JOURNAL OF AIRCRAFT
Vol. 39, No. 2, March–April 2002

Propeller Performance Tests of Wright Brothers' "Bent-End" Propellers

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A pair of Wright brothers bent-end wooden propeller reproductions were tested in the Langley Full Scale Wind Tunnel to document the Wright brothers' pioneering propeller design contributions, achieved during the first decade of powered human flight. Measurements have confirmed the effectiveness of their ingenious use of Wilbur Wright's blade element theory, exploiting large-diameter propellers, turning at low rotational speeds. Their optimized propeller designs utilized rearward blade sweep and incorporated a type of composite fiber tip covering (over their laminated spruce propeller blades) to produce propellers with maximum efficiencies above 85% at nominal advance ratios slightly above one. Not only did their circa 1905 propeller designs approach modern wooden propeller efficiency levels, but their lightweight, laminated wood construction and manufacturing techniques produced propellers that were structurally strong, which enabled the Wright brothers to retain their basic propeller designs for the entire life of the Wright Company. The Wright brothers' intuitive approach to airplane design, coupled with their desire to commercialize their flyers, interfered with technical dissemination of the theory behind their propeller designs; thus, the work of others became the basis for the evolving methodology for propeller design. The Wright brothers' achievements are discussed in the context of the published propeller research of their time.

Nomenclature

C_P	=	propeller power coefficient, $2\pi Q/(\rho n^2 D^5)$
C_T	=	propeller thrust coefficient, $T/(\rho n^2 D^4)$
D	=	propeller diameter, ft
J	=	propeller advance ratio, U/nD
n	=	rotational speed of the propeller, revolutions/s
p	=	pitch of the propeller, ft/revolution
Q	=	measured propeller shaft torque, ft · lbf
T	=	measured propeller thrust, lbf
U	=	forward velocity of the propeller, fps
η	=	propeller propulsive efficiency
ρ	=	density of air, slugs/ft^3

Introduction

BETWEEN 1902 and 1912, the Wright brothers expended a considerable amount of time and resources in perfecting efficient, practical wooden propeller designs. As we approach the 100th anniversary of the Wright brothers' first controlled, powered flight, it is important to recognize that the Wright brothers were successful because they used a building block, systems engineering approach to airplane design.[1] They developed state-of-the-art airfoil technology and aircraft structures, while pioneering flight control concepts. Their propeller designs were of comparable performance to present day similar large-diameter, slow-turning propellers used for human-powered flight and wind turbines. They also became leaders in creating an aviation industry, exploiting the aeronautical breakthroughs that they had gained through ingenious methods of experimentation and remarkable intuition. A great deal has been written about Wilbur Wright's development and subsequent patent of wing warping for controlling turns in flight because that development was key to evolving controlled, powered flight. However, the Wright brothers could not have achieved powered flight using their heavy, inefficient gasoline motors without incorporating propellers that were far more efficient than any other propeller designs of that era. Wilbur Wright's somewhat intuitive development of blade element theory and the Wright brothers' subsequent development of efficient bent-end wooden propellers is an important case study. The purpose of this paper is to document aspects of the Wright brothers' pioneering propeller research and to report the results of full-scale performance tests of two reproduction bent-end propellers.

Historical Overview

To place the Wright brothers' propeller design contributions in perspective, their gasoline engine designs could not be considered cutting edge. That they were able to achieve controlled, powered flight in late 1903, using an engine that produced approximately 12 hp, while weighing slightly more than 200 lb (Ref. 2), is truly remarkable. For comparison, Samuel P. Langley's unsuccessful 1903 *Great Aerodrome* was powered by a 53 hp, five-cylinder radial engine that weighed 125 lb (Ref. 3). Wilbur Wright can be credited with developing a type of blade element theory,[4,5] but the writings of the Wright brothers, culled from four notebooks and from Orville Wright's notes, do not document the theory adequately. (see Ref. 4, pp. 594–640, for a compilation of their propeller design documentation.) Anderson[5] has recognized the Wright brothers' contribution to propeller design as a major contribution to applied aerodynamics in and of itself. In the context of the 1902–1918 time frame, our tests confirm Anderson's assertion.

Received 25 April 2000; revision received 17 October 2001; accepted for publication 22 October 2001.

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Wilbur and Orville Wright were self-educated for the most part and, like most of the early airplane builders, they lacked the mathematical sophistication needed to utilize the existing theoretical work of Leonhard Euler (1707–1783), Hermann L. F. von Helmholtz (1821–1894), Joseph-Louis Lagrange (1736–1813), and Pierre-Simon Laplace (1749–1827) that would have permitted the development of airplane wing and propeller designs based on rigorous mathematical principles. The Wright brothers are known to have studied the published work of Sir George Cayley (1773–1857), Samuel Pierpont Langley (1834–1906), and Otto Lileanthal (1848–1896),[4] and they relied heavily on the experimental measurements of John Smeaton (1724–1792) in estimating expected aerodynamic performance. Smeaton's coefficient was the widely accepted (for more than 100 years) constant density estimate of the dynamic pressure in air, reported as 0.005 in English units in a paper that most surely is the first publication on propeller (windmill) design.[6] (see Ref. 4, pp. 574, 575, for a discussion of how the Wright brothers utilized their 1902 glider tests to correct Smeaton's constant to $k = 0.0033$, in English units.) Reference 6 is arguably the first engineering journal publication to utilize a methodical, parametric experimental approach to engineering design. Furthermore, Smeaton was probably the first to report on using scale models systematically in his experiments (see Ref. 7). Before 1901, the Wright brothers did not realize that Langley had used his earlier rotating airfoil experiments to correct Smeaton's coefficient (to a value of 0.003), but their 1900 and 1901 glider flight-test experiments produced lift and drag inconsistencies when compared with their design estimates, causing them to initiate a wind-tunnel testing program in late 1901 that corroborated Langley's correction (see Ref. 5).

