The birth of flight control: An engineering analysis of the Wright brothers' 1902 glider

G. D. Padfield
Professor of Aerospace Engineering
B. Lawrence
Research student

Department of Engineering
The University of Liverpool
Liverpool, UK

SUMMARY

In the autumn of 1902 the Wright brothers spent just over eight weeks at their test site in the Kill Devil Hills near Kitty Hawk, North Carolina, testing their third Glider design. During the trial period they implemented an inter-linked roll-yaw control system. Together with the forward canard surface, this gave them control over vertical and horizontal components of the flight path. They were also able to hone and perfect their piloting skills. In just two days in the final week, they made about 250 glides. The success of the trials instilled the confidence in the Wright brothers to proceed rapidly to the construction of a powered aircraft. Within a month of returning to Dayton, they were writing to engine manufacturers with their specification – an engine that would develop eight to nine brake horse power, weigh no more than 180lb and be free from vibration; they would not find a suitable powerplant and had to design and build their own. The invention of the powered aeroplane in 1903 somewhat overshadows the earlier critical flight control developments, but the birth of flight control in 1902 opened the way for aviation to flourish. With the aid of modern flight science techniques – wind-tunnel testing, computational flight dynamics and piloted simulation, this paper examines the technology of the Wrights' 1902 glider. The research forms a part of the Liverpool Wright Project, aiming to bring to life the Wright brothers' achievements in this centenary period. Wilbur and Orville Wright are recognised by many as the first aeronautical engineers and test pilots. In so many ways they set standards that today's engineers and organisations benefit from. Their work in the period 1901 to 1902 reflects their genius and the paper reviews this work in detail, examining the design, aerodynamic characteristics and flying qualities of the aircraft that first featured a practical three-axis control system.

NOMENCLATURE

$\mathbf{A}$	system matrix
AR	aspect ratio (span^2/wing area)
b	wing span
$\mathbf{B}$	control matrix
c	wing chord
C_D	drag coefficient
C_l	rolling moment coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
C_n	yawing moment coefficient
g	gravitational acceleration
H_n	static margin
I_{xx}, I_{yy}, I_{zz}	moments of inertia about body axes
k	(Smeaton) coefficient of air pressure
K_θ, K_ϕ, K_ψ	pilot gains
K_p	pilot transfer function between error and control
p, q, r	perturbation angular velocities about body axes
Re	Reynolds number ($\rho Vc/\mu$)
S	wing area
$T_{\theta 1}$, $T_{\theta 2}$	time constants of closed-loop zeros
T_D	time to double amplitude
T_s	spiral mode time constant
T_{SP1}, T_{SP2}	time constants of 'short period' mode
$\mathbf{u}$	control vector
U_e	trim (equilibrium) speed component along x axis
u,v,w	perturbation velocities along body axes
V	flight velocity
X_w, M_w	aerodynamic derivatives

Paper No. 2854. Manuscript received 22 August 2003 accepted 29 September 2003.

Figure 1. The Wright brothers glider on 10 October 1902, Orville at the controls, Wilbur at the starboard wing, Dan Tate to port.

$\mathbf{x}$	state vector
$Y^{\theta}_{\delta c}$	transfer function between canard and pitch attitude
α	angle of incidence (attack)
β	angle of sideslip
δ_c	canard angle (positive pitch up)
δ_w	warp angle (positive roll left) = incidence right tip – incidence left tip
δ_r	rudder angle (positive nose right)
ζ_p, ω_p	damping ratio and frequency of phugoid
ζ_d, ω_d	damping ratio and frequency of Dutch roll
μ	coefficient of viscosity
ρ	air density
θ, ϕ, ψ	Euler attitudes
θ_e, θ_d	pitch attitude error and demand
λ	eigenvalue
$\partial C_l / \partial \delta_w$	rate of change of rolling moment coefficient with warp angle
$\partial C_n / \partial \delta_r$	rate of change of yawing moment coefficient with rudder angle

1.0 INTRODUCTION

The Wright brothers had intended their flights on 17 December 1903 to be a private matter and had no intention of making a detailed public statement. However, since, as Wilbur wrote, "*the contents of a private telegram, announcing to our folks at home the success of our trials, was dishonestly communicated to the newspapers,*" they felt the need to put the record straight(1). Wilbur's statement to the *Associated Press*, written on 5 January 1904, ended thus,

> *"...... we were determined, before returning home, to know whether the machine possessed sufficient power to fly, sufficient strength to withstand the shocks of landings, and sufficient capacity of control to make flight safe in boisterous winds, as well as in calm air. When these points had been definitely established, we at once packed our goods and returned home, knowing that the age of the flying machine had come at last."*

In this brief and reluctant communication to the world, Wilbur revealed the purposeful intentions of their aeronautical endeavours, emphasising performance, structural strength and control as the combined objectives of the world's first successful flight test of a powered aeroplane. The following two years were to prove that the Wrights had much more development work to do to arrive at a practical aeroplane†, but the fundamental challenge of flight control had been solved through research and development over the two years leading up to December 1903. The critical breakthrough came in the autumn of 1902.

On the night of 23 October 1902, Orville Wright wrote to his sister Katharine from their camp at the Kill Devil Hills near Kitty Hawk, North Carolina(1).

> *"The past five days have been the most satisfactory for gliding that we have had. In two days we made over 250 glides, or more than we had made all together up to the time Lorin left. We have gained considerable proficiency in the handling of the machine now, so that we are able to take it out in any kind of weather. Day before yesterday we had a wind of 16 meters per second or about 30 miles an hour, and glided in it without any trouble. That was the highest wind a gliding machine was ever in, so that we now hold all the records! The largest machine we handled in any kind of weather, made the longest distance glide, the longest time in the air, the smallest angle of descent, and the highest wind!!!"*

The 'machine' that Orville referred to was the Wright brothers' 1902 glider, featuring, for the first time, three-axis control over the motion of the aircraft. The Wrights had flown between 700 and 1,000 flights in this aircraft during the autumn of 1902. It is testament to the genius of the Wrights that they had accomplished this achievement working part time in about three years.

Figure 1 shows one of Orville's first flights with the three-axis control operational on the 1902 glider. He and Wilbur had "thought together" to arrive at this design innovation. The aircraft weighed 119lbf (53kgf) empty, 259lbf (115kgf) with Wilbur on board and 264lbf (118kgf) with Orville on board. According to Orville's diary(1), the longest distance of 622ft was flown by Wilbur in 26 seconds with a glide angle of just over 8 deg. The best glide angle was quoted as about 6 deg(1) (see Ref. 1, p 266 for flights on 30 September) when the wind was 5ms^{-1} and speed over ground averaged 23ft/sec††. The longest and highest duration glides were made on the north slope of the big Kill Devil Hill (max slope 9·5°, Ref. 1 p 259) on 23 October with a glide slope of between 8° and 9°. Over the few weeks at the end of September and into October, the brothers developed and perfected their flying skills. To quote their friend and aeronautical colleague, Octave Chanute(1),

> *"The two brothers glided alternately and they soon obtained almost complete mastery over the inconsistencies of the wind. They met the wind gusts and steered as they willed. They did not venture to sweep much more than one quarter circle, so as not to lose the advantage of a headwind, but they constantly improved in the control of the machine and in learning the arts of the birds. Some 800 glides were made."*

The autumn flight test campaign of 1902 was very successful for the Wrights and one is left with the thought that their solution to three-axis control, linking roll and yaw control to mitigate the powerful adverse yaw effects, was one of 'the' critical breakthroughs in the history of aviation and aeronautical engineering. Peter Jakab sums this up in his book on the Wrights' process of invention(3); "*If the Wright brothers are to be cited as the inventors of the airplane based on having resolved all the fundamental problems of mechanical flight then it is not necessary to look beyond the 1902 glider… what was innovative about the (1903) Flyer was present in the earlier 1902 glider..*"

This paper records a study of this aircraft and its development, set in the context of aeronautical knowledge at the turn of the 20th century and reflected by the synthesis and analysis conducted in the Liverpool Wright project. Section 2 presents a resume of the Wrights' work prior to the 1902 tests and Section 3 goes on to interpret the research and development process undertaken during the winter of 1901-2. Section 4 describes the 1902 flights tests and how the three-axis control

---

† On 16 Oct 1905 the Wrights flew their Flyer No 3 for the last time until May 1908; two weeks before, Orville had flown for 39km in 38 minutes. In the first two weeks of October 1905, the Wrights (Ref. 1, p 517) "*..did more flying than in all our previous flights of three years put together*." The first powered aircraft flight in Europe (by Santos Dumont) would not take place until the autumn of 1906 (Ref. 2).

†† The Wrights regularly mixed their units as a result of both US and European influences.

solution evolved. In Section 5, the Wrights' invention is re-visited with modern engineering tools including wind tunnel testing, computational aerodynamics, flight dynamics analysis and piloted simulation. Here, some of the fundamental aspects of the Wrights' approach – the use of the canard, wing warping and the warp-rudder interlink, wing anhedral and the mastery of control over stability – are explored to reveal the unique nature of their genius. The paper is rounded off with a very brief reflection on the consequent, post-1902, activities of the Wrights in Section 6 and some concluding remarks in Section 7.

2.0 THE WRIGHT BROTHERS AND THEIR PRE-1902 WORK

2.1 Background

Wilbur was born in 1867 and Orville in 1871, the same year the family moved into a new house, No 7 Hawthorn Street, in Dayton, Ohio. They had two elder brothers Reuchlin and Lorin, and a younger sister, Katharine. A clear picture of the kind of life the Wright brothers experienced during their upbringing is portrayed in Tom Crouch's thesis on a life of Wilbur and Orville Wright – The Bishop's Boys(4). Their father, Milton Wright, a minister in the Church of the United Brethren in Christ, established a 'corporate' family identity. Crouch describes Milton as "*rather uncompromising and strong principled… inherited from his father and passed to his children.*" Milton considered that "*the world was not a friendly place for honest men and women, temptations beckoned, unscrupulous persons lay in wait; friends would fall away in times of trial… and ultimately the strength of family bonds offered the only real support one could hope for in life.*" This austerity seems to have been balanced by the caring attention of their mother, Susan Catherine (Koerner) Wright. Crouch notes that while no diary survived to show her side of the story, she played a key role in her children's fascination for engineering. "*Her children remember her as having considerable mechanical aptitude, having spent time in her father's carriage shop as a young girl. She designed and built simple household appliances for herself and made toys for her children. When the boys wanted mechanical advice and assistance, they came from their mother. Milton was one of those men who had difficulty driving a nail straight.*" Crouch makes the keen observation that, "*Wilbur and Orville had their mother to thank for their extraordinary ability to visualise the operation of mechanisms that had yet to be constructed.*"

Tom Crouch provides us with vivid images of the two inventors; to paraphrase – Wilbur was an outgoing person and a gifted speaker, never rattled in thought or temper; cool, aloof and controlled. He had struggled to overcome fits of depression in his young manhood, developing considerable self confidence in the process. He drew friends from his older brother's circles. Orville, on the other hand, was especially close to his sister Katharine, almost her protector. He was impulsive and excitable, an enthusiast and optimist, on fire with new inventions. While the airplane was Wilbur's idea, Orville supplied the drive to continue in difficult times. With the family, Orville was something of a tease and practical joker, but with strangers he was painfully shy. He outlived Wilbur by 36 years but refused to speak in public.

When Wilbur was eleven and Orville seven years old, Milton bought them a toy helicopter, designed by the Frenchman Alphonse Pénaud, who himself had based his design on one of Leonardo da Vinci's aircraft concepts. This made a big impression and the brothers went on to construct several models from their own designs. We see here the seed of their interest in aviation and it was to be nurtured over the next 20 years in a variety of ways – their fascination with bird flight, following the work of the German engineer and glider pilot, Lilienthal, and the confidence in their own engineering knowledge and skills gained from designing and making their own bicycles – the Van Cleve, the St Clair and the Wright Special – during the late 1890s. The story of the Wright brothers is a fascinating one, leaving the thought that the invention of the aeroplane was the result of a combination of several critical success factors and brought to us by the first aeronautical engineers who addressed structural strength, performance and control with equal attention. They took what we now describe as a systems approach but they also realised that control was the most critical aspect.

Figure 2. Wilbur and Orville Wright.

2.2 1899-1900: The quest begins

By the time Wilbur was 32 he was ready to begin a serious study of aviation. On 30 May 1899, he wrote to the Smithsonian Institution in Washington DC(1).

> *"I have been interested in the problem of mechanical and human flight ever since as a boy I constructed a number of bats of various sizes after the style of Cayley's and Pénaud's machines. My observations since have only convinced me more firmly that human flight is possible and practicable. It is only a question of knowledge and skill just as in acrobatic feats. Birds are the most perfectly trained gymnasts in the world and are specially well fitted for their work, and it may be that man will never equal them, but no one who has watched a bird chasing an insect or another bird can doubt that feats are performed which require three or four times the effort required in ordinary flight. I believe that simple flight at least is possible to man and that the experiments and investigations of a large number of independent workers will result in the accumulation of information and knowledge and skill which will finally lead to accomplished flight…. I am about to begin a systematic study of the subject in preparation for practical*

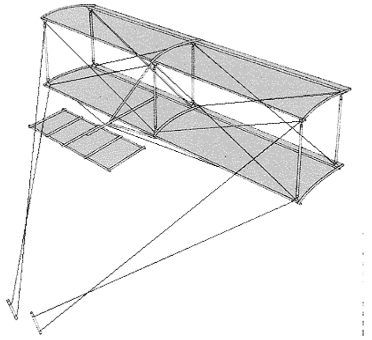


Figure 3. Sketch of the Wrights' 1899 Kite.

> *work to which I expect to devote what time I can spare from my regular business. I wish to obtain such papers as the Smithsonian Institution has published on this subject, and if possible a list of other works in print in the English Language. I am an enthusiast, but not a crank in the sense that I have some pet theories as to the proper construction of a flying machine. I wish to avail myself of all that is already known and then if possible add my mite to help on the future worker who will attain final success."*

Wilbur's request was granted and the Smithsonian sent him a list of their publications, which included works by Chanute, Langley and Means, in addition to a set of Smithsonian pamphlets including ones by Lilienthal and Langley. In the summer of 1899 Wilbur constructed his first kite with a span of 5ft. He was convinced that the method of control adopted by birds, by shifting their centre of pressure, was more efficient than by shifting the centre of gravity, a method used in several glider designs during the 1890s e.g. those by Lilienthal, Pilcher and Chanute. Wilbur's control mechanism consisted of wing-warping for lateral control, whereby the outer sections of the wings of the biplane were twisted by rotating the control levers in opposite directions; longitudinal control was achieved through a symmetric rotation of the two levers, shifting the two surfaces longitudinally relative to one another, and simultaneously rotating the canard surface (Fig. 3).

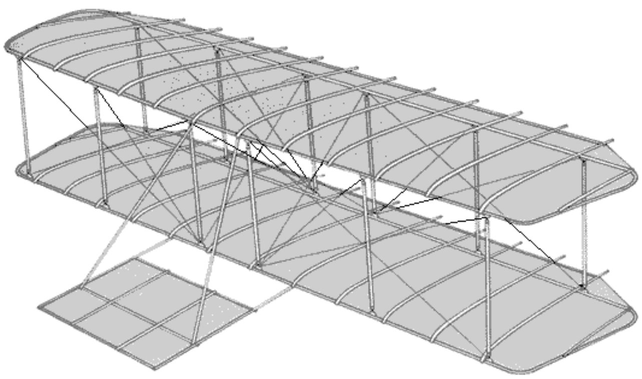
Confident in his method of control, Wilbur proceeded to design a man-carrying glider, based on Lilienthal's data, with a wing area a little over 150ft^2. This would be flown tethered, and, according to the data Wilbur had access to, would support the weight of a man in a wind of about 16mph, to give the operator practice in control, with minimum effort. Wilbur needed a location where such steady winds blew daily during the autumn and winter months, the period his business commitments allowed him to pursue his new hobby. He wrote to the US Weather Bureau in December 1899 and received information on the locations where such steady winds could be found. Eventually, Wilbur chose the place with the 6th highest average wind in the US, Kitty Hawk in North Carolina, as the location where the brothers would conduct their flying trials over the next four years. Eager to set up a dialogue with the author of the book *Progress in Flying Machines*, Wilbur wrote to Octave Chanute on 17 May 1900. This would be the first of a great many communications between the two friends until Chanute died in 1910. The letters, making up a large part of Ref. 1, provide us with a trail of the work of Wilbur and Orville Wright, unfolding the process of discovery and invention and documenting much of the engineering data collected by the Wrights over the period 1900-1905.

In his first letter, Wilbur shared with Chanute his plans to build a flying machine;

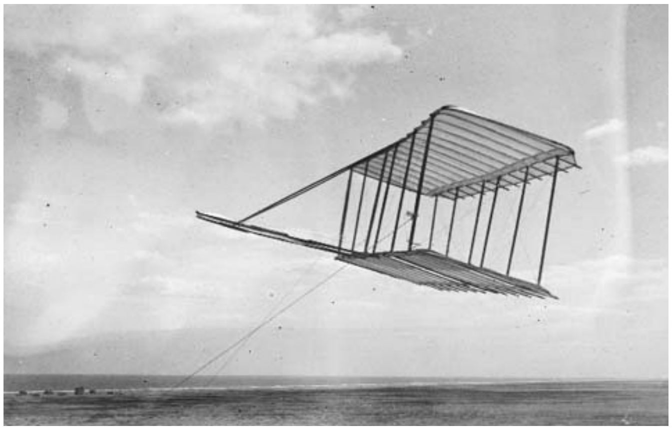
> *"My general ideas on the subject are similar to those held by most practical experimenters, to wit: that what is chiefly needed is skill rather than machinery. The flight of the buzzard and similar sailors is a convincing demonstration of the value of skill, and the partial needlessness of motors. It is possible to fly without motors, but not without knowledge and skill. This I conceive to be fortunate, for man, by reason of his greater intellect, can more reasonably hope to equal birds in knowledge, than to equal nature in the perfection of her machinery…. My observation of the flight of buzzards leads me to believe that they regain their lateral balance, when partly overturned by a gust of wind, by torsion of the tips of the wings. If the rear edge of the right wing tip is twisted upward and the left downward, the bird becomes an animated windmill and instantly begins to turn, a line from its head to its tail being the axis."*

Wilbur was confiding in Chanute to

> *"learn to what extent similar plans have been tested and found to be failures, and also to obtain such suggestions as your great knowledge and experience might enable you to give me. I make no secret of my plans for the reason that I believe no financial profit will accrue to the inventor of the first flying machine, and that only those who are willing to give as well as to receive suggestions can hope to link their names with the honor of its discovery."*



(a) perspective sketch.



