AIAA 2001-0309.

Evolution of Wright Flyer Propellers between 1903 and 1912

By
Robert L. Ash, Stanley J. Miley, Drew Landman,
Aerospace Engineering Department, Old Dominion University, Norfolk VA 23529-0247
and Kenneth W. Hyde,
The Wright Experience, Warrenton, VA

Abstract

Reproductions of a 1903 and a 1904 Wright propeller have been tested in the Langley Full Scale Tunnel, and will be compared with the 1911 Wright brothers' "bent end" propellers that were developed during their 1905 testing campaign. Wind tunnel testing was completed on December 29, 2000 and the purpose of this paper is to give a status report.

Introduction and Historical Background

In order to understand the contributions of Wilbur and Orville Wright to aeronautics, it is necessary to place the brothers and their work in the context of the time. Only then is it possible to appreciate the critical importance of their evolution of efficient propeller designs.

It is probable that Wilbur and Orville Wright had read about Otto Lilienthal's early glider experiments in the September 1894 issue of *McClure's Magazine*, and it is believed that Wilbur read of Lilienthal's fatal crash in late August 1896, while caring for Orville, who was seriously ill with typhoid fever[1]. The two brothers had opened their first bicycle shop in Dayton, Ohio in 1892, initiating manufacture of their own safety bicycle designs in 1895; during the fateful summer of 1896, they were concerned primarily with their bicycle business. During Orville's illness, Wilbur became convinced that he and his brother should try to design and build a flying machine.

Although neither brother finished high school, they were voracious readers and they had probably read a great deal of the popular literature on flying machines of that period. Wilbur recognized that learning to fly would be more difficult than learning to ride a bicycle and after Lilienthal's death, he determined that even though Lilienthal had conducted more than 1,000 glider flight experiments, Lilienthal's accumulated flying time was approximately five hours. Wilbur did not believe that it was possible to master piloted flight in only five hours of practice.

There is little evidence of aeronautical research on the part of the Wright brothers between the summer of 1896 and early 1899. In the spring of 1899, after they had read *Animal Mechanism* by Etienne J. Marey, Wilbur began to actively study flying machines, writing to the Smithsonian Institution on May 30, 1899, requesting that they provide him with copies of any important publications on mechanical and human flight[2]. The brothers were already convinced that using movement of the pilot's body to shift the center of gravity of a flying vehicle for primary attitude control was not an acceptable approach.

During the summer of 1899, while playing with a small pasteboard box, Wilbur conceived the idea of wing warping as a practical method for roll control. Wilbur and Orville had been pursuing a variety of wing and wing-control structural concepts prior to that discovery and it was only after Wilbur demonstrated the wing warping control technique with a small homemade biplane kite in August of 1899[3], that the Wright brothers began to pursue flying machines in earnest. Even though they had studied virtually all of the published literature on airfoil performance and airplane design of that time, their decision to build gliders and learn to fly them in the steady winds of Kitty Hawk, North Carolina was their first major commitment to building an airplane. The use of their 1900 and 1901 gliders to both learn to fly and to validate their flying machine design concepts was a remarkable achievement. Their 1900 and 1901 glider flight test campaigns convinced them finally that there were fundamental errors in the published correlations for estimating lift, drag and power requirements for flying machines. The development of a high-quality wind tunnel and the planning and execution of their airfoil test program during the fall and early winter of 1901 was arguably the world's first modern-day aeronautical testing program[4]. The balance system they finally designed and used to measure the lift of various airfoil models, by comparing the lift force acting on their test airfoil with the force exerted normal to an eight square inch rectangular "reference" plate at the same wind speed, is a remarkable example of their inventive genius and creativity. Dynamic pressure was not being used correctly as a scaling parameter at that time (i.e. Smeaton's coefficient was multiplied by the velocity squared rather than using one-half of the density multiplied by the velocity squared) and the Wright brothers did not have instrumentation that could resolve accurately the aerodynamic forces produced by their wind tunnel wing and airfoil models. Thus their decision to relate the forces produced by their models to the forces produced by a rectangular reference plate was truly ingenious. The lift-measuring device that they designed and built is both elegant and subtle. Because that instrument enabled them to generate all of the lift data used for both their flying machines and their propellers, that device is discussed in the Appendix of this paper.