Between the Wright brothers' propeller tests in February 1903 and the development of their production *Wright Flyer, Model B* in 1909–1910, they evolved wooden propeller designs that achieved efficiencies that are comparable to present day propellers of similar type. Wilbur Wright's notebook entry on 6 March 1903 appears to estimate the efficiency of their *Wright Flyer* propellers as 66% (see Ref. 4, p. 128). The propellers on the 1903 *Wright Flyer* were based on Wilbur Wright's blade element theory. It should be noted that Octave Chanute sent Wilbur a copy of a book containing Drzewicki's blade element theory[8] in June of 1903 (see Ref. 4, p. 315); however, the Wright brothers had completed their propeller studies before receiving that book (see Ref. 4, pp. 315–318). As further evidence of their originality, after studying Drzewicki's work,[8] Wilbur Wright informed Chanute that Drzewicki's theory for designing screw propellers for ships and dirigibles was neither consistent with the Wrights' approach nor fully applicable to airplane propellers, having failed to include the influence of induced local velocities on blade performance (see Ref. 4, pp. 335–337). Because the Wrights were experimentalists rather than theorists, it is interesting to see how they proceeded from their 1903 propellers to their breakthrough propeller design of 1905.

The modest performance of the Wright engines translated to a necessary requirement for high propulsive efficiency. (Their engines produced 0.06 hp/lb, compared with 0.42 hp/lb for Langley's *Great Aerodrome.*) Between 1904 and 1908, the Wright brothers concentrated a great deal of their time and energy on increasing the performance capabilities of their engines and improving the efficiency of their propellers. Using very primitive instrumentation, they were able to measure increased horsepower from slightly modified engines. However, propeller designs presented a different challenge because they knew that propeller performance was different during forward flight than when tested under static conditions. Static thrust levels were obtained by measuring the force produced when pairs of airplane propellers were driven at various rotational speeds while the host airplane sat on the ground, tethered to a grocery scale. The true propeller performance aspects of their experimental program required flight tests, but it was very difficult and time consuming to design, build and flight test a large number of propeller designs.

After the 1903 *Wright Flyer* was damaged severely by a wind gust on 17 December 1903, the Wright brothers salvaged its propellers for their initial propeller performance tests during their subsequent 1904 *Wright Flyer* development program. In addition to the salvaged propellers, at least three other propeller designs were built and tested in 1904, but some of those designs appear to have been tested only via static tests.[4] The Wright brothers believed that increasing the horsepower of their engines and improving propeller efficiency were of comparable importance in their overall research and development strategy, but they did not try to isolate the two variables.

By 1905, the Wrights had determined that the improved propeller performance they had expected from their newest propeller designs was not being demonstrated in either static or flight tests. Their improved propeller designs incorporated increased blade widths, increased maximum blade pitch angles, and thinner blade airfoil cross sections; however, it became apparent that the newer designs did not yield performance improvements that were consistent with their predictions. They must have suspected that the degraded performance was due to blade deflections (uncontrolled blade twist was their biggest concern) because increased blade width (increased blade forces) and decreased blade thickness (decreased torsional stiffness) both contribute to increased propeller blade torsional deflections under load. Lacking any sort of instrumentation to verify their conjectures, they elected instead to install small flap devices, which they called little jokers (see Ref. 4, p. 510), on the leading and/or trailing edges of a tapered-end propeller. There are no known photographs or sketches of the little joker devices, but the hole pattern on the tapered propeller that was used in those tests suggests that the little jokers were 20 gauge steel (used extensively by the Wright brothers for their wind-tunnel models) flaps, screwed onto either edge of the propeller blade. It is not known if the Wright brothers understood the blade torsional deflection problem or whether they simply wanted to find out if either the leading or trailing portion of the wider propeller blades had greater influence on propeller performance, by using the removable little jokers. Either way, those tests enabled them to decide that wide propeller blades with a rearward blade sweep improved propeller performance. Using the little jokers on the blade trailing edges, they were able to counteract effectively the aerodynamic forces, which we now suspect were acting to untwist the blades, and to demonstrate that the modified propellers produced improved performance levels. Their intuition, thus, enabled them to demonstrate that blade torsional deflection (untwisting) degraded performance, and they proceeded to their remarkable bent-end design during the 1905 testing campaign. The blade flexibility was alleviated substantially when the leading edge of the propeller blade, near the blade tip, was swept backward with respect to the neutral (elastic) axis of the blade (Fig. 1). The widened bent-end blades produced torsional loads on the blade airfoil sections that tended to increase the twist of the blades into the wind, increasing the local pitch angles of the leading edge. Sweeping the blades rearward moved the local blade center of lift closer to the blade elastic axis, thus reducing the associated twisting moment. Today, we recognize their design problem as a basic aeroelastic effect, known as static divergence, and we know that rearward blade sweep mitigates static divergence, whereas forward sweep promotes it. By sweeping the outer portion of the propeller blade backwards, they found that

