

## Flying Qualities of the Wright 1903 Flyer: From Simulation to Flight Test

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### Abstract

A reproduction 1903 Wright Flyer has been flown by The Wright Experience to acquire data about this most historic aircraft. Wind tunnel test data from the Flyer has been used to develop a flight simulator. The simulator has aided in the training of pilots to fly the machine during an encampment at Kill Devil Hills, North Carolina from November 3 to December 5, 2003. A flight data recorder allowed the acquisition of 15 channels of data so that limited flight time could be analyzed in more detail. Four flights were completed in the Flyer, with two of them extending 97 feet and 115 feet. The flight data recorder revealed large canard control deflections that seem to be necessary to compensate for lags inherent in a flexible structure such as the Flyer. An understanding of airspeed effects on performance as well as engine and atmospheric effects have been gained. Lateral control effects have been studied during side-slipping conditions.

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### Nomenclature

$\alpha$  = Angle of attack  
 $\beta$  = Sideslip  
 $\delta_c$  = Canard deflection  
 $\delta_w$  = Warp deflection  
 $Q$  = Dynamic pressure  
 $C_L$  = Lift coefficient  
 $C_D$  = Drag coefficient  
 $C_l$  = Roll coefficient  
 $C_n$  = Yaw coefficient  
 $C_m$  = Moment coefficient  
 $C_{mq}$  = Pitch coeff. / pitch rate  
 $C_{L\alpha}$  = Lift coeff. slope

### Introduction

Although the Wrights completed four successful flights of the Kitty Hawk Flyer on December 17, 1903, they remained the only flights of this aircraft in its original configuration until nearly 100 years later. Prior to 2003, a replica 1903 machine was constructed and flown by Kellett<sup>1</sup> in honor of the 75<sup>th</sup> and 80<sup>th</sup> anniversaries of the first flight. A non-authentic engine was used for these flights which Kellett described as "...uncontrollable. It starts porpoising the minute you leave the launch rail, and it just gets worse."

During 2003, other organizations have joined the quest to experience flight in the 1903 Machine. The Wright Aeroplane Company in Dayton, Ohio has constructed a Flyer replica and flown it with a modern engine in Dayton, Ohio on December 6. The aircraft was damaged on landing. Wright Redux of Glen Ellen, Illinois flew their replica with a modern engine in the summer of 2003, and again in October, 2003 with a replica Wright engine. Although damage was sustained on landing, a 350-foot flight was achieved using the modern engine.

More recently, the Wright Experience (WE), based in Warrenton, Virginia has flown a reproduction Flyer four times during a recent encampment at the Wright Memorial in Kill Devil Hills, North Carolina. In one flight, the aircraft in its original configuration flew 97 feet and landed with no damage; a first for this aircraft in 100 years. Another flight of 115 feet resulted in four broken ribs, again considered minor damage. These flights were significant in that they did not terminate in a pitch-up or pitch-down departure, providing assurance the aircraft is controllable. All flights of the WE Flyer have been conducted using an authentic reproduction horizontal-four Wright engine.

Based on photographs and existing artifacts from 1903, the WE aircraft deviates from machines built strictly from previously existing plans in subtle but significant ways, such as the shape of the canard and the placement of bracing wires. While the 1985 Smithsonian drawings are an accurate representation of the museum artifact, the Flyer has changed somewhat since its flights in 1903. After the fourth flight in 1903, the aircraft was tumbled in a wind gust causing significant damage. The Wrights disassembled the aircraft and transported it back to Dayton where it suffered flood damage in 1913. It was rebuilt in 1916 and again in 1925, resulting in slight variations to the original design.

The use of period tools to carve exact duplicates of the Wrights' propellers is one example of how the Wright Experience aircraft has been constructed to retain the exact 1903 design. A digitized scan of the remaining pieces of the 1903 propellers aided in producing the exact propeller shape. The correct size of the gouge used to finish the concave side of the blades was determined from these artifacts as well.

This paper reviews the flight experiences of the WE Flyer and compares these flights to the predicted performance based on wind tunnel data. The Bihrl Applied Research (BAR) D-Six simulator is used to examine flight behavior during maneuvering and cross-wind flight to better understand the Flyer's characteristics. An on-board digital flight data recorder developed by Aero Space Consultants and Vigyan, Inc. allowed the acquisition of 15 channels of flight parameters during all evaluation flights, providing an expanded look at actual in-flight behavior.

