Flight Handling Qualities of the Wright Brothers 1905 Flyer III

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The success of the first powered, controlled flights at Kitty Hawk on December 17th 1903 was a breakthrough in aviation, substantiating the Wright Brothers' research and design concepts. However, there was still much work to be done to improve the flying qualities of their aircraft to a standard suitable to be marketed to the world. The years 1903-05 represent this period where the Wrights evolved the design of their powered aircraft, culminating in 1905 with the Flyer III in which they were able fly significant cross country distances. The 1905 Flyer III was the Wrights first true practical design, flying 38km in 38 minutes - this was to be their last flight for nearly two years whilst they tried to sell their invention to the governments of the Europe and the United States. This paper reflects on that engineering challenge faced by the Wright Brothers and reports on recent research that analyzed the Wright aircraft using modern flight science techniques. This paper reports the challenges involved in developing simulation models of the Wright 1902 Glider and the 1903/04 and 1905 powered aircraft and assessing them in real time piloted simulation. This paper will focus specifically on the 1905 machine and uses results from wind tunnel tests, computational flight dynamics analysis and piloted simulation trials to look back at the evolution of the Wrights' designs 1902-1905. The critical innovation of flight-control and its effect on the handling qualities of the aircraft is an area, where the Wright brothers, devoid of any stability theory, strove to overcome the pitch and roll instability of their canard-configured biplane aircraft. The story of the Wrights technological journey is one of systematic analysis and clear, methodical development. They developed practices recognizable to modern aeronautical engineers and also became the first true 'test pilots'. This work acknowledges and celebrates the Wright brothers' achievements in this centenary of powered flight.

Nomenclature

$\mathbf{A}_{lat}$	=	*System matrix (lateral-directional)*
c.g.	=	*Center of gravity*
Cl	=	*Rolling moment coefficient*
C_{l_β}	=	*Non-dimensional derivative, rolling moment coefficient due to sideslip*
C_L, (C_{Lmax})	=	*Lift coefficient, (maximum)*
C_M	=	*Pitching moment coefficient*
C_n	=	*Yawing moment coefficient*
C_{n_β}	=	*Non-dimensional derivative, yawing moment coefficient due to sideslip*
g	=	*Gravitational acceleration*
H_n	=	*Static margin* ($\partial C_M / \partial C_L$)
HQR	=	*Handling qualities rating*
Kp	=	*Pilot gain, (Pitch attitude feedback)*
Lr, L_v, M_q, N_v	=	*Aerodynamic derivatives*

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MTE	=	*Mission Task Element*
PIO	=	*Pilot Induced Oscillation*
Re	=	*Reynolds number*
T_2	=	*Time to double amplitude*
$\mathbf{u}$	=	*Control vector*
u,v,w	=	*perturbation velocities along body axes*
V	=	*Flight velocity*
$\mathbf{x}$	=	*State vector*
$Y^{\theta}_{\delta c}$	=	*Transfer function between canard and pitch*
α	=	*Angle of attack/incidence*
β	=	*Angle of Sideslip*
λ	=	*Eigenvalue*
θ	=	*Pitch attitude*
ϕ	=	*Roll Attitude*
τ	=	*Pilot neuromuscular lag*

I. Introduction

On the 5th October 1905 Wilbur Wright brought the 1905 'Flyer III' into land. He had just run out fuel having completed around 30 circuits of their flying field at Huffman Prairie near the Wright family home in Dayton, OH. This was their longest flight yet, making 38km in 38minutes. This was no fluke; the Wrights had been steadily increasing the distances flown throughout late September and early October. Amazingly, this last flight had only ended because the Wrights had neglected to fill the fuel tank prior to takeoff! These achievements mark the 1905 Flyer as the world's first practical airplane (see figure 1).

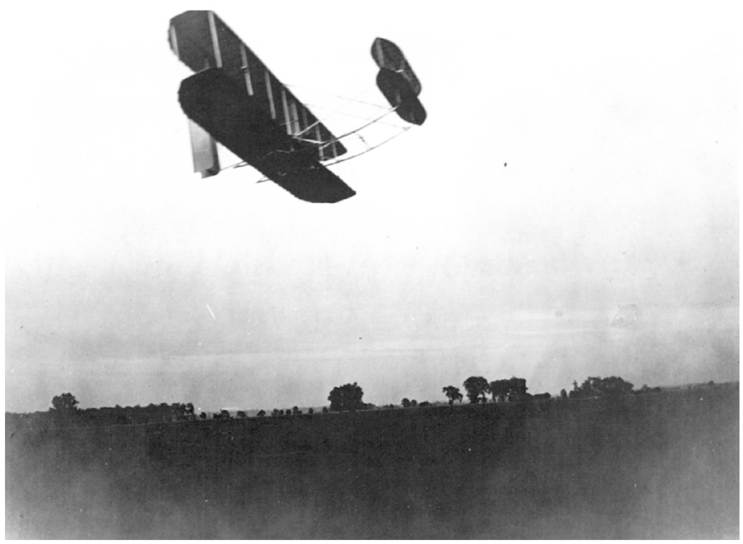


Figure 1 The 1905 Flyer in flight

To understand how this aircraft acquired this position in aviation history we must look back to the beginnings of powered flight in 1903. Between the first flights on December 17th 1903 and the fall of 1905, the Wrights conducted a program of flight-test and evaluation. During this period, the Wrights incrementally improved the flying qualities and performance of their 'Flyers'. This paper examines the 1905 Flyer and compares it to its predecessors: The 1904, 1903 Flyers and the 1902 glider. One of the most interesting features of this study is how the Wrights struggled to overcome the pitch instability of their 'canards'. We shall see that from 1903 through 1904 the Wrights consistently made the longitudinal flying qualities of their machines worse –it wasn't until mid-1905 that they managed to improve the situation. Also, the Wrights still had much to learn about lateral-directional control, they hadn't completed more than a ¼ circle in 1902 and flew in straight lines in 1903. By September 1904 they had completed their first circuit at Huffman prairie. However, once they had started making turns, they often struggled with the control, complaining that they were, *'unable to stop turning'* (Monday 26th September 1904)[1]. The Flyer was clearly exhibiting a strong spiral instability. This was partly due to the anhedral layout and partly due to what Fred Hooven[2] termed a 'stall turn', where the aircraft had insufficient lift to carry the additional centrifugal load generated in the turn. Moreover, Fred Hooven's paper of 1978[2] contains excellent analysis of the flying events post-1903. He poses the question 'why did the Wrights persist with the canard configuration?' His analysis looked at how the position of the centre of gravity and neutral point varied with each design modification and he also ran simulations to assess the dynamic stability in pitch. He draws two main conclusions: one was that the canard configuration was advantageous because it avoided the stall-dive typical of aft-tailed aircraft. This has been shown to be present on the 1902 glider from recent research conducted by the authors[3]. The second conclusion was that the Wrights were probably lulled into a false sense of security by the relatively benign stability characteristics of their gliders, in particular, the 1902 version. This paper will explore these subjects from a modern perspective using results from recent wind tunnel tests and piloted flight simulations. This analysis will demonstrate the handling qualities challenges faced by Wrights as well as evaluating the effectiveness of the improvements they made in 1903-1905.

II. The 1905 Flyer III

Figure 2 depicts the 1905 Flyer in its final configuration, with a biplane canard of approximately 84ft^2, a wing area of 503ft^2 and a weight of approximately 920lbs (including pilot, ballast and fuel) (*Wilbur and Orville Wright's Notebook O, 1908-1912, p.12)*[1]. The main wing camber was 1/20 – an increase from 1904 (1/25) but the same as 1903. The reason for this was not recorded but perhaps it was reinstated because of the Wrights confusion over the effects of camber. The Wrights first experience of these problems was with the 1901 glider. The glider initially had a very large camber of 1/12 which required an aft c.g. position to achieve longitudinal trim. This made the glider particularly unstable. Their fix was to reduce the camber, enabling a more forward c.g. position, thus reducing the instability. The Wrights never forgot this lesson but misinterpreted the situation. It wasn't the camber causing the instability but it the different c.g. positions that resulted. In 1902, their camber was reduced further and the stability was improved. By 1903, the camber increased again and the stability deteriorated again. The Wrights were probably very confused by this state of affairs. In 1904 they began to realize the truth, the 1904 Flyer had a lower camber than 1903, but the aircraft was still particularly unstable, possessing a tendency to '*undulate'*, as the Wrights would have put it. They attempted to remedy the situation by moving the center of gravity, but they had decided to move it further aft. Naturally, this made the problem worse. This was a turning point and from then onwards both the 1904 and 1905 Flyers featured ballast of up to 70lbs on the forward framing to move the centre of gravity forwards.

