

FLIGHT TESTING SIMULATIONS OF THE WRIGHT 1902 GLIDER AND 1903 FLYER

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ABSTRACT

It was the Wright Brothers who successfully used the process and discipline of flight-test one hundred years ago. Annual flight test campaigns in the years 1900-1905 clearly show how the Wright brothers used flight-testing to assess the performance, analyse the flight dynamics and propose improvements to their aircraft designs. This paper will present an analysis of the 1902 Glider first flight-tested in the fall of 1902 and the 1903 Flyer first flight-tested on December 17th 1903. Results will be taken from a research project underway at the University of Liverpool where the technical achievements of the Wright Brothers in the period 1900-1905 are being assessed using modern analytical and experimental methods. Results from piloted handling tests conducted on the Liverpool Flight Simulator, featuring six motion axes and six visual channels will be presented. The results show how the simulation trials were treated with a contemporary approach in terms setting handling qualities requirements and assessing the aircraft in a predefined 'role'. Investigations have been made into the different types flown in 1902-1905 and variations on those, including some 'what if' configurations. One example is the critical innovation of 3-axis flight control, a direct result of flight-test. In conclusion the paper will present how the Wrights understood the importance of flight control and pilot skill and how both were developed through a controlled and systematic programme of flight-test.

NOTATION

| | | | |
|-------------------|-----------------------------|---------------------------------|-----------------------------|
| b | Wingspan | C_M | Pitching moment coefficient |
| c | Wing chord | C_n | Yawing moment coefficient |
| c.g. | Centre of gravity | C_Y | Side-force coefficient |
| p, q, r | Roll, pitch and yaw rate | D | Drag |
| C_D | Drag coefficient | H_n | Static margin |
| C_l | Rolling moment coefficient | HQR | Handling qualities rating |
| $C_L, (C_{Lmax})$ | Lift coefficient, (maximum) | $K_p, K_\phi, K_\theta, K_\psi$ | Pilot gain, (Roll, |
| $C_{L\alpha}$ | Lift curve slope | | |

| | | | |
|---------------|---------------------------------|---|--|
| L | Pitch, Yaw) Lift | $\delta_c, \delta_r, \delta_w, \delta_{wr}$ | Canard, rudder, warp, warp and rudder deflection |
| $(L/D)_{max}$ | Lift-to-drag ratio (maximum) | | |
| MTE | Mission Task Element | $\theta_c, (\theta_e)$ | Command pitch angle, (pitch angle error) |
| T_D | Time to double amplitude | λ | Eigenvalue |
| α | Angle of attack/incidence | ϕ, θ, ψ | Euler attitude angles |
| α_0 | Angle of attack at $C_L = 0$ | | |
| β | Angle of Sideslip | | |

INTRODUCTION

Overview

This paper presents an analysis of the flying characteristics of the Wright Brothers' aircraft, specifically focusing on the 1902 Glider and the 1903 Flyer. The approach to the research has been to use modern analytical techniques to assess the flight performance of these aircraft within a modern flying qualities engineering context. The main research tools utilised have been wind tunnels and FLIGHTLAB modelling, combined to develop high fidelity simulations of the aircraft. These have been flown in a number of handling qualities trials at the University of Liverpool's flight simulator (Ref 1). Through the use of simulation, this paper will show how the Wright Brothers, through a program of flight-test, encountered several handling qualities difficulties and how the designs were evolved to overcome them.

Historical Background

The years 1899-1905 represent the most technically significant period for the Wright Brothers. Within this period, the Wrights continually evolved their flight vehicle concept through one kite, three gliders and three powered aircraft. The 1902 Glider and 1903 Flyer fit into the centre of this design evolution. They represent the transition from the un-powered gliders to the powered 'Flyers'. The story of the development of all of these aircraft is one of systematic experiment in aerodynamic design and flight-testing, with a central focus throughout of control over stability.

The 1902 glider was designed using data obtained by the Wrights' wind tunnel experiments in the winter of 1901-02. These tests were conducted because of the relatively poor performance of their 1901 glider. The 1901 glider during its flight trials is shown in figures 1 and 2.

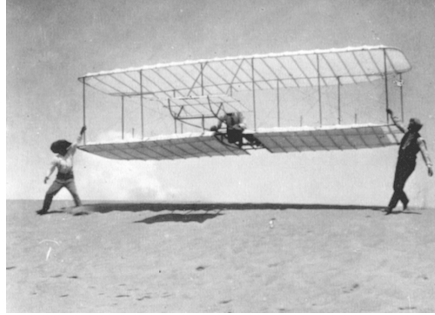


Figure 1 Launching the 1901 Glider

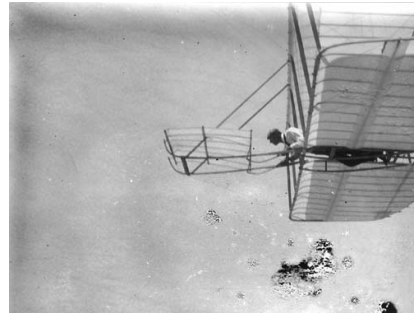


Figure 2 The 1901 Glider almost 'soaring'

The 1901 glider had performed poorly in three key areas:

- Aerodynamic performance, the low aspect ratio wings (22x7ft, $AR=3.14$) of the 1901 glider lifted only about $1/3^{\text{rd}}$ as much as predicted. Consequently, flight was only possible at high angles of attack or at the higher wind speeds.
- Longitudinal stability and control; the 1901 glider was designed with a $1/12$ (8%) camber airfoil section. This had caused problems, as the large negative pitching moment associated with such an airfoil, required a significant aft movement of the centre of gravity to achieve trim.
- Lateral-directional control. The Wright Brothers had developed a roll control system known as 'wing warping'. Unexpectedly, there was a large adverse yawing moment created by the wing warping action. This caused the aircraft to yaw away from the desired turn direction. Figure 3 shows one of the problems caused by the adverse yaw on the 1901 glider.

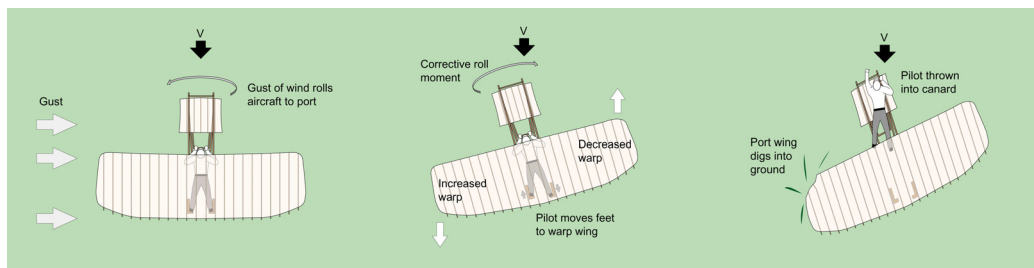


Figure 3 Adverse yaw with the 1901 Glider

The flight-testing of the 1901 glider highlighted these deficiencies to the Wrights. They were able to address the longitudinal control, (by reducing the camber to $1/19$ (5.1%)) in the field. Overall, the insufficient performance of the 1901 glider prevented the Wrights from their primary objective - to be able to gain practice in flying.

The new 1902 machine (figs 4 & 5) featured a higher aspect ratio wing (32x5ft, $AR=6.4$), with an even lower airfoil camber than in 1901 ($1/24$ (4.2%)) and a double surface vertical tail. The Wrights first flew the glider as a kite to ascertain the glide performance and they knew immediately they had succeeded

in producing an improved design. The kite strings were almost vertical indicating a high lift to drag ratio as shown in figure 4.