The airfoil performance data for 38 airfoil models tested in 43 configurations (including several multi-wing arrangements) for angles of attack starting from *no lift* and proceeding through 45^{o}, were produced in approximately three weeks between late November and early December 1901[5]. Those data were the basis for all of the wing and propeller designs used in the Wright flyers that have been studied to date.

The Wright brothers' 1902 glider utilized their new airfoil data and for the first time, their glider demonstrated aerodynamic performance that was consistent with their estimations. That glider incorporated a vertical rudder and it flew so well that Orville was allowed to fly for the first time[6]. Their 1902 glider test campaign at Kitty Hawk was completed on October 28, and was so successful that Wilbur and Orville believed that they could achieve controlled, powered flight and started to study the design of a propulsion system. On December 3, 1902, the Wright Cycle Company sent letters to at least ten gasoline engine manufacturers asking for quotes on a gasoline engine that could produce eight or nine brake horsepower, weighing less than 180 lbs[7].

None of the companies that were contacted were able to provide a quote for a motor that met their requirements. Furthermore, Wilbur and Orville determined quickly that they could not translate the design approach employed for marine propellers to the design of airplane propellers. Not only could airplane propellers utilize the lift produced on the front surfaces without encountering cavitation, but they discovered that the marine screw propeller designs were based upon empirical formulae rather than fundamental principles[8].

Evolution of the Wright Propellers

The first Wright propeller model was tested using the Wright Cycle Company shop motor on December 15, 1902[9]. Wilbur's propeller theory is incomplete at this time, but the brothers had decided that their propellers could be designed by using a specific propeller reference radius (approximately 5/6 R_{MAX}—called the propeller's center of pressure), and varying the pitch of the propeller blade with radius so that it maintained a constant angle of attack with respect to the oncoming wind. Their original propeller model was 28 inches in diameter with a maximum blade width of seven inches, a camber of 1/25 and a design pitch angle of 15^{o}. They found that at 1600 rpm, the propeller generated a thrust of 12 lbs, and required 0.8 horsepower. They estimated the propeller angle of attack to be 2 1/2^{o} with respect to the moving air (estimated speed of 25 mph). They also observed that the thrust varied approximately with the square of the rotational speed.

By February 1903, Wilbur and Orville had built their first motor and constructed their first full size propeller[10]. Although it was similar to the propellers used on the 1903 Flyer, the propeller that was tested had a different pitch than the '03 pair[11]. The actual '03 propellers were tested in November and December of 1903[12]. Furthermore, the 1903 Flyer propellers were tested later with the 1904 motor, in order to estimate the horsepower produced by the 1903 powerplant[13].

McFarland has devoted a section to the Wright brothers' propellers[14], but the theoretical basis for their designs is incomplete. They utilized a form of blade element theory and they understood the momentum theory of Rankine and Froude[15]. However, their methodology is not even mentioned in contemporary literature, even though they were achieving propeller performance levels by 1905 that were only achieved by others after World War I.

It is our intention to document the evolution of the Wright propellers, starting with the 1903 Wright Flyer and proceeding through the bent end propeller designs that became standard on Wright flying machines after 1912. Subsequently, we intend to utilize the writings of Wilbur and Orville to finally document and present their original propeller design theory. Presently, *The Wright Experience* has produced 1903, 1904 and *circa* 1911 bent end propeller reproductions that have been tested in the Langley Full Scale Tunnel, operated by Old Dominion University. The most recent test series was completed on December 29, 2000 and this paper should be considered as a status report.

The Wright Experience-Langley Full Scale Tunnel Propeller Testing Program

The *Wright Experience* has been engaged in the reproduction of Wright flyers and gliders for more than a decade. Starting in 1999, Old Dominion University has been supporting The Wright Experience via full-scale testing of Wright flyer components at its Langley Full Scale Tunnel (LFST). Thus far, results of our bent-end propeller tests have been reported[16,17] and the performance of the Model B airfoil has been investigated[18].

The Model B has been the initial focus of this research because it is the best-documented early Wright Flyer. More than 80 Model Bs were produced between 1909 and 1915 at five factories in the U.S. and Europe, making it necessary to control and document the manufacture. Consequently, it has been possible to capture the manufacturing techniques and materials used by the Wright brothers in their early Wright Flyer machines. We are now beginning to "unengineer" back from the 1911 Model B toward accurately reproducing the 1903 Wright Flyer.

