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Handling-Qualities Analysis of the Wright Brothers' 1902 Glider

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From a handling-qualities standpoint, it can be argued that the Wright brothers' 1902 glider represents their most significant design breakthrough on the basis that their subsequent aircraft retained the same basic control concept. This paper is a study of that aircraft, and results from wind-tunnel tests, modeling, and flight simulation trials are presented. Unstable in both longitudinal and lateral axes, the 1902 glider's flight dynamics provide maneuverability but also a tendency to pilot-induced oscillation in tight tracking tasks. The Wrights taught themselves to fly on this aircraft and paved the way for the development of their powered flyer. This paper stands as a celebration of the achievements made by the Wrights 101 years ago and demonstrates the technological leaps they made in the process of designing, building, and flight testing the 1902 glider. The results are placed in the context of modern handling-qualities engineering.

Nomenclature

b	=	wing span
C_D	=	drag coefficient
C_L, ($C_{L\max}$)	=	lift coefficient, (maximum)
C_{L_α}	=	lift-curve slope
C_l	=	rolling-moment coefficient
C_M	=	pitching-moment coefficient
C_n	=	yawing-moment coefficient
C_Y	=	side-force coefficient
c	=	chord
D	=	drag
H_n	=	static margin
I_{XX}, I_{YY}, I_{ZZ}	=	roll, pitch, and yaw moments of inertia
K_p, K_φ, K_θ, K_ψ	=	pilot gain (roll, pitch, yaw)
L	=	lift
L_r	=	aerodynamic derivative, rolling moment caused by yaw rate
Re	=	Reynolds number
T_D	=	time to double amplitude
T_r, T_s	=	roll subsidence, spiral mode time constant
α	=	angle of attack/incidence
α_0	=	angle of attack at $C_L = 0$
β	=	angle of Sideslip
γ, ($\gamma_{\min}$)	=	glide angle (minimum)
δ_c, δ_r, δ_w, δ_{wr}	=	canard, rudder, warp, warp and rudder deflection
θ_c, (θ_e)	=	command pitch angle (pitch-angle error)
λ	=	eigenvalue
φ, θ, ψ	=	Euler attitude angles
ω_d, ζ_d	=	Dutch roll frequency, damping ratio

Introduction

Background—Events of 1902

IN the period September to October 1902, Orville and Wilbur Wright had completed their third season of glider flight testing at Kill Devil Hills, Kitty Hawk, in the Outer Banks, North Carolina. A few days before the Wrights left Kitty Hawk to return home to Dayton, Ohio, Orville wrote to his sister Katharine describing their recent experiments[1]:

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

The Wrights were successful with their new machine, and the optimism for the future was a far cry from when Wilbur had proclaimed to Orville at the end of the previous year's experiments,[2] "Man will not fly for fifty years!" These two quotes together "bookend" the revolutionary year that 1902 had been for the Wright Brothers, a year ultimately ending with the Wrights forging the design of the first powered aircraft, the 1903 *Flyer*.

At the center of this revolution was the 1902 glider, the first aircraft to have sufficient performance and control such that the pilot could "soar" on the winds. During September and October of 1902, between 700 and 900 glides were made with the glider. By the end of their 1902 season, the Wrights were regularly making glides of 300–500 ft long and had made a record glide of 622 ft lasting for 26 s. These glides would have often been made at low level, hugging the sand dunes at altitudes of a few feet to a few inches. Sometimes the pilot would soar at a height of 10 ft, making very little forward progress over the ground. The Wrights were gaining practice in handling the machine in every flight. They achieved this by gliding on the slopes of the three main sand hills at Kill Devil Hills: the Big Hill, the Little Hill, and the West Hill, with heights of about 100, 30, and 60 ft, respectively. The Wrights preference was to soar, to glide in an upwardly rising current of air such that the resultant force was vertical, directly opposing gravity. This way the glider would effectively hover over the ground while the pilot manipulated the controls to keep the aircraft aloft in the varying winds. It turned out that the Wrights only soared the 1902 glider on the Little Hill. This had a slope of 7 deg, barely sufficient to soar the glider, but the Wrights frequently made glides of 8–15 s duration. Any momentary lessening of the wind or an error by the pilot would cause the glider to come to a landing. The Wrights considered that the Big Hill, with its steeper slopes, would prove superior for soaring, but they were hesitant to take the greater risks as Wilbur describes in his lecture to the Society of Western Engineers, 24 June 1903 (Ref. 1):

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> It would be well within the power of the machine to soar on the Big Hill, which has steeper slopes, but we have not felt that our few hours of practice is sufficient to justify ambitious attempts too hastily. Before trying to rise to any dangerous height a man ought to know that in an emergency his mind and muscles will work by instinct rather than by conscious effort. There is no time to think.

Wilbur and Orville were always mindful not to take any unnecessary risks in their experiments. They were all too aware of the fate of their predecessors such as Otto Lilienthal who had plunged to his death while gliding in 1896.

The primary purpose of the 1902 glider was for the Wright Brothers to train themselves to fly and to become familiar with the flying qualities of the glider so that they would be adept at reacting to any situation that they would find themselves in. This was possible because of the unique nature of the 1902 glider's control system. The Wrights fundamentally believed in the power of control over stability, and in its final form (Fig. 2) the Wright 1902 glider was the first aircraft to feature three-axis flight control—control over pitch, roll, and yaw. However, it was not initially designed as such. At the beginning the 1902 glider had only two-axis control: pitch control using the forward rudder (canard) and roll control by use of the Wrights' wing-warping mechanism. When they first started flying the 1902 glider, the Wrights were satisfied with the control, as Orville noted on 19 September 1902, "Made about 25 glides during afternoon. The front rudder containing just 15 feet of surface gives abundant control with a change of not more than two or three degrees to either side of 0°" (Ref. 1). The warp control was also operating well. Orville mentions in his diary on 23 September[1]:

> Will soon became expert enough in the manipulation of the wing ends that he could make a glide of over 200 feet and keep the ends practically level, though through an excessive twist of the wing tips he caused the machine to sway from side to side, sidling one way and then the other a half dozen times in the distance of the glide.

(When Orville refers to the manipulation of "wing-ends," he is describing the wing-warping mechanism).

It was not all plain sailing for the Wrights. In the same diary entry Orville continued to describe how he had survived a serious crash on one his earliest full "free" flights. The accident occurred when one wing had risen up and the aircraft began to sideslip. Orville tried to correct using the warp, but in doing so he neglected the longitudinal control, and the aircraft pitched up and eventually crashed, with the aircraft traveling backward at one point. His final description of the event being, "The result was a heap of flying machine, cloth, and sticks in a heap, with me in the center without a bruise or a scratch."[1] Evidently, although controllable, this aircraft was still tricky to fly and could easily end up in unrecoverable flight conditions. On the positive side, the "crash-worthiness" of the glider was excellent, the pilot emerging unscathed and the glider repairable—they would be flying again in matter of a couple of days. This crash continued to play on Orville's mind, and the 1902 glider's control was still not quite what the Brothers wanted. Retrospectively, Wilbur alluded to the problem that was still troubling them[1] (Wilbur's lecture to the Society of Western Engineers, 24 June 1903): "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." A solution came to Orville on Friday, 3 October. After spending the previous night thinking about the problem, at breakfast Orville proposed to his brother that the vertical tail should be made movable by the pilot such that it could used to create yawing moments on demand. Wilbur, who Orville expected to respond by saying that "he had already thought of that," listened, thought for a couple of minutes, and then approved Orville's idea. He added a suggestion that the pilot's workload was already high with two controls (pitch and warp) and that the movable vertical 'rudder' should be interlinked so that it moved in concert with the warp control.

Thus three-axis flight control was born. The story is indicative of the brother's synergistic relationship, where one would play ideas off the other, testing theories, but ultimately working together for the common goal. With this final modification the 1902 glider's evolution was complete. Wilbur described the performance of this change in his lecture in 1903: "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 mastery over the forces tending to disturb the equilibrium."[1]

The success of the 1902 glider was a culmination of a number of breakthroughs in the technical understanding of the Wright Brothers in the late 1901 through 1902 period. They had harnessed the aeronautical tools of analysis, wind-tunnel testing and flight testing, to get to the point that they were ready to attempt powered flight. Peter Jakab sums up the Wrights' situation at the end of 1902 in his book[2]: "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."

Liverpool Wright Project

The research presented in this paper reflects a subsection of the Liverpool Wright project. The project's objectives are to provide analysis of the Wright Brothers' technical achievements in the period 1899–1905 accompanied by a treatise on the Wright's critical success factors and how they relate to modern systems engineering. This project celebrates the 100 years since the Wrights' activities and uses modern flying qualities synthesis and analysis methods to achieve these goals. Available to the researchers in this project is a full motion flight simulator located within The University of Liverpool's Bibby Flight Simulation Laboratory. This system provides the pilot with an immersive synthetic environment with visual, aural, and vestibular cues giving them the illusion of flight.[3] A number of simulation trials involving Wright aircraft have been conducted, and this paper will present results from some of these tests.

Overview

This paper is a study of the 1902 glider and its development. The analysis is set in the context of the knowledge of the Wrights and their contemporaries, but uses the analytical tools available to the modern flying qualities engineer. The second section of this paper describes the vehicle itself and details its design and subsequent development. The third section focuses on the aerodynamic characteristics of the 1902 glider and how these have been identified using scale-model wind-tunnel tests. The fourth section presents an analysis of the 1902 glider through modeling and simulation of the aircraft's dynamic response and stability and control characteristics. The fifth section introduces the pilot-in-the-loop and extends the analysis of the fourth section to real time simulation and results from the handling-qualities tests performed in the Liverpool Simulator. Finally, the last section ends the paper with some concluding remarks.