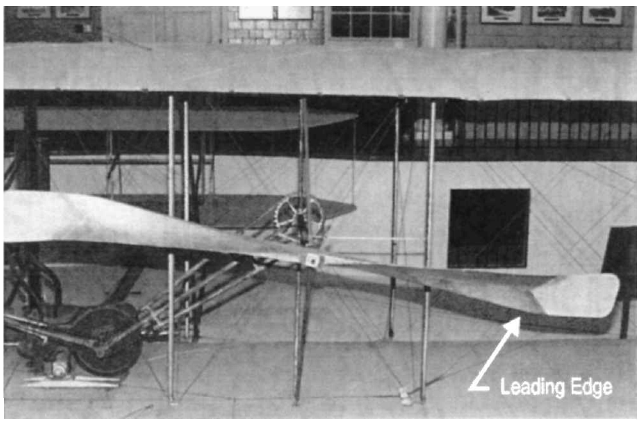

Fig. 1 Wright brothers 1905 bent-end propeller.

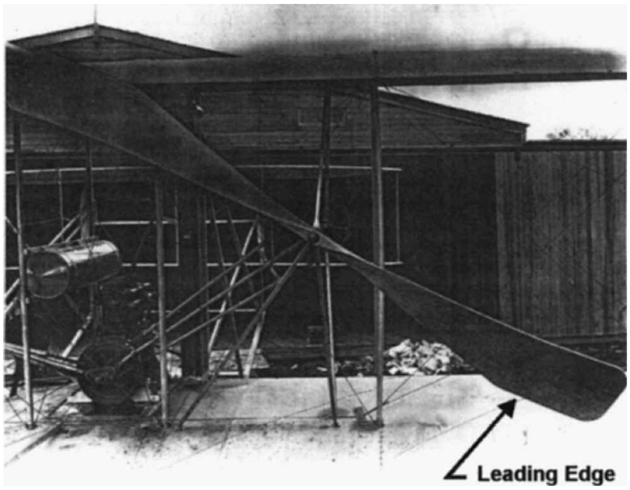

Fig. 2 Wright brothers 1910 bent-end propeller.

propeller efficiency was increased, and they must have concluded that the reduced discrepancies between their measurements and their predictions was due to their effective improvement of the rigidity of their propeller blade design. After 1905, their bent-end propellers became their standard design. (For comparison, Fig. 2 is a photograph of a 1910 propeller.) This is further evidence of the Wright brothers' remarkable ability to decide when they had achieved an acceptable solution to a particular aspect of airplane design and then move on to attack other problems.

Because the Wright propeller designs were basically frozen from immediately after the 1905 bent-end propeller development until 1915, when the Wright Company was sold, it is instructive to evaluate that design[4] relative to contemporary propeller technology.

The standard bent-end propellers were used primarily during Wilbur Wright's 1908–1909 flight demonstration campaign in Europe. During that period, a Prussian dirigible captain, Eberhardt,[9] was able to make measurements of the bent-end propellers that were being used, and by estimating the shaft horsepower, he estimated the propeller efficiency to be 71% at 15 m/s and 76% at 16 m/s (Ref. 4, p. 595). In 1912, Caldwell and Lehman[10] measured the performance of five contemporary propellers, including one bent-end Wright propeller, as part of their undergraduate theses at Massachusetts Institute of Technology (MIT). A large whirling arm, located at Worcester Polytechnic Institute, was used to generate a speed-controlled airflow through the test propellers. Thrust measurements were made using a calibrated spring scale, connected mechanically to a stylus that recorded the spring deflection on a rotating drum. An acceptable scientific effort was expended, considering the period, and Caldwell continued to contribute to aeronautical research, but the measured propeller thrust levels, reported in Ref. 10, were low compared to later investigations employing more sophisticated instrumentation. Besides the MIT attempt, the present authors have found no other performance measurements reported for the Wright bent-end propeller designs.

On 30 April 1909, the Prime Minister of Great Britain formed an Advisory Committee on Aeronautics and appointed Lord Rayleigh as its chairman. The committee was charged with placing aerial navigation on a more satisfactory footing, overseeing investigations at the National Physical Laboratory, and providing general advice on scientific problems arising in connection with aerial construction and navigation.[11] In the first committee report, Greenhill[12] reported on screw propeller design methods that had been developed for ships and discussed their application to airplane propeller design. He suggested an extension of a counter-rotating ship propeller design to propulsion for a helicopter that would not require a tail rotor, and he discussed using similitude to estimate scaling effects. Greenhill defined velocity of advance np as the pitch p (axial displacement along a helix, in feet, produced by a screw with the same pitch angle as the propeller, after completing one revolution) multiplied by the rotational speed n (revolutions per second), and slip s was defined as the departure of the forward velocity of the aircraft, for example, U (feet per second), from the velocity that would be achieved by a perfect screw propeller, that is,

$$s = 1 - U/(np) \tag{1}$$

Greenhill advocated using a small-scale railroad locomotive with propellers mounted ahead of the engine as an alternative to flight tests or wind-channel testing to measure propeller performance during forward flight.

