A RETROSPECTIVE: DEVELOPMENT OF SIMULATION MODELS FOR THE 1903 AND 1905 WRIGHT FLYERS

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The centennial of flight has brought about a renewed interest in the first airplanes and their flight characteristics. It is known that the first Wright Flyers were unstable, but history showed that they were flyable. It is the longitudinal handling characteristics that are of interest in this paper. Wind tunnel tests have been performed on the 1903 Flyer and provide limited aerodynamic data, but a higher fidelity model is needed to fully simulate the aircraft within nonlinear regions. Simulation models of the 1903 and 1905 Flyers were created by using the results of wind tunnel tests, using inviscid flow analysis, and expanding the data to include high angles of attack. The two models were simulated in the PC-based FlightGear Flight Simulator, and the results show that both aircraft require continuous pilot input, but they are flyable with practice.

Introduction

On December 17, 1903 the world changed as two bicycle shop owners made their first flight in an airplane they designed and built themselves. The first flight only lasted 12 sec and for a distance of about 120 ft, but it was enough to show that the years of research and design the Wright brothers conducted successfully led to a flyable machine. The brothers were very systematic to the design of their aircraft. They used gliders and airfoils tested in their own wind tunnel to test and modify their designs. Using what they learned from their first attempt, the Wright Brothers went on to design several more Flyers, one of which was the 1905 Flyer.

Now on the centennial of that first flight, technology has made it possible to simulate the first Wright Flyers on desktop PCs. It was the authors' goal to create high fidelity, nonlinear simulation models for both the 1903 and 1905 Flyers. The two aircraft are not only historically interesting, but also their designs are quite unusual compared to modern conventional designs. The longitudinal handling qualities of the two Flyers are known to be difficult, so simulation models were created in order to be able to study and compare the them. While the two aircraft are similar in design and static margin, Papachristodoulou and Culick[1] noted an increase in the pitch damping coefficient due to the larger canard on the 1905 Flyer.

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Nonlinear aerodynamic models were created for the 1903 and 1905 Flyers using data from an inviscid flow analysis of the wing and canard and data from wind tunnel tests on full- and sub-scale models of the 1903 Flyer. These models were integrated into the FlightGear Flight Simulator.[2] Simulated flights of these models demonstrate that constant attention is needed to keep these aircraft in the air, but the 1905 Flyer is much easier to control than the 1903 Flyer.

In this paper, a brief history of the two flyers is first presented, followed by a description of the inviscid flow analysis method and the flight simulator. A discussion of the development of the two simulation models is then presented, where the method of obtaining the aerodynamic data is addressed. Finally, results from simulation of the two Wright Flyers are presented.

Brief History of the Two Flyers

The history of the two Flyers is well documented, so that only a brief history of the two Flyers is given to better understand why these aircraft warrant analysis.

1903 Wright Flyer

At the beginning of the twentieth century, flight was on the brink of being obtained. People all over the globe were trying with varying degrees of success to become the first in flight. It took two bicycle shop owners from Dayton, Ohio to make this dream a reality.

The Wright brothers approached flight in a manner different than most of their contemporaries. Before building an aircraft that could fly, they first designed a system that could control the aircraft. This approach led them to the use of gliders as testing platforms. The brothers had a good base of information available to them from such researchers as Otto Lilienthal and Octave Chanute from which to start their own experiments.[3,4] From their gliders, they were able to design, test, and refine their ideas.

Leading to their invention of the airplane, the Wright brothers made several important discoveries and innovations. Their early glider tests demonstrated that the lift they were producing was less than predicted. In order to acquire necessary aerodynamic data, the brothers built their own wind tunnel and systematically tested airfoils and planforms to provide data they required. To control the rolling of the aircraft, the brothers devised a system to warp the wing tips thus increasing and decreasing the lift on the wings to induce a rolling moment. Testing of such a wing warping system led the Wrights to the discovery of adverse yaw. While using the warping system to initiate a turn, the nose of the glider would yaw in the opposite direction. To counteract this behavior, the brothers first used a stationary and then later a movable rudder. Another innovation of the Wright brothers was their method of propeller design. The brothers realized that a propeller for an aircraft does not behave in the same manner as one for a boat. Instead of propelling an aircraft by just moving air, a propeller is a rotating wing that creates a lifting force in the horizontal direction. Using their own propeller theory and wing tunnel tests of different airfoils, the brothers were able to design propellers unlike any in existence at that time.[5] Their method of tackling the problem of flight has rightfully given them the honor as the first aeronautical engineers.[6]

All of the knowledge the Wright brothers learned from their glider tests was used to create their first Flyer in 1903. The design of this airplane is unusual compared to conventional modern designs. Figure 1 shows a three-view of the aircraft. It is a biplane design with a biplane canard and twin rudder. The wing has a span of 40.3 ft, a chord of 6.5 ft, and an area of 510 ft^2. The canard has a span of 12 ft, a chord of 2.5 ft, and an area of 48 ft^2. The rudder has an average span of 6.9 ft, a chord of 1.5 ft, and an area of 20 ft^2. The aircraft weighs 605 lbs without a pilot, and according to Papachristodoulou and Culick,[1] the center of gravity is located 29.7% of chord behind the leading edge of the wing and the neutral point is located 3.9% of chord behind the leading edge.

On December 17, 1903 at 10:35 am, Orville Wright in the 1903 Flyer became the first in flight when the airplane lifted off the ground and flew for 120 ft in 12 sec (Fig. 2). Three more flights were made with the fourth being the longest at 852 ft in 59 sec. Because of its significance, the original 1903 Flyer is now proudly displayed at the National Air and Space Museum in Washington, DC.

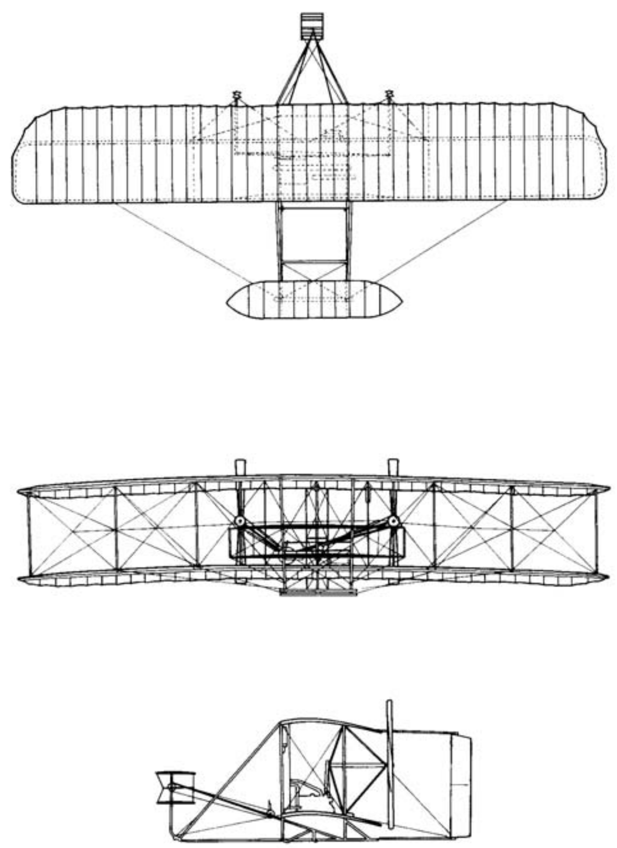

Fig. 1 Three-view of the 1903 Wright Flyer (Library of Congress).