1902 Glider

The 1902 glider was a design born of the aerodynamic data the Wrights obtained from wind-tunnel tests during the winter of 1901–1902. Over 200 miniature surfaces were examined to study the effects of aspect ratio, camber, taper, and superposing (biplanes, triplanes). Figure 1 shows the general arrangement of the 1902 glider at the end of the 1902 gliding experiments. The wing span of the machine was 32 ft and 1 in. (9.78 m), and the chord was 5 ft (1.52 m), conferring an aspect ratio for each wing surface of 6.4. The total wing area was 305 ft^2 (28.34 m^2), a slight increase over that of the previous 1901 glider. A wing camber of 1/24 was selected for the 1902 glider wing airfoil section. The Wrights never tested an airfoil section of 1/24 camber, but obviously they felt confident enough in their new-found knowledge to extrapolate beyond the boundaries of their database.

The Wrights designed a new canard that had an elliptical planform of span 9 ft and an area of 15 ft^2. The actuation of the canard by the pilot was via a "roll bar," which connected to the hinge point

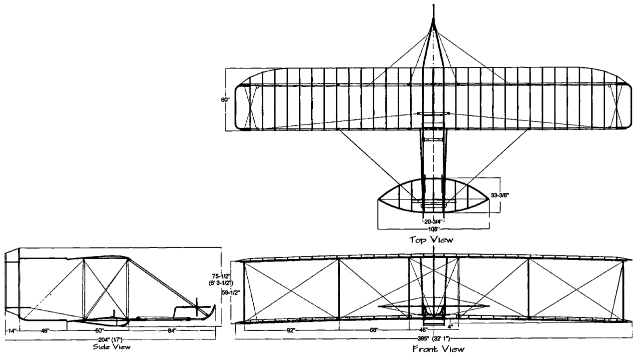

Fig. 1 Three-view diagram of the 1902 glider. Courtesy of Wright Brothers Aeroplane Company, Dayton, Ohio.

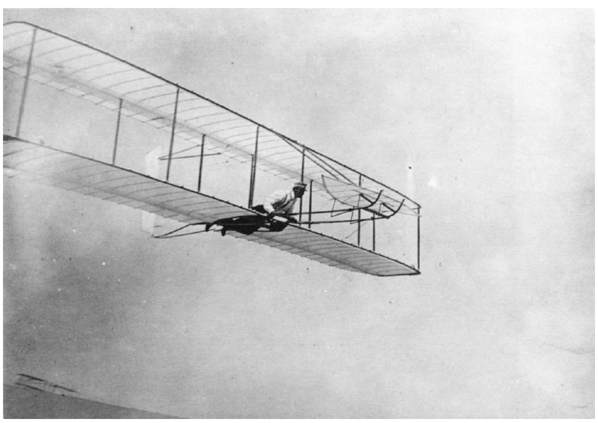

Fig. 2 Developed 1902 glider with a controllable single surface rudder.

of the canard by wires. For roll control, the wing-warping system that the Wrights had incorporated in all of their designs was continued: however, there was a new method of operation. Previously a foot-operated "kick" bar had controlled the warp, but now a cradle, where the pilot rested their hips, was used. By swaying their hips to the left or right, the cradle pulled on wires, which caused the wings to warp. This deformation caused one pair of wingtips to twist to a higher incidence and the other pair to twist to a reduced incidence.

As already mentioned, the original 1902 glider sported a twin-surface fixed vertical tail (see Fig. 3), with a total surface area of 12 ft^2. The difficulties the Wrights had with the glider when it acquired a lateral velocity resulted in the twin-surface tail being replaced with single tail of 5.9 ft^2, which was actuated by linking wires connected to the wing-warping wires. A further modification the Wright Brothers made during the 1902 gliding season was the incorporation of wing anhedral. Orville writes,[1] "After altering truss wires so as to give an arch to the surfaces, making the ends four inches lower than the centre. . . ." They did this because, without the anhedral, the glider's response to side gusts was such that the wing on the side of the gust tended to rise. The Wrights did not like this, as side gusts continually disturbed the lateral equilibrium in a glide. The Wrights favored the slightly unstable response given by the anhedral shape. After the modification Orville writes,[1] "We found that the trouble experienced heretofore with a crosswind turning up the first wing it struck had been overcome, and the trials would seem to indicate the opposite effect was attained. The machine flew beautifully. . . ."

The 1902 glider design had descended from the previous 1900 and 1901 machines, but numerous improvements and modifications had been made to optimize the basic concept. But why was the 1902 machine such an improvement? How did the design features affect the aerodynamic performance, and ultimately how did these contribute to the flying qualities of the 1902 glider? This paper will review these questions using modern theory and practice to bring to light the technical achievements of the Wright Brothers.

Aerodynamic Performance—Wind-Tunnel Testing

Experimental Configuration and Test Conditions

This section presents results from wind-tunnel tests of a $\frac{1}{8}$-scale model of the 1902 glider. The primary objectives for the tests were to measure force and moment coefficients over ranges of angle of attack and sideslip, combined with effects of control surface deflections, such that detailed simulation models could be developed. As part of the Liverpool Wright project, 1901 glider models were also tested, and some results from those tests are also presented to illustrate the comparative performance of the 1901 and 1902 gliders.

In total, three models were constructed; two 1901 gliders at $\frac{1}{5}$ scale (4.4-ft span) and one 1902 glider at $\frac{1}{8}$ scale (4.01-ft span). The 1901 glider scale models were constructed in-house at the University of Liverpool. Northwest Aerodynamic Models, Ltd., was contracted to build the 1902 glider. 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. Figure 4 shows the 1901 1/19 camber model mounted in the University of Manchester, United Kingdom, Goldstein tunnel, where the tests were conducted. The 1902 glider model also had wing warping, an adjustable canard, and a single, adjustable vertical tail. Figure 5 shows the 1902 glider model in the tunnel.

The test facility used was the Flow Science, Ltd. AVRO closed-return wind tunnel. This wind tunnel was originally installed at the A.V. Roe factory at Woodford, Cheshire, United Kingdom, in the early 1950s and in 1988 was acquired from British Aerospace by Flow Science, Ltd. In 1989 the shell was transferred to the University of Manchester's Goldstein Laboratory, Barton Aerodrome, where it was refurbished including flow quality improvements, a new data-acquisition system, and a moving ground facility. The tunnel is closed return, runs at atmospheric pressure, and has a working section of 9×7.3 ft; the flow is provided by a single-stage, four-bladed fan, driven by a 355-kW motor.

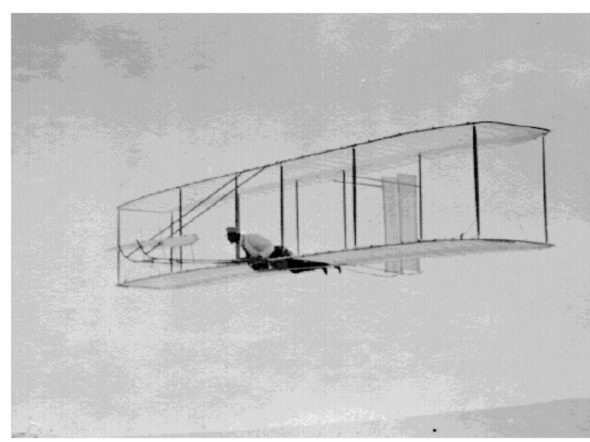

Fig. 3 Original 1902 glider with double surface tail.

Fig. 4 1/5-scale 1901 glider model.

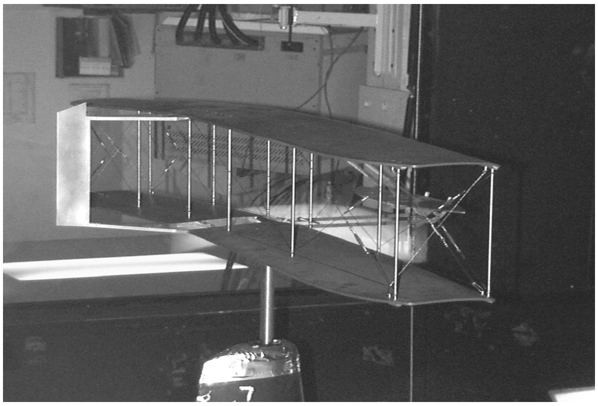

Fig. 5 1/8-scale 1902 glider model.

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 nose supported by a vertical nose wire. This configuration gave the minimum of interference from the strut mount with the aerodynamic surfaces and left no attachments along the wings—an important feature to allow for the wing warping.

The overall plan for the tests was to conduct a parametric study of the aircraft gathering data on the effects of canard, warp, and rudder deflections over a range of α (-10 deg to $+24$ deg)- and β (± 30 deg). The conventions for the various control deflections are as follows: 1) canard positive leading edge up (pitch up) $+\delta_c$; 2) warp positive—right wing tip increased incidence, that is, control input positive, $+\delta_w$ gives a roll to the left ($i_{\text{right}} - i_{\text{left}}$); 3) rudder control positive trailing edge to starboard (yaw to right) δ_r; and 4) 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 14–15 m/s, conferring a Reynolds number (based on the wing chord, $c = 0.426$ m) of 4.3×10^5. This compares with a full-scale Reynolds number at 20–30 mph of $1.28 \times 10^6 - 2.1 \times 10^6$ ($c = 2.1336$ m), that is, the difference between the 20-mph case and the model Reynolds number being a factor of 3. The 1902 glider was tested at speeds of 17.5–21.5 ms^{-1}, that is, a $Re = 2.23 \times 10^5$, while full scale at 20–30 mph gives $Re = 9.1 \times 10^5 - 1.37 \times 10^6$. The tests were conducted at a quarter of full-scale values. The increase in span of the 1902 glider over the 1901 glider meant that, because of tunnel size limitations, a smaller scale for the 1902 aircraft was required, thus reducing the Reynolds number. However, 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.[4,5] The primary Reynolds-number effect is a reduction in the $C_{L\max}$ of around 10% when reducing the $Re \approx 1 \times 10^6$ to 1×10^5. This factor is interesting as it was fortuitous for the Wrights also, as their 1902 design was based on very low-Reynolds-number data ($<10^4$). It is likely they were not aware of the Reynolds-number effect.