Another addition in 1905 was a pair of semi-circular vertical surfaces known as 'blinkers' in between the canard surfaces. These were designed to assist in preventing sideslip in turns. However, these were soon removed once it was discovered that these had a negative effect on the directional stability, especially in take-off. The aircraft was powered by the same engine as in 1904 which now produced 21HP. This turned two contra-rotating propellers that pushed the aircraft to speeds of 30-35mph.

Lateral control was performed by the Wright's wing-warping system which the pilot operated via a hip-cradle. At the beginning of the 1905 season, the hip-cradle also deflected the rudder via an interconnect system. Later, this was disconnected and the rudder was controlled by a separate stick whilst the Wrights were investigating why their aircraft could not be returned to level flight from tight turns.

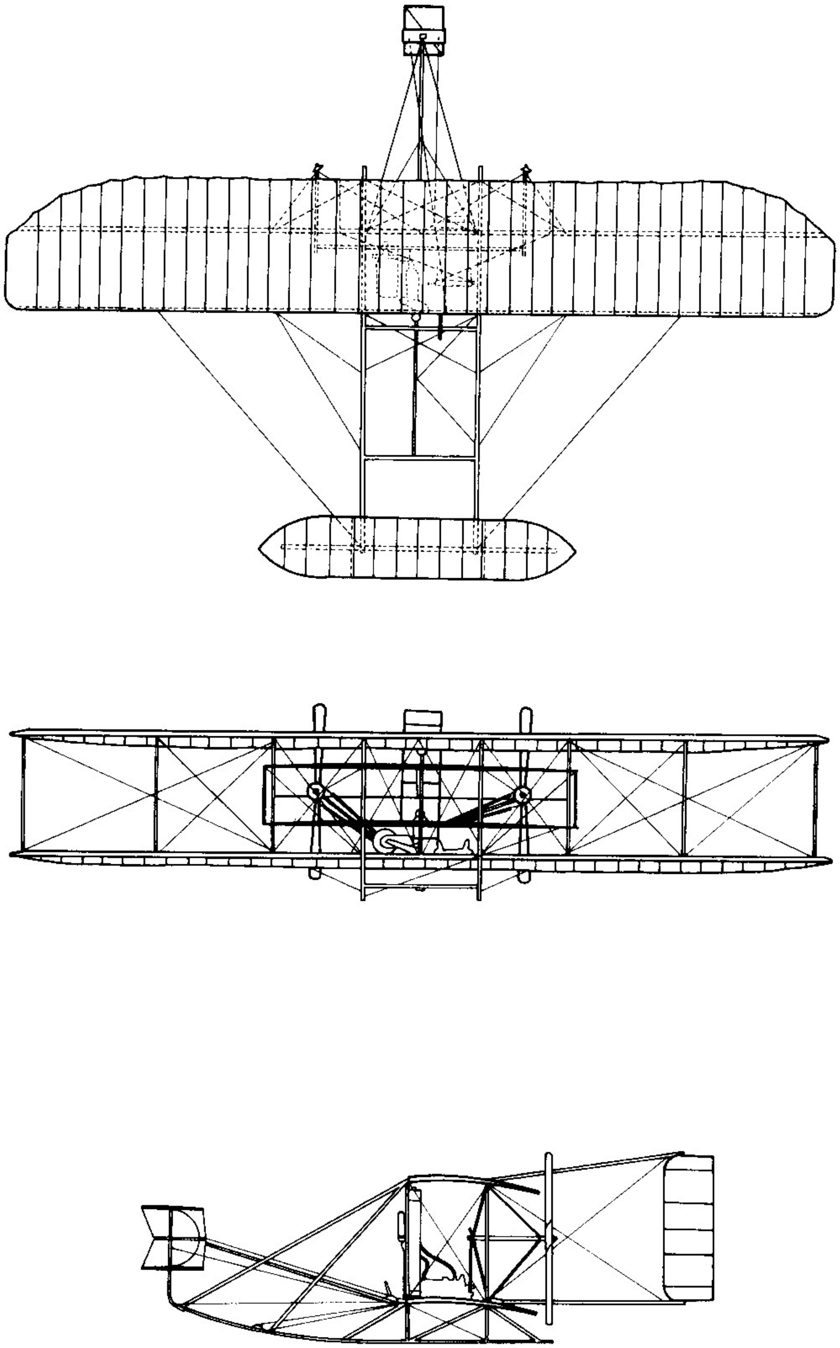


Figure 2 The 1905 Flyer

III. The Wright Brother's 1905 Flying Season

The flying began in 1905 with the Wrights experiencing many of the same problems as 1904. The main problem was controlling the aircraft in pitch. The Wrights were struggling to make flights of any distance. Wilbur writes to Octave Chanute ...*"We have accomplished nearly ten trials with the 1905 machine but have accomplished nothing notable as yet, the longest flight but only 750ft"*, [Letter to Octave Chanute, July 16th, 1905][1] – more than 100ft shorter than the longest flight the Wrights had made at Kitty Hawk in 1903. In fact, this letter was written two days after Wrights had made two crucial modifications to their machine: *"First fight. O.W. distance 568ft. time about 12sec….The machine seemed to steer all right laterally, but after attaining high speed began to undulate somewhat and suddenly turned downward and struck at a considerable angle breaking front skids, front rudder, upper front spar and about a dozen rib, and a lower front spar and one upright... In repairing machine a number of changes were made. Front rudder* [canard] *increased to about 84 ft and placed 12ft from front edge of machine…"*[Wilbur Wrights Diary F, 1905][1]. This was a scenario that the Wrights had already experienced several times in 1905 but the severe damage of this crash had clearly offered the Wrights an opportunity to make significant configuration changes. Afterwards, the Wrights began to improve their performances and soon started to make several flights of over 1km. Figure 3 shows the distances flown by the Wrights in 1905 with the major configuration changes highlighted. Generally speaking, with each modification there is a positive increment in the distances flown by the Wrights.

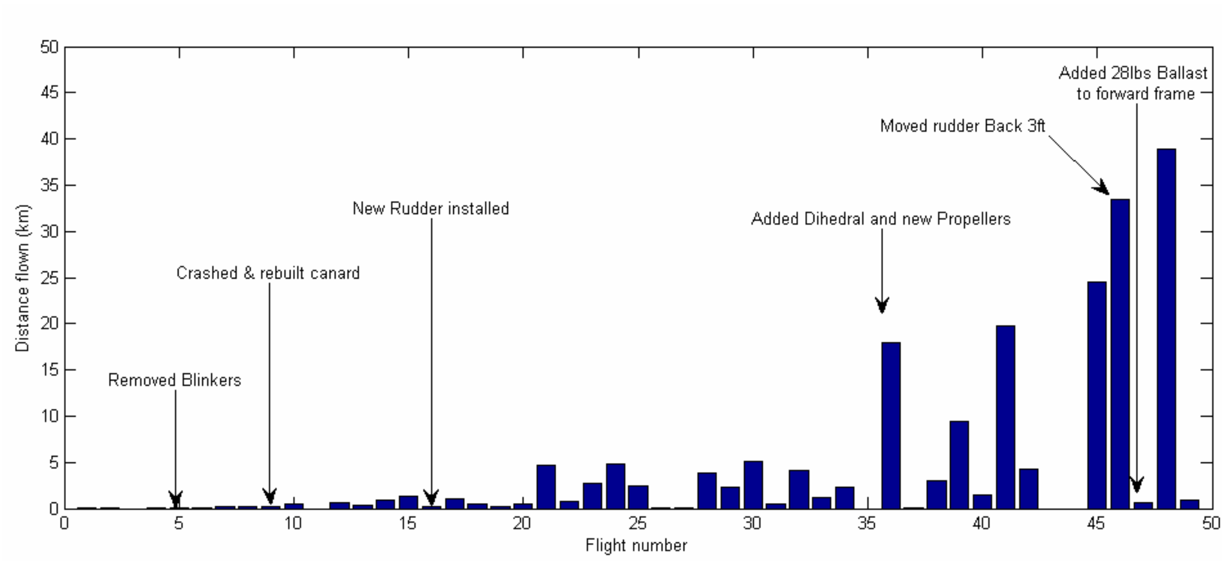


Figure 3 The Wright brothers' 1905 flights

IV. Aerodynamics of the 1905 Flyer – Wind Tunnel Results

As part of The University of Liverpool's Wright Brothers project a number of FLIGHTLAB simulations have been developed to examine flying qualities of these pioneering aircraft. In support of the simulation model development, computational aerodynamic models and wind tunnel experiments have been used to identify the aerodynamic coefficients. The most recent tests featured the 1905 Flyer III (see figure 4). The objective for these tests was to acquire the six-degree-of-freedom force and moment coefficients for a range of incidences and control positions for use in the computer simulations. The wind tunnel model featured a variable incidence canard that was simplified for the model. On the actual 1905 Flyer, the canard had a more complex system that varied the camber with incidence (figure 5). For the wind-tunnel model it was not feasible to implement this system from a structural and materials aspect so a parallelogram-type deflection was used to imitate the mechanics of the canard deflection. The effect of the canard flexure has been accounted for analytically in the simulations. The wings were flexible enough to allow wing-warping and the rudder could also be deflected.