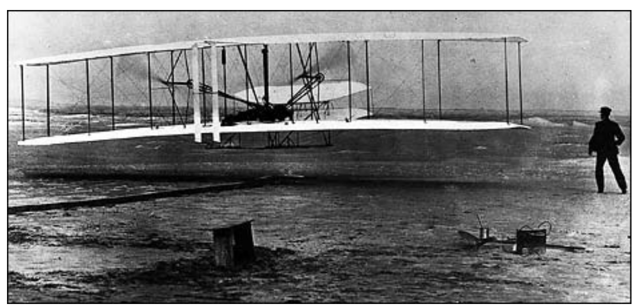

Fig. 2 First flight of the 1903 Wright Flyer.

1905 Wright Flyer

After the success of the 1903 Flyer, the Wright brothers returned to Dayton, Ohio to improve on their design. They knew that if they were going to sell their airplanes, they would need a design that would stay in the air much longer than one minute. For the 1904 and early 1905 Flyers, the brothers used a design close to the 1903 Flyer. They tested these airplanes at Huffman Prairie close to Dayton. Unfortunately the brothers did not see much improvement in their flight performance while at this test site during June and July of 1905. Flights were short with the longest only being about 20 sec.[7] On July 14 with Orville at the controls, the 1905 Flyer suffered a terrible crash destroying large parts of the Flyer.

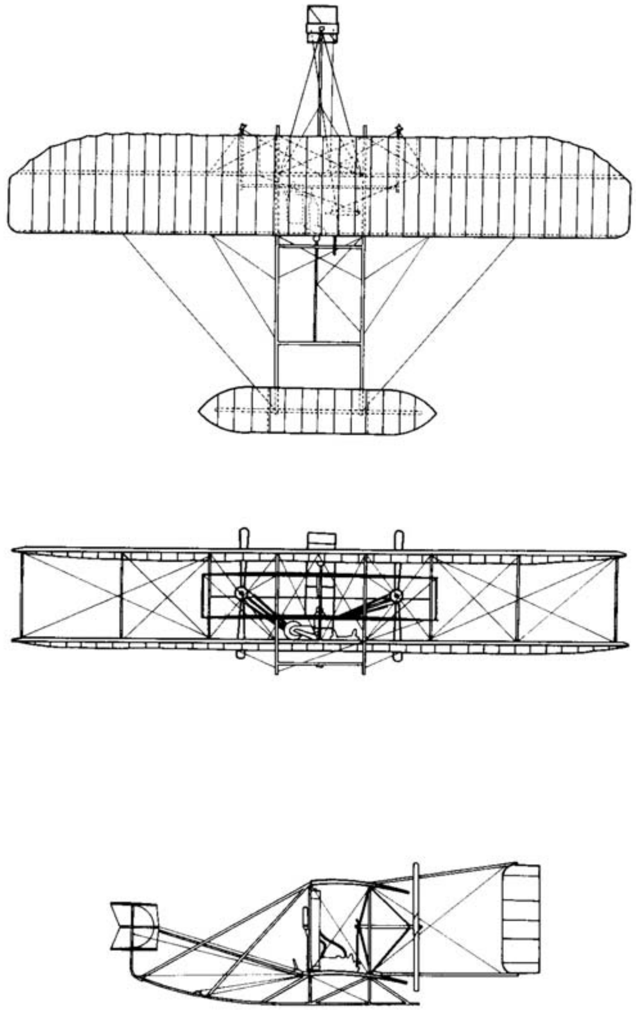

Fig. 3 Three-view of the 1905 Wright Flyer (Library of Congress).

The crash forced the Wrights to address the pitch instability in their airplane that sometimes caused it to be uncontrollable. Keeping the wings similar to the 1903 Flyer, the brothers rebuilt the forward part of the airplane to improve the pitch instability. The area of the 1905 canard was increased from 52.75 ft^2 to 83 ft^2, and the distance between the wing and canard was increased from 7.32 ft to 11.7 ft.[7] Figure 3 shows a three-view of the new design. The wing has a span of 40.5 ft, a chord of 6.5 ft, and an area of 503 ft^2. The canard has a span of 15.6 ft, a chord of 3.1 ft, and an area of 83 ft^2. The rudder has a span of 7 ft, a chord of 2.5 ft, and an area of 34.8 ft^2. The aircraft weighs 710 lbs without a pilot, and according to Papachristodoulou and Culick.,[1] the center of gravity is located 12.8% of chord behind the leading edge of the wing and the neutral point is located 14.6% of chord in front of the leading edge.

The aircraft was back in the air at the end of August, and the new design showed tremendous improvement in performance. The brothers were soon able to fly for minutes at a time, and flight time steadily increased

Fig. 4 1905 Wright Flyer above Huffman Prairie (McFarland[3]).

over the next month. By the beginning of October, flights were lasting around 30 minutes. Their longest flight was on October 5, 1905 when Wilbur flew the Flyer for 24 miles in 39 min 23.8 sec. Now the Wright brothers had a practical airplane. Figure 4 shows the 1905 Flyer in the air above Huffman Prairie. The 1905 Flyer is now on display at the Carillon Historical Park in Dayton, Ohio.

Development Tools

Inviscid Flow Analysis

Inviscid flow analysis of the 1903 and 1905 Wright Flyers was performed using CMARC.[8] CMARC is a C++ port of the Fortran code PMARC.[9] These two codes implement a low-order panel method that uses constant strength doublet and source panels placed on the surface of the body to be modeled. An internal Dirichlet boundary condition is used, while the wake is modeled using constant-strength doublet panels. The aerodynamic forces are calculated by integrating the pressures over all the surface panels, while a more accurate induced drag coefficient can be calculated using a Trefftz plane analysis. All the models in the current study used planar wakes oriented parallel to the free-stream flow direction. Only the right half of the geometry was modelled explicitly, and the flowfield was assumed to be symmetrical in the xz-plane. The flow analysis was performed with the wing and canard sections in isolation. The wing analysis was also used to obtain the induced velocities at the location of the canard aerodynamic center.

The airfoils used for the panel model were obtained by scanning and digitizing accurate blueprints of the 1903 and 1905 Wright Flyers. The original Wright Flyers had fairly blunt leading and trailing edges on the canards, so that the leading edges of the canard airfoils had to be slightly rounded for the inviscid flow analysis, while the trailing edges were modified to a sharp point. The trailing edge of the main wing airfoil was similarly modified from a finite thickness to a

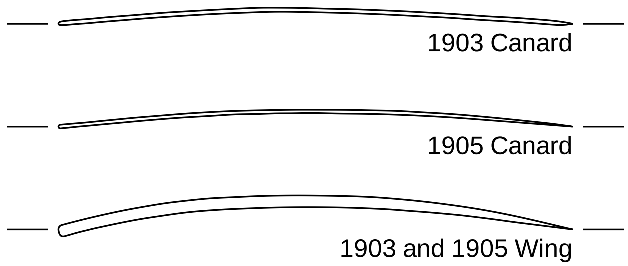

Fig. 5 Airfoils used for CMARC panel mesh.