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. In summary it is believed that the Reynolds-number effects are not critical to the validity of the results.

Longitudinal Aerodynamics

Figures 6 and 7 display the lift and lift-to-drag ratio recorded for the 1901 and 1902 glider models. For the (1/19) 1901 glider model a C_{L_α} of 0.0445/deg was measured; this compares well to a value of 0.045/deg quoted in Kochersberger et al.[6] Because of its increased aspect ratio, the 1902 glider has an 50% increase in C_{L_α} of 0.066/deg. The angle for zero lift (α_0) is -1.9 deg for the 1902 and -2 deg for the 1901 model. The $C_{L\max}$ for both models was approximately 0.9. The last point to note for the lift behavior is that the C_L is preserved at near to the maximum value well beyond the stall angle.

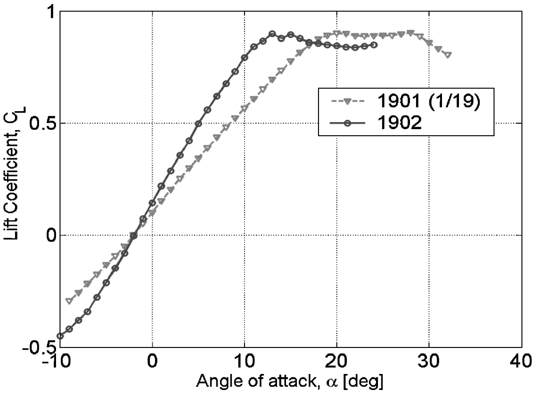

Fig. 6 Comparison of lift coefficient variation for 1901 and 1902 gliders.

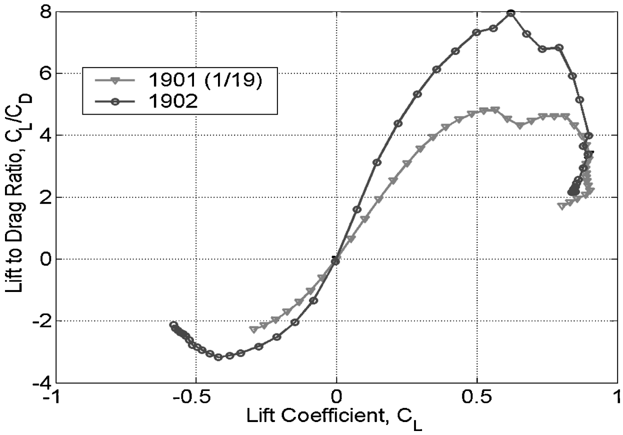

Fig. 7 Comparison of lift/drag ratio for 1901 and 1902 gliders.

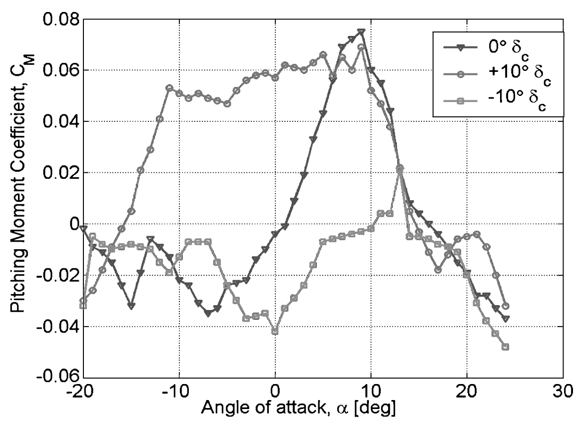

Fig. 8 Pitching-moment coefficient C_M about center of gravity as a function of incidence.

The lift-to-drag ratio (L/D) is plotted against the lift coefficient in Fig. 7. The 1902 glider clearly has a superior L/D over the 1901 machine, the maximum value for the 1902 glider at approximately 8 and the 1901 at 4.8. This parameter is directly related to the minimum gliding angle, which in still air is the descent angle γ.

$$D/L = \tan\gamma \tag{1}$$

From Eq. (1) $\gamma_{\min} = 7.125$ deg for the 1902 glider, whereas for the 1901 glider $\gamma_{\min} = 11.76$ deg.

The pitching-moment characteristics are displayed in Figs. 8 and 9. Strong nonlinearity is clearly visible with a reversal of the

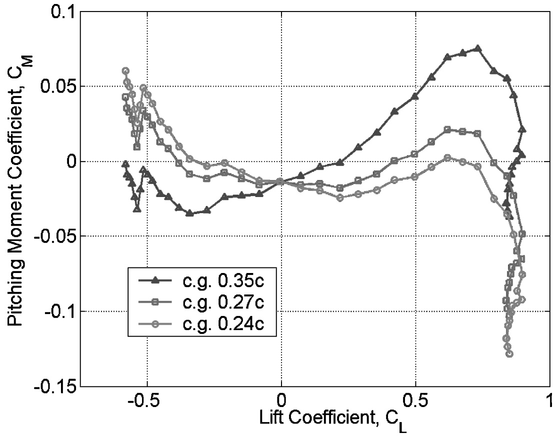

Fig. 9 Pitching-moment coefficient C_M about center of gravity for different c.g. locations.

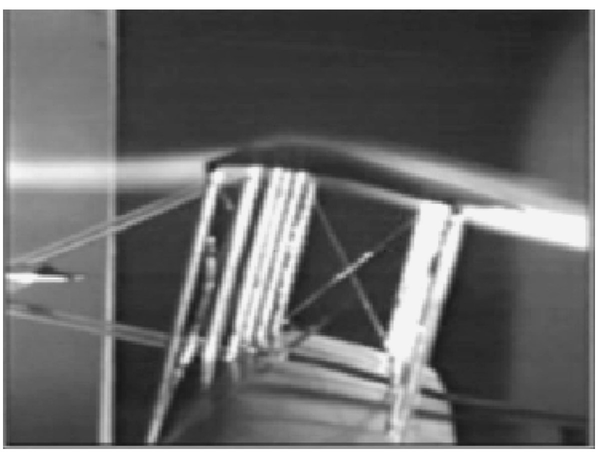

Fig. 10 Smoke flow visualization $\alpha \approx 6$ deg.

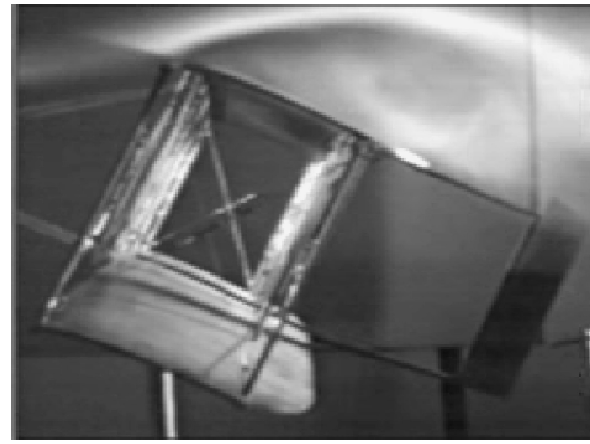

Fig. 11 Smoke flow visualization $\alpha \approx 20$ deg.

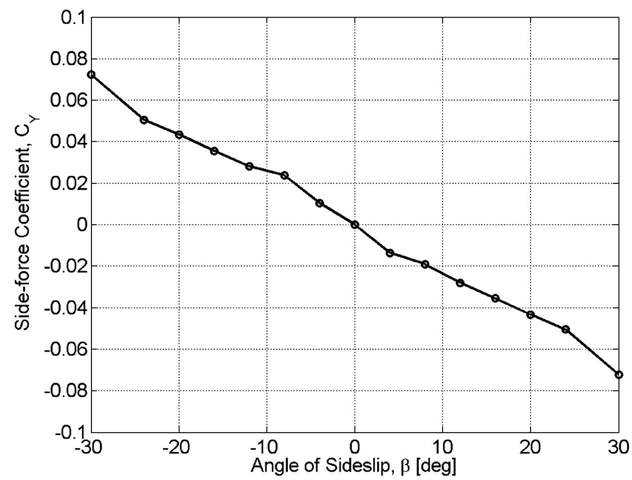

Fig. 12 Side force C_Y vs sideslip angle β.

overall slope at higher incidences. In Fig. 8 the canard can be seen to give a positive, albeit weak, increase in moment up to $+6$ deg α with $+10$ deg δ_c. Any further increase in α results in no further nose-up control moment. The same is seen for a -10 deg δ_c, where at -5 deg α there is no further nose down pitching moment. In both cases the canard is stalling at incidences of around $\pm$15–16 deg. The slope of Fig. 9 $\partial C_M/\partial C_L$ is equivalent to the static margin H_n; a value of -16% is measured for $C_L = 0.2$–0.6. This value is for a c.g. position 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,"[1] indicating an easily controlled vehicle.

Also shown in Fig. 9 is the effect of shifting the c.g. in the 1902 glider. The c.g. 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 will shift forward as they place their c.g. (a human's c.g. is approximately their waist) in the hip cradle at about 1 ft aft of the wing leading edge. Taking the glider's weight of 116 lb and the pilot's (Orville) weight of 140 lb, the resultant c.g. is calculated to be approximately at the 24% chord position. At this c.g. position, the static margin is positive (stable) at low C_L but slightly unstable, $H_n = -6.6\%$ for $C_L = 0.2$–0.6, reflecting the strong dependency of the stability on the angle of incidence.

The other major feature of Figs. 8 and 9 is the reversal of the slope indicating a large change in the pitching moment at high incidence. This effect is caused by 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 center of pressure aft causing a large nose-down pitching moment.