Bairstow, Bramwell and Sillick reported on propellor tests using a new rotating table dynamometer apparatus in the 1910–1911 report of the Advisory Committee on Aeronautics.[13] They reported on tests performed using 2-ft-diam model propellers, and they included data on a 15-ft-diam propeller supplied by Messrs. Vickers, Ltd., which had a measured propeller efficiency of 64%. Expanded model propeller test results were reported in the 1911–1912 report,[14] including a comparison between the $\frac{2}{15}$-scale model of the Vickers propeller, which achieved an efficiency of 61.9% (with a slip velocity of 37.5%) and the measured efficiency of 64% for the full-scale propeller. The committee tested 11 model propellers, varying slip, pitch ratio (p/D, where D is the propeller diameter), and disk area ratio (area occupied by the propeller blades divided by $\pi D^2/4$) and measured the efficiencies under different operating conditions. They found that the propellers all had similar characteristics, and even though the maximum efficiencies occurred at different combinations of slip, pitch ratio and disk area ratio for the different designs, the actual maximum efficiencies only varied between 71 and 76.7%. They found that even though the propeller performance varied only slightly with disk area ratio and pitch ratios, maximum efficiencies were achieved with "fairly high" pitch ratios and moderate disk area ratios. They also found that propellers with higher pitch ratios obtained higher efficiencies at higher slip, compared with moderate and low pitch ratios.

In the committee report of 1911–1912, Bolas[15] described the design methodology that had evolved at the Royal Aircraft Factory as of March 1912. The Royal Aircraft Factory design methodology was based on Drzewiecki's 1902 blade-element theory[8] and was called the constant incidence method. In the committee report, Greenhill[16] inserted W. John Macquorn Rankine's paper entitled "The Principles and Action of Propellers," which had been presented originally at the Institution of Naval Architects in 1865. Greenhill then proceeded to hypothesize that the theoretical propeller efficiency e was equal to the pitch helix advance ratio[16] $U/(pn)$, that is,

$$e = 1 - s = U/(pn) = \text{pitch helix advance ratio} \tag{2}$$

Following Greenhill's report,[16] Bramwell[17] reported that propeller efficiency could exceed Greenhill's prediction[16] and proposed a modified efficiency prediction based on estimates of the propeller wake velocity. Bramwell's modified theory[17] appeared to predict that the maximum efficiency always approached 100%.

Because the Model B propellers were built and flown before the 1912 report of the Advisory Committee on Aeronautics, it is fair to say that the state of the art in propeller design, as represented by the Royal Airplane Factory and the Advisory Committee on Aeronautics in the United Kingdom during the Wright brothers' bent-end propeller era, was as follows: 1) The Advisory Committee on Aeronautics utilized the blade element design approach of Drzewiecki[8] and made no reference to the Wright brothers. 2) The U.K. researchers were divided on how to predict propeller performance accurately. 3) Based on all of the committee's reported propeller tests, a maximum efficiency of 76.7% was reported for one model propeller at one slip velocity, using the resources of the National Physical Laboratory. As of 1905, the Wright brothers had used Wilbur Wright's blade element theory to design their propellers, evolved their bent-end propeller design, and determined that propeller performance was degraded by blade torsional deflections unless they modified the overall propeller blade geometry to reduce bending under load. Between 1905 and 1909, the Wright brothers experimented only with minor alterations of blade shape and pitch distributions from their bent-end propellers (see Ref. 4) and for all intents and purposes, they employed the bent-end propeller design from 1905 until the Wright Company was sold in 1915. In comparing the Wright brothers' developed propeller with that of European and other American efforts, it must be remembered that the flight speed of the intended aircraft and the method of driving the propeller from the power plant (geared vs direct) influences the propeller design; large-diameter, low rotational speed vs small-diameter, high rotational speed. High rotational speeds and direct drive power plants, necessary for high-speed flight, requires a tradeoff of some aerodynamic refinements for increased structural strength to withstand the increased static and dynamic loads. For instance, high-speed propeller blade root sections must depart from the desired slender airfoil shape in favor of a thickened elliptical section.

The U.S. Army issued specifications for procuring a flying machine on 23 December 1907 (see Ref. 18). On 17 September 1908, the Wright brothers' *1908 Signal Corps Flyer* experienced a propeller failure during demonstration flights for the Army, killing passenger Thomas Selfridge and seriously injuring pilot Orville Wright. The propeller failure prompted the Wright brothers to modify their propellers, returning to their standard 8-ft, 6-in.-diam, bent-end design (the failed bent-end propeller was 9 ft in diameter) and henceforth employing a fabric covering on the outer portions of the propeller blades. Because of their manufacturing techniques, they essentially created a single-layer fiber material composite coating that contributed to the surprising stiffness of their laminated spruce propeller blades. The Wright brothers finally delivered an acceptable airplane to the U.S. Army on 2 August 1909.