### **1903 Flyer Analysis**

The earliest detailed analysis of a Wright Flyer dates to 1980, with the test of a 1/6-scale model Flyer conducted by Culick using the GALCIT tunnel<sup>2</sup>. This test was followed shortly thereafter by a 1/8-scale model tested at the Northrop Corporation in 1981. Wolko, et. al.<sup>3</sup> documented longitudinal and lateral coefficients for the Flyer and proceeded to examine handling characteristics with a pilot-in-the-loop model. One significant finding was that, with an error gain of four, a pilot would be able to control the aircraft longitudinally using the canard, although this amount of gain results in significant overcontrolling which has been verified in actual flights.

In 1999, a full scale 1903 Flyer was tested at the NASA Ames Research Center in the 40 x 80 tunnel<sup>4</sup>. This test improved estimates of aerodynamic coefficients and revealed the effects of camber in the deflected canard as well as asymmetries inevitable on a large, flexible structure. Power effects were observed, although due to motor problems the test was unable to simulate cruise power conditions and document power and thrust required.

In February, 2003, the WE Flyer was wind tunnel tested at the Langley Full Scale Tunnel (LFST) in Hampton, Virginia. A 20 HP frequency-controlled AC motor was installed on the aircraft mounting frame to drive the propellers over a range of speeds simulating flight conditions. Sixty runs and 20 hours of test time were used to measure lateral and longitudinal coefficients with and without power. Canard and warp controls were deflected over their range of operation to determine control power with  $\alpha = -4^\circ$  to  $+12^\circ$  and  $\beta = \pm 30^\circ$ . A load cell arrangement on the electric

motor provided brake motor torque so that accurate power at the output shaft could be determined. Britcher, et. al.<sup>5</sup> has presented a performance analysis of the Wrights' fourth flight based on the wind tunnel data.

To train the WE pilots for the reenactment of the first flight on December 17, 2003, the BAR D-Six simulator was programmed using tables generated from the LFST wind tunnel test. This simulator uses look-up tables of aerodynamic coefficients that are presented as a function of angle of attack to represent the aircraft aerodynamics. Variables such as thrust effects and landing gear compliance are modeled to give a realistic assessment of the aircraft's handling behavior both on the rail and in-flight. The next section examines the coefficients used to program the simulator. It should be noted that, due to time constraints, all wind tunnel data presented here is uncorrected for boundary interferences, although these are expected to be small and will be included in a future publication. In addition, a rigorous statistical analysis of the measured coefficients has not been completed but will appear in a future publication.

### **Longitudinal Characteristics**

Figure 1 shows the basic, non-trimmed lift coefficient as a function of angle of attack. Since the lower wing is nominally 2.0 feet above the ground during the takeoff roll, there is a substantial contribution to lift in ground effect in addition to the reduction in induced drag. Kalman, et. al.<sup>6</sup> has also shown that wings with an anhedral shape will produce an additional increase in  $C_{L\alpha}$  when in ground effect. Using published values by Katz<sup>7</sup> as well as vortex lattice modeling of the Flyer for the non-reflected and reflected geometries, a 20% increase in measured  $C_{L\alpha}$  has been estimated and used for takeoff performance calculations. In addition to this, thrust effects will progressively add lift as the angle of attack increases.

The plotted drag coefficient represents a "props off" condition in ground effect, and final performance is obtained by overlaying the thrust behavior of the 1903 props when operated at a set engine power state. Figure 3 shows the thrust determined from the wind tunnel, and Britcher<sup>5</sup> has published power available/power required plots for the aircraft.

Figure 4 shows the trim flight speeds at standard conditions as a function of angle of attack, using the on-rail lift conditions. Due to tail clearance issues, the Flyer should only rotate  $\theta = 3.5^\circ$  which, if  $\alpha = \theta$ , the target rotation speed will be 26 MPH. A higher rotation angle at a lower airspeed is possible, but the tail will strike the rail which does not necessarily result in damage since the tail assembly is hinged. Flight experience in the Flyer shows that controlled flight can occur at a few feet of altitude, so ground effect can be assumed to play a significant role throughout the flight profile.