Figures 10 and 11 show two images illustrating the flowfield around the wing. The wing in Fig. 10 is at an angle of attack where the flow is smooth and attached to both surfaces, representing the α range 2–8 deg. Figure 11 shows that when the incidence increases beyond 8 deg the flow separates and a recirculation bubble on the upper surface forms. The consequences are a low but sustained $C_{L\max}$ and a large C_M break. Both of these characteristics are typical of very thin, cambered airfoils. To attest to this point, 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] (Orville Wright, Diary B, 12 Sept. 1902). The effect of this on the flight characteristics is that if the pilot were to attain a high α flight condition by pitching nose up and losing airspeed there would a restoring pitching moment nose down. Also, Fig. 10 displays a second crossing of the X axis ($C_M = 0$) at a high incidence of around 15–16 deg. This trim point, combined with the $C_{L\max}$, 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 stall.

Lateral Aerodynamics

Figures 12–16 display the lateral aerodynamic characteristics of the 1902 glider model. Figure 12 shows the side-force coefficient C_Y vs sideslip angle, with the model developing positive side force with negative β, as expected. The side-force coeffcient magnitude is fairly low, $C_Y = \pm 0.055$ at $\beta = \pm 30$ deg, a result of the 1902 glider having relatively little projected side area. From Fig. 13, the yawing-moment coefficient, the 1902 glider can be seen to be directionally stable with a positive slope of $\partial C_n/\partial \beta$. Also recorded in Fig. 13 is the effect of rudder deflection δ_r. 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 roll stability is presented in Fig. 14. Because of the anhedral angle of the wings, the slope of

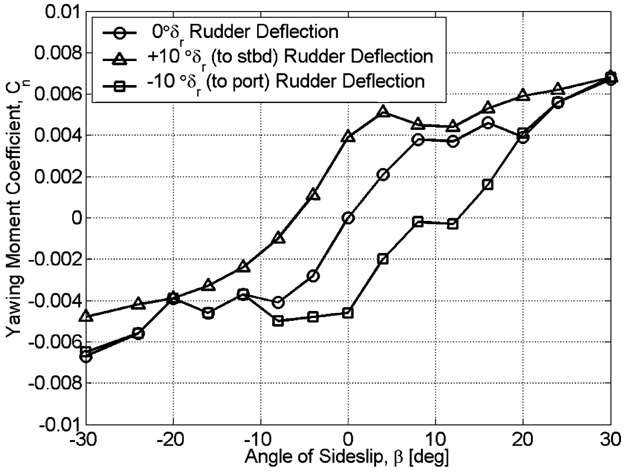

Fig. 13 Yawing moment C_n vs sideslip angle β.

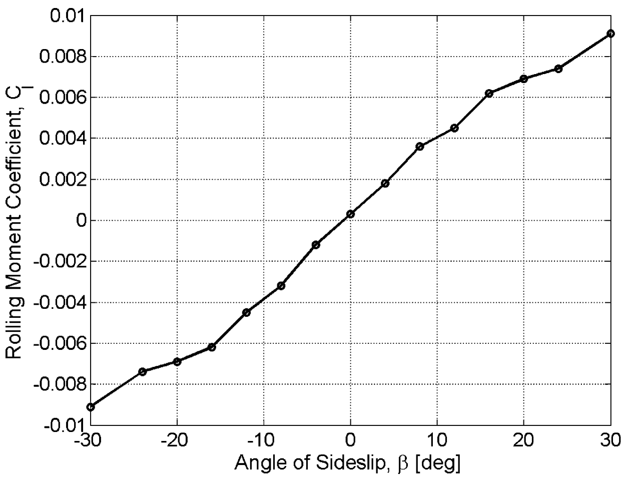

Fig. 14 Rolling moment C_l vs sideslip angle β.

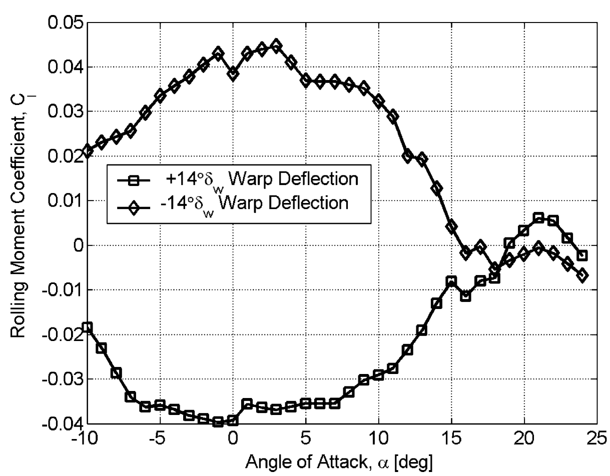

Fig. 15 Rolling moment caused by warp δ_w.

$\partial C_l/\partial\beta$ is positive; hence, the roll response to a sideslip velocity causes the aircraft to roll into the direction of the oncoming airflow, an unstable response.

The effect of wing warping is illustrated in Figs. 15 and 16. Figure 15 shows the rolling-moment coefficient plotted against the angle of attack with three curves for warp angles, δ_w of $+14$, -14, and 0 deg. The warp control is effective at creating rolling moments at angles of incidence between -5 deg and $+10$ deg. Beyond those angles the roll control effectiveness drops off, and by $\alpha = 15$ deg, $\partial C_l/\partial C_w \approx 0$. Figure 16 presents the yawing moments created when the warp control is operated. Large adverse yaw moments are generated, becoming increasingly worse with increasing

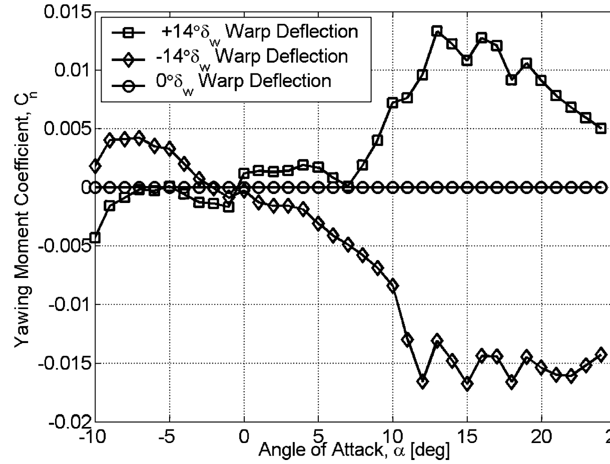

Fig. 16 Yawing moment caused by warp δ_w.

incidence. For the α range of -5 to $+10$ deg, the adverse yawing moments are less severe for the maximum warp of ± 14 deg. Comparing the yawing moments available from the rudder and the warp controls, it can be seen that a ΔC_n of $\approx \pm 0.004$ for ± 10 deg δ_r is achieved, and a maximum ΔC_n of $\approx \pm 0.005$ for ± 14 deg δ_w is not achieved until $\alpha = 10$ deg. This indicates that the warp-to-rudder interlink system devised by the Wrights was effective at cancelling the adverse yaw moments. In their paper, Jex and Culick[7] refer to a gearing ratio of $\delta_r = 1.25\delta_w$. Comparing the control derivatives of $\partial C_n/\partial\delta_r = 0.0004\,\mathrm{deg}^{-1}$ and $\partial C_n/\partial\delta_w = 0.00036\,\mathrm{deg}^{-1}$ (worst case below $\alpha = 10$ deg), it can be seen that proverse yawing moments are created by hip cradle motion.

Modeling and Simulation—Dynamic Response

FLIGHTLAB Modeling of the 1902 Glider

The Glider simulation models were created using FLIGHTLAB.[3] The software was developed to address the particular demands of high-fidelity simulation of rotorcraft and uses a multibody dynamics approach to model flight vehicles. FLIGHTLAB provides a range of tools using a modular approach to assist in rapid generation of complex, highly nonlinear models. The wind-tunnel tests provided a new set of data describing the aerodynamic characteristics of the aircraft as a whole. This type of data did not fit well with the multibody methodology, which requires data describing the performance of specific subcomponents. To incorporate these data, a multiple look-up table FLIGHTLAB supercomponent was developed. This component calculated the total aerodynamic loads of the canard, wings, vertical surfaces, airframe, and pilot-in-one system. The model uses look-up tables containing the six-degrees-of-freedom force-and-moment coefficients, the tables being up to three dimensions with the coefficients a function of α, β, and $\delta_{\mathrm{control}}$. The supercomponent 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 center of gravity and moments of inertia about the body axes. No published data were available for the 1902 glider inertias, and so a spreadsheet method[8] was developed to estimate the moments of inertia, I_{XX}, I_{YY}, and I_{ZZ}. 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 behavior of the landing skids on a sandy surface.

Once developed, a number of FLIGHTLAB analyses can be carried out on the simulation model. These include trim, parameter sweeps, linearization and stability analysis routines, dynamic response, and a real-time simulation environment.

Trim and Performance

Using the trim analysis tool, the static performance characteristics of the 1902 glider can be analyzed. Figure 17 shows the canard deflection angle required for trim across a speed range for three

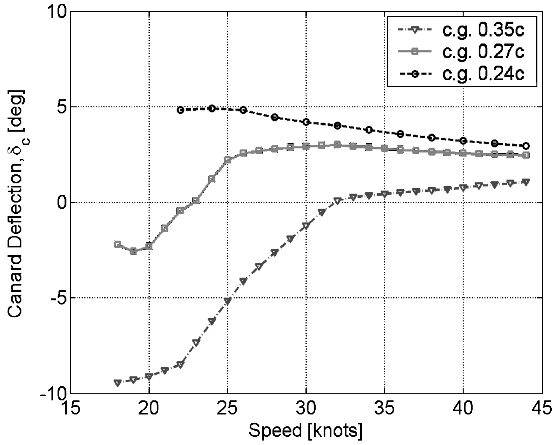

Fig. 17 Canard angle for trim.

