AIAA-2000-0511
The AIAA 1903 Wright 'Flyer' Project Prior to Full-Scale Tests at NASA Ames Research Center

Jack Cherne, TRW, Inc., Redondo Beach, CA
Fred E.C. Culick, California Institute of Technology, Pasadena, CA
Pete Zell, NASA Ames Research Center, Moffett Field, CA

AIAA 38th Aerospace Sciences Meeting

January 10-13, 2000/Reno, NV

The AIAA 1903 Wright 'Flyer' Project Prior to Full-Scale Tests at NASA Ames Research Center

Jack Cherne [†], Fred E.C. Culick [§] and Pete Zell [‡]

ABSTRACT

Members of the Los Angeles Section of the AIAA founded the Wright 'Flyer' Project twenty years ago. The Project adopted two main objectives:

1) To construct a full-scale replica of the 1903 Wright 'Flyer' aerodynamically precise and suitable as a model for full-scale tests in the wind tunnel at NASA Ames Research Center; and 2) to construct a replica, minimally modified from the original, to be flown repeatedly and safely in public, giving faithful replications of the first flights on December 17, 1903. This paper summarizes the activities of the Project to date, and the preparations for the wind tunnel tests. Results of the tests are reported in the following paper, AIAA No. 2000-0512.

1. INTRODUCTION

In 1953, to celebrate the 50th anniversary of powered flight, the aircraft industry of Southern California commissioned a full-scale replica of the 1903 'Flyer', shown in Figure 1 with an F-89. The aircraft was presented to the Institute of Aeronautical Sciences. A fitting centerpiece for meetings, it hung from the ceiling of the auditorium in the Los Angeles IAS headquarters.

Figure 1

When the IAS merged with the American Rocket Society to form the AIAA, the building was declared surplus and the replica was loaned to the San Diego Aerospace Museum.

The Los Angeles section of the AIAA began its Wright 'Flyer' Project in late 1978. Earlier that year, the replica of the 'Flyer' had been lost in the terrible fire that destroyed the San Diego Aerospace Museum. Our financial base was the insurance claim - $20,000.00. Howard Marx, now retired from the Northrop Corporation, as Chairman of the Committee on Special Events, was responsible for the fund. He proposed that a flying replica be constructed.

At that time, Fred Culick was designing and constructing a 1/6-scale model for testing in the GALCIT 10-foot wind tunnel. He became the second member of the Project (the first second member had left the L.A. area soon after Marx had publicized his proposal). Jack Cherne joined shortly and the real effort began with a well-attended organization meeting in late 1978.

[†] Chairman and Chief Designer, Wright 'Flyer' Project; Associate Fellow, AIAA

[§] Project Engineer and First Pilot, Wright 'Flyer' Project; Richard L. and Dorothy M. Hayman, Professor of Mechanical Engineering, California Institute of Technology; Fellow, AIAA

[‡] Aerospace Engineer: Test Manager, Wright 'Flyer' Test, NFAC, NASA Ames Research Center

In addition to Marx, Culick and Cherne, the initial team guiding the Project included Bill Sparks, Carl Friend, Bud Chamberlain, Fred Erb, Gary Moir, Chuck McPhail, Bud Gurney and John Graves. In 1980, Marx became Chairman of the Los Angeles Section and Cherne became Chairman of the Wright 'Flyer' Project—a position he has held continuously since that time. Over the two decades, more than seventy people have contributed to the construction and testing of our 'Flyer'.

The primary goal of the Project was to replicate the flights accomplished by the Wrights on December 17, 1903. We want an aircraft minimally changed to allow repeatable flights by several people. Our intention has been to give an accurate impression of the first controlled powered flights of a piloted aircraft. Because the original airplane was seriously unstable and dangerously difficult to fly, we have from the beginning planned to make small changes to the design. We are convinced that we will accomplish our goal. As a result of the sub-scale tests and our test program in the 40 x 80 low speed tunnel at NASA Ames Research Center, we understand fully all characteristics of the airplane.

A summary of the first nine years of the Project, and a brief history of early aeronautics relevant to the Wrights' work, has appeared in the paper "Building a 1903 Wright 'Flyer', by Committee" (Culick, 1988). We will therefore concentrate here on those activities directly leading to the full-scale tests discussed in the following paper.

2. THE WRIGHTS' INVENTION OF THE AIRPLANE: THEIR TEST PROGRAM 1899-1905

From 1899 to 1905, the Wright Brothers formulated and executed the first modern program of Research and Development. Repeated reasoning, analysis, design, testing and processing test results formed the framework in which they worked. In addition to several original ideas, it was the style of their working that explains their success while their contemporaries struggled in the familiar manner of 19th century invention. Culick (1988) has discussed that interpretation of the Wrights' program.

With their background of building and using bicycles, a leading-edge technology in the 1890's, the Wrights were thoroughly accustomed to controlling an unstable vehicle. It is therefore not entirely surprising that after observing how birds maintain their lateral equilibrium, by twisting their wings, Wilbur conceived the idea of differential warping a box-like structure. Applied to a biplane configuration, this method gave both a means of maintaining equilibrium and exerting control in roll, necessary to achieving bank-to-turn maneuvers. The use of dihedral for stability in roll had been known for 100 years since Cayley's work but control in roll was stunningly original. It was that idea that became the basis for the Wrights' basic patent, issued in 1906, and never overturned.

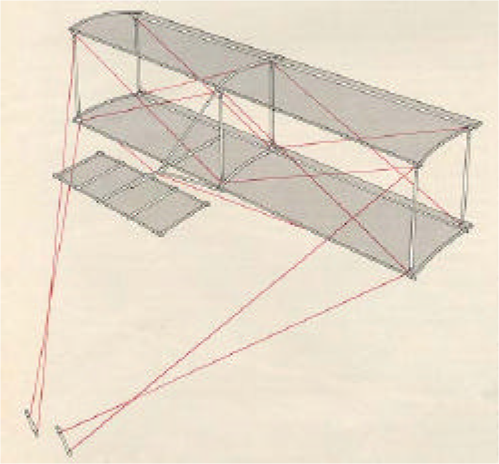


Figure 2

The Wright Brothers soon built a 5-foot kite, which Wilbur flew in August 1899. Figure 2 shows the kite, cleverly designed to allow testing not only the idea of roll control by warping the biplane box, but also pitch control by changing the angle of attack of the elevator and the effectiveness of having a forward or aft elevator. Such a kite was entirely novel.

Kites had been known for more than a thousand years (Hart 1967); a fixed wing powered model had been first successfully flown by Pénaud in 1872, (Pénaud 1872) and used very successfully by Langley (1891) as part of his attempt to develop a full-scale piloted airplane. What was special about Wilbur's kite was that it was designed and flown for a very specific purpose, namely to answer the questions the Brothers posed themselves concerning the feasibility of roll and pitch control.

The intention, the planning and the execution of their brief 1899 test program already distinguished the Wright Brothers from all of their predecessors in aeronautics — indeed, from the entire field of invention generally. The Wrights' creation of the airplane was truly the first great invention of the 20th Century, accomplished in the familiar manner of the 20th Century. They carefully documented their work in both words and pictures so we understand well both what and how they achieved their success.

Much has been written about the subsequent five years leading to construction and test flights of the Wrights, and the world's first practical heavier-than-air flying machine in 1905. Most of those writings are based entirely on the superb collection of letters, diaries and papers assembled by McFarland (1953). In his previous progress report, Culick (1988) gave a broad summary of that history. We are concerned here primarily with the Wrights' testing activities from 1900 to 1903. In each of those years, they spent extended periods at Kitty Hawk: five weeks in 1900; seven weeks in 1901; nine weeks in 1902; and ten weeks in 1903. Thus the Wrights' test program lasted a total of 31 weeks at Kitty Hawk, spread over four years.

The tests in 1900 were a direct extension of Wilbur's kite flying in 1899. The chief purpose was to test the controls in a device intended to be flown both as a kite and as a glider carrying a pilot (except for Orville’s few seconds aboard the 1900 kite, Wilbur did all the flying until 1902 when both brothers learned to fly.) Shown in Figure 3, the kite/glider had a span of 17 feet, wing area 165 square feet and elevator (canard) area 12 square feet; with pilot, the weight was about 190 pounds, giving a wing loading of 1.15 pounds per square foot. Although the glider was flown largely as a kite, Wilbur and Orville both flew as pilots for brief flights at altitudes of 2-3 feet.