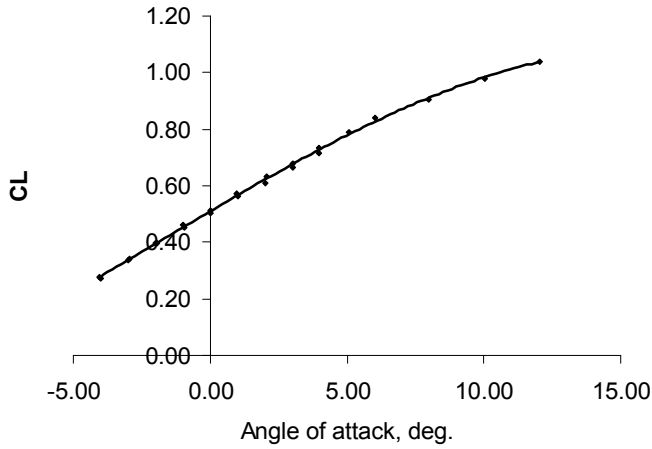
With a C.G. reported by the Wrights at 24 in. aft of the wing leading edge<sup>8</sup> and a 5% cambered airfoil, the aircraft is substantially unstable in pitch which has contributed to the lack of actual flights of the machine. The moment plot is shown in Figure 5 for the "props off" configuration, and the additional pitching moment caused by thrust is shown in Figure 6 for a thrust line 1.7 ft. above the center of gravity. Taking a 2-degree angle of attack in ground effect as a reference, the trim canard angle with props turning at a nominal 380 RPM will be  $\delta_c = +8^\circ$ . This coincides favorably with flight test, although it can be difficult to find an average canard deflection given the magnitude of pitch variations typical during flight.

The aircraft is nominally 17% statically unstable at  $\alpha = 2^\circ$ , which is a few percent less than previously measured in full-scale and reduced-scale wind tunnel tests. A principal reason for this may be the use of trim canard deflections which reduces instability because some effectiveness is lost at higher canard angles (Fig. 5). The reader is cautioned from reading too much into these stability values since the aircraft never flies strictly at trim but will operate over the full range of canard travel and corresponding variations in angle of attack.

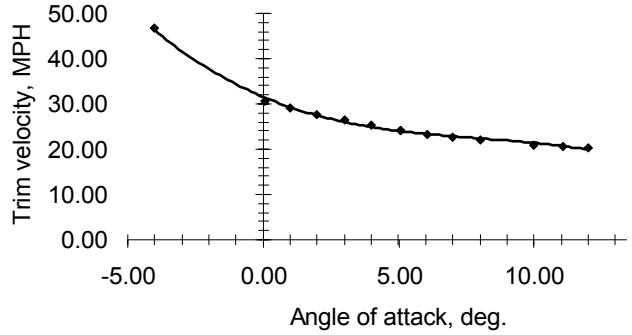
### **Lateral Characteristics**

Directionally, the 1903 Flyer must be operated within a narrow range of warp deflections and sideslip angles to maintain control. Figure 7 shows the roll control power and the yaw due to warp for power on and off conditions at cruise. The roll is approximately invariant to power effects, but yaw is affected by propwash over the