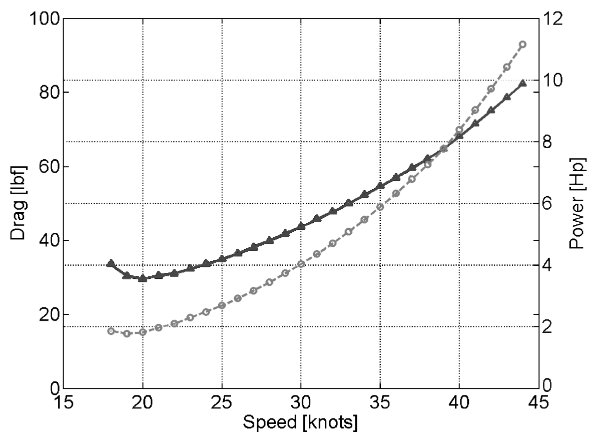

Fig. 18 Trim sweep showing drag and power curves.

centers-of-gravity positions. It can be seen that as the c.g. moves forwards from the aft position ($0.35c$) the slope changes from positive to negative, indicating the change from an unstable to a stable aircraft. The minimum speed that the model would trim was 16 kn; below that there was insufficient control power to trim. The minimum drag speed is about 20 kn, and the minimum power required for flight is 1.78 hp at about 18.5 kn. 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.

Flight Dynamics and Flight Handling Qualities

The most common flight speed that Wrights glided at was approximately 24 kn, and this case has been selected for further analysis using the linear state-space model formulation.

$$\dot{x} = Ax + Bu \tag{2}$$

From the nonlinear FLIGHTLAB model a linear model that is valid for small perturbations from the trim flight condition can be derived. Presented next are the state-space matrices in dimensional form, which contain the dimensional derivatives, as presented in McRuer et al.,[9] for the decoupled longitudinal and lateral dynamics of the 1902 glider simulation model: trim speed, 24 kn (40.5 ft/s); weight 252 lb; $I_{XX} = 228$ slugs-ft^2; $I_{YY} = 48$ slugs-ft^2; $I_{ZZ} = 229$ slugs-ft^2; and $b = 32$ ft, $c = 5$ ft, $S = 305$ ft^2.

Longitudinal A matrix $x = [u \;\; w \;\; q \;\; \theta]^T$, c.g. @ $0.35c$ units (ft/s, ft/s, radians/s, radians):

$$A_{\text{Long}} = \begin{bmatrix} -0.2158 & 0.7225 & -2.7944 & -32.0204 \\ -1.0274 & -8.1751 & 44.9362 & 3.3716 \\ -0.0643 & 0.9543 & -3.5995 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Longitudinal A matrix, c.g. @ $0.24c$:

$$A_{\text{Long}} = \begin{bmatrix} -0.1742 & 0.6877 & -2.5623 & -32.0961 \\ -1.1065 & -7.6488 & 43.0690 & 2.6753 \\ -0.0074 & 0.1191 & -3.2926 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Longitudinal B matrix $u = [\delta_c]$ [per/rad], c.g. $= 0.35c$, $0.24c$, respectively:

$$B_{\text{Long}} = \begin{bmatrix} 9.6691 \\ -18.2279 \\ 18.5695 \\ 0 \end{bmatrix} \qquad B_{\text{Long}} = \begin{bmatrix} -2.1548 \\ -2.5659 \\ 12.6496 \\ 0 \end{bmatrix}$$

Lateral A matrix $x = [v \;\; p \;\; r \;\; \varphi]^T$ units (ft/s, radians/s, radians/s, radians):

$$A_{\text{Lat}} = \begin{bmatrix} -0.3460 & 1.8597 & -40.4611 & 32.0208 \\ 0.0441 & -14.7847 & 3.2618 & 0 \\ 0.0625 & -1.6653 & -0.9663 & 0 \\ 0 & 1 & -0.1053 & 0 \end{bmatrix}$$

Lateral B matrix $u = [\delta_{\text{wr}}]$; $u = [\delta_w \;\; \delta_r]^T$ [per/rad]:

$$B_{\delta\text{wr}} = \begin{bmatrix} 4.470 \\ -13.8699 \\ -2.2536 \\ 0 \end{bmatrix} \qquad B_{\text{Lat}} \begin{bmatrix} 0 & 4.5321 \\ -13.8699 & 0 \\ 0.4796 & -2.0197 \\ 0 & 0 \end{bmatrix}$$

For the longitudinal axes of flight, the B matrix represents the effects of the canard control δ_c. The lateral axes has two control matrices. The first $B_{\delta\text{wr}}$ represents the control by using the warp-rudder interconnect system; the second breaks down the effect of warp δ_w or rudder δ_r alone. The eigenvalues for the longitudinal and lateral state matrices are as follows:

1) longitudinal eigenvalues (c.g. @ $0.35c$): -12.7758, 1.9558, $-0.5852 + 1.2865i$, and $-0.5852 - 1.2865i$; 2) longitudinal eigenvalues (c.g. @ 0.24c): -8.5371, -2.0827, -0.8833, and 0.3875; 3) Lateral eigenvalues: -14.3685, $-0.9226 + 1.4639i$, $-0.9226 - 1.4639i$, and 0.1168.

Examining the eigenvalues, both the longitudinal and lateral dynamics have positive real roots, representing unstable modes. The longitudinal mode $\lambda = 1.9558$ is particularly unstable, with a time to double amplitude $T_D = 0.35$ s. In the lateral axes the spiral mode is also unstable $\lambda = 0.1168$, but this is a much slower mode with a $T_D = 5.9$ s.

Flying-qualities documents such as the MIL-F-8785C (Ref. 10) and MIL-HDBK-1797 (Ref. 11) contain a number of criteria to which the modes of an aircraft can be compared to predict the expected flying-qualities levels. The 1902 glider is compared against these modal criteria to illustrate some of the flight characteristics. There are a number of aircraft types that the criteria refer to, with four classes that these types fall into, none of which the Wright 1902 glider could be accurately classified within. However, the closest comparison could be to a small light aircraft, which is a class I category aircraft. There are four levels of flying qualities, numbered 1–4. Level 1 flying qualities imply that an aircraft's flying qualities are clearly satisfactory to perform a specific task with acceptable pilot workload at all times. At level 2, the aircraft still has adequate flying qualities, but the pilot workload has increased, or the achievable task performance is reduced. Level 3 flying qualities denote degraded flying qualities such that the aircraft is controllable, but the task performance is inadequate, and the pilot workload is very high. Level 4 corresponds to situations where there is a high risk of loss of control.

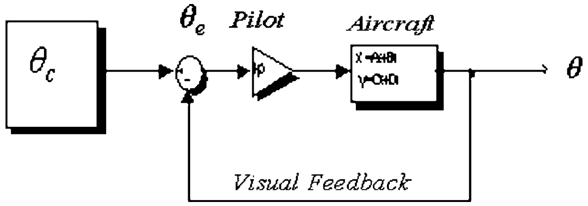

Fig. 19 Proportional control pilot model.

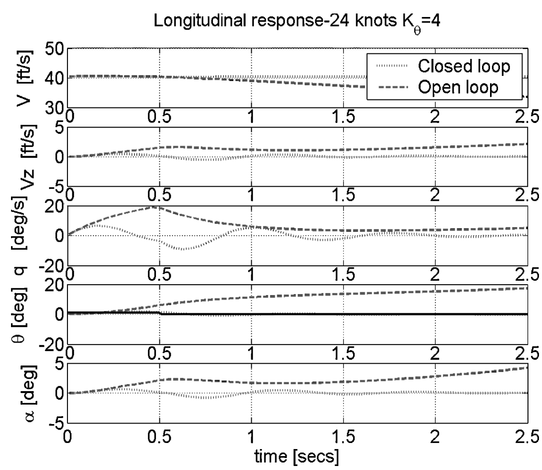

Fig. 20 Time response comparison of open- and closed-loop control.

Longitudinal Dynamics

Referring to the short-period criteria within MIL-F-8785C, with the c.g. at $0.35c$ the dynamics lie outside the level 3 boundary. The pitch dynamics must be stable to achieve the level 3 standard. Moving the c.g. forward to $0.24c$, the instability reduces ($\lambda = 0.3875$, $T_D = 1.79$ s), but the aircraft remains unstable. This instability predicts level 3 longitudinal flying qualities for the aircraft, using the standard metrics such as the thumbprint plot, the control anticipation parameter, or the pitch attitude bandwidth.[12,13]

An unstable aircraft is not necessarily unflyable however. Up to now only the aircraft's natural or open-loop dynamics have been discussed, but we now consider the inclusion of the pilot in the system. Figure 19 displays a schematic describing the aircraft–pilot system. The pilot's action is approximated as a proportional controller.[7] This simple strategy requires the pilot to estimate an error in the parameter being controlled. The sensors in this case are simply the pilot's own senses, primarily visual. Using airframe and outside world references such as the canard and horizon, the pilot can deduce the error between the desired 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 pilot control.

Figure 20 shows the comparison of the 1902 glider linear model under open- and closed-loop control, when disturbed by a 0.5-s control impulse. The unstable mode causes the open-loop aircraft to diverge in pitch, reaching $\theta = 20$ deg after only 2.5 s. For the closed-loop response, the pilot gain K_θ was set to 4 (deg canard/deg pitch attitude error). The closed-loop response is stable with the aircraft attaining a steady-state condition after a number of oscillations.

The effect of closing the loop on the system can be best visualized by looking at the root locus of the system. The root locus shows how the various modes of a system move as the gain is varied from $0 \to \infty$. The modes when $K_\theta = 0$ represent the open-loop poles, that is, the eigenvalues of the uncontrolled system. As the gain increases, the poles move, changing the stability. Figures 21 and 22 show the root loci for the longitudinal axes of the 1902 glider with two different c.g positions.