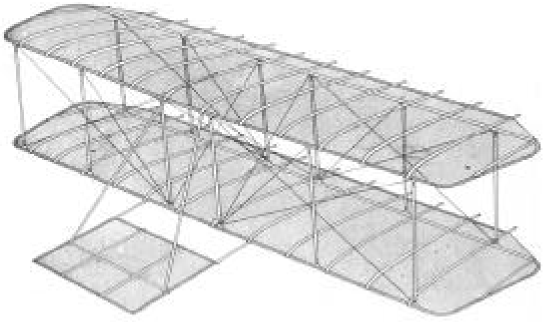


Figure 3

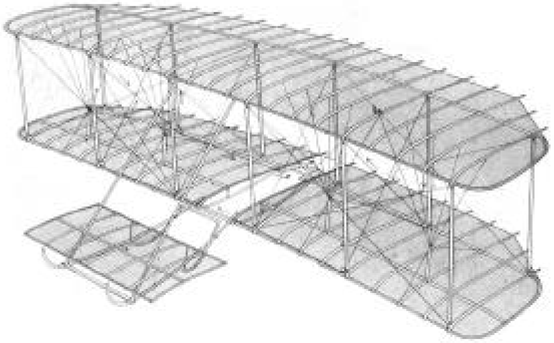


Figure 4

That short test program in 1900 established that the pitch and roll controls were effective; and that the pilot could operate the machine successfully in a prone position. A major negative conclusion was that the glider did not develop the amount of lift that the brothers had anticipated, based on Lilianthal's tables of lift and drag for essentially the same airfoil they were using. It's interesting, and important, that (like others trying to build aircraft at that time) the Wrights were unable to solve theoretically, the gliding problem because they (like their contemporaries) never wrote down the equation for pitching moments. In simplest form, the gliding problem presents three unknown quantities: the speed, glide path angle, and angle of attack. Thus three equations are required, but the Wrights used only the conditions for equilibration of forces in the directions perpendicular to and parallel to the flight path. They had to guess the value of one variable, the usual choice being the glide speed.

Because the lift on the 1900 glider was unexpectedly low, The Wrights returned to Kitty Hawk in 1901 with a larger glider having the span of 22 feet, wing area of 290 square feet and weighing 250 pounds with pilot, for a wing loading of 0.78 pounds per square foot. (Figure 4) The flying season 10 July – August 1901 was a watershed in the Wrights' program. They learned about the influence of camber on the pitching moment (they could not identify the effect they observed in those terms); they learned about stalling of a surface, and the consequent reversed moment of the center of pressure; they determined again that their wings did not produce the lift they expected; and as test pilot, Wilbur discovered the phenomenon of adverse yaw, a truly remarkable result.

Those results of their test program in 1901 effectively began the final steps leading to the configuration of their aircraft. In order to understand the reasons for the apparently poor performance of their wings, the Wrights carried out their famous wind tunnel tests, devoted almost entirely to measurements of lift and drag on airfoil sections. They solved the problem of adverse yaw by mounting a vertical aft tail, their first. In the beginning of their 1902 test flights, they fixed the tail, but soon learned that it had to be moveable to create suitable yawing moments. It now seems strange that the Wrights were not particularly concerned about directional stability, which of course their gliders lacked without the vertical tail. Moreover, they did not like the response that dihedral gave when the gliders were struck by lateral disturbances ("side gusts"). That view led them eventually to install negative dihedral (anhedral) in their 1903 airplane, producing negative roll stability and an innovation they eventually abandoned.

The 1902 glider is shown in Figure 5. It had a wing area of 305 square feet, only slightly larger than the 1901 glider, but the span was 32 feet. From their wind tunnel tests, the Wrights had learned that the more slender wing, i.e., one having higher aspect ratio, had superior lift/drag ratio. The wing loading of the piloted glider was 0.8 pounds per square foot. With the vertical tail, the 1902 airplane was controllable about three axes and became a very successful machine. In their nine-week test period at Kitty Hawk, both brothers learned to fly, executing about 1000 glides.

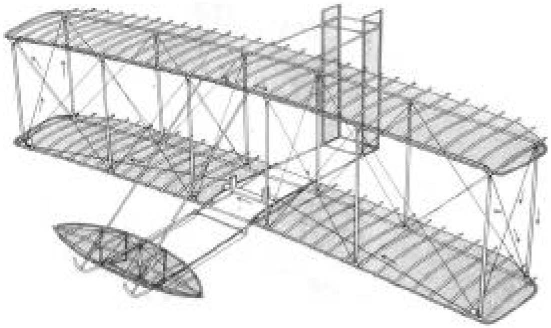


Figure 5

Although the Wrights did not invent the wind tunnel, it had been known for thirty years since the work of Wenham and Browning in England. They were first to obtain extensive data directly useful for designing wings. However, following Lilienthal, they tested only thin airfoils, most of them highly cambered. Lilienthal had chosen sections modeled after birds' wings and after extensive tests with a whirling arm apparatus, had published his results in his classic book, *Bird Flight as the Basis of Aviation*. (Lilienthal, 1896).

McFarland (1953, Appendix II, pp. 547-593) discussed thoroughly the Wrights' wind tunnel tests and their results. Most of the experiments, carried out in a period of two weeks, 22 November – 7 December 1901, produced all the data the brothers believed they needed. They used their measurements as the basis for their selection of strut cross-sections; wing planform; and the airfoil shape used as an aid to their propeller design in 1903. Although they constructed a second wind tunnel in 1902, it seems that they made little use of it. The results obtained in their 1901 tests comprise essentially all of the aerodynamic data that the Wright Brothers acquired in their entire program. Their last biplane aircraft, the Model C (1912) fitted with an aft horizontal tail, had essentially the same airfoil section and wing planform as the 1903 'Flyer', but with a slightly smaller span.

A significant consequence of that gap in their understanding of aerodynamics, shared by their contemporaries, was that the Wrights could not appreciate the difficulties they caused themselves by using highly cambered airfoils. For the 1901 glider, the airfoil initially had a roughly parabolic shape having 8% camber with the pilot on board. After realizing that some extreme flying characteristics were likely due to the large camber, they reduced the camber by installing wing posts and wires, to about 5%. The airfoil in the 1902 glider had about 3 1/2 % camber. Their 1901 wind tunnel tests showed that the 'most efficient' airfoil, i.e., that having the highest lift/drag ratio of those they tested, had an approximately parabolic camber line with 5% camber. Thus in 1903, they adopted that profile which they seem to have used in all their subsequent aircraft. They had no way of knowing that the larger zero-lift pitching moment associated with higher camber caused serious problems of pitch stability in their full-scale aircraft.

After 17 December 1903, the Wrights returned to Dayton and began their two-year program to perfect their powered aircraft. Their testing was now all flight testing directed to improve the configuration. They used virtually the same biplane cell as for the 1903 airplane. Figures 6 and 7 show three views of the 1903 and 1905 aircraft, taken from McFarland (1953). The major changes are those one would make to improve pitch stability: The canard is larger (83 square feet in contrast to 48 square feet in 1903) and moved forward, and—less apparent—is the weight distribution giving a more forward center of gravity. Estimates by Hooven (1978) and by members of the AIAA Wright 'Flyer' Project show that the static margin was improved from about –30% in 1903 to –15% in 1905. Ironically, it is likely that the 1902 glider was substantially less unstable than either of those powered aircraft, and noticeably easier to fly.