(b) kiting the 1901 Glider.

Figure 4. The Wrights' 1900 Glider.

Wilbur would be more cautious in sharing his ideas in years to come, but for the crucial few years ahead, he was open in his correspondence and the encouragement and curiosity displayed by Chanute was clearly a spur to Wilbur's progress during the development of the flying machine up to 1905.

Wilbur went on to describe his wing warping concept and his plan to erect a tower for tethering his new glider design, thereby enabling 'soaring' flight. Wilbur arrived in Kitty Hawk on 11 Sept 1900 (Orville, who was now very much part of the team, arrived on 28 September). The 1900 glider (Fig. 4), with its wing area of about 165ft^2, aspect ratio 3·4 (per surface) and 1/23 camber, was assembled and tested as a kite in early October. From the entries in Wilbur's notebook we can get an understanding of the kind of data he was gathering from these tests(1) –

> *"the proportion of total drift† to lift would have been less at thirty five miles per hour than at twenty because the drift of surfaces due to the smaller angle would have decreased faster than the resistance of framing increased."*

Wilbur was acknowledging the difference between pressure drag and skin friction drag; he had also discovered that a wing's efficiency improves with speed; later he would realise that the drift to lift ratio had a minimum value. "*At small angles of incidence threads projecting from the under side of the surfaces were turned forward.*" This reversed flow effect contributed to the large movement of the centre of pressure on the cambered section.

---

† used to mean drag.

> *"With the wind blowing up a slope of one in twelve, the resistance of the machine at 50lbs was only three or four pounds, the wind blowing over 20 miles. On the face of a steep hill (one-in-three) the machine soared in a wind of about ten miles. When a rope is used to prevent drift the center of gravity must coincide with both center of lift and center of drift, and the rope must be attached to this point."*

Wilbur eventually managed to glide a distance of several hundred feet with the warp control tied off and flying very close to the surface of a one-in-six hill, landing at nearly 30mph. Referring to the pitch, fore-and-aft control, Wilbur informed Chanute from Dayton on 16 November that. "*The ease with which it was accomplished was a matter of great astonishment to us….we never found it necessary to shift the body.*" Wilbur's excitement with the partial success of the first trials was shared by Chanute[†] and the latter was keen to report the progress in a paper he was writing. He asked permission to do this and Wilbur reluctantly agreed but stated that ..*"…for the present (we) would not wish any publication in detail of the methods of operation or construction.*" The methods of operation were the warp and canard control concepts and Wilbur Wright knew that his design was innovative and unique. He had spent about two minutes airborne but was convinced that the problem was one of performance and that more wing area was essentially all that was required.

2.3 1901: Second step into the unknown

The Wright brothers arrived in Kitty Hawk on 11 July with a new glider. Their 1901 glider had been designed with ample margin to fly in winds less than 15mph. With a 22ft wing span and a chord of 7ft, the total lifting wing area was approximately 300ft^2 (Fig. 5). They also increased the camber to one-in-twelve, the value used by Lilienthal on his circular arc wing sections. Pitch control was achieved through varying the camber of the canard by pushing down on a pitch bar; roll control through wing warp was activated through foot pedal controls.

The 1901 trial period lasted about six weeks, although the first test flight did not take place until 27 July and they left for Dayton on 20 August. They were joined for part of this period by Chanute. While they had some success, the overwhelming feeling was of failure. Later, when reflecting on this period, Wilbur would state(4),

> *"..we doubted that we would ever resume our experiments. Although we had broken the record for distance in gliding, yet when we looked at the time and money which we had expended, and considered the progress made and the distance yet to go, we considered our experiments a failure. At this time I made the prediction that men would sometime fly, but that it would not be within our lifetime."*

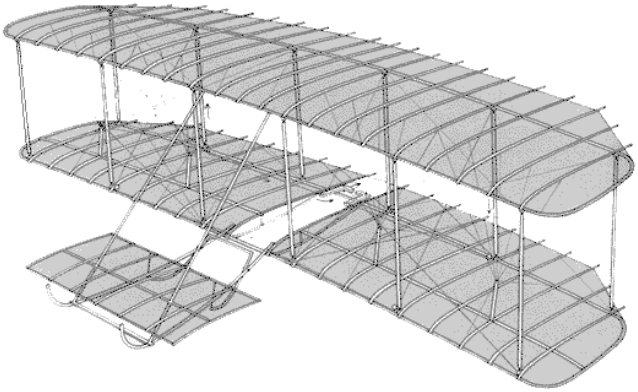
The problems fell into three categories and we look to Wilbur's diary to get his impressions;

Performance (29 July 1901)

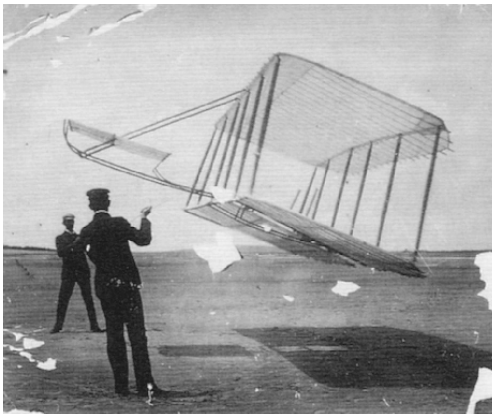
"*Afternoon spent in kite tests. Found lift of machine much less than Lilienthal tables would indicate, reaching only about a third as much. Found that machine at 100lbs would not glide at 3° or 4° on wind of less than about 23 to 25 miles per hour.*"(1) During a glide on 8 August, the measurements indicated that 10deg of incidence were required at 24mph. With this level of performance there was little chance of achieving soaring flight, although Fig. 6 shows a classic picture of Wilbur almost soaring.

Longitudinal Control (30 July 1901)

> *"The control of our machine is not as good as last year. We attribute this to the fact that the travel of the center of pressure toward the front edge is slower than in the machine of last year*



(a) perspective sketch.



(b) kiting the 1901 Glider.

Figure 5. The Wrights' 1901 Glider.

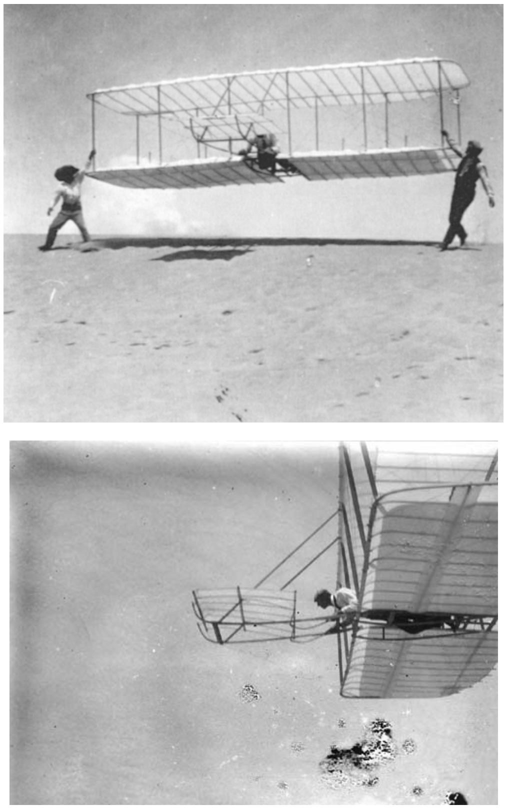
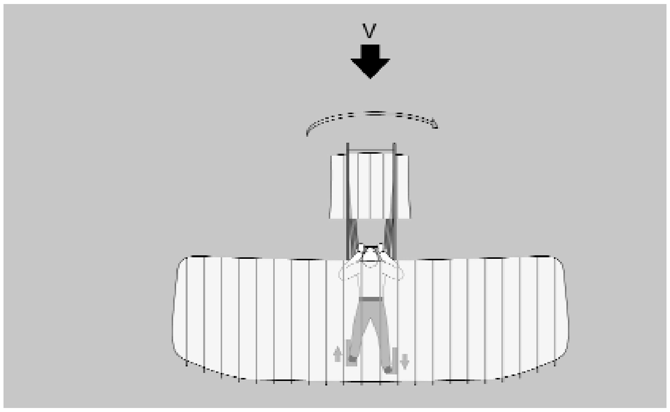
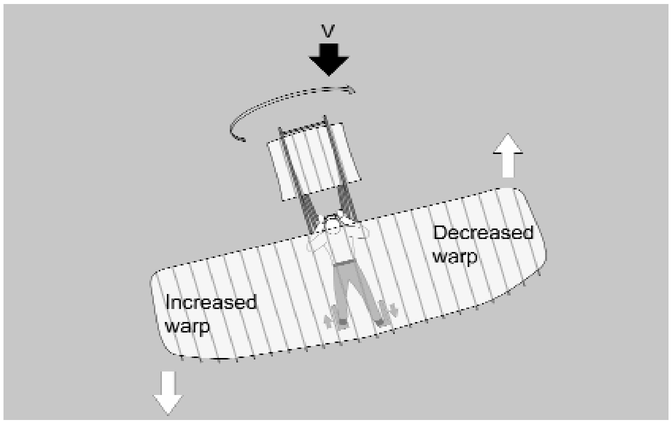


Figure 6. Wilbur being launched and almost soaring in 1901.

[†] Crouch (Ref. 3) notes that Chanute may never have properly understood Wilbur's control mechanism, being rather fixed in the view that turning an aircraft was accomplished by yawing, much like a boat.



(a) pilot applies warp to roll to starboard.



(b) adverse yaw turns aircraft to port.

Figure 7. Sequence showing effects of warp-induced adverse yaw.

> *which had less fore-and-aft curvature. We even think that the direction of travel reverses at an angle within those used in gliding so that the forward plane, and the variation between centers of pressure and gravity, instead of counteracting each other, at times act together to disturb the equilibrium."*

The use of the 1/12 camber had created such a large nose down pitching moment that the pilot had to move back to avoid nose diving into the sand. Wilbur later described the first test flight in his first public Lecture entitled '*Some Aeronautical Experiments*', in September 1901. Referring to himself as pilot, he stated that,

> *"He kept moving further and further back with each trial, till finally he occupied a position nearly a foot back of that at which we had expected to find the center of pressure…..The machine then sailed off and made an undulating flight of a little more than 300ft. To the onlookers this flight seemed very successful, but to the operator it was known that the full power of the rudder*[†] *had been required to keep the machine from either running into the ground or rising so high as to lose all headway. In the 1900 machine, one fourth as much action had been sufficient to give much better control."*

Wilbur was experiencing the consequences of flying a pitch-unstable aircraft. The center of gravity was behind the neutral point, the aerodynamic centre of the whole aircraft. The large nose down pitching moment on the cambered wing section meant that the center of pressure (cp) was a long way aft at very small angles of incidence, moving forward as the incidence increased and moving aft again at high incidence. The reversing of the movement of the cp caused major problems for the Wrights. During the 1901 flight tests, they would reduce the camber to about 1/20 by 'trussing down the rib in the center.' Even with this arrangement the aircraft was likely to have been, at best, marginally stable, requiring the full concentration of the pilot to stay safely airborne.

Lateral control (22 August 1901)

> *"…we proved that our machine does not turn towards the lowest wing under all circumstances, a very unlooked for result and one which completely upsets our theories as to the causes which produce the turning to right or left"*

The problem is illustrated in the sequence in Fig. 7.

The pilot applies warp to roll and turn the aircraft to starboard, (a). The increased lift on the port wing induces an increase in drag leading to an adverse yawing motion, dragging the port wing back (b), and sometimes resulting in the aircraft turning to port rather than starboard.

The pitch, roll and yaw problems were inherent in the unstable configuration selected by the Wrights but they seemed to know instinctively that control was more important than stability and that, at the low speeds they wanted to fly, the increased control power conferred by the canard was quite critical for manoeuvrability. The Wrights placed a great deal of emphasis on control while at the same time, not wholly appreciating the role of the aerodynamic moments in stability(5)[†]. This is entirely understandable considering the mathematical complexities involved in quantifying the dynamic behaviour of aircraft; these were being worked on at the time by the British mathematician Bryan, and would be published for the first time two years later(6).

Despite their obvious despondency as a result of the performance and control problems, the Wright brothers had some positive aspects to reflect on. Their aircraft, the largest ever flown, was very strong and had withstood many heavy landings. In higher winds they had glided for more than 300ft. Their confidence in the canard first design was strongly reinforced. To quote from Wilbur's Lecture again,

> *"In one glide the machine rose higher and higher till it lost all headway. This was the position from which Lilienthal had always found difficulty to extricate himself, as his machine then, in spite of his greatest exertions, manifested a tendency to dive downward almost vertically and strike the ground head on with a frightful velocity. In this case a warning cry from the ground caused the operator to turn the rudder*[††] *to its full extent and also to move his body slightly forward. The machine then settled slowly to the ground, maintaining its horizontal position almost perfectly, and landed without any injury at all. This was very encouraging as it showed that one of the very greatest dangers in machines with horizontal tails had been overcome by the use of a front rudder."*

They had experienced this nose dive tendency at stall with their 1900 glider flown with a tail, but their 1901 glider tended to stall flat.

In a letter to Chanute on 29 August, Wilbur refers to the "*muddled state of affairs*" left over from the 1901 trials. On the same day he performed extensive analysis on the measurements of glide angles and wind speeds, estimating values for drift and lift. He deduced that it would not be possible to glide permanently at an angle less than 8° in still air. He calculated that, based on Lilienthal's tables, a glide angle of 4° should be possible at 17mph. Also on 29 August, Wilbur received a letter from Chanute inviting him to present a paper on their gliding experiments to the Society of Western Engineers in Chicago in three weeks time. His sister Katharine "*..nagged him into going. He will get acquainted with some scientific men and it may do him a lot of good.*" Wilbur's paper, published in full in Ref. 1, contained about 7,000 words of text, figures and photographs and was a classic research paper on applied aeronautics. It is easy to imagine that the failings of the 1901 glider and the reflections Wilbur made in writing his 'Some Aeronautical Experiments' paper were spurs to the next and critical stage of development.

[†] The Wrights often used the term rudder when referring to the canard control surface.

[†] In Ref. 4, Culick observes that "...the backward state of the general theory and understanding of flight mechanics hindered them and in fact caused them considerable difficulties."

[††] Again, the Wrights are referring to the canard pitch control surface.

3.0 1901-1902: INTERPRETING THE WRIGHTS' PROCESS OF INVENTION

In Ref. 1, the account of activities during the period between October 1901 and February 1902 is documented in about 100 pages of text, numerous table and figures, and is arguably the richest record of progress in the entire reference. Here we see the Wright brothers working together towards a greater understanding of the performance problems they had experienced. They had made extensive use of Lilienthal's data tables in their design and were perplexed by the results, losing confidence in the process. In a letter to Chanute written on 6 October 1901, Wilbur writes, "*I am now absolutely certain that Lilienthal's table is very seriously in error…*" Less than two weeks later, after painstaking analysis of available data Wilbur wrote to Chanute again, describing a new balance they would be using to measure lift and drift; Wilbur adds, "*…It would appear that Lilienthal is very much nearer the truth than we have heretofore been disposed to think…*" In this same month, Chanute would send Wilbur a translation copy of Lilienthal's book(7), which would serve to inform him even further of the errors that both he and Lilienthal had made; Wilbur's letter to Chanute on 2 November(1) summarising his analysis of errors reads like a classic researcher's logbook. One of the major discoveries made by Wilbur in the analysis of existing data was the error in the, so-called, Smeaton coefficient in the expression that Wilbur believed Lilienthal had used for computing lift,

$$\text{Lift} = k\,S\,V^2\,C_L \qquad \ldots (1)$$

k is the Smeaton coefficient of air pressure(8), S the wing area, V the velocity and C_L the lift coefficient. Wilbur assumed that Lilienthal had used Smeaton's value of 0·005 for k. In fact, Lilienthal had measured C_L directly and had no need to use the Smeaton coefficient, so Wilbur's back-calculation to estimate the required wing area and resulting glide angles were based on an erroneous assumption (Ref. 8 gives a detailed explanation of how the interpretation error came to pass). Wilbur had reported his suspicion that the Smeaton coefficient was too high in his letter to Chanute on 26 Sept, "*…Professor Langley and also the Weather Bureau officials found that the correct coefficient of pressure was only about 0·0032, instead of Smeaton's 0·005…*". Wilbur had unearthed one of the reasons for the performance shortfall in the 1901 glider, but he was determined to establish the optimum wing design.