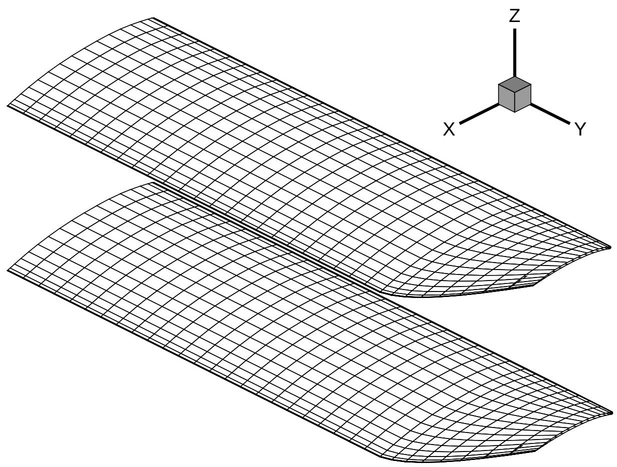

Fig. 6 Mesh for the 1905 wing.

point. The airfoils used for the flow analysis are shown in Fig. 5.

The panel mesh was generated using a custom surface modeler and mesh generator. Although the 1903 and 1905 Wright Flyers have very similar wings, the 1903 Flyer had a small amount of anhedral that was removed for the 1905 aircraft. The anhedral on the 1903 wing was modeled using a linear deflection along the span. It is believed that this simplification over the actual deflection shape has a negligible effect on the longitudinal stability and control characteristics. The mesh generator was also used to deflect the canard surfaces to simulate elevator input from the pilot. The mesh for the wing of the 1905 Flyer is shown in Fig. 6. The mesh uses a cosine panel distribution in the chordwise direction and a linear distribution in the spanwise direction over both the inner and the tip sections. The upper and lower wing each used 1280 panels for a total of 2560 panels to model the entire wing geometry. The canards combined also used a total of 2560 surface panels. Examples of the 1903 and 1905 canard panel meshes are shown in Figs. 7 and 8, respectively.

FlightGear Flight Simulator

The 1903 and 1905 Wright Flyer models were implemented and tested using the FlightGear Flight Simulator (FGFS),[2] a cross-platform, open-source, PC-based flight simulator written in C/C++ and utilizing OpenGL graphics. In conjunction with the NASA Smart Icing Systems project,[10] the authors helped in

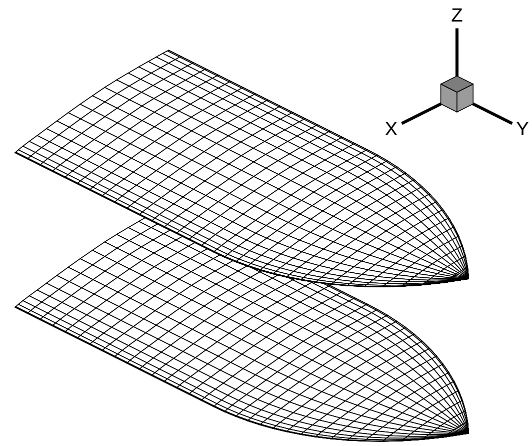

Fig. 7 Mesh for the 1903 canard.

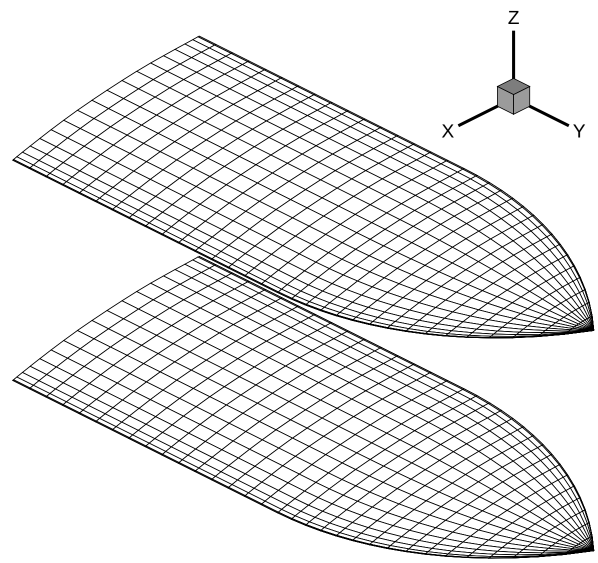

Fig. 8 Mesh for the 1905 canard.

modifying FGFS to create a reconfigurable aircraft model[11] based on the NASA Langley LaRCsim flight dynamics module.[12] The reconfigurable aircraft model allows for the simulation of a model by specifying aircraft characteristics in an input file. Data required by the input file includes the geometry, mass, aerodynamic model, engine model, and gear model of the aircraft. The nonlinear aerodynamics models used for the 1903 and 1905 Flyers use a combination of stability and control derivatives and lookup tables. Figures 9 and 10 show typical images of the 1903 Wright Flyer and the 1905 Wright Flyer, respectively, in FlightGear.

Model Development

In the development of the flight model, emphasis was placed on synthesizing data that properly characterized the handling qualities in longitudinal flight. Nevertheless, a full six degree-of-freedom aircraft model was developed to simulate lateral-directional flying qualities and ground reactions. Only a simple thrust model was implemented, sufficient for flight, and aero-

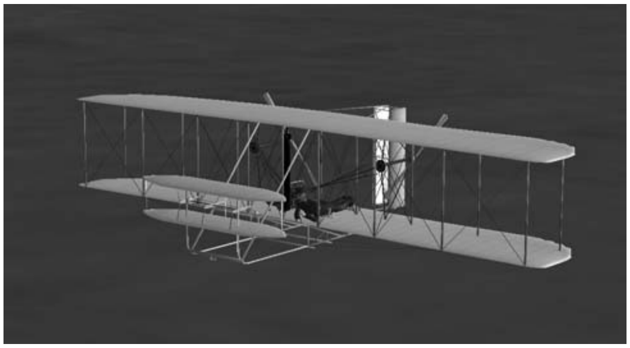

Fig. 9 Front perspective view of the 1903 Wright Flyer in FlightGear.

Fig. 10 Front perspective view of the 1905 Wright Flyer in FlightGear.

dynamic ground effects were ignored.

For the aerodynamics model, the stability axis system was used, and the conventional approach was taken as described. The three components of the longitudinal mode of the aerodynamic model were functions of the angle of attack, canard deflection, and pitch rate. The lateral-directional components were functions of the sideslip angle, wing warping, rudder deflection, roll rate, and yaw rate. Each component of the aerodynamic model took the form of a coefficient build up where the coefficient was constructed of a base part and several incremental parts. The base part is the value of the coefficient with no control surface deflections or angular rates. The base parts of the longitudinal components were a function of the angle of attack, and the lateral-directional components were a function of sideslip angle. Incremental parts due to control surface deflections and angular rates were then added to their respective base parts as is standard practice in flight simulation modeling.