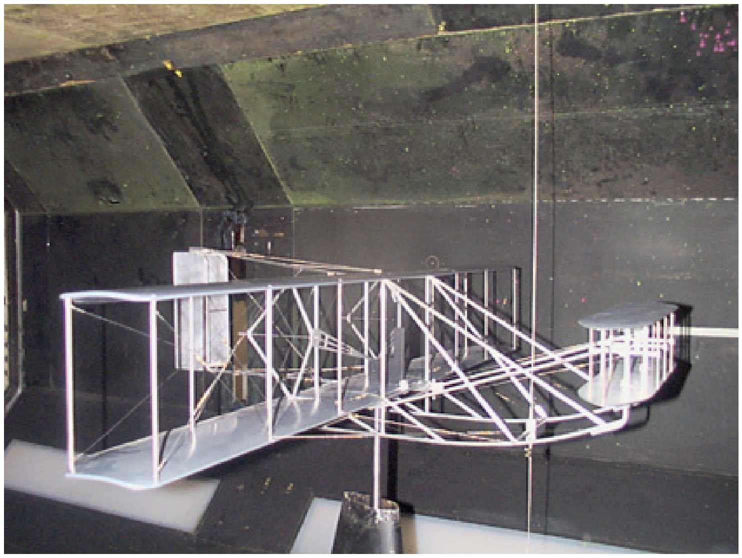


Figure 4 1/8th Scale 1905 Flyer Model in the University of Manchester's 9x7.3ft Wind Tunnel

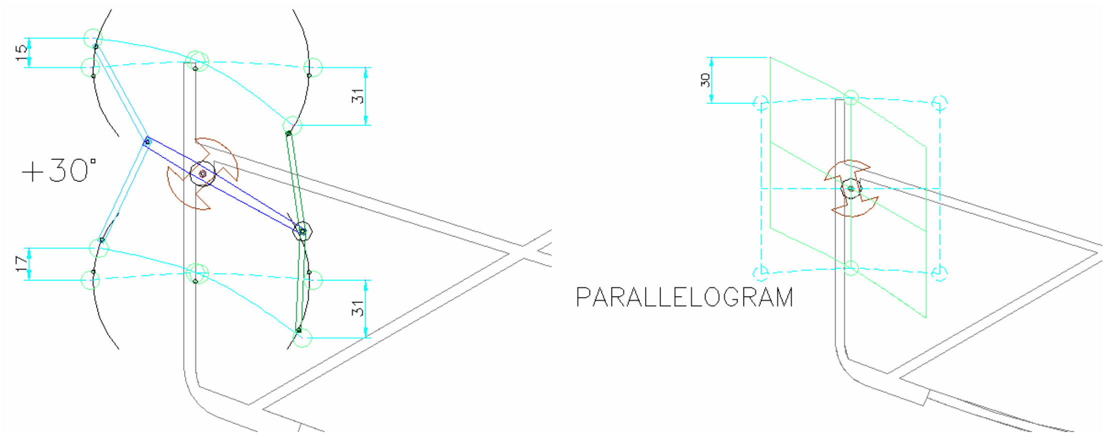


Figure 5 Left: Original canard mechanism, Right: Simplified mechanism

A. Longitudinal Results

The model was 1/8th scale which conferred a wingspan of 5.0625ft and chord of 1.3ft. The tunnel velocity was approximately 20ms^{-1} giving a Reynolds number of 0.53x10^{6} compared to full scale Reynolds number of 2.25x10^{6} (V=17ms^{-1}). Figure 6 shows typical lift characteristics for Wright aircraft with a 'flat top' to the curve. This is very similar to results from previous wind tunnel tests of the 1901 and 1902 gliders[3]; however the higher camber of 1/20 provided a greater $C_{Lmax} \approx 1.2$ than the 1902 machine. The lift stays virtually constant up to incidence angles of 20-25 degrees. This was an important safety factor for these aircraft because if too much airspeed was lost, then there was no drastic loss of lift and the aircraft could 'pancake land' from low altitudes. This situation often occurred for the Wrights where the aircraft would almost come to a stop in the air, would then 'stall' (the Wrights began to use this word in 1904)[1] and crash land – sometimes traveling backwards! In these situations it was important that the pilot could control the pitch attitude – and most of the time the Wrights could. Figure 7 shows the pitching moment characteristics for the 1905 Flyer (c.g. at 0.128c). The 1905 machine is unstable and displays a high degree of non-linearity, denoting changing static stability with incidence. At lower incidences ($\alpha < 5°$) the slopes are very steep and positive, but as the incidence grows the curves flatten out (reduced instability), as the lift on the destabilizing wing and canard reaches the maximum values. At very high incidences, the curves begin to increase again due to the high drag of the upper wing and canard causing a further increment to the nose-up pitching moment. Figure 7 also shows the effect of various canard deflections, showing an ability to maintain trim over quite a large incidence range (note: these results are for the non-flexing surface as in figure 5).

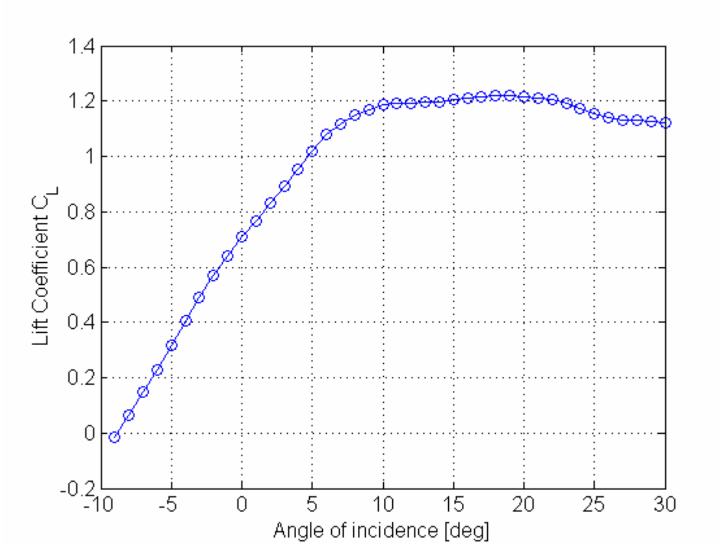


Figure 6 Lift coefficient v angle of attack, 1905 Flyer

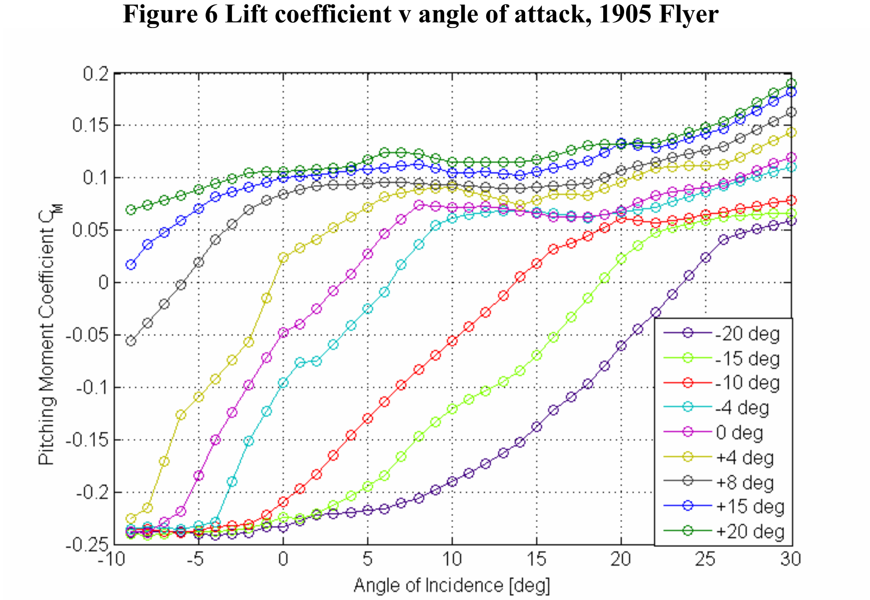


Figure 7 Pitching Moment coefficient v angle of attack and canard deflections, 1905 Flyer

B. Lateral Results

Near the end of the 1905 season (see figure 3) the Wrights installed some dihedral in the inner wing sections of their machine to add some roll stability. The 1905 Flyer model exhibited static stability in roll ($C_{l_\beta} = +0.00249$ rad^{-1}), although the model only featured straight wings as displayed in figure 2. However, it is likely that there was some upward deformation of the model's wingtips when under load. Another factor in creating the stable roll condition is the dihedral effect of the high wing relative to a low c.g. The 1905 Flyer is directionally stable, with a $C_{n_\beta} = +0.0403$ rad^{-1}, $[-16° < \beta < +16°]$. Results published by Jex, Grimm et al[4] showed the 1903 Flyer to have a $C_{n_\beta} = +0.0368$ rad^{-1}. Using these two sets of data, predictions for the characteristics for the earlier versions of the 1905 Flyer can made.