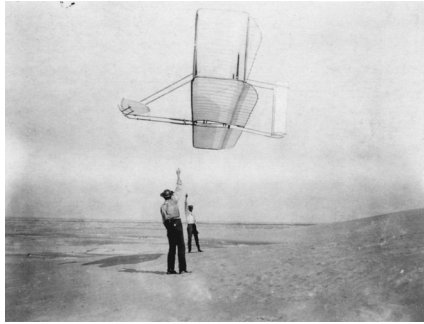


Figure 4 Kiting the 1902 Glider

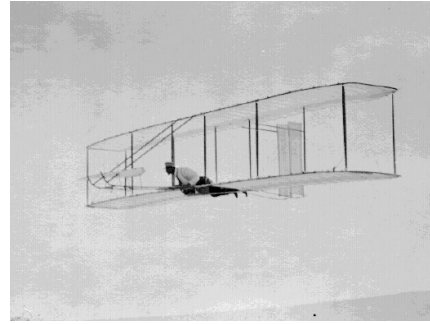


Figure 5 The double-surface fin version of the 1902 Glider in flight

The 1900 and 1901 gliders had featured a low-aspect ratio, flexing canard to provide pitch control (see fig 2). The 1902 glider incorporated a re-designed canard with a higher aspect, elliptical planform. The control mechanism was reworked with the canard now being operated by a 'roll bar'. This system worked by rolling the bar forwards to rotate the canard nose down (pitch down control) and vice-versa. Prior to 1902, the Wrights had used a foot operated 'kick bar' to control the wing warping, but this too was adapted. For the 1902 glider, the pilot rested his hips in a cradle, which by movement to the left or right pulled on wires which twisted the wings.

The Wright Brothers began to glide with their 1902 machine and found the machine's performance particularly satisfactory. The pitch control was acting well but there were still problems in the lateral motions. The first problem encountered was due to another change in the design of the 1902 glider. The previous 1901 glider had a slight downward droop of the wingtips (anhedral). This had been removed for the 1902 version, which featured wings with the tips at the same height as the centre. In the flight tests, the Wrights soon discovered that the response to side-gusts with this feature was undesirable. So they returned to the anhedral shape, and matters improved instantly "*We found that the trouble experienced heretofore with a crosswind turning up the first wing it struck had been overcome, and the trials would seem to indicate the opposite effect was attained. The machine flew beautifully...*" (Orville Wright, 22nd September, (Ref 2). Still, there were problems. Orville had suffered a serious crash whilst over-concentrating on the lateral control. He neglected the pitch axis and the aircraft pitched up, lost airspeed and crashed. The problem seemed to arise when the glider was subjected to prolonged side gusts, or a change in the wind direction. The Wrights had installed a vertical tail on the 1902 glider and in short side gusts this helped to stabilize the heading of the aircraft (figure 6). In the longer gusts/wind change the tail made the aircraft response worse. The pilot reacted to this wind change by operating the warp control. However, this caused adverse yaw, dragging the low wingtip further back and the aircraft corkscrewed, driving the low wingtip into the sand (figure 7). The crux of this problem was that the

pilot only had control over two axes, pitch and roll. There was no way that they could affect the yaw motion or deal with the adverse yaw. The solution was that the vertical fin should be controllable by the pilot such that it gave yawing moments. In fact, the Wrights arranged the action of the rudder such that it moved simultaneously with the warp control (figure 8). In this way the rudder created proverse yawing moments to counteract the warp adverse yaw, and so the first three-axis flight control system was developed.

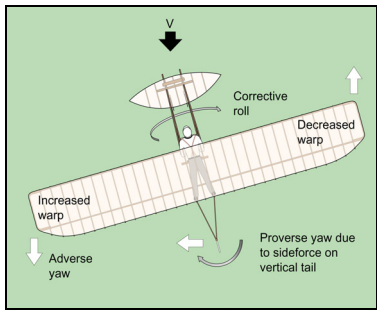


Figure 6 Fixed tail counteracting a short gust

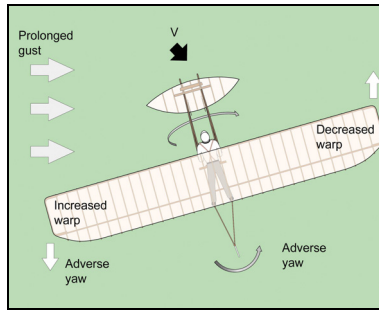


Figure 7 Fixed tail causing problems in a prolonged gust

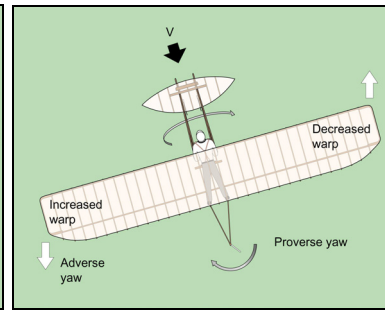
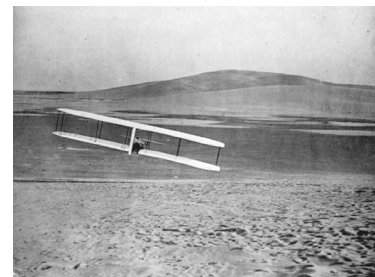
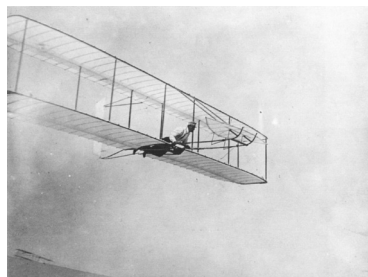


Figure 8 Warp-rudder interlink counteracting the adverse yaw

With this final development the Wrights made many glides as depicted in figures 9-11. Between 700-900 glides were made with the 1902 glider in total. A record glide of 622 ft was made that lasted for 26 seconds, and Orville stated in a letter to his sister, Katherine, the records broken, *“The past five days have been the most satisfactory for gliding we have had. In two days we made over 250 glides, or more than we had made all together up to the time Lorin left. We have gained considerable proficiency in the handling of the machine now, so that we are able to take it out in any kind of weather. Day before yesterday we had a wind of 16 meters per second or about 30 miles an hour, and glided in it without any trouble. That was the highest wind a gliding machine was ever in, so that we now hold all the records! The largest machine we handled in any kind of weather, made the longest distance glide, the longest time in the air, the smallest angle of descent, and the highest wind!!!”* Ref 2 (p.279).



Figures 9, 10 & 11 The 1902 Glider under flight-test by the Wrights

The success of the 1902 machine spurred the Wrights onwards and they proceeded to design their first powered machine, the 1903 ‘Flyer’. This built upon

the success of the 1902 glider, keeping the anhedral and the warp-rudder interlink system. To compensate for the increase in weight due to the propulsion system the wing area was increased to 510 sq ft and the canard and rudder both featured double surfaces instead of single ones as on the 1902 glider.

The development of the engine-propeller combination was a technical masterpiece in itself and was another example of the Brothers innovative skills. The engine was the first gasoline internal combustion engine to feature an aluminium crankcase. This offered a much lighter engine than any of the automobile manufacturers could offer at the time. The propellers were also highly advanced. The Wrights returned to their 1902 wind tunnel data and selected an airfoil shape that would give them excellent performance. The Wrights had realised that the propeller was, in essence, a wing travelling in a helical path and developed a theory to optimise the twist and chord distribution of the blades. The Wrights achieved efficiency levels of around 85% for their propellers, an achievement not to be matched for next 20 years (Ref 3).

Before flying their new powered machine the Wrights returned to the 1902 glider to refresh their flying skills and managed to increase the longest flight time to 71¾ seconds. A number of mechanical failures had delayed the Wrights from making their first flight with their powered machine. It wasn't until December 14th that they were ready to launch the Flyer. The winds were low, only 4-8 mph so the starting rail was laid on a downhill slope. Wilbur had won the toss to fly first and at the first attempt the aircraft rose some 6-8 feet from the launch rail and then pitched up rapidly and stalled about 60 ft from the end of the rail. The aircraft descended and broke some of its forward structure. On the 17th the aircraft was repaired and ready to fly again. Orville now took the controls, this time the winds were much higher, around 24 mph, and he took off from the level. He flew around 120ft in about 12 seconds. Four flights were made that day with Wilbur making the longest of 852ft over the ground in 59 seconds. The age of powered flight had begun.