Data used in generating the flight model was derived from several sources. First, drawings of the 1903 and 1905 Flyers were obtained[13,14] and used for mass and geometry information. Also, invaluable experimental data were obtained from wind tunnel tests on a full-scale replica of the 1903 Flyer tested at NASA Ames.[15] Augmenting these experimental results were the predictions derived from CMARC as previously described. The aforementioned experimental results and the validity of the predictions were limited to angles of attack for which there was limited flow separation—in the first case due to structural concerns and in the latter due to the assumption of inviscid flow. Thus, nonlinear data into the stalled flight regime had to be created based on trends gleaned from a diverse collection of literature on stalled wings (not all of which is cited in this paper).

The approach taken to modeling the longitudinal aerodynamics was to consider the biplane wing and canard separately. Thus, in the simulation the canard can stall independently of the biplane main wing. Upwash effects on the canard due to the main wing are included in realtime in the simulation based on the circulation strength of the main wing. No influence of the canard on the main wing was considered.

The main biplane wing was analyzed in isolation in CMARC, and the results are shown in Fig.11. As seen the effects of separation leading to stall are not modeled by the panel method. Also, shown in Fig.11 are the lift data from the NASA Ames Tests.[15] This wind tunnel test data is only that shown between the two bullet symbols. The agreement between the CMARC runs and the NASA data is seen to be quite good, with discrepancies likely due to the effects of non-ideal flow, the presence of the Canard and also perhaps, as has been suggested,[16] deformation of the fabric. Departures from the CMARC data and NASA Ames data have been estimated based on the stall behavior of biplane wings,[17] wind tunnel test data shown in Ref. 16, and 2D stall characteristics of thin cambered airfoils. Pitching moment data for the main wing is shown in Fig. 12, and the nonlinear aerodynamics have been estimated as previously described. In the simulation the lift and moment data from the solid lines in Figs. 11 and 12 were used. Drag data for the main wing was deduced from the NASA Ames tests,[15] and will be presented later. (But again it should be added that modeling drag and its thrust counterpart were somewhat secondary goals of this work that centered around interest in the longitudinal handling qualities.)

As with the main biplane wing, the canard contributes lift, drag and moment to the overall aerodynamics. The most important contribution, however, derives from the lift on the canard and at high angles of attack the chordwise normal force on the canard as these forces produce the necessary control moments for trimmed flight. Figure 13 shows the CMARC predictions for the lift coefficient as a function of canard deflections ranging from -30 to 30 deg. (The given lift coefficients were nondimensionalized by the canard area of 48 ft^2.) Based on the airfoil used on the canard, stall was estimated to occur at $C_L \sim -0.5$ and 0.9. Data beyond stall is representative of the normal force coefficient, which has an important contribution to the total pitching moment of the aircraft in the nonlinear flight regime. The solid line force coefficient data

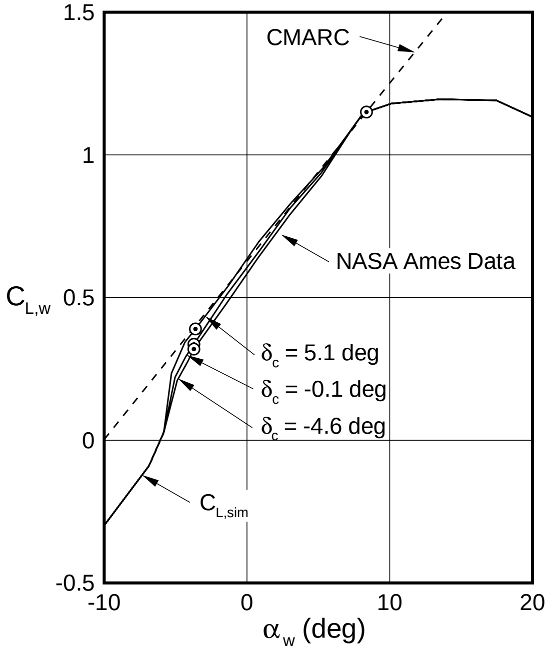

Fig. 11 Lift coefficient versus angle of attack from CMARC and wind tunnel tests for the main biplane wing.

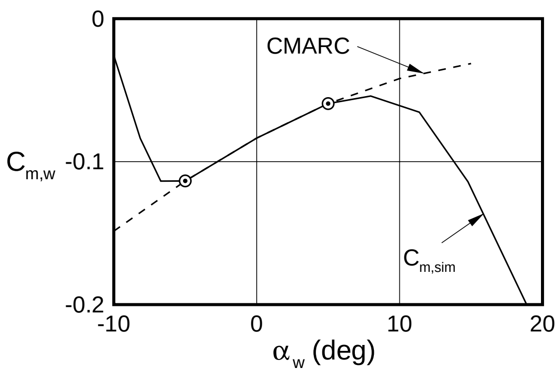

Fig. 12 Pitching moment coefficient versus angle of attack for the main biplane wing of the 1903 Flyer.

shown in Fig. 13 was then used to determine the control power of the canard, which is shown in Fig. 14. In the simulation only the solid lines are used. The canard contribution to the overall lift is not explicitly included as that contribution has already been embodied in the lift data shown in Fig. 11. Likewise, the drag has been included in the total aircraft drag measured in the NASA Ames data used in this work.

It is worth mentioning that when the main wing and canard pitching moment contributions are added (taking into account upwash effects on the canard) the results are in quite good agreement with the NASA Ames data.[15] Of course the result is that the 1903 Flyer is statically unstable as has been well documented in the literature.

For the 1903 Flyer, the canard deflection limits have not been reported in the literature nor in the

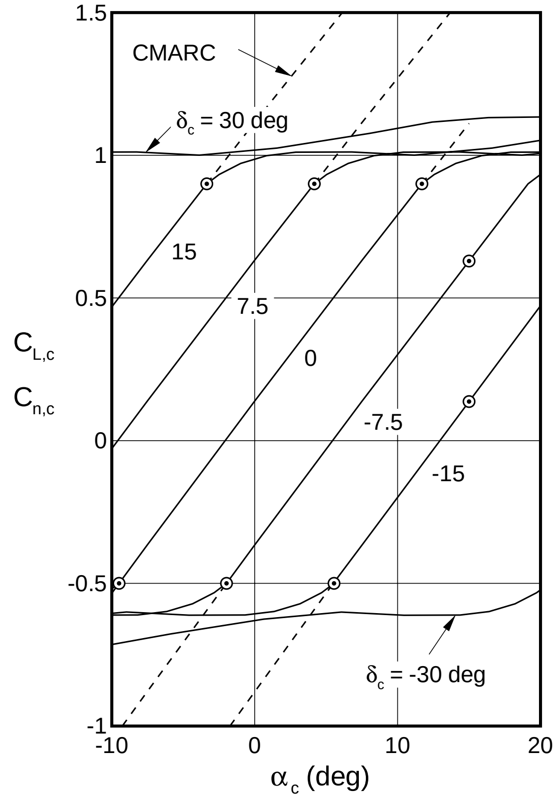

Fig. 13 Lift coefficient versus angle of attack for the 1903 canard at canard deflection angles ranging from −30 to 30 deg.