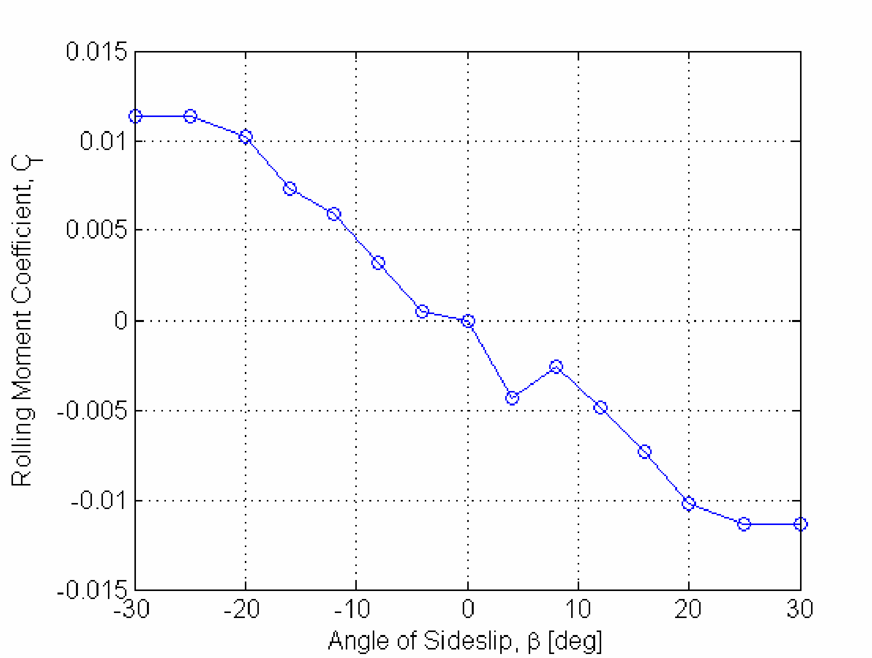


Figure 8 Rolling Moment Coefficient with sideslip, 1905 Flyer

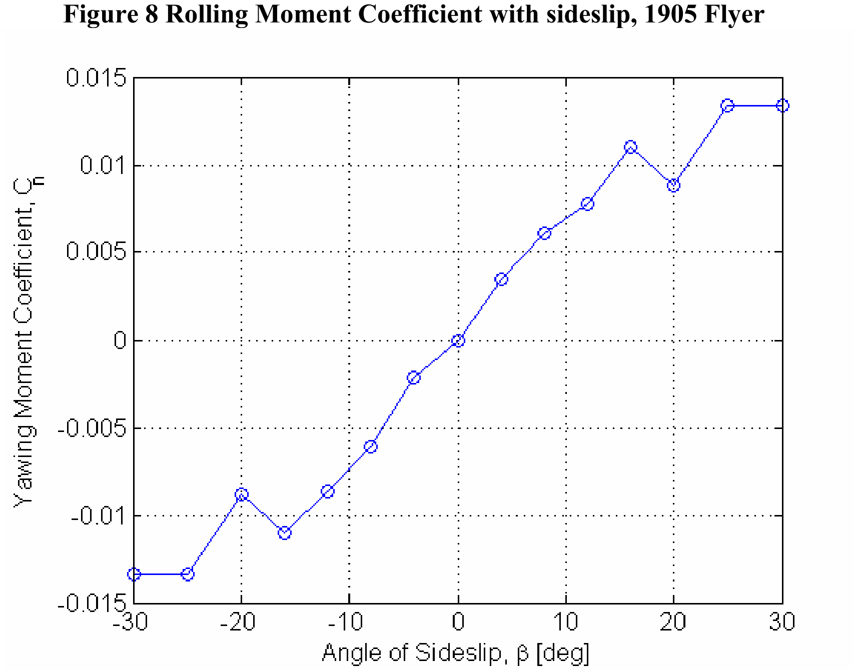
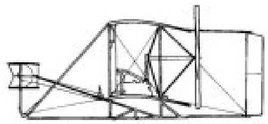


Figure 9 Yawing moment coefficient with sideslip, 1905 Flyer

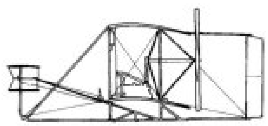
Figure 10 shows how the 1905 Flyer evolved, starting out much like the 1903 and 1904 versions, with the addition of the blinkers between the canard surfaces. With a total area of 7 ft^2 the blinkers certainly would have an adverse effect on the directional stability. What is unclear is whether the blinkers only appeared on the earlier shorter nosed version of 1905 machine, and not the long nosed version of the 1905 Flyer as drawn in figure 2. The drawing of figure 2, from McFarland[1], made in 1949 is of a restored 1905 Flyer kept at Carilllon Park, Dayton, OH. A photograph of this machine made in the 1950's shows the blinkers installed. However, the pictures from the Wrights experiments only show the blinkers on the early short-nosed version. In the short-nosed version, the blinkers have been estimated to generate a $\Delta C_{n_\beta} = -0.0085$, reducing the total C_{n_β} to 0.0297 (based on 1903 measurements of C_{n_β} [4]). The further lateral-directional changes are considered in figure 10 with estimations of the effect on the directional stability.



1905 version #1. Small canard, short tail, small vertical surface and blinkers.

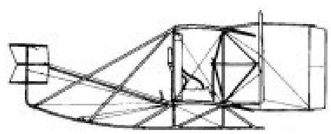
$\Delta C_{n_\beta} = -0.0085$ (Due to blinkers)

$C_{n_\beta} = 0.0297$



1905 version #2. Small canard, short tail, small vertical surface blinkers removed.

$C_{n_\beta} = 0.0364$ (As 1903)

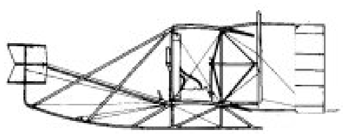


1905 version #3. New large canard, short tail, small vertical surface, no blinkers.

$\Delta C_{n_\beta} = -0.0423$ (No large tail)

$\Delta C_{n_\beta} = +0.0165$ (1903-like tail)

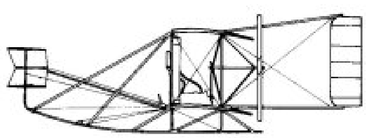
$C_{n_\beta} = 0.0145$



1905 version #4. New large canard, short tail, Larger vertical surface, no blinkers.

$\Delta C_{n_\beta} = +0.0122$ (larger tail 34.8ft^2)

$C_{n_\beta} = 0.0267$



1905 version #5. New large canard, Long tail, Larger vertical surface, no blinkers.

$\Delta C_{n_\beta} = +0.0136$ (Tail back 3ft)

$C_{n_\beta} = 0.0403$

Figure 10 Evolution of 1905 Flyer, June-Oct 1905

Often, a correlation can be seen when comparing the configuration changes to the Wrights' diary descriptions of their flights. For example, flights 1-4 were beset by problems with the lateral directional control. The Wrights identified the problem as the presence of the blinkers combined with an over-balanced rudder. The removal of the blinkers should have given a configuration similar to 1903 and 1904 where there were no reports of directional problems. It seems that although the blinkers were adding to the problem, the overbalanced rudder was the major problem. Further into the experiments, it appears that the new, larger canard had a destabilizing effect that made the configuration with the long-nose and original tail the least stable directionally. Referring to the Wrights diary entries, flights 10-15 were made with this configuration and all but one featured problems. However, none of these specifically identified the tail as a problem. Frustratingly, the sole piece of information that Wilbur wrote was: *"…Made complete circle and landed at starting point. Found the rear tail apparently too small…"*[1] The Wrights subsequently enlarged the fin, and, after a few flights (#16-19) where they had problems with an over-balanced rudder control again, they began to make significant improvements.