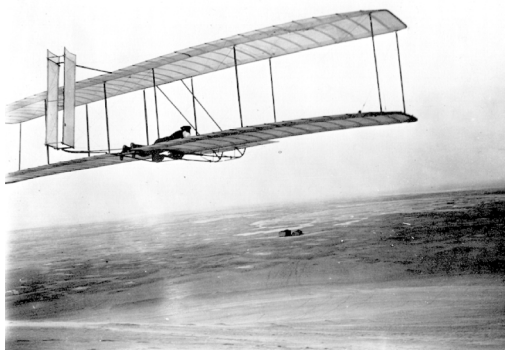
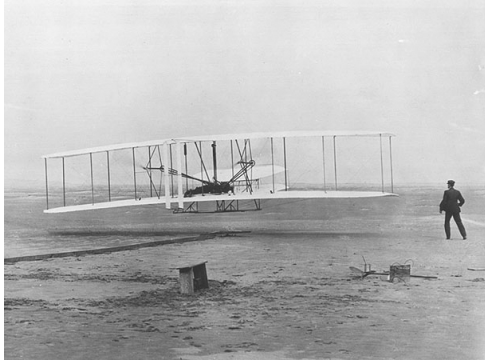


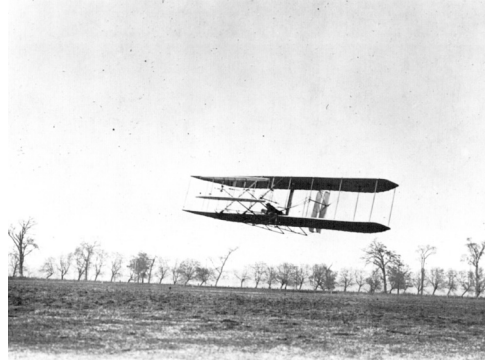
Figure 12 The 1902 Glider flying at Kitty Hawk in 1903



Figure 13 The 1903 Flyer ready on the launch rail



**Figure 14 First flight -
December 17th 1903**



**Figure 15 The 1904 Flyer 2,
Huffman Prairie, Dayton, OH**



**Figure 16 The 1905 Flyer 3 – The world's first
practical airplane**

AERODYNAMIC PERFORMANCE

Wind Tunnel Tests

As part of the Liverpool Wright Brothers project, wind tunnel models of the Wright 1901 and 1902 gliders have been tested at the University of Manchester's 9x7.3 ft Goldstein tunnel. The objectives of the tests were to quantify the aerodynamic characteristics of these aircraft. From these data, the flight dynamic simulation models could then be developed. The 1901 glider model was at 1/5th scale (4.4ft span) and the 1902 glider at 1/8th scale (4.01ft span). The models were mounted on a 'T' strut connected to an overhead six degree-of-freedom force and moment balance. The models were tested inverted with the nose supported by a vertical 'nose-wire'. This configuration gave the minimum of interference from the strut mount with the aerodynamic surfaces and left no attachments along the wings – an important feature to allow for the wing warping. The overall plan for the tests was to conduct a parametric study of the aircraft gathering data on the effects of canard, warp and rudder deflections over a range of α (-10° to +24°) and β ($\pm 30^\circ$). The conventions for the various control deflections are as follows:

- Canard positive leading edge up, (pitch up) $+\delta_c$
- Warp positive - right wing tip increased incidence, i.e. control input positive, $+\delta_w$ gives a roll to the left (incidence right-incidence left).
- Rudder control positive trailing edge to starboard (yaw to right), δ_r .
- The reference datum for the angle of incidence was the chord line from the leading edge to trailing edge of the wing.

Results - Longitudinal

One of the primary objectives for the Wrights in the design of the 1902 glider was to achieve superior lifting performance over the 1901 machine. The key parameter in determining the glide performance is the lift to drag ratio. From the tunnel data, the relative performance of the 1901 and 1902 machines is displayed in Figure 17.

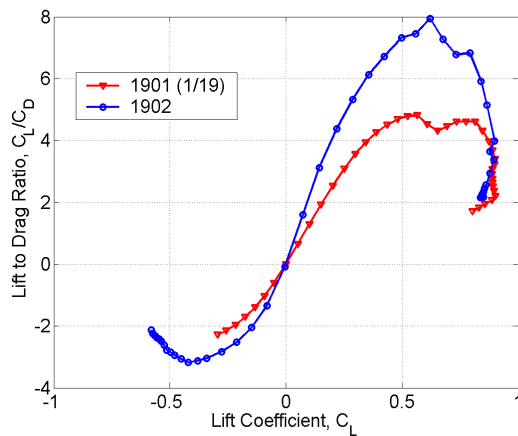


Figure 17 Lift-to-drag ratios of the 1901 and 1902 Gliders

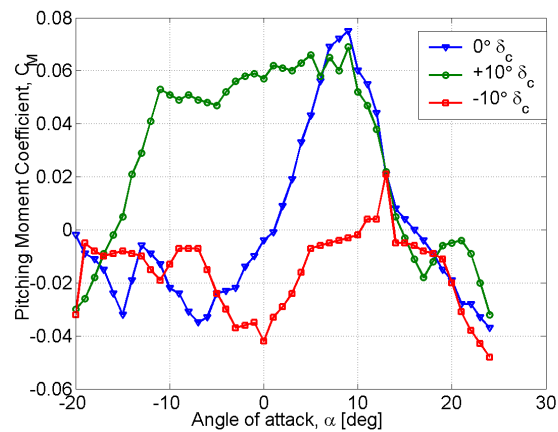


Figure 18 Pitching moment coefficient v α -1902 glider

The 1902 glider shows a maximum L/D ratio of nearly 8 - a 66% increase over the 1901 glider, which only achieved a $(L/D)_{MAX}$ of 4.8. This increase was a result of the new higher aspect ratio wing (1902, $AR=6.4$; 1901, $AR=3.14$ per surface), and a generally cleaner design with less drag inducing posts and wires. Figure 18 shows the pitching moment coefficient, C_M , versus angle of attack derived from the tunnel tests. At low incidence ($\alpha = -3^\circ \rightarrow +9^\circ$) the 1902 glider with the c.g. at $0.35c$ is statically unstable, an increase in α inducing an increase in C_M . At higher incidence, the reversal of the slopes indicate a rapid movement of the centre of pressure. This causes the glider to become statically stable beyond $\alpha=9^\circ$. Additionally, the lines cross the X-axis for a second time. This is significant as this represents a type of 'deep stall' condition where the aircraft finds a natural trimmed flight condition. It is probable that this represents the flat stall condition that the Wrights sank into when they lost too much airspeed.

Results – Lateral

Figures 19-22 show some of the lateral aerodynamic characteristics of the 1902 glider. Figure 19 shows the rolling moment coefficient, C_l plotted against sideslip angle β ; the slope of $\frac{\partial C_l}{\partial \beta}$ is positive, denoting instability in the roll axis, caused by the anhedral angle of the wings. This characteristic was also a feature of the 1903 Flyer and the 1904 Flyer 2 machines, until the Wrights encountered difficulties turning with the Flyer 2 and subsequently removed it. The wing warping mechanism that the Wrights devised was used throughout their designs. Figures 20 and 21 illustrate the performance of that system. For the 1902 glider (figure 20), a maximum twist of around $\pm 7^\circ$ at the wingtips ($\delta_w = \pm 14^\circ$) gave maximum rolling moment coefficients of ± 0.04 . However, the effectiveness of the warp control depends on the incidence, with the rolling moment due to warp falling off as the 'stall' angle of $\alpha \approx 15^\circ$ is approached. The other significant feature of the warping mechanism is the adverse yaw moment that is created. Figure 21 shows that the yawing moment is positive for a $+14^\circ \delta_w$, i.e. a full left roll command. Also important is how the adverse yaw varies with incidence, α . This can be seen to increase rapidly beyond an incidence of around 7° or 8° . For example, with the maximum warp of $\pm 14^\circ$ the adverse yaw at $\alpha = 15^\circ$ is clearly much larger than at $\alpha = 0-5^\circ$. The Wrights installed a vertical tail in 1902 to counteract the adverse yaw due to warp and Figure 22 shows the effect of the tail. The results shown are for the 1902 glider with the single moveable tail. Directional stability is attained ($+\frac{\partial C_n}{\partial \beta}$) and rudder deflections of $\pm 10^\circ$ create yawing moment coefficients, C_n of ± 0.004 . Comparing these values with those in figure 21 it can be seen that the rudder would have been able to overcome the adverse yaw at incidences below $\alpha = 7^\circ$ or 8° .