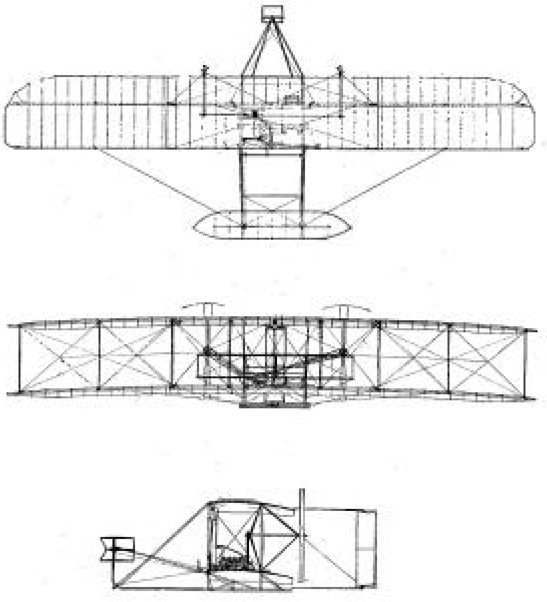


Figure 6

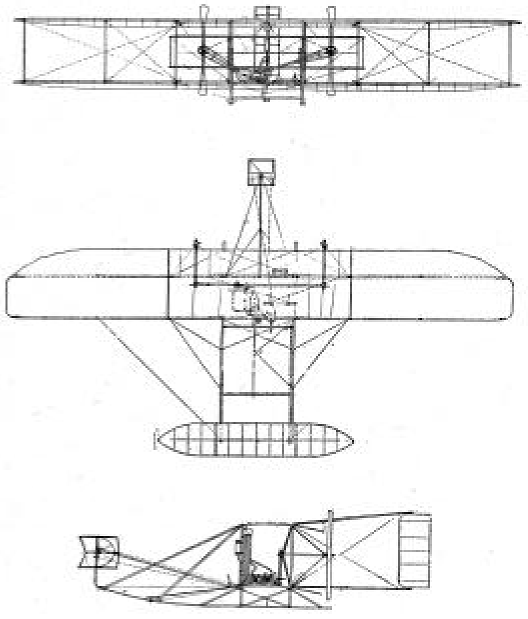


Figure 7

3. SUB-SCALE TESTS IN THE AIAA WRIGHT 'FLYER' PROJECT

Prior to the activities described here, no tests had been done with the Wright 'Flyer' configuration. In 1978, Culick received a small contract, No. NAS1-15668, from NASA's Office of Aeronautics to design, construct and test in the Caltech GALCIT 10-foot wind tunnel, a 1/6-scale model of the 1903 'Flyer'. Dr. John Klineberg, Associate Administrator for Aeronautics, appointed Dr. John Houbolt, Assistant Director of the Langley Research Laboratory, as Contract Monitor. The model was tested during the period19 December 1979 to 4 January 1980; the results were published as GALCIT Report No. 1034 (Bettes and Culick, 1982). Photographs of the uncovered and covered model mounted in the tunnel are reproduced in Figure 8.

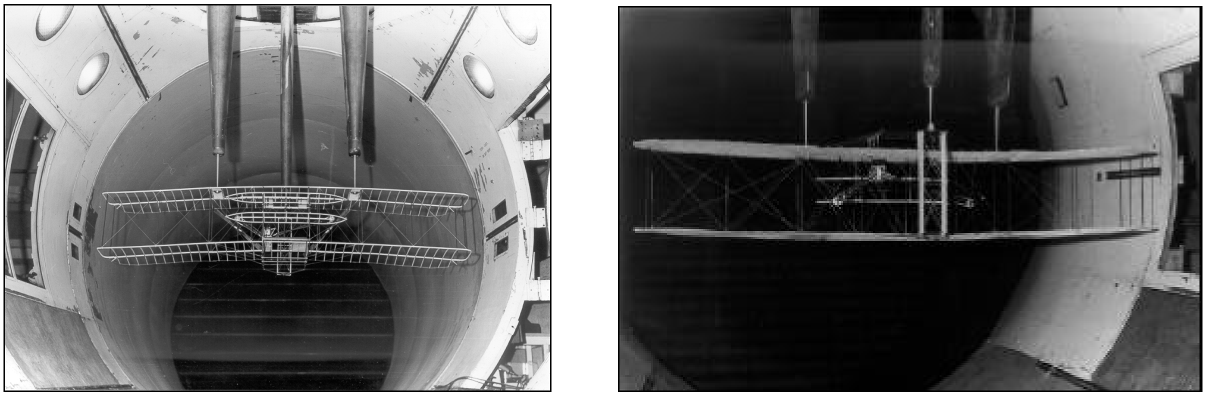


Figure 8

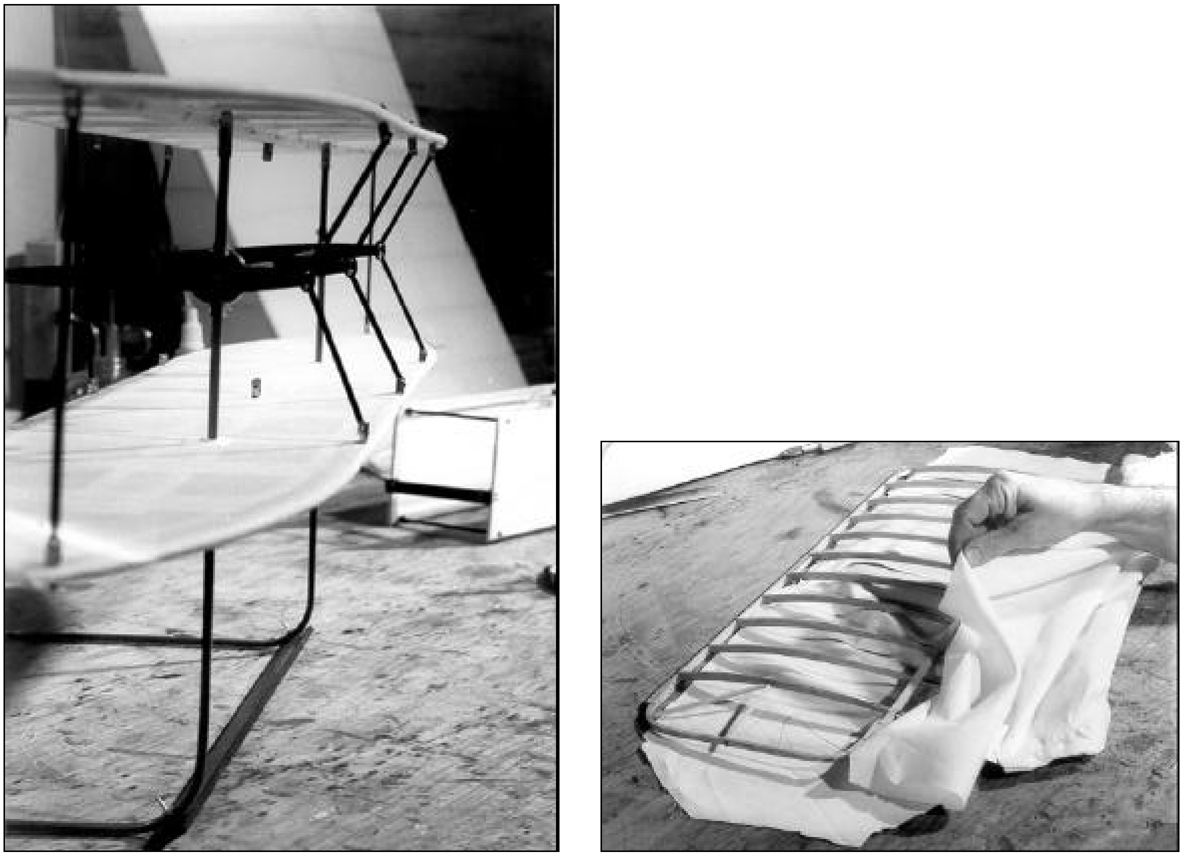


Figure 9

The plans available from the Smithsonian National Air and Space Museum were used for the model, requiring re-drawing from 1/8- to 1/6-scale. Although the structure was greatly simplified, the materials were similar to provide both faithful replication of the geometry and to allow warping of the wings. Figure 9 shows the canard structure and a portion of a partially covered wing. A scale propulsion system was assembled, including specially carved wooden propellers, and 1/6-scale chain, driven by a 1/25 HP electric motor. The test period was too short to permit powered tests, although several exploratory runs were made.

Except for one run carried out at 80 MPH, all tests were run at about 60 MPH. The sub-scale Reynolds number was 0.43×10^6 for most tests, compared with 1.9×10^6 for the flights on 17 December 1903 (assuming V = 31 MPH). Thus the tests of the 1/6-scale model were conducted at roughly .23 full-scale Reynolds number based on the wing chord. For these relatively low Reynolds numbers, and the broad range of structural shapes and sizes, there is a strong possibility that the aerodynamical properties of the airplane cannot be well characterized by a single Reynolds number. Hence for a thorough understanding of the original 'Flyer' it is essential to have data taken at the full-scale Reynolds number.

For nearly three years at the beginning of the Wright 'Flyer' Project, we intended to build only the single full-scale replica to fly. Therefore, to obtain data at full-scale Reynolds numbers it was necessary to test a sub-scale model at very high speeds. For that purpose, a 1/8-scale steel model was constructed and tested under the direction of Dabney Howe at the Northrop Corporation. That project was used as part of a training program for technicians and engineers at Northrop. Two views of the model mounted in the Northrop 7x10 foot tunnel are shown in Figure 10. The results of the tests were published in October 1982 in a report having limited distribution.