After formation and capitalization of the Wright Company, on 22 November 1909, the Wright brothers began to concentrate on construction and marketing of airplanes. By early 1910, the Wrights were no longer devoting significant amounts of time to fundamental studies of aeronautics (see Ref. 4). They completed the first production version of their *Wright Flyer Model B*, on 29 June 1910 (see Ref. 18). Wilbur Wright died of typhoid fever in 1912, and the Wright Company was sold to a syndicate in 1915.

An interesting question then is how to evaluate the Wright brothers' technical accomplishments in the areas of propeller design and construction with other efforts underway in the period following their pioneering first flight. Furthermore, to put the current bent-end propeller performance measurements in perspective, it is necessary to move forward in time sufficiently to have evolved systematic procedures for the design and evaluation of propellers. Vincenti[7] has an excellent overall history of the evolution of propeller design, whereas Rosen[19] has provided a pictorial history of the evolution of commercial airplane propellers. The reader is referred to their work for a more complete historical overview.

Even though the United States did not enter World War I until 1917, by 1915 it was apparent that airplanes could be employed as instruments of war and Great Britain, Germany, and France were moving ahead of the United States in the development of aviation technologies. In response to that pending technology gap, President Woodrow Wilson created NACA on 3 March 1915, appointing a 12-person advisory committee on 15 April 1915. NACA was approved by Congress (as a rider to the 1915 Navy Appropriations Bill), and it was charged "to supervise and direct the scientific study of the problems of flight, with a view to their practical solutions."[20] William F. Durand (1859–1958) of Stanford University was one of the original NACA committee members, and at their first meeting on 23 April 1915, he proposed that his group at Stanford University be authorized to conduct research on propellers. NACA responded favorably, and a contract was awarded to Stanford University in October 1916. Between 1916 and 1926, Durand and Lesley conducted a comprehensive propeller test program, producing a database that continued to be employed throughout World War II (see Ref. 7). Their research adopted Eiffel's[21] basic dimensionless group

$$U/nD \equiv J \tag{3}$$

and that parameter has come to be known as the advance ratio, the fundamental independent variable for which propeller performance data are presented.

During World War I, airplanes were used initially as observation platforms, but new airplanes were developed quickly for use as fighters and primitive bombers. At the end of World War I, the Western Allies had manufactured almost 160,000 airplanes, of which 15,000 were manufactured in the United States,[22] and only a small fraction had been manufactured by the Wright Company. Reliable and efficient high rotational speed wooden propellers were a major aircraft concern throughout World War I, due to poor quality control and excessive noise and vibration. Research on blade twisting had become an important area of research, but was a major source of frustration because of wood's inherent heterogeneity, resulting in variations in measured blade twist distributions that could differ by as much as a factor of six for opposite blades of the same propeller.[23] In 1918, Griffith and Hague[23] wrote

> Experiments have been made, from time to time, with a view to discovering an extension of the ordinary theory of bending and twisting of long beams which would represent adequately the behaviour of propeller blades, but the result has always been unsatisfactory, so much so, indeed, that it has usually been necessary to express the unknown quantities by means of a number of empirical constants at least equal to the number of experiments.

The Wright brothers developed their propellers using original theory for design, coupled with experimental validation of performance estimates. They were limited, however, in their access to basic instrumentation and test facilities that would have enabled them to illuminate and interpret the fundamental physics underlying the success of their bent-end propeller designs. Recently, Old Dominion University and The Wright Experience, Inc., in cooperation with the NASA Langley Research Center (LaRC), conducted tests to determine the aerodynamic performance and structural deflection characteristics of Wright brothers' bent-end (Model B) propellers.

Propeller Tests

Aerodynamic Measurements

Two 1911 *Wright Flyer, Model B* propeller reproductions were built for testing, using measurements from the propellers on the 1911 Model B located at the Franklin Institute in Philadelphia and from the Harry Atwood Burgess, Wright Model F propeller (employing the same bent-end propellers as the Model B). The Wright Experience, Inc., built two 8.5-ft-diam (2.59 m), bent-end propeller reproductions, carefully duplicating the construction materials, dimensions,[4] and manufacturing techniques employed by the Wright brothers. One propeller, designated B-01, weighed 9.0 lb (4.08 kg), and the other propeller, designated B-02, weighed 8.9 lb (4.04 kg).

The propellers were tested in Old Dominion University's Langle Full Scale Wind Tunnel[24] (LFST). The propeller test rig, shown in Fig. 3, was originally designed, built, and delivered to NASA LaRC by Mississippi State University in 1980.[25] The test rig tower was

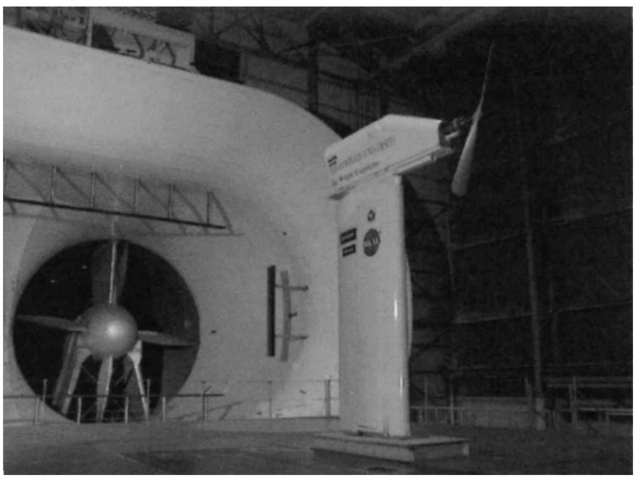

Fig. 3 Propeller test stand installed in LFST.