With the purpose of creating a detailed aerodynamic database that would serve their design goals, the Wright brothers built a wind tunnel and two force balance systems that would provide, effectively, direct measurements of the lift coefficient and the ratio of drift to lift. The operation of this balance is very well described by Jakab in Ref. 3. They made measurements to examine the effect of a wide range of design parameters – aspect ratio, camber, point of maximum camber, biplane surface spacing and others – on the lifting capacity and efficiency of the surfaces. Wilbur wrote to Chanute on 15 December, continuing the information exchange with a summary of the main results to date, but also indicating that the experimenting had now to stop to give way for bicycle making. In his letter Wilbur described 'laws' for superimposing multiple surfaces, re-shaping single surfaces and revealed the major effect of aspect ratio on the lift curve slope. He emphasised the benefits of their systematic approach in this context,

> *"It has been a great advantage we think to make a systematic measurement of several typical series of surfaces rather than to work blindly on all sorts of shapes, as a study of the series plates quickly discloses the general principles which govern lift and tangential and thus renders the search for the best shapes much easier. A mere glance shows that while increasing the ratio of breadth to length does not increase the maximum lift to any great extent it does cause the maximum to be reached at a smaller angle; and the wider the spread from tip to tip the smaller the angle at which large lifts can be obtained."*

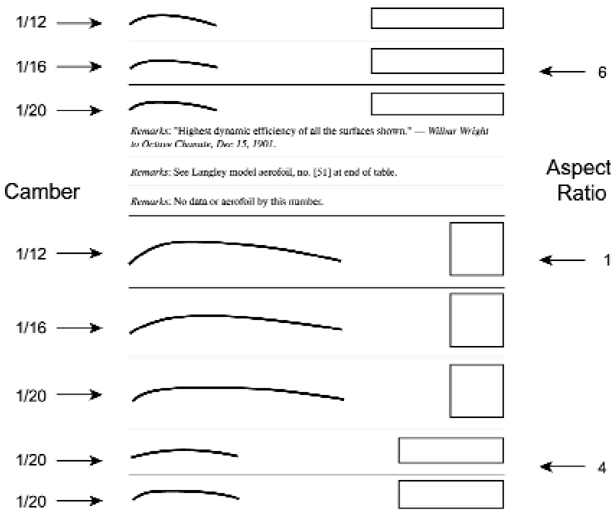


Figure 8. Sample of surfaces tested with three aspect ratios and three cambers.

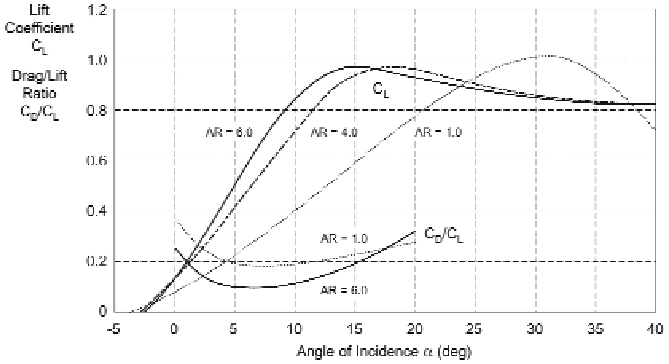


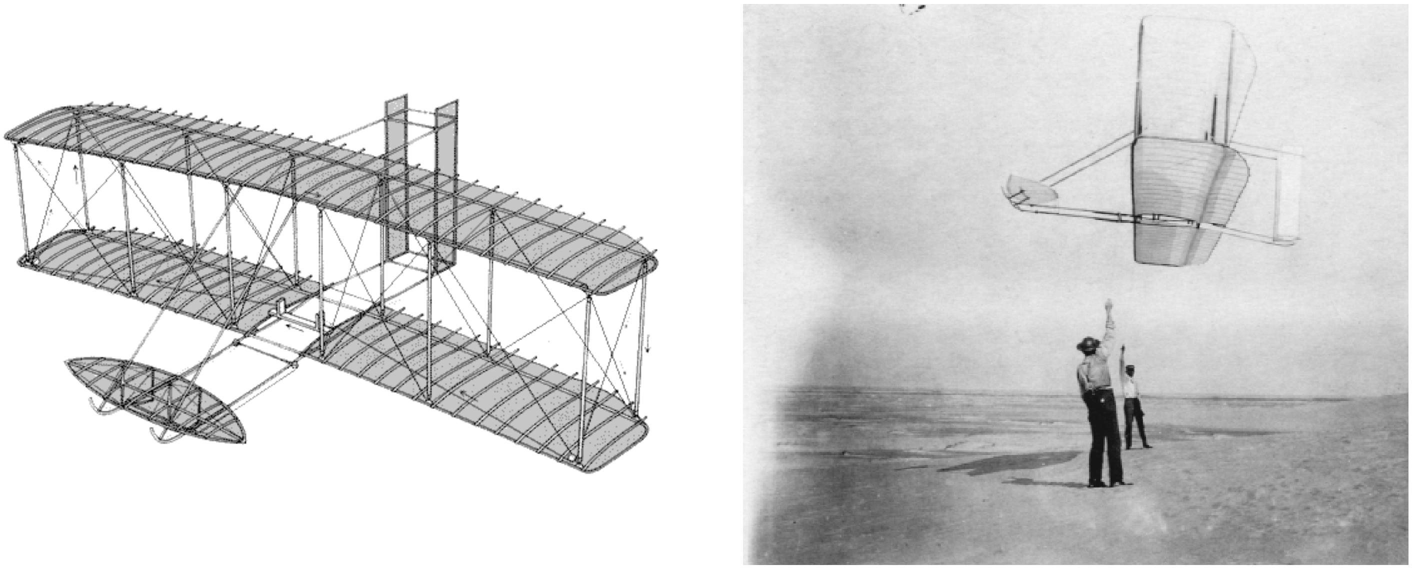
Figure 9. Lift coefficient and drag/lift ratio of surfaces with different AR's.

Wilbur's breadth was what we now call the wing span while his length was our chord. In this paragraph, he emphasised the word 'best', acknowledging that the physics of aerodynamics clearly did favour particular arrangements.

The Wrights tested more than 150 surfaces during the last quarter of 1901. Figure 8, redrawn from Ref. 1, shows eight planforms and corresponding cambers.

The lift coefficient and drag/lift ration for many of these surfaces are tabulated in Ref. 1, along with the raw measurements from which these were derived. Figure 9 shows the effect of aspect ratio (AR) on lift coefficient and drag/lift ratio, for the parabolic section with 1/20 camber (Wright designated surfaces nos 12 (AR = 6), 19 (AR = 4) and 17 (AR = 1)). All had an area of 6in^2. The aspect ratio of the wing of the 1901 glider had been about 3·14 (per surface) and the Wrights could now see clearly the efficiency penalty arising from their choice of this configuration relative to, say, using a wing with an AR of 6. Over the range of typical incidences used in gliding, a wing with an aspect ratio of 3·5 might only be able to lift 75% as much as a wing with an aspect ratio of 6.

Moreover, the comparison of drag/lift ratio shown in Fig. 9 must have been a startling revelation to the Wrights. This was a direct measure of the glide angle at different angles of incidence, or the efficiency of the lifting surface. The Wright brothers could see for the first time that a minimum occurred, and that the AR = 6 surface was twice as efficient as the AR = 1 surface. They could also see that the minimum for the AR = 6 surface was around 0·1 and occurred at an angle of incidence of about 6°. If this worked out in practice they



(a) perspective sketch.

(b) Kiting the 1902 Glider.

Figure 10. The Wrights' 1902 Glider.

would be able to glide flat down a 6° slope! For the 1901 design, they had used a value of the pressure coefficient which was 50% too high and they could now see that by changing the aspect ratio from 3·1 to perhaps 7, they could compensate for this error and design a new glider with essentially the same wing area as in their 1901 machine. The aspect ratio effect came as a surprise to the Wrights, even though Lilienthal's machine clearly had a higher ratio and they had used Lilienthal's tables apparently oblivious to this important design parameter. In Ref. 7, Lilienthal recommends particular dimensions; to quote from his list of 'fundamental construction points';

> *"9th – It will be a matter of experiment to determine whether the broad shape of wing with resolved pinions, such as we see in birds of prey, or the long pointed shape of wing of the sea birds, are preferable.*
>
> *10th – In the former case the dimensions of the wing would be 8m span, and 1·6m greatest width (AR = 5).*
>
> *11th – When employing the slender wing shape, the corresponding dimensions would be 11m span and 1·4m greatest width (AR=7·9)."*

Wilbur had written in his letter to Chanute on 24 November that,

> *"It is very evident from these measurements that a table based on one aspect and profile is worthless for a surface of different aspect and curvature. This no doubt explains why we have had so much trouble figuring all our machines from Lilienthal's table."*

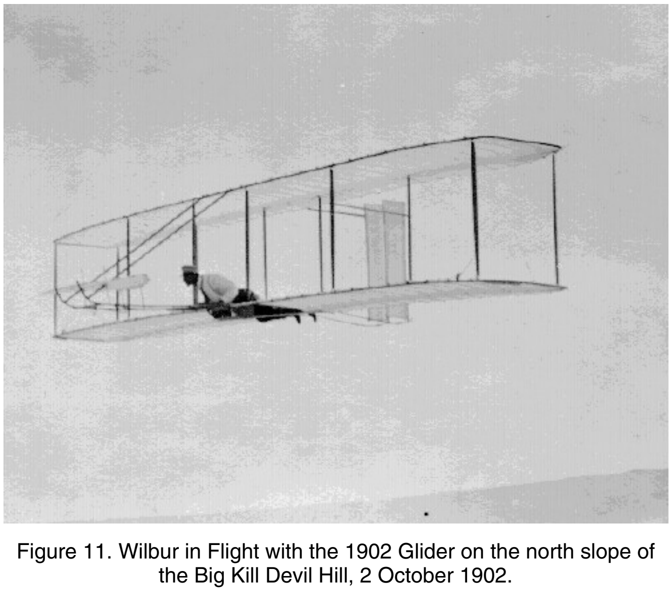


Figure 11. Wilbur in Flight with the 1902 Glider on the north slope of the Big Kill Devil Hill, 2 October 1902.

In his book, *A History of Aerodynamics*(8), John Anderson provides a comprehensive analysis of the causes of the under-performance in the Wrights' 1901 glider, compared with their expectations – a combination of using a lower aspect ratio than Lilienthal, using a parabolic section rather than a circular arc and using a pressure coefficient of 0·005, meant that the Wrights' lift calculations were in error by a factor of 0·36, correlating very closely with Wilbur's assertion recorded in his diary on 29 July 1901, that they, "*..Found lift of machine much less than Lilienthal tables would indicate, reaching only about 1/3rd as much.*"

The wind tunnel experiments conducted during the months of October to December 1901 had provided the Wrights with the answers to the performance questions arising from their 1901 flight trials. For Wilbur and Orville Wright, the control and stability problems were intractable to solution at model scale or by analysis, and they would have to wait until the next flight tests to address these.

On 20 August 1902, Katharine Wright, in a letter to her father, writes,

> *"…The flying machine is in process of making now. Will spins the sewing machine around by the hour while Orv squats around marking the places to sew. There is no place in the house to live but I'll be lonesome enough by this time next week and wish that I could have some of their racket around.…"*

By 'this time next week', Wilbur and Orville had left for Kitty Hawk, arriving on Thursday 28 August to undertake their third flight trial.

4.0 OCTOBER 1902: THE BIRTH OF THREE-AXIS FLIGHT CONTROL

The aircraft the Wrights made over the summer is illustrated in Figs 10 and 11.

The aircraft featured several design changes compared with 1901. The aspect ratio was 6·4, the wing area just over 300ft^2, the wing camber reduced to 1/24, the canard had an increased area and aspect ratio and the aircraft was fitted with a fixed two-surface vertical tail, located 3·5ft aft of the wing trailing edge. A small amount of wing anhedral was built into the new aircraft. The vertical tail was included to compensate for the adverse yaw caused by wing warp, but they may also have anticipated the adverse effects of anhedral with this design feature. It is interesting to note that the wing camber and aspect ratio of the new design was not one that they had tested in their wind tunnel during the winter. The Wrights' also changed the control mechanism for warp and canard pitch. Wing warping was effected by the operator moving his hips in a cradle in the direction of turn and the canard was now operated by a twist bar – twisting up for increased pitch.

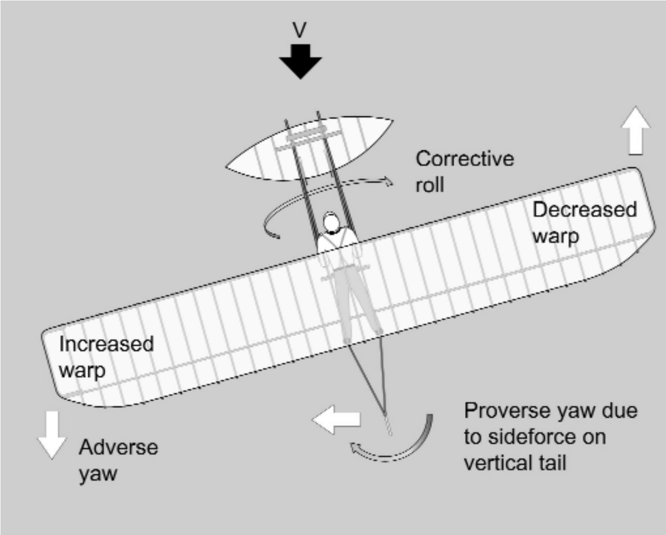
Wilbur recorded his satisfaction with the first kite tests (see Fig. 10) in a letter, written on 16 September, to his aeronautical colleague, George Spratt, who had joined the 1901 trials for a period.

> *"We had it out making some tests of its efficiency today and are very much pleased with the results of our measurements. ….In a test for soaring as a kite the cords stood vertical or a little to the front on a hill having a slope of only 7·5°, (see Fig. 10(b)). This is an immense improvement over our last year's machine which would soar only when the slope was 15° to 20°, as you will remember."*

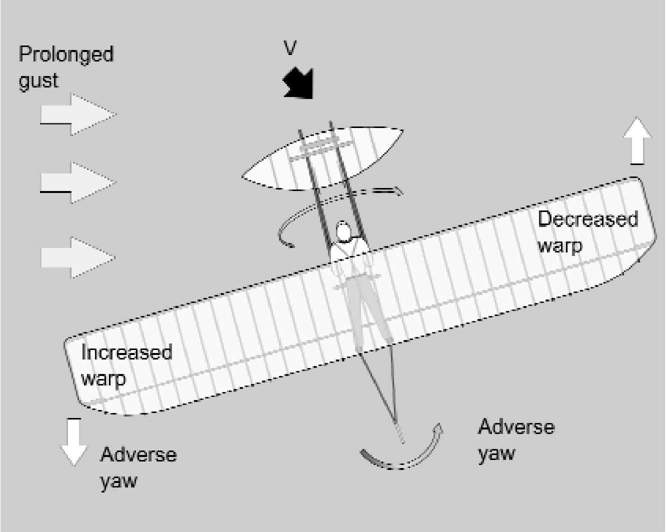
They began testing on 19 Sept and made about 50 glides during the first two days. Wilbur crashed during one glide when he inadvertently increased the canard pitch when the glider began rolling due to a port gust. In a letter to Chanute, written on a rainy Sunday, 21 Sept, Wilbur invited Chanute to join the trial and noted that, "*I made a glide of 140ft at an angle of 7º 10′ on a straight slope whose greatest inclination was 7º 30′, exactly facing the wind, at a speed of about 10 miles over ground, and wind of nine miles, a total of not over 19 miles.*" Their prediction that they would be able to glide at 7º appeared to be correct and they could now look forward to many hours learning to fly. However, during the following Tuesday, when they made about 75 glides, Orville, on his first 'free' flight, had a serious crash, surviving "*..without a bruise or a scratch.*" The problem stemmed from the strong coupling between longitudinal and lateral motions (incidence and sideslip) when the aircraft began to yaw, although Wilbur and Orville could not agree on the exact nature of the problem(1).

After the machine was repaired, they continued testing for another week but Orville remained uneasy about the control problems they were continuing to experience. Later, Wilbur would recall the nature of the outstanding problem in his second lecture to the Society of Western Engineers on 23 June 1903(1). To quote, "*It had been noticed during the day that when a side gust struck the machine its effect was at first partly counteracted by the vertical tail, but after a time, when the machine had acquired a lateral motion, the tail made matters worse instead of better.*" The vertical tail was suppressing the adverse yaw but then making things worse. The expression 'necessity is the mother of invention' comes to mind when making sense of the Wright brothers next move. On the morning of 3 October, Orville shared with Wilbur his idea of giving the pilot separate control of the vertical tail so that the compensation could be reversed as required. Wilbur was concerned about giving the operator too much to do and proposed that the movement of the vertical tail be inter-linked with the wing warp so that when the right roll was commanded, the tail was displaced into the turn giving a more coordinated motion and reducing the build up of sideslip. The problem and solution are illustrated in the sequence in Fig. 12.

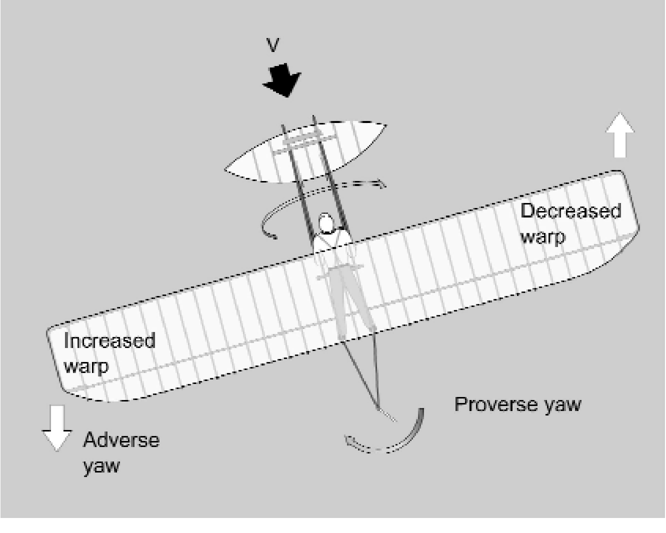
Following a side gust, the anhedral wing causes the aircraft to roll into the gust (a much stronger effect than on the flat winged 1901 machine). Figure 12(a) shows how the fixed tail worked as designed during a transient disturbance, leading to a proverse, restoring, yawing moment, following the pilot's corrective warp input. However, if the sideslip builds up, as with a sustained gust or change of wind direction, then the fixed tail contributed an adverse yaw, due to the weathercock effect, making the situation worse (Fig. 12(b)). The operation of the warp-rudder interconnect caused an additional proverse yaw even when the aircraft slipped out of the direction of the turn (in Fig. 12(c), the turn is to starboard). The roll-yaw interlink effectively assisted turns or corrective rolls. The three-axis



(a) corrective roll and yaw following side gust.