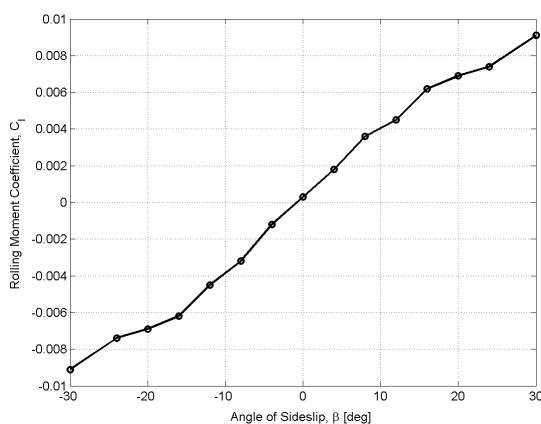


Figure 19 Rolling moment coefficient v sideslip –1902 Glider

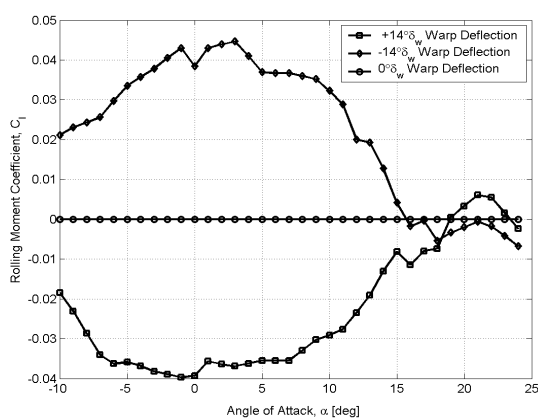


Figure 20 Rolling moment coefficient due to warp v α –1902 Glider

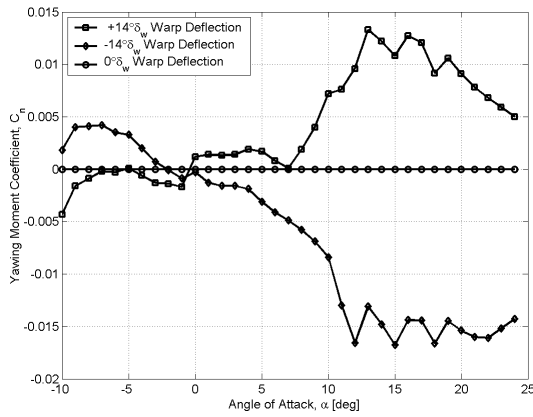


Figure 21 Yawing moment coefficient due to warp v sideslip

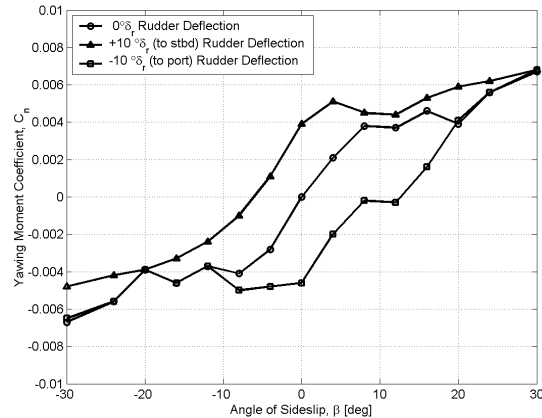


Figure 22 Yawing moment coefficient due to rudder v sideslip – 1902 Glider

The wind tunnel results have shown, or rather confirmed, that the 1902 glider was both unstable in pitch and roll. They have also shown that all the control mechanisms provide the desired effect but are ineffective or have other adverse secondary effects beyond small angles of incidence and sideslip. The results presented in Ref 4 and Ref 5 have provided similar data and drawn similar conclusions for the 1903 Flyer. Having a similar configuration to the 1902 machine, the Flyer showed many similar characteristics. In particular, the 1903 Flyer was unstable in pitch and roll and suffered from adverse yaw from the warp control.

MODELLING AND FLIGHT SIMULATION

FLIGHTLAB Modelling

The simulation models were created using FLIGHTLAB (Ref 1). The software uses a multi-body dynamics approach to model flight vehicles and provides a range of tools using to assist in rapid generation of complex, highly non-linear models. Once developed, a number of FLIGHTLAB analyses can be carried out on the simulation model. These include trim, parameter sweeps, linearization and stability and dynamic response routines. In addition, FLIGHTLAB provides a real-time simulation environment in which the model can be flown. The models were developed using the data from the tests conducted by the authors and Ref 4 and Ref 5 provided data for the 1903 Flyer simulation model.

Flight Dynamics

Using the FLIGHTLAB linearization routines, the complex non-linear models were reduced to simpler linear models. These models assumed that the longitudinal and lateral dynamics were decoupled and that the motions could be approximated to small perturbations from the trim condition. The most common flight speed for the 1902 glider was approximately 24kts, and a typical flight

speed for the 1903 Flyer was 26kts. These cases were selected for further analysis using the linear state-space model formulation, $\dot{x} = Ax + Bu$. The linear models provide useful parameters such as periods and damping and the stability of the various dynamic modes can be easily obtained. A useful tool for this analysis is the root locus. Figures 23 and 24 show the root loci for the longitudinal dynamics of the 1902 and 1903 machines respectively.

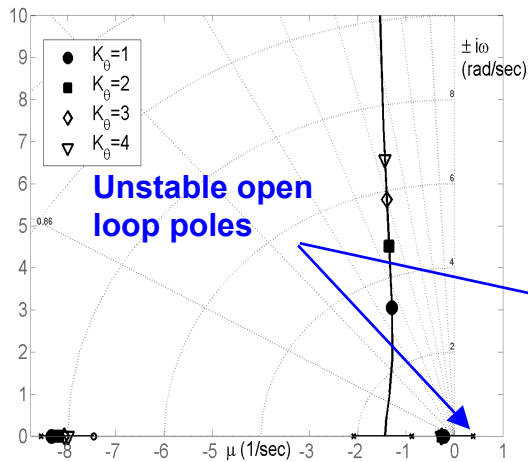


Figure 23 Root Locus, pitch attitude feedback to canard, c.g. @ 0. 24c – 1902 Glider

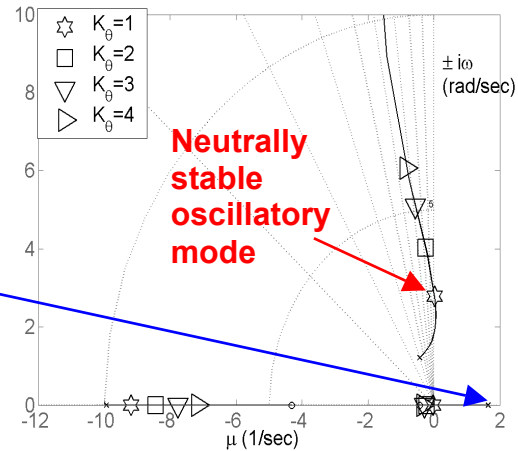


Figure 24 Root Locus, pitch attitude feedback to canard, c.g. @ 0. 3c – 1903 Flyer

The longitudinal static instability of both the 1902 and 1903 machines causes there to be an unstable ‘open loop’ mode. The modes are unstable because they lie on the right hand side of the y-axis. The modes represent an unstable divergence, any pitch disturbance causing a rapid increase in pitch angle. The application of feedback or ‘closing the loop’ can stabilize the aircraft; this is analogous to the pilot applying control to maintain a pitch attitude. The amount of correction per error is known as the pilot gain, K_θ , and the root locus shows how this parameter changes the dynamics as it is varied from $0 \rightarrow \infty$. The 1903 machine was particularly unstable, with the static margin, $H_n = -20\%$ (Ref 5). This was result the addition of the engine and propellers shifting the centre of gravity aft and the neutral point moving forwards (due increased canard volume). This compares to only around -4% for the 1902 glider with its most likely c.g. position (c.g. @ 0.24c, $C_L = 0.2-0.6$). This difference is reflected in the root loci with the unstable pole near to $\mu = 1.7$ ($T_D = 0.41s$) for the 1903 machine compared to $\mu = 0.35$ ($T_D = 1.98s$) (1902). As the gain is increased, these unstable modes move to the left, becoming stable. However, the application of gain drives another mode to increase in frequency, and in the case of 1903 Flyer the mode moving right reaches a neutrally stable (on the Y-axis) condition before coming back left with increased frequency. In summary, control from the pilot stabilizes the unstable divergent behaviour of the aircraft but instead forms a lightly damped, oscillatory pitching motion. In reality, a real pilot is able to effect more complex

strategies in control of the aircraft, but this classical pilot model can give some prediction of the dynamics of the aircraft when under pilot control.