The propellers that have been reproduced by The Wright Experience and tested at LFST to date are shown in Figure 1. Starting from the left are reproductions of: two *circa* 1911 "bent end" propellers; the 1904 propeller that was used by Wilbur Wright in their world's first public demonstration flight—in LeMans, France on August 8, 1908—and a 1903 Wright Flyer propeller.

Figure 1. Photograph of Wright Brothers propeller reproductions between 1911 (left) and 1903 (right). Propeller lengths are 8 ft. 6 inches.

The 1903 propeller is shown separately in Figure 2 and the 1904 propeller in Figure 3. The shape differences between the bent end propellers and the earlier propellers are obvious. It is also apparent that the Wright brothers were able to reduce the thickness (and weight) of each succeeding propeller. They saw the benefits of exploiting large propeller diameters, rotating at slow speeds, and since the height of their early flyers was approximately eight feet, the 8 ft. 6 in. length was close to their maximum limit. (Lt. Thomas Selfridge was killed when one of Orville's nine ft. diameter propellers failed on Sept. 17, 1908[19], and subsequently the 8 ft. 6 in length propellers were their primary size.)

Figure 2. 1903 Wright Flyer Propeller Reproduction.

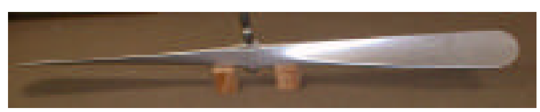

Figure 3. 1904 Wright Flyer Propeller Reproduction.

The Wright family loaned The Wright Experience the 1904 propeller that was used in LeMans in 1908. The Wright brothers painted dates on their propellers and The Wright Experience was able to show that this particular propeller can be traced to the August 8, 1908 flight by comparing the repaired crack found in the Wright estate propeller with the visible marks on the propeller in the photograph of Wilbur Wright and Hart O. Berg, taken in front of the Wright Flyer, on August 8, 1908. The Wright Experience obtained a digital representation of the 1904 propeller and those data were used to drive a five-axis milling machine, milling the propeller from a laminated spruce lay-up that replicated the material and dimensions of the original propeller. The final finish and the cloth propeller "tip sheaths" (using the same thread-count muslin fabric as was used on the original propeller) was done by hand. The 1904 propeller was to the accuracy of measurement an exact reproduction of the original. That propeller had a maximum blade width of 8 _ inches, with a pitch of 25 4/5^o, as tabulated by McFarland[20]. The original (from the Wright estate) propeller weighed 6 _ lbs., whereas the reproduction weighed 7 _ lbs. Obviously, nearly 100 years of "drying" reduced the weight of the original, but the density of spruce varies as well.

After the December 17, 1903 flights, the badly damaged '03 Flyer was placed in a crate and shipped back to Dayton. Subsequently, the Wright brothers reused the '03 propellers and possibly other parts from the original Flyer in the construction and testing of their 1904 flying machine. Similarly, parts from their '04 machine were used in 1905, and so on. However, the unused original parts for the 1903 Flyer were left in the original shipping crate and stored in Dayton. In 1916, after Wilbur's death in 1912 and after the 1903 Flyer storage crate was salvaged from a flood in 1913, Orville agreed to reassemble the 1903 Flyer for use as a display at the dedication of a new building at the Massachusetts Institute of Technology. The original engines and propellers were not used in the restoration and were stored separately at South Park as late as 1921[21].

The broken original 1903 propellers, stored previously at South Park, are in the possession of the National Park Service. The Wright Experience was allowed to examine the pieces of the original and, working with a digital imaging company, has been able to create a complete three-dimensional representation of an intact 1903 propeller with sufficient accuracy to be compatible with current rapid prototyping manufacturing standards. However, automated reproduction of an original 1903 Wright propeller was not the approach used by The Wright Experience.

We would like to acknowledge the support of BAE Systems' Space Electronics and Communications Division who loaned Mr. Larry Parks to The Wright Experience for the purpose of reproducing a 1903 propeller. Mr. Parks is an expert on *circa* 1900 woodworking tools and woodworking techniques. Using his expertise, The Wright Experience was able to identify the specific woodworking tools (hatchet, drawknife, spokeshave and gouges) utilized by the Wright brothers. Subsequently, Mr. Parks was able to determine the woodworking strokes actually employed on the original propeller and then copy them in reproducing the 1903 propeller.