Fig. 4 Test propeller installation showing balance and slipring assembly.

attached to the permanent LFST drag balance and was shrouded with a cowling and streamlined strut fairing (mounted to the LFST ground board). The axis of the propeller shaft was located 15 ft (4.57 m) above the ground board along the center of the 30 by 60 ft (9.14 × 18.29 m) open test section of the LFST. The propellers were operated as tractor propellers in contrast with the pusher propeller configuration employed by the Wright brothers, to minimize flow interference resulting from the obstructions produced by the test stand and drive system. The 2-in.-diam (5.08 cm) propeller drive shaft was powered by a Teco Westinghouse, 25 hp (18.65 kw), MAX-E1 variable speed motor that could be operated over a speed range from 0 to 1250 rpm. The motor was connected via a chain drive through a 40:15 reduction gear, thus providing a propeller speed range between 0 and 465 rpm. LaRC provided a silver conducting surface slip ring and a thrust–torque balance. The particular thrust–torque balance was a NASA 600 Series,[26] with a maximum axial thrust specified as 600 lb (2700 N) and a maximum torque of 3350 in.-lb. (68 Nm) NASA LaRC calibrated the balance before the test as part of their support for this investigation. Balance strain gauge excitation voltages were provided by a Hewlett–Packard (HP) E3615A power supply. The installed balance/slip ring assembly is shown in Fig. 4. Data were acquired using an HP 3497A, 6.5-digit, data acquisition unit, with a general purpose interface bus (GPIB) interface to a personal computer running LabView™ software. The measured thrust and torque data were displayed in dimensionless coefficient form as thrust coefficient C_T and power coefficient C_P, respectively.[27] The thrust coefficient is defined as

$$C_T = T/[\rho n^2 D^4] \tag{4}$$

where T is the measured thrust and ρ is the density of air during the test; n and D were defined earlier as the propeller speed and propeller diameter, respectively. The power coefficient C_P is given by

$$C_P = 2\pi Q/[\rho n^2 D^5] \tag{5}$$

where Q is the measured torque.

Both propellers were subjected to the same test conditions. Before the wind tunnel was started, static thrust and torque measurements were acquired for propeller rotation speeds up to 420 rpm. Subsequently, wind-tunnel speed was varied to produce thrust and torque data over an advance ratio range from zero to the point where no torque was required to windmill the propeller.

As already mentioned, the data were acquired both in raw form and as thrust and power coefficients at the various controlled advance ratios. Propeller efficiency was obtained subsequently from the relation

$$\eta = JC_T/C_P \tag{6}$$

The propellers are designated B-01 and B-02, conforming to the Wright Experience, Inc., designations, to display the data in Figs. 5–7.

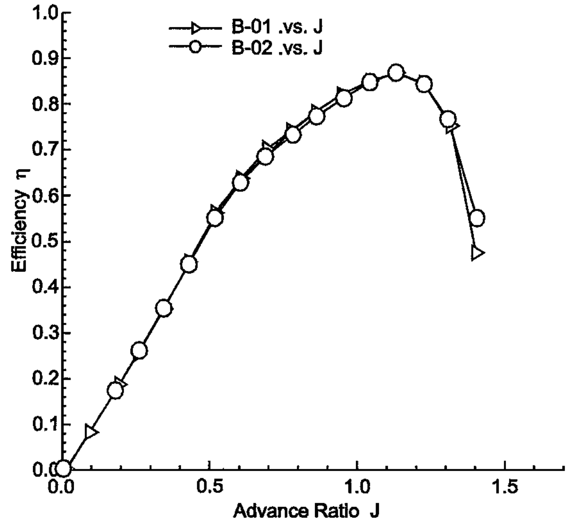

Fig. 5 Measured thrust coefficient vs advance ratio.

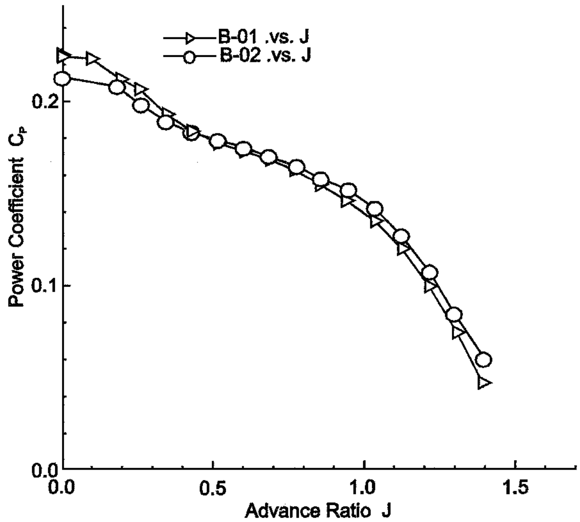

Fig. 6 Measured power coefficient vs advance ratio.