In Fig. 21 the application of pilot feedback is seen to stabilize the unstable mode. With a gain of $K_\theta = 1$ the mode is still unstable, and the oscillatory phugoid mode has been driven to a condition of neutral stability. 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. This represents the probable worst-case stability for the 1902 glider with a highly unstable mode that can "just" be stabilized with pilot control. As discussed earlier, the c.g. position was probably nearer $0.24c$. The root locus for this condition presented in Fig. 22. Figure 22 shows four aperiodic modes, three subsidences and one unstable divergence. When closed-loop control is applied, this mode is stabilized with a gain of $K_\theta = 1$ sufficient. Two of the aperiodic modes then join to form an oscillatory mode similar to the c.g. $= 0.35c$ case.

The effect of the movement of the center of gravity is illustrated in Fig. 23, showing how the unstable mode moves from the right-hand

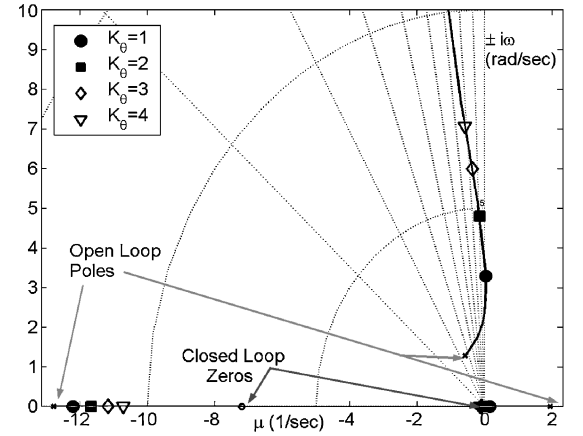

Fig. 21 Root locus, pitch attitude feedback to canard, c.g. @ 0.35*c*.

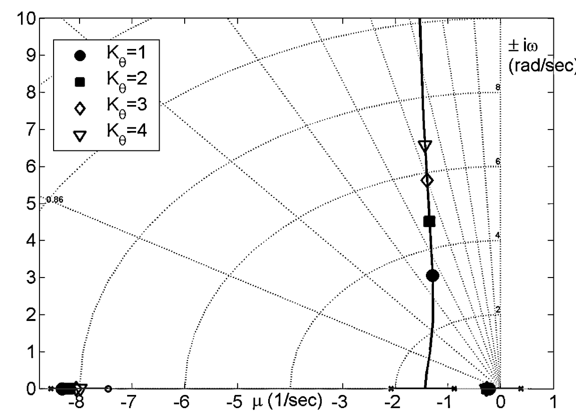

Fig. 22 Root locus, pitch attitude feedback to canard, c.g. @ 0. 24*c*.

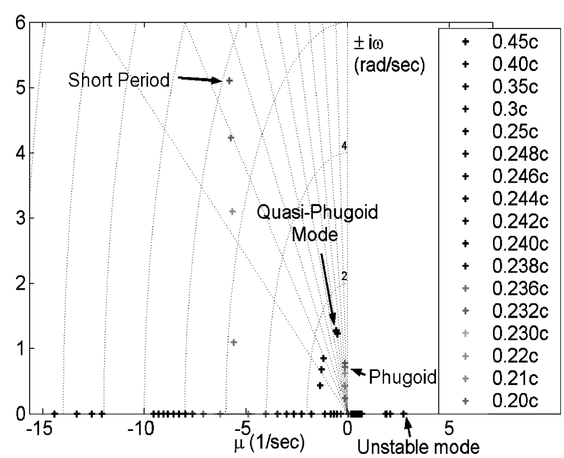

Fig. 23 Root locus showing effect of c.g. location.

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 phugoid. The remaining pole splits and travels left to form another oscillatory mode of higher frequency and high damping—the short-period mode.

The moving of the c.g. forward clearly makes the 1902 glider more stable, and so a question that arises is why did the Wrights persist with the unstable aft c.g.? Part of the reason was that the configuration of the aircraft forced the c.g. to be aft, and the pilot could only practically get their body so far forward within the aircraft. Second, if the c.g. is too far forward then the canard has to have a significant upload to trim; for the $0.2c$ c.g. location, $\delta_c = 10$ deg at 24 kn. With the estimated canard stall angle of 12–15 deg, there is little control margin left for pitch-up control, and at the lower speeds the pilot would lose sufficient control power to achieve a trim.

In conclusion, the 1902 glider was likely to have been marginally unstable, but controllable. However, the conditions flown in would have been gusty and turbulent, resulting in the pilot making continuous control corrections to keep the aircraft on course, the likelihood being that aircraft would "undulate" in a lightly damped oscillation. Furthermore, the frequencies (3–7 rad/s, 0.47–1.11 Hz) of the closed-loop oscillatory mode indicate that at moderate levels of gain there is a high probability of the pilot-initiating pilot-induced oscillations (PIO) unless a degree of anticipation could be applied.

Lateral Flight Dynamics

The 1902 glider also featured an unstable spiral mode. This mode is one of three modes usually associated with the lateral axis, the remaining two being the roll subsidence and the Dutch roll modes. The roll subsidence is largely dependent on the roll inertia, I_{XX}, and the wing aerodynamic damping.[12] Referring back to the flying-qualities criteria given in MIL-F-8785C, there are limiting acceptable values of the time constant $T_r = 1/\lambda_r$; the criteria for level 1 for all flight phases requires the $T_r < 1.4$ s. At 24 kn the 1902 glider roll mode $\lambda_r = -14.3685$ gives $T_r = 0.0695$ s, well within the boundary and indicating a highly damped mode, a consequence of the relatively low roll inertia and a large span wing.

The Dutch roll is a coupled oscillation between yaw/sideslip and roll, a complex mode usually determined by the characteristics of the rolling and yawing moments with sideslip. For the 1902 glider the Dutch roll mode is stable ($\lambda = -0.9226 \pm 1.4639i$). Again referring to the MIL-F-8785C, the criteria for level 1 are $\zeta_d > 0.19$, $\omega_d > 1.0$, and $\zeta_d\omega_d > 0.35$. Comparing the 1902 glider values, these are $\zeta_d = 0.63$, $\omega_d = 1.4639$, and $\zeta_d\omega_d = 0.9223$. Again, level 1 behavior for this mode is met. The remaining mode, the spiral mode, has already been established as being unstable ($\lambda = 0.1168$). A certain degree of spiral instability can be accepted for different flying qualities levels. For level 3 flying qualities the spiral mode time constant T_s must be greater than 7.2 s. For the 1902 glider this parameter (defined $T_s = 1/\lambda_s$) is calculated to be 8.5 s, inside the level 3 boundary but below the level 2 defined at $T_s > 11.5$ s.

The unstable behavior is a result of the wing anhedral. It was known to aviators at the time that a dihedral angle gave stability, but the Wrights had deliberately installed an anhedral angle. This was because they were uncomfortable with the roll response to side gusts with dihedral, which tended to lift the wing on the side of the gust and drive the other wing tip toward the ground. The anhedral induced unstable response tended to cancel the sideslip caused by the gust by rolling the aircraft into the wind.

The lateral problems had not completely disappeared with the addition of anhedral, and, as described in the earlier section, the Wrights linked the warp to the vertical tail that had been fitted (Figs. 24–26). This vertical tail gave the 1902 glider a degree of directional stability, which, after being disturbed by a short side gust, stabilized the heading of the aircraft by creating a restoring proverse yawing moment (Fig. 24). However in a prolonged gust or a change of wind (Fig. 25), the aircraft would roll toward the gust and also yaw toward the gust because of the directional stability provided by the vertical tail. The pilot, 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 wing tip further around toward the wind, causing a yaw rate induced roll (positive L_r) increasing the roll angle. This behavior was dubbed "well digging" by the Wright Brothers—one wing tip would drive into the sand and dig in with the aircraft corkscrewing around this point. This represented a 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.

The fix was to replace the double vertical surface with a controllable single surface tail that moved with the wing warp (Fig. 26). 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 second, when the wing was

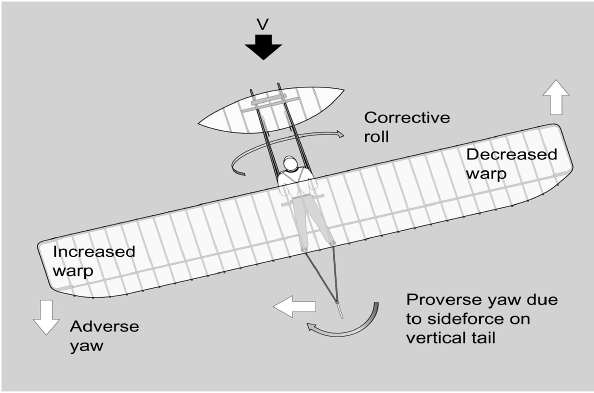

Fig. 24 Vertical tail counteracting short gusts.

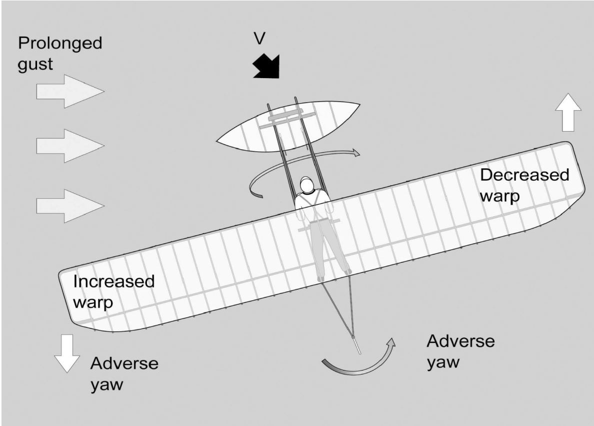

Fig. 25 Vertical tail causing adverse yaw in sustained lateral gust.