Wilbur and Orville tested their '03 propellers on November 21 and November 28, 1903. They also measured the performance during their fourth flight of the '03 Flyer on December 17, 1903. Their notebook entry for November 21, 1903[12] states that they recorded a static thrust of between 132 and 136 pounds (for two propellers) when their engine-driven propellers were turning at a speed of 350 rpm. Besides making geometrical comparisons, we have been able to compare the static thrust produced by our reproduction when it is turning at a speed of 350 rpm and compare it with the 66 to 68 lb. range reported for the original.

The reproductions of the Wright brothers '03 and '04 propellers, shown in Figures 2 and 3, were tested in the ODU Langley Full Scale Tunnel in December, 2000, using the propeller test stand and instrumentation described in References 16 and 17. Static condition runs over a range of rotational speeds and forward flight condition runs over a range of advance ratios were performed. The test results for the static condition runs for the '03 and '04 propeller reproductions are given in Figures 4 and 5. Also plotted are the Wright brothers measurements from their 1908 notebook[12]. The Wright data were reduced to thrust coefficient by assuming atmospheric conditions at 1000 feet pressure altitude (corresponding to the nominal elevation of Dayton, OH) and a temperature 20^o F lower than a Standard Day (i.e., a temperature of 39^{o}F) for the '03 propeller (tested outside in Dayton, OH, November 21, 1903) and a Standard day + 20^{o}F temperature (79^{o}F) for the '04 propeller (tested indoors in Dayton, OH, June 8, 1905). The Wright data for the '03 propeller were recorded as a thrust range between two values, as represented by the 2 square symbol data points in the Figure. As a basis for comparison, when the

’03 reproduction was tested at a nominal rotational speed of 350 rpm (350.1 0.6 rpm), we measured a thrust of 64.2 1.1 lb (at a tunnel ambient temperature of 46^{o}F and a barometric pressure of 29.97 inches of mercury). The Wright brothers’ static thrust measurements were 67 1 lb at a rotational speed of 350 rpm at Dayton, OH ambient conditions on November 21, 1903. The Wright brothers’ 1908 notebook includes one static thrust measurement of 160 lbs for a pair of ’04 propellers turning at 377 rpm, on June 8, 1905. We recorded one static thrust measurement of 82.66 lb for the ’04 propeller reproduction, turning at a rotational speed of 377.8 rpm (at 48^{o}F, 30.06 in hg). Both thrust coefficient plots show very good to excellent agreement between the Wright brothers’ measurements and the measurements taken during the current test series.

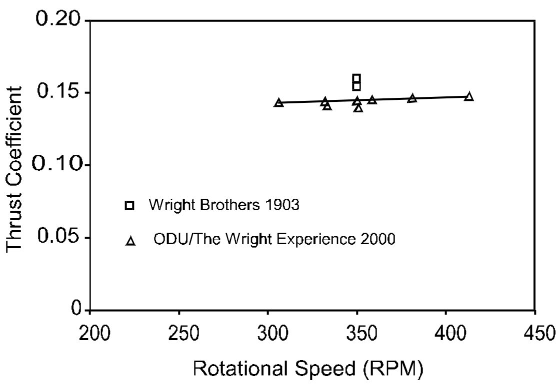

Figure 4. Test results of the Wright 1903 propeller reproduction and comparison with the original 1903 propeller.

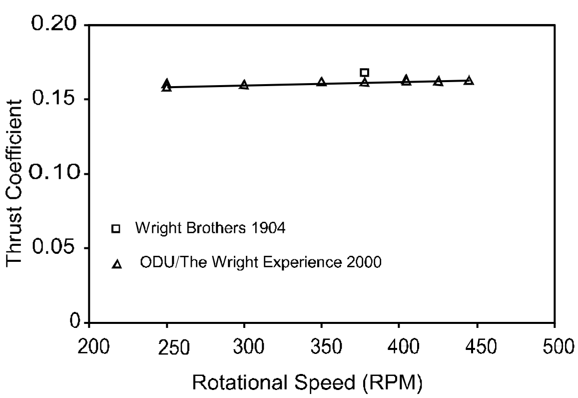

Figure 5. Test results of the Wright 1904 propeller reproduction and comparison with the original 1904 propeller.

In viewing the performance differences between original Wright propellers and the present reproductions, it should be remembered that by today’s standards, the force measurement tools available to the Wrights were relatively crude. Also while reducing the force values to coefficient form removes atmospheric density as a factor in the comparison, its effect is still present in the blade torsional moment forces. Differences in dynamic pressure produce different normal force distributions on the rotating blades and that can cause different amounts of blade twisting at the same rotational speed.