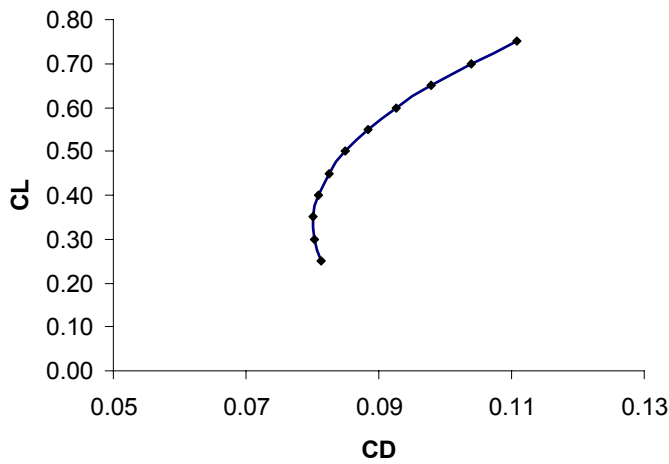
**Figure 1 – Basic Lift Coefficient**



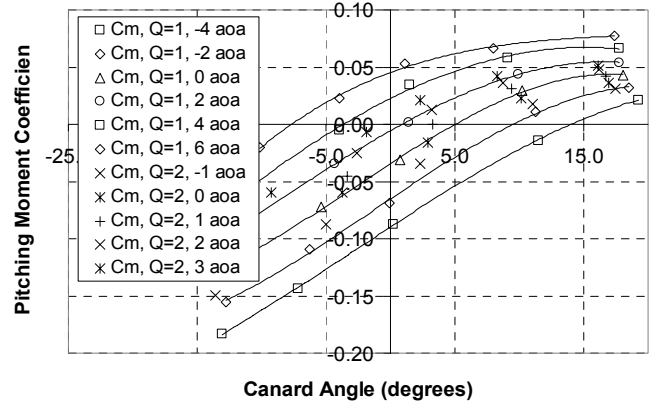
**Figure 4 – Trim Flight Speeds**



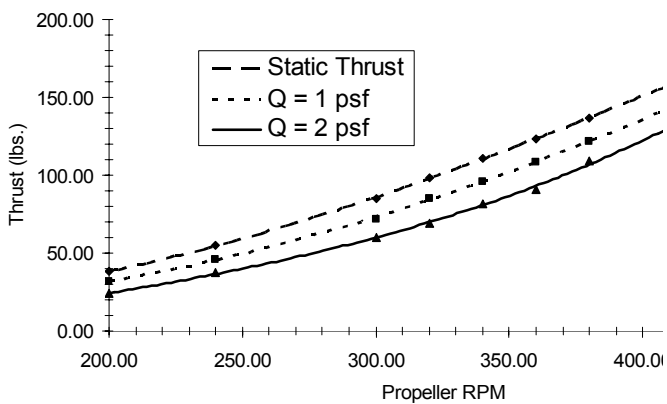
**Figure 2 – Drag Coefficient, On Rail**



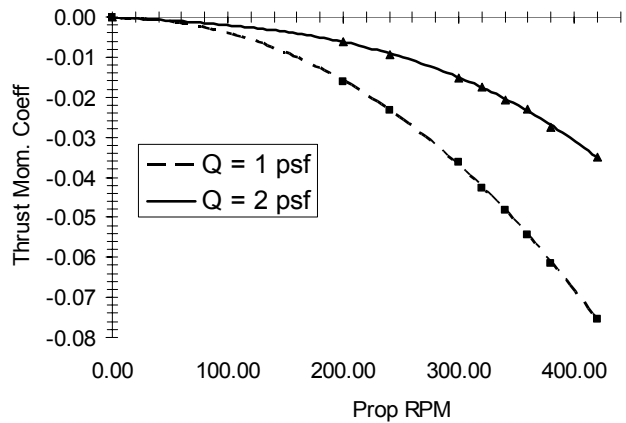
**Figure 5 – Canard Control Power**



**Figure 3 – Flyer Thrust**



**Figure 6 – Thrust Pitching Moment**

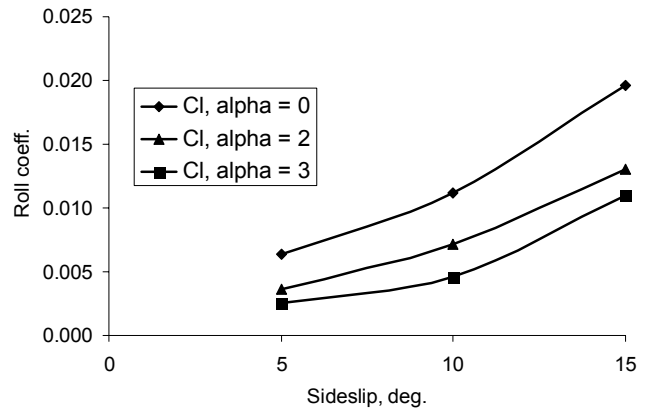


vertical tail. Like the 1902 glider, the 1903 machine has an interconnected rudder that operates with the warp control, deflecting  $31^\circ$  at full warp. The roll power shown in Figure 7 is about double of what was found in the 1902 machine, and that in turn was about double of what was measured on the 1901 machine<sup>9</sup>. For higher warp deflections, Figure 7 shows less yaw which becomes adverse at approximately  $\alpha = 4^\circ$ . Because of the large roll power available, the need for full deflection is diminished, reducing the adverse yaw problem.