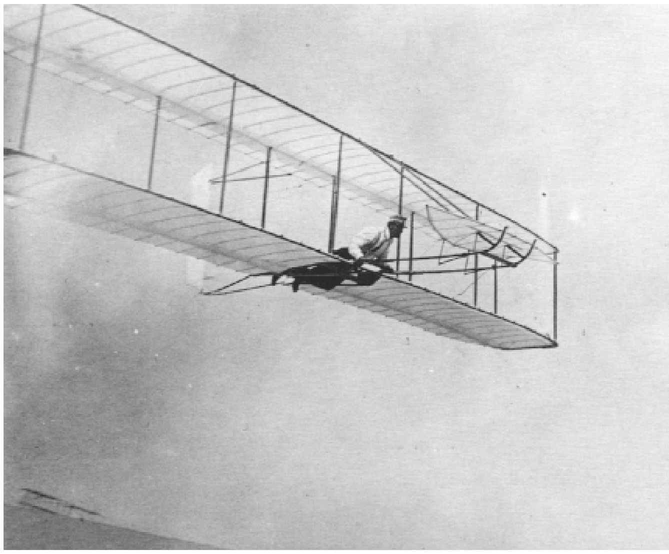


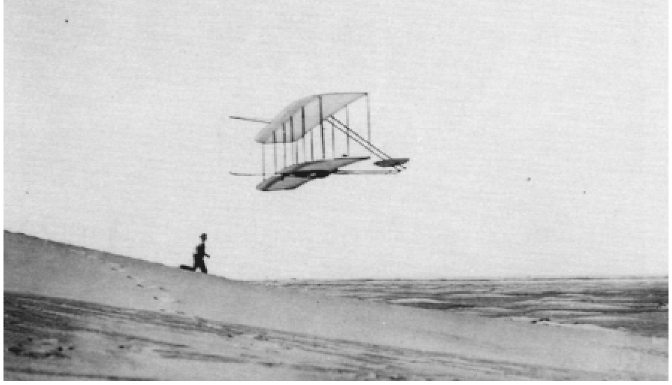
(b) prolonged gust leads to increased adverse yaw.

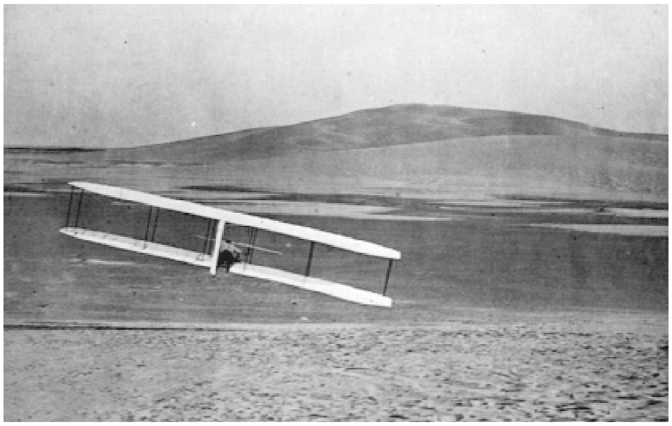


(c) interlinked wing-warp and rudder suppressing adverse yaw.

Figure 12. The 1902 glider, (a) vertical tail counteracting wing adverse yaw, (b) vertical tail giving adverse yaw in sustained lateral gust, (c) interlinked warp-rudder counteracting effects of sustained gust.







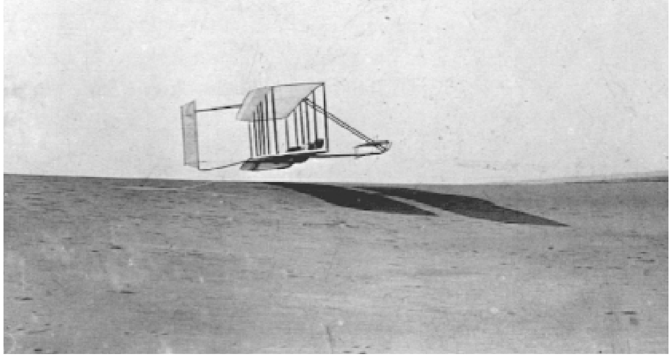


Figure 13. Wilbur Wright flying the modified 1902 Glider; from the top – 10 Oct, 10 Oct, 24 Oct and 10 Oct.

control system would later feature as the basis of the Wright Brother's patent, first applied for in 1903 and finally granted in the United States in 1906[†].

On 4 October, Orville noted in his diary, "*…we began making new vertical rudder, one that is operated at same time as end tips*". They began testing the new aircraft on 8 October. Later, in his second paper to the Society of Western Engineers on 24 June 1903, Wilbur would record, "*With this improvement our serious troubles ended and thereafter we devoted ourselves to the work of gaining skill by continued practice. When properly applied the means of control proved to possess a mastery over the forces tending to disturb the equilibrium. Since balancing was effected by adjustments of the surfaces, instead of by movements of weights, the controlling forces increase in power in the same ratio as the disturbing forces, when the machine was suddenly struck by a wind gust.*" Figure 13 shows four of the collection of photographs taken during the last two weeks of the 1902 flight trials. In the first picture, the faint image on the hillside behind the glider may well be the Chanute-Herring multi-wing machine, with its top surface removed. It is known that this aircraft was tested in this configuration during this period(1).

During the trial period the Wrights and their colleagues made measurements of the performance of the glider. They recorded glide distance and time, the glide angle, the wind speed and ground speed. From these data, tabulated in Ref. 1, the airspeed can be estimated. Knowing the weight of the aircraft (115kg with Wilbur on board and 118kg with Orville on board(1)), and assuming a constant sea level density, the lift coefficient can be computed. Figure 14 shows the collected data points plotted on a chart of lift/drag ratio *vs* lift coefficient, along with the best (least squares) fit for a quadratic variation. The scatter in the data is so large, and hence correlation so weak, that any estimate of an average performance is likely to be significantly in error. The problem stems from the single point nature of the data whereas in reality the glide slope and airspeed almost certainly varied significantly during the glides. In correspondence between Wilbur Wright and Octave Chanute during July 1903, their differing opinions on the value of the glide measurements would aggravate the developing tension between the two colleagues.

Chanute was confused by the measurements and implied in a letter, written on 12 July that the Wrights may have over-estimated the performance of their glider. Wilbur replied robustly, in a letter dated 14 July, requesting that "*If you will furnish us data of the speed at starting, rate of acceleration, maximum speed, rate of retardation, speed at landing, and a diagram of the path and undulations of the machine, with a mark to indicate the points at which observations of angle were taken, I think it would be possible to compute one of these glides though it might require some time.*" Wilbur had clearly tried to make the same computations as shown in Fig. 14 himself and the tone of his response hardly concealed his frustration with Chanute. Later in the same letter, Wilbur made the point firmly, "*The data of ordinary glides are, in my opinion, almost worthless for purposes of computation unless a possible error of 50%, or sometimes more, is no serious objection.*" During his lecture on Experiments and Observations in Soaring Flight, given to the Western Society of Engineers on 24 June 1903 and later published in their journal in December 1903, Wilbur stated that "*Observations were almost constantly being made for the purposes of determining the amount and direction of the pressures upon the sustaining wings; the minimum speed required for support; the speed and angle of incidence at which the horizontal resistance became least; and the minimum angle of descent at which it was possible to glide. To determine any of these points with exactness was found to be very difficult indeed….*" With a total weight of 250lb, Wilbur estimated that a horizontal resistance

---

[†] In Ref. 3, Crouch notes that the first application, filed on 23 March 1903, was rejected on the grounds that it was" incapable of performing its intended function!"

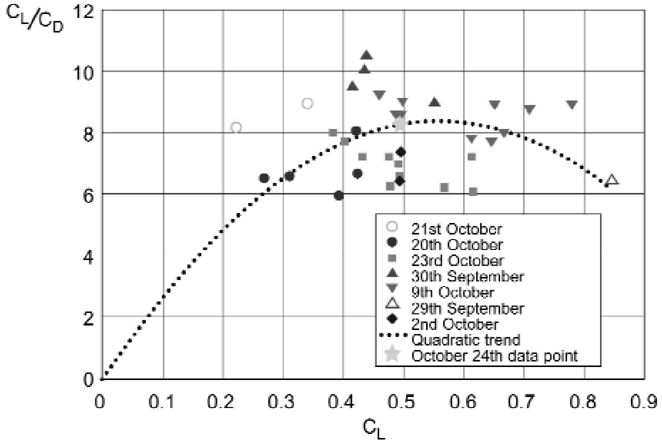


Figure 14. Lift/Drag *vs* C_L for the 1902 Glider data (from Ref. 1 tables).

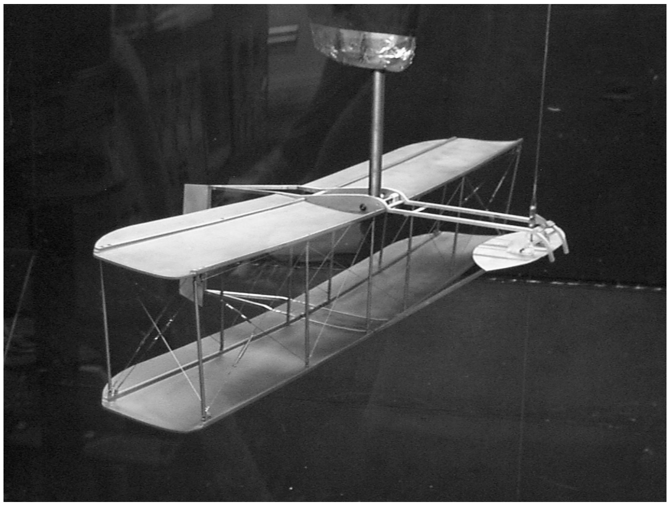


Figure 15. 1/8th scale 1902 glider model.

of the machine was 30lb and remained nearly constant at speeds between 18 and 25mph. These speeds correspond to a lift/drag of approximately 8·33 and C_L values between 0·75 and 0·5, corresponding very roughly to the maximum portion of the fitted curve in Fig. 14. In his lecture, Wilbur actually remarks on the flights made on 24 October declaring the point shown on Fig. 14 to be a good estimate of the glider performance; coincidently, it lies on the line of best fit.

From Orville's diary dated Tuesday 21 October 1902, the centre of gravity of the machine was "*approximately 18″ from front edge.*" The centre of gravity of the aircraft plus pilot was probably close to this point. With its 5ft chord, the aerodynamic centre of the main wing was therefore ahead of the cg and the aerodynamic centre of the whole aircraft, the neutral point, was even further in front. The Wrights had designed an unstable aircraft, but just how unstable – how much negative static margin was present and how much dynamic instability – requires different aerodynamic measurements and analyses than the Wrights were able to handle or contemplate. Later in this paper, the critical success factors of the Wright brothers' work are reviewed, and the notion that Wilbur and Orville perceived that control was more important than stability is further discussed. As Culick notes in Ref. 5, "*Only the Wright brothers recognised that the great problem of control still remained to be solved….They faced and effectively solved, to the extent they required, problems of stability and control about all three axes.*" Their accomplishments are all the more impressive when put in the context of the continuing development of aircraft flight mechanics post 1903; as pointed out by W.H. Phillips in Ref. 9, "*The entire period from the Wright brothers to 1935, is characterised by a lack of understanding of the relation between stability theory and flying qualities.*"

Wilbur and Orville left Kitty Hawk for Dayton on 28 October 1902, just a few days after Orville had shared his euphoria with his sister, "*The past five days have been the most satisfactory for gliding that we have had… we are able to take it out in any kind of weather.*" The flying practice they had gained would stand them in good stead and the success of the 1902 glider, from both performance and control standpoints, would define a central thread of the Wright brothers' progress for some years to come. To gain a better understanding of the capabilities and shortcomings of this aircraft, in the following section the 1902 glider design is appraised using current day engineering methods including wind-tunnel testing, simulation modelling and the syntheses and analyses of aircraft flying qualities.

5.0 MODELLING AND SIMULATION OF THE WRIGHT GLIDERS

From a flight mechanics perspective, the 1902 glider was rich in characteristics that have continued to feature, in one form or another, in aircraft throughout the 100 years of powered flight – adverse yaw, deep stall, unstable pitch motion etc. The aims of the Liverpool Wright Project are to synthesise and analyse the flight characteristics of the Wright aircraft from 1900 to 1905 using modern engineering methods. The primary motivation behind the project is to create 'high-fidelity' simulations of the Wright aircraft and to make formal handling qualities assessments of the aircraft including test pilot evaluations. The process of discovery experienced by the Wright brothers can be powerfully brought to life through the piloted tests and the important threads in the design evolution highlighted. The three elements of the engineering analysis of the Wright Glider are – wind tunnel testing, simulation model development and handling qualities analysis – activities under these three headings applicable to the 1902 Glider will be summarised in the remainder of the paper. A full description of the project will be given in the second author's PhD thesis, due to be published in 2004. Some of the results for the 1902 Glider can also be found in Ref. 10.

5.1 Wind-tunnel testing

The objectives of the tests were to measure force and moment coefficients over ranges of angle-of-attack, α (–10° to +24°) and sideslip β (±30°), combined with effects of control surface deflections, to provide the 'steady' aerodynamic data for the simulation model. Three Glider models have been constructed, two 1901 gliders at 1/5th scale (4·4ft span) and one 1902 glider at 1/8th scale (4·01ft span). The 1901 glider models featured the original 1/12 camber and the modified 1/19 camber. Both models featured a variable camber canard and wing-warping. The 1902 glider model featured wing warping, an adjustable canard and a single, adjustable vertical tail. Figure 15 shows the 1902 model mounted in the Manchester University Goldstein tunnel, where the tests were conducted. The tunnel is closed return, runs at atmospheric pressure and has a working section of 9 × 7·3ft.

The models were mounted on a 'T' strut connected to an overhead six degree-of-freedom force and moment balance. The models were thus tested inverted with the front supported by a vertical 'nose-wire'. This configuration gave the minimum of interference from the strut mount with the aerodynamic surfaces and left no attachments along the wings – an important feature to allow for the wing warping.

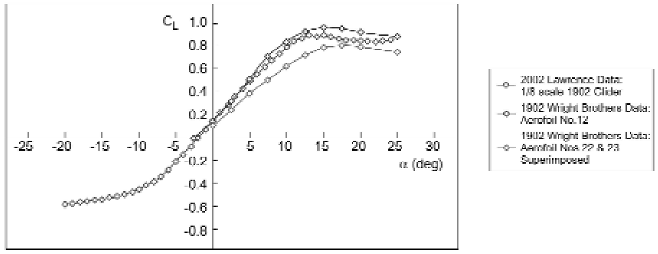


Figure 16. Lift coefficient *vs* Incidence.

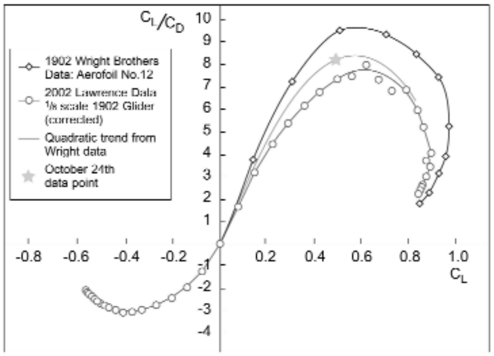


Figure 17. Lift/Drag ratio of 1902 Glider as a function of C_L.

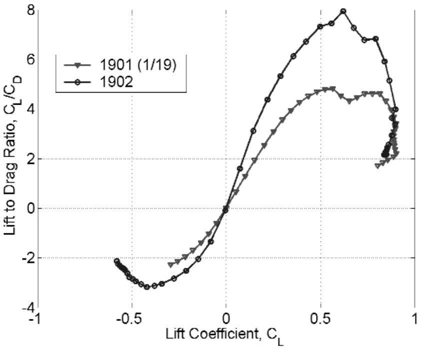


Figure 18. Comparison of the Lift/Drag ratio of 1901 (●) and 1902 (▲)Gliders.

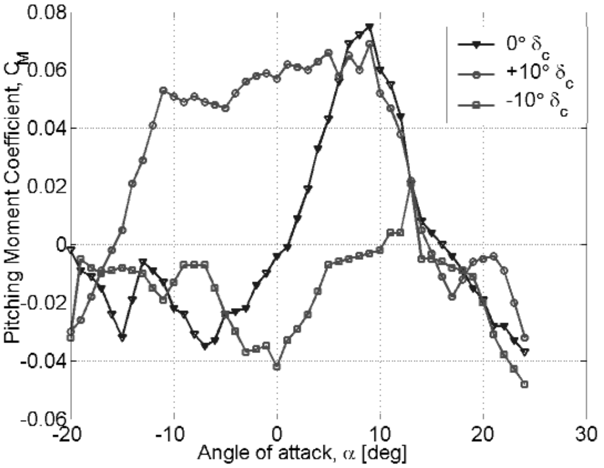


Figure 19. Pitching moment coefficient about centre of gravity (0·35*c*) as a function of incidence.