V. Flight Dynamics

A. Longitudinal Flight Dynamics

The analysis of the aerodynamic data has showed us that the 1905 Flyer was unstable in pitch, this is no surprise, but what is interesting is that even in its final form, the 1905 Flyer has a greater static instability than the notoriously unstable 1903 machine. This is calculated by measuring $\partial C_M / \partial C_L$. This is known as the Static Margin, H_n, the non-dimensional distance between the centre of gravity and the neutral point. The 1905 Flyer, with a c.g. position of 12.8% chord (from leading edge), showed an average $H_n=0.288$ ($C_L=0.2\text{-}1.2$) whereas the 1903 Flyer had an average $H_n=0.24$ ($C_L=0.3$-1.2, c.g. @ 30% chord)[4], the greater the value the greater the static instability. Despite this, the 1905 Flyer was an easier aircraft to fly. Even when accounting for the extra practice the Wrights had accumulated, why was this? The canard's more forward position and larger size is the key. Although this made the aircraft more statically unstable, it also increased the damping in pitch[5] and the pitch control power.

Using the FLIGHTLAB simulations the dynamic stability has been analyzed. In particular, figure 11 shows the root locus of the feedback of pitch attitude to canard angle for the main versions of Wright aircraft 1902-1905. The root locus shows the movement of the closed loop poles as the gain, K_p is increased. This is analogous to a simple pilot model where the pilot makes a proportional canard control input in response to a perceived error in pitch. All the aircraft display a single unstable open loop pole (marked by crosses) to the right of the y-axis. These poles represent a non-oscillatory divergence – essentially the unstable pitch mode. The application of feedback stabilizes these unstable modes by bringing the poles to the left-half plane. By increasing the gain, the other modes also move, and for the 1902 glider, two non-oscillatory modes combine to form an oscillatory mode that increases in frequency with increasing gain. The powered Flyers however, all have an open loop oscillatory mode of relatively low damping and medium frequency (1-1.5 rad.s^{-1}). These modes tend to migrate towards the stability boundary as the gain increases even crossing and becoming divergent for the 1904 Flyer with the c.g = 0.3358c. This mode represents the undulations or oscillations that the Wright canards exhibited when in flight. We can see that the Wrights struggled to overcome this instability from 1903 onwards. The 1902 glider was fairly manageable, but in 1903, the Flyer I was extremely unstable. Early in their 1904 season, the Wrights moved c.g. back a further 3 inches in an effort to reduce the oscillations only to discover that this was wholly incorrect. In response, the forward framing was ballasted with 70lbs to move the c.g. 5 inches forward of the original position, thus reducing the instability.

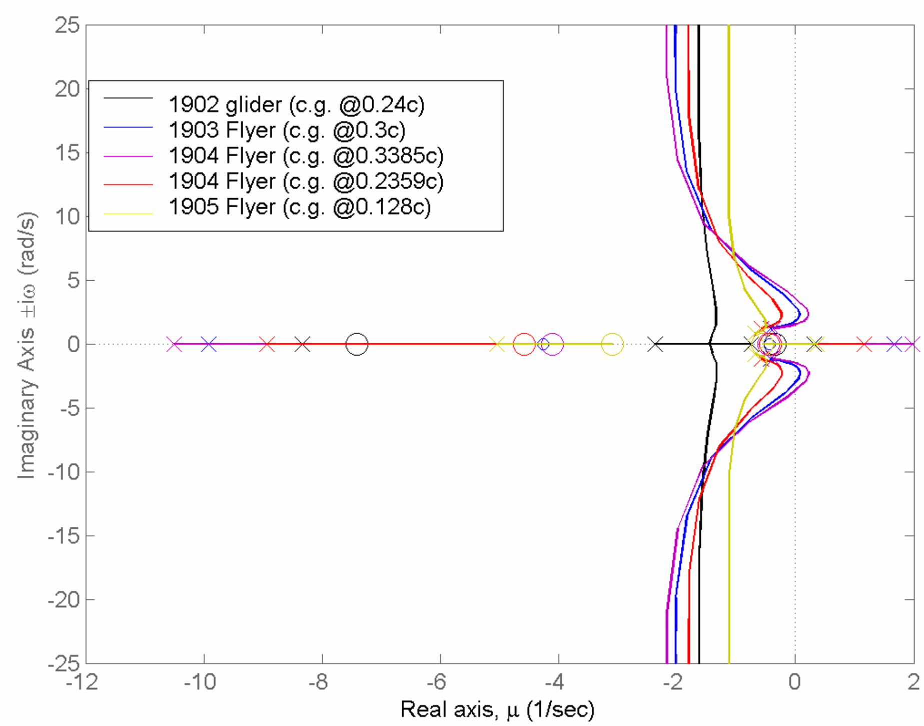


Figure 11 Closed Loop Stability of Wright Aircraft 1902-1905 (All 26kts except 1902, 24kts)

By the end of the 1905 season, the enlarged canard and 28lbs of forward ballast resulted in the most dynamically stable Flyer so far and figure 11 reflects this. It also depicts how the second oscillatory mode does not approach as close to the y-axis as the closed-loop gain is increased meaning that the oscillations induced by the closed loop control has greater damping and is less unstable.

Although this model of the closed loop behavior of the aircraft is relatively simplistic it gives a good impression of the controlled flight dynamics of these aircraft and the level of workload required to keep them under control. An interesting extension to this model is to introduce the effect of pilot delay. The original feedback used an assumption that the stabilizing input was made instantaneously; a real pilot cannot accomplish this feat due to what is known as ‘neuromuscular delay’. This delay represents the time elapsed during which the pilot perceives, processes and then acts on any attitude error. A reasonable estimate of this parameter is approximately τ=0.2s[6]. This parameter forms part of the ‘crossover model’ of human pilot behavior[7]. Equation 1 shows the transfer function describing this model. It comprises of the pilot’s neuromuscular lag and a separate lead and lag, T_1 and T_2, which the pilot adjusts when trying to control the aircraft.

$$Y_{\delta_c}^{\theta} = K_p e^{-\tau s} \frac{T_1 + 1}{T_2 + 1} \tag{1}$$

As before, K_p represents the pilot gain. Ignoring the pilot lead and lag, figure 12 shows the effect of the pure delay on the migration of the modes, in this case comparing the 1903 and 1905 Flyers. It can be seen that the application of feedback still stabilizes the unstable mode, but now the oscillatory modes move towards the stability boundary and continue to move right with increasing gain. A gain of $K_p=0.8$ has been highlighted in figure 12 to show that even with delay, the 1905 Flyer modes are stable. For the 1903 Flyer, the same gain stabilizes the unstable open loop mode but drives the oscillatory mode unstable. In terms of flying qualities, this means the 1905 Flyer was more forgiving. Pilot delay is inevitable, but in reality, can be counterbalanced by the pilot’s lead inputs. However, lead inputs are strongly linked to pilot workload. Generally speaking, the more lead required, the greater the workload[6]. Considering this, the 1903 Flyer would have required a greater workload which, in a high gain situation, could have lead to a PIO and loss of control.

