that resulted in opposite direction turns from the wing warping input. Small control inputs from the operator and some flight experience were undoubtedly required to master the lateral control system.

Results of this test showed that the evolution of Wright aircraft designs were not as straight forward as one might imagine. The lateral control anomaly was a result of adverse yaw and dihedral stability acting against the wing warping command, with neither phenomenon having been identified at the time of the experiments. Adding a vertical surface in 1902 to reduce the adverse yaw tendency did not solve the turning problem until the surface became a movable rudder, used mainly to arrest roll rate into the low wing.

The quest to master three-axis control was the result of iteratively solving the problems that developed with every new glider design. Things that worked, such as the canard control effectiveness, were retained and changed little over the years leading to 1903. The addition of the movable rudder and wing anhedral in 1902 were the product of observations and intuition that resulted in adequate, predicable lateral handling qualities necessary for powered flight. The 1901 glider was critical in providing the Wrights many important observations needed to solve the overall problem of powered flight, and in many ways, 2002 is the 100th anniversary of the beginning of the systematic approach to aeronautical engineering.

Acknowledgements

The authors would like to acknowledge the support of the National Aeronautics and Space Administration, Langley Research Center, under Education Cooperative Agreement NCC-1-379, for supporting portions of this research.

The Wright Experience™ is also acknowledged for providing the 1901 glider used in the test.

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