The conventions for the various control deflections are as follows:

a) Canard positive leading edge up (pitch up control), $+\delta_c$
b) Warp positive – right wing tip increased incidence, i.e. control input positive, $+\delta_w$ gives a roll to the left ($i_{\text{right}}–i_{\text{left}}$).
c) Rudder control positive trailing edge to starboard (nose to right), δ_r.

The reference datum for the angle of incidence was the chord line from the leading edge to trailing edge of the wing.

The 1901 glider was tested at speeds between 14-15ms^{-1}, giving a Reynolds number (based on the wing chord, c = 0·426m) of Re = 400,000 – 430,000. This compares with a full scale Reynolds number at 20 – 30mph of $1{\cdot}28 \times 10^6 – 2{\cdot}1 \times 10^6$ (c = 2·1336m). The 1902 glider was tested at speeds of 17·5-21·5ms^{-1} giving a Re = 223,000 – 275,000, while full-scale at 20 – 30mph gives Re = 910,000 – $1{\cdot}37 \times 10^6$. The 1902 tests were thus conducted at a quarter of full-scale Re values. Nevertheless, it is considered that the results are relatively insensitive to Reynolds number over the range between full scale and model tests. Several sources report the performance of thin cambered airfoils as fairly insensitive to Reynolds numbers (e.g. Ref. 11). The primary Reynolds number effect is a reduction in C_{Lmax} of around 10% when reducing the Re ≈ 1×10^6 to Re ≈ 1×10^5. The remaining components of the aircraft such as the struts, wires and attachments are made up from standard shapes (cylinders, squares) and have known Reynolds number properties and are either insensitive to the Reynolds number difference between full-scale and model, or experience a large degree of flow separation.

Longitudinal Aerodynamics; Despite the foregoing differences, Fig. 16 shows remarkable agreement between the lift coefficient results from the current tests and those documented by the Wrights in Ref. 1 for single aerofoil No 12. Also shown on Fig. 17 are results for the biplane combination of aerofoils Nos 22 and 23, which were very similar to the No 12 aerofoil. The Wright wind tunnel was run at about 25mph (11·2ms^{-1})(1). The biplane model (aerofoils 22 and 23 superimposed) had a chord of 0·66in (0·017m) giving a Re of only about 13,000. The thin sections used on both model and full scale reduce the flow differences due to Re effects but as pointed out by Anderson in Ref. 8, at low Re's, below 100,000, the lift curve slope reduces to about 70% of full scale, as suggested in Fig. 16. Wilbur had noticed this loss of efficiency with superimposed surfaces. In a letter to Chanute on 15 Dec 1901, he points out that(1) that his data "*...will tend to establish a general law that the lift and tangentials of a set of superimposed or following surfaces spaced about their length apart are approximately equal to those of a single surface of similar profile or curvature having a breadth equal to that of one surface and a length equal to the sum of their lengths.*" Wilbur refers to the chord as the length and the span as the breadth and is noting an equivalence between superposition and aspect ratio, as far as lift curve slope is concerned.

The Lawrence data in Fig. 16 shows a zero-lift angle-of-attack of about –2·5 deg and a lift curve slope of about 3·8/rad. C_L peaks at about 0·85 and remains at this level through to the measurement range limit of 25°. Flow visualisation reveals a large leading-edge separation bubble over the upper surface at high angles-of-attack, preserving the low pressure and inhibiting the lift loss at stall. The drag increases however and Fig. 17 shows comparisons of the glider efficiency – the ratio of lift to drag, plotted against the lift coefficient. In Fig. 17, the drag coefficients for the struts, wires and supporting structure have been 'corrected' for known Re effects.

Included on Fig. 17 is the trend line from the Wrights' flight tests and the 24 Oct data point referred to by Wilbur in his 1903 lecture to the Society of Western Engineers. The Wrights would have realised from their flight tests that the performance was not as good as the wind tunnel data suggested. Nevertheless they had improved significantly on their 1901 glider as illustrated in Fig. 18 where the lift/drag ratio of the two glider models are compared to show a 60% increase in maximum efficiency.

The pitching moment characteristics are shown in Fig. 19 (as function of incidence for three canard settings) and 20 (as function of C_L for three cg locations). Strong non-linearity is clearly visible with a reversal of the overall slope at higher incidences (for $\alpha >$ 10deg for zero canard). In Fig. 19 the canard can be seen to give a positive, albeit weak, increase in moment up to about +6° α with +10° δ_c. Any further increase in a results in α total loss of nose up control power. The same is seen for a –10° δ_c where at –5° α there a loss of nose down control. In both cases the canard is stalling at incidences of around ± 15°. The slope of the curve at low α in Fig. 20 is equivalent to the static margin, H_n. A value of –16% is measured for the working range of C_L between 0·2 and 0·6. This value corresponds to a cg location of 0·35c, and is probably more unstable than when the Wrights were flying. Wilbur describes the action of the 1902 glider, "*The action of the machine is almost perfect…*", suggesting an easily controlled vehicle. Shown in Fig. 20 is the effect of shifting the cg in the 1902 glider. The cg of the 1902 glider without pilot is quoted as being "*approximately 18 inches from the wing leading edge*"(1). This is at 30% chord, and when the pilot is included this is likely to shift slightly forward. Taking the glider's weight of 116lb and the pilot's (Orville) weight of 140lb the resultant cg is calculated to be approximately at the 24% chord position. At this cg position, the static margin is slightly unstable, $H_n = –6.6\%$, for C_L between 0·2 and 0·6. The shifting centre of pressure with incidence was noted by the Wrights and reflects a corresponding variation in stability.

Another major feature of the Figs 19 and 20 is the reversal of the slope, indicating a large change in the pitching moment, at high incidence. This effect is due to separated flow near the leading edge of the airfoil. At high incidence, the wing continues to create lift, but a change in the pressure distribution moves the centre of pressure aft causing a large nose-down pitching moment. Figures 21 and 22 show two flow visualised images. The wing in Fig. 21 is at an angle-of-attack where the flow is smooth and attached to both surfaces, representing the α range 2° – 8°. Figure 22 shows the model at high a when the flow separates and a re-circulation bubble on the upper surface forms. The consequences are a low but sustained C_{Lmax} and a large C_M break. Both of these characteristics are typical of very thin, cambered airfoils. The Wrights also detected this phenomenon when testing a single surface of their 1902 glider – "*Found that surface tended to duck at large angle, but on increase of wind and decrease of angle of incidence centre of pressure seemed to move forward, and pitching ceased.*"(1), The consequence of this effect is that if the pilot were to attain a high α flight condition, by pitching nose-up and losing airspeed, there would a restoring nose-down pitching moment. Also, Fig. 19 displays a second crossing of the x-axis (C_M = 0) at a high incidence of around 15-16°. This zero moment 'trim' point, combined with the C_{Lmax} which is preserved up to high angles-of-attack, represents a flight condition that the Wrights would often find themselves in, where the aircraft would lose airspeed and descend in a flat 'deep-stall'. Many of the longitudinal problems with the 1901 and 1902 Gliders can be explained by examination of the detailed features in Fig. 19; such information was, of course, not available to Wilbur and Orville.

Lateral-Directional Aerodynamics; Figs 23-26 illustrate the lateral-directional aerodynamic characteristics of the 1902 glider wind-tunnel model. Figure 23 shows the yawing moment coefficient with sideslip at three rudder settings; the aircraft is directionally stable. The control sensitivity $\partial C_n / \partial \delta_r$ is approximately constant up to the stall angle of the tail surface, whereupon it falls off rapidly. The rolling moment is shown in Fig. 24; the anhedral angle of the wings gives a positive value of $\partial C_l / \partial \beta$.

The effect of wing-warping is illustrated in Figs 25 and 26. Figure 25 shows the rolling moment coefficient plotted against the angle of attack with curves for warp angles, δ_w of +14, –14, and 0°. The warp control is effective at creating rolling moments at angles of incidence between –5° and +10°. Beyond these angles the roll control sensitivity falls off, and by $\alpha = 15°$, $\partial C_l / \partial \delta_w \approx 0$. Figure 26 presents the yawing moments created when the warp control is operated (without interlinked rudder). Large adverse yaw moments are generated,

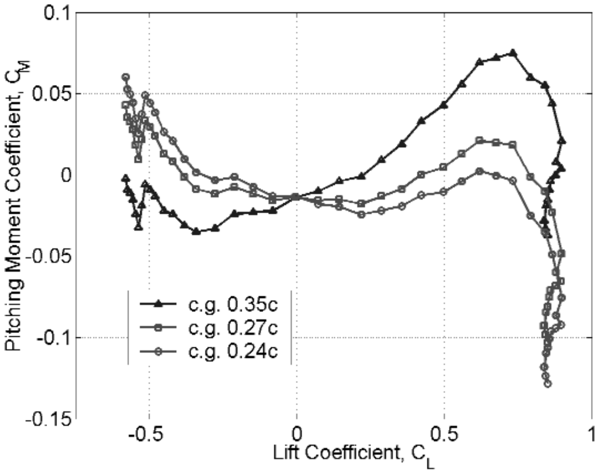


Figure 20. Pitching moment coefficient about centre of gravity for different cg locations.

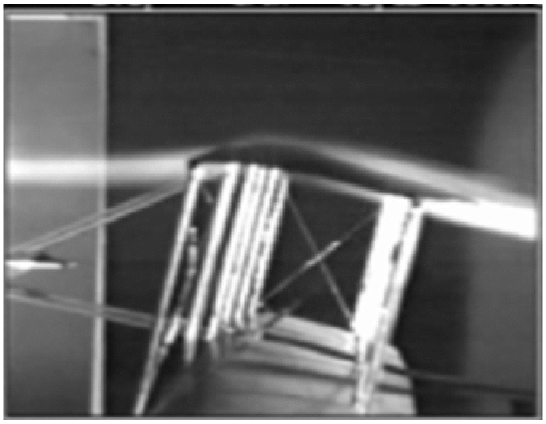


Figure 21. Smoke flow visualisation $\alpha \approx 6°$.

Figure 22. Smoke flow visualisation $\alpha \approx 20°$.

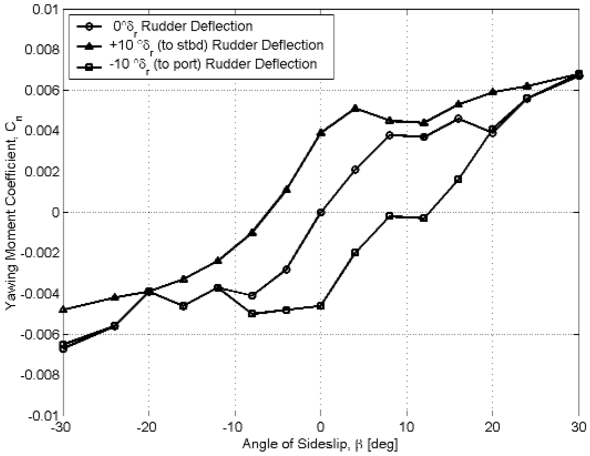


Figure 23. Yawing moment coefficient as a function of sideslip.

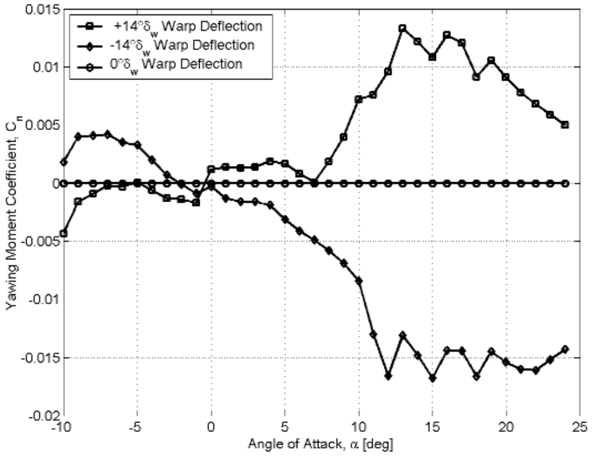


Figure 26. Yawing moment coefficient as a function of incidence.

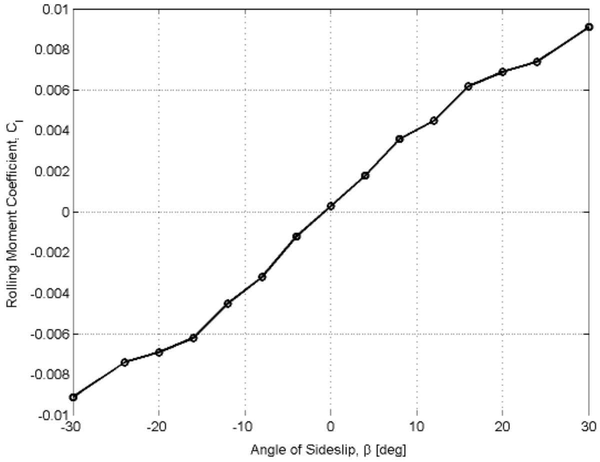


Figure 24. Rolling moment coefficient as a function of sideslip.

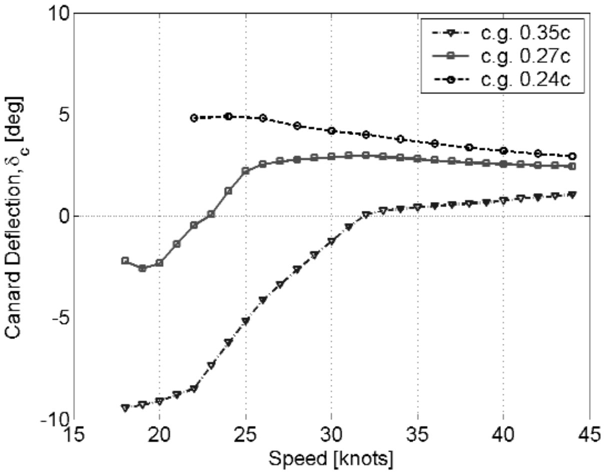


Figure 27. Canard angle to trim as a function of speed.

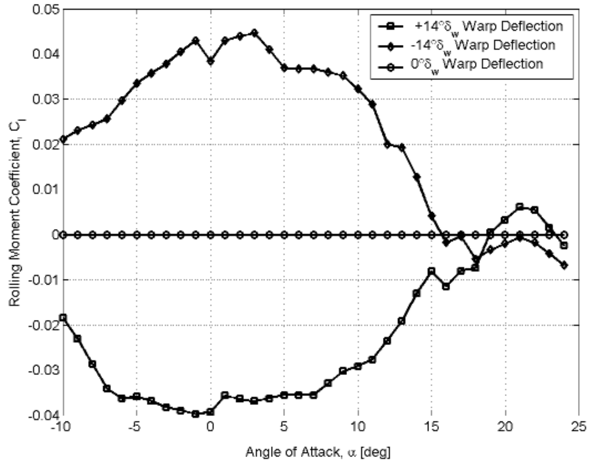


Figure 25. Rolling moment coefficient as a function of incidence.

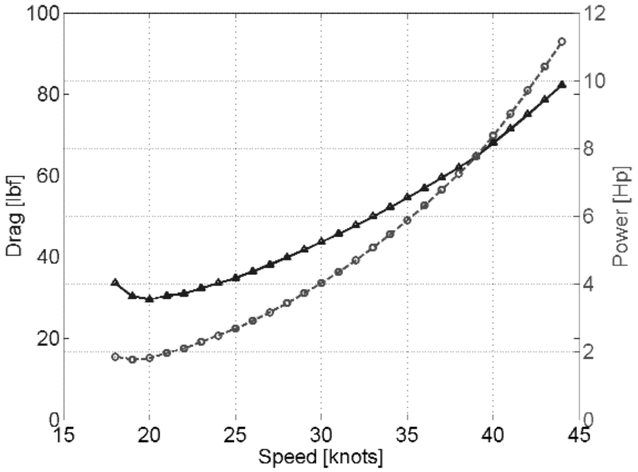


Figure 28. Drag and power as a function of speed.

becoming increasingly worse with increasing incidence. For the α range of –5 to +10°, the adverse yawing moments are less severe for the maximum warp of ±14°. Comparing the yawing moments available from the rudder and the warp controls, it can be seen that a ΔC_n of $\approx \pm 0{\cdot}004$ for ±10° δ_r is achieved, and the maximum ΔC_n of $\approx \pm 0{\cdot}005$ for $\pm 14°\delta_w$ is not achieved until $\alpha = 10°$. This indicates that the warp-to-rudder interlink system devised by the Wrights was very effective at cancelling the adverse yaw moments. In Ref. 12, Jex and Culick refer to a gearing ratio of $\delta_r = 1{\cdot}25\delta_w$. Comparing the control derivatives of ${}^{\partial C_n}\!/\!{}_{\partial \delta_r} = 0{\cdot}0004\text{deg}^{-1}$ and ${}^{\partial C_n}\!/\!{}_{\partial \delta_w} = 0{\cdot}00036\ \text{deg}^{-1}$ (worst case below $\alpha = 10°$), it can be seen that small proverse yawing moments are created by hip cradle motion.