The lateral dynamics are also treated with the same analysis; figure 24 shows the effect of closing the loop on the lateral motion on the 1902 Glider. By the feedback of the roll attitude to the roll control (warp), the unstable spiral mode (caused by the anhedral) is stabilized. Again, similar to the longitudinal dynamics, as the gain is increased a new oscillatory mode forms, although this mode is much more highly damped. The Dutch roll mode is not affected much by the change in gain.

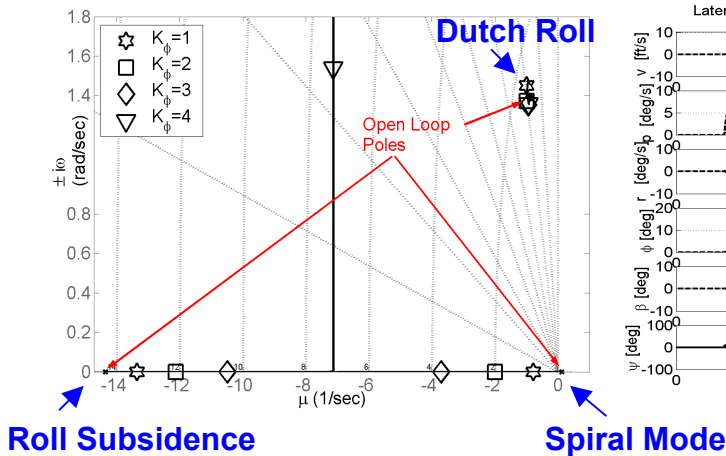


Figure 24 Root locus, roll attitude feedback to warp –1902 Glider with interlink

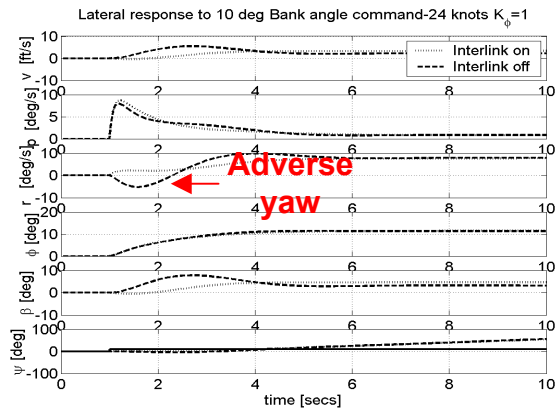


Figure 25 Time response - Roll attitude feedback to warp

The development of the warp-rudder interconnect system was a result of the problems of adverse yaw due to the warp control. Figure 25 shows the benefits of the system under closed loop control. Illustrated is a $+10^\circ$ bank angle command using a pilot gain of $K_\phi = 1$, i.e. 1 degree of warp for every degree of error in the roll attitude. The response without the interconnect results in an ungainly turn entry with large adverse yaw rates and large sideslip motions. Comparing this to the response to that with the interconnect system implemented, the adverse yaw is negated and the sideslip reduced. This system does not change the stability, but using the simple pilot model, it is seen improve the turn entry characteristics.

Piloted Simulation Trials

The previous analysis has shown the pilot model, at moderate levels of gain, could control the static instability of the 1902 and 1903 machines. The wind tunnel tests revealed a degree of non-linearity, which is not reflected in the linear models. The following analysis presents results from piloted simulation trials on the FLIGHTLAB 1902 Glider and 1903 Flyer models. The test pilot for the simulation trials possessed extensive vintage aircraft experience on types such as the 1910 Bristol Boxkite and the 1909 Bleriot XI. The objective for the trials

was to fly the aircraft in a number of manoeuvres so that handling qualities ratings could be made using the Cooper-Harper rating scale (Ref 6). The manoeuvres were selected using the modern concept of mission task elements (MTE's) as used in Ref 7. This approach breaks down a typical mission for an aircraft into a number of simple manoeuvres. Obviously, the Wright aircraft were experimental and not too much can be expected from their performance. However, the ultimate goal was to create a practical airplane. The manoeuvres were selected carefully to address this without being unfair to the Wrights within the context of their period. A typical mission profile for such an aircraft would be take off, climb, level cruise, turn/manoeuvre, descent and land. Certain emergency situations such as engine failure were also considered. The 1902 machine, although a glider, prototyped most of the significant features of the 1903 Flyer and was analysed with the same procedure. By providing a continuous vertical wind of around 450-600 ft/min, the 1902 glider was able to sustain itself indefinitely in the tests. The 1903 Flyer model was also given slightly more engine power with a maximum of around 18-19 hp, a small increase over the historical value of 12-15 hp. This was done to give the pilot some margin in power as it was found that 15 hp was required to sustain the 1903 Flyer at trim condition of 26kts airspeed. This compares well with the analysis in Ref 8 which quotes the 1903 engine output at around 15.76 hp, reducing to 75% as the engine overheated after a few minutes running. The 1904 engine, which was a slightly improved 1903 engine, initially created 15-16 hp and reached 20-21 hp by 1905 when worn in. Certainly, the first flights in 1903 were successful due to a combination of low temperatures, high-density air, high winds, an under-estimation of the engine power available and possibly some ground effect reducing the power required. The 1904 machine was essentially the 1903 design with a reduced main wing camber ($1/20 \rightarrow 1/25$) and the new engine and it is felt that the FLIGHTLAB 1903 Flyer model results are especially relevant to the flights made with that machine.

Longitudinal MTE's

Figures 26 and 27 present examples of the manoeuvres performed to assess the handling characteristics in the longitudinal axis. Figure 26 shows the 1902 glider in a manoeuvre in which the task was to fly the aircraft down the edge of a runway tracking the runway/field interface and maintaining altitude. Specific desired and adequate performance standards were set for the heading, altitude and lateral position. The two different sets of data presented in figure 26 represent cases where either the height or the heading was regulated within tighter performance standards. This task was flown several times with two different c.g. positions and the pilot gave better HQR's when keeping tight control of heading rather than the height. This was probably due to the higher level of instability in pitch than in the lateral-directional axis. This is indicated by the increased activity in the canard control and greater pitch disturbances for the height tracking. Interestingly, although the onus was on the heading in the heading-tracking task the height is under good control and few deviations from

the mean value are visible. There is a separate rating scale known as the PIO (Pilot Induced Oscillations) rating scale (Ref 9). This aids the pilot in making a judgement on how much the pilot-vehicle system in the given task has tendency to oscillate and/or induce PIO's. the pilot awarded worse PIO ratings for the height tracking task. Again the tighter performance standards caused the pilot workload to increase and induced PIO's more often. The PIO was especially prevalent for the 1903 Flyer as shown in figure 27. With greater instability, the pilot workload was greatly increased just to maintain control and the probability for a PIO was high. In figure 27, two PIO's are seen within 40 seconds of each other, the second resulting in a loss of control with aircraft hitting the ground. The usual practice for recovering from a PIO is to release the controls. Unfortunately, this was not a viable option for the '03 Flyer as the aircraft would have continued to diverge and either stall or nose-dive into the ground.