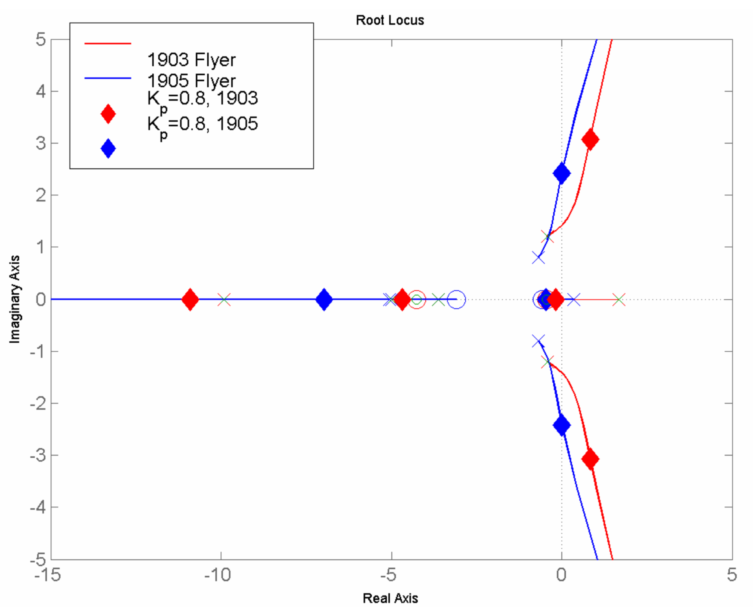


Figure 12 Root locus of pitch attitude feedback with pilot time delay, 1903 and 1905 Flyers

As stated earlier, the improvement in longitudinal stability comes from the increases in pitch damping and pitch control power. The damping in pitch in non-dimensional form is C_{m_q}, this is mainly dominated by the canard’s changing lift with pitch rate, with some contribution from the main wings. For the 1903 Flyer, C_{m_q} has been estimated to be approximately -1.53[8]. Using the wind tunnel data and Vortex-Lattice computations C_{m_q} has been computed to approximately -2.62 for the 1905 machine. This is a significant increase, more than 1.5 times the 1903 value. In comparison, Culick and Papachristodoulou[5] have estimated C_{m_q} = -4.67 for the 1905 machine, offering even greater increase. In its dimensional form, M_q, the contribution to the pitch stability can be assessed by examining equation 2.

$$\lambda^2 - (Z_w + M_q)\lambda + Z_w M_q - M_w (Z_q + U_e) = 0 \tag{2}$$

This equation represents an approximation to the Short Period mode[3], the solution for which is given by equation 3:

$$\lambda = \frac{\left(Z_w + M_q\right) \pm \sqrt{-\left(Z_w + M_q\right)^2 + 4\left(Z_w M_q - M_w (Z_q + U_e)\right)}}{2} \tag{3}$$

What can be clearly seen is that M_q, which is normally negative in sign, has a direct relationship to the real part of the mode represented by λ. Consequently, the time to double amplitude of the unstable mode is directly linked to M_q via equation 4.

$$T_2 = \frac{\ln 2}{\lambda} \tag{4}$$

This is the cause for the 1905 Flyer, although possessing a greater negative static margin, to have T_2*=2.192s* (λ*= 0.3162)*. This is compared to the 1903 Flyer that has a T_2*= 0.41s* (λ*= 1.6861)*. The increase in the time to double-to-double amplitude is significant, a five-fold increase.

B. Lateral Flight Dynamics

The improvement in the longitudinal flying qualities was probably the most significant to the Wrights progress in 1905 but there were also modifications to improve the lateral-directional characteristics. As discussed earlier the 1905 Flyer was shown to be statically stable in roll and yaw. Again, we can use the simulations to investigate the lateral dynamic stability. Of particular interest is the spiral mode, many times during 1904 and 1905 the Wrights complained that they were unable to stop turning. This implies that full control was applied to return the aircraft to a wings level condition yet the aircraft would not recover. For a 26kts (30 mph) nominal flight condition the eigenvalues of the linearised model in equation 5 are as follows:

Lateral A matrix $\mathbf{x} = [v\ p\ r\ \phi]^T$
units : [ft/s, radians/s, radians/s, radians]

$$A_{Lat=} \begin{bmatrix} -0.3473 & 0.9570 & -42.1176 & 32.1890 \\ -0.0121 & -3.6021 & 1.8799 & 0 \\ 0.0304 & 0.4962 & -0.6880 & 0 \\ 0 & 1 & -0.0235 & 0 \end{bmatrix} \tag{5}$$

Eigenvalues:

-3.8984 (Roll Mode)
-0.4944 + 1.2038i (Dutch Roll)
-0.4944 - 1.2038i (Dutch Roll)
0.2499 (Spiral Mode)

The real positive root is the Spiral mode, which is a mode featuring a complex coupling of the roll, yaw and sideslip motions. In this mode the roll and yaw stability act against each other, if the roll stability dominates than usually the spiral mode is stable, and vice-versa if the yaw stability is stronger. The latter is the case for the 1905 Flyer where the directional stability causes an unstable spiral mode despite the stable roll mode. A useful approximation to the Spiral mode is given in equation 6[3].

$$\lambda_s = \frac{g}{L_p}\left(\frac{L_v N_r - N_v L_r}{V N_v + \sigma_s L_v}\right) \tag{6}$$

$$\text{Where } \sigma_s = \frac{g - N_p V}{L_p} \tag{7}$$

Using this approximation we can compare the approximations to the 'exact' values as well as assessing the influence of the various stability derivatives. Equation 6 gives λ_s = 0.3184, a reasonable approximation. Furthermore, in the numerator of equation 6 we can see the balance between the roll and yaw static stability, represented by L_v and N_v respectively. In this expression N_v is multiplied by L_r, the rolling moment due to yaw rate derivative, which tends to dominate the approximation. It is this effect that causes the pilot to hold out-of-turn stick, as the outer wingtip has a greater velocity and therefore lifts higher whilst the inboard tip is at lower speed and drops. As the aircraft rolls it will sideslip toward the lower wing and causing into–turn yaw due to the directional stability. For the Wrights, the problem was even greater for two reasons: Firstly, their warp-rudder interlink system caused the rudder to generate more into-turn sideslip when the pilot held out-of-turn warp, pushing the aircraft toward the lower wingtip. Secondly, if the Wrights started a turn at too low a speed the additional centrifugal load could have potentially stalled the inboard wingtip. This is because the inboard wingtip would have been at higher incidence due the increased warp. This would have caused high drag and thus a strong adverse yawing moment whilst generating little lift increment to raise that wingtip. The Wrights found solutions to both: First by making the rudder independent - their first true 3-axis control system. The second was overcome by learning to dip the nose in a turn to keep the airspeed up and reduce the overall incidence on the wing. Once they applied this procedure they were able to level the wings from a turn before the aircraft sank to the ground.

VI. Flight Handling Qualities Analysis

So far we have discussed several of the aerodynamic and flight dynamic characteristics of the 1905 Flyer. By comparing this with some of the previous Flyers, the analysis has been able to quantify the effect of many of the improvements that the Wrights made. However, their ultimate goal was to make the Flyer into a useful, practical airplane. One approach in assessing the success of such an endeavor is to use the methodology of modern handling qualities theory and practice to make a subjective appraisal of the aircraft. The principle of flying or handling qualities did not exist at the time of the Wrights but certainly it is not unreasonable that the aircraft should be expected to be flyable within reasonable levels of skill and be able to perform a set of pre-requisite tasks. Indeed, just a few years on from 1905 in 1909, the Wrights were engaged in developing a Flyer for the US Signal Corps. As part of the procurement process the US government set out a set of what might be considered basic 'handling qualities requirements' these were US Signal Corps specification [No.486]. Summarizing, the document goes onto specify for an aircraft that could carry a pilot and one passenger, carry fuel for a range of 125 miles and possess a target speed of 40mph. It terms of the operational capability of the aircraft, it was also required that the aircraft:

- *'remain continuously in the air without landing'* [over a 1 hour trial flight],
- *'It shall return to the starting point and land without any damage that would prevent it starting upon another flight'*
- *'During this trial of one hour it must be steered in all directions without difficulty and at all times under perfect control and equilibrium'.*
- *'It should be provided with some device to permit of a safe descent in case of an accident to the propelling machinery'*
- *'It should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time.'*

There were also a number of other specifications regarding the transporting and assembly but these last few requirements are probably the most interesting from a flight control standpoint. The only comment on the required flying qualities of the aircraft states that the aircraft should be: *'steered in all directions without difficulty and at all times under perfect control and equilibrium'*. The role that the Signal Corps would have used the aircraft for lead us to a conclusion that, at minimum, the aircraft should be capable of a take off, a climb, level cruise, turn/maneuver, a descent and landing under safe control[9]. This breakdown of the maneuvers or tasks that might be expected of the machine fits comfortably with today's concept of the handling qualities Mission Task Element or MTE. The premise of the MTE is that a particular mission or role of an aircraft is subdivided into well-defined maneuvers with a corresponding set of performance standards. The standards have desired and adequate levels of performance for the parameters considered critical for a particular MTE. The parameters can be aircraft states (i.e. pitch, roll attitudes, speeds, angular rates etc), spatial position (position relative to a track or marker) or the time to complete the given task. The pilot's assessment of the aircraft's performance in the MTE was obtained using the standard Cooper-Harper rating scale[10].