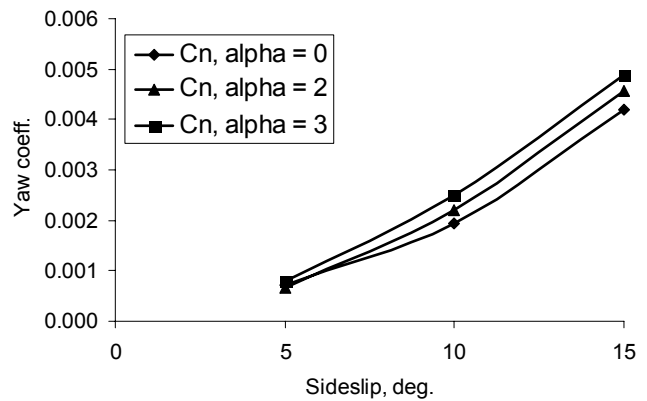
Lateral stability is shown in Figures 8 and 9. Due to the anhedral in the wing, the Flyer is roll unstable in sideslip at low angles of attack, such as would be experienced during the ground roll phase of the flight. With a crosswind component, the takeoff phase is complicated by the fact that warp corrections held on the rail must be lessened immediately at rotation as the aircraft angle of attack increases. The aircraft sits at  $\alpha = -1.7^\circ$  when on the takeoff rail.

Figure 9 shows adequate yaw stability at cruise angles of attack, being about 80% greater than what was found on the 1902 glider<sup>10</sup>. Due to time constraints, analysis at higher angles of attack was not possible, and the reader is cautioned that adverse yaw conditions will likely occur near stall, similar to the 1902 glider.

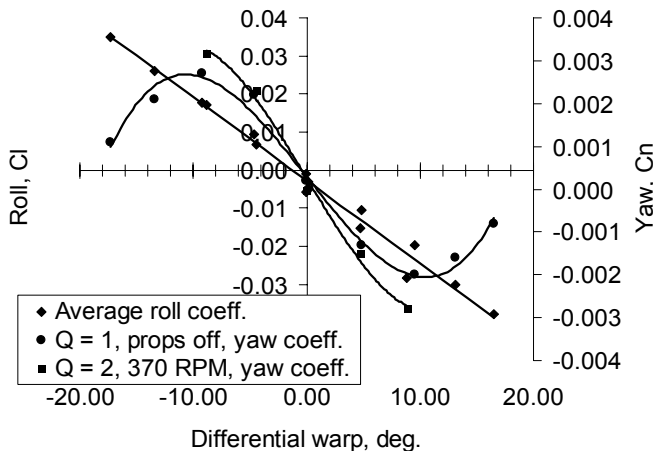
**Figure 8 – Roll Stability**



**Figure 9 – Yaw Stability**



**Figure 7 – Warp Coefficients**



**In-flight data acquisition**

From November 3 to December 5, the Wright Experience (WE) set up an encampment at the Wright Memorial in Kill Devil Hills to fly a reproduction Flyer. On November 20, the aircraft was launched in a northerly direction near the sight of the first flights into a 12 MPH wind on a 150 ft. long rail. The aircraft flew 97 feet beyond the lift-off point, which was only three feet from the end of the rail. Figure 10 shows the aircraft in flight. To the author’s knowledge, this flight marked the first time in 100 years that a Wright Flyer was successfully flown and landed without damage using an authentic powerplant.