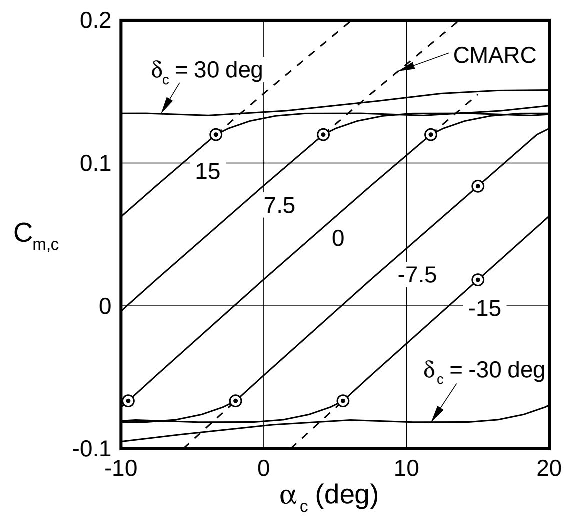

Fig. 14 Pitching moment coefficient versus angle of attack for the 1903 canard at canard deflection angles ranging from −30 to 30 deg.

blueprints of the Smithsonain.[13] Inspection of Fig. 2 showing the first flight contains important information on canard deflection, which appears to be quite extreme at the given instant. Using the simulation 3D graphics model, trial and error was used to set the canard deflection at an angle that most closely matched that shown in Fig. 2. The resulting match appears in Fig. 15, which was generated using a canard deflection

Fig. 15 View of the 1903 Wright Flyer with a 30 deg canard deflection in FlightGear.

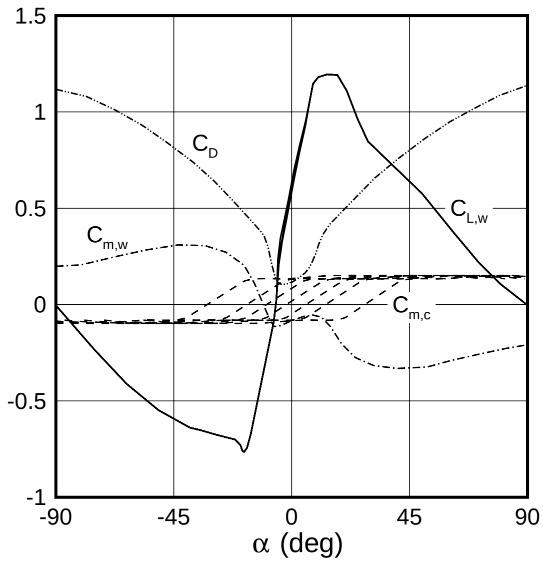

Fig. 16 Aerodynamic coefficients for the 1903 Flyer from −90 to 90 deg angle of attack.

of 30 deg. Note the match between the images part-for-part is not perfect due to the imperfect (but quite representative) 3D model. This 30 deg deflection from the horizontal plane has led to the inclusion of the −30 to 30 deg data in the simulation model. (Based on the results of this work and experience in flying the model in the simulation, a deflection any higher than 30 deg does not lead to more control power. In fact the 30 deg case is already highly stalled, but understandably 30 deg canard deflection could result from over control to avoid collision with the ground.)

In order to model high angle of attack excursions resulting from stalled flight, the data has been extended over the range of −90 to 90 deg (see Fig.16) based on estimates and data taken from several sources. It is worth noting that at the extreme limits the drag coefficient does not reach a value of 2 due to the projected area of the biplane wing being roughly half that of the reference area, which for the 1903 Flyer is 510 ft^2.

For the 1905 Flyer, a similar process was taken for generating the aerodynamic data for the simulation. Although the 1905 Flyer used the same wing biplane cell as the 1903 Flyer, the center of gravity moved[1] and this obviously leads to differences in the longitudinal aerodynamic data. Other substantial differences derive from the larger canard and the reduced canard deflection limits of ±15 deg reported in Ref. 14.

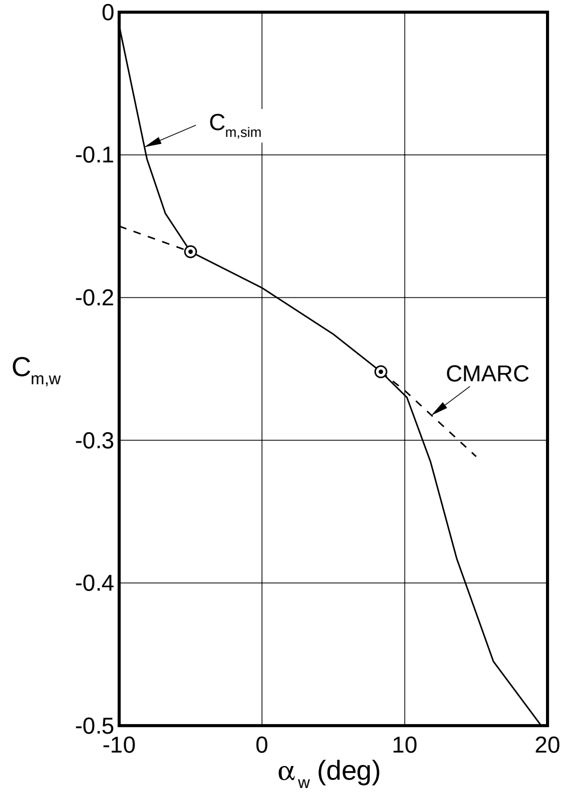

Fig. 17 Pitching moment coefficient versus angle of attack for the main biplane wing of the 1905 Flyer.

The lift characteristics used in the simulation are the same as that shown in Fig. 11. Differences due to the larger canard would affect these results, but this relatively small effect is neglected in the current model. The pitching moment shown in Fig. 17 differs principally from the center of gravity shift from 29.7% of chord as it is for the 1903 Flyer to 12.8% of chord for the 1905 Flyer.[1] The larger canard leads to considerably more control power as shown in Figs. 18 and 19. Although the ±30 deg canard deflection data is shown, it is not used in the simulation in which the canard deflection is limited to ±15 deg per the 1905 blueprints. Figure 20 shows all of the data together over an angle of attack range of ±90 deg.

Other data contributing to the simulation included lateral-directional stability and control data that was estimated from the NASA Ames test data.[15] Rudder power effects and yaw data for the 1905 Flyer were scaled up from the 1903 Flyer measurements and reduced to constant stability derivatives. Rotary derivatives (yaw and roll) have yet to be completely modeled, again due to emphasis being placed on longitudinal flying qualities. However, apparent mass effects in roll, pitch and plunge were calculated, and the results are mostly consistent with those reported in Ref. 18.