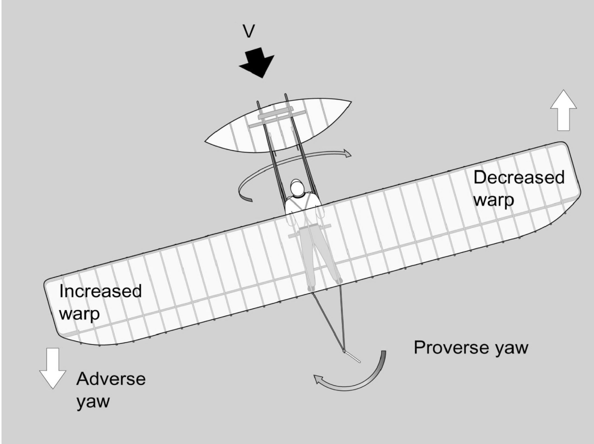

Fig. 26 Interlinked warp-rudder counteracting effects of sustained gust.

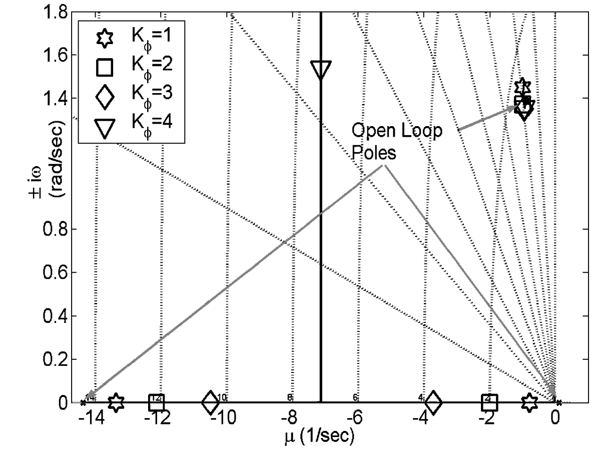

Fig. 27 Root locus, roll attitude feedback to warp—with interlink.

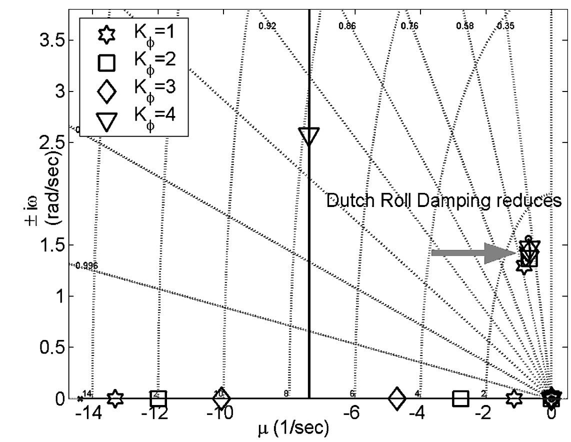

Fig. 29 Root locus, roll attitude feedback to warp—no interlink.

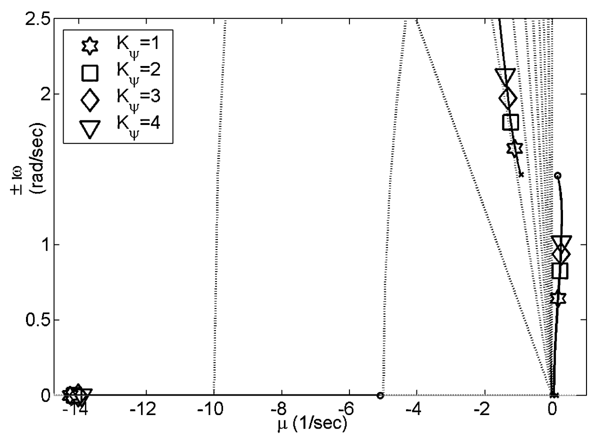

Fig. 28 Root locus, yaw attitude feedback to warp—with interlink.

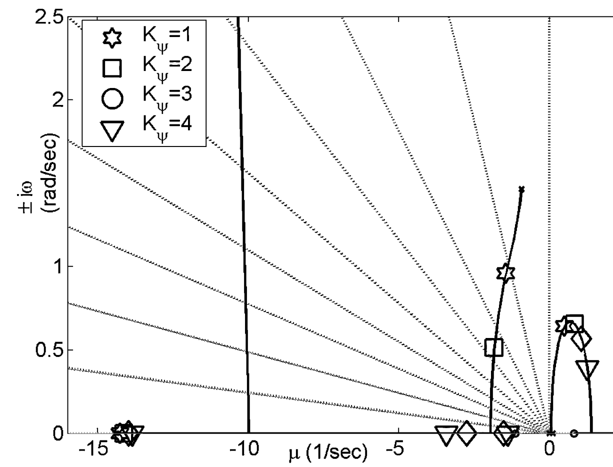

Fig. 30 Root locus, yaw attitude feedback to warp—no interlink.

warped to counter the into-wind roll, the rudder created a proverse yawing moment, thus cancelling the warp adverse yaw.

The maneuvers discussed in Figs. 24–26 are all concerned with closed-loop control of the aircraft. The analysis carried out for the longitudinal axis using the model presented in Fig. 19 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 27 shows the root locus for the bank angle φ controlled with the warp and interlinked rudder control δ_{wr}. The effect of increasing the gain is to stabilize the spiral mode, moving it left along the X axis. The gain increase has little effect on the Dutch roll mode, but by increasing gain to $K\varphi = 4$ a second, highly damped oscillatory (roll) mode forms. The feedback of the heading ψ is shown in Fig. 28. The spiral mode and zero directional mode combine to form a unstable oscillatory mode. These should be compared these to Figs. 29 and 30, where the warp-to-rudder interconnect is disabled. There is little difference for the $\delta_w \rightarrow \varphi$ root locus, except for the reduction in Dutch roll damping (Fig. 29). Looking at the closed-loop heading control in Fig. 30, the spiral mode couples with the zero mode again to form a divergent oscillatory mode that becomes an aperiodic divergence at high gains.

Time responses for the negative feedback gains of $K_\varphi = 1$ and $K_\psi = 1$ are presented in Figs. 31 and 32. Two lines are plotted in each, one with the interconnect system in operation and one with it disabled. Note that for bank-angle command (Fig. 31) the response with interconnect off exhibits an untidy turn entry with large amounts of adverse yaw and sideslip. With the interconnect enabled, the turn entry is smooth and more controlled. As shown in the root loci, heading control using proportional control alone is unstable for

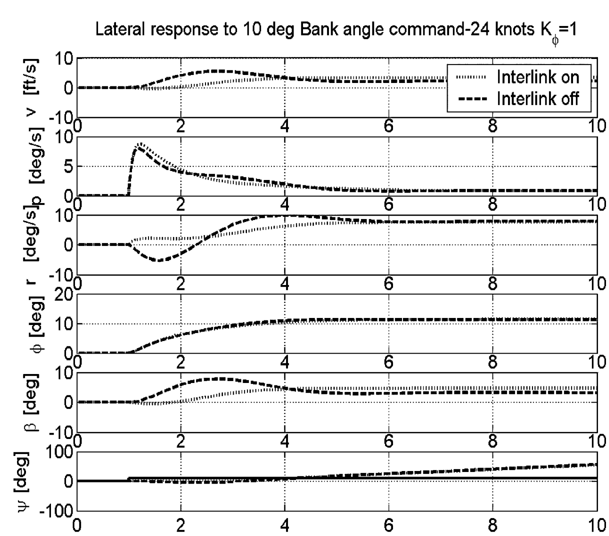

Fig. 31 Time response—roll attitude feedback to warp.

both situations, the interconnect-off case diverging in an oscillation in which maximum yaw angles of -10 and $+20$ deg are achieved within the first 5 s.

The previous analyses have shown that the 1902 glider was unstable in both pitch and roll. The pitch stability is predicted to be outside of the level 3 flying-qualities boundary, based on contemporary flying-qualities theory. For the lateral axis, level 1 criteria are met for the roll subsidence and Dutch roll modes. The spiral mode

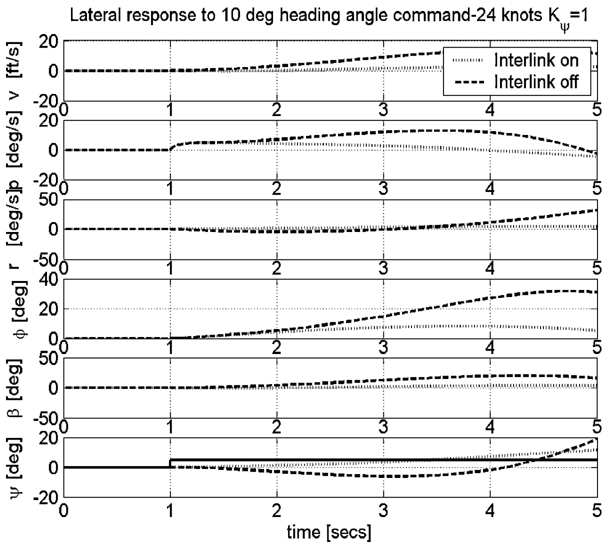

Fig. 32 Time response—yaw attitude feedback to warp.

is unstable, falling into the level 3 range. The rudder-to-warp interconnect has no effect on stability of course, but is seen to improve the turn entry characteristics when using the simple pilot model.