5.2 Simulation model construction

The Wright aircraft simulation models are created using the FLIGHTLAB modelling and simulation software environment(13). The software was developed to address the particular demands of high-fidelity simulation of rotorcraft and uses a multi-body dynamics approach to model flight vehicles. It provides a range of tools using a modular approach to assist in rapid generation and analysis of complex, non-linear models. FLIGHTLAB has a number of 'high-level' graphical user interfaces to aid the generation of models – GSCOPE, FLIGHTLAB model editor (FLME) and XAnalysis. GSCOPE and FLME enable the construction of models through the manipulation of icons or model trees. The process builds scripts (code) using FLIGHTLAB's interpretative language SCOPE. Not all the features required to model the Wright aircraft were available in the component library. Consequently, for the Wright models, a library of novel user-defined components and model scripts were developed to implement the features required. XAnalysis offers a suite of functions that enable the user to conduct control system synthesis and overall vehicle analyses on the simulation model. Within XAnalysis, the user has the ability to set the desired test conditions, trim the aircraft and perform dynamic response, stability, performance and handling qualities analyses. Finally the real-time operating system, Pilotstation, links with FLIGHTLAB to enable piloted simulation.

The wind tunnel tests provided a new set of data describing the (static) aerodynamic characteristics of the aircraft as a whole. In order to incorporate this data a multiple lookup table, 'super-component', was developed. This component calculates the total aerodynamic loads for the canard, wings, vertical surfaces, airframe and pilot in one system. The aero-tables are generally three dimensional, with the coefficients a function of α, β, and δ_{control}. The super component is then attached to the aircraft model at a predefined airload reference point. The structure of the aircraft is modelled as a rigid body with a mass placed at the aircraft centre-of-gravity and moments of inertia distributed about the body axes. No published inertial data were available for the 1902 glider hence a spreadsheet method was developed, based on Ref. 14, to estimate the moments of inertia. A simple landing skid model based on the standard FLIGHTLAB two-strut undercarriage model was included to enable the glider to be landed. The spring, damping and friction coefficients were selected to emulate the behaviour of landing skids on a sandy surface.

Aerodynamic damping effects are included in derivative form for pitch, roll and yaw based on simple linear, two-dimensional theory(15).

5.3 Handling qualities analysis

Handling Qualities analysis addresses the requirements for trim, stability and response and the consequent pilot's impressions of an aircraft's suitability for its role, defined by a collection of mission task elements. Using the FLIGHTLAB trim analysis tool, the steady performance characteristics of the 1902 glider can be analysed. Figure 27 shows the canard deflection angle required for trim across a speed range for three locations of the centre of gravity. It can be seen that as the cg moves forwards from the aft position ($0{\cdot}35c$), the slope changes from positive to slightly negative at a speed of 24kt. The minimum speed that the model would trim was about 16kt; below that there was insufficient control power to trim. For the unstable configurations, aft stick was required to trim as the speed increased. Figure 28 shows the variations in drag and power (drag × speed) with forward speed. The minimum drag speed occurs at about 20kt and the minimum power required for flight is 1·8 horsepower at a speed of about 18·5kt. The speed at minimum drag corresponds to the minimum glide angle (maximum C_L/C_D), whereas the minimum power speed represents the condition for the minimum sink rate.

Table 1
Configuration data for 1902 Glider analysis

Trim speed 24kt ($40{\cdot}5\text{ms}^{-1}$)
Weight 252lbf
$I_{XX} = 228$ slugs-ft^2
$I_{YY} = 48$ slugs-ft^2
$I_{ZZ} = 229$ slugs-ft^2
Span $b = 32$ft
Chord c = 5ft
Total wing area = 305ft^2

The most common flight speed that Wrights glided at was approximately 24kt, and this case has been selected for further analysis using open and closed loop stability analysis. From the non-linear FLIGHTLAB model a linear model can be derived, valid for small perturbations from the trim flight condition. Table 1 gives the configuration data for the trim case.

The system and control matrices for the aircraft at the 24kt flight condition are given below in semi-normalised form (e.g. X_u (1/sec), M_w (rad/ft.sec), $M_{\delta c}$ (1/sec^2)). The perturbation velocities along the body-fixed X, Y and Z axes are u, v and w; the angular rates are p, q and r and the Euler angles are θ, ϕ and ψ. The system equations are in the general form;

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \qquad \ldots (2)$$

Longitudinal **A** matrix ; $\mathbf{x} = [u\ w\ q\ \theta]^{\mathrm{T}}$, cg @ $0{\cdot}35c$

$$\mathbf{A}_{\mathbf{Long}} = \begin{bmatrix} -0{\cdot}2158 & 0{\cdot}7225 & -2{\cdot}7944 & -32{\cdot}0204 \\ -1{\cdot}0274 & -8{\cdot}1751 & 44{\cdot}9362 & 3{\cdot}3716 \\ -0{\cdot}0643 & 0{\cdot}9543 & -3{\cdot}5995 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Longitudinal **A** matrix, cg @ $0{\cdot}24c$

$$\mathbf{A}_{\mathbf{Long}} = \begin{bmatrix} -0{\cdot}1742 & 0{\cdot}6877 & -2{\cdot}5623 & -32{\cdot}0961 \\ -1{\cdot}1065 & -7{\cdot}6488 & 43{\cdot}0690 & 2{\cdot}6753 \\ -0{\cdot}0074 & 0{\cdot}1191 & -3{\cdot}2926 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Note the positive M_w derivative (element 3,2), indicating the static instability of the aircraft (particularly strong in the aft cg configuration) and the relatively large heave and pitch dampings (Z_w and M_q). Longitudinal **B** matrix, $\mathbf{u} = [\delta_c]$, for cg at $.35c$ *and* $.24c$ respectively.

$$\mathbf{B}_{\mathbf{Long}} = \begin{bmatrix} 9{\cdot}6691 \\ -18{\cdot}2279 \\ 18{\cdot}5695 \\ 0 \end{bmatrix}, \mathbf{B}_{\mathbf{Long}} = \begin{bmatrix} -2{\cdot}1548 \\ -2{\cdot}5659 \\ 12{\cdot}6496 \\ 0 \end{bmatrix}$$

Lateral **A** matrix, $\mathbf{x} = [v\ p\ r\ \varphi]^T$ cg @ 0·35*c*

$$\mathbf{A}_{\text{Lat}} = \begin{bmatrix} -0\cdot 3460 & 1\cdot 8597 & -40\cdot 4611 & 32\cdot 0208 \\ 0\cdot 0441 & -14\cdot 7847 & 3\cdot 2618 & 0 \\ 0\cdot 0625 & -1\cdot 6653 & -0\cdot 9663 & 0 \\ 0 & 1 & -0\cdot 1053 & 0 \end{bmatrix}$$

Lateral-Directional **B** matrix, $\mathbf{u} = [\delta_{wr}]$; $\mathbf{u}=[\delta_w\ \delta_r]^T$

$$\mathbf{B}_{\delta\text{wr}} = \begin{bmatrix} 4\cdot 470 \\ -13\cdot 8699 \\ -2\cdot 2536 \\ 0 \end{bmatrix}, \quad \mathbf{B}_{\text{Lat}} = \begin{bmatrix} 0 & 4\cdot 5321 \\ -13\cdot 8699 & 0 \\ 0\cdot 4796 & -2\cdot 0197 \\ 0 & 0 \end{bmatrix}$$

Note the high value of roll damping L_p, the adverse yaw effects (N_p and $N_{\delta w}$), negative dihedral (positive L_v) and relatively weak weathercock stability, N_v.

For the longitudinal motions, the **B** matrix represents the effects of the canard control, δ_c. For lateral-directional motions, $\mathbf{B}_{\delta wr}$ represents the control with the warp-rudder interconnect system, while $\mathbf{B}_{lat}$ breaks down the separate effects of warp, δ_w, and rudder, δ_r.

The eigenvalues for the longitudinal and lateral-directional system matrices are:

Longitudinal eigenvalues (cg @ 0·35*c*)

–12·7758
1·9558
–0·5852 + 1·2865i
–0·5852 – 1·2865i

Longitudinal eigenvalues (cg @ 0·24*c*)

–8·5371
–2·0827
–0·8833
0·3875

Lateral-directional eigenvalues (cg @ 0·35*c*)

–14·3685
–0·9226 + 1·4639i
–0·9226 – 1·4639i
0·1168

Both longitudinal and lateral-directional motions are unstable. For the aft cg case, the pitch mode with λ = 1·9558/sec, is particularly unstable, with a time to double amplitude T_D = 0·35 seconds. The spiral mode, λ = 0·1168/sec, has a T_D = 5·9 seconds. In the following discussion, the flying qualities of the 1902 Glider are referred to modern day criteria set in standards such as Refs 16 and 17, and referred to flying qualities Levels as originally defined by Cooper and Harper(18).

Longitudinal Dynamics

Referring to the short period criteria within MIL-F-8785C(16), with the cg at 0·35*c* the dynamics lie outside the Level three boundary. Moving the cg forward to 0·24*c* reduces the instability (λ = 0·3875, T_D = 1·79s) but the aircraft remains unstable. This confers Level 3 flying qualities for the aircraft. The source of the problem for the Wrights was, of course, the positive pitching moment change with incidence, already referred to in Fig. 19, and the requirement for aft stick to trim as the speed increased in Fig. 27. The derivative M_w at both cg locations is positive, reflecting the negative static margin but it is interesting to examine the manoeuvre margin and the short period approximation for these cases. The approximation for the short period eigenvalues (λ)[†], assuming no speed changes during this rapid incidence adjustment mode, is given by;

Table 2
Comparison of Exact and Approximate 'Short Period' eigenvalues

	cg @ 0·35c		cg @ 0·24c	
	Exact	**Approx**	**Exact**	**Approx**
λ_1	–12·7588	–-12·8239	–8·5371	–8·6129
λ_2	1·9558	1·0493	–2·0827	–2·3285

$$\lambda^2 - \left(Z_w + M_q\right)\lambda + Z_w M_q - M_w (Z_q + U_e) \ = 0 \qquad \ldots (3)$$

The term $Z_w M_q - M_w (Z_q + U_e)$ is proportional to the manoeuvre margin and is negative (-13·4) with the cg @ 0·35 and positive (+20) with the cg @ 0·24. A comparison of the exact and approximate roots is given in Table 2. The large stable root is captured well in both cases but the unstable mode is only captured in the aft cg configuration and then with a nearly 50% error. The forward speed change in this mode is clearly significant. In the forward cg configuration, the approximation picks up the stable pitch mode; as the cg is moved further forward these two real roots combine to form the true short period mode and the approximation given in Table 2 then captures both frequency and damping very well.

The approximation for the phugiod mode, assuming a motion made up of essentially vertical and horizontal motions(19) is given by the expression;

$$\lambda^2 + \left\{ \frac{-X_u + \left(X_w - \text{gC os}\Theta_e / U_e\right)\left(Z_u M_q - M_u \left(Z_q + U_e\right)\right) + \left(X_q + W_e\right)\left(Z_w M_u - M_w Z_u\right)}{M_q Z_w - M_w \left(Z_q + U_e\right)} \right\}\lambda$$

$$-\frac{\text{gC os}\Theta_e}{U_e}\left\{ Z_u - \frac{Z_w \left(Z_u M_q - M_u \left(Z_q + U_e\right)\right)}{M_q Z_w - M_w \left(Z_q + U_e\right)} \right\} \ = \ 0 \qquad \ldots (4)$$

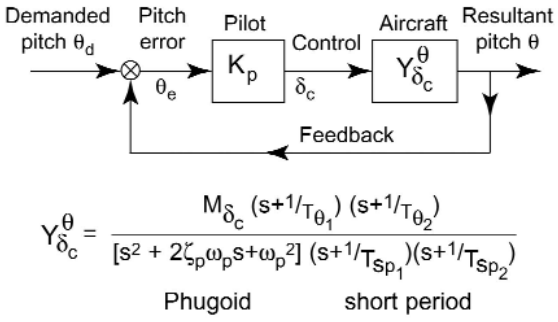
A comparison of exact and approximate eigenvalues is given in Table 3. Although an oscillation is predicted for the aft cg configuration, the frequency and damping are more than 50% in error. For the forward cg configuration the pitch instability is now predicted, although with a 30% error. The approximations given by Tables 2 and 3 rely on a weak coupling between the motions and a wide separation between the modes. For conventional aircraft they tend to give good approximations and provide insight into the derivatives that contribute to stability and instability. The 1902 glider was unconventional and the success of the approximations is much more limited.

An unstable aircraft is not necessarily un-flyable of course. Acting as sensor and actuator elements in the feedback loop, a pilot can modify the closed loop dynamics in a wide variety of ways. Figure 29 shows a schematic describing the aircraft-pilot system. The pilot's action is approximated as a proportional controller (in a

Table 3
Comparison of Exact and Approximate 'Phugoid' eigenvalues

	cg @ 0·35c		cg @ 0·24c	
	Exact	**Approx**	**Exact**	**Approx**
Real	–0·5852	–0·2762	–0·8833	–0·6346
Imag.	±1·2865i	±1·9706i	±0i	±0i
Real	–	–	0·3875	0·5052
Imag.	–	–	±0i	±0i

[†] Note that with real eigenvalues there is strictly no 'short period' mode but the approximation can still work for aperiodic modes when the constant speed assumption holds.



$$Y^{\theta}_{\delta_c} = \frac{M_{\delta_c}\,(s+1/T_{\theta_1})\,(s+1/T_{\theta_2})}{[s^2 + 2\zeta_p\omega_p s+\omega_p{}^2]\,(s+1/T_{sp_1})(s+1/T_{sp_2})}$$

Figure 29. Closed-loop system with pilot model.

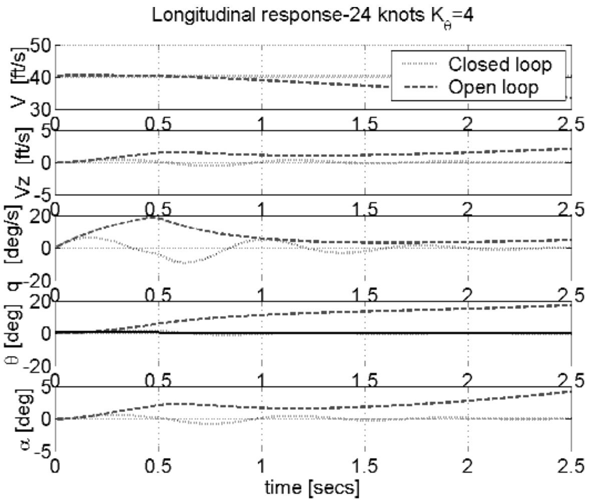


Figure 30. Time response comparison of open and closed loop control.

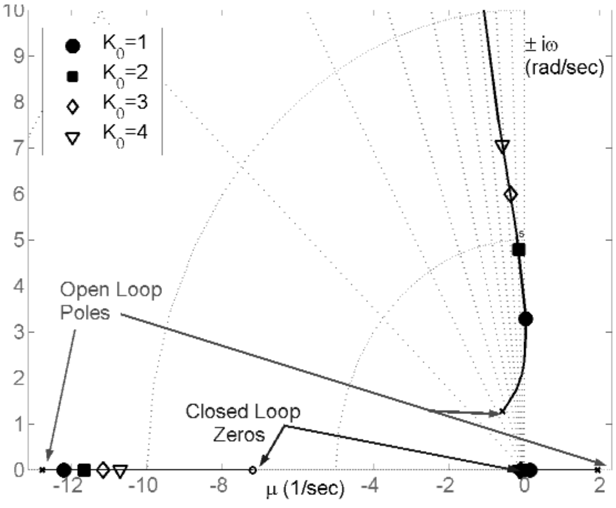


Figure 31. Longitudinal root loci for varying K_θ; cg @ 0·35*c*.

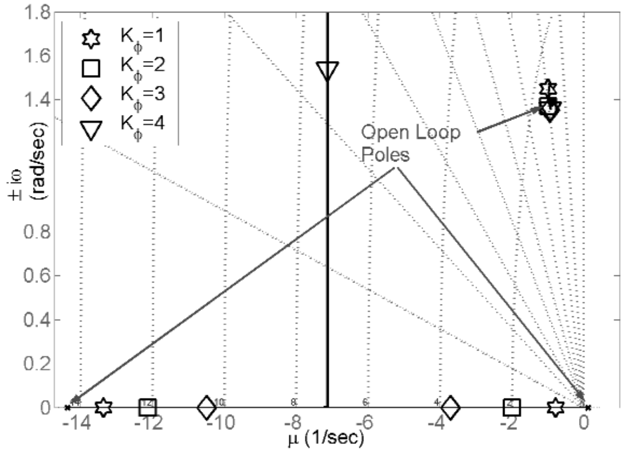


Figure 32. Longitudinal root loci for varying K_θ; cg @ 0·24*c*.

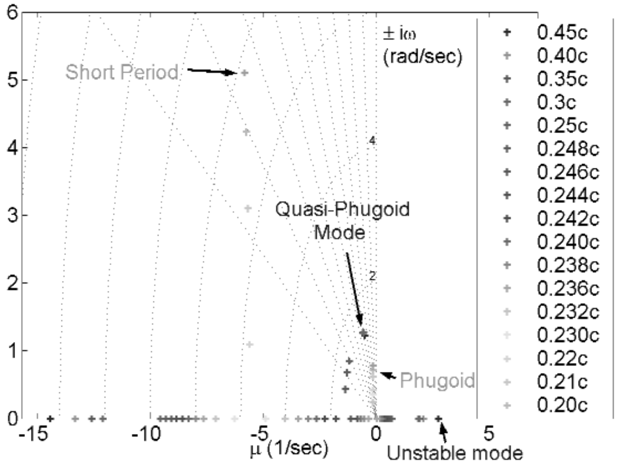


Figure 33. Root loci showing effect of cg location on the longitudinal modes.