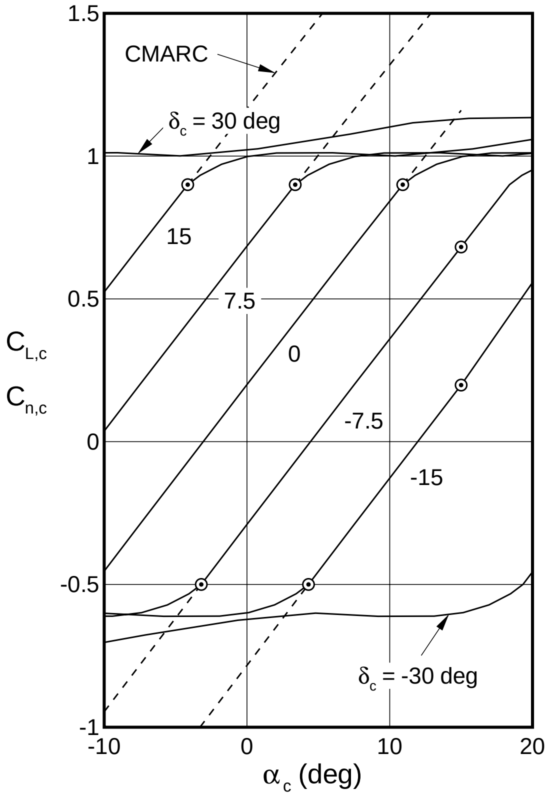

Fig. 18 Lift coefficient versus angle of attack for the 1905 canard at canard deflection angles ranging from −30 to 30 deg.

For reference, the wing warping deflection limits were ±8.5 deg and for the 1903 Flyer the rudder deflection was coupled to the wing warping using the relation $\delta_r = 2.5 * \delta_w$. For the 1905 Flyer, no coupling was used, and in the simulation a rudder deflection of ±15 deg was found to be sufficient for coordinated flight.

Mass and moment of inertia data for the 1903 Flyer were taken from Ref. 18. For the 1905 Flyer, moment of inertia data was estimated by subtracting off the canard and rudder structure moment of inertia values from the 1903 Flyer and then adding back the canard and rudder structure moment of inertia values for the 1905 Flyer. This approach gave estimates that were close to those estimated from a weight build-up approach. For the 1905 Flyer, the values used in the simulation are as follows: $I_{xx} = 1331$, $I_{yy} = 563$, $I_{zz} = 1645$ slug-ft^2.

Finally, it should be mentioned that in a paper of this size there is insufficient space to include all of the simulation data. However, all of the data and related source code is available freely over the Internet at the website www.flightgear.org. Updates to the data are likely to occur as the simulation models evolve and become more refined when new information is found.

Results

The complete aerodynamic models for the 1903 and 1905 Wright Flyers were implemented in FlightGear

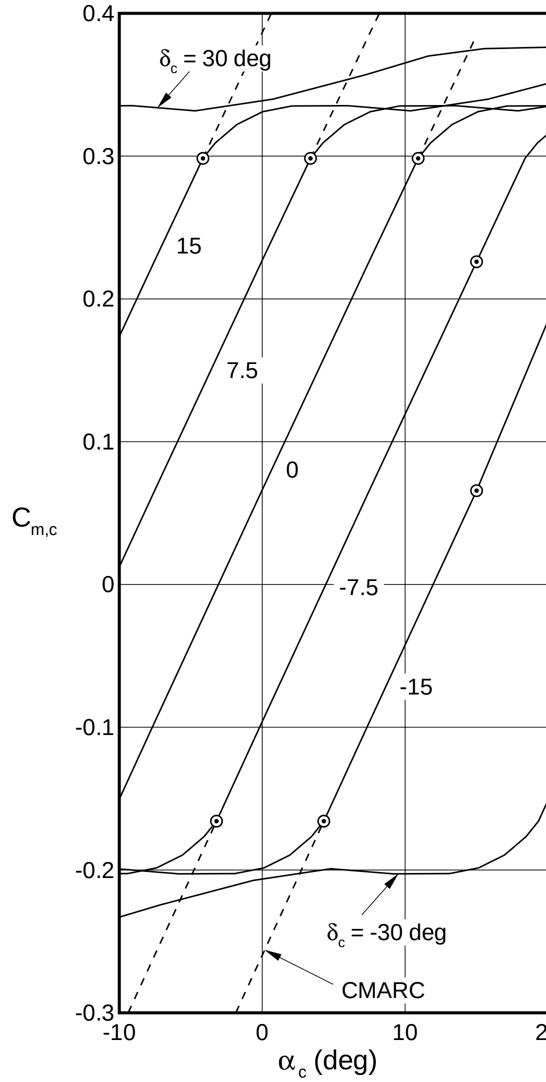

Fig. 19 Pitching moment coefficient versus angle of attack for the 1905 canard at canard deflection angles ranging from −30 to 30 deg.

as was mentioned earlier. These models were flown to demonstrate the handling qualities of the two aircraft. The results of these flights are shown in Figs. 21– 25. Each of the figures are a plot of the time histories of the canard deflection, angle of attack, airspeed, pitch rate, pitch angle, and altitude. The altitude shown in the plots is that of the center of gravity of the aircraft, so when the aircraft is on the ground, the altitude is not zero.

Figure 21 shows the 1903 Flyer in a stall shortly after takeoff. The aircraft climbs to approximately 20 ft while reaching the angle of attack reaches almost 45 deg before nosing down and impacting the ground. This flight and the flights shown in Figs. 22 and 23 demonstrate the aircraft is very sensitive to canard deflections and that the pilot has to continuously take action to keep the plane under control. The flight shown in Fig. 22 is of several short hops performed by the 1903 Flyer. The instability of this

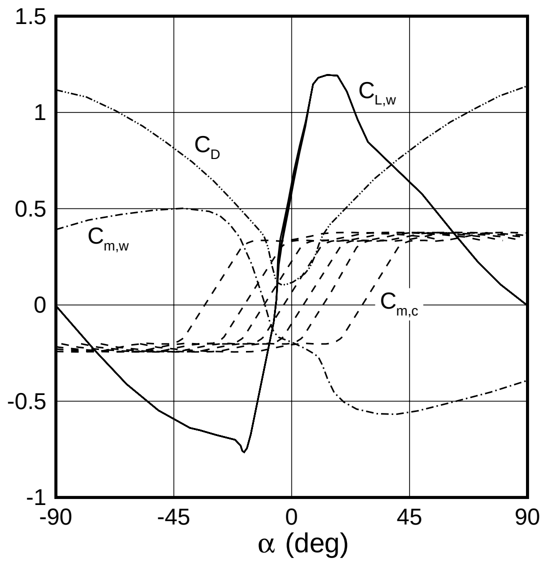

Fig. 20 Aerodynamic coefficients for the 1905 Flyer from −90 to 90 deg angle of attack.

aircraft leads to difficulty in keeping the aircraft in the air. It should be noted that the sudden jumps in data shown in Fig. 22 near 12 and 14 sec are due to the aircraft hitting the ground and the ground reaction model taking affect. Figure 23 shows a takeoff with the 1903 Flyer, and demonstrates the constant control action required to keep the aircraft in the air. Even when the aircraft is in the air as shown in Fig. 24, the pilot must still take continuous action. In the air the 1903 Flyer is difficult to keep steady, and oscillations in pitch and altitude are common. Figure 25 shows a takeoff and climbout for the 1905 Flyer. Even though the aircraft has more pitch damping and is easier to control, it still requires continuous corrections. During takeoff the pilot must continuously adjust the canard, but once in the air, the amount of correction required is greatly reduced compared to the 1903 Flyer. These time histories demonstrate the differences in the handling qualities of the two aircraft. While both require constant canard deflections to stay airborne (which illustrate the piloting skills of the Wright brothers), the amount and magnitude of the adjustments needed are significantly different.