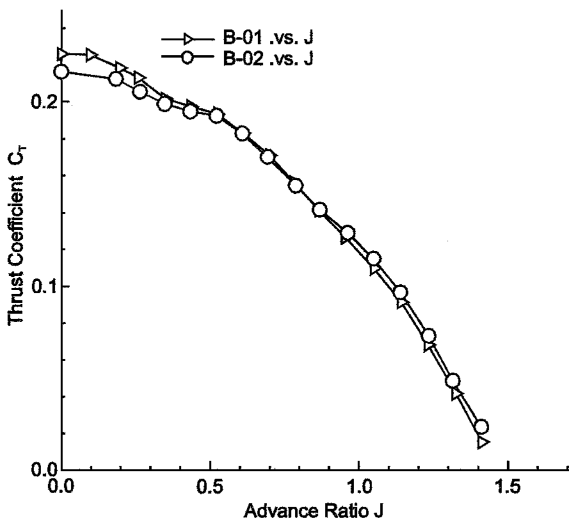

Fig. 7 Measured propeller efficiency vs advance ratio.

From Eq. (6), we see that propeller efficiency varies linearly with wind-tunnel speed U, through the advance ratio J [Eq. (3)]. Calibration of the flow conditions at the location of the propeller disk was required to eliminate that possible source for error. A rake system, consisting of four, five-hole probes, spaced on 3-ft (0.91 m) centers ($\pm$1.5 ft horizontally and $\pm$1.5 ft ($\pm$0.457 m) vertically, with respect to the rake centerline), was used to survey the propeller disk plane, absent the propeller test stand. Pressure readings were recorded and correlated with the wind-tunnel reference dynamic pressure over the range of wind-tunnel motor speeds used for the propeller tests. When the average flow velocity was calculated using the four, five-hole probes (to determine reference velocity U for these tests), it was possible to develop a velocity correction factor (U/U_{tunnel}) as a function of wind-tunnel motor speed. That correction factor increased monotonically from $U/U_{\text{tunnel}} = 0.97$ at a wind-tunnel motor speed of 60 rpm to 0.99 at 200 rpm. This velocity correction, therefore, reduced the calculated propeller efficiencies by up to 2%, depending on the test conditions. Propeller B-02 achieved a maximum efficiency in excess of 86% (with a 95% confidence interval of $\pm$2.5%; see the Appendix for details) at an advance ratio of $J = 1.13$ (Fig. 7). Note that more than two Model B propellers were manufactured during the educational portion of duplicating and perfecting the Wright brothers' propeller manufacturing process. Propeller B-02 was the second propeller that was produced after the manufacturing process had been perfected and is, therefore, the best representation of Wright Company propellers from the perspective of blade contours and surface finish. When the respective thrust and power coefficient curves, presented in Figs. 5 and 6, are compared, propeller B-02 appears to have a slightly higher effective pitch than propeller B-01. Both propellers had nominal static thrust coefficients of 0.225, which would have been substantially higher than the static thrust coefficients of the wright brothers' earlier designs. The maximum efficiency of 86+% for the Wright brothers' circa 1905 bent-end propeller design is interesting when compared with later developed propellers tested by Durand[28] and Durand and Lesley[29–31] at Stanford University and summarized in Diehl's 1923 propeller efficiency compilation.[32] Note that we are comparing the large-diameter, slowly rotating propellers of the Wright brothers with the small-diameter, high-speed designs, required for future high-performance aircraft and being tested by Durand and Lesley.[29–31] The Wright brothers' decision to employ large-diameter, slowly rotating propellers with wide blades of thin cross section enabled them to achieve propulsive efficiencies that approach the levels obtained presently for human-powered airplanes.[33]

Structural Deflection Measurements

The bent-end propeller design, modified only slightly after 1905, was the Wright brothers' solution to controlling excessive blade torsional deflections under load. They could only infer that blade deflections were reduced by using the fact that the bent-end propellers exhibited superior propulsive efficiency in comparison with their previous unbent (unswept), wide blade designs. During our static propeller tests, which produced the maximum propeller blade loads, a strobe light system, provided by NASA LaRC, was employed and used with the LFST video camera system to acquire freeze frame video tape images of the blade tips (on which strips of reflecting tape were mounted). Figure 3 shows a mounted test propeller viewed from the front, looking downstream. The propellers rotated clockwise in this view. The video camera and strobe systems were located in the propeller plane, to the left at floor level. We were able to measure blade deflections for one bent-end propeller under different loads using a video camera system and a frame grabber. Visual observations, accelerometer records and our propeller performance data for the two propellers (B-01 and B-02) under various operating conditions showed that both propellers behaved similarly. Therefore, to avoid disruptions resulting from special lighting, digital video record management, and documentation requirements associated with the blade deflection measurements, we restricted blade deflection tests to one propeller (B-02).

The video camera was mounted on a tripod, located on a walkway beside the test-section ground board. The camera was mounted so that its lens was located nominally in the plane of the rotating propeller, at a horizontal distance of 22 ft (6.71 m) from the centerline of the ground board (therefore, 26.6 ft (8.11 m) from the propeller hub on the test tower and 18.4 ft (5.61 m) from the blade tip). Propeller B-02 was rotated until its blade span axis was aligned with the line of sight and a static tip reference condition was recorded, creating image frames such as the one in Fig. 8. Subsequently, a grid system (with $\frac{1}{2}$-in. (1.27 cm) spacing increments) was placed on the blade tip and recorded, as shown in Fig. 9, to enable digital image pixels to be converted into physical dimensions in the plane of the blade tip. Using similar framing and a digitized coordinate reference system, obtained in situ before the propellers were activated, it was possible to measure the maximum changes in blade twist and blade bending. It was later determined that the viewing plane containing the propeller blade tip had an image resolution of 34 pixels per inch (13.4 pixels/cm) (when the image plane was perpendicular to the camera line of sight).

