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Flight Handling Qualities of the Wright Brothers' 1905 Flyer 3

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The success of the first powered, controlled flights at Kitty Hawk on 17 December 1903 was a breakthrough in aviation, substantiating the Wright brothers' research and design concepts. The years 1903–1905 represent a period wherein the Wrights evolved the design of their powered aircraft, culminating with the 1905 Flyer 3, which they were able fly significant distances. The 1905 Flyer 3 was the Wrights' first true practical design, flying 38.956 km in 39 min 23 s. This was to be their last flight for nearly two and half years while they tried to sell their invention to the governments of Europe and the United States. The engineering challenges faced by the Wright brothers are reflected on, and research studying the Wright aircraft using modern flight science techniques is reported. The methods used in developing simulation models of the Wright 1902 Glider and the 1903/1904 and 1905 powered aircraft are reported on, and their piloted simulations are assessed in real time. The Wrights' technological journey is one of systematic analysis and clear, methodical development. They developed practices recognizable to modern aeronautical engineers and were also the first true test pilots. The Wright brothers' achievements in this centenary of practical flight are studied and celebrated.

Nomenclature

A_{lat}	=	system matrix (lateral–directional)
C_L, $(C_{L\max})$	=	lift coefficient (maximum)
C_l	=	rolling moment coefficient
C_M	=	pitching moment coefficient
C_n	=	yawing moment coefficient
C_{n_β}	=	nondimensional derivative, yawing moment coefficient due to sideslip, rad^{-1}
c_{l_β}	=	nondimensional derivative, rolling moment coefficient due to sideslip
g	=	gravitational acceleration
H_n	=	static margin, $\partial C_M/\partial C_L$
Kp	=	pilot gain (pitch attitude feedback)
Lr, L_v, M_q, N_v	=	aerodynamic derivatives
Re	=	Reynolds number
T_2	=	time to double amplitude, s
$\boldsymbol{u}$	=	control vector
u, v, w	=	perturbation velocities along body axes
V	=	flight velocity
$\boldsymbol{x}$	=	state vector
$Y^{\theta}_{\delta c}$	=	transfer function between canard and pitch atttitude
α	=	angle of attack/incidence
β	=	angle of sideslip
θ	=	pitch attitude
λ	=	eigenvalue
τ	=	pilot neuromuscular lag
ϕ	=	roll attitude

Introduction

ON 5 October 1905, Wilbur Wright brought the 1905 Flyer 3 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, Ohio. This was their longest flight yet, making 38.956 km in 38 min and $23\frac{4}{5}$ s. 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 before takeoff. These achievements mark the 1905 Flyer as the world's first practical airplane (Fig. 1).

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 17 December 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 and 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 to mid-1904, the Wrights almost consistently made the longitudinal flying qualities of their machines worse: It was not until mid-1905 that they managed to improve the situation more satisfactorily. Also, the Wrights still had much to learn about lateral–directional control. They had not completed more than a one-quarter 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, 26 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 Hooven[2] termed a "stall turn," where the aircraft had insufficient lift to carry the additional centrifugal load generated in the turn. Moreover, Hooven's paper of 1978 (Ref. 2) contains an excellent analysis of the flying events post-1903. He poses the question, "why did the Wrights persist with the canard configuration?"[2] His analysis looked at how the position of the center 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 safe stall characteristic 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

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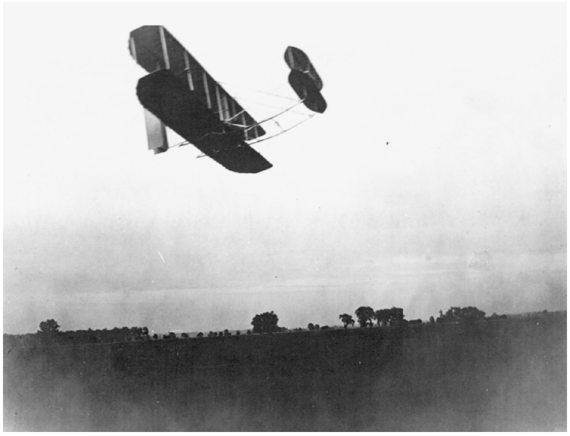


Fig. 1 Photograph of 1905 Flyer in flight.

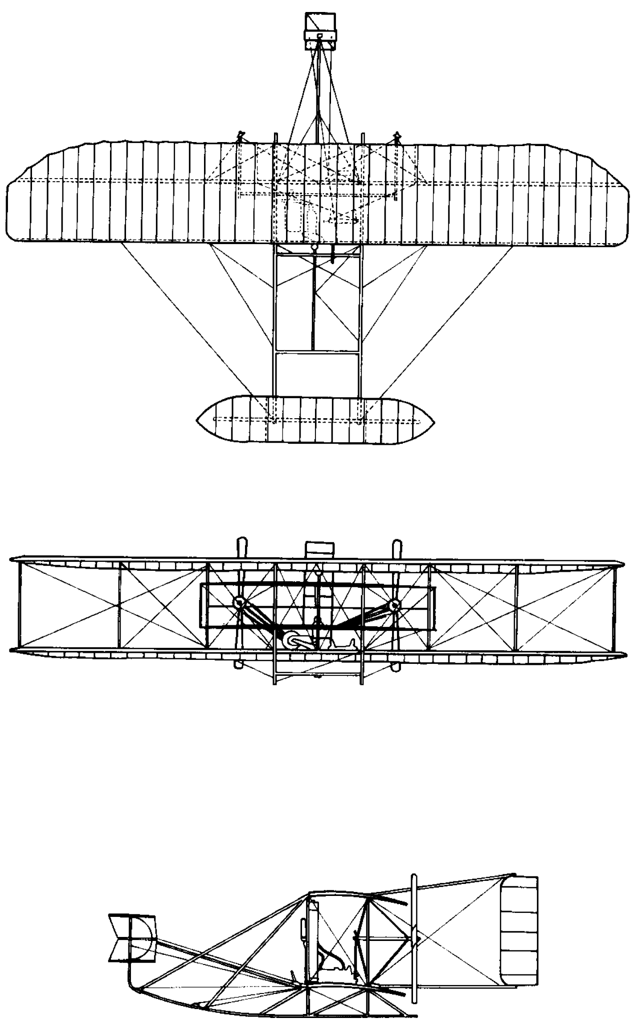


Fig. 2 Final configuration 1905 Flyer.

well as evaluating the effectiveness of the improvements they made in 1903–1905.

1905 Flyer 3

Figure 2 shows the 1905 Flyer in its final configuration, with a biplane canard of approximately 84 ft^2, a wing area of 503 ft^2, and a weight of approximately 920 lb (including pilot, ballast, and fuel). The main wing camber was 1/20, an increase from 1904 (1/25) but the same as that used in 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 that 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 perhaps misinterpreted the situation. It was not the camber causing the instability, but instead the resulting different aft c.g. positions required for trim. In 1902, they reduced the camber further, and stability was improved. By 1903, they increased the camber again, and the stability deteriorated again. The Wrights were probably very confused by this state of affairs. In 1904, they began to realize that the the 1904 Flyer had a lower camber than the 1903 Flyes, 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 c.g., but they had decided to move it farther aft. Naturally, this made the problem worse. This was a turning point, and from then onward both the 1904 and 1905 Flyers featured ballast of up to 70 lb on the forward framing to move the c.g., forward.

Another addition in 1905 was a pair of semicircular 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 takeoff. The aircraft was powered by the same engine as in 1904, which produced 21 hp. This turned two contrarotating propellers that pushed the aircraft to speeds of 30–35 mph.

Lateral control was performed by the Wrights' 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 while the Wrights were investigating why their aircraft could not be returned to level flight from tight turns.

Wright Brothers' 1905 Flying Season

The flying began in 1905 with the Wrights experiencing many of the same problems as they did in 1904. The main problem was controlling the aircraft in pitch. The Wrights were struggling to make flights of any distance. Wilbur wrote 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 750 ft. This distance was more than 100 ft 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 568 ft. time about 12 sec.... 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 12 ft from front edge of machine...

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. Afterward, the Wrights began to improve their performances and soon started to make several flights of over 1 km. 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.

Aerodynamics of 1905 Flyer: Wind-Tunnel Results

As part of the University of Liverpool's Wright brothers project, a number of FLIGHTLAB[4] simulations have been developed to examine flying qualities of these pioneering aircraft. In support of the simulation model development, computational aerodynamic

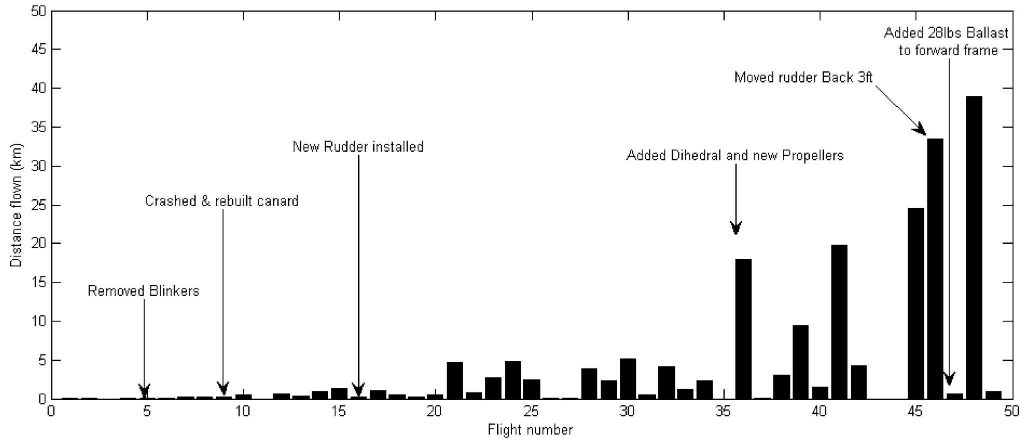


Fig. 3 Wright brothers' 1905 flights.

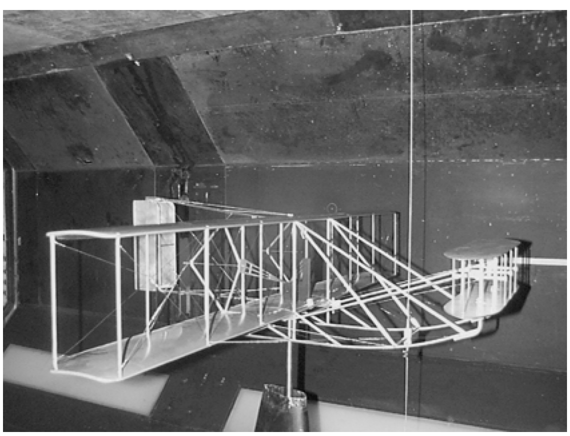


Fig. 4 One-eighth-scale 1905 Flyer model in University of Manchester's 9 × 7.3 ft wind tunel.

models and wind-tunnel experiments have been used to identify the aerodynamic coefficients. The most recent tests featured the 1905 Flyer 3 (Fig. 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 (Fig. 5). For the wind-tunnel model, it was not feasible to implement this system from a structural and materials aspect, and 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.

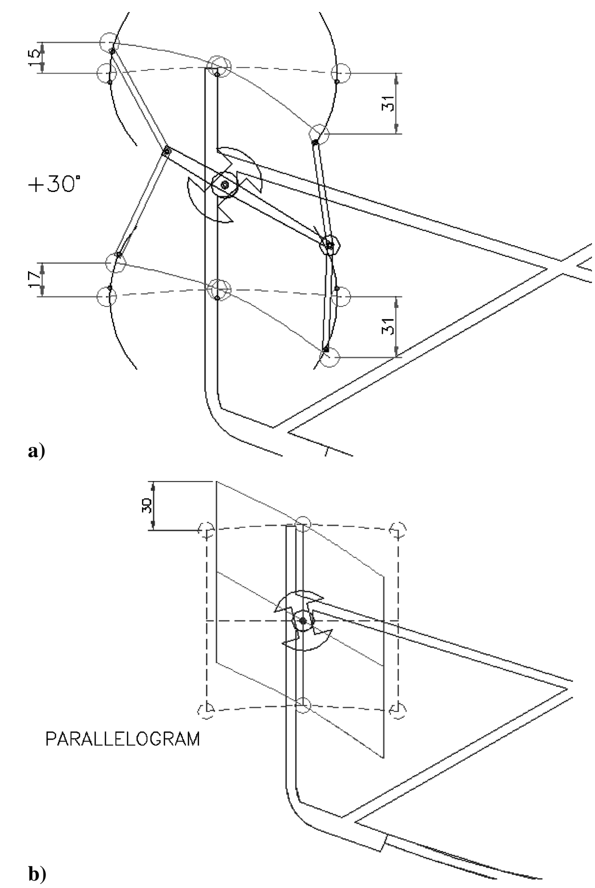


Fig. 5 Comparison of possible construction methods for canard on the 1905 Flyer wind tunnel model: a) original canard mechanism and b) simplified mechanism.

Longitudinal Results

The model was one-eight scale, which conferred a wingspan of 5.0625 ft and chord of 0.8125 ft. The tunnel velocity was approximately 20 ms^{-1}, giving a Reynolds number of 0.33×10^6 compared to a full-scale Reynolds number of 2.25×10^6 ($V = 17\ \mathrm{ms}^{-1}$). 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 greater camber of 1/20 provided a larger $C_{L\max} \approx 1.2$ than the 1902 machine. The lift stays virtually constant up to incidence angles of 20–25 deg. 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 a word (the Wrights began to use in 1904)[1] and crash land, sometimes traveling backward. 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 the curves display a high degree of nonlinearity, denoting changing static stability with incidence. At lower incidences, ($\alpha < 5$ deg), 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 reach their maximum values. At very high incidences, the curves begin to increase again due to the high drag of the upper wing and canard (being above the c.g. at those incidences), 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

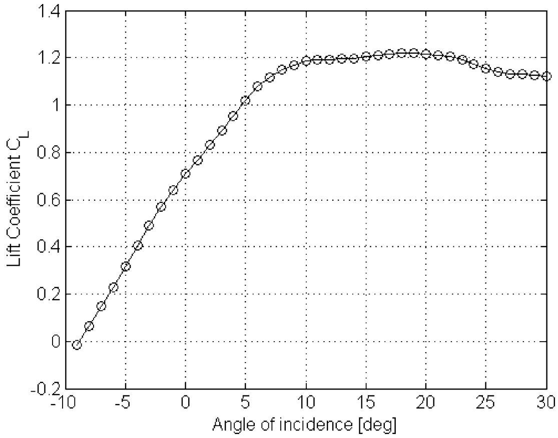


Fig. 6 Lift coefficient vs. angle of attack, 1905 Flyer.

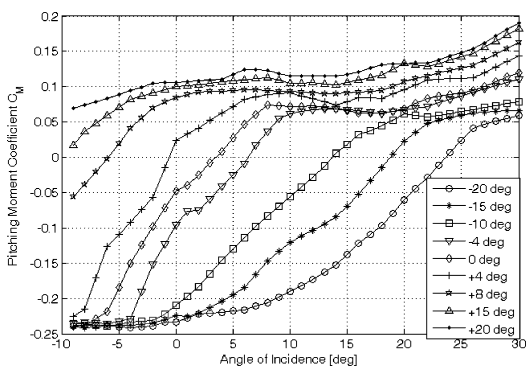


Fig. 7 Pitching moment coefficient vs. angle of attack and canard deflections, 1905 Flyer.

trim over quite a large incidence range. (Note that these results are for the nonflexing surface as in Fig. 5.)

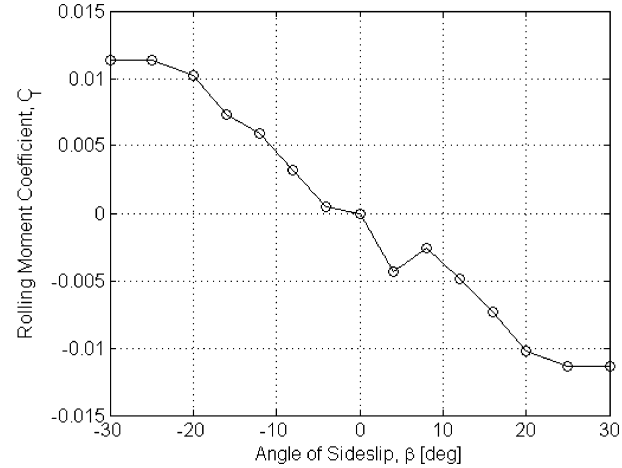


Fig. 8 Rolling moment coefficient with sideslip, 1905 Flyer.

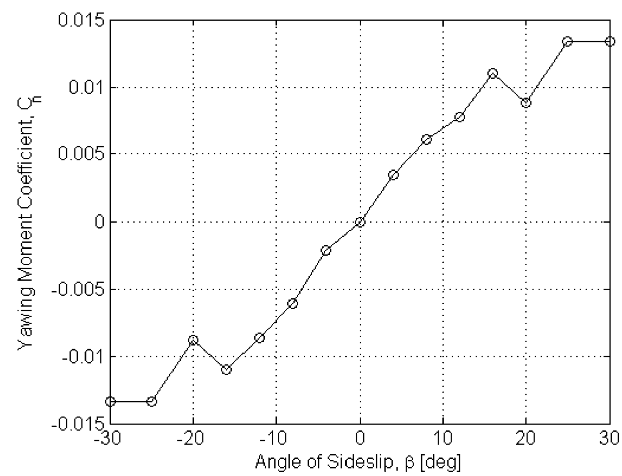


Fig. 9 Yawing moment coefficient with sideslip, 1905 Flyer.

Lateral Results

Near the end of the 1905 season (Fig. 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} (see Fig. 8), although the model only featured straight wings as displayed in Fig. 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} (see Fig. 9), $[-16 \text{ deg} < \beta < +16 \text{ deg}]$. Results published by Jex et al.[5] showed the 1903 Flyer to have a $C_{n_\beta} = +0.0368$. When these two sets of data are used, predictions for the characteristics for the earlier versions of the 1905 Flyer can be made.

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 some adverse effect on the directional stability. What is unclear is whether the blinkers only appeared on the earlier shorter-nosed version of the 1905 machine and not the long-nosed version of the 1905 Flyer shown in Fig. 2. Figure 2, from McFarland,[1] drawn in 1949, shows the restored 1905 Flyer kept at Carilllon Park, Dayton, Ohio. A photograph of this machine taken in the 1950s shows the blinkers installed. However, the pictures from the Wrights' experiments only show the blinkers on the early short-nosed version. Also, for that version, the blinkers have been estimated to generate a $\Delta C_{n_\beta} = -0.0085$, reducing the total C_{n_β} to 0.0297 [derived from the 1903 measurements of C_{n_β} (Ref. 5)]. The further lateral–directional changes are shown in Fig. 10 with estimations of the effect on the directional stability.

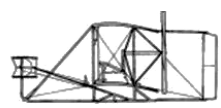
Often, a correlation can be seen when comparing the configuration changes to the Wrights' diary descriptions of their flights. For example, flights 1–4 were beset by problems with the lateral–directional control. The Wrights identified the problem as the presence of the blinkers combined with an overbalanced rudder. The removal of the blinkers should have given a configuration similar to that from 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 probable major problem. Further along 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. With reference 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. 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 flights 16–19, where they had problems with an overbalanced rudder control again, they began to make significant improvements in their flying distances.

Flight Dynamics

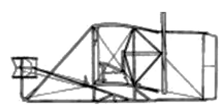
Longitudinal Flight Dynamics

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 nondimensional distance between the c.g. and the neutral point. The 1905 Flyer, with a c.g. position of 12.8% chord (from the leading edge),[6] showed an average $H_n = 0.288$ ($C_L = 0.2$–1.2), whereas the 1903 Flyer had an average $H_n = 0.24$ ($C_L = 0.3$–1.2, c.g. at 30% chord.[5] The greater the value, the greater the static instability. Despite this, the 1905 Flyer seemed to be an easier aircraft to fly. Even when accounting for the extra practice the Wrights had accumulated, the reason for this was unaccounted for. 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[7] and the pitch control power.

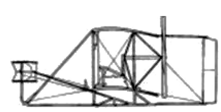
The dynamic stability was analyzed using the FLIGHTLAB simulations. In particular, Fig. 11 shows the root locus of the feedback of pitch attitude to canard angle for the main versions of Wright aircraft



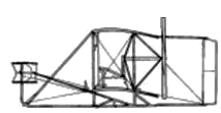
a) 1905 version 1: Small canard, $\triangle C_{n_\beta} = -0.0085$ (due to blinkers) short tail, small vertical surface, $C_{n_\beta} = 0.0297$ and blinkers.



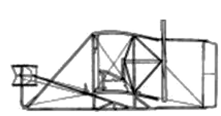
b) 1905 version 2: Small canard, $C_{n_\beta} = 0.0364$ (as 1903) short tail, small vertical surface, blinkers removed.



c) 1905 version 3: New large $\triangle C_{n_\beta} = -0.0423$ (no large tail) canard, short tail, small vertical $\triangle C_{n_\beta} = +0.0165$ (1903-like tail) surface, no blinkers. $C_{n_\beta} = 0.0145$



d) 1905 version 4: New large $\triangle C_{n_\beta} = +0.0122$ (larger tail 34.8 ft^2) canard, short tail, larger $C_{n_\beta} = 0.0267$ vertical surface, no blinkers.



e) 1905 version 5: New large $\triangle C_{n_\beta} = +0.0136$ (tail back 3 ft canard, long tail, larger $C_{n_\beta} = 0.0403$ vertical surface, no blinkers.

Fig. 10 Evolution of 1905 Flyer, June–October 1905.

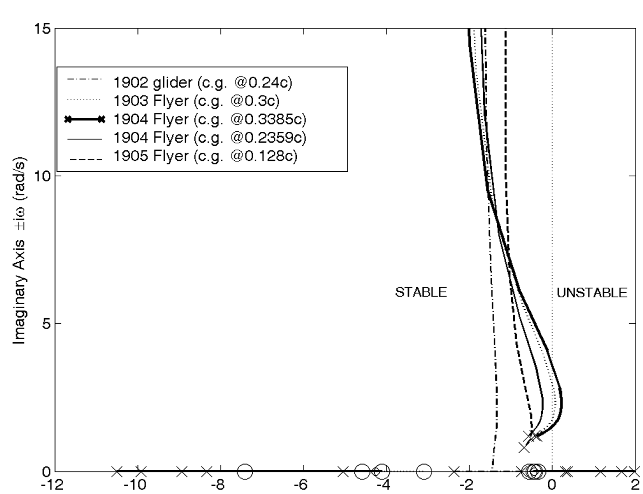


Fig. 11 Closed-loop stability of Wright aircraft 1902–1905 (all 26 kn except 1902, 24 kn).

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.[8] All of the aircraft display a single unstable open-loop pole (marked by crosses) to the right of the y axis. These poles represent a nonoscillatory divergence, essentially the unstable pitch mode. The application of feedback stabilizes these unstable modes by bringing the poles to the left half-plane. When the gain is increased, 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 $\cdot$ s^{-1}). These modes tend to migrate toward the stability boundary as the gain increases and even cross the boundary and become divergent for the 1904 Flyer with the c.g. at $0.3358c$. This mode is the reason for 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 onward. In comparison, the 1902 glider was fairly manageable, but in 1903, the Flyer 1 was extremely unstable. Early in their 1904 season, the Wrights moved the c.g. back another 3 in. in an effort to reduce the oscillations, only to discover that this was wholly incorrect. In response, the forward framing was ballasted with 70 lb to move the c.g. 5 in. forward of the original position, thus reducing the instability.

By the end of the 1905 season, the enlarged canard and 28 lb of forward ballast resulted in the most dynamically stable Flyer to that point, and Fig. 11 reflects this. Figure 11 also shows how the second oscillatory mode does not approach as close to the y axis as the closed-loop gain is increased. This means that the oscillations induced under closed-loop control have greater damping and are 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 $\tau = 0.2$ s (Ref. 9). This parameter forms part of the crossover model of human pilot behavior.[10] Equation (1) shows the transfer function describing this model. It comprises the pilot's neuromuscular lag and a separate lead and lag, T_1 and T_2, that the pilot adjusts when trying to control the aircraft,

$$Y_{\delta_c}^{\theta} = K_p e^{-\tau s}[(T_1 + 1)/(T_2 + 1)] \tag{1}$$

As before, K_p represents the pilot gain. Figure 12 shows the effect of the pure delay on the migration of the modes, ignoring the pilot lead and lag, in this case comparing the 1903 and 1905 Flyers. Note that the application of feedback still stabilizes the unstable mode, but now the oscillatory modes move toward the stability boundary and continue to move right with increasing gain. A gain of $K_p = 0.8$ has been highlighted in Fig. 12 to show that, even with a delay, the 1905 Flyer modes are marginally 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 that the 1905 Flyer was more forgiving. Pilot delay is inevitable, but, in reality, it 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.[9] Given this, the 1903 Flyer would have required a greater workload, which, in a high-gain situation, could have lead to pilot-induced oscillations and loss of control.

As stated earlier, the improvement in longitudinal stability comes from the increase in pitch damping and pitch control power. The aerodynamic damping in pitch in nondimensional 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}

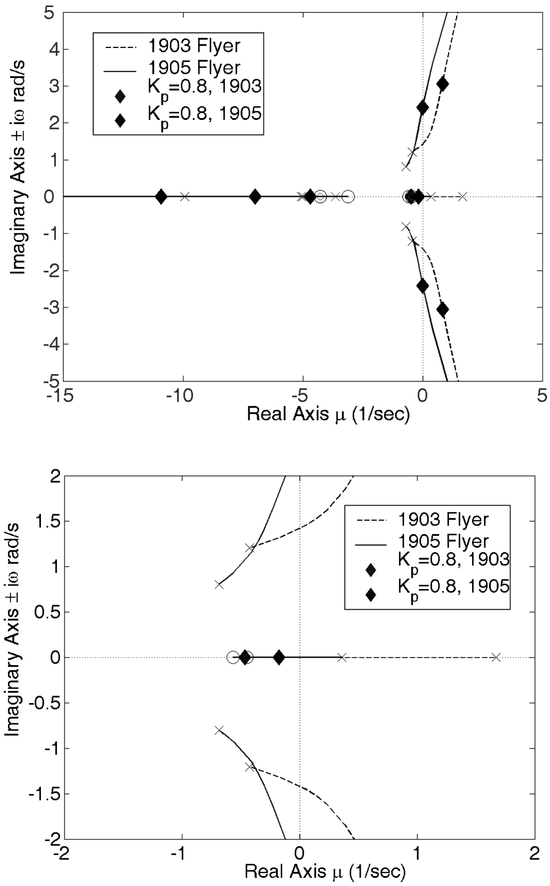


Fig. 12 Root locus of pitch attitude feedback with pilot time delay, 1903 and 1905 Flyers with zoomed view below.

has been estimated to be approximately −1.53 (Ref. 11). When the wind-tunnel data and vortex–lattice computations were used, C_{m_q} was 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[7] have estimated $C_{m_q} = -4.67$ for the 1905 machine, offering an even greater increase. In its dimensional form, M_q, the contribution to the pitch stability can be assessed by examining Eq. (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 of which is given by Eq. (3),

$$\lambda = \Big[(Z_w + M_q) \pm \sqrt{-(Z_w + M_q)^2 + 4(Z_w M_q - M_w(Z_q + U_e))}\Big]\Big/2 \tag{3}$$

Note 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 the amplitude of the unstable mode is directly linked to M_q via Eq. (4),

$$T_2 = \ell n 2/\lambda \tag{4}$$

This is the reason for the 1905 Flyer, although possessing a greater negative static margin, to have $T_2 = 2.192$ s ($\lambda = 0.3162$). This is compared to the 1903 Flyer that has a $T_2 = 0.41$ s ($\lambda = 1.6861$). The increase in the time to double-to-double amplitude is significant, a fivefold increase.

Lateral Flight Dynamics

The improvement in the longitudinal flying qualities was very important to the Wrights' progress in 1905, but there were also significant modifications made to improve the lateral–directional characteristics. The wind-tunnel results have shown the 1905 Flyer 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 26-kn (30-mph) nominal flight condition, the eigenvalues of the linearized model in Eq. 5 are as follows: For lateral A matrix $\boldsymbol{x} = [v\ p\ r\ \phi]^T$

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

the eigenvalues are −3.8984, roll mode; $-0.4944 + 1.2038i$, Dutch roll; $-0.4944 - 1.2038i$; Dutch roll; and 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 static roll and yaw stability act against each other (L_v and N_v). If the roll stability dominates, then 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 dihedral effect. A useful approximation to the spiral mode is given in Eq. (6) (Ref. 3),

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

where

$$\sigma_s = (g - N_p V)/L_p \tag{7}$$

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 $\lambda_s = 0.3184$, a reasonable approximation. Furthermore, in the numerator of Eq. (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 because the outer wingtip has a greater velocity and, therefore, lifts higher while the inboard tip is at lower speed and drops. As the aircraft rolls, it will sideslip toward the lower wing, causing into-turn yaw due to the directional stability. For the Wrights, the problem was even greater for two reasons: First, 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. Second, 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 while generating little lift increment to raise that wingtip. The Wrights found solutions to both problems, the first by making the rudder independent, their first true three-axis control system. The second problem 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.

Flight Handling Qualities Analysis

Thus far we have discussed several of the aerodynamic and flight dynamic characteristics of the 1905 Flyer. When these are compared with those of 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 during the Wrights' time. However, 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 prerequisite tasks. Indeed, in

1909, the Wrights were engaged in developing a Flyer for the U.S. Army Signal Corps. As part of the procurement process, the U.S. government set out a set of what might be considered basic handling qualities requirements, namely, U.S. Army Signal Corps Specification No. 486.[12] In summary, the document goes onto specify that, for an aircraft that could carry a pilot and one passenger, the aircraft must carry fuel for a range of 125 miles and possess a target speed of 40 mph. In terms of the operational capability of the aircraft, the following were also required:

1) The aircraft must "remain continuously in the air without landing" (over a 1-h trial flight).

2) "It shall return to the starting point and land without any damage that would prevent it starting upon another flight."

3) "During this trial of one hour it must be steered in all directions without difficulty and at all times under perfect control and equilibrium."

4) "It should be provided with some device to permit of a safe descent in case of an accident to the propelling machinery."

5) "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 handling qualities perspective. The only direct comment on the required handling 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 in which the U.S. Army Signal Corps would have used the aircraft leads us to a conclusion that, at minimum, the aircraft should be capable of a takeoff, a climb, level cruise, turn/maneuver, a descent, and landing under safe control.[13] This breakdown of the maneuvers or tasks that might be expected of the machine fits well with today's concept of the handling qualities mission task element (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, that is, pitch, roll attitudes, speeds, angular rates, etc.; spatial position, or the 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.[14]

Over the past years, a number of piloted simulation trials focusing on the Wright brothers' aircraft have been conducted on the University of Liverpool flight simulator (Fig. 13). The simulator features six-degree-of-freedom motion and a 135-deg horizontal field of view[15] combined with reconfigurable scenery and FLIGHTLAB simulation models. The nonlinear FLIGHTLAB simulations of the 1903 Flyer and 1905 Flyer were flown by test pilots who used conventional flight controls (center stick, throttle, and pedals) in a number of handling qualities trials where the aircraft were exercised in a number of MTEs. Figure 14 shows a radar plot of the HQR rating for the MTEs, the higher rating (worse), the further along a spoke the rating is plotted. Note that the data set is for a limited number of pilots (two) and sorties, but a good impression of the relative performance can be obtained. The MTEs 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 (ground referenced) were a task where the pilots were required to follow a fixed circular path on the ground as though they were circling a target of observation.] Other MTEs included a roll step,[16] (Fig. 15) which was a lateral–directional maneuver that tested the aircraft's accuracy as well as agility. An emergency landing following an engine failure was also tested. This last MTE was selected with in consideration of the U.S. Army Signal Corps specification that "[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 MTEs were assigned a set of performance standards (Table 1) that were set to give a reasonable expected level of accuracy and performance for the times.

Fig. 13 External and internal views of University of Liverpool flight simulator.

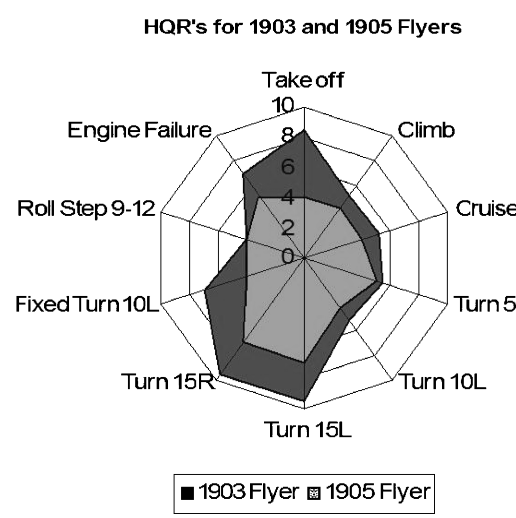


Fig. 14 HQRs for variety of MTEs for 1903 and 1905 Flyers.

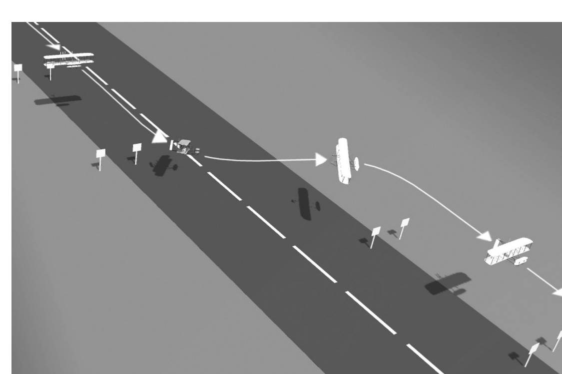


Fig. 15 General layout for roll-step MTE.

Table 1 MTE performance standards

MTEs	Overall description	Desired	Adequate
Takeoff	Accelerate along runway to takeoff speed. Lift off and maintain heading and pitch attitude. Once airborne, enter into climb phase.	±5-deg heading ±5-deg roll	±10-deg heading ±10-deg roll
Climb	Set climb rate and maintain heading and climb to 250 ft.	±5-deg roll ±5-deg heading ±3-kn speed	±10-deg roll ±10-deg heading ±6-kn speed
Cruise	Set cruise speed and trim while maintaining heading and altitude.	±25-ft altitude ±5-deg heading ±3-kn speed	±50-ft altitude ±10-deg heading ±6-kn speed
Turn 1	Enter a steady turn of 5, 10, or 15-deg bank angle. Maintain bank angle and height until instructed to end turn maneuver.	±25-ft altitude ±3-deg roll attitude ±3-kn speed	±50-ft altitude ±6-deg roll attitude ±6-kn 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

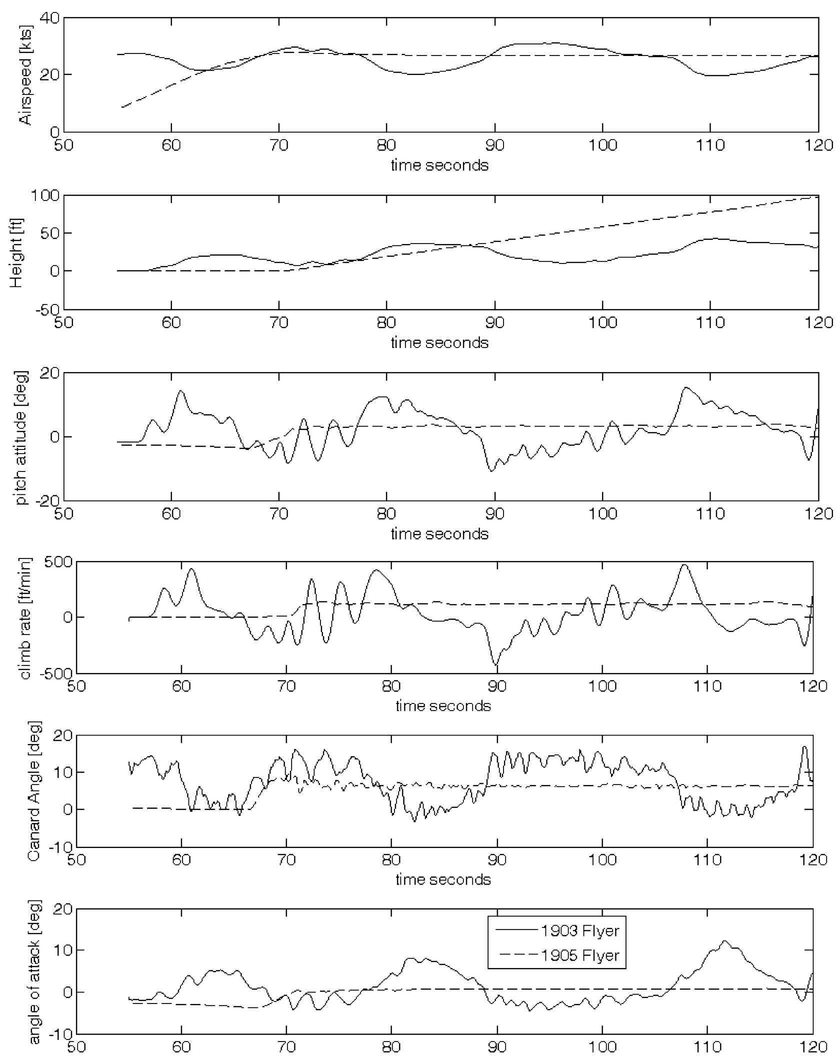


Fig. 16 Takeoffs in 1903 and 1905 Flyers.

From Fig. 14, some general trends can be identified. For example, for both aircraft the HQRs degrade with increasing bank angle. Also note that maneuvers with lowest HQRs for the 1903 machine were the takeoff and steep turns reaching in excess of a HQR of eight. The HQRs for the 1905 Flyer are better (lower) for almost all of the MTEs, reinforcing that the 1905 Flyer was much improved and was, relatively speaking, a practical airplane. It can be seen that turns of up to 10 deg 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 takeoff MTE was seen as a result of the improvement in the pitch stability and, to some extent, in the improved performance. Improvements were also achieved for other longitudinal maneuvers such as climb and cruise. Although the longitudinal flying qualities were much improved, the HQRs did not improve beyond four. This was because the instability required that the pilot had to stay in the loop continuously and could never divert too much attention away from the basic stabilization task.