We have not completed reduction of the thrust and power coefficient data for the ’03 and ’04 propeller reproductions and also for a repeat of the bent end propeller that was tested previously. Those data will be part of a subsequent publication.

Conclusions

The Wright Experience and Larry Parks have been able to capture the geometrical and manufacturing details of a suite of Wright brothers propeller reproduction. The static thrust measurements produced by the propeller reproductions are in excellent agreement with the thrust measurements for the ’03 and ’04 propellers recorded by Wilbur and Orville Wright in 1903 and 1905.

Appendix

Wright Brothers' 1901 Lift Balance Apparatus

When Wilbur and Orville Wright returned to Dayton, OH from Kitty Hawk, NC on August 20, 1901, after their second glider flight test campaign they knew that there were serious problems with their glider designs. Their 1901 glider, though larger than the 1900 glider, did not handle well and its (lift and drag) performance did not agree with their predictions. Although Wilbur was busy preparing a paper to be read at the Western Society of Engineers meeting in Chicago (on Sept. 18, 1901), the brothers had already become convinced that the published airfoil performance tables of Lilienthal and others, used as the basis for their glider designs, failed to yield reliable glider performance predictions. They just didn’t know what aspects of the published data and theories were incorrect.

They decided that the only way they could resolve the discrepancies between the published data of others and their actual glider performance measurements was to conduct their own experimental airfoil evaluation program.

In early October 1901, the Wright brothers constructed a rather ingenious airfoil test apparatus that used a bicycle rim and hub mounted horizontally in front of the handlebars of one of their bicycles for the purpose of comparing the lift performance of their own airfoil designs with the performance of a reference surface[22]. They attempted subsequently to pedal the bicycle at constant direction and speed, using it as a sort of wind tunnel (in calm or uniform air) to generate wind forces and then compare the aerodynamic forces acting on test airfoils with the forces acting on a rectangular plate used as a reference surface. Hence, they had already decided to compare the forces produced by test airfoils with the force produced by a specific reference standard (at the same wind speed) rather than try to measure those forces directly.

In Wilbur Wright's letter to Octave Chanute on October 6, 1901[23], he described how they had tried to relate the lift force acting on their rather large airfoil models (8" x 18") to the forces acting normal to an 8" x 12" plate—both attached to the bicycle rim. Although the bicycle apparatus proved to be unsatisfactory as an airfoil testing system, the Wright brothers had already eliminated significant measurement uncertainties with their test apparatus concept. Wilbur explained how the force measurement problem was bypassed by using a mechanical apparatus that responded proportionally to the relative magnitude of the lift force acting on a test airfoil with the drag force acting on a rectangular reference plate that was positioned to be perpendicular with the wind; thus they could avoid the requirement for direct measurement of very small forces. In that same letter, Wilbur reported that they had determined from their glider experiments that Smeaton's coefficient[24] (used to estimate the dynamic pressure in air) was incorrect and that their measurements were in agreement with the "still air" measurements of Langley[25].

Using McFarland as our primary source, it is not clear when the Wright brothers scrapped their "bicycle wind tunnel" in favor of a wooden starch box that was modified to be used as a primitive wind tunnel. However, by October 16, 1901, Wilbur and Orville had proceeded from their bicycle rim lift-measuring apparatus through a somewhat complicated lift-measuring device used in their first wooden wind tunnel[26] to the design of an ingenious lift-measuring apparatus and a constant-speed wind tunnel that had characteristics that appear to be comparable to modern wind tunnels[4]. According to McFarland[27], Octave Chanute shared photographs of a wind tunnel designed by Professor Etienne J. Marey (the author of the book on ornithology that had energized their pursuit of flight in 1899) when he visited them in Kitty Hawk during the summer of 1901. Marey's wind tunnel had incorporated flow straighteners and (silk) screens to produce a uniform flow[27]. The Wright brothers may have benefited from Marey's work, because they completed the design, construction and "calibration" of their second wooden wind tunnel[28] sometime in November 1901, and it incorporated flow straighteners and a wire screen ahead of the fan to produce a high-quality 27 mph air flow[4].