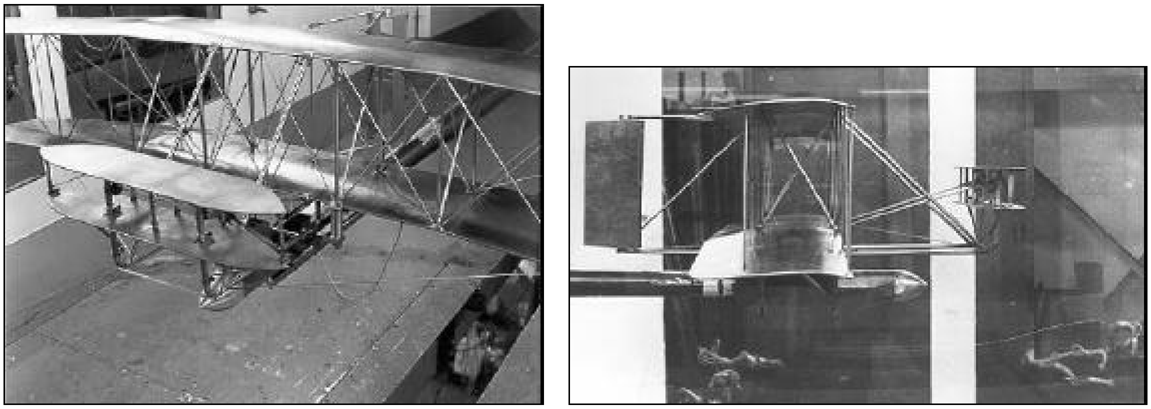


Figure 10

The most significant differences between the two models were that the steel model was unpowered and of course the wings could not be warped. Thus the only data available for the effectiveness of wing warping were those from the 1/6-scale 'Flyer' tests. A great advantage of the 1/8-scale tests was that changes of configuration were investigated as part of the effort to determine possible consequences of design changes for the flying replica.

During the early part of the project, while construction of the full-scale replica was being planned and just beginning, the Aerodynamics Committee, also concerned with stability and control, was especially active. Mel Schorr was the first chairman of that committee; after his death, Henry Jex became chairman in 1982 and continues to the present. The members of that committee have been responsible for planning details of the wind tunnel tests of the 1/6-scale, 1/8-scale and full-scale models; supervising the data requisition and processing; and interpreting the results. All of that work forms the basis for design changes to be incorporated in the full-scale flying replica to be constructed in the next three years.

Results obtained in the sub-scale tests were discussed in two papers. Culick and Jex (1983) and Jex and Culick (1983) used the aerodynamic from the two test programs to investigate the stability and dynamics[1] of the full-scale Wright 'Flyer'. Some of those results are reviewed in the following paper, in the context of the test results for the full-scale airplane. The main conclusions reached in the earlier works with the sub-scale models are:

1) as expected, the airplane is seriously unstable in pitch, with a large negative static margin;
2) the anhedral (see Figure 6) causes the 'Flyer' to be unstable in roll;
3) owing to the small vertical tail having a relatively small moment arm, the airplane is weakly directionally stable.

Because the aerodynamical data are not in precise agreement, the static margins implied by the test results for the two models are different: approximately –27% for the covered 1/6-scale model and –20% for the rigid 1/8-scale model.

On the other hand, because the response of the aircraft is slow, it is flyable, as the Wright Brothers demonstrated, although with great difficulty.

---

[1] The two papers contain simulations of longitudinal and lateral motions carried out by Ray Magdaleno of Systems Technology, Inc. While not included in the roster of the Wright 'Flyer' Project, Ray's contributions have been crucial to our work.

Not only the test results, but also independent estimates (Hooven, 1978, and others worked out by members of the Wright 'Flyer' Project) showed beyond any doubt or argument, that to achieve our objectives listed above, we must modify the airplane. While the sub-scale data were being processed, we were offered the opportunity to test a full-scale replica of the 'Flyer' in a wind tunnel at NASA Ames Research Center. We therefore changed the purpose of the Project now to build two full-scale replicas, one for wind tunnel tests and one to fly.

In fact, we believed that with our extensive results from the tests of the 1/6- and 1/8-scale tests, we had sufficient information to make rational changes of the design to improve the flying and handling qualities of the airplane. Wind tunnel tests of a full-scale replica would, however, fill in some gaps in our information, notably the effects of power and wing warping. The results obtained for wing-warping in the 1/6-scale tests had been limited and not entirely reliable, owing to internal structural damage. Moreover, there is considerable justification for such tests in the historical context of the development of technology in the United States. We therefore did not hesitate to commit our Project to constructing two aircraft.

4. EARLY IDEAS CONCERNING DESIGN MODIFICATIONS

Already in the early 1980's we knew that to soften the extreme pitch instability, we had to modify the airfoil. Even with the original highly-cambered airfoil having an unusually large negative pitching moment at zero lift, it is certainly possible to have an aircraft stable in pitch. To do so, however, requires noticeable changes in the geometry of the canard. How noticeable becomes apparent upon comparison of the 1903 and 1905 aircraft, Figures 3 and 4. For two reasons we elected early in our deliberations not to pursue this approach: The geometrical distortion of the original design is unacceptably large; and even with those changes, the airplane is still quite unstable with a static margin of about –15% (Hooven, 1979).

Therefore, the Aerodynamics Committee made the recommendation that the airfoil should be changed. Their first choice was an airfoil essentially identical to one designed in the late 1920's by Max Munk, the M3, having a reflexed trailing edge and zero pitching moment at zero lift. The AIAA version was called the " Schorr Airfoil" after Mel Schorr (deceased) who chaired the Aerodynamics Committee. A few years later, the profile was re-examined by Dr. Robert Liebeck of the then Douglas Aircraft Company. Liebeck's analysis showed that the shape of the leading edge should be changed to give gentler stall characteristics. The airfoil, now known as the Schorr-Liebeck airfoil shown in Figure 11, with the Wright and the Schorr (M3) profiles.

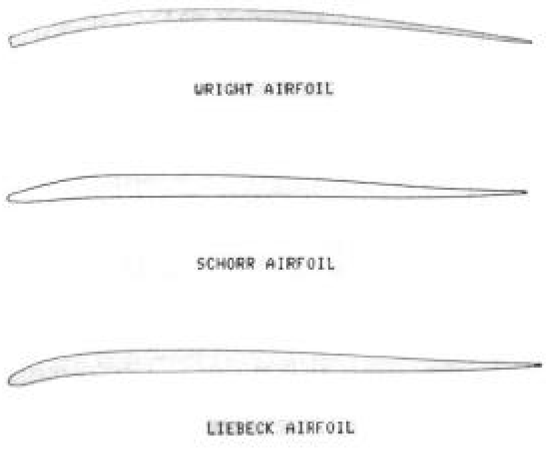


Figure 11

In February 1992, Cherne and Culick witnessed several demonstration flights of a flying replica of the 1903 'Flyer'. The constructor and pilot was Giancarlo Zanardo and the location was Treviso, Italy, an hour's drive north of Venice. Culick had learned of Zanardo's work from an article in *World War I Aero*. A self-educated constructor of historic aircraft, Zanardo has also built and flown a Fokker Triplane, a Gypsy 'Moth' and a 1909 Bleriot, which he flew across the English Channel on the 80th anniversary of Bleriot's crossing.

Even close up, Zanardo's 1903 'Flyer' certainly resembles the original quite well in fact, if one is unacquainted with details. The major revisions are the airfoil, which looks like a slightly thinned Clark Y; an enlarged canard; and zero dihedral. The aircraft is shown in Figure 12. Although the wing surfaces are quite thick and the fabric is doped, Zanardo warps the wings for warp control. He arrived at this modified design by trial-and-error during a year of testing. Despite the changes in the configuration, flight of the airplane is indeed impressive. Zanardo has flown circles at altitudes up to many tens of feet but he now limits himself to straight flights at low levels, out of concern for the poor flying qualities.

Figure 12

5. CONSTRUCTION OF THE FULL-SCALE REPLICA; STATIC LOAD TESTS

The decision to build two replicas of the 'Flyer' didn't effect matters of construction because we would build them in series, the wind tunnel model first. There was no urgency to decide on the revisions to be incorporated in the flying version, and because the wind tunnel tests had not been scheduled, there was no external pressure to hasten construction of the wind tunnel mode. That was a fortunate circumstance, for three reasons: 1) almost no one in the Project had experience building a wood, wire and fabric aircraft. 2) we had no place to build and assemble the structure; 3) with entirely volunteer labor, almost all of whom were busy with other activities, construction proceeded very deliberately.