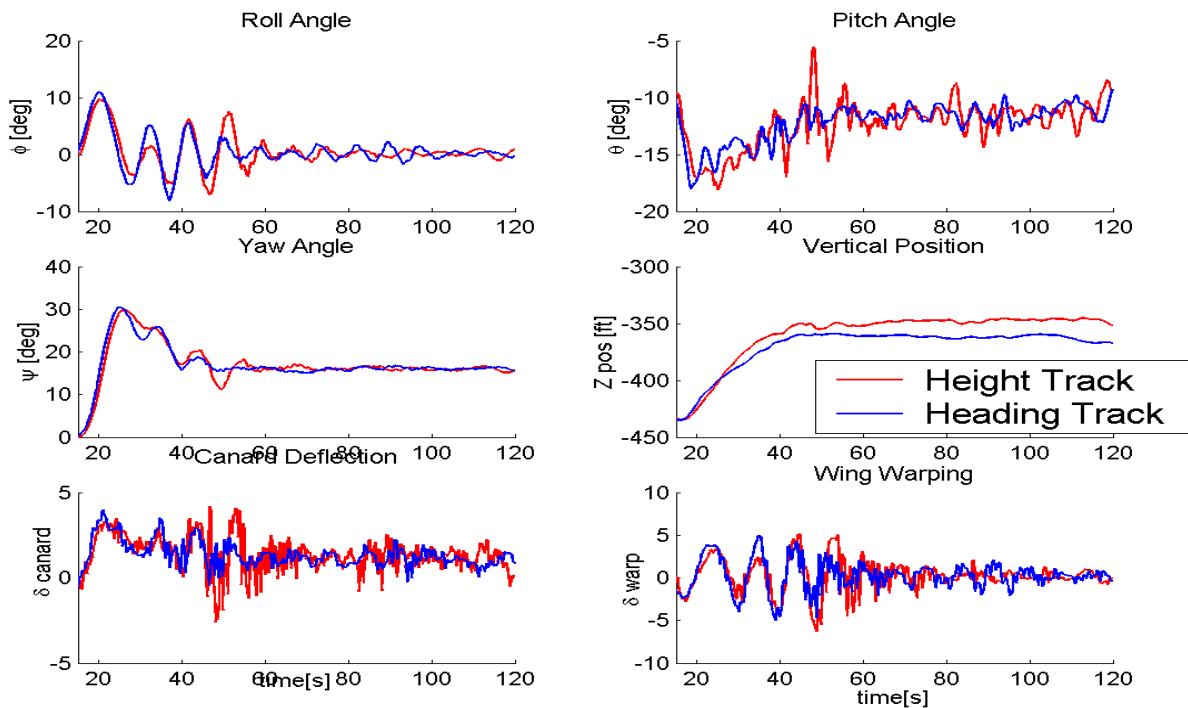


Figure 26 Piloted simulation trial – Height and heading tracking MTE, 1902 Glider

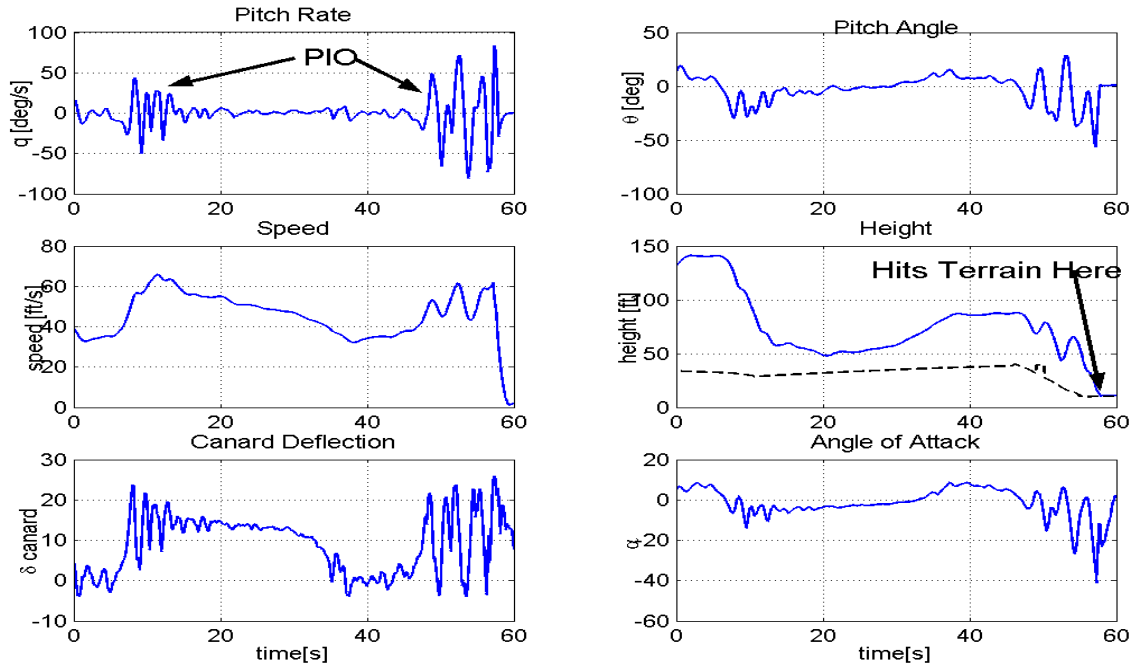


Figure 27 Piloted simulation trial – Longitudinal manoeuvre, 1903 Flyer

Lateral MTE's

The pioneering use of roll control by the Wrights revealed the most effective way to turn an aircraft. Previously in this paper it was shown that the instability in roll could be stabilised by closed loop control with the simple pilot model. Figures 28 and 29 show the turn performance of FLIGHTLAB 1902 and 1903 machines respectively. Figure 28 shows the 1902 glider turning with a steady roll angle of approximately 6° . The aircraft turns smoothly through a heading of 120° in around 20 seconds without any trouble. The strength of the spiral instability causes the pilot to hold reversed warp control ($+\delta_w \rightarrow$ negative rolling moment) to maintain the roll attitude. If the roll attitude were allowed to increase beyond small angles ($>10^\circ$), as depicted by the second trace (blue) in figure 28, the sideslip builds and forward speed is lost. The combination of these effects leads to the glider pitching up and sliding off at a high sideslip angle with the pilot losing control. This behaviour is also exhibited by the 1903 Flyer as shown in figure 29. In this instance, the pilot allows the roll angle to build rapidly in the turn. Likewise, for the 1902 glider the sideslip builds and the forward speed drops to 33 ft/s (19.5 kts). The angle of attack increases accordingly and causes a large pitch up motion. Just after the pitch up, the aircraft loses around 150 ft of altitude in 3-4 seconds. However, if the roll angles were kept to below angles of around $10\text{-}15^\circ$ then controlled turns could be made.