For understanding purposes, the dynamic pressure produced by 27 mph air is approximately 0.0126 lb_f/in^2 (87.4 Pa). Hence, forces acting on an 8 square inch plate are on the order of 0.1 lb_f (0.5 N). Assuming that the characteristic length of an 8 in^2 plate is 2.8 in., the Reynolds number characterizing the Wright brothers' "reference plate"* is estimated to be 58,000, and the estimated drag coefficient for a rectangular plate at that Reynolds number[29] is $C_{D,Ref}$ = 1.17. Hence, our estimated of the Wright brothers' actual reference force is 0.12 lb_f (0.5 N, or less than 2 ounces), and it is their genius that enabled them to design the lift-measuring instrument shown in Figure 1.

The evolution of the design can be followed by reading Wilbur's letters to Octave Chanute, written between October 6, 1901 and January 23,

* The Wright brothers calibrated or tuned the metal fingers employed in their drag balance to produce a drag force that was exactly equal to the drag force acting on an 8 in^2 plate at their wind tunnel flow conditions. Since all of their tests were performed at nominally the same ambient conditions and speed, the drag elements can be treated as being equivalent to a square plate.

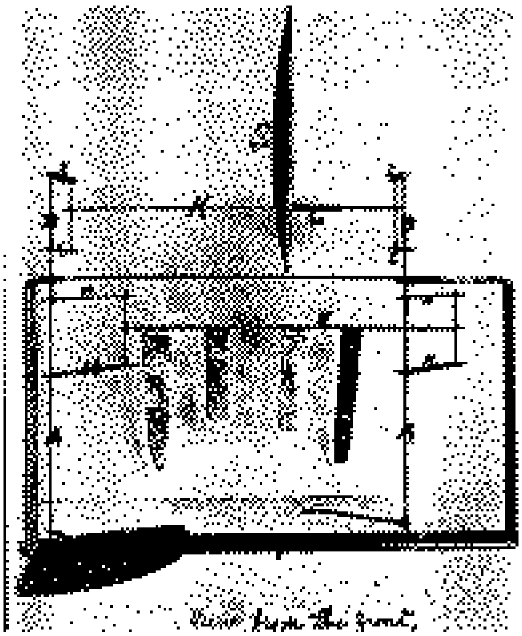

Figure 1. Wilbur Wright's photograph of their lift apparatus, sent to Octave Chanute on January 14, 1902.

1902[30]. Wilbur’s sketch of the mechanism is shown in Figure 2, and on January 19, 1902, Wilbur sent this sketch to Octave Chanute, along with instructions on how to use the instrument[31].

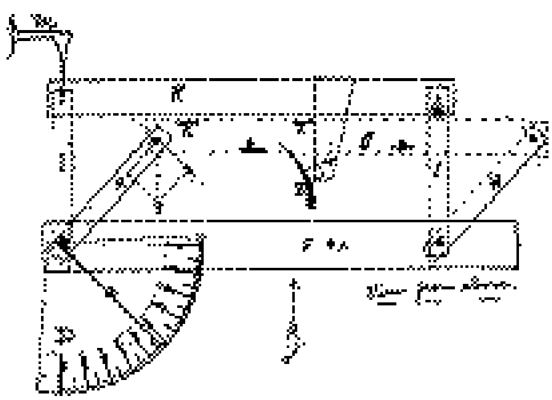

Figure 2. Wilbur Wright's sketch describing how their lift-measuring apparatus operated.

The interested reader is referred to Wilbur’s original instructions for a more complete discussion. Wald[32] discussed the workings of the lift-measuring apparatus and his sketch is used in the present discussion to emphasize the simplicity and elegance of the apparatus. Referring to Figure 1, the actual device is shown with the Wright brothers’ airfoil model number 20 mounted for testing[33]. The Wright brothers could not estimate the neutral axis of their airfoil and to eliminate any influences due to an uncontrolled pitching moment, they mounted the airfoil on the linkage ABB’A’, shown in Figure 3 (elements I, K, and I in Figure 2). If properly fabricated, that linkage cannot transmit any pitching moment produced by the test airfoil. However, the variable drag force produced by the test airfoil (call that force “D”) acts to oppose the normal force acting on the reference elements (shown in Figure 1). Referring to Figures 1 and 3, it can be seen that the lift force on the test airfoil produces a torque that will cause the reference element to translate back and forth in the wind tunnel flow until the moment produced by the reference plate is offset by the moment produced by the airfoil, transmitted along shafts AB, shown in Figure 1. Now, a careful examination of the general case shows that the drag force produced by the test airfoil also contributes to the moment transmitted to the reference linkage *unless the airfoil test linkage elements (labeled “I” in Figure 2, and AB, in Figure 3) are aligned with the wind direction (as shown in Figure 2)*. Wilbur called the spring elements, designated as “B” in Figure 1, *friction sleeves*, but they were employed to “lock” and “unlock” the airfoil linkage to the reference linkage. When an airfoil was being tested in the wind tunnel, the wind tunnel operator (Wilbur or Orville) had to adjust the friction sleeves until the linkage elements, labeled as “I” in Figure 1,