Subsequently, the Wright Experience Flyer flew three more flights, with the second flight resulting in substantial damage and the third flight resulting in minor damage. On the third flight, the aircraft flew 115 feet but landed with the left wing low resulting in four broken wing ribs. The fourth flight was made on December 17, during a reenactment of the Wrights' flight 100 years ago to the day. A lack of wind and an engine that progressively misfired during the ground roll resulted in a six-inch lift from the dolly and a stall that settled the plane back to the track. The lack of engine power, partly due to unfavorable atmospheric conditions, precluded a successful flight. No more flights were made on this aircraft, and after the Centennial celebration the aircraft was shipped to Dearborn, Michigan for permanent display at the Henry Ford Museum.

The in-flight data acquisition system provided by Vigyan was installed on the Flyer for flights 1-3. Fifteen analog channels of data were acquired along with one digital channel that recorded prop shaft RPM; all recorded signals are summarized in Table 1. On-board and stationary video cameras recorded the flight paths to supplement the recorder data so that a detailed analysis of the flights could be made.

### **Simulator development**

The flight simulator developed by Bihrlé Applied Research (BAR) of Hampton, Virginia used measured data from the Langley Full Scale Tunnel (LFST) during the 1903 Flyer test in February, 2003. With pilot feedback, refinements were made to the simulator to improve its fidelity, mostly involving the refinement of rate derivatives that could not be measured in the tunnel. Although pitch inertia was measured to be  $365 \text{ lb}\cdot\text{sec}^2 \cdot \text{ft}$ . by pivoting the aircraft with springs installed at the bottom of the canard skids, the actual inertia is probably somewhat less due to air resistance during the test and airframe flexibility. This test would also include the effects of apparent mass. When the simulator is operated with a joystick, inertia had to be lowered to  $150 \text{ lb}\cdot\text{sec}^2 \cdot \text{ft}$ . to obtain control response similar to in-flight conditions. A larger inertia is more acceptable when a cockpit simulator including hip cradle and canard control stick is used.

### **Typical Flyer longitudinal behavior**

In order to better understand the Flyer's characteristics, a simulation of a typical flight was made using the D-Six Simulator with a 390 RPM engine. Engine RPM remains fairly constant over the range of flight speeds, so for the simulations it is acceptable to use a single RPM to model the engine performance. Figure 11 shows the simulated longitudinal characteristics for the aircraft on a standard day. These plots compare favorably with flight data acquired during the Nov. 20 and Dec. 3 flights, however due to the preliminary nature of this data, Figure 12 shows only canard deflection, speed and prop RPM. A future publication will include all flight data acquired during these trials. Of particular interest is the frequency of canard control input, approaching 2 Hz. Over-controlling is one way of handling the aircraft instability given the flexibility in the canard structure and the necessity of a quick response to minimize control lag.

### **Typical Flyer lateral behavior**

Flight no. 3 on December 3 demonstrated the roll instability in the aircraft and its behavior in side slipping conditions. In about one-second after liftoff, an eight-degree left crosswind component became an eight-degree right crosswind component causing the airplane to roll right. While the pilot compensated for the left crosswind by holding slight right warp during roll (opposite of dihedral-stable aircraft), upon rotation the right warp and anhedral effect caused a right roll in the wind shift, with the right wingtip grazing the ground. The aircraft recovered and continued to fly, although the ground strike ultimately caused a 30-degree left crosswind component which resulted in a strong left roll. The aircraft landed left wing low after a 115-foot flight.

To simulate the No. 3 flight, the Bihrlé D-Six simulator was run with a 3 ft./sec. left crosswind that shifts to a 3 ft./sec. right crosswind shortly after takeoff. Figure 13 shows the warp control response to the crosswind component and the roll response of the aircraft. The anhedral effect is clearly seen, with warp control input almost equaling the sideslip angle in degrees. Once flight is established, the wind shifts and the warp control is employed to maintain the aircraft in a wings level attitude. Although this is counterintuitive, i.e., flying the airplane in a sideslip, the directional

stability is sufficient to return the airplane to coordinated flight while avoiding a wingtip ground strike such as would occur in a banking turn.