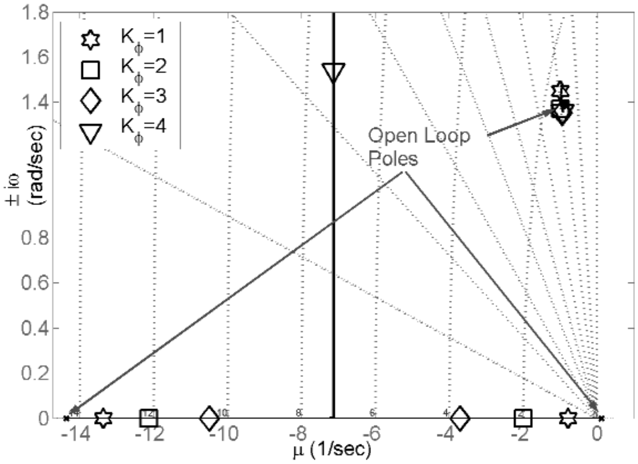


Figure 34. Lateral-directional root loci for varying K_ϕ.

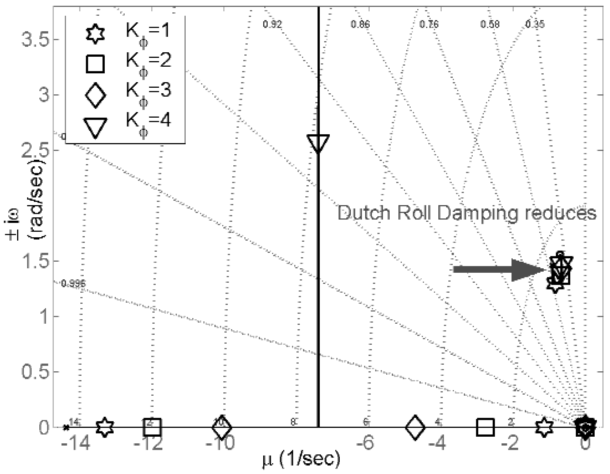


Figure 35. Lateral-directional root loci for roll control with warp-rudder interlink disconnected.

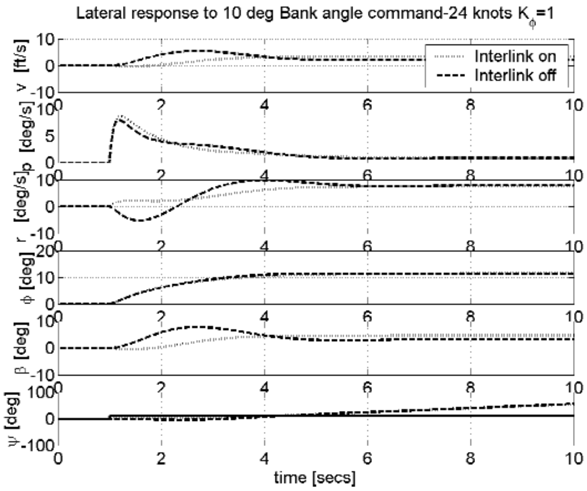


Figure 36. Time response – roll command.

similar manner to the Jex and Culick studies of the Wright 1903 Flyer in Refs 12 and 20). Using airframe and outside world references such as the canard and horizon, the pilot can deduce the error between the desired pitch attitude and the current sensed attitude and enter a proportional amount of control deflection to reduce the error. This classical pilot model can be used to predict the dynamics of the aircraft when under the simplest form of pilot control with constant gain $K_p = K_\theta$. It also provides insight into how the Wright brothers initially experienced the flying characteristics of their Glider.

In Fig. 29, the open loop transfer function $Y^{\theta}_{\delta c}$ is shown as the ratio of the finite zero's polynomial and the open loop transfer function containing the short period and phugoid modes.

Figure 30 shows a comparison of the response of the 1902 glider under open loop and closed loop control when disturbed by a 0·5 second control pulse. The unstable mode causes the open loop aircraft to diverge rapidly in pitch, reaching $\theta = 20°$ after only 2·5 seconds. In the closed loop response, the pilot gain, K_θ was set to four(deg canard/deg pitch attitude error). The closed loop response is stable with the aircraft motion damping out after about three oscillations.

The effect of closing the loop can also be investigated through the root loci for the system, showing how the various modes change as the gain is increased. Figs 31 and 32 show the longitudinal root loci for the two different cg locations.

In Fig. 31 the application of pilot feedback is seen to stabilize the unstable mode at high gain. With a gain of $K_\theta = 1$, the pitch mode is still unstable and the oscillatory phugoid mode has been driven to a condition of neutral stability. This loss of stability in the oscillatory mode is a consequence of the condition that pitch attitude feedback cannot change the overall damping of the system – hence if in one mode the damping increases, in another the damping must decrease. If the gain is further increased the unstable aperiodic mode becomes marginally stable and the oscillatory mode moves away from the right hand side but with increased frequency.

As discussed earlier the cg location was probably nearer 0·24c when the Wrights flew their 1902 Glider, and the root loci for this condition is shown in Fig. 32. In the open loop configuration, we see four aperiodic modes. When closed loop control is applied, the divergent mode is stabilised with a gain of $K_\theta < 1$. Two of the aperiodic modes then join to form an oscillatory mode similar to the cg = 0·35*c* case.

The effect of the movement of the centre of gravity is illustrated in Fig. 33, showing how, as the cg is moved forward, the unstable mode moves from the right hand side to the left meeting another pole that was formed by the splitting of the 'quasi – phugoid' mode. This new mode forms a low frequency, weakly damped mode – the classical phugoid. The remaining pole splits and travels left to form another oscillatory mode of higher frequency and high damping – the classical short period mode.

The moving of the cg forward clearly makes the 1902 glider more stable so a question that arises is – why did the Wrights persist with the unstable aft cg? Part of the reason was that the configuration of the aircraft forced the cg to be aft and the pilot could only practically get his body so far forward within the aircraft. Secondly, if the cg is too far forwards then the canard has to have a significant upload to trim; for the 0·2*c* cg location, $\delta_c = 10°$ at 24kt. With the estimated canard stall angle of 12-15° there is little control margin left for pitch up control, and at the lower speeds the pilot would not have adequate control power to achieve a trim.

In summary, the 1902 glider was likely to have been marginally unstable as flown by Wilbur and Orvillle, with ample control power, pitch up and down. However, the conditions flown in would have been gusty, resulting in the pilot needing to make continuous control corrections to keep a steady flight path. In these conditions the aircraft would 'undulate' in a lightly damped oscillation. Furthermore, the frequencies (3-7 rad/s, 0·47-1·11Hz) of the closed-loop oscillatory mode, corresponding to proportional gains of between 1 and 4 deg/deg, indicate a susceptibility to PIOs (Pilot Induced Oscillations), unless a degree of anticipation could be applied. The skill to apply this anticipation would come with practice and the Wright brothers had plenty of opportunity to develop such skills during the autumn of 1902.

Lateral – directional dynamics

The 1902 glider also featured the classical set of lateral-directional modes – an unstable spiral mode, (T_D = 5·9 secs) a moderately damped Dutch roll oscillation and heavily damped roll subsidence. At 24kt, the 1902 glider roll mode λ_r=-14·3685 has a time constant, T_r = 0·07 seconds, well within the Level 1 HQ boundary (and matching the classical approximation, L_p = –14·79 well). The Dutch roll is a coupled yaw/sideslip/roll oscillation, with a mix determined by the characteristics of the rolling and yawing moments with sideslip and body rates. For the 1902 glider, the Dutch roll mode is stable (λ = –0·92 ± 1·46i). MIL-F-8785C requires for Level 1 that ζ_d > 0·19, ω_d > 1.0 and $\zeta_d\omega_d$ >0·35. Comparing the 1902 glider values, these are ζ_d = 0·54, ω_d = 1·73 and $\zeta_d\omega_d$ = 0·92. Hence Level 1 handling qualities are met for this mode. A good approximation to the Dutch roll mode can be derived by assuming the motion is a coupled yaw-roll motion with little sideways motion (sideslip is derived only from yaw and roll – Ref. 21). Then we can write;

$$2\zeta_d\omega_d = -\frac{\left(N_r + Y_v + \sigma_d\left[\frac{L_r}{V} - \frac{L_v}{L_p}\right]\right)}{\left(1 - \frac{\sigma_d L_r}{L_p V}\right)} \qquad \ldots (5)$$

$$\omega_d{}^2 = \frac{\left(VN_v + \sigma_d L_v\right)}{\left(1 - \frac{\sigma_d L_r}{L_p V}\right)} \qquad \ldots (6)$$

$$\sigma_d = \frac{g - N_p V}{L_p} \qquad \ldots (7)$$

$\zeta_d\omega_{d\text{approx}}$ = 0·973 (exact = 0·92)

$\omega_{d\text{approx}}$ = 1·523 (exact = 1·73)

The cross damping derivatives N_p and L_r determine the ratios of roll and yaw in the Dutch roll. In the 1902 Glider, both are strong effects, N_p being even stronger than the damping N_r and, of course, adverse.

A certain degree of spiral instability can be accepted. For Level 3 flying qualities, the spiral mode time constant, T_s must be greater than 7·2 secs. For the 1902 glider this parameter (defined $T_s = 1/\lambda s$) is calculated to be 8·6 seconds, just inside the Level 3 boundary but outside Level 2, defined at $T_s >$ 11·5s. The unstable behaviour is partly a result of the wing anhedral. It was known to aviators at the time that a dihedral angle gave stability and this was favoured by model aircraft makers for obvious reasons, but the Wrights had deliberately designed their aircraft with anhedral. They were uncomfortable with the roll response induced by side gusts with dihedral, which tended to lift the wing on the side of the gust and drive the opposite wingtip toward the ground. The unstable response tended to cancel the sideslip induced by the gust by rolling the aircraft into the wind. The pilot would apply warp to lift a dropped right wing. The warp induced yaw would pull the starboard wing back, inducing left sideslip which would further decrease the roll angle. The classical approximation to the damping of the spiral mode is given by the expression;

$$\lambda_s = \frac{g}{L_p}\left(\frac{L_v N_r - N_v L_r}{VN_v + \sigma_s L_v}\right) \qquad \ldots (8)$$

where

$$\sigma_s = \sigma_d \qquad \ldots (9)$$

giving, λ_s (approx) = +0·24, compared with +0·12 for the exact value, a rather poor comparison. It can be shown that the approximation is dominated by the L_r effect;

$$|N_v L_r| >> |L_v N_r|,\ |VN_v| >> |\sigma_s L_v|$$

which itself causes the pilot to hold significant out-of-turn warp control during a turn.

The lateral problems had not completely disappeared with the addition of anhedral, and, as described in the earlier section, the Wrights linked the wing warp to the vertical tail. This vertical tail gave the 1902 glider a degree of directional stability which, after being disturbed by a short duration side gust, stabilised the heading of the aircraft by creating a restoring, proverse, yawing moment. In a prolonged gust or a change of wind however, the aircraft would roll and yaw toward the gust because of the directional stability provided by the vertical tail. The pilot, trying to maintain heading towards some fixed point, would naturally try to keep the wings level, warping the wings to correct. The warp produced an adverse yaw bringing the low wingtip further around toward the wind and causing a 'yaw rate' induced roll (positive L_r) further increasing the roll angle. This behaviour was dubbed 'well digging' by the Wright brothers – one wingtip would drive into the sand and dig in with the aircraft corkscrewing around this point.

Well-digging was the result of a rather complex situation featuring closed loop control by the pilot and the rapid loss of airspeed with the subsequent angle of incidence changes as the aircraft acquired large sideslip velocities. As discussed earlier in the paper, the Wrights struggled to understand what was happening. Orville notes in his diary that he and Wilbur disagreed about the source of the problem(1)"*...I now became thoroughly convinced that the trouble in the fore and aft control was a result of one wing getting higher than the other, ...Will maintained the trouble was just the reverse, and that the lateral tipping of the machine was the result of the loss of forward motion...*" Figures 25 and 26 show us that the source of the problem was the loss of roll control combined with the significant increase in yaw response to warp at high incidence. So, in a sense, both Orville and Wilbur were correct and they found the solution together. The fix was to replace the double vertical surface with a controllable single surface tail that moved with the wing-warp. The effect of this was twofold. The first was that the smaller tail area reduced the directional stability, which reduced the tendency of the aircraft to swing into the wind, and secondly, when the wing was warped to counter the into-wind roll, the rudder created a proverse yawing moment cancelling the warp adverse yaw (see Fig. 12). Unfortunately, the large rolling moment due to yaw rate meant that during a turn, as already mentioned, the pilot had to hold out-of-turn lateral control, which in turn gave an out-of-turn rudder input; the aircraft then side-slipped into the turn and the Wrights could never fly properly co-ordinated turns.

The analysis carried out for the longitudinal motion can also be applied to the lateral axis, either feeding back the roll attitude, φ, or the heading angle, ψ to the wing-warping control. Of course, the 1902 glider had no independent yaw control, the only yaw control coming via the warp-rudder interconnect system. The two-axis control without interconnect system is also investigated.

Figure 34 shows the root loci for bank angle control with the interlinked warp and rudder control, δ_{wr}. The effect of increasing the gain is to stabilise the spiral mode. The gain increase has little effect on the Dutch Roll mode; the numerator in the roll-warp transfer function features a second order 'zero' with similar dynamics to the open loop pole. Increasing the gain to $K_\phi = 4$, a second damped oscillatory (combined roll-spiral) mode forms. This insensitivity of the Dutch roll to warp control can be considered as a design feature of the aircraft, although the Wrights' never interpreted it in quite this way of course. Another positive feature of the anhredral wing is that the effective directional stability in closed-loop control(19) $N_{v\mathit{effective}} = N_v - \frac{N_\zeta}{L_\zeta} L_v$ is increased when adverse yaw is present.

Figure 35 shows the roll loci with warp-to-rudder interconnect disconnected. There is little difference compared with Fig. 34.

Time responses for the feedback gain of $K_\phi = 1$ are presented in Fig. 36. Results for the interconnect system operating and disconnected are compared. In contrast with the stability results in the root loci, the time responses show significant differences in yaw and sideslip response. The response with interconnect-off exhibits an untidy turn entry with large amounts of adverse yaw and sideslip, whereas with interconnect-on the turn entry is smooth and more controlled.

The previous analyses have shown that the 1902 glider was unstable in pitch and roll-yaw. For the aft cg configuration, the pitch stability is predicted to be outside of the Level three boundary, based on contemporary flying qualities theory. For the Lateral axis, Level one criteria are met for the roll subsidence and Dutch roll modes. The spiral mode is unstable, falling into the Level three range. The rudder-to-warp interconnect has no effect on open-loop stability of course, and only a minor effect on closed loop stability, but is seen to improve the turn entry characteristics when using the simple warp-to-roll pilot model.

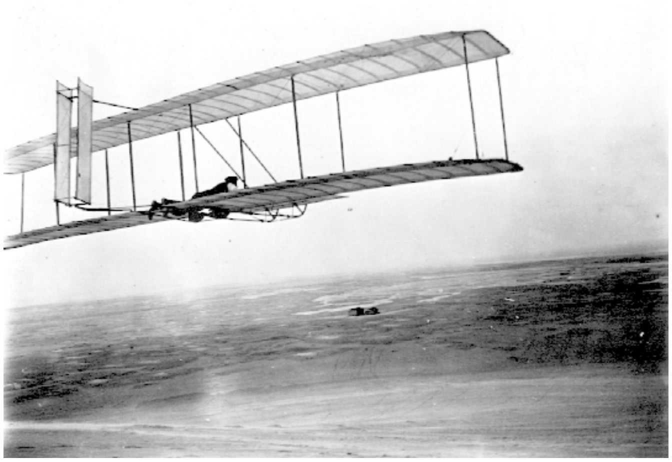


Figure 37. Testing the two-surface rudder on the 1902 glider in October 1903.

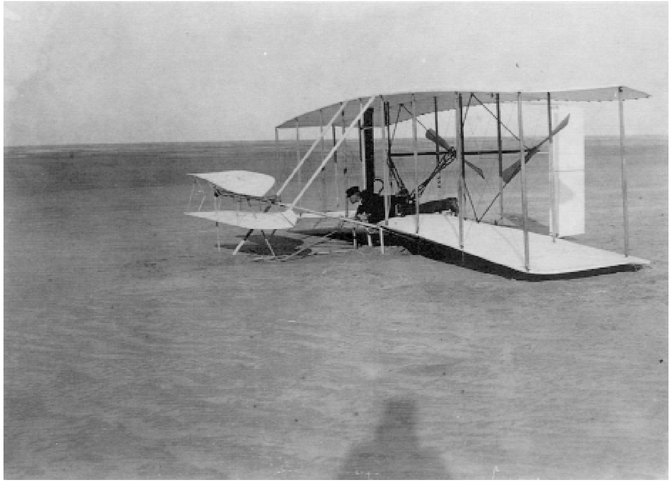


Figure 38. The Wright Flyer crashes on take-off – Wilbur at the controls on 14 December 1903.

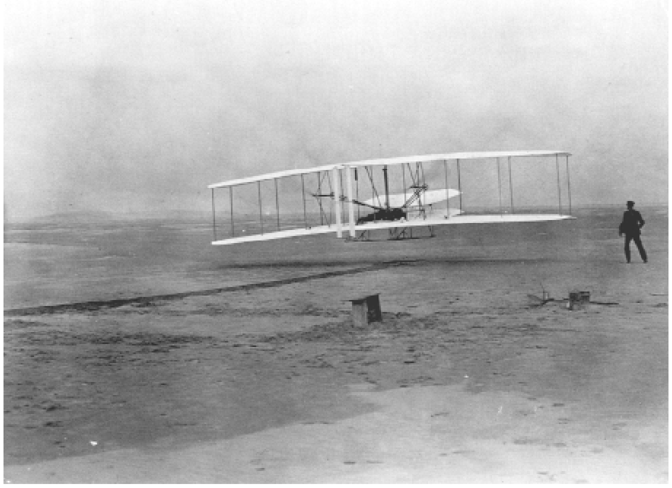


Figure 39. The First Flight of the Wright Flyer – Orville at the controls on 17 December 1903.