Fortunately, we did have two members who knew well what to do about construction – Fred Erb of the Northrop Corporation and Bud Guerney (now deceased), long ago Charles Lindbergh's flying buddy and retired in 1968 as a Captain of DC-8's for United Airlines. Bud had experience with fabric covered aircraft since the early 20's, including restoration of several of his own. He donated a large part of the wood used in our 'Flyer' and construction began in his garage. For the early stages of construction, we created a small cottage industry. The Northrop Corporation provided an area in a factory in Torrance, CA., where we could assemble the aircraft. At times, the repetitive construction requirements became tedious—someone in the Project counted more than 8400 parts of the airplane.

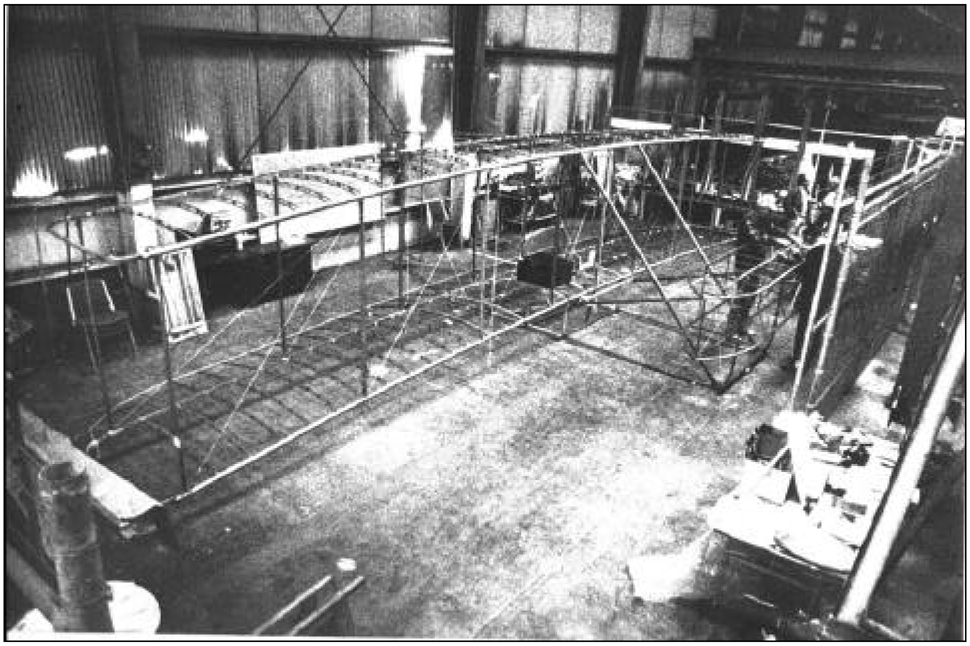


Figure 13

Our construction program proceeded quite well and the uncovered aircraft was fully assembled in 1983 (Figure 13). It remained in that state for several years. We moved the aircraft on two occasions for public display.

Special components caused special problems. After two years of searching unsuccessfully for muslin covering material, we were able to share in an order procured by the National Air and Space Museum for re-covering their original 'Flyer'. We were even more fortunate with the chain drive. The Diamond Chain Company who had made the chain for the Wrights still had the tooling to make the now non-standard chain and manufactured ours.

A problem arose, however, because the new 'old' chain was too stiff to cross. Crossed chain, in tubular guides, is required to produce counter-rotation of the propellers. To remove the stiffness we chose to run-in the chain with an applied side load. In fact, the procedure is better described as 'wear-in' because it was necessary to keep the chain dirty and without lubrication to loosen the joints. We ran the chain in this manner for about one year before it functioned properly (good construction and good material). Figure 14 is a photograph of the process.

Figure 14

The Wright Brothers' use of a sprocket/chain drive for the propulsion system—likely inspired by their experiences with bicycles—was a good choice.[2] Like others who have worked with the Wrights' design, we have forced this to be a very robust system. It operated without difficulty throughout our static tests and many hours in the wind tunnel. The only problems we had were overheated bearings, due to depleted lubrication.

In the early to mid 1980's we maintained occasional contacts with those responsible for the full-scale wind tunnels at NASA Ames. They were enthusiastic about the prospect of testing our aircraft in their 80' x120' tunnel. Following several meetings, we established the changes required in the aircraft necessary to mount it on three vertical struts extending from the floor of the tunnel. We also had to satisfy several requirements before we could conduct a test program. For mounting the airplane in the tunnel, we designed and fabricated a special internal wing structure comprising mainly two steel ribs ten inches wide, installed in the center section of the lower wing at the joint with the other panels. Two of the ball-joints in the tunnel struts would fasten there, and the third would be attached to a steel cross bar on the landing skid. The last was normally located at the tail of a test aircraft, but for our purpose the turntable in the floor of the tunnel would be rotated 180 degrees.

The requirements we had to satisfy were related to structural strength and integrity. Carl Friend (now deceased), a retired engineer from Lockheed, did a thorough analysis of the entire aircraft. NASA normally requires that no part of the aircraft in a wind tunnel should fail at five times the maximum load experienced during a test. For our airplane, the critical load factor was reduced, by agreement with NASA, from five to three. Friend's analysis revealed several weaknesses. As a result, we constructed the canard outriggers of steel, and the material in several pieces of the vertical tail was changed from wood to aluminum. Also, the wing warp wire and pulley guide were strengthened.

We made another minor structural change for practical reasons rather than due to structural weakness. Rigging the biplane cell can be a tedious and lengthy process. The Wrights cut their diagonal truss wires exactly to predicted sizes, a procedure that doesn't allow for stretching which must occur during both the static tests and the wind tunnel tests. We therefore chose to use adjustable turnbuckles supplied to us by the Bell-Memphis, Inc.

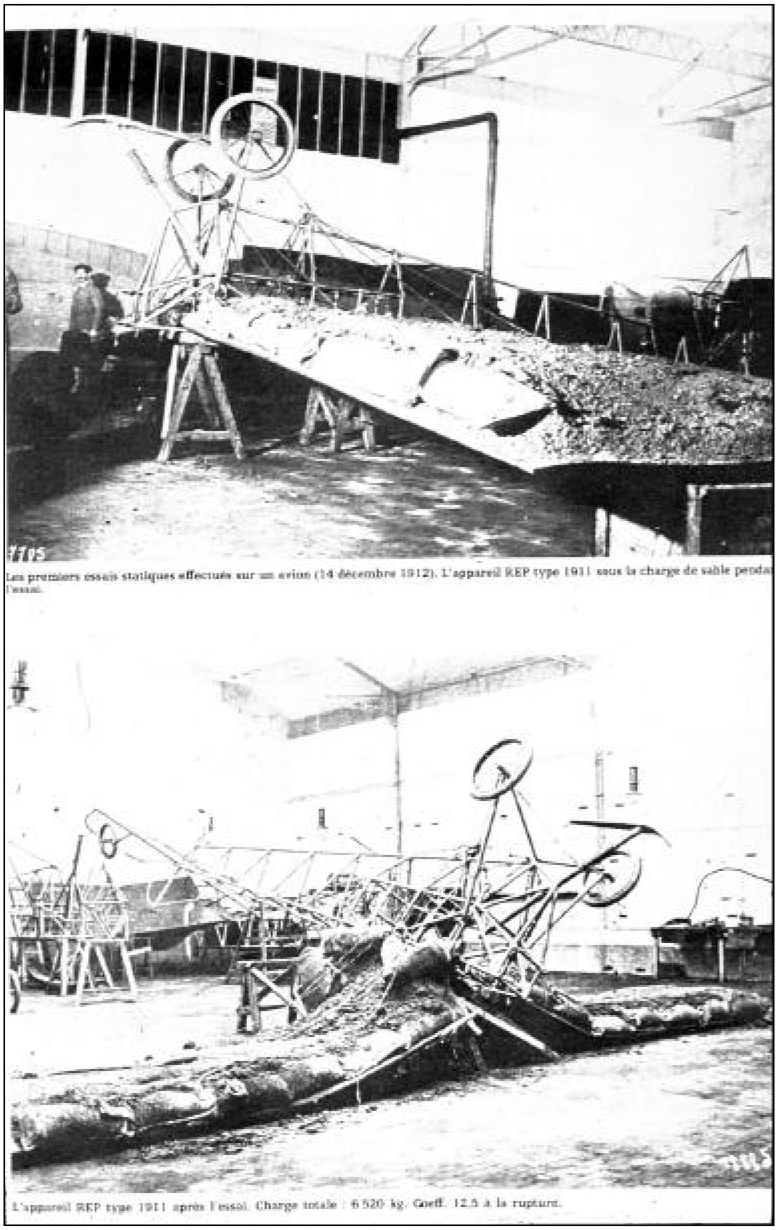
Over a period of about 3–4 years, we covered the airplane, which was finally assembled in 1992. For the long seams, Philip's Draperies in Pasadena donated a considerable amount of their labor. Figure 15 shows attachment of fabric to one outer wing panel. To prove our structural analysis, we had to carry out a static load test. That required assembling the aircraft inverted and supported at the three attachment points in a test rig. To simulate the loads, more than 3000 plastic bags were filled with 3000 pounds of sand and distributed over the wing and canard surfaces. Construction of the support rig took more than a year and the test was performed in February 1993.