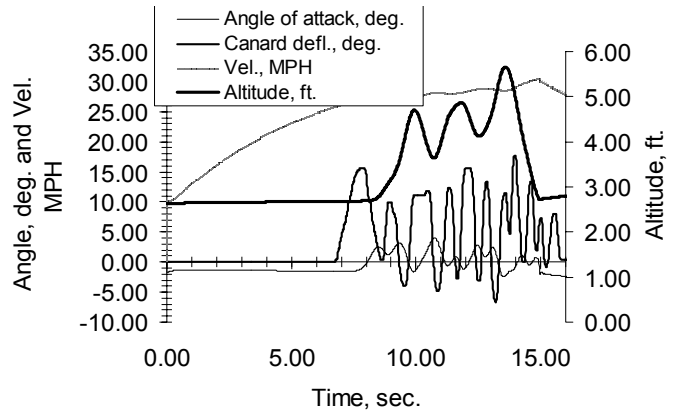
**Table 1 – Measured flight parameters**

ch	Measurement	Units
0	Static Pressure	psi
1	Total Pressure	psf gage
2	Angle of Attack	deg
3	Angle of Side Slip	deg
4	Pitch Control Stick Position	deg
5	Wing Warp Position	deg
6	Torque at L Prop Shaft	ft-lbs
7	Fwd Longitudinal Accel.	g's
8	Fwd Lateral Accel.	g's
9	Fwd Normal Accel.	g's
10	Fwd Temp Accel.	deg F
11	CG Longitudinal Accel.	g's
12	CG Lateral Accel.	g's
13	CG Normal Accel.	g's
14	CG Temp Accel.	deg F
15	Flow Temp Sensor	deg F
DI	RPM at L prop Shaft	rpm

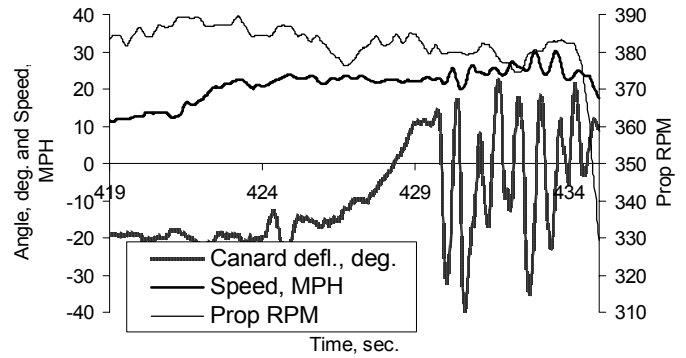
**Figure 10 – Flyer in Flight**



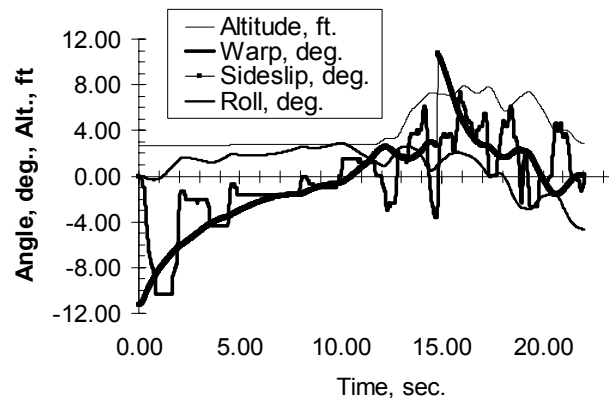
**Figure 11 – Simulated Longitudinal Flight**



**Figure 12 – Flight # 1 Data**



**Figure 13 – Lateral Simulation**



## **Pilot perspective on handling**

Much has been published regarding the handling difficulties of the 1903 Flyer, with the general consensus being that the airplane is extremely difficult to control<sup>11, 12</sup>. Due to the expense of constructing and flying the airplane, analysis has served as a substitute for rating the Flyer's characteristics. The WE Flyer was flown by the pilot team four times, with two of those flights covering 97 feet and 115 feet. From these flights, a reasonable assessment of the aircraft from the pilot's perspective has been developed.

The arched shape that one must assume for forward visibility is not comfortable for long periods of time, and some relief could be gained by shifting around in the cradle during engine start, prior to launch. After releasing the holdback wire latch, it is necessary to concentrate on keeping wings level during the takeoff roll since ground clearance is less than two feet at the wingtips. The canard is held neutral to reduce drag without a risk of rotation; a positive canard deflection of at least 10 degrees is necessary to initiate flight. With no airspeed indicator, experience in the 1902 glider at typical flight speeds may have provided the Wrights some ability to detect speed in the Flyer. Recent glider training at a much reduced level from what the Wrights experienced has given modern pilots limited airspeed detection capability.