Summary

In order to expand the understanding of the handling qualities of the 1903 and 1905 Wright Flyers, nonlinear aerodynamic models were created for each aircraft and simulated with a flight simulator. Aerodynamic data was generated by using wind tunnel tests of the 1903 Flyer and from inviscid flow analysis using a panel method. The wing and canard for both aircraft were modeled separately to allow both elements to stall independently of each other. The aerodynamic data was extended from −90 to 90 deg angle of attack in order to model the nonlinear behavior of the aircraft at high angles of attack. The resulting aerodynamic models were then implemented in the PC-based FlightGear Flight Simulator. Time histories of flights flown in the simulator demonstrate some of the differences in handling qualities between the two aircraft. Both aircraft require constant pilot attention, but the 1905 Flyer requires much less than the earlier 1903 design.

Acknowledgments

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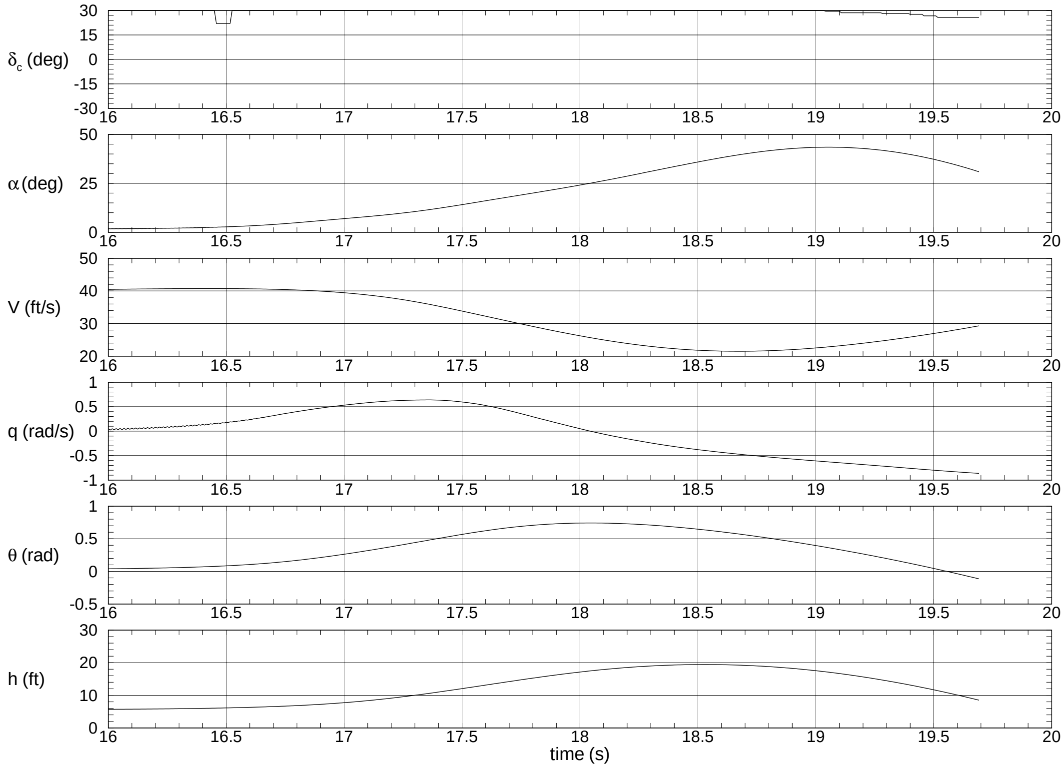

Fig. 21 Time history of the 1903 Flyer in a stall.

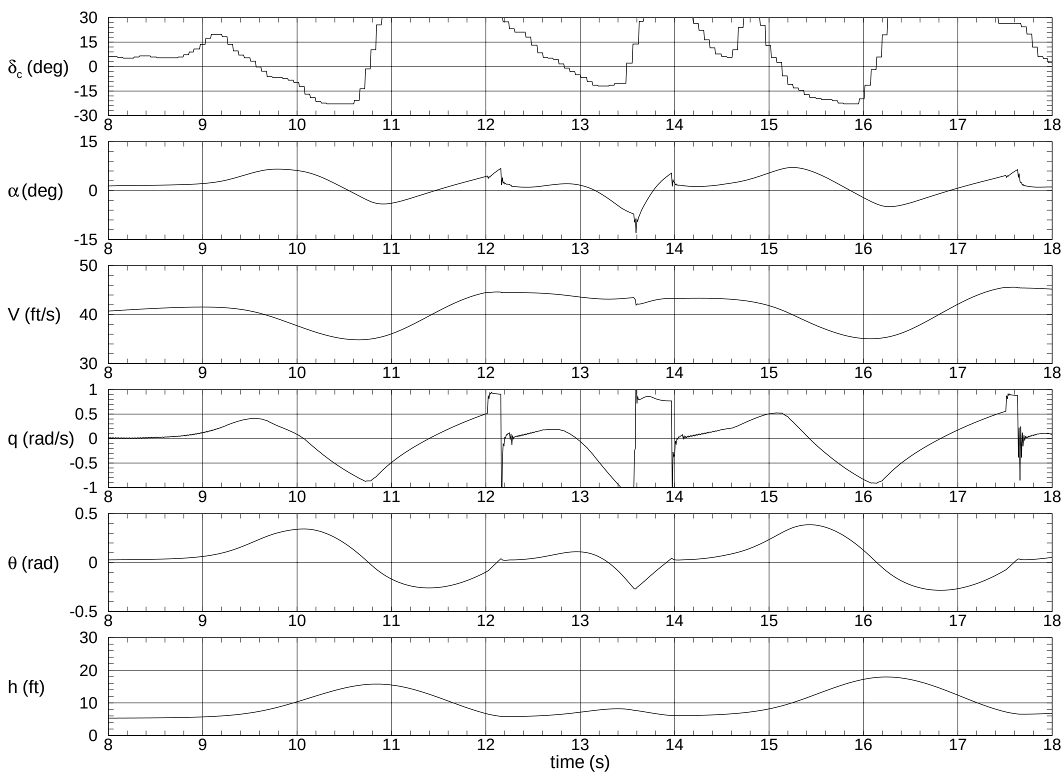

Fig. 22 Time history of the 1903 Flyer performing some takeoff hops.