Figure 15

---

[2] This was one of many clever design features of their airplane that was explicitly appreciated by the French pioneers who had experienced problems with their propulsion systems.

In fact, a static test of this sort requires a great deal of planning: Miscalculations, poor planning, or errors in execution or possible intended purpose, could lead to catastrophic failure (see Figure 16 for an early example in France). The execution must be well choreographed to avoid undesirable differential loading. Fifty people participated in the actual test, placing six differently weighted bags on each rib, in each of four increments: 24 bags per rib (Figures 17 and 18). The first attempt to test failed within a few hundred pounds of maximum load when two strut fittings pulled from the wing span. Poor quality control was the reason: screws of the wrong size had been used. The damage is shown in Figure 19. Two weeks later the test was successful. Howard Marx planned the static load test and prepared the report (Marx, 1993).



Les premiers essais statiques effectués sur un avion (14 décembre 1912). L'appareil REP type 1911 sous la charge de sable penda
l'essai.

L'appareil REP type 1911 après l'essai. Charge totale : 6 520 kg. Coeff. 12,5 à la rupture.

Figure 16

Figure 17

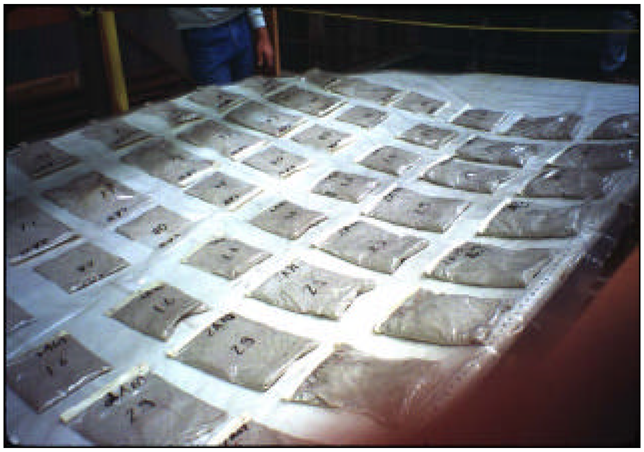


Figure 18

Figure 19

Following the static test, the aircraft was removed from the rig and rotated upright. Shortly after that event, Northrop informed us that we could no longer have our space because they were vacating the factory. We were extremely fortunate that a very good friend of the Project, Mr. ‘Bic’ Bickford, immediately offered us even more space (and cleaner) in his company quarters, International Die Casting, Inc. in Compton—a convenient central location, free of rent. We moved there in 1993 and stayed until the Fall of 1997, when we moved to the Able Corporation in Yorba Linda. The airplane rested there until we transported it to Moffett Field in March 1998.

6. THE PROPULSION SYSTEMS

Before we decided to build a wind tunnel model, the Project's Propulsion Committee, under Chairman John Graves (now retired from Hughes), investigated the problem of propulsion for the flying replica. Using a copy of the original engine was eliminated as a possibility for two reasons—both matters of safety: reliability and power. Because our primary objective was, and remains, to re-create the impression of the first flights safely and repeatedly by several pilots, we have never felt constrained to use the Wrights' engine.

We therefore wanted a modern engine, flight-qualified if possible. After examining many options, we selected the Revmaster, a flight-qualified derivative of the Volkswagon engine. Remarkably, the engine we purchased came with a planetary gearbox producing RPM equivalent to that of the Wrights' engine. With gearbox and accessories, the Revmaster weighs about the same as the Wrights' engine, is equipped with magnetos and dual ignition, and can produce as much as 45 horsepower instead of the 12–16 developed by the 1903 engine.

Early in our Project, we commissioned two sets of propellers hand-carved, by the well-known craftsman Mr. Olle Fahlen and his son, according to the original design. One pair lives permanently on the wind-tunnel test aircraft; the other is intended for the flying replica. This pair was carved according to the design worked out by Professor Eugene Larrabee (retired from M.I.T.), which, subject to our requirement of closely original appearance, have the highest possible efficiency for the flying conditions of the Wright 'Flyer'. That design will allow safer operation at the historically correct value of RPM.

As part of our work preparatory to the test at Ames, we also had to operate the propulsion system for ten hours. To minimize the possible consequences of failure of the system installed in the aircraft (vibration is the most serious cause of difficulties) and for easier adjustments during the first tests, we built a test rig (Figure 20).

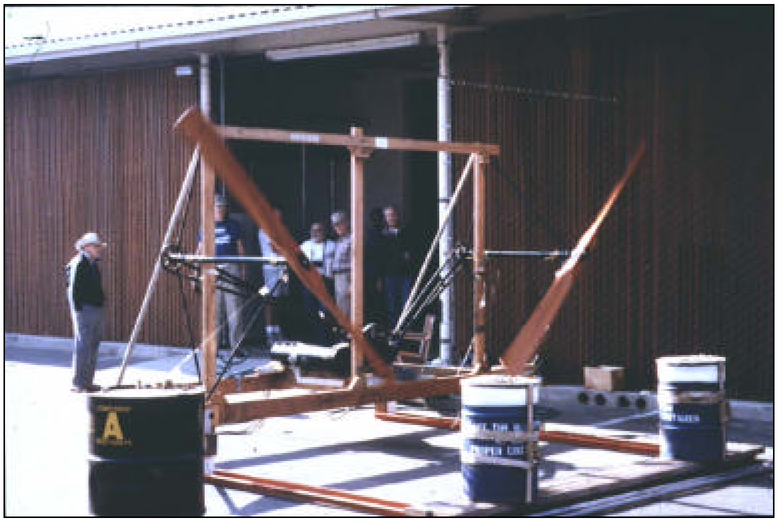


Figure 20

Because we were not permitted to use our internal combustion engine in the wind tunnel, NASA provided a water-cooled variable frequency electric motor having a diameter of eight inches but generating 45 horsepower. That installation required some additional components to connect with the chain drive arrangement. The test rig contained all of the essential parts of the propulsion system, including the two diamond frames that support the propeller shafts and are primary structural elements in the biplane cell.

After considerable searching, we finally found a variable-frequency power source at the Able Corporation, manufacturers of variable-frequency motors and wind tunnel balances for NASA. Through the generosity of their founder and owner, Elmer Ward, we ran our development test at his factory, in 1989 and again in 1997.

7. PREPARATIONS FOR TESTING AFTER 1993

In September 1992, eight members of the Wright 'Flyer' Project visited Ames Research Center for a meeting with test personnel. All participants were enthusiastic about the tests, likely to occur within 12-18 months, depending on the scheduled use of the 80x120 tunnel. Then sometime in 1993, as NASA's budget declined, decisions at the highest level of management at Ames led to cancellation of our opportunity to test. We were notified of the decision while we were beginning the last phase preparing the airplane for the tests. We had an airplane—but no place to go.

We contacted Langley Research Center and heard a similar story: We could test in their 30x60 tunnel, but at a price we could not possibly afford—more than $500,000.00—which would be extremely difficult to accumulate with gifts and fund-raising. Culick's investigation of facilities around the world led to the discovery that there was only one other wind tunnel that we could use. It is located in the TsAGI complex in the town of Zhoukowski, close to Moscow, Russia. We conceived the idea of generating more sympathy to our cause within NASA if we seriously discussed a possible test program at TsAGI.

As an Academician in the International Academy of Aeronautics (IAA), Cherne had long known a fellow Academician and well-known mathematician/aerodynamicist, Gorimir Chernyi of Moscow State University. Chernyi arranged a connection with the Director of TsAGI and Culick visited there for a day in September 1994. Their test group was as enthusiastic as NASA's, and needed the work. With plans of the airplane in hand, they spent three months determining the technical feasibility of the proposed tests, and how the tasks would be distributed between TsAGI and the Wright 'Flyer' Project to accomplish the interfaces for mechanical, electrical and instrumentation systems.