5.4 Exploratory piloted simulation tests

The dynamic analysis presented in the previous sections has shed some light on the flying characteristics of the 1902 glider, explaining many of the problems experienced by the Wrights. However, the assumptions concerning linear aerodynamics, decoupled longitudinal and lateral control and the simple pilot model, preclude one from answering some important questions – how did the lateral and longitudinal axes couple? What is the manoeuvre flight envelope and generally – how well can a pilot fly the 1902 glider? How prone is the aircraft to 'pilot-induced-oscillations? To answer these questions, piloted trials using the full non-linear FLIGHTLAB simulation model have been carried out at the University of Liverpool's flight simulation laboratory, using a single seat cockpit on a six-axes motion system. The project test pilot, experienced in flying vintage aircraft, flew a set of 'mission task elements' (MTEs) in exploratory trials. MTEs are manoeuvres that are considered critical to the mission performance of an aircraft and are selected to 'qualify' the handling qualities throughout the operational flight envelope[†]. MTEs are derived as tasks from a typical 'mission'. The 1902 glider was an aircraft developed as a test bed to refine the flight control system and allow the Wrights to gain flying experience. Hence, the MTEs could be relatively simple (see Refs 10 and 22 for more details).

To enable sustained flight, the glider was operated in a continuous 'thermal' of strengths varying between 450-600ft/min, allowing the aircraft to be flown straight and level and also to climb. The initial flight by the test pilot highlighted many of the characteristics discussed in the previous section. The pilot noted that the aircraft, although pitch unstable, became stable at high angle of attack. He also commented on the spiral instability, the adverse warp-yaw and found particularly control difficult if the sideslip were allowed to build up beyond about 10°. The piloted tests also confirmed many of the predictions of the closed-loop analysis, including the undulating oscillations (weakly damped pitch/heave mode) typical of many of the Wright canard aircraft. Lateral control was effective and as long as bank angles were kept below about 15°, successful turns could be made. However, if the airspeed were allowed to reduce below about 20kts (minimum drag speed) then the lateral control became sluggish and the aircraft would often sidle off, building up high, and eventually uncontrollable, sideslip angles. The handling qualities ratings awarded for the different (simple) tasks were in the 4-7 range, surprising good considering the aircraft being studied. Undoubtedly, the aircraft required skill to fly but offered unprecedented levels of control and manoeuvrability for the time. Results from these trials will be reported in detail in future publications and initial findings are discussed in Refs 10 and 22.

6.0 BRIEF REVIEW OF THE WRIGHT BROTHERS WORK POST-1902

This paper concerns the birth of flight control as conceived by the Wright brothers in the design of their 1902 Glider. The story would be incomplete, however, without a brief mention of how this was taken forward in the powered aircraft designs. In his lecture to the Society of Western Engineers on 24 June 1903, Wilbur remarked that "*.. at the slower speed (18mph), 166lb were sustained for each horsepower consumed; at the higher speed (25mph), 125 pounds per horsepower.*" Discussing power requirements, the Wrights were well advanced on the next stage of their aeronautical progress at this time. Late in 1902, after a lengthy dialogue on the data from the 1902 tests, Chanute enquired of Wilbur, "*How far do you think of carrying on aeronautical work?*" Wilbur relied, " *It is our intention next year to build a machine much larger and about twice as heavy as our present machine. With it we will work out problems relating to*

[†] MTEs were originally introduced in the mid-1980s as part of the helicopter handling qualities engineering discipline(21) but have since seen more general use by the fixed-wing community.

starting and handling heavy weight machines, and if we find it under satisfactory control in flight, we will proceed to mount a motor."

Their thinking quickly developed over the next few months and, with no suitable powerplant to be found on the market, they proceeded to design and build their own complete drive system – engine, transmission and propellers. The Wrights designed and constructed the components of their 4th piloted flying machine, the Flyer (see Ref. 23 for a comprehensive technical review of this aircraft), and they journeyed to Kitty Hawk in September 1903 to assemble and test the aircraft. They spent the first month further developing their flying skills and refining the control system on the 1902 Glider; Orville recorded in his diary on 26 October, "*We succeeded in breaking our former record six times out of about 20 attempts*"(1) (see Fig. 37).

Their first attempts to run the new engine mounted on the Flyer in early November failed due to excessive vibration. Then, on two occasions, propeller shaft failures delayed their progress further. The Wrights were very concerned that the weight had increased to over 700lb " *the thrust required might be 100lb, and we got to doubting whether the engine would have the power, using the gears we have, to give the necessary thrust*"(1). Finally the machine was ready for its first flight on 14 December. With Wilbur at the controls, "*the machine turned up in front and rose to a height of about 15 feet from ground… After losing most of its headway it gradually sank to ground turned up at an angle of probably 20º incidence….Time of flight from end of track was 3½ seconds, for a distance of 105ft.*"(1). On its first flight, The Flyer had crashed on take off (Fig. 38) and Wilbur stated in a letter to his father on the same day,

> *"the real trouble was an error in judgement, in turning up too suddenly after leaving the track, and as the machine had barely speed enough for support already, this slowed in down so much that before I could correct the error, the machine began to come down, though turned up at a big angle." Characteristically, Wilbur was first to admit his mistake and it took two days to repair the damage. They took the machine out again on the morning of 17 December.*

Figure 39 captures take-off on the first of four flights made on 17 December Orville flew for about 12secs, covering a ground distance of 120ft. On the fourth flight Wilbur flew for 59 seconds covering a distance of 852ft(1).

The four flights on 17 December 1903 gave the brothers a very brief glimpse of the future. It would take another nine months before the Wrights were able to fly a circuit of the Huffman field near Dayton, Ohio and a further twelve months before they were satisfied that they understood the handling qualities sufficiently well to fly safely at altitude. The autumn of 1905 in many ways mirrored the autumn of 1902, with the Wrights flying extensively for two weeks to master the flying characteristics of their Flyer No 3. To quote from Wilbur Wrights' summary of the 1905 experiments, written in 1912.

> *"…The trouble was really due to the fact that in circling, the machine has to carry the load resulting from centrifugal force, in addition to its own weight, since the actual pressure that the air must sustain is that due to the resultant of the two forces. The machine in question had but a slight surplus of power above what was required for straight flight, and as the additional load, caused by circling, increased rapidly as the circle became smaller, a limit was finally reached beyond which the machine was no longer able to maintain sufficient speed to sustain itself in the air. And as the lifting effect of the inner wing, owing to its reduced speed, counterbalanced a large part of the increased lift resulting from the greater angle of incidence on that wing, the response to lateral control was so slow that the machine sank to the ground, usually before it had been brought back to the level again. In other words the machine was in what has come to be known as a stalled condition…. When we had discovered the real nature of the trouble, and knew that it could always be remedied by tilting the machine forward a little, so that its flying speed would be restored, we felt that we were ready to place flying machines on the market."*

Wilbur, perhaps unknowingly, was also highlighting that a pitch unstable aircraft required forward stick in a turn to counter the negative manoeuvre margin. From autumn 1902 to autumn 1905 the Wrights would work hard to design a powered machine with satisfactory flying qualities, but without design criteria or supporting analytical tools their progress would be limited. Wilbur also believed that "*The remedy for the difficulty lies in more skilful operation of the aeroplanes*" and one wonders whether he considered that instability was the natural condition of flying, much as it was for bicycle riding. However, he was not alone and it would be 10 years after the first powered flight that the first aircraft with satisfactory all-round inherent stability flew (the Farnborough BE2 in 1913, a Green-de Havilland design – Ref. 2).

The Wrights returned to Kitty Hawk in May 1908 to carry out the final design refinements to the Flyer No 3 and prepare for their aerial demonstrations in the US and Europe. The pilot now sat up in the machine, and had independent control of pitch, roll and yaw. Flights with a passenger on board were also being made and the time of Wilbur's last flight at the Kill Devil Hills (on 14 May 1908) was seven minutes 29 seconds, covering a distance of over 8km; the flight ended in a crash! In the months to come, Wilbur would amaze the world with his feats of aerial navigation in the skies over France. He wrote to Orville from Le Mans on 15 August(1), "*The newspapers and the French aviators nearly went wild with excitement. Blériot and Delagrange were so excited they could scarcely speak, and Kapferer could only gasp and could not talk at all.*" Bleriot was quoted as saying, "*I consider that for us in France and everywhere a new era in mechanical flight has commenced…it is marvelous*." What the Wright brothers had achieved three years earlier far exceeded the progress in Europe since the first powered flight there in 1906 – the Europeans could only fly in straight lines! With Wilbur demonstrating what could be done, after 1908 the rate of progress in aviation was quite startling; progress which, in many ways, would leave the Wright brothers behind – with their legacy as the first aeronautical engineers and first test pilots(24). Perhaps they had reached their horizon?

7.0 CONCLUDING REMARKS ON THE WRIGHT CRITICAL SUCCESS FACTORS

October 1902 was a watershed in the history of aviation. The use of three-axis flight control paved the way for the invention and development of powered flight to proceed. Flight control issues would continue to feature large in the Wright brothers' aircraft for the next five years but the basic design concept would remain the same – forward canard for pitch/vertical flight path, wing warp for roll and rudder for yaw.

Looking back to the period leading up to the autumn of 1902, it is possible to suggest the critical success factors for the birth of flight control

1) The Wright brothers were very capable engineers, very good at conceptual design and what is described as visual thinking, and particularly good at being able to stay focused on goals,
2) They had developed a high proficiency in the practical skills of manufacturing and a knowledge in the use of materials,
3) They understood the laws of physics and aspects of the mathematical analysis of mechanical systems,
4) They were powerfully motivated to learn how to fly, and made thousands of gliding flights to develop performance, flight control concepts and piloting skills,
5) They designed, built and tested exhaustively (aerofoil aerodynamics, structures, control systems, engines, propellers etc.),
6) They realised that control and manoeuvrability were more important than stability,

7) They took what is nowadays referred to as a systems approach to their work – understanding that an aeroplane is a technological system of discrete elements, including the pilot, all of which had to be successfully designed and integrated to achieve success. Within this context their continuity of design was also important, solving problems in an evolutionary fashion,
8) They were a team, sharing responsibilities, sharing a common vision.

Other success factors can be mentioned, including the Wrights choice of test site, their willingness and (financial) ability to undertake annual campaigns, but from the above list, factor number six was particularly important. The aft cg and canard control conferred the 1902 Glider with greater control power than an equivalent tailed aircraft, crucial at the low speeds flown by the Wrights; the manoeuvrability was further enhanced by the negative static margin (and for the furthest aft case, negative manoeuvre margin). The canard also provided a powerful attitude reference and protection during 'heavy' landings or crashes. Of critical importance to the Wrights, the wing design gave safe stall characteristics. The wing anhedral increased the effective roll control power and closed-loop directional stability and the warp-rudder control interlink assisted turn entry.

All of the success factors listed above are considered important, and it is hard to imagine the invention of powered flight being achieved quite so rapidly, or without more serious mishaps, in the early 1900s without the Wright Brothers and their pursuit of excellence. In the years to come, many chief designers would be noted for similar attributes. Nowadays, however, although University degree and Industry training programmes encourage innovation, and attempt to instill a broad appreciation of the technologies involved and an ethos of engineering excellence, few practicing engineers have the opportunity to work across such a broad front and put ideas into practice quite so readily as the Wrights did. Perhaps this is a shortcoming of our current systems and the centenary of powered flight provides a good opportunity to reflect on this. For the Wrights, almost at every turn, 'necessity was the mother of invention'. The desire to fly and ultimately to invent the practical aeroplane was the spur to their relentless pursuit of the mastery of flight control. Perhaps one of the challenges for 21st century aerospace engineering is to understand how to enable innovation to flourish amidst so much 'advanced' technology.

Wilbur and Orville can also teach us something about patience. They first applied to patent their three-axis flight control system in March 1903. It was rejected by the US Patent Office, who claimed the description was "vague and indefinite" and "incapable of performing its intended function"(4). The patent was eventually granted in the US in May 1906, two years after Great Britain and France had approved the application.

This paper has presented the story of the birth of flight control as featured in the Wrights' 1902 Glider, and appraised in the Liverpool Wright Project. High-fidelity simulations of the 1901 and 1902 gliders and the 1903 Flyer are currently operational on the motion simulator at Liverpool and work is underway to create a simulation of the 1905 design, the first practical aircraft. This ongoing research is supported by a Royal Aeronautical Society Centenary Award. Future publications will report the continuing progress.

ACKNOWLEDGEMENTS

The research reported in this paper was partly funded by an UK EPSRC Doctoral Training award for the second author. Financial support from The Friends of The University of Liverpool, enabling the wind-tunnel testing to be conducted, is greatly appreciated and acknowledged. The authors would like to thank Peter Jakab and Tom Crouch, Aeronautics Curators at the National Air and Space Museum, Washington DC, for fruitful discussions and for the opportunity to work with them in this Centenary period. The authors are also particularly grateful to Professor Norman Wood at the University of Manchester and the team at Flow Science for the use of the Goldstein wind-tunnel facilities. The project Test Pilot, Roger 'Dodge' Bailey from Cranfield University/Shuttleworth Collection has worked with the Liverpool team during the project; his insight into handling qualities from the pilot's perspective has proved invaluable. Most of the photographs taken during the Wrights' test campaigns and presented in this paper are the property of the US Library of Congress who are gratefully acknowledged. Figure 10(b) and Figs 13(a), 13(b) and 13(d) are the property of Wright State University who are also acknowledged. The Sketches in Figs 3, 4 and 10 were taken from Ref 25.

REFERENCES

1. McFarland, M.W. (Ed), *The Papers of Wilbur and Orville Wright, including the Chanute-Wright Letters and other papers of Octave Chanute*, 1953, McGraw Hill, New York.
2. Gibbs-Smith, C.H. The Aeroplane; An historical survey of its origins and development, 1960, Her Majesty's Stationery Office, London.
3. Jakab, P.L. *Visions of a Flying Machine, The Wright Brothers and the Process of Invention*, 1990, Smithsonian Institution Press.
4. Crouch, T.D. *The Bishop's Boys, A Life of Wilbur and Orville Wright*, 1989, W.W. Norton, New York.
5. Culick, F.E.C. What the Wright brothers did and did not understand about flight mechanics – in modern terms, AIAA-2001-3385, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 2001 Salt Lake City, Utah.
6. Bryan, G.H. and Williams, W.E. The longitudinal stability of gliders, June 1903, Proc Royal Society of London.
7. Lilienthal, O. Der Vogelflug als Grundlage der Fliegekunst. Berlin: R. Gaertners Verlagsbuchhandlung (Birdflight as the Basis of Aviation, American Aeronautical Archives, Markowski International Publishers, 2001).
8. Anderson, J.D. *A History of Aerodynamics and its Impact on Flying Machines*, 1998, Cambridge University Press.
9. Phillips, W.H. Flying qualities from early airplanes to the space shuttle, Dryden Lectureship in Research, AIAA 26th Aerospace Sciences Meeting, Reno Jan 1988, AIAA *J Guidance and Control*, July-August 1989, **12**, (4).
10. Lawrence, B. and Padfield, G.D. A handling qualities analysis of the Wright brothers 1902 Glider, AIAA Atmospheric Flight Mechanics Conference, Austin, Texas, 11-14 August, 2003.
11. McCormick, B.W. *Aerodynamics, Aeronautics, and Flight Mechanics*, 1995, 2nd ed, John Wiley and Sons, New York, 1995.
12. Jex, H.R. and Culick, F.E.C. Flight control dynamics of the 1903 Wright Flyer, 1985, AIAA Paper, p 534-548.
13. Padfield, G.D and White, M.D. Flight simulation in academia; HELIFLIGHT in its first year of operation, *Aeronaut J,* October 2003, **107**, (1076), (also in 'The challenge of realistic rotorcraft simulation', RAeS Conference, London, Nov 2001).
14. Kochersberger, K., Sandusky R., Hyde K., Ash R., Britcher C. and Landman, D. An evaluation of the Wright 1901 Glider using full scale wind tunnel data, AIAA Aerospace Sciences Meeting & Exhibit, 40th, Reno, NV, 2002.
15. Etkin, B. *Dynamics of Atmospheric Flight*, 1972, John Wiley and Sons, New York.
16. Anon MIL-F-8785C, Military Specification Flying Qualities of Piloted Airplanes. U.S. Department of Defense, 1980.
17. Anon MIL-HDBK-1797, Flying Qualities of Piloted Aircraft, US Department of Defense, 1997.
18. Cooper, G. E., Harper, R.P. The use of pilot rating in the evaluation of aircraft handling qualities and pilot evaluation, NASA TN D-5153, April 1969
19. Milne, R.D. and Padfield, G.D. The Strongly controlled aircraft, *Aeronaut Q,* May 1971, **XXII**, pp 146-168.
20. Culick, F.E.C. and Jex, H.R. Aerodynamics, stability and control of the 1903 Wright Flyer, The Wright Flyer, an engineering perspective, National Air and Space Museum, Washington DC, 1987.
21. Padfield, G.D. *Helicopter Flight Dynamics*, 1996, Blackwell Science, Oxford.
22. Lawrence, B. and Padfield, G.D. Flight testing simulations of the Wright 1902 Glider and 1903 Flyer, 34th Annual International Symposium of the SFTE, Portsmouth, Va, September 2003.
23. Wolko, H.S. (Ed) *The Wright Flyer; an engineering perspective*, 1987, Smithsonian Institution.
24. Culick, F.E.C. Wright brothers: first aeronautical engineers and test pilots, Sept 2001, 45th Annual Symposium of the Society of Experimental Test Pilots, Los Angeles, California.
25. Culick, F.E.C., The origins of the first powered, man-carrying airplane, December 1979, Scientific American.