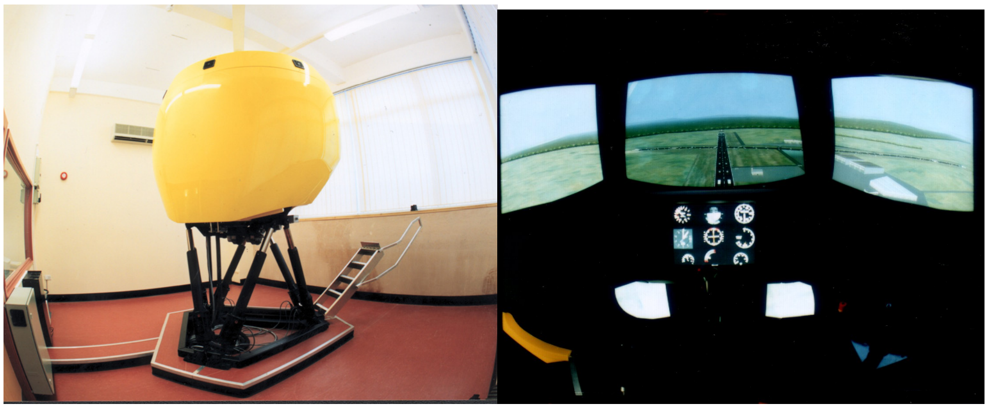


Figure 13 External and internal views of University of Liverpool Flight Simulator

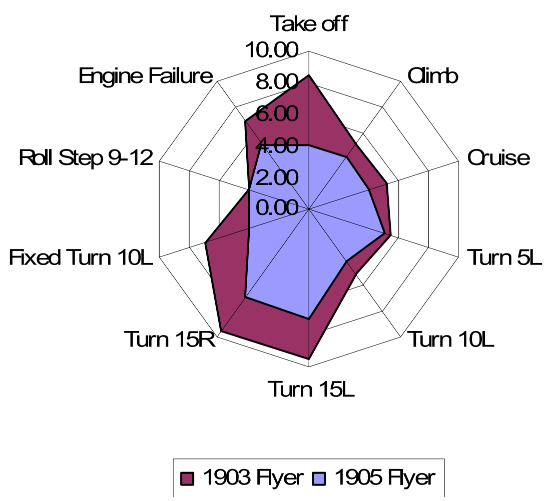


Figure 14 HQR's for variety of MTE's 1903 and 1905 Flyers

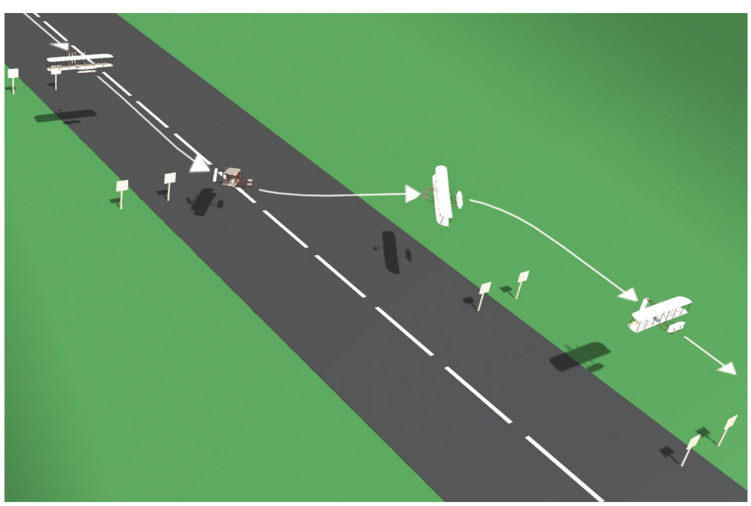


Figure 15 General layout for the roll-step MTE

Over the past years a number of piloted simulation trials have been conducted on the University of Liverpool flight simulator (Figure 13). The simulator features 6 degree-of-freedom motion and 135° horizontal field of view (see Padfield and White[11]) combined with reconfigurable scenery and FLIGHTLAB simulation models. The non-linear FLIGHTLAB simulations of the 1903 Flyer and 1905 Flyer were flown using test pilots who used conventional flight controls (centre stick, throttle and pedals) in a number of handling qualities trials where the aircraft were exercised through a number of MTE's. Figure 14 shows a 'radar' plot of the HQR rating for the MTE's, the higher rating (worse), the further along the arm the rating is plotted. It must be noted here that the dataset is for a limited number of pilots (2) and sorties but a good impression of the relative performance can already be obtained. The MTE's cover most of the possible flight tasks that such an aircraft would have to undertake including turns of varying bank angles and types (Fixed turns were a task the pilots were required to follow a fixed circular path on the ground as though they were circling a target of observation). Other MTE's including a roll-step[12] (see figure 15) which was a lateral-directional maneuver that tested the aircraft's accuracy as well as agility and emergency landing following an engine failure. This last MTE was selected with consideration to the Signal Corps specification '*It should be provided with some device to permit of a safe descent in case of an accident to the propelling machinery'*. Each of the MTE's were given a set of performance standards (table 1) that were set to give a reasonable expected level of accuracy and performance for the times.

Mission Task Elements (MTE's)	**Overall Description**	Desired	Adequate
Take off	Accelerate along runway to take-off speed. Lift-off and maintain heading and pitch attitude. Once airborne enter into climb phase.	± 5° Heading ± 5° Roll	± 10° Heading ± 10° Roll
Climb	Set Climb rate and maintain heading climb to 250 ft.	± 5° Roll ± 5° Heading ± 3kts speed	± 10° Roll ± 10° Heading ± 6kts speed
Cruise	Set Cruise speed and trim whilst maintaining Heading and altitude	± 25 ft Altitude ± 5° Heading ± 3kts speed	± 50 ft Altitude ± 10° Heading ± 6kts speed
Turn 1	Enter a steady turn of 5, 10 or 15° roll angle, maintain bank angle and height until instructed to end turn maneuver.	± 25 ft Altitude ± 3° Roll Attitude ± 3kts speed	± 50 ft Altitude ± 6°Roll Attitude ± 6kts speed
Emergency engine failure and landing	Touchdown on runway	Subjective assessment of Handling Only	
Roll Step	Follow slalom Track down runway maintaining altitude and lateral position flying through specified gates	± 10 ft lateral position ± 25 ft altitude	± 25 ft lateral position ± 50 ft altitude

Table 1 MTE performance standards

Further inspecting figure 14, some general trends can be identified. For example, for both aircraft the HQR's degrade with increasing bank angle. Also it can be seen that maneuvers with lowest HQR's for the 1903 machine were the take-off and steep turns reaching in excess HQR8. The HQR's for the 1905 Flyer are better (lower) for almost all the MTE's reinforcing the rationale that the 1905 Flyer was much improved and was, relatively speaking, a practical airplane. It can be seen that turns of up to 10° were still only Level 2 (HQR4-6) but turns of greater bank angles were still Level 3 (HQR7-9). A good improvement in the HQR for the take-off MTE was seen as a result of the improvement in the pitch stability. Improvements were also achieved for other longitudinal maneuvers such as the climb and cruise. Although the longitudinal flying qualities were much improved, the HQR's did not improve beyond 4, this was because the instability required that the pilot had to continuously 'stay in the loop' and could never divert too much attention away from the basic stabilization task.

Some example results from the piloted simulation trials are presented in figures 16-17. In each figure runs using the 1903 and 1905 Flyer are plotted for comparison. Figure 16 shows take-off runs for each aircraft and the improvement in handling qualities is immediately visible. The 1903 Flyer pitches continuously with the pilot making continuous and rapid control inputs. The take-off in the 1903 Flyer was found to be a particularly difficult maneuver from both handing and performance aspects as the large pitching motion would degrade the already minimal climb performance. This is seen in the height trace where the 1903 Flyer only manages an altitude of 25-30ft 60 seconds after lift-off. In the 1905 Flyer the pitch activity is markedly reduced, the pilot was able to rotate cleanly at lift-off, set a pitch attitude, and then maintain a steady climb rate of 120 ft/min. The canard control activity is much reduced, with minimal activity once the new trim position was set.