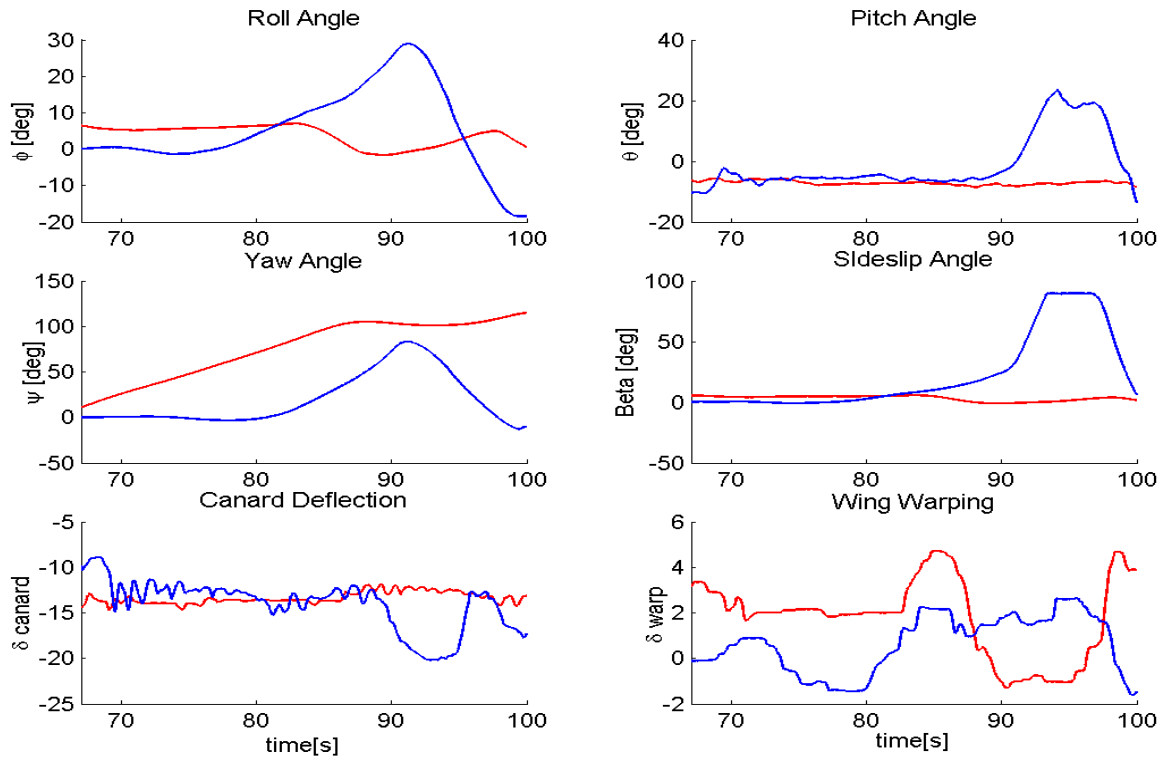


Figure 28 Piloted simulation trial – Turning MTE, 1902 Glider

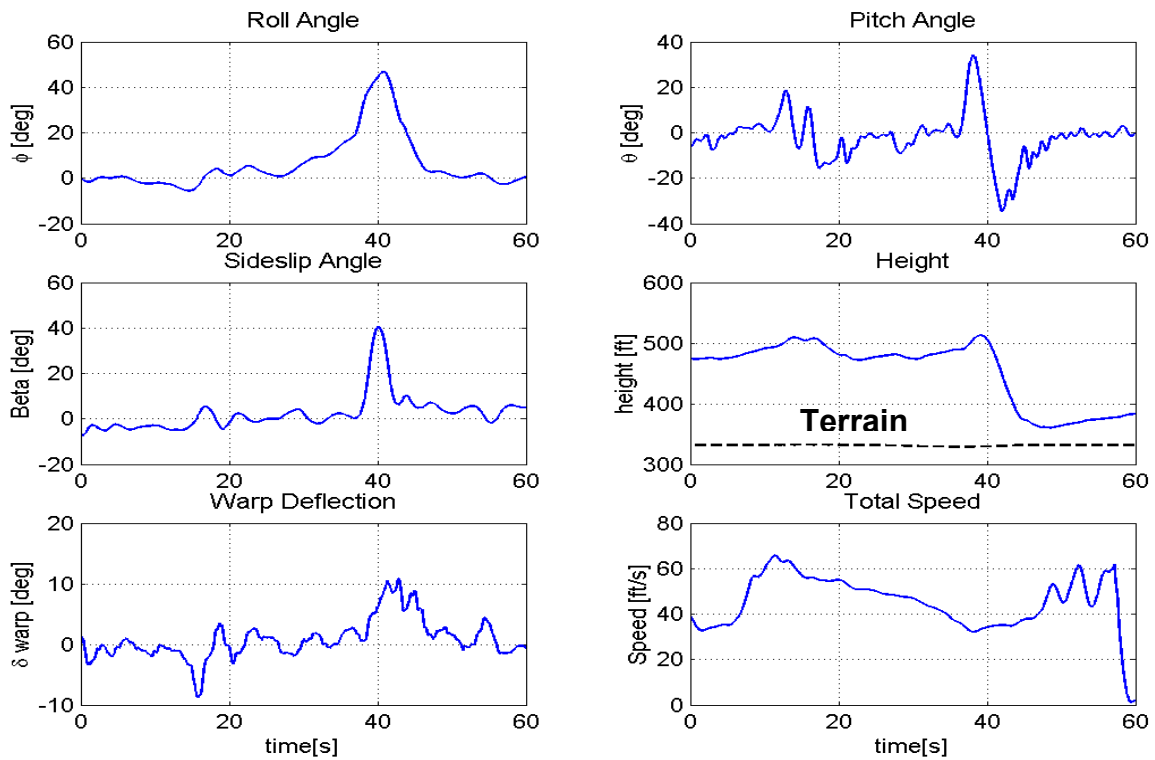


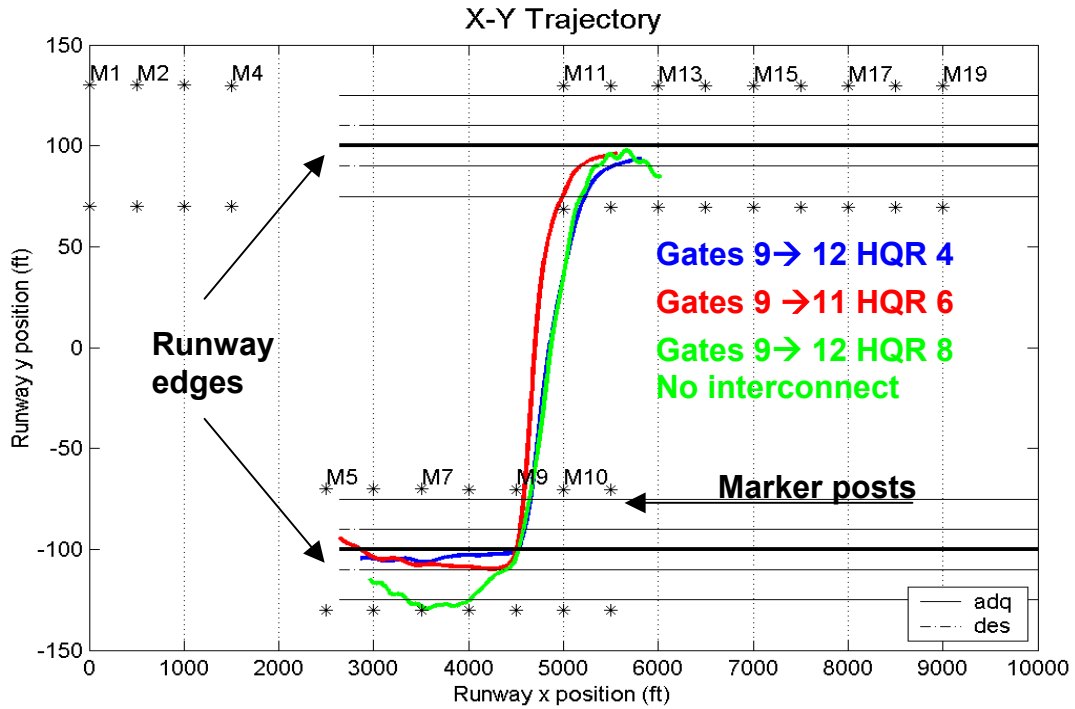
Figure 29 Piloted simulation trial – Turning MTE, 1903 Flyer

The difficulties in pitch and roll in the simulation trials are representative of what the Wrights experienced themselves. Orville noted on December 17th 1903 how the 4th and longest flight of the 1903 Flyer progressed with Wilbur at the controls: *“The machine started off with its ups and downs as it had before, but by the time he had gone over three or four hundred feet he had it under much better control, and was travelling on a fairly even course. It proceeded in this manner till it reached a small hummock out about 800 feet from the starting ways, when it began its pitching again and suddenly darted into the ground.”* Certainly, Wilbur was having difficulty controlling the instability of the Flyer -especially in the gusty conditions. From the description, he probably encountered PIO at least twice in the flight the last one resulted in a crash landing. This trend continued, and the Wrights records of their flight-testing in 1904 contain many instances of where the aircraft would ‘dart into the ground’. The Wrights began to realise that the source of the difficulty was related to the centre of gravity position. Initially they moved it further aft by shifting the engine and propellers back –an uncharacteristic error. Once they realised the mistake, 70 lb of ballast (Ref 10) was placed on the canard to shift the c.g. forwards and reduce the longitudinal instability.