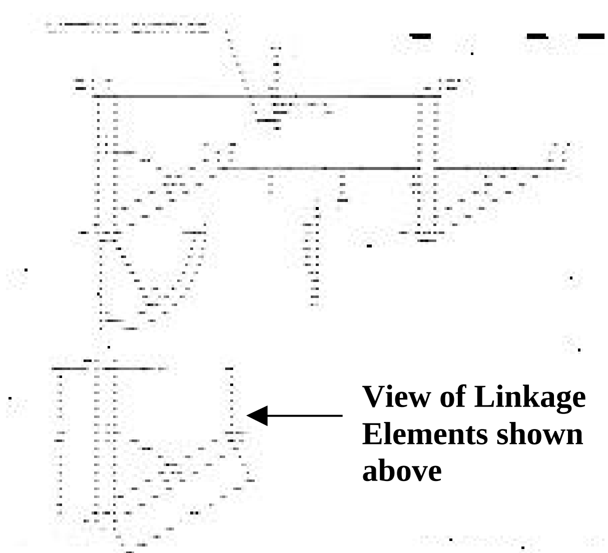

Figure 3. Modification of Wald's sketch of the Wright lift measuring apparatus.

were parallel with the wind tunnel flow direction. In that way, the drag force produced by the test airfoil did not produce a moment that affected the moment produced by the reference element. Consequently, if the sketch of the linkage elements shown in Figure 3, is used to represent the balance of moments, we see that:

$$LAR - FAR \sin a = 0,$$

or

$$LAR = FAR \sin a,$$

or

representing the (unknown) lift force, L, as the dynamic pressure (_ ΔV^2) multiplied by the lift coefficient (C_L), multiplied by the wing area (A_{WING}), and representing the reference force, F, as the dynamic pressure multiplied by the drag coefficient ($C_{D,Ref}$ =1.17 at a Reynolds number of 58,000), multiplied by the reference area (8 in^2), we have

$$\_\ \Delta V^2 C_L A A_{WING} AR = \_\ \Delta V^2 C_{D,Ref} A A_{reference} AR \sin a,$$

or

$$C_L = (A_{reference} / A_{WING}) C_{D,\, Ref} \sin a.$$

Since the drag coefficient for a rectangular plate was not know accurately at the time of the Wright brothers' tests, it was taken nominally equal to unity, and we see that the Wright brothers' lift apparatus design not only eliminated the need to measure small forces directly, but it actually enabled them to estimate their airfoil lift coefficient as simply the sine of angle "a", where that angle was measured using the stylus mounted at the bottom of left shaft A, shown in Figure 1. When the airfoil area was equal to the reference plate area (eight square inches), the sin of angle "a" corresponded to the lift coefficient[34]. Most of the airfoils that were tested had wing areas of six square inches.

The device used to determine the ratio of drag force to lift force for their airfoil models was just as ingenious[35]. That device was a rectangular frame so constructed that when the lift and drag forces (L and D, respectively) were produced on the airfoil being tested, the frame assumed the shape of a parallelogram whose acute angle, 2, (as indicated by a pointer attached to a pedestal beneath one of the pivot shafts) obeyed the relation:

$$D/L = C_D/C_L = \tan 2.$$

Thus, by measuring a single acute angle, the ratio of airfoil drag to airfoil lift was gotten by simply computing the tangent of the angle.

ACKNOWLEDGEMENT

This work was supported by the NASA Langley Research Center under Cooperative Educational Agreement CA NCC-1-369. Propeller construction was supported partially by the Virginia Center for Innovative Technology, and by the contribution of the personal services of Larry Parks from BAE Systems. The electric motor propeller drive and speed control unit were donated to Old Dominion University by Teco Westinghouse.