Once takeoff speed is reached, the Flyer requires significant positive canard to rotate, in part due to the nose-down moment caused by the thrust line. A strong engine will require more positive canard to "unstick" the aircraft, while a weak engine requires less. This is important to consider since a premature takeoff could occur with a weak engine as the canard angle is slowly increased. Complicating the canard control input is the fact that unstable airplanes trim with more positive canard at higher speeds and less at lower speeds, requiring the pilot to adjust trim reference continuously with respect to airspeed.

Canard control forces are reasonable, although the placement of one's elbows can be awkward because of the location of the fuel mixture control and the fuel line. The hip cradle requires about the same force that the Wrights' measured on their machine, 14 lbs.<sup>13</sup>, which is estimated to be about double the force experienced on the 1902 glider. A good grip on the canard actuator crossbar is needed to work

the hip cradle, otherwise the operator's body moves and the cradle remains stationary.

Due to the high workload after takeoff, extraneous information such as the sound of the engine can disappear. Once airborne, pitch corrections must be applied at a relatively high frequency (measured at almost 2 Hz) to arrest the unstable behavior. The airplane flies more like a powered kite than an aircraft, with a "soft" feel to the handling in part caused by the lag between the canard input and the pitch response. In addition to the aerodynamic instability, this aircraft is very flexible which makes all control inputs a little less crisp than what the pilot would prefer. With the canard being operated almost to the limits of its control repeatedly, there is some sense to the pilot that the aircraft is being over-controlled. This may be the necessary result of operating an unstable aircraft with control lags built in, but due to the lack of flight time this question will remain unanswered.

Laterally, the WE Flyer flew briefly in a 30 degree crosswind component based on preliminary data from the flight data recorder. At this sideslip angle, the roll rate due to the wing anhedral can be significant and will likely terminate the flight prematurely. The use of anhedral was a benefit for this ground effect machine since it allows the pilot to fly wings level, reducing the risk of a tip strike, while the aircraft seems to accommodate the resulting sideslip with little complaint. This philosophy may partly explain the lack of vertical surface area on all of their early aircraft.

## **Conclusions**

The Wright brothers progressively solved the problems of powered flight starting in 1899 with a kite that proved their lateral control concept called wing warping. With trips to Kitty Hawk in 1900, 1901 and 1902, they learned what critical issues had to be resolved in developing a successful powered machine. The fundamental research of airfoil behavior and the development of a three-axis controlled glider in 1902 gave them the necessary tools to design an airframe, propellers and additionally a powerplant of sufficient power for their 1903 Flyer. Four successful flights on December 17, 1903 confirmed their theories and established Wilbur and Orville as pioneers of powered flight.

One hundred years later, we are still asking the question, "how did they do it?" The answers not only serve the academic community, but also provide an excellent example of what is required to solve our most technically challenging problems. With the recent encampment and flights at Kill Devil Hills, North Carolina by the Wright Experience team, new light has been shed on many of these important questions.

The technical challenges faced by the Wrights have been well documented. A control system, efficient propeller design, adequate powerplant and a rail launching system are some of the achievements that made the Flyer successful. *Implementing* these technologies in an unforgiving environment has not been well documented until the encampment. The handling, operation and maintenance of the Flyer has revealed an aircraft that runs not only on gasoline, but ingenuity and perseverance.

As this airplane was an extension of everything the Wrights had developed and learned about flying machines, they were well equipped to handle the biggest challenges. Knowing the health of the engine prior to launch can change how the pilot flies the airplane off the rail. The view looking forward in an unstable canard aircraft was a familiar sight from their gliding experience, and this aided in understanding the proper canard input during an upset. Likewise, they knew lateral control of anhedral-rigged biplanes from their experiences with the 1902 glider, allowing them to maximize flight time in unsteady wind conditions.

Putting everything together for successful flights was achieved in 2003, but not without an enormous effort that translated to respect for the breadth of what the brothers were able to accomplish. Not the least of which is a recognition of just how competent they were as operators of their flying machines, something that 100 years of flying has not improved upon.

### **Acknowledgements**

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