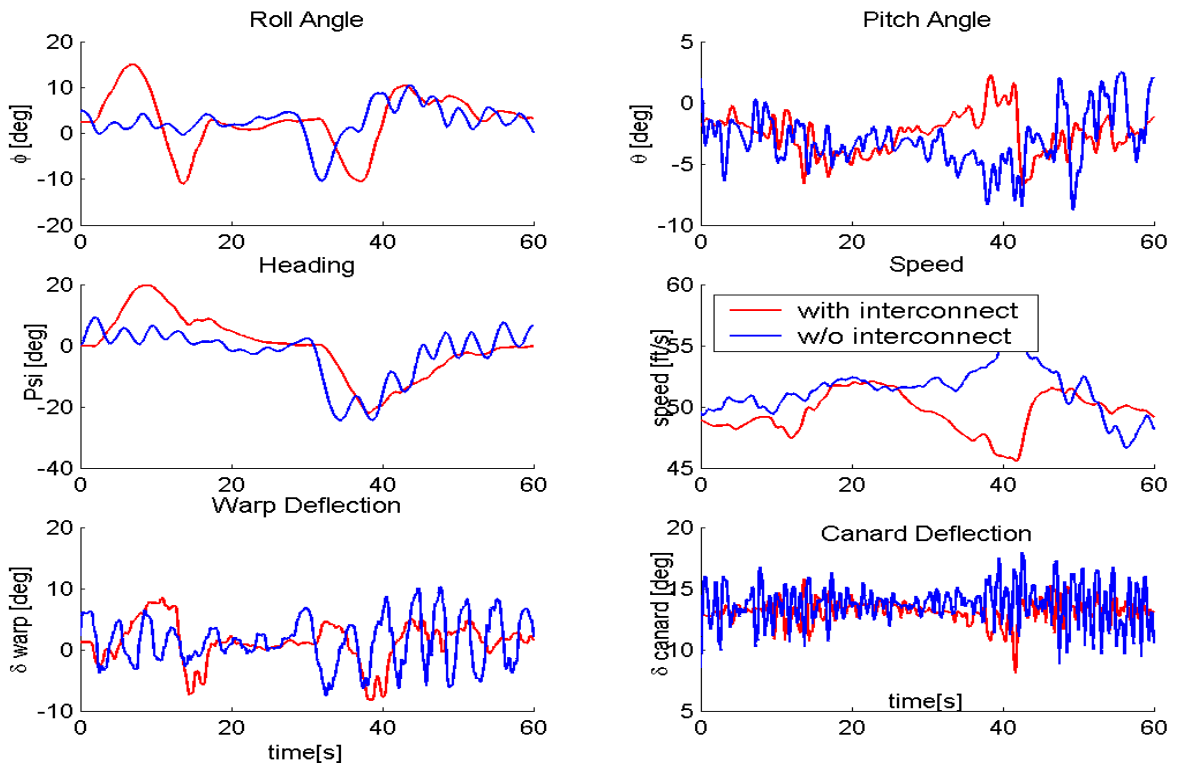
The Wright Brothers had never completed more than a 90° turn with the 1902 glider, mainly because they had to keep aligned with the prevailing winds. They never noted much difficulty with the unstable spiral mode in those turns; it is likely that this was because they kept the roll attitudes to a minimum. They never tried a turn with the 1903 Flyer machine –it was enough just to keep going straight and level. The problems started to arise with the 1904 Flyer 2. The Wrights completed many circles of their flying field at Huffman Prairie, Dayton, OH, and noticed the tendency for the aircraft to want to roll further into a turn – *“...Unable to stop turning & broke engine & skids & both screws”*. The pilot tried to counteract this tendency by using out-of-turn warp control, however, this also caused the rudder to deflect out of turn via the warp-rudder interlink system. The result of which caused the rudder to create a side-force tending to ‘push’ the aircraft further into the turn. These difficulties led to Wrights abandoning the anhedral angle for a dihedral angle in late 1904, reducing the sideslip in the turn.

Finally, figures 29 and 30 present some example results from the roll-step manoeuvre. This manoeuvre task was adapted from one used in a project assessing the handling qualities criteria for a future European civil tilt-rotor aircraft (Ref 11) and was designed to provide some insight into the lateral agility/manoeuvrability of the 1902 Glider and 1903 Flyer. The task consisted of flying down one side of the runway maintaining altitude and heading –much like the task described earlier in this paper, followed by a lateral side step to the other runway edge. The manoeuvre is marked out by gates numbered 1-19 and are placed at different locations either on the left or right-hand side of the runway. The pilot is then instructed to initiate the roll-step part of the manoeuvre after flying through a designated gate and then to align on the opposite runway edge after passing through another specified gate. Varying the gates to be flown between controls the level of aggression for the manoeuvre. The gates used in the Wright aircraft trials were either 9 through 12 or 9 →11, which were

respectively at 1000ft and 500ft gaps along the runway. The runway width was 200ft. Figure 30 shows three example runs using the 1903 Flyer simulation from a plan view. Two runs are using the standard configuration (red and blue) through gates 11 and 12 respectively and the final run (green) was made with the warp-rudder interconnect system disabled. The pairs of the lines bracketing the line representing the runway edges mark the performance standards for the lateral positioning of the aircraft. The inner pair are the desired and the outer ones the adequate standards. Referring to the flight handling qualities analysis, the higher aggression manoeuvres (i.e. Gates 9→11) were awarded worse HQR ratings due the pilot's increased workload. Overall, the 1902 glider and 1903 Flyer performed very similarly in the manoeuvre and the piloted commented that the predictability of the aircraft in roll control was low and that any large lateral manoeuvring tended to upset the pitch axis control, increasing the pilot workload. With the warp-rudder interconnect system enabled, desired standards are achieved at both aggression levels. When the system was disabled, the workload increased significantly. Figure 31 shows a comparison between the roll-step made with and without the interconnect system. The aircraft without the interconnect system oscillates in pitch, roll and yaw. The adverse yaw due to warp causes the oscillation in heading which the pilot attempts to reduce using the warp control. Without yaw control, the problem is accentuated. This yawing/rolling oscillation couples into the longitudinal axes in two main ways; firstly it disturbs the aircraft angle of attack causing changes in the pitching moment. Secondly, it diverts the pilot workload away from controlling the high pitch instability. The result was the pilot being unable to achieve the adequate performance standards and consequently awarding a HQR of 8. The interconnect system makes a difference in this high workload manoeuvre and ensures a reasonable level of control over the coupling between the roll and yaw axes.



**Figure 30 Piloted simulation trial – Roll Step MTE, 1903
 Flyer plan view (X position v Y position)**



**Figure 31 Piloted simulation trial – Roll Step MTE, 1903 Flyer with
 interlink on and off comparison**

CONCLUSIONS

The paper has described research underway at The University of Liverpool to develop a detailed understanding of the handling characteristics of the Wright Brothers aircraft. Simulation trials, using high fidelity models of the Wright aircraft, have uniquely recreated how the 1902 glider and 1903 Flyer may have flown. As expected, the two aircraft showed high levels of similarity in their handling qualities. Indeed, upon a successful circle with their 1904 machine Wilbur wrote, *“Since we have been making longer flights and getting more practice, the machine is becoming much more controllable and now seems very much like our gliders at Kitty Hawk.”* - a testament to the design pedigree. The flight-testing of the 1902 glider and the 1903/04 Flyers developed the Wright's concepts from a 2-axis control glider, through to the 3-axis powered aircraft. This experience not only developed their knowledge in aircraft design but also trained them as the world's first test pilots. They were extraordinary innovative and visual thinkers, and they could relate their piloting experiences to the engineering problems and solutions. Through the use of modern analytical techniques, this paper has been able to provide an insight into the flying qualities of the Wrights' 1902 and 1903 machines. Specifically, the longitudinal and lateral instabilities have been highlighted and both were shown to be controllable by the Wrights' unique system of control. The development of the 3-axis control system was the key to their success and is reflected in the trials by the level of manoeuvrability and the subsequent Handling Qualities Ratings awarded. Mostly Level 2 HQs were achieved (HQR 4-6), a surprising result when considering the subject aircraft. In summary the paper has highlighted the following key factors:

- a) The wind tunnel tests have quantified the performance increase from 1901 to 1902, that enabled the Wrights to fly at lower, more efficient, angles of incidence.
- b) The stability and control characteristics of the 1902 glider changed significantly with angle of incidence –therefore any simulation of this kind of aircraft needs a sufficient angle of attack envelope to account for these effects.
- c) From a control standpoint, the 1902 glider featured all the novel developments present in the 1903/04 machines developed through a program of flight tests at Kitty Hawk.
- d) The 1903/04 Flyer featured greater pitch instability than the 1902 glider, due to the addition of the propulsion system moving the c.g. aft.
- e) The lateral-directional control system of a warp-to-rudder interconnect was effective at counteracting adverse yaw and coordinating in entry into turns.

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BIOGRAPHIES



Ben Lawrence received his BEng (Hons) degree in Aerospace Engineering (2000) from the University of Liverpool, UK. Following that he became one of the founder members of the Flight Science and Technology research group in the University of Liverpool's Department of Engineering. He is currently studying for his Ph.D focusing on the Flight Handling Qualities of the early Wright Brothers' aircraft. Ben's research interests are oriented around simulation and flight dynamics and he is a key contributor in a number of simulation projects being conducted at the

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Gareth Padfield received a BSc(Hons) degree in Aeronautical Engineering at the University of London in 1969 and Ph.D in Flight Dynamics at Cranfield in 1976. During the intervening years he worked at Westland Helicopters as a stability and control engineer. He joined the Royal Aircraft Establishment in 1977 and during his 23 year career at the RAE/DERA, he specialised in helicopter flight research; his final position in DERA was the Air Systems Rotorcraft Chief Scientist. He was the UK lead for the TTCP collaboration on Handling Qualities and Helicopter-Ship Dynamic Interface

research from 1985 to 1999. Gareth Padfield took up the James Bibby Chair in Aerospace Engineering at The University of Liverpool in 1999, where he is Director the Aerospace Engineering School and leads the Flight Science and Technology (FST) Research Group in the Department of Engineering. His

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