In December 1994, Culick returned to TsAGI to find everything proceeding well, including drawings of hardware that would have to be fabricated.[3]

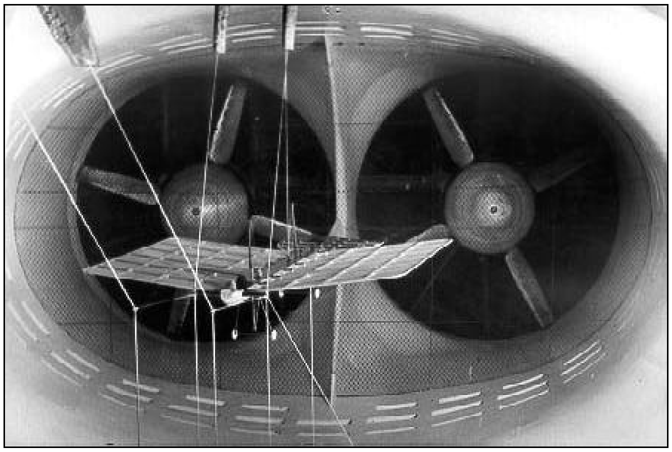


Figure 21

Agreement was reached to press on with planning. The group at TsAGI would also prepare a budget which turned out later to be between $150,000.00 and $200, 000.00 depending on the extent of the tests and of the supporting effort. In addition, of course, we would be faced with the task of getting our airplane there.

Meanwhile we had informed NASA Headquarters (both Dan Goldin, Administrator, and Wes Harris, the Associate Administrator for Aeronautics) of our plans and intentions. At a 1994 meeting of the IAA, Goldin had informed Cherne that he would find a way for us to test at Ames. Eventually the arrangements were made through NASA's Educational Outreach Program, with much of the NASA work effort provided by volunteers.

---

[3] An interesting tangential point was that the TsAGI group had constructed and tested a model of a Mazhaiskii airplane designed and alleged (by some Russian historians) to have flown before the Wrights (Figure 21). The TsAGI engineers say that their tests showed that the airplane could not have successfully flown: they credit the Wrights with the invention of the powered airplane.

Thus the Wright 'Flyer' Project resumed serious planning with the test group at NASA Ames, now led by Zell. Meetings at Ames led to the decision to mount the airplane on a sting attached to the underside of the lower wing. The principle reason was that the aerodynamic forces and moments generated by the Wright 'Flyer' would barely be resolvable at the low end of the load ranges covered by the balance system associated with the strut mountings. The sting contains a six-component strain gage balance.

However, this change of measurement system brought with it substantial work on design and fabrication. The large load concentrated in the center section of the wing required that the wood spars[4] be replaced by aluminum, and the steel ribs would be removed. A large, heavy steel structure was designed and built to make the interface between the sting and the wing. Votaw Manufacturing Company and the Marfab Corporation, fabricated the parts at no cost.

After the construction work was completed (including a further donation of sewing by Philip's Draperies), the airplane was moved to the Able Corporation. There we completed the instrumentation and data acquisition system and carried out propulsion tests of the complete configuration of the 'Flyer' to be used in the tests at Ames.

8. THE MOVE TO AMES

Transporting the 'Flyer' is relatively straightforward in some respects but does present some practical difficulties. The canard with outrigger is attached with cleverly designed joints at the wing leading edge and the skid. Thus the entire assembly, as well as the rudder assembly with support connections to the upper wing and the skid, can be removed from the wing cell.

Marilyn Ramsey and Steve Shackelford of the Los Angeles FAA office were able to arrange transportation in two new 50-foot air ride trailer trucks with all costs donated (equivalent value $40,000.00) by American Red Ball Moving and Storage Company and De Vries Moving and Storage. The biplane cell occupied one trailer; the other trailer carried the canard and tail assemblies, and various pieces of equipment. The entire move from Able Corporation in Yorba Linda to Moffett Field was executed flawlessly by the truly professional personnel of the two trucking companies.

As part of the Project's Public Relations and Educational Outreach Activities, directed by Ramsey and Shackleford, the trip to Moffett Field took seven days. Marilyn, Steve, and several other members of the Project accompanied the two trucks: Arvin Basnight, Bud Chamberlain, Don Dotson, Bill Haynes, Joe Lander, Wendall Seward (deceased), and Bob Trelease. They stopped at six schools and airports on the way to give public talks to about 3000 people, most of them young students.

On the seventh day, the 'Flyer' arrived at Moffett Field. It was unloaded and assembled in historical Hanger No. 1, former home of the U.S. Navy's rigid airship fleet in the 1930's. The interior is large enough to hold three *Titanics* side-by-side, and is longer than Wilbur's longest flight of 852 feet on 17 December 1903.

On 15 April 1996, NASA held a press conference to announce the test program (Figure 22). The event was covered by media in the Bay Area and by reporters from national radio and television organizations.

---

[4] Two breaks in the spars had already been discovered, likely caused during the move between facilities. The change to aluminum spars had therefore been contemplated before the decision to test on a sting.

Figure 22

The 'Flyer' remained in a fenced area in Hanger No. 1 and was the site for many educational meetings with teachers and students. Members of the Project made regular visits to complete work on the airplane's control and data collection system. To ensure that the airplane could be assembled and operated on the sting in the tunnel, a Pathfinder test was carried out. The sting assembly was moved from the tunnel and the airplane was mounted with a dummy balance, the balance block and the interface assembly. It was then operated through the entire range of angle of attack planned for the tests.

9. INSTALLATION OF THE AIAA WRIGHT 'FLYER' IN THE AMES 40x80 TUNNEL

By the fall of 1998, it became clear that the tunnel would become available sometime early in 1999. That tends to be a wet season in the Bay Area. The 80x120 tunnel is an open system, drawing air from the outside. That is not a good situation for the untreated fabric covering in the 'Flyer' so the tests were rescheduled for the 40x80 section placed in a closed loop.

The change to the 40x80 section meant that the airplane would be lifted from the building floor roughly 100 feet over the top of the test section and lowered into the tunnel. That exercise required a hoisting sling to be designed, fabricated and proof-tested for the expected load.

In February 1999, the airplane was once again disassembled and trucked one mile from Hanger No. 1 to the wind tunnel building where the airplane was re-assembled on the floor. Final calibrations were made of the LVDTs supplied by Lucas Aerospace for measuring the position of the controls. The last test prior to mounting the aircraft in the tunnel was operation of the propulsion system to ensure that it would work with the NASA power supply and to train the NASA operator. That two-hour test was completely successful.

On 1 March 1999, NASA personnel hoisted the AIAA Wright 1903 'Flyer' into the 40x80 test section (Figure 23). The procedure was accompanied live on the Web by a conversation between Fred Culick and a member of the Ames Public Relations Office. It was indeed, an emotional event, the climax of 18 years work.

Four days later, NASA opened the tunnel to the media to display the first airplane now mounted on the sting in one of the world's largest wind tunnels (Figure 24). The event was reported in hundreds of newspapers, magazines and TV stations around the world.[5]

Simultaneously with the open house, NASA maintained a live Web site on which key people involved in the Project were interviewed during the entire test program and subsequently, the web site provided interviews, chat rooms, data and suggested projects for students k-12.

---

[5] It was reported as well by the Voice of America beamed to Moscow.

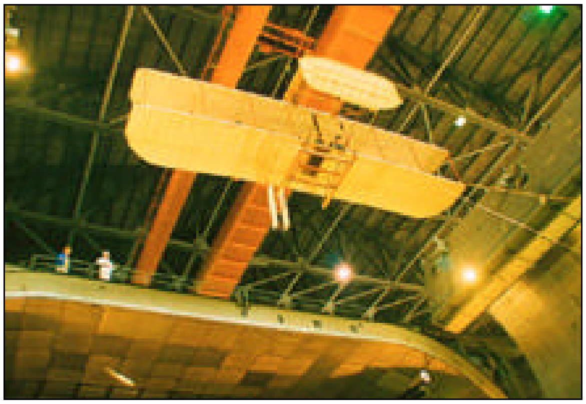


Figure 23

Figure 24

10. PREPARATION AT AMES FOR THE TESTS

The 40x80ft Wind Tunnel has a maximum test section airspeed capability of 300 knots. Airspeed is adjusted using a set of six variable blade angle and rpm fans. The very low airspeed requirement of 25 knots for the 1903 Wright 'Flyer' test raised two concerns during test planning. First, would the facility produce uniform flow through the test section at the extreme low end of the operating envelope? And second, was the existing facility wind speed measurement system adequate to meet data accuracy requirements?