Because maximum blade loadings occur when the propeller is driven with zero advance, propeller deflections were measured at four different rotational speeds without wind-tunnel air motion. The static blade image and the grid system records are considered to be runs 1 and 2, and the four blade loading deflection tests were runs 3–6. The test conditions are summarized in Table 1.

Table 1 Summary of test conditions for B-02 deflection tests

Run	RPM	Thrust, lb	Torque, in.-lb	Twist, deg	Bending, in.
3	201.3	27.4	485.8	66.8	0.27
4	300.1	63.5	1113	66.7	0.67
5	409.9	121.3	2144	66.6	1.14
6	420.3	127.8	2264	66.5	1.31

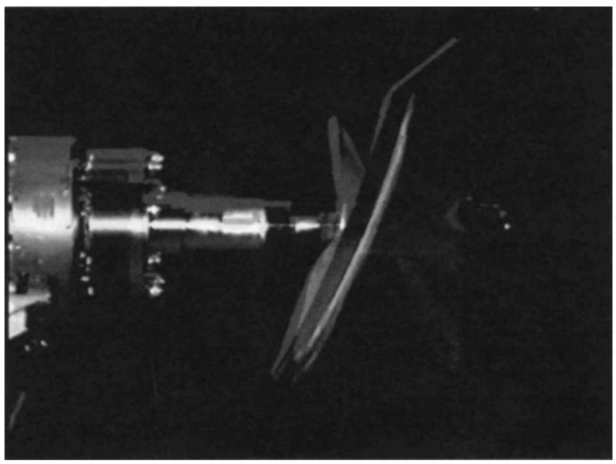

Fig. 8 Blade tip used for blade deflection measurements.

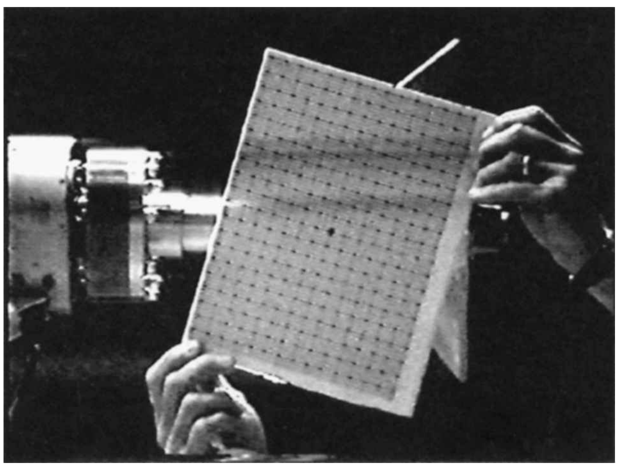

Fig. 9 Reference grid used in the propeller structural deflection measurements.

The strobe light system was used to illuminate the rotating propeller blade, and the strobe light was synchronized to coincide with the passage of each blade tip through the camera line of sight. Reflecting (red) tape was applied to the blade tips to maximize illumination. One blade tip had a solid tape strip whereas the other tip was striped, to differentiate between the two tips. The (30 frames/s) video camera could not be synchronized with either the propeller or the strobe light, and it was, therefore, necessary to make 1-min video records of each test condition and then search through the video records to find frames containing an illuminated blade tip, passing through the camera line of sight.

Old Dominion University's television production facilities dubbed the videotapes with time reference codes, and it was necessary subsequently to identify the specific times when video frames contained appropriate blade tip images. Approximately 100 frames were identified, and the production facilities were used again to convert those images to JPEG digitized file formats and then store them on a CD-ROM. The JPEG files were analyzed using Corel Draw™ to extract geometric measurements from the images.

A typical data reduction image is shown in Fig. 8. Although it was difficult to establish the chord line of the blade tip, changes in twist angle were relatively easy to measure, and the hub to tip deflection was measured by determining the axial shift in the blade tip chord line relative to the fixed propeller hub. The initial (static) blade twist angle was 67.8 deg. The variation in blade twist angle with load is tabulated as twist in Table 1, and the deflection of the blade tip relative to the blade hub is tabulated as bending. As a basis for comparison, Wieck[34] analyzed the behavior of an 8-ft 11-in.-diam standard aluminum alloy, Bu-Aero Propeller (4412), powered by a 170-hp motor at 1700 rpm and reported that at an 82 mph flight speed it had an estimated increase in twist angle of 1.8 deg and a forward bending deflection of 0.75 in. Hence, the mechanical behavior of the Wright brothers' laminated spruce, bent-end propellers under maximum aerodynamic loads was similar to the behavior of aluminum alloy propellers in climbing flight, two decades later (operated at a substantially higher rotational speed and shaft horsepower).

Conclusions

A historical perspective and investigation into the Wright brothers' