

The birth of the practical aeroplane: An appraisal of the Wright brothers' achievements in 1905

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ABSTRACT

In this second *Aeronautical Journal* paper providing a technical appraisal of the Wright brothers' achievements, the authors use modelling and simulation and associated flight dynamics analysis to present the development of the first practical aeroplane. The aircraft in question, the Wright Flyer III, was deemed fit for service by the Wrights in October 1905, and had evolved significantly from the first powered aircraft of 17 December 1903. The appraisal tries to shed light on many of the flight handling problems that the Wright brothers faced during this, their third phase of aeronautical endeavour, in 1904 and 1905. They retained their unstable configuration born in the 1901 and 1902 gliders, gradually refining the performance and handling until they considered the aircraft was ready for market. Their process of refinement has been reconstructed in simulation within the Liverpool Wright project, highlighting the many important developments during a period when Wilbur and Orville's own documentation was limited. Apart from their engineering excellence, the Wright brothers are to be acknowledged for their perseverance and resolve in overcoming setbacks, for their ability to innovate and to recover and learn from their mistakes. In many ways the Wright brothers represent a model for the modern aeronautical engineer, and it is hoped that their legacy will be better preserved through the documentation of this project.

1.0 INTRODUCTION

Unknown to the world, the flights of December 1903 had marked the invention of the powered aeroplane. In a letter to the associated press written on 5 January 1904, Wilbur Wright described his final flight of 17 December 1903⁽¹⁾.

"...at the fourth trial, a flight of fifty-nine seconds was made, in which time the machine flew a little more than a half a mile through the air, and a distance of 852 feet over the ground. The landing was due to a slight error of judgement on the part of the aviator. After passing over a little hummock of sand, in attempting to bring the machine down to the desired height, the operator turned the rudder too far; and the machine turned downward more quickly than had been expected. The reverse movement of the rudder was a fraction of a second too late to prevent the machine from touching the ground and thus ending the flight. The whole occurrence occupied little, if any, more than one second of time."

Figure 1 shows the variation in pitch angle, canard angle and aircraft height, plotted as a function of distance, taken from a reconstruction of the third flight on 17 December, flown on the Liverpool Flight Simulator.

The Wright Flyer was unstable, far more unstable than the Wrights had experienced in their gliders during the last three test campaigns at Kitty Hawk. In flight dynamics parlance, the time to double amplitude of the pitch divergence of the Flyer was about 0.5

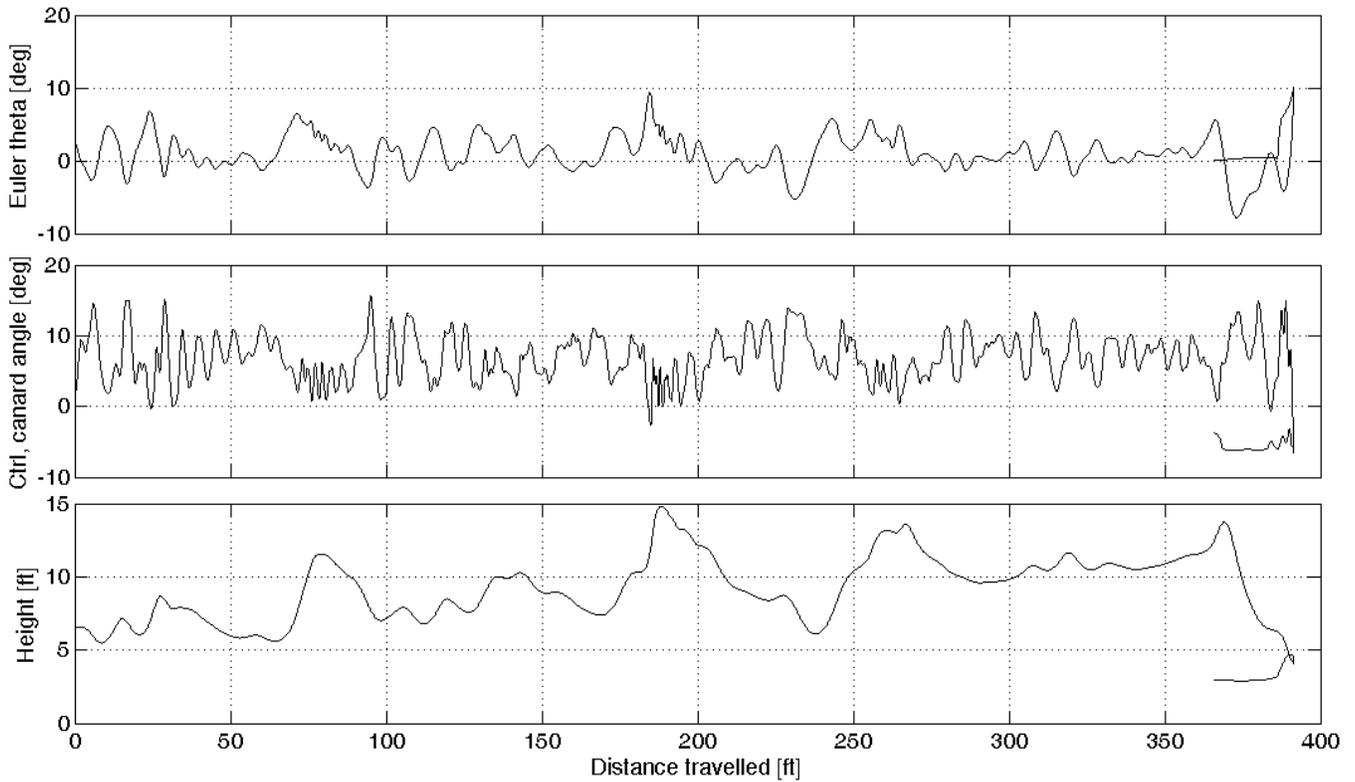


Figure 1. Reconstruction of the third flight of the Wright Flyer, 17 December 1903.

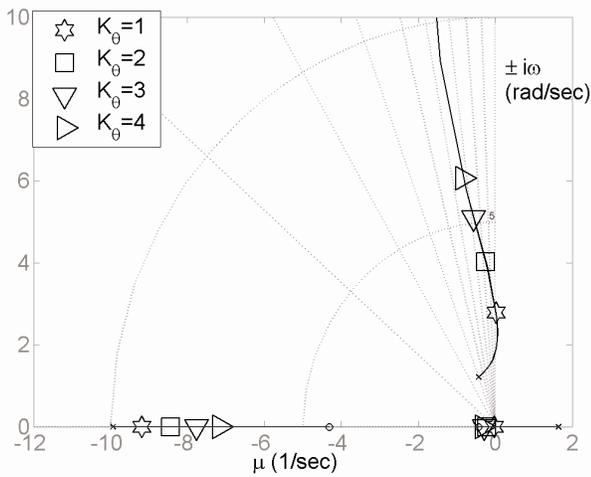


Figure 2. Root loci for 1903 Flyer showing longitudinal modes as a function of pilot gain.

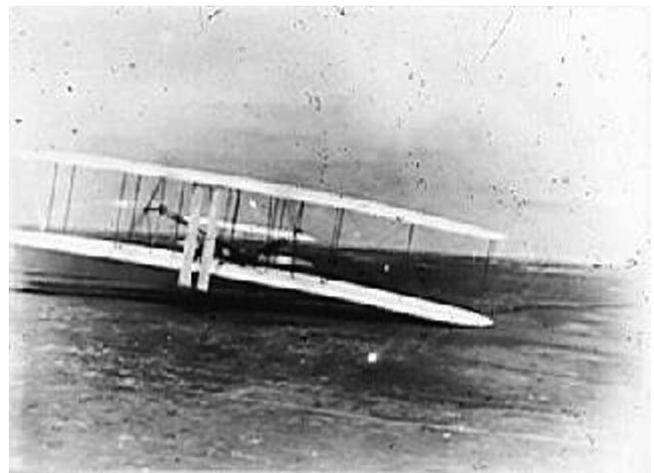


Figure 3. The 'other' photograph taken on 17 December. Orville at the controls during the third flight.

seconds; the static margin was less than -20% . With the pilot controlling pitch attitude, and the pilot had a clear attitude reference with the canard surface, closing the loop with a gain of about 4 deg canard/deg pitch attitude, the divergence was effectively neutralised but a 'new' coupled (pilot-aircraft), poorly damped pitch oscillation dominated the flight behaviour. As first demonstrated by Culick and Jex^(2,3) this closed-loop mode had a frequency of about 6rad/sec at this level of gain. Evidence of this can be seen in Fig. 1, with the

aircraft flying at a ground speed of about 10ft/sec. To reinforce this point, Fig. 2 shows the root loci of the longitudinal modes of the aircraft under the action of a pure gain pilot controlling pitch attitude with the canard. It can be seen that although a relatively low value of gain (K_θ) is sufficient to suppress the divergence, this initially drives the oscillatory pitch-flight path mode unstable. Proportional attitude feedback cannot change the total damping of the aircraft, hence the stability trade-off between the modes.

As the Wrights improved their flying skills they would have learned to anticipate the pitch motion, thus requiring less gain to stabilise the aircraft and adding damping to the short period mode. However, the coupled aircraft-pilot pitch mode would remain a feature of their aircraft for many years. Figure 3 shows the aircraft banked to the right, probably as a result of a lateral gust, because there is no evidence that the Wrights planned any turn manoeuvres during the 1903 tests. On this, his second, flight Orville would probably have been concerned to correct this upset because the starboard wing tip is seen to be practically touching the sand. The roll-yaw interlink, carried forward from the 1902 glider⁽⁴⁻⁷⁾ would have allowed small corrections in bank without the adverse changes in heading caused by warp-drag effects, and neither Orville nor Wilbur would have experienced any adverse effects of this innovative design feature at this stage. Nine months later, they would have to face the negative effects of their enabling design feature head on, as they tried to turn the Flyer II.

In Ref. 4, the authors make the point that the four flights on 17 December 1903 were the culmination of four years of research, design and development by Wilbur and Orville Wright. Within this time they had developed and integrated the technologies required for powered flight and, most importantly, refined the control system to give the pilot control of vertical and horizontal components of the aircraft's flight path. These flights also marked the beginning of a new phase of activity for the Wrights, which commenced properly in May 1904, when they began testing a new aircraft, although essentially a replica of the 1903 machine. Their new test site was Huffman Prairie, eight miles east of their home in Dayton, Ohio, and they commenced with a 100ft launch rail. On the first attempt, with Orville at the controls, the engine fired on only three cylinders and the aircraft, with insufficient power, came down soon after leaving the rail (26 May). It would not be until 16 August that they would exceed the 17 December distance over the ground with a flight of 1,304ft. During 1904 most of their attempts ended in crashes or forced landings within the field. They flew their first circuit of the field on 20 September and finished their 1904 campaign with two flights on 9 December; Wilbur's diary records, "2nd flight...unmanageable." Most of the development of the first practical aeroplane occurred in 1905.

The story of the Wright brothers has a strong technical theme but also a powerful human dimension. Their situation at the end of 1904 is somewhat reminiscent of their return from Kitty Hawk in the winter of 1901. On both occasions they were experiencing difficulties that were testing their engineering skills and commitment, yet on both occasions they found the resolve to continue within their own partnership and the will to succeed. This paper picks up the thread of the story where Ref. 4 left off, using modelling, simulation and flight mechanics analysis to reconstruct the development of the first practical aeroplane from December 1903 up to October 1905, when the Wrights were regularly flying for more than half an hour at a time. Included in Appendix A is a description of the FLIGHTLAB simulation model of the Wright Flyers and associated wind tunnel testing to create an aerodynamic database.

2.0 THE FLIGHTS OF DECEMBER 1903

It can be argued that the flights of 17 December 1903 only occurred as a fortuitous combination of events. Analysis from Ref. 5 has shown that a combination of a strong headwind, ground effect and luck enabled the Wrights to get airborne. The achievement is in no way lessened by this statement, but it rather highlights the skill displayed by the Wrights in keeping the 1903 Flyer airborne at the very edge of its performance. As shown in Fig. 1, the unstable Flyer would have demanded a high level of concentration simply to maintain straight and level flight. Although no turn manoeuvres were attempted in 1903, the Wrights would surely have been actively controlling the warp to maintain wings level. In the reconstructed

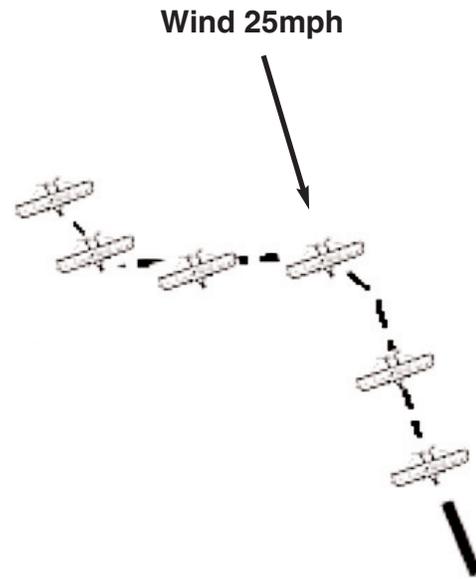


Figure 4. Ground track of aircraft during a reconstructed flight of the Wright Flyer.

flights on the Liverpool Flight Simulator, it has been found that the wind fraction was so high that if any roll attitude was left on, lateral drift developed with aircraft literally flying sideways relative to the ground (see Fig. 4) requiring the pilot to be very active in trying to minimise the roll error, such as Orville would have been during flight no. three, shown in Fig. 2.

The reconstruction flights have shown that there was hardly any performance margin on this aircraft. Little height was gained during the flights, which were mainly being flown between 5 and 15ft above the ground and any lateral manoeuvring resulted in the aircraft losing altitude and impacting the ground. From another reconstruction (Fig. 5), this time plotted against time, it can be seen that there are two distinct frequencies in the pilots control movements.

One, already noted, is a 'high' frequency stabilisation activity at between 1-2Hz. The second motion has a longer period of about 8 seconds. This is associated with the pilot flying between the two 'trim' points for the same power setting. Figure 6 shows the thrust available and drag curves as a function of speed. The lines cross at speeds either side of the deep bucket, at 34ft/s (20.1kt) and 45ft/s (27kt). Between these speeds the pilot was able to oscillate about a trim but if the pilot pitched at the higher speed, the aircraft decelerated towards the low-speed trim condition. Conversely, if the aircraft was pitched forwards from the low-speed condition, the aircraft would accelerate to the higher speed condition. The low-speed condition, on the 'back-side' of the drag curve, was very close to stall, and one can imagine Wilbur Wright would have been anxious about this during the final few moments of his second flight on 17 December. The difficulties flying in the bucket are exacerbated by the non-linear pitching moment with incidence; the aircraft was actually most unstable in the low-speed region (see Fig. 7, from Ref. 2). The 27kt trim condition corresponds to a C_L of about 0.6; increasing C_L leads to an increasing slope of the moment curve, as the flow begins to separate.

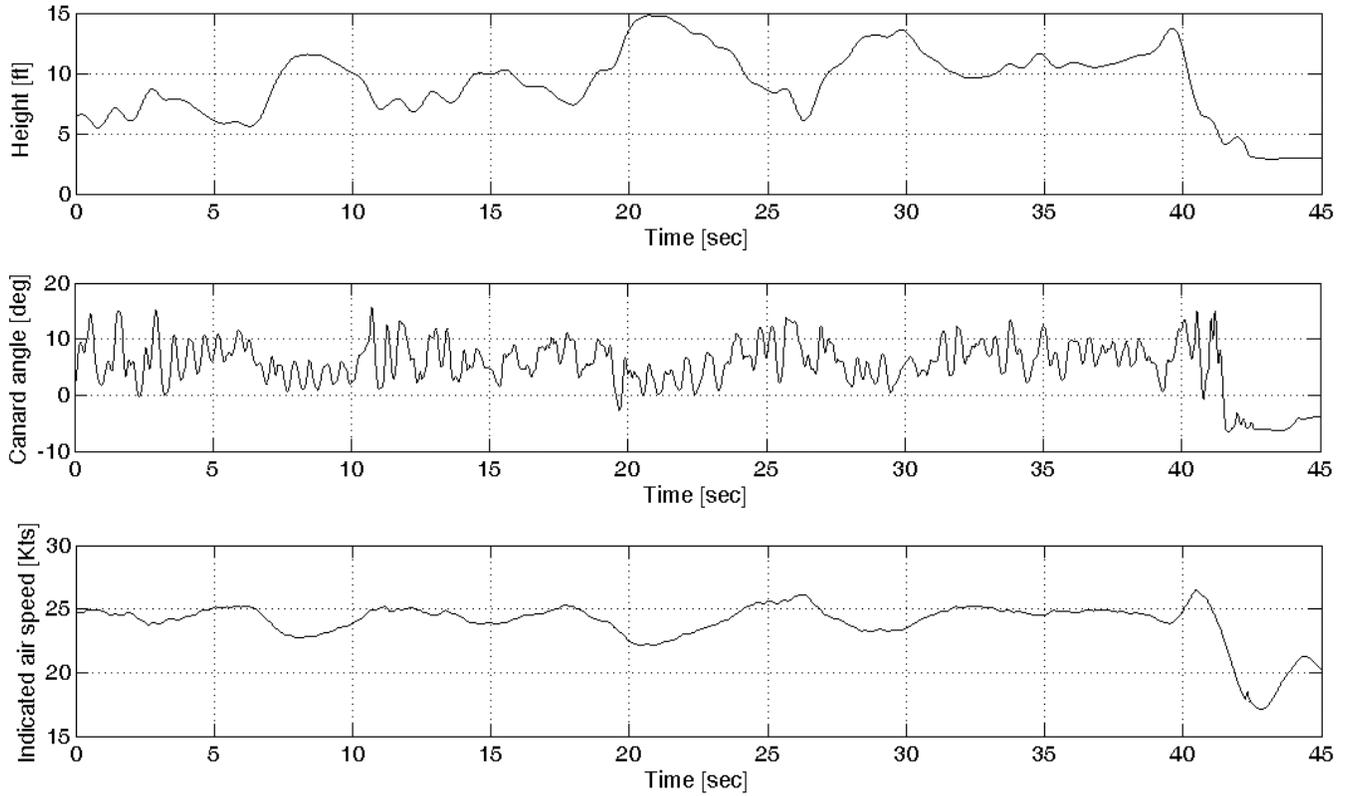


Figure 5. Canard deflection, height and speed during a reconstructed flight.

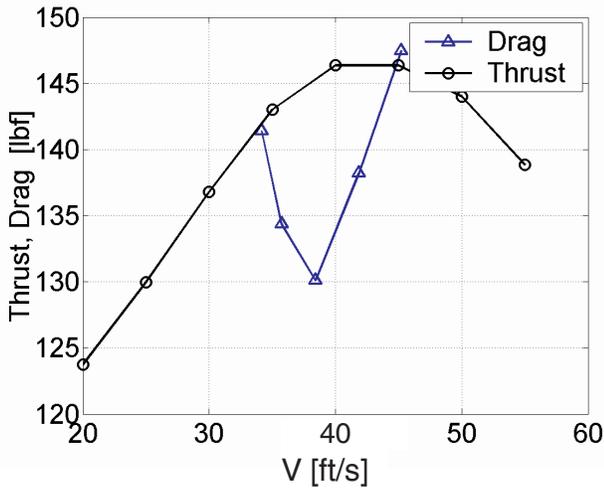


Figure 6. Variations of drag and thrust available of the simulated 1903 Wright Flyer with speed.

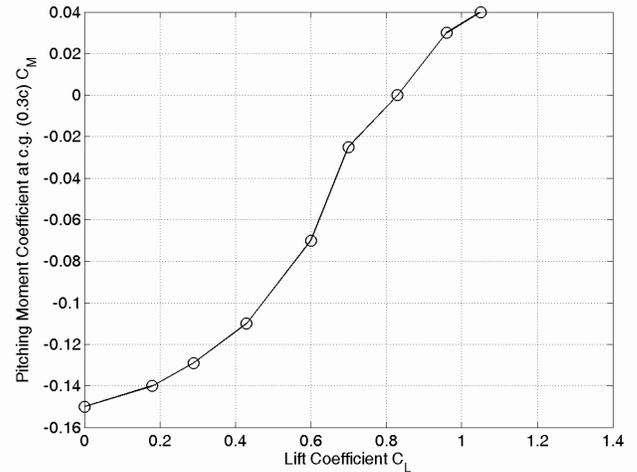


Figure 7. Variation of pitching moment coefficient with lift coefficient, 1903 Flyer⁽²⁾.

3.0 DEVELOPMENTS DURING 1904; WRESTLING WITH HANDLING QUALITIES

The remarkable achievement of 1903 becomes even more apparent when the 1904 experiments are considered. The Wrights best flight on 17 Dec was not matched until August of 1904, after more than a

month of flight testing. During the first half of 1904 the Wrights were busy manufacturing new aircraft (see Ref. 1, page 412 where there is a reference to “working on hinges for three machines”). Octave Chanute visited the Wrights in Dayton on 22 January to congratulate them but also to discuss their participation in a planned air race in St Louis. Wilbur visited the fairground in St Louis on 17 February but he was concerned about having to make a ‘forced landing’ on the rough field. Chanute was persistent with the Wrights

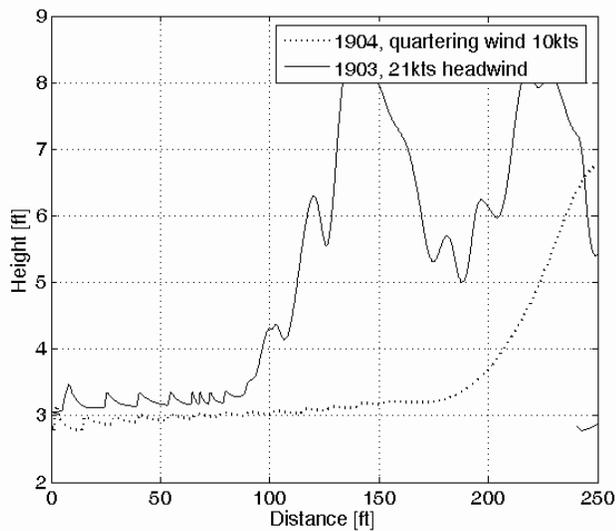


Figure 8. Height variations during reconstructed take offs.

and Wilbur wrote again to him on 1 March claiming that, “...if we enter it will be to win”. Later, Wilbur would deny any interest in competitions. The Wrights were also spending time filing patents in several countries.

On Monday, 26 May 1904, Orville Wright flew about 25ft; they had laid 100ft of track and the wind was $\frac{3}{4}$ m/sec. Later that week the aircraft crashed on take-off, breaking several spars. The machine was “...entirely new, except for old screws.” Their test site was Huffman Prairie, eight miles east of Dayton, Ohio – a large meadow, about 100 acres, skirted west and north by trees. On 21 June Orville noted that he ‘stalled’ after 200ft, taking off at 18mph in a wind of 8mph. The difficulty was mainly with getting airborne; the winds at Huffman prairie were often light and even with a much longer take-off rail of 160ft (compared with 60ft in 1903), the Wrights struggled to take-off. The simulation reconstructions have confirmed this behaviour and the pilots would need the entire take-off rail and often more. If they did try to get airborne before the end of the rail the amount of aft control required to ‘unstuck’ the aircraft would result in a rapid pitch up once airborne which either caused a PIO and subsequent crash, or stalled the aircraft which then ‘pancaked’ back to the surface. Figure 8 shows a comparison of takeoffs with the 1903 Flyer I into wind and the 1904 Flyer II into a much lower wind.

The Figure shows that the Flyer with a much greater headwind was able to get airborne in approximately 60-70ft whereas with a 10kt quartering wind (16 August 1904), the 1904 Flyer needed about 175ft. Both figures compare reasonably well with actual flights where the aircraft were able to get airborne at the end of their respective 60ft and 160ft take off rails. At this time the Wrights also increased the propeller rpm, after conducting thrust tests (Ref. 1, Wilbur Wright Diary, 4 July, 10in screws at 1,120rpm gave 128lb thrust, 7.5 inch screws at 1,340rpm gave 160lb). This thrust increase would be critical to achieving successful take offs.

Once airborne the Wrights were still struggling with the longitudinal stability of their Flyer. In trying to address this problem the Wrights made an uncharacteristic error – they moved the centre-of-gravity (cg) further aft. In a letter to Octave Chanute on July 1st, Wilbur wrote that “...all experiments have shown that cg rather too far forward, so moving engine, man and water tank to rear”. They were presumably confused between what to do to compensate for the large nose-down pitching moment from the wing camber, and to

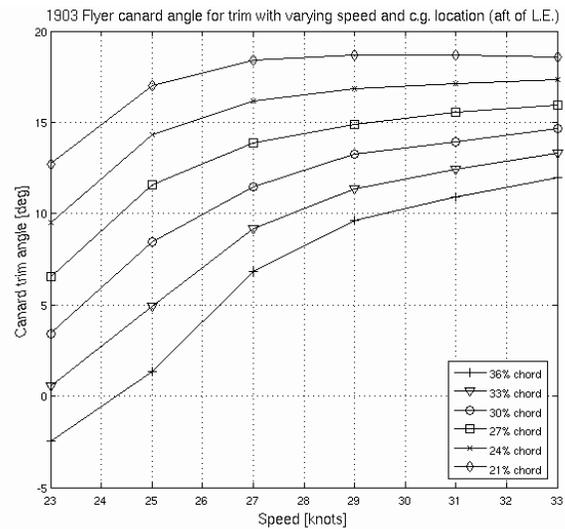


Figure 9. Variation of canard angle with airspeed and cg location.

correct for static instability. The aft shift made the Flyer even more unstable, of course, and the Wrights quickly recognised their error, reversed the change and even went as far as adding 70lb of ballast to the canard framing. This fix was successful in reducing the longitudinal instability but it was a solution that was only effective up to a point. The more forward ballast, the greater the load the canard must carry. Figure 9 shows the canard angle for trim for different cg positions and flight speeds; the lift on the low aspect ratio surface would continue to increase at high angles of attack but was clearly limited at the forward cg locations. The slope of the canard-to-trim curve was positive up to speeds of about 28kt, so the pilot needed to hold the stick further aft as the trim speed increased. At the forward cg locations the trim curve flattens and almost neutral stability is established. At the very aft cg locations the canard would have been carrying a download.

It would seem that the Wright brothers rarely engaged with the concept of stability during the 1904-5 trials and the notion of time to double amplitude (T_2) would have been alien to them. Figure 10 shows how T_2 , for the pitch mode of all three simulated Flyers, varies with airspeed. The 1903 Flyer features a T_2 of about 0.5 seconds at the 27kt trim condition. The initial modifications in 1904 would have made the aircraft impossible to fly (T_2 of about 0.3 seconds). As the speed increased, and incidence decreased, the pitching moment slope lessened and the aircraft was less unstable. The final configuration in 1905, at speeds about 30kt, featured a T_2 of about one second. Discussion on this aircraft will continue in the next section.

In a letter to Octave Chanute dated 28 August, Wilbur made the point that;

“... we find that the greatest speed over the ground is attained in the flights against the strongest breezes. We find that our speed at starting is about 29 or 30 ft per second... When the wind averages much below 10ft per second, it is very difficult to maintain flight, because the variations of the wind are such as to reduce the relative speed so low at times that the resistance becomes greater than the thrust of the screws. Under such circumstances the best of management will not insure a long flight, and at best the speed accelerates very slowly. In one flight of $39\frac{1}{4}$ seconds, the average speed over the ground was only 33ft. per second, a velocity only about 3ft. per second greater than that at starting. The wind aver-

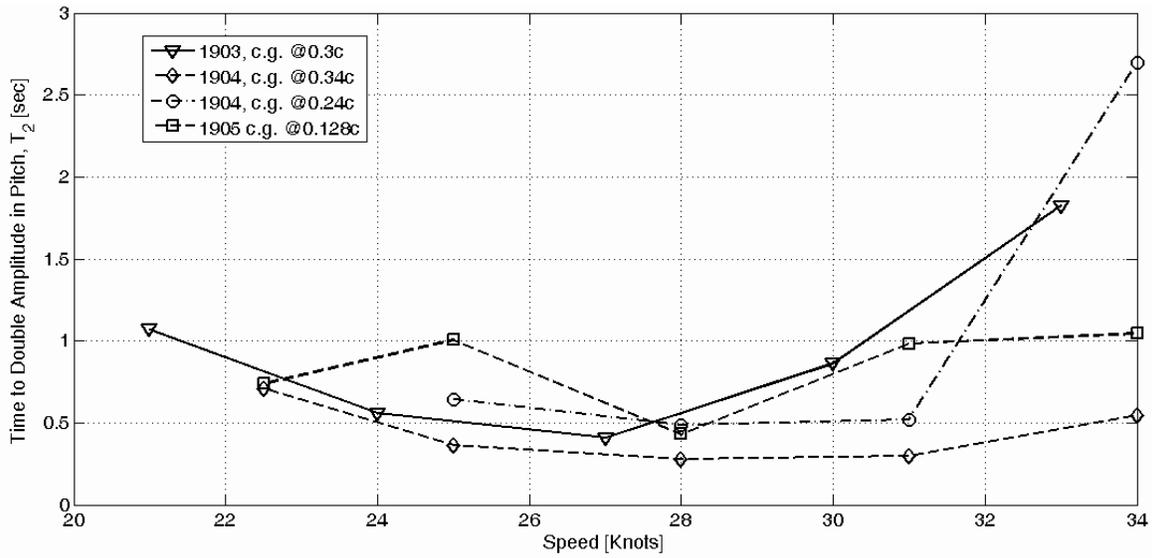


Figure 10. Variation of time to double amplitude of simulated Wright Flyers as a function of airspeed.

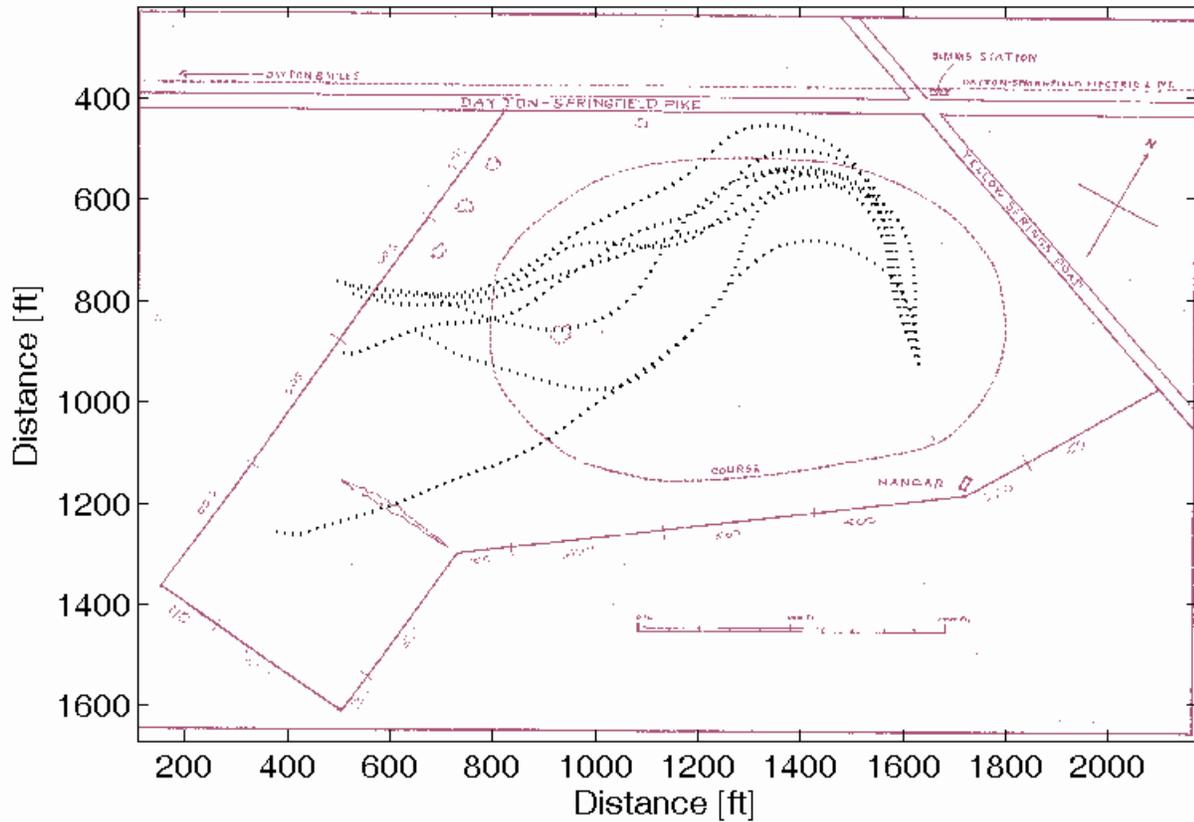


Figure 11. S-turns completed by test pilots flying FLIGHTLAB 1904 Flyer simulation over the reconstructed Huffman Prairie test site.

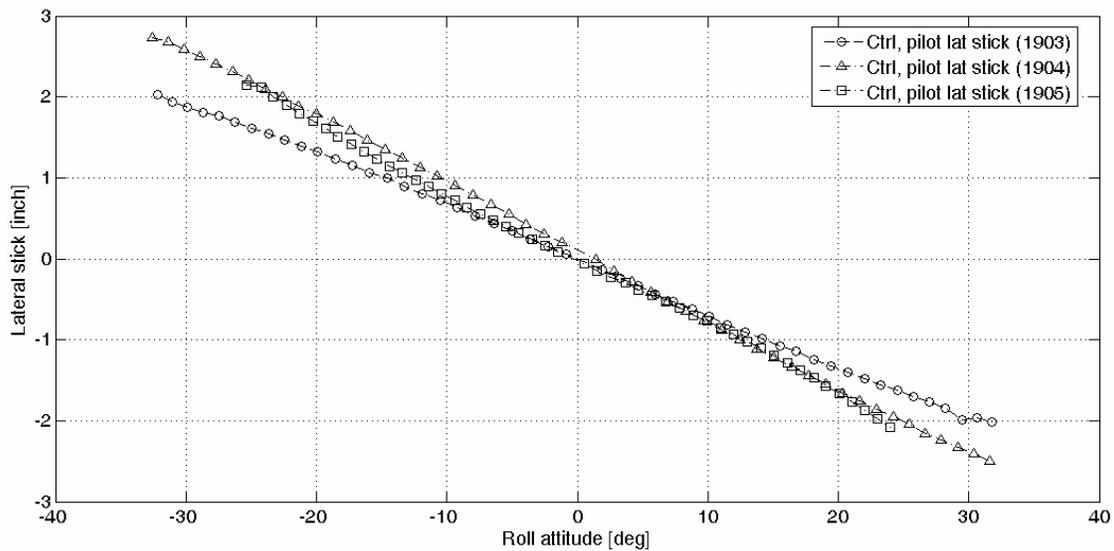


Figure 12. Lateral 'stick' on the simulated Flyers in trimmed turning flight.

aged 12ft. per second. In a flight against a wind averaging 17ft. per second, the average speed over the ground was 42ft. per second, an average relative velocity of 59ft. per second, and an indicated maximum velocity of 70ft. per second. We think the machine when in full flight will maintain an average relative velocity of at least 45 miles an hour. This is rather more than we care for at present."

The performance figures highlight the improved thrust delivered from the engine of the 1904 Flyer compared with 1903 (see Fig. 6, where the thrust first equals drag at about 34ft. per second; in a previous letter to Chanute, Wilbur had indicated that the resistance falls below the thrust at about 40ft per second). Wilbur also informed Octave Chanute that they had flown over 1,400ft. and also that they were building a starting device. Chanute congratulated them on their 'good progress' in his reply, but did not engage in any discussion about their achievements. This is somewhat surprising, but perhaps indicates a growing caution and tentativeness in the communications, that had for three years provided such a fruitful channel for the development of technical understanding. The seeds of tension may well have been sown eight months before with the Wrights' communication to the Associated Press; Chanute wrote to Wilbur referring to this statement on 14 January;

"In the clipping which you sent me you say: "All the experiments have been conducted at our own expense, without assistance from any individual or institution." – Please write me just what you had in your mind concerning myself when you framed that sentence in that way."

Chanute's view of his contribution to the Wrights achievement was somewhat different to those of the Wright brothers.

By September 1904 the Wrights had completed building their launching derrick (see Fig. 13), and using weights of up to 1,400lb and various track lengths, began to achieve more consistent, successful performance. The increased take-off speeds enabled them to attempt their first turns and the handling qualities of turning flight would plunge them into a new state of confusion. On 20 September the Wrights were airborne in flights of over one minute and covering

distances greater than 1,000m. They also made several S-turns around the trees and Wilbur flew the first circuit of the Huffman field during Flight number 52 on Tuesday 20, September, covering a distance of over 4,000ft. and flying for more than one and a half minutes. Amos Root had travelled from Medina to witness the Wrights' flights that day and later wrote in his 'Gleanings in Bee Culture' magazine⁽⁸⁾ – "imagine this white locomotive, with wings that spread 20 feet each way, coming right towards you with a tremendous flap of its propellers, and you will have something like what I saw. The younger brother bade me move to one side for fear it might come down suddenly: but I tell you friends, the sensation that one feels in such a crisis is something hard to describe. ...these two brothers have probably not even a faint glimpse of what their discovery is going to bring to the children of men. No-one living can give a guess of what is coming along this line...". The Wrights were more focused on their immediate goal; they had learned to fly a circuit of the field but were now encountering new handling difficulties as they tried to turn more tightly in the small field.

Figure 11 shows the flight-paths for a series of reconstructed S-turn flights overlaid on Orville Wright's sketch of the Huffman Prairie and the so-called 'course' that they would subsequently fly circuits over. The test pilots' experience flying the Flyer on the Liverpool simulator echoed the descriptions in the Wrights' diaries (see Ref. 1, pages 456-472). A principal characteristic was the need to hold out-of-turn warp to prevent the aircraft from spiralling (see Fig. 12, showing how out-of-turn control was required on all three Flyers). In the Liverpool simulator the pilot uses a conventional centre stick control; positive stick deflection (to starboard), corresponds to hip cradle movement to starboard.

In a steady turn to the left, the negative rolling moment due to yaw rate (L_r) reflects the increased lift on the starboard wing, requiring out-of-turn warp to balance. The interlinked rudder then deflects out-of-turn causing the aircraft to sideslip into the turn and the directional stability (N_v) then increases the yaw rate in the turn. With the wings set at a slight anhedral angle, the rolling moment due to sideslip (L_v) rolls the aircraft further into the turn, requiring even more out-of-turn warp. The warp on the port wing increases the drag

Table 1
Stability derivatives of various Wright Flyers 1903-05 (all 26)

	N_v	L_r	L_v	N_r	μ
1903	0.0483	1.6808	0.0152	-0.8594	0.094
1904 Version 1	0.0441	1.6920	0.0125	-0.8412	0.085
1904 (aft cg)	0.0411	1.6917	0.0117	-0.8236	0.08
1904-5 dihedral	0.0331	1.6870	-0.0326	-0.8375	0.029
1905 Version 1 inc blinkers	0.0235	1.6685	0.0177	-1.0556	0.058
1905 (final)	0.03	1.8856	-0.012	-0.6832	0.048

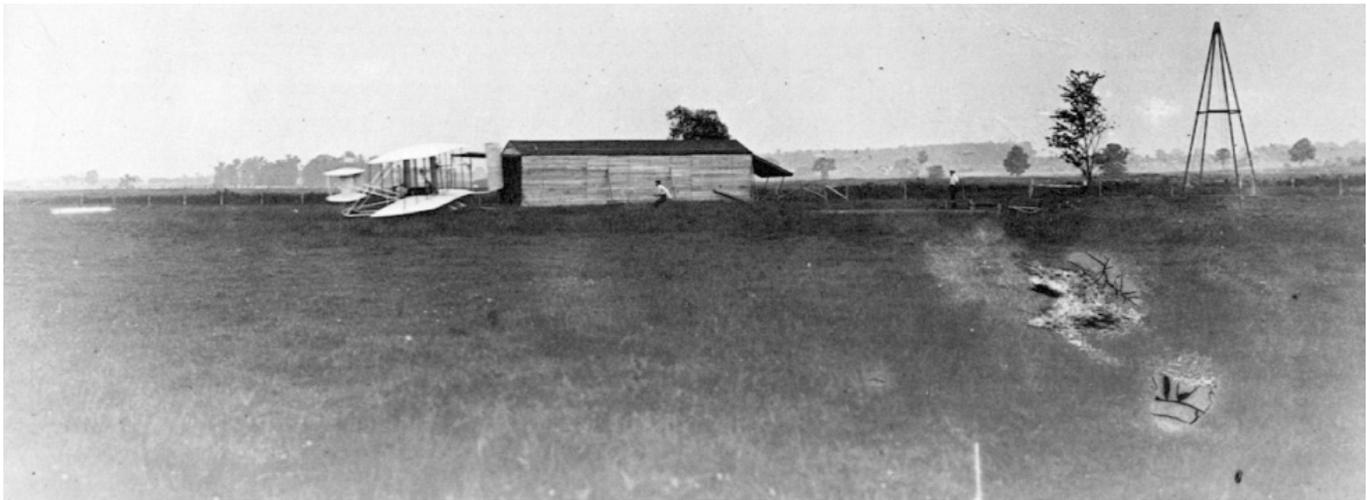


Figure 13. The first flight of 1905, 23 June, Orville Wright at controls.

of that wing, further increasing the yawing moment into the turn. Orville would later describe the configuration with anhedral and fixed tail as "... the most dangerous used upon any machine I have ever flown" (Ref. 1, page 470). He was referring to flights in the 1902 glider and he goes on to say that removing one of the vertical surfaces "... only slightly mitigated the evil influence of vanes". The Wrights were experiencing the unstable effects of what would become known as the spiral mode, the dynamic characteristics of which are defined by the expression⁽⁴⁾,

$$\mu = N_v L_r - L_v N_r \quad \dots (1)$$

N_v is the weathercock stability derivative and L_v the dihedral derivative. N_r is the yaw damping and L_r the yaw-to-roll coupling, discussed above.

Equation 1 can also be written in terms of an effective weathercock stability;

$$\mu = (N_v - L_v N_r / L_r) L_r \quad \dots (2)$$

Strong weathercock stability combined with weak dihedral, or even anhedral, makes the spiral mode very unstable. Table 1 gives values of the spiral derivatives for the various Wright configurations. Even the move from anhedral to dihedral in 1904 would not stabilise the mode; the 'evil vanes' as Orville described the rear rudder, gave too strong an N_v . The final 1905 Flyer III featured a spiral mode with a time to double amplitude of about 2.5 seconds⁽⁹⁾.

The Wrights retained the anhedral wing in the 1904 Flyer II giving a small positive (destabilising) value of L_v . The dominant effect in the spiral mode was the combination of derivatives N_v and L_r which, without separate control of yaw motion, and with warp control close to the out-of-turn stop, could easily lead to an

uncontrollable situation. On several occasions, the Wrights found that they were "unable to stop turning" (e.g. Flight 87, Ref. 1, page 465). A question is – did the Wrights introduce separate control of the vertical rudder in 1904? In Wilbur Wright's summary of the experiments of 1904 (Ref. 1, page 469), referring to flights in September through November 1904, he states that "In all these flights the warping wires and the wires controlling the vertical tail were interconnected". However, in Orville Wright's deposition of 13 January, 1920 (Ref. 1, page 471), he states that

"...The controls of the 1905 machine were operated in a slightly different manner from those of the 1903 machine. The vertical rear rudder was not connected up, so as to automatically operate in conjunction with the wing warping, but instead was coupled up to a lever, so that it could be operated either independently of the warping or in conjunction therewith. It was operated in this manner in a few of the flights in 1904, but not in many of that year."

In the 1904 diary notes published in Ref. 1, there is no mention of the Wrights changing the method of control. In a letter to Octave Chanute dated 15 November 1904, Wilbur states that "The changes made to remedy the trouble which caused Orville's misfortune gave the machine an unfamiliar feeling...". Chanute had been present at Dayton to witness Flights 68-70 and noted in a memorandum (Ref. 1, page 462) "Wrights think machine arched too much and speed too great across wind". So did the Wrights remove the anhedral or did they explore giving the pilot a separate control of the vertical rudder during the 1904 season? Unfortunately Chanute did not enquire into the details in his reply. In his final letter to Chanute in 1904, dated 20 December, Wilbur Wright provides a little more insight into their findings.

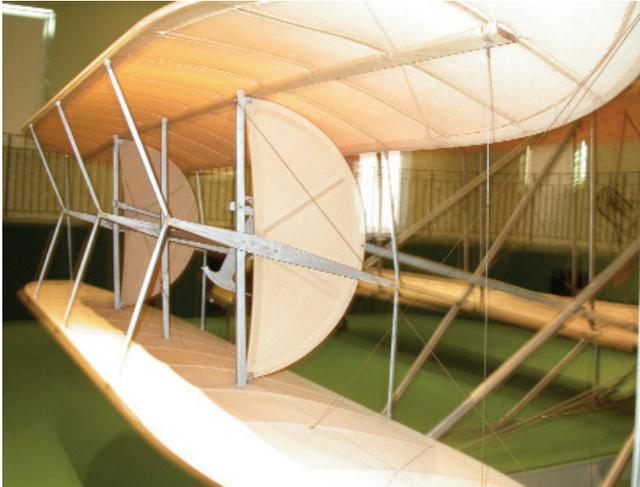


Figure 14. The canard and front vanes (blinkers) on the National Historic Landmark, the Flyer III.



Figure 16. The rear rudder on the Flyer III.



Figure 15. Model of Wilbur in the Flyer III at Carillon Park showing control mechanisms.

"We finished our experiments several weeks ago and have now dismantled the machine. During the season one hundred and five starts were made. The best flights since my last letter were on Nov 16th and Dec 1st, the flights being 2¼ turns of the field on the first named date, and almost four rounds on the last. Although 70lbs of steel were carried in this last flight to balance the machine, it was still insufficient and the flight was made with pressure on the top side of the front rudder. We succeeded in curing the trouble caused by the tendency of the machine to turn up too much laterally when a short turn was made."

In his reply Chanute again congratulated the Wrights but again did not enquire about details; was he interested? So questions remain as to what exactly the Wright brothers did in those last few weeks of 1904 to modify the lateral-directional flight characteristics. But they had reached a watershed in the development of a practical aeroplane. Of those 105 starts in 1904, many had resulted in premature crashes on take off, and they had spent more time repairing than flying. In 1905 they would begin a major re-design of their aircraft.

4.0 DEVELOPMENTS DURING 1905; THE FINAL PUSH

Orville Wright took to the air in the first flight of 1905 on 23 June. Wilbur writes *"The machine was fitted with two semicircular vertical front vanes (7 sq. ft.) and was very hard to control"* (see Fig. 13, also showing launching derrick). Of the third flight on 24 June Wilbur wrote,

"Machine turned suddenly to left and struck left wing tip, breaking rear spar of left lower wing, and cracked end bow. The trouble in management is attributed to presence of front vanes combined with unskilful handling of rear rudder."

There is a clear reference here to the pilot having control of the rear rudder (Ref. 1, page 499).

By the time the Wrights had repaired this serious structural damage and were ready to fly again, it was 30 June and *"the front vanes had been removed"* (Ref. 1, page 500). Interestingly, the restored 1905 Flyer III, at Carillon Park, Dayton Ohio, features the front vanes (see Fig. 14), although these would not appear again on the 1905 machine after Flight number 8 on 30 June. The Wrights believed that their aircraft had too much directional stability, although they never expressed it this way, and until they introduced dihedral they would be plagued with a very unstable spiral mode.

They continued to have problems with steering. Of the fourth flight on 30 June, Wilbur notes in his diary,

"Machine refused to steer properly, and while attempting to shift rear rudder W.W. shut off power by mistake. The machine turned up and came almost to a standstill, and dropped very hard, breaking rear centre spar and front left spar at corner, and two uprights. The troubles in steering this day were evidently due to hinging the rear rudder behind the centre of pressure and failing to hold it under firm control by hand."

(Ref. 1, page 500). Figure 15 shows the pilot's control configuration on the Flyer III – pitch control with canard in left hand, yaw control with rear rudder in right hand and roll control through the hip cradle. It must have been difficult to affect precise control with such an arrangement. The leverage required to move the hip cradle was presumably achieved by resting the pilot's weight on his elbows and lower arms, control of the front and rear surfaces then being achieved by wrist movement. The feet would presumably be positioned in front of the rear foot rest, giving further leverage. Pilots flying the Liverpool simulation of the Flyer III (Ref. 9) returned Level 2 handling qualities ratings flying with conventional stick and rudder pedals. The

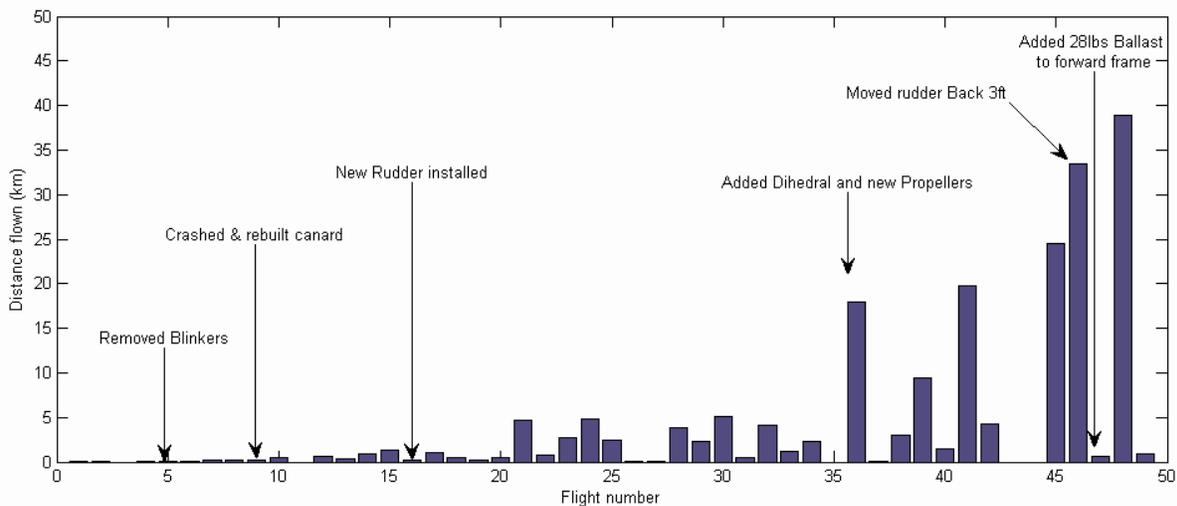


Figure 17. Summary of flights (distance achieved) in 1905 and associated modifications.

fuel control was clearly close to the pilot's right handle control and a sudden reduction in thrust would have resulted in a large nose up pitching moment, the thrust line being above the cg.

The problem of balancing the rear rudder was a challenge for the Wrights, prompting them to make further measurements of the movement of the centre of pressure on surfaces. Figure 16 shows the final configuration of the Flyer III with the hinge axis at about 30% chord. The surface is actually fairly flat with a centre of pressure leading the hinge line; retaining some (negative) aerodynamic stiffness would have made it easier to move the surface using the control inceptor shown in Fig. 15.

The Wrights were ready to fly again on 14 July but Orville lost control during the first flight (Flight number 9), (*"the machine...began to undulate somewhat and suddenly turned downwards and struck the ground at a considerable angle breaking... O.W. was thrown violently out, but suffered no injuries at all."*). The Wrights picked themselves up again, their resolve yet again emphasising their belief that they were close to success. The period between Flight 10, on 24 August, and Flight 49 on 16 October, when they ended their flying, is documented in about nine pages in Ref. 1 (compared with about 100 pages describing the aerodynamic developments during late 2001 and early 2002). The period is one of intense learning and development, summarised in Fig. 17 which shows the changes made at the various flight numbers and corresponding distance flown.

The Wrights increased the size of the canard and its distance from the pilot, increased the size of the vertical rudder and re-wired the wing to add dihedral (Saturday 23 September). On 28 September, Orville flew over 9km before impacting a honey locust tree during a turn. On 3 October Orville flew for more than 24km in 25 minutes and the next day he flew over 34km in 34 minutes. The next day, Flight 48 on 5 October, Wilbur Wright flew 39km in 39 minutes. At this point the flights were being witnessed regularly by travelers on the passing traction cars and by various visitors. The Wrights were getting nervous, partly because their patents had not yet been secured. Wilbur wrote in his diary later on the 5th, *"experiments discontinued for the present"*; this action was also stimulated by an article in the local *Daily News* that evening. Wilbur wrote to Octave Chanute on 19 October informing him of their progress (Ref. 1, page 517). *"The wet grounds did not permit us to resume experiments till the last week of September, but the next two weeks were so fine that*

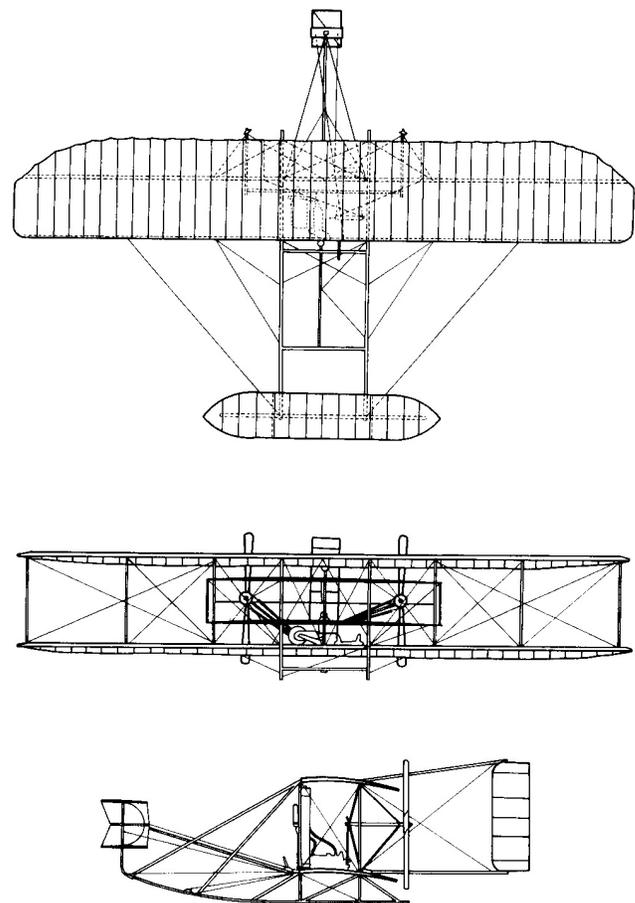


Figure 18. The Wright Flyer III.

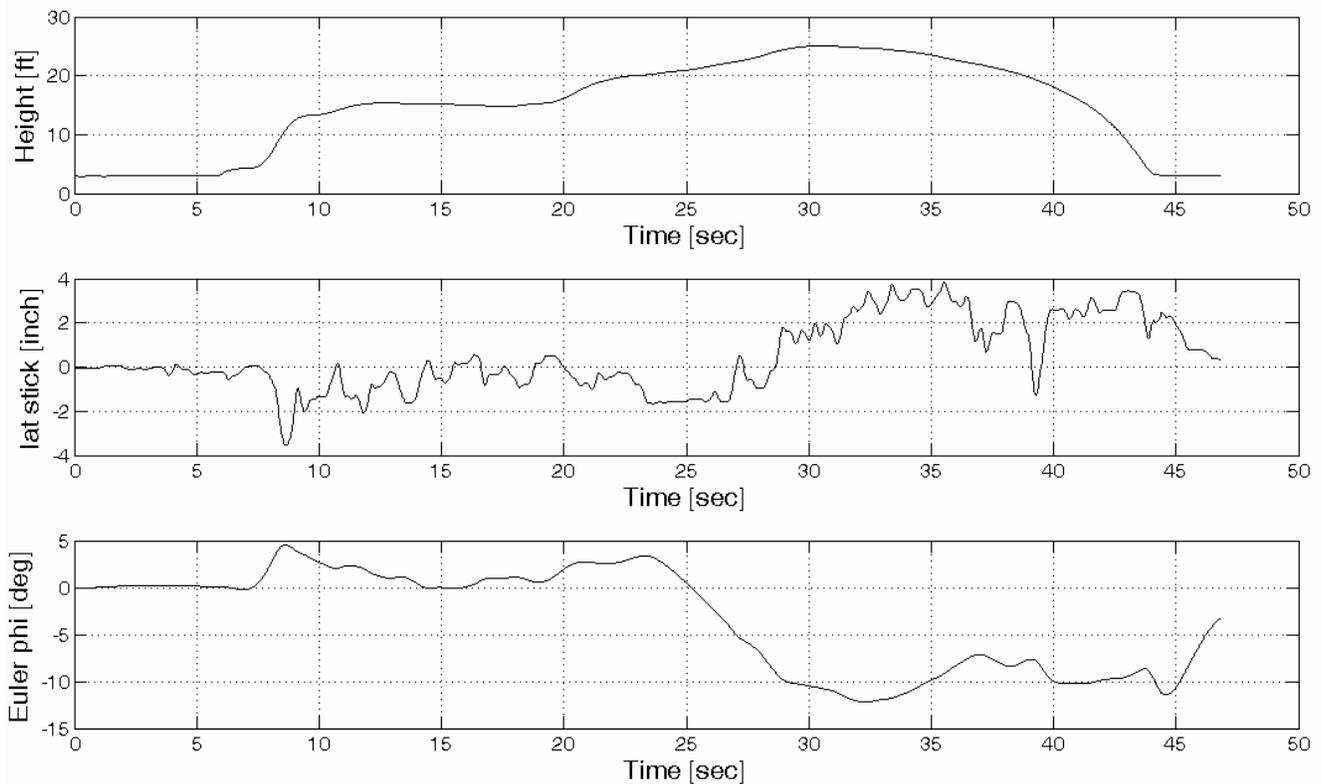


Figure 19. Wing warp and roll angle in turn.

we did more flying than in all our previous flights of three years put together." The Wrights planned to attempt a flight of more than one hour, but a brief flight on 16 October ended their flying for the season; they would not fly again until they returned to the relative privacy of Kitty Hawk during May 1908.

Figure 18 shows the 1905 Flyer in its final configuration, with a biplane canard of approximately 84ft², a wing area of 503ft² and a mass of approximately 920lb (including pilot, ballast and fuel) (Wilbur and Orville Wright's Notebook O, 1908-1912, p12, Ref. 10).

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 Wright's confusion over the effects of camber. The Wright's first experience of the problems associated with high camber was with the 1901 glider. The glider initially had a very large camber of 1/12 which required an aft cg position to achieve longitudinal trim. This made the glider particularly unstable. Their fix was to reduce the camber, enabling a more forward cg position, thus reducing the instability. The Wrights never forgot this lesson but likely misinterpreted the situation. As noted earlier, it wasn't the camber causing the instability, of course, but the consequent cg position. In 1902, their camber was reduced further and the stability was improved. By 1903, the camber was increased again and the stability deteriorated again. The Wrights were probably very confused by these effects. In 1904 they began to understand the problem; 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, as noted earlier, 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 70lb on the forward framing to move the centre of gravity forwards. 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 more than 35mph.

In his summary of experiments of 1905 (Ref. 1, page 519) Wilbur Wright provides an interesting insight into their thinking and practices at the time.

"In 1905 we built another machine and resumed our experiments in the same field near Dayton, Ohio. Our particular object was to clear up the mystery which we had encountered on a few occasions during the preceding year. During all the flights, we had made up to this time we had kept close to the ground, usually within ten feet of the ground, in order that, in case we met any new and mysterious phenomenon, we could make a safe landing. With only one life to spend we did not consider it advisable to attempt to explore mysteries at such great height from the ground that a fall would put an end to our investigations and leave the mystery unsolved. The machine had reached the ground, in the peculiar cases I have mentioned, too soon for us to determine whether the trouble was due to slowness of the correction or whether it was due to a change of conditions, which would have increased in intensity, if it had continued, until the machine would have been entirely overturned and quite beyond the control of the operator.... A flight was made on 28th September 1905, with the rudder wires entirely disconnected from the warping wires (Author's note – in other places it appears that the disconnection was first made at the beginning of the 1905 season, or even at the end of the 1904 season). When it was noticed that the machine was tilting up and sliding towards the tree, the operator turned the machine down in front and found that the apparatus then responded promptly to lateral control. The remedy was found to consist in the more skillful operation of the machine and not in a different construction."



Figure 20. The Wright Flyer III over Huffman Prairie in 1905.

Wilbur was partly correct; with their unstable configuration, that had served them so well for the last four years, pilot skill was the 'solution' to the handling deficiencies. Figure 19, taken from one of the reconstructed flights, shows how the out-of-turn lateral control builds up as the roll angle and, therefore turn rate, is increased. Eventually the pilot runs out of corrective control and, if this loss of control was not enough, another problem could well have caused the Wrights further difficulty. The warp on the inside wing may well have been so high that the tip was 'stalled'; the drag would then have pulled the wing even further around. It seems that the Wrights were rarely able to appreciate the benefits of linear aerodynamics.

Figure 20 shows the 1905 Flyer III flying over the Huffman Prairie. By the time the Wrights had completed development of this aircraft they were sufficiently confident in its performance, flying characteristics and structural robustness that they were ready to put it on the market.

5.0 DISCUSSION

The question is often asked – why did the Wrights persist with an unstable configuration? Early in their aeronautical journey, they firmly established for themselves the advantages of the canard surface for control of the vertical flight path and wing warping for the control of the horizontal flight path. The canard configuration is not in itself unstable, this being determined by the relative positions of the neutral point (aerodynamic centre of the whole aircraft) and centre of gravity. The Wrights used large camber on their surfaces, so when they tried to fly with the 'auxiliary' surface at the tail, they discovered the need for a large download, and also the dangerous nose down pitch at stall due to the aft shift of the centre of pressure. Flying at ten feet above the surface, this nose down stall was not recoverable. So their canard configuration was more efficient and safer at stall, although more difficult to fly. As bicycle engineers, the Wrights were familiar with machines that required continual correction by the operator in normal use so this feature would not necessarily have concerned them. The operator would have to develop the skills to fly. The canard also provided two other positive characteristics; it gave the pilot a powerful attitude reference, very important in a pitch-unstable aircraft, and it also took the brunt of impact, protecting the pilot during the many crashes that the Wrights experienced.

The anhedral wing configuration, with warping coupled with the small single surface vertical fin, gave the 1902 aircraft almost neutral roll response to lateral gusts, while allowing the pilot to

correct the small changes in heading caused by shifts in wind direction. This is exactly what was required during the flying at Kitty Hawk (see Ref. 4), and enabled the Wright brothers to master flying skills and gave them the confidence to develop a powered machine. On a more general note, the natural instabilities gave the Wright aircraft more responsiveness, very important when flying close to the ground at low-speed. Nowadays, such features are also deliberately designed into aircraft, to provide for more agility and aerodynamic efficiency, with active control functions in the flight control computers working to provide the stability when required.

After their experiences in 1901, when their gliders did not perform as well as they expected using other people's data, the Wright brothers produced their own aerodynamic database from wind-tunnel testing, creating the most extensive set of aerodynamic knowledge available at the time. From this, and the consequent development of the 1902 glider, they would have gained considerable confidence, but also an understanding that they could only really trust their own data and experience; they must have felt alone and very much in the lead in their quest. They would have to face the challenges in 1904 and 1905 with the same resolve. However, there was no flight dynamics theory available to them and no scope for wind tunnel testing of the aircraft dynamics. The evolving process of invention in these two important years relied on the Wright's skills, not only as engineers, but also as pilots. They were obviously very motivated to fly, but also to complete their developments and progress with the commercialisation, now very much on their agenda; aeroplane making would replace bicycle making as their business. So the Wright brothers paused in October 1905. In modern handling qualities engineering parlance, they had produced a Level 2 aircraft (see appendix A and Reference 9) and it would be many years until they, or indeed anyone else, would know how to design for fully safe (Level 1) handling qualities.

As the Liverpool Wright project continues, the authors plan to examine developments during the 1907-1909 period, with the so-called 1907-model, model Type A and Signal Corps Machine. All these aircraft were essentially developments of the 1905 Flyer III, but important changes would include the pilots now sitting and operating independent control levers, and the addition of a passenger seat. During the period up to 1908, European aviation pioneers were making faltering attempts to fly but it was Wilbur Wright's demonstration flights at the Hunaudières race track in August 1908 that finally opened the door to European development. In his book *The Bishop's Boys*, Tom Crouch quotes from *L'Aerophile* –

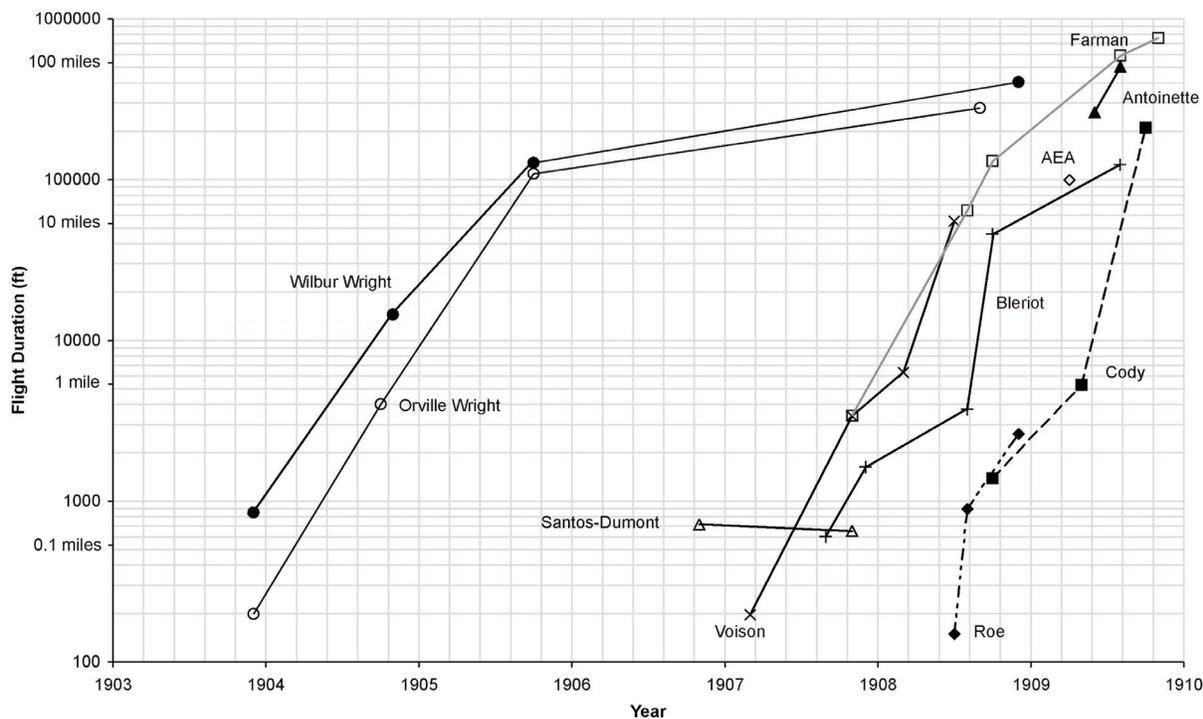


Figure 21. Powered flights 1903-1910 (from Ref. 12 data).

“the facility with which the machine flies, and the dexterity with which the aviator gave proof from the first, in his manoeuvring, have completely dissipated our doubts. Not one of the former detractors of the Wrights dare question, today, the previous experiments of the men who were truly the first to fly...”

Blériot added – *“I consider that for us in France and everywhere a new era in mechanical flight has commenced...it is marvellous.”* (Ref. 11, page 368). Of course, the Wrights had first flown nearly five years previously. After the spectacular flights in France, Wilbur wrote to Orville who was preparing for similar demonstration flights in the US at Fort Myer. Wilbur had experienced new difficulties in flying the machine and described them to Orville, ending with a caution – *“...Be awfully careful in beginning practicing and go slowly.”*

Since those early days, aviation has held the twin goals of performance and safety in the balance. It is interesting to examine the various flights of the Wright brothers in terms of one of the most important performance parameters – aircraft range. Figure 21 shows flight duration in feet/miles of the different actors over the period 1903-1910, plotted on a log-linear scale (data taken from Ref. 12, page 278). We start with the Wrights in 1903, when they flew 852 feet over the sands at Kitty Hawk. In October 1905 they flew nearly 25 miles. In 1906, the Brazilian Santos Dumont flew his 14-Bis for 722 feet at Bagatelle, France, making this the first flight in Europe, but flight durations with his Demoiselles are unknown to the authors. By the end of 1908, Wilbur Wright had set a new record of 77 miles at Avours France, while Orville had flown 53 miles at Fort Myer in the USA. Henri Farman was

chasing hard and had flown 25 miles at Chalons in October in a modified Voison. Wilbur’s record was beaten on 25 August 1909 by Roger Sommer flying a Henri Farman machine, only to be beaten the following day by Hubert Latham in an Antionette (96 miles). Both these flights took place at Rheims in France during ‘La Grande Semaine d’Aviation de la Champagne’. Later that year Farman would fly his own aircraft for 144 miles at Mourmelon in France. The rate of progress in this period, at the end of 1909, measured by Henri Farman’s progress was about 110 miles per year. Forecasting this forward on a linear scale, aviators at the time might have predicted that in 100 years the maximum range of an aircraft would be about 11,000 miles. The Boeing 777-200LR is due to enter scheduled service in 2006 with a range of nearly 10,000 miles.

The 1909 ‘air show’ at Rheims was a showcase for the progress in European aviation. A few months before, only ten people had flown for more than one minute at a time, but by the summer of 1909, all of the records set by Wrights were broken. The Wright brothers themselves did not attend the show, they were too involved with their aeroplane business. However, Wright Flyers were present and flown by several pilots. Interesting insight into the characteristics of these aircraft can be gleaned from Ref. 13 (quoted in Ref. 12, page 247) ...

“watching the performance from a distance indicated the following points: The Antionette was certainly the steadiest. The machine proceeding with perfect regularity. The Curtiss was also very fairly steady and regular. The Farman and the Blériot were, perhaps, not quite so satisfactory in their general behaviour. The

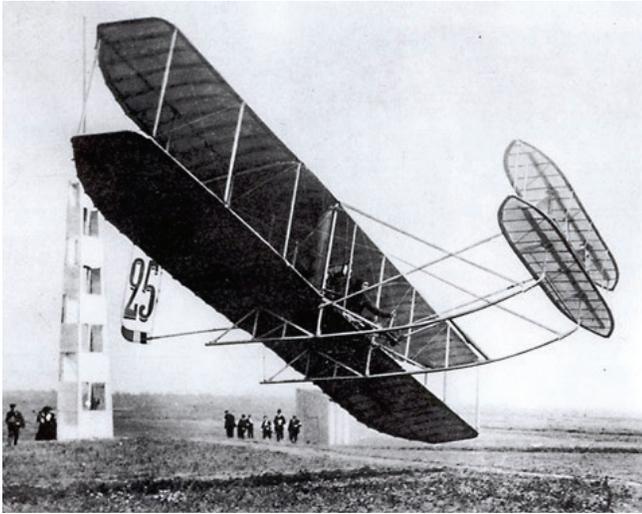


Figure 22. Lefebvre flying a Wright Type A at Rheims in 1909.

Voison struck one as being rather cumbrous and uncertain, while the Wright was distinctly unsteady and continually pitching. This is, however, not the impression gained when watching Mr Wilbur Wright himself (who did not fly at Rheims) steering the machine. It looks as though very much depended upon the pilot, although three different men, Comte de Lambert, M. Tissandier, and M. Lefebvre, handled the machine at Rheims, yet in each case they moved unsteadily, though they appeared to manoeuvre and turn with more ease than other machines."

Figure 22 shows Lefebvre flying a Wright Flyer around the pylons at the circuit. The picture conveys a sense of the intrepid airman, thrilling the crowd with acts of considerable daring. The Wright model A had the lowest wing loading of all the aircraft at Rheims at only 1.92lb/ft², compared with the Blériot at 5.8lb/ft² and the Farman at 2.85lb/ft². The low wing loading would increase the gust response but also reduce the time constant of the lift response (the so-called incidence lag) and this, coupled with the pitch instability, would make the aircraft very responsive, but requiring the pilot's full attention to maintain the required flight path.

6.0 CONCLUDING REMARKS

The Wright brothers achievements are to be celebrated during this centenary period not only for the products of their efforts, the invention of powered flight and the Flyer III, but also for their practices as aeronautical engineers and test pilots. The extent of their technical developments and aeronautical knowledge were not appreciated by the general public until the full record of their work was published in *The Papers of Wilbur and Orville Wright* (Refs 1 and 10, published 1953). The early part of this comprehensive record of their progress was stimulated by their friendship with Octave Chanute, who became something of a sounding board for the developments in their thinking, particularly in the period 1901-1903. However, the Wrights relationship with Chanute became strained partly as a result of Chanute's eagerness to share their progress with the wider aeronautical community. In any case, the Wright brothers had realised early on that they were largely on their own in their endeavours, and they continued the development of their gliders into a practical flying machine achieving their goal within three years. Unfortunately during the

crucial period 1904-5, their reluctance to share their developing understanding with Chanute makes the task of unravelling exactly what happened quite difficult. Wilbur's reluctance to share his thinking may well also have slowed progress, as the constant dialogue seems to have been something of a spur to innovation during the early years.

This second *Aeronautical Journal* paper reporting progress in the Liverpool Wright project has described how the various developments during 1904-5 affected the handling qualities of the Wright Flyers. Piloted simulations tests have reconstructed particular flight scenarios that occurred as the Wrights modified their aircraft with the goal of making a practical flying machine. They eventually achieved this in October 1905 with a 25 mile flight, comprising 37 circuits of the Huffman Prairie flying field, near their home in Dayton, Ohio. They would not fly again for 2½ years.

The paper has tried to bring the Wright's progress during 1904-5 alive, through piloted tests and analysis using models created through an integration of wind tunnel tests, aerodynamic theory and flight mechanics analysis. The work has provided engineering insight into the extent of the handling difficulties experienced by the Wrights and the manner in which they coped with problems. Their approach is relevant today, not least because of the value of incremental development, trading performance and safety, and of technical integrity in design. The Wrights were themselves men of substantial personal integrity and remained true to form as their success became more widely accepted. In a letter written in October 1906, Wilbur Wright challenged Octave Chanute's assertion that "other able inventors" might be close to the solution of flight,

"Do you not insist too strongly on the single point of mental ability? To me it seems that a thousand other factors each one rather insignificant in itself in the aggregate influence the event ten times more than the mere mental ability or inventiveness... If the wheels of time could be turned back... it is not at all probable that we would do again what we have done... It was due to a peculiar combination of circumstances which might never occur again."

The present authors interpret Wilbur's statement as an acknowledgement that chance plays a part in innovation and creativity, but we also believe that he held back from acknowledging how critically important Orville's and his personal motivation, drive and teamwork were to the invention of powered flight.

ACKNOWLEDGEMENTS

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APPENDIX A

A.1.0 FLIGHTLAB MODELS OF THE WRIGHT FLYER AND ASSOCIATED WIND TUNNEL TESTS

A.1.1 1905 Flyer – wind-tunnel tests

The wind-tunnel tests of the 1905 Flyer III (see Fig. A.1) were carried out in the AVRO 9×7 ft wind tunnel at the University of Manchester's Goldstein Laboratories. The model was 1/8th scale with a wingspan of 5.06ft and chord of 0.81ft. The tunnel velocity was approximately 20ms^{-1} giving a Reynolds number of 0.53×10^6 compared to full scale Reynolds number of 2.25×10^6 (at $V = 17\text{ms}^{-1}$) (see Refs 4 and 5 for discussion on the scaling issues). The wings of the model were constructed of a PVC plastic material; this had many advantages – it was easy to machine and was flexible, whilst still being sufficiently strong to carry the airloads. The flexibility was important to allow the wing warping which was replicated on the model. The vertical rudder was also adjustable to a number of preset angles.

The model was mounted in the tunnel using a strut and nose-wire configuration with no attachments on the wings leaving them free to be warped. The tests consisted of the measurement of the six-degree



Figure A.1. 1/8th Scale 1905 Flyer Model in the Goldstein 9×7 -ft Wind Tunnel.

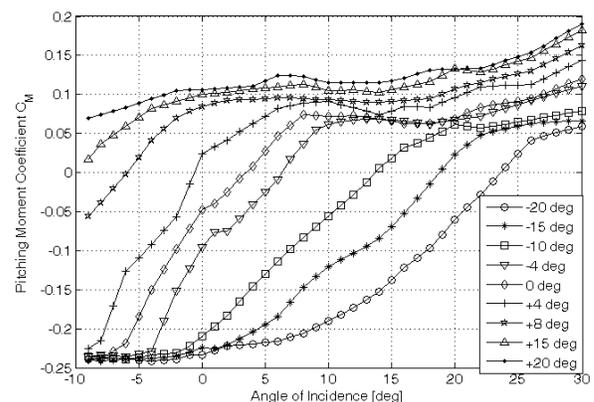
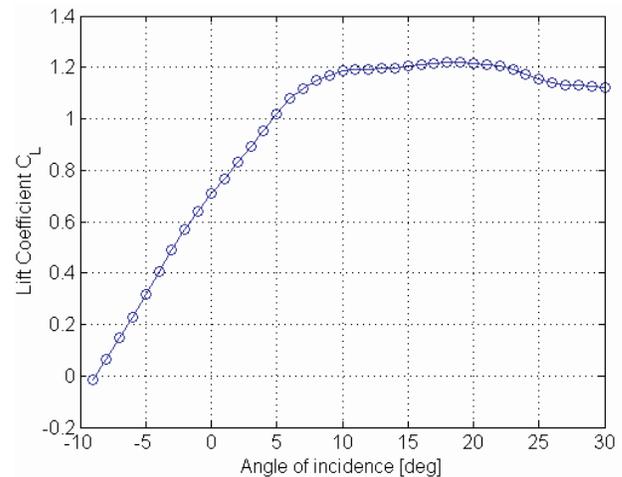


Figure A.2. Lift coefficient and pitching moment coefficient (about the cg) for varying angles of incidence and canard deflections.

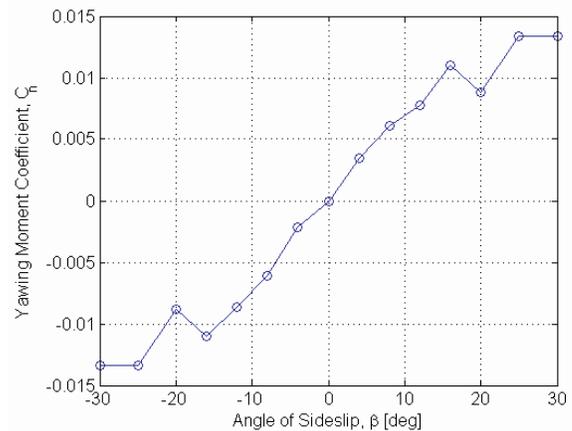
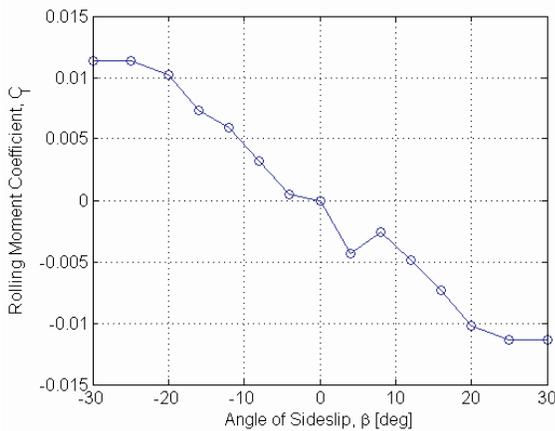


Figure A.3. Rolling moment and yawing moment coefficient as a function of sideslip angles.

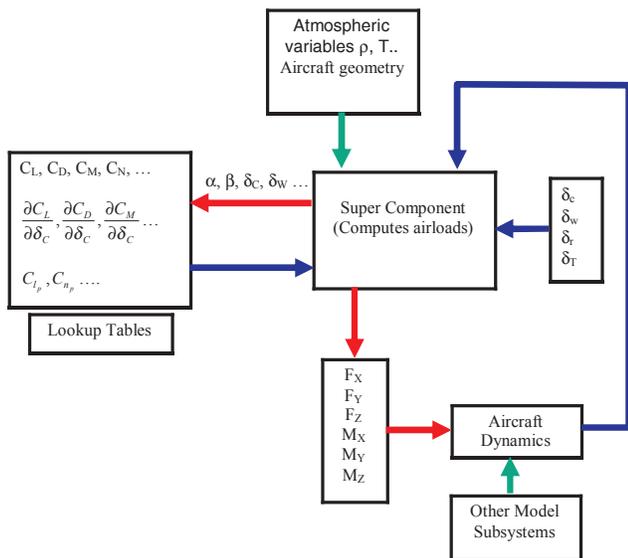


Figure A.4. Flowchart for the 1905 Flyer simulation look-up table 'super component'.

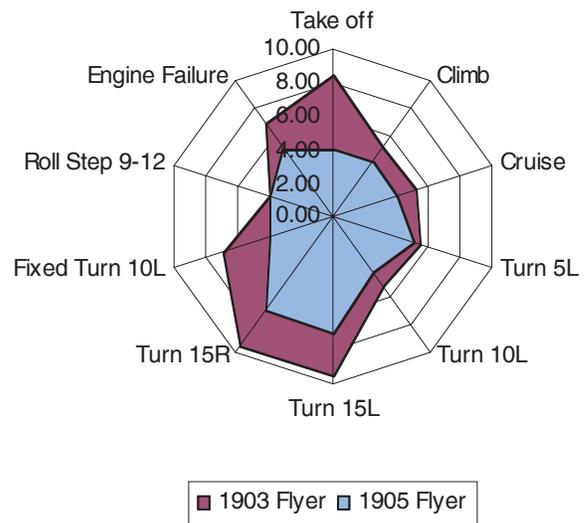


Figure A.5. Comparison of handling qualities ratings for the Flyer I and III.

of freedom (6-dof) forces and moments (lift, drag, sideforce, rolling, pitching and yawing moment) for a wide range of angles of attack and sideslip and also control surface deflections.

Figure A.2 shows the typical lift characteristics for the Wright aircraft with a 'flat top' to the curve. This shape is very similar to results from previous wind tunnel tests of the 1901 and 1902 gliders (Refs 4, 5); however, the higher camber of 1/20 provided a greater C_{Lmax} (≈ 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. The pitching moment leveled off at these higher incidences as well, also shown in Fig A.2, shown about a cg at 0.128c. The 1905 machine is unstable, of course, and the aerodynamics are highly non-linear, resulting in varying static and dynamic stability with incidence. Figure A.2 also shows the effect of canard

deflections, indicating an ability to maintain trim over quite a large incidence range, even when the main wing is stalled.

Near the end of the 1905 season the Wrights re-configured the aircraft to include dihedral on the inner wing sections of their machine. The 1905 Flyer wind tunnel model exhibited dihedral stability in roll ($C_{l\beta} = -0.0025\text{rad}^{-1}$), and directional stability, with a $C_{n\beta} = +0.00403\text{rad}^{-1}$, $[-16^\circ < \beta < +16^\circ]$, for (see Fig. A.3).

A.1.2 Modelling the 1905 Flyer in FLIGHTLAB

The simulation models described in this paper were developed in the FLIGHTLAB simulation package (see Ref. 14). FLIGHTLAB uses an object-orientated software approach allowing 'multi-body' simulation models to be created and analysed. The models are built in this approach using 'components' which represent modelling primitives

such as hinges, translations, masses, aerodynamic surfaces, gears and shafts, which are connected together to form a complete model. For the 1905 Flyer simulation, the airframe aerodynamics were modelled using a single airload ‘super-component’. This component featured an airload computation point where the 6-dof forces and moments act. Using this structure the aerodynamic coefficients obtained in the wind tunnel tests can be used in multi-dimensional lookup tables. The loads due to angular rotations (e.g. C_{lp} , C_{mq}) were computed using a hybrid analytical-numerical (vortex-lattice) approach, and were included as linear derivatives in additional lookup tables. Fig A.4 shows the overall super-component structure and flowchart.

The remainder of the model sub-systems were included in the multi-body system. The propulsion system featured a thermodynamic engine model, driving the two propellers. Drawing on FLIGHTLAB’s rotor modelling capability, the propellers were modelled using a blade-element approach with each two-bladed propeller separated into five aerodynamic segments, the propeller inflow was modelled using a three-state inflow model (see Ref. 5).

The FLIGHTLAB simulation package features two further user interfaces, Xanalysis and PilotStation. Xanalysis provides the ability to perform trim, dynamic response, linearisation and frequency domain analysis. PilotStation is the interface that provides a real-time environment for the simulation, allowing the engineer to perform desktop or piloted simulations in the University of Liverpool’s full motion simulator (Ref. 14). In the real-time simulations the model can be subjected to winds, parameters can be adjusted in-flight, and there is a data-capture facility for post-sortie analysis.

A.1.6 Handling qualities results 1903 Flyer vs 1905 Flyer

A comparison of the handling qualities ratings (HQRs) given by three test pilots who flew the FLIGHTLAB 1903 and 1905 Flyer simulations is shown in Fig. A.5, where the intervals on the radial spokes is two HQR points and HQR 10 is the outer ring. The pilots were asked to perform a set of test manoeuvres with performance standards in terms of adequate and desired perturbations in aircraft states such as attitudes and airspeeds. What was immediately obvious was that, although some improvements were made in the longitudinal flying characteristics from 1903 to 1905, and the turn control was significantly improved, the Flyer III remained a Level 2 handling qualities aircraft, degrading to Level 3 in the tighter (15 deg bank) turns. The pitch instability demanded a high pilot concentration and workload through continuous monitoring and adjustment in even the simplest of flying manoeuvres. The lateral-directional HQs of the 1905 aircraft were considered to be a significant improvement over the deficiencies of the 1903 machine. This is especially so for the turn manoeuvres, where the 1903 Flyer was consistently awarded HQRs of 8-9. These ratings also came with a caveat, as the HQR could easily become 10 if the pilot banked beyond 15 degrees, when the ability to control the bank angle and recover to level flight became almost impossible. The 1905 Flyer simulation, which possessed static roll stability, could be recovered from greater bank angles with much greater ease. Also, the addition of independent rudder control (using pedals in the simulator) gave the pilot the ability to minimise the sideslip in the turn and also to control heading in the takeoff and turn manoeuvres. A full discussion of these and related handling qualities results and analysis on the 1905 Flyer III can be found in Ref. 9.