The 90, highly twisted fan blades of the 40x80ft Wind Tunnel (Figure 25) are optimized to operate near maximum blade angle and rpm. The 25 knots required for the 1903 Wright 'Flyer' test was achieved by operating the fans at 36 rpm (20% of max.) and 16.5° blade angle (52° is max.). It is expected that a large portion of each fan blade is stalled during such low speed operations and that the outflow of the six fans is extremely non-uniform.

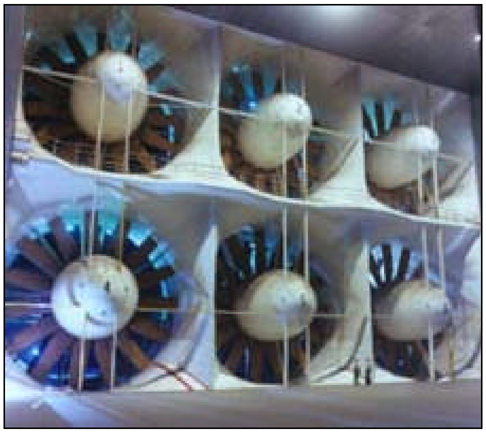


Figure 25

A test section survey was conducted using a hand-held wind anemometer to assess flow uniformity. Results of this survey at several speeds are presented in Figure 26. The facility produced a relatively flat velocity distribution. This result created confidence that the Wright 'Flyer' would see a constant velocity, wing-tip to wing-tip, during testing. Flow unsteadiness was observed during the test section velocity survey. This effect was felt to be random turbulence and that data sampling times could be optimized to eliminate any effects on measurements.

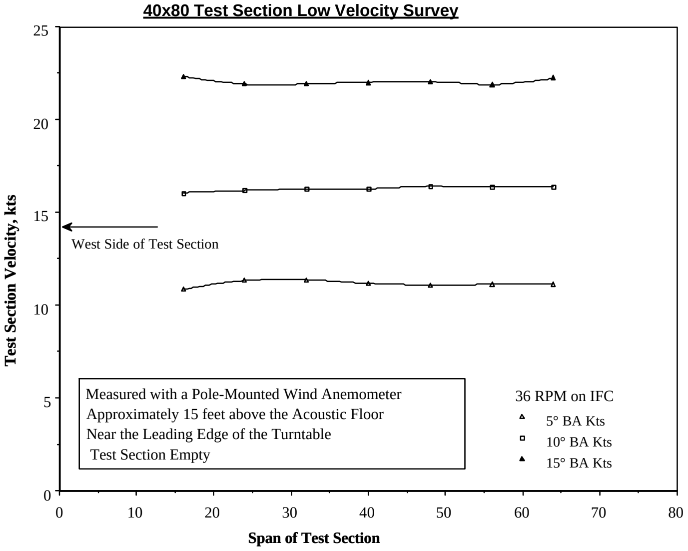


Figure 26

The existing facility dynamic pressure/velocity system was deemed inadequate to measure the low airspeed for the 1903 Wright 'Flyer' Test. The solution was to deploy two atmospheric sonic wind sensors near the entrance to the test section, ahead of the 'Flyer'. These sensors were mounted on 15' tall struts that raised them to the elevation of the model at 0° angle of attack. They were also mounted laterally approximately ±15' from centerline. The readings from the sensors were averaged and used to set tunnel conditions for the test. NASA worked with the sensor manufacturer to improve measurement accuracy of the anemometers to approximately ±0.1 knot.

Balance selection for wind tunnel testing is generally a process that involves compromise. It is rare to find an existing balance with capacities in all six components that are ideal for the planned test envelope. The 1903 Wright 'Flyer' was no exception. A four-inch diameter Mark II internal balance was selected after determining that the large facility external balance would not meet data accuracy requirements. This balance was confirmed to have acceptable accuracy and repeatability in the lower 10% of the normal (lift), axial (drag), and side force ranges. Expected pitching and yawing moments were also found to be well within the capacity of the Mark II.

The ratio of the span of the model (40') to the diameter of the Mark II balance (4") was 120 to one. Rolling moment predictions for full wing warping showed that the full balance capacity of 16,000 in-lbs would be required during the test. Operating the balance at nearly full rolling moment capacity while measuring the other five balance components at the very low end of range raised concerns about interaction errors. This was evaluated by looking at offsets with the balance loaded to capacity in roll. Interactions were determined to be manageable however, at full roll capacity, the balance was found to deflect over 1.25°. This deflection is addressed in data reduction equations. The concern was that this balance “softness” in roll could result in dynamic excitation of the model during testing. Mechanical roll stops were thus integrated into the model mounting hardware to protect against inadvertent balance overload.

Operating the facility so far off of the optimum running line combined with a large-span model mounted on a soft balance to create some excitement during early runs. The 'Flyer' was observed to randomly rock in roll with occasional large excursions (up to ±6” at the wing-tips). This rocking caused data alias problems with 30-second duration data points. Efforts to operate the facility at higher fan rpm (closer to the optimum running line) did not improve flow conditions. Data point sampling durations were extended to two minutes, resulting in acceptable data quality. Time history data was also acquired to allow for potential post-test data processing to filter the effects of flow unsteadiness.

Acquiring balance data for a full two minutes per data point made it impossible to meet pre-test productivity expectations. Yet, the goal to accurately measure relatively small forces and moments from a 40' wingspan, wood and fabric 1903 Wright 'Flyer' model with props rotating was achieved.

In the following paper, AIAA Paper No. 2000-0512, Jex, Hange, Latz and Grimm summarize the results of the full-scale tests conducted at Ames Research Center during two weeks in March 1999. Comparisons with the data obtained from the earlier tests with the 1/6- and 1/8-scale models are given.

The 1/6-scale model hangs in Fred Culick's living room; the 1/8-scale model is in storage, to be put on public display later at some place to be determined; and the full-scale wind tunnel model is on loan for display in the FAA Building in Los Angeles (Figure 27).

Figure 27

ACKNOWLEDGMENTS

The Wright 'Flyer' Project is especially indebted to the Northrop Corporation for providing rent-free space for construction of our airplane from 1981 to 1993 where all of the covering, assembly and static testing took place. International Die Casting, Inc. gave us space from 1993 to 1999. Throughout our entire project, Systems Technology, Inc. with the special help of its Presidents Duane McRuer and (since 1998) Wade Allen, has given us desperately needed support for much of our analysis of wind tunnel data and the aircraft dynamics, as well as in preparation of several papers and reports.

REFERENCES

Bettes, W.H. and Culick, F.E.C. (1982) "Report on Wind Tunnel Tests of a 1/6-Scale Model of the 1903 Wright 'Flyer'", Guggenheim Aeronautical Laboratory, California Institute of Technology, GALCIT Report No. 1034.

Culick, F.E.C. (1988) "Building a 1903 Wright 'Flyer' – By Committee", AIAA 26th Aerospace Sciences Meeting, AIAA Paper No. 88-0094.

Culick, F.E.C. and Jex, H.R. (1983) "Aerodynamics, Stability and Control of the 1903 Wright 'Flyer'", in proceedings of The Wright 'Flyer': An Engineering Perspective, National Air and Space Museum, Smithsonian Institution.

Hart, C. (1967) Kites: An Historical Survey, Frederick A Praegs Publishers, N.Y.

Hooven, F. (1988) "Longitudinal Dynamics of the Wright Brothers Early Flyers", in proceedings of The Wright 'Flyer': An Engineering Perspective, National Air and Space Museum, Smithsonian Institution.

Jex, H.R. and Culick, F.E.C. (1985) “Flight Control Dynamics of the 1903 Wright 'Flyer'”, AIAA 12th Atmospheric Flight Mechanics Conference, AIAA Paper No. 85-1804-CP.

Langley, S.P. (1891) Experiments in Aerodynamics, Smithsonian Institution Publication 801.

Lilienthal, O. (1911) Birdflight as the Basis for Aviation, Translated by A.W. Isenthal, Longmans Green and Co., London.

Marx, H. (1993) “Static Proof Load Test of a Full-Scale 1903 Wright 'Flyer' Fitted for Wind Tunnel Testing”, AIAA Aircraft Design Systems and Operations Meeting, AIAA Paper No.93-3937.

McFarland, M. Ed. (1953) The Papers of Wilber and Orville Wright, McGraw-Hill Book Co., New York.

Pénaud, A. (1872) “Aeroplane Automoteur: Equilibre Automautique” L’Aeronaute, Vol. 5, pp. 2–9.