REFERENCES

1. Jakab, P.L., 1990, *Visions of a Flying Machine*, Smithsonian Institution Press, Washington, D.C.
2. McFarland, M.W., 1953, *The Papers of Wilbur and Orville Wright, Including the Chanute-Wright Letters, Volumes I and II*, (Republished in 2001 by the McGraw-Hill Publishing Company, New York), Volume I, pp. 3-4.
3. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 5-12.
4. Lewis, G.W., 1939, "Some Modern Methods of Research in Problems of Flight", *Journal of the Aeronautical Society*, Oct. 1939, pp. 771-778.
5. Jakab, P.L., 1990, *Op cit.*, pp. 138-140.
6. Jakab, P.L., 1990, *Op cit.*, pp. 152-182.
7. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 286-287.
8. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 596-597.
9. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 598-600.
10. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 600-605.
11. McFarland, M.W., 1953, *Op cit.*, Volume I, p. 602.
12. Photocopy of Wilbur and Orville Wright's 1908 Notebook, pg. 13.
13. McFarland, M.W., 1953, *Op cit.*, Volume I, p 636.
14. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 594-640.
15. Rankine, W.J.M., 1865, "On the Mechanical Principles of the Action of Propellers", *Transactions of the Institution of Naval Architects*, Read at the Sixth Session on April 16, 1865.

See also *R&M No. 64, Technical Report of the Advisory Committee for Aeronautics for the Year 1911-12*. William Froude's contribution to the momentum theory was published only as a discussion at the end of Rankine's paper. Froude summarized his contributions to propeller theory later in "On the Elementary Relation between Pitch, Slip, and Propulsion Efficiency", *National Advisory Committee for Aeronautics, Technical Memorandum No. 1, 1920*.

16. Miley, S.J., Ash, R.L., Hyde, K.W., Landman, D., and Sparks, A.K., 2001, "Propeller Performance Tests of Wright Brothers' 'Bent End' Propellers", submitted to the *Journal of Aircraft*, April 2000.
17. Ash, R.L., Miley, S.J., Landman, D., and Hyde, K.W., 2000, "Propeller Performance of Wright Brothers' 'Bent End' Propellers", presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, July 2000, *AIAA Paper No. 2000-3152*.
18. Landman, D., Blackburn, S., Ash, R.L. and Hyde, K.W., 2001, "Wind Tunnel Testing of the Wright Brothers' Model B Airfoil", presented at the 39th AIAA Aerospace Sciences Meeting, Reno, NV, January, 2001, *AIAA Paper No. 2001-0310*.
19. McFarland, M.W., 1953, *Op cit.*, Volume I, p. 639.
20. McFarland, M.W., 1953, *Op cit.*, Volume I, p. 635.
21. McFarland, M.W., 1953, *Op cit.*, Volume II, p. 1189.
22. McFarland, M.W., 1953, *Op cit.*, Volume I, Plate 118.
23. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 123-128.
24. Smeaton, J., 1759, "An Experimental Enquiry Concerning the Natural Powers of Water and Wind to Turn Mills, and Other Machines, Depending on a Circular Motion", *Philosophical Transactions of the Royal Society*, Vol. 51, pt. 1, pp. 100-174. (See McFarland, *op cit.*, pp. 574-575, for a discussion of how the Wright brothers utilized their 1902 glider tests to validate their correction of Smeaton's constant—to k=0.0033, in English units.)
25. Langley, S.P., 1891, *Experiments in Aerodynamics*, Washington, D.C.
26. McFarland, M.W., 1953, *Op cit.*, Volume I, p. 134.
27. Marey, E. J., 1901, *Comptes Rendus*, Vol. 132, No. 22, pp. 1291-1296.
28. McFarland, M.W., 1953, *Op cit.*, Volume I, Plates 115-117.
29. Hoerner, S.F., 1965, *Fluid-Dynamic Drag*, published by the author, pgs. 3-14 to 3-16.
30. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 122-209.
31. McFarland, M.W., 1953, *Op cit.*, Volume I, pp. 206-207.
32. Wald, Q.R., 1999, *The Wright Brothers as Engineers, An Appraisal & Flying with The Wright Brothers, One Man's Experience*, published by the author, pp. 26-32.
33. McFarland, M.W., 1953, *Op cit.*, Volume I, Plate 127 and p. 563.
34. McFarland, M.W., 1953, *Op cit.*, Volume I, p. 578.
35. McFarland, M.W., 1953, *Op cit.*, Volume I, p. 555.