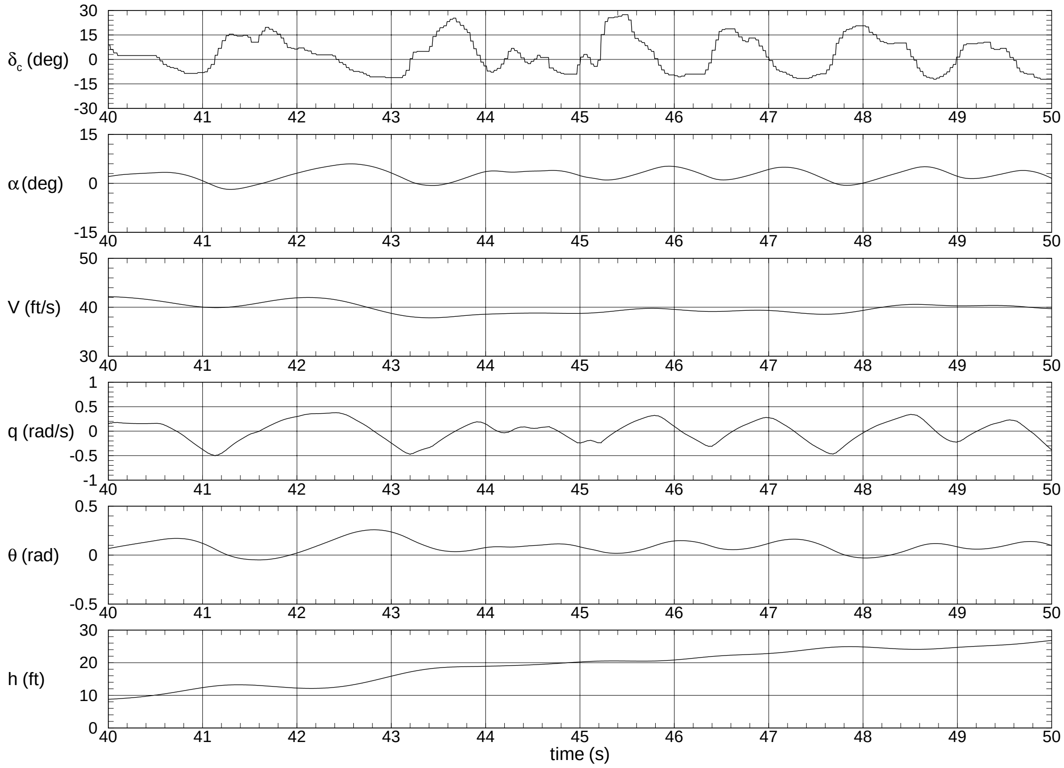

Fig. 23 Time history of the 1903 Flyer in a takeoff.

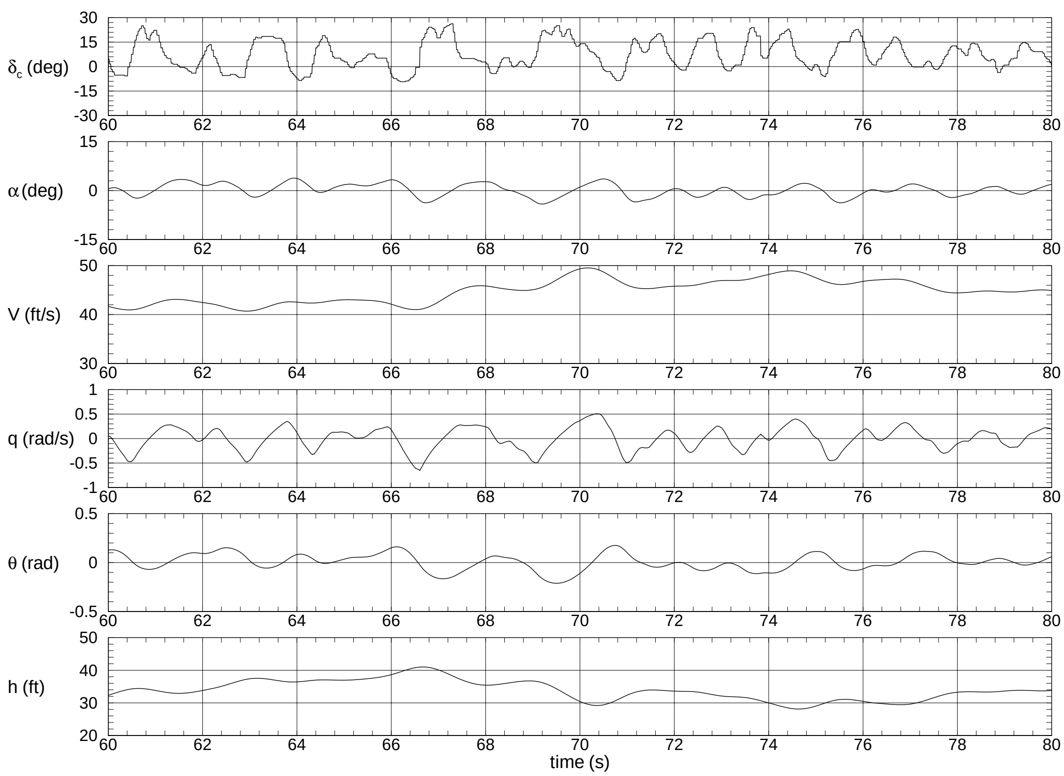

Fig. 24 Time history of the 1903 Flyer in the air.

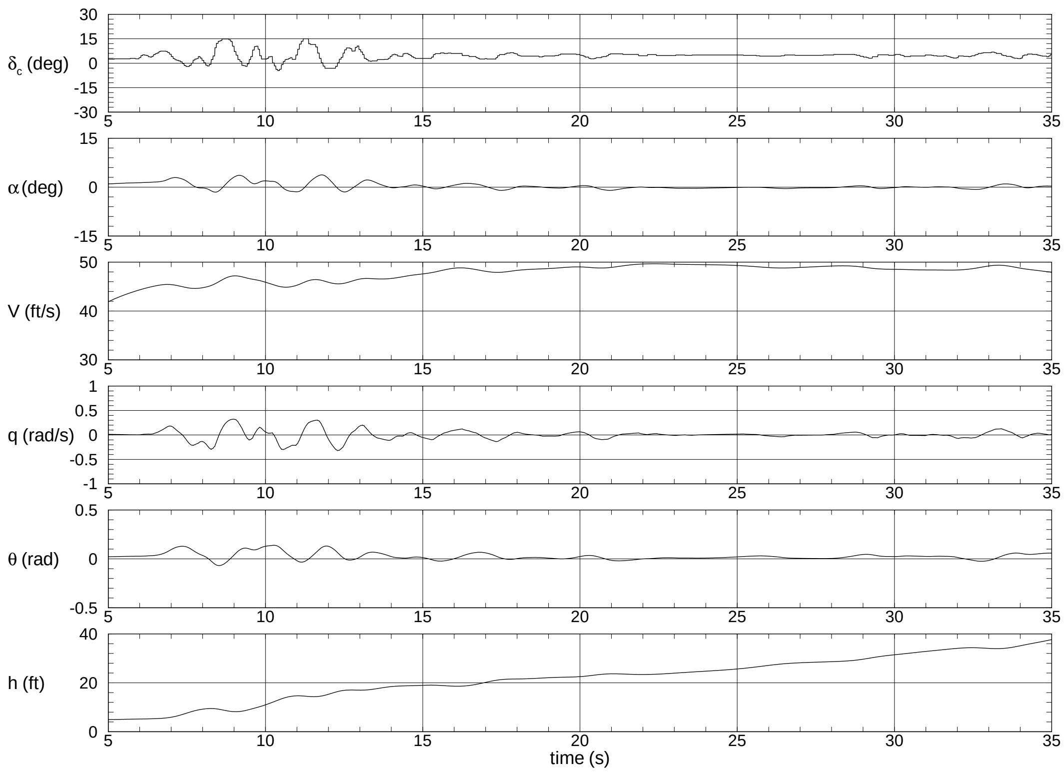

Fig. 25 Time history of the 1905 Flyer in a takeoff and in the air.