Some example results from the piloted simulation trials are presented in Figs. 16 and 17. In each of Figs. 16 and 17, runs using the 1903 and 1905 Flyers are plotted for comparison. Figure 16

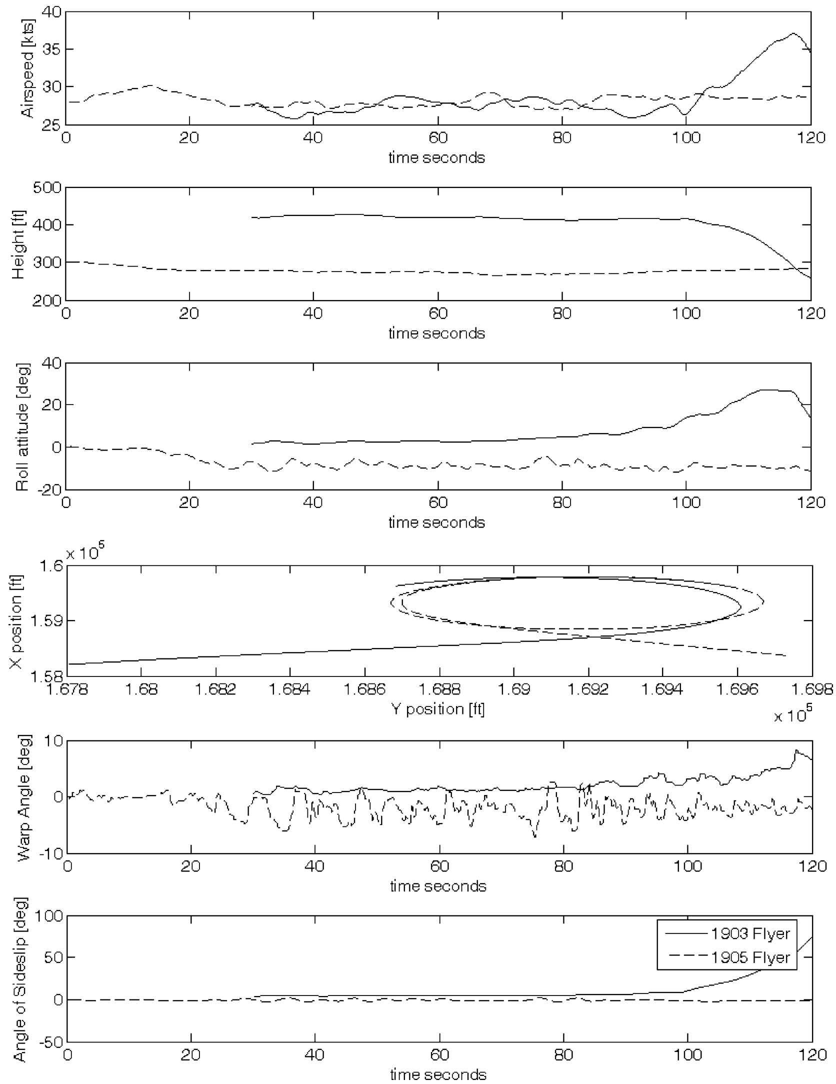


Fig. 17 Turns about fixed point (no wind), 1903 and 1905 Flyers.

shows takeoff 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 takeoff in the 1903 Flyer was found to be a particularly difficult maneuver from both handing and performance aspects because 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 25–30 ft 60 s after liftoff. In the 1905 Flyer, the pitch activity is markedly reduced. The pilot was able to rotate cleanly at liftoff, 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 is set.

Figure 17 shows the lateral–directional improvements made from 1903 to 1905. The task was for the pilot to make a turn about a fixed point on the ground following a ground track. (Note that the aircraft are flying the circuit in opposite directions.) The track was set up such that the pilot would maintain a bank angle of approximately 5 deg. 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 deg, the sideslip did not exceed 2–4 deg for the 1905 machine, whereas the sideslip steadily grew for the 1903 machine. This was important because being able to prevent the sideslip enabled the pilot to maintain the altitude in the turn. A number of factors contributed to this improvement. These included the extra power, improved roll stability through the removal of the anhedral, and the addition of the dihedral and independent rudder control. The last factor was important because the turns in the 1905 Flyer still required an out-of-turn stick to maintain the roll angle in the turn (negative warp creates positive roll). The original warp-rudder interlink was advantageous for turn entry and for the straight flights in 1902 and 1903, but was not helpful in a steady turn because the out-of-turn stick input generated unwanted rudder deflection. 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 deg. The pilot found it was almost impossible to recover to wings level from greater bank angles.

In summary, the 1905 Flyer benefited from greater damping and pitch, better sideslip characteristics in the turn, and increased power, all of which made the aircraft more forgiving of mistakes. In other maneuvers, such as engine failure, the 1905 Flyer displayed similar behavior as the 1903 Flyer, with a rapid pitchup following the loss of thrust that 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 24 kn 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.

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 real test pilots and full-motion simulation. This has not only offered new technical insight, but has also provided new scientific evidence to support many existing theories. 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 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 of 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 that they considered to be ready for market.

The results in this paper show that the 1905 Flyer was much improved over that of 1903 and could have been flown for prolonged periods. However, 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.

Acknowledgments

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