Real-Time Simulation—Piloted Handling-Qualities Tests

So far, the dynamic analysis has explained and quantified the instability of the 1902 glider and made some predictions of the likely flying characteristics. However, several assumptions were made, including linear aerodynamics, decoupled longitudinal and lateral control, and a simple, instantaneous, proportional pilot model. These assumptions provide insight into many of the secrets of the flight dynamics. However, there are many questions not answered—how did the lateral and longitudinal axes couple? What is the maneuver flight envelope, and how well can a pilot fly the 1902 glider? Will the pilot excite a PIO? To answer these questions, piloted trials using the full nonlinear FLIGHTLAB simulation model were performed in the University of Liverpool's flight simulation laboratory. A single test pilot, experienced in flying vintage aircraft, flew these exploratory trials. The simulation trials used the concept of specifying simple maneuver tasks described as mission task elements (MTE). Maneuvers that could be considered critical to the mission performance of the 1902 glider were selected in order that quantitative and qualitative assessments could be made. Firstly, a typical "mission" had to be identified for the 1902 glider. The glider was developed as a machine with which the Wrights hoped to 1) perfect their flight control concepts such that the pilot can maintain control in the changing winds, 2) have sufficient control such that the pilot can direct the aircraft to the desired heading, and 3) gain enough flight practice in preparation for the further development of the powered machine.

Three MTEs were developed to investigate these points; 1) a height and heading tracking task, 2) a turning maneuver, and 3) a roll-step maneuver. Performance standards are defined here: For a coupled directional and height hold, the desired standards were ±15 ft altitude, ±3-deg heading, ±10 ft lateral position; and the adequate standards were ±30 ft altitude, ±6-deg heading, ±30 ft lateral position. The first maneuver consisted of flying along the edge of a runway between marker posts while maintaining control on the height. The second test maneuver required the pilot to turn the aircraft through certain heading changes at varying angles of bank, and the final maneuver required the pilot to make a controlled turn through specified gates from one side of a runway to the other, exercising the precision and agility in turning flight. To enable sustained flight, the glider was operated in a continuous up-gust or thermal of strengths varying between 450–600 ft/min. This allowed the aircraft to be flown straight and level and climb. The opening flight by the test pilot highlighted many of the characteristics discussed in the preceding section, with the pilot noting that the aircraft, although pitch unstable, became stable at high angle of attack. He also discovered the lateral instability, the adverse yaw, and found control difficult if the sideslip were allowed to build up.

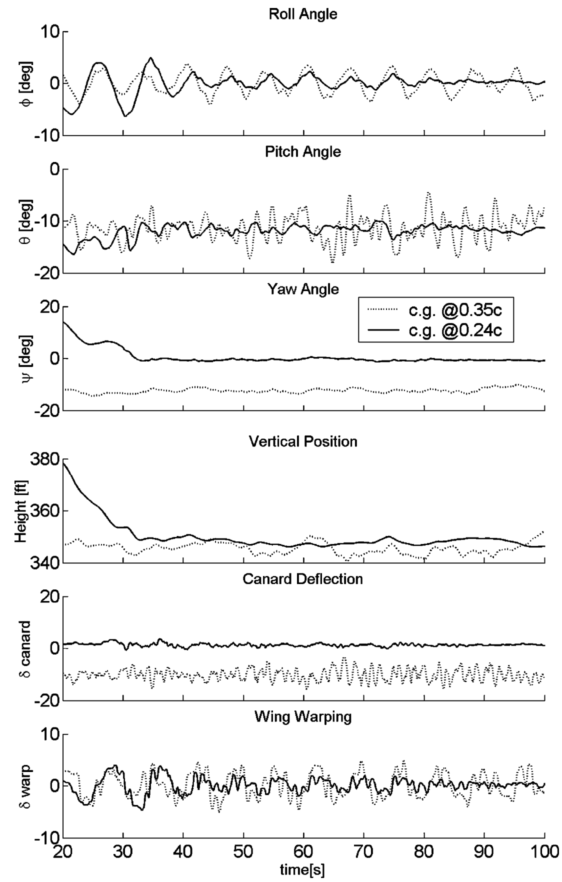

Fig. 33 Height and heading tracking task, c.g. comparison.

Figure 33 shows the results of the pilot flying the tracking man oeuver; the configuration was with the c.g. $= 0.35c$ and the interlink system engaged. It appears that the pilot is driven by the performance standards (Table 1) into a PIO in both the longitudinal and lateral axes. The pilot awarded a Cooper–Harper Handling Qualities Rating (HQR)[14] of six for this maneuver and PIO rating of four for all axes. The second configuration is for the c.g. $= 0.24c$, with the pilot commenting that the aircraft was still unstable but was much easier to control in pitch. This is confirmed by the measured data, with reduced amplitudes in the oscillations for the pitch and canard angles and the height being controlled more smoothly. Consequently a HQR of four was awarded, but the PIO rating remained at four, as the aircraft still oscillated around mean values for pitch, roll, and yaw attitude.

A time history from another height and heading tracking task run is shown in Fig. 34. The comparison is between the performance achieved with and without the interlink system. The main effect of removing the interlink system is that the roll and yaw oscillations are less damped, with oscillation settling with an amplitude of about ±3 deg in both axes. The increase in the oscillations significantly increased the pilot workload and had an adverse effect on the task performance such that the HQR dropped to seven.

Figure 35 shows the response for a turning maneuver. In this instance the pilot banked the aircraft to the right and allowed the roll angle to increase. During the turn, the sideslip steadily built up until a point where the pilot had lost most of his forward airspeed and pitched up as result. Note that once the turn was initiated the pilot needed to hold out-of-turn stick to trim in the turn. This exacerbated the increase in the sideslip because the rudder was deflected to give an out of turn yaw via the interlink system. This created a side

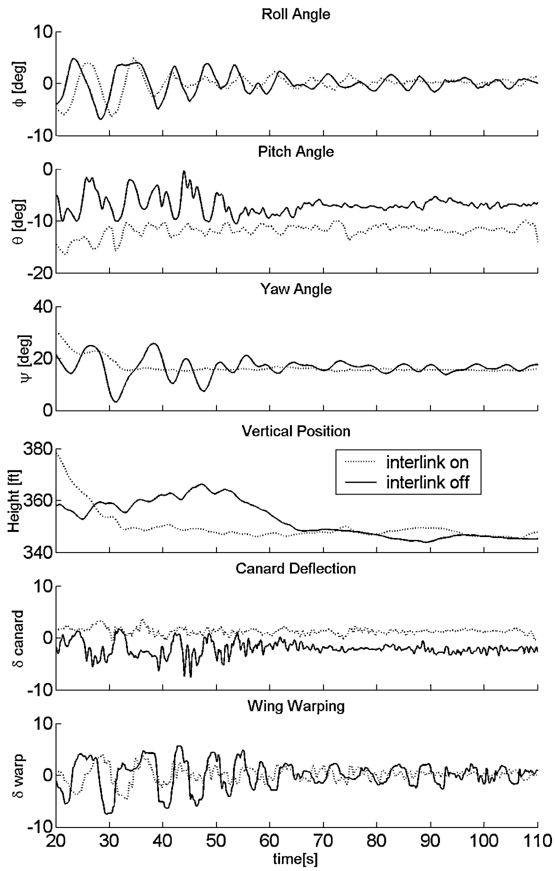

Fig. 34 Height and heading tracking task, interlink comparison.

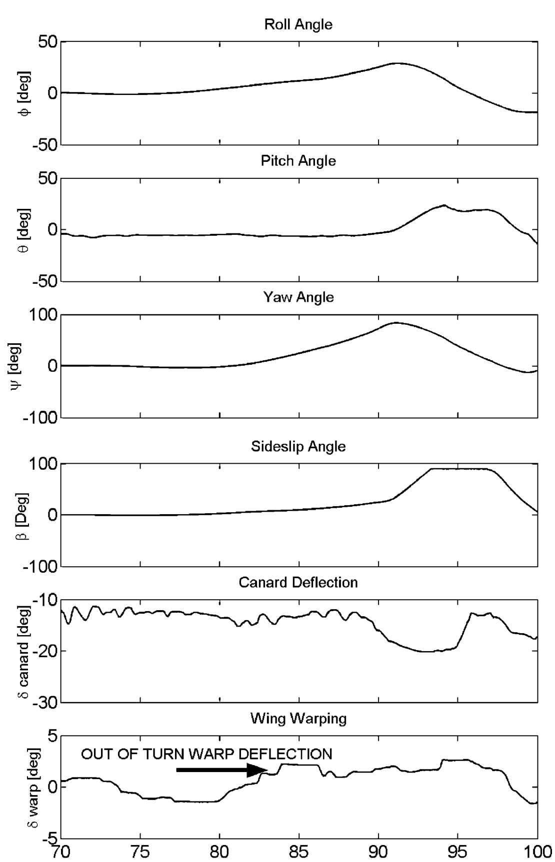

Fig. 35 Turn maneuver.

force in the direction of the turn, pushing the aircraft further into the sideslip. The real-time simulation 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. The lateral control was effective and as long as bank angles were kept below 10–15 deg, then successful turns could be made. However, if the airspeed were allowed to reduce below about 20 kn (minimum drag speed) then the lateral control became sluggish and the aircraft would often sidle off at high sideslip angles.

The handling-qualities ratings awarded for the different tasks were in the 4–7 range, surprisingly respectable considering the vehicle being studied. Undoubtedly, the aircraft required skill to fly but offered unprecedented levels of control and maneuverability for the time and validated the Wright Brothers' ethos of control over stability.

Conclusions

The paper has presented an analysis of the handling qualities of the Wright Brothers' 1902 glider. The performance, stability, and control of this aircraft are a key testament to the Wright Brothers place in history as the first aeronautical engineers, epitomized by 1) their understanding of the importance of aerodynamic data in the design phase, 2) their continued refinement of the three-axis flight control concept, and, more generally 3) their understanding that a successful flying machine is a result of the integration of structures, aerodynamics, control, and pilot skill. Perhaps the most critical success factor was their focus on flight control, specifically their mastery of instability. Through aerodynamic testing, modeling, and simulation, this paper has raised some of the flying qualities issues that became a feature of the later powered aircraft, particularly the instability in pitch, which would become even more challenging in the 1903 design, and in roll/yaw, initially designed in by the Wrights, but later removed because of problems found when turning their powered aircraft. The flight control system in the 1902 glider was arguably the single most important of the Wrights' innovations in this development period.

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