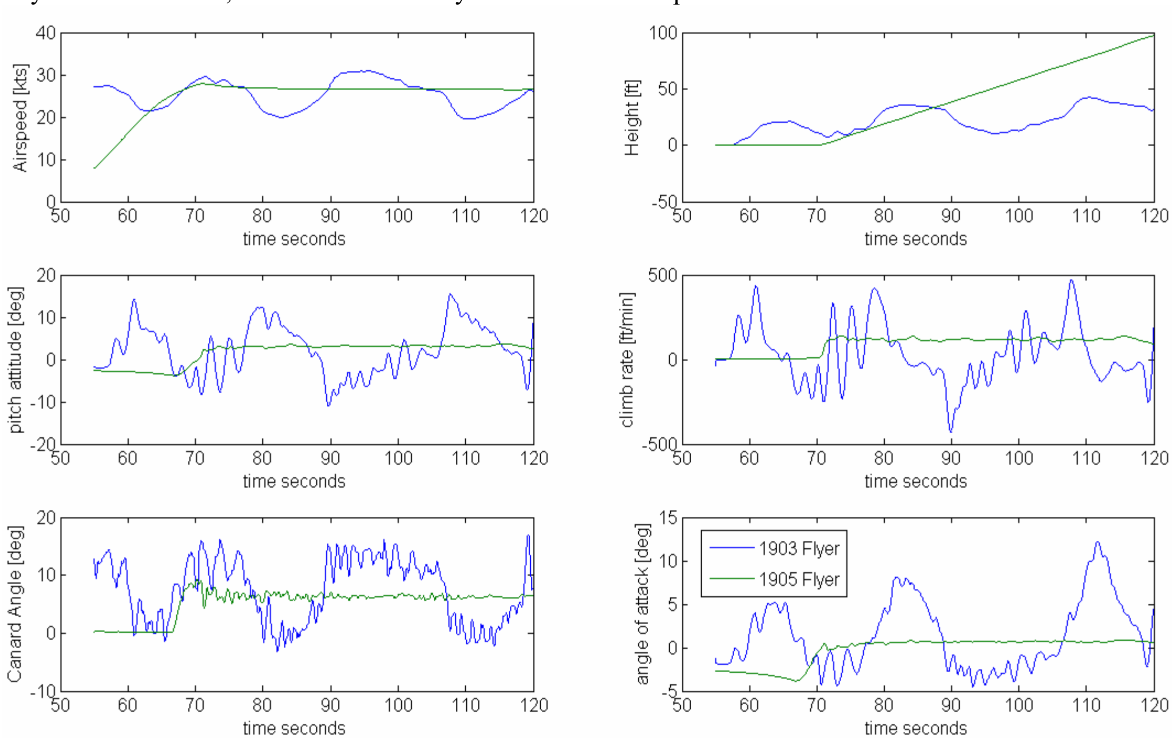


Figure 16 Take-offs in the 1903 and 1905 Flyers

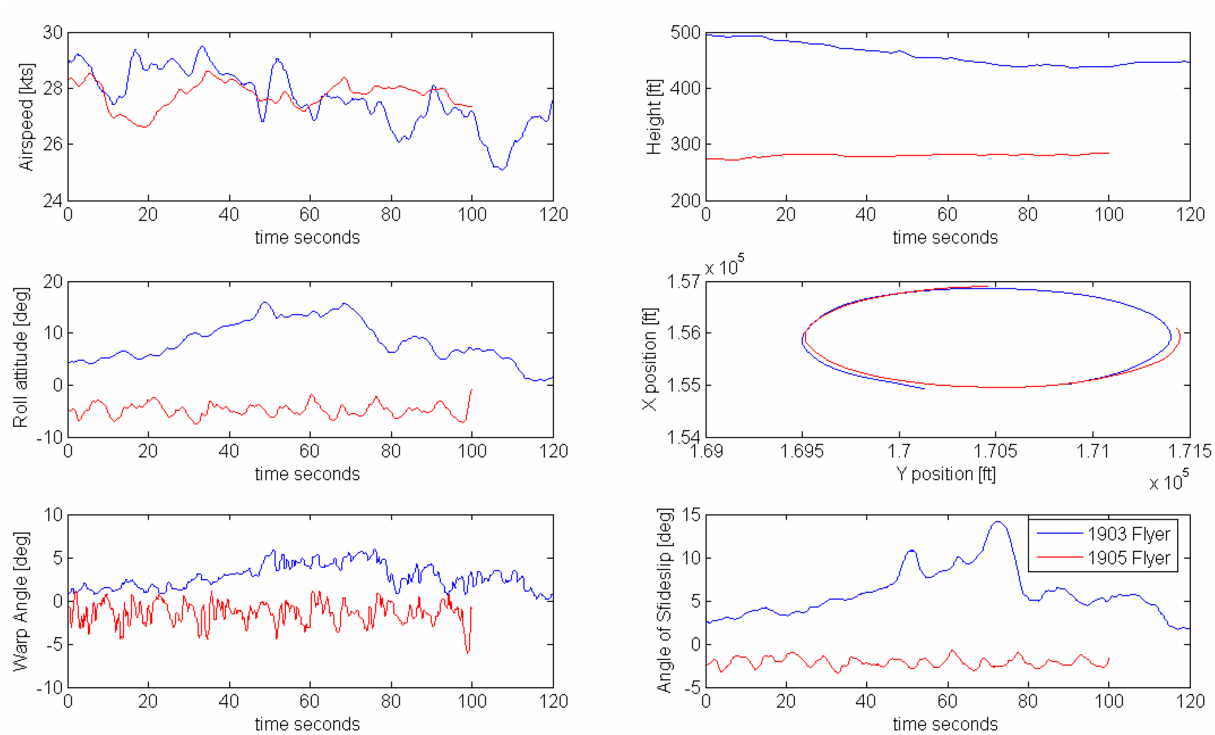


Figure 17 Turns about fixed point (no wind), 1903 and 1905 Flyers

Figure 17 shows the lateral-directional improvements made form 1903 to 1905. The task was for the pilot to make a turn about a fixed point on the ground following a ground track. The track was set up such that the pilot would maintain a bank angle of approximately 5 degrees. The main difference between the aircraft was that the 1905 Flyer was able to minimize the sideslip in the turn. We can see that throughout the 360° the sideslip did not exceed 2-4° for the 1905 machine whereas the sideslip steadily grew for the 1903 machine. This was important, as being able to prevent the sideslip enabled the pilot to maintain the altitude in the turn as well as maintaining effective roll control by suppressing the loss of forward airspeed to sideslip. A number of factors contributed to this improvement. These included the extra power, roll stability through the removal of the anhedral/addition of dihedral, and independent rudder control. The last factor was important as the turns in the 1905 Flyer still required out-of-turn stick in the steady turn (negative warp creates positive roll). The warp-rudder interlink was advantageous for turn-entry, but was not helpful as the out-of-turn stick input generated unwanted rudder inputs. Independent control gave the pilot the ability to generate yaw inputs on demand. More generally for the turns, the limiting bank angle was found to be approximately 15-20°, the pilot found it was almost impossible to recover to wings level from greater bank angles.

In summary, the 1905 Flyer benefited from the greater damping and pitch, better sideslip characteristics in the turn, and increased power made the aircraft more forgiving to mistakes. In other maneuvers, such as the engine failure, the 1905 Flyer displayed similar behavior as the 1903 Flyer with a rapid pitch up following the loss of thrust which acts above the c.g. line. However, the handling qualities ratings for this MTE were improved because of the greater pitch control power which enabled the pilot to regain control more easily. With respect to the steep turning problems that the Wrights suffered, it was found that if lateral maneuvering was attempted at 24kts or less the roll control became very unresponsive with strong adverse yaw. If a turn was attempted at these speeds the aircraft rapidly became uncontrollable, with full warp control deflections having little effect.

VII. Conclusions

The objective of this paper was to demonstrate the improvements that the Wright brothers were able to make from 1903 to 1905 through the use of modern flight science techniques. The paper has shown new data revealing the aerodynamic characteristics of the 1905 Flyer and how they contributed to the flight dynamics. The simulation trials have offered a unique opportunity to investigate the handling qualities of this aircraft in free flight using human test pilots and full-motion simulation. This has not only offered new technical insight but provided new scientific evidence to support many existing theories. Fred Hooven's hypothesis that the Wrights were 'lulled' by the stability of the 1902 glider is supported and reinforces the mystery that surrounds the Wrights general understanding of the pitching moments generated by the aerodynamic surfaces. The reason for why the Wrights first moved the c.g. back in 1904 before realizing their error is particularly confusing, especially considering the Wrights scientific approach. After all, they showed a strong understanding of forces and commonly used vector representations of them. Hooven's[2] suggestion that they ceased to be keen analytical scientists and became busy builders after 1903 is also attractive but it seems to be a major shift in philosophy by the Wrights if it were true, especially considering all the work up to 1903. However, the activities of 1903-1905 still showed the Wrights to be exceptional pilots and to have keen engineering insight. In the end, they still managed to achieve a solution which they considered to be ready for market.

The results in this paper show that the 1905 Flyer was much improved over 1903 and could have been flown for prolonged periods, but there were still areas to be treated with caution especially steep turns and landings without power. The 1905 Flyer, with an unstable pitch and spiral mode, continued to demonstrate the Wrights' ethos of 'control over stability'.

VIII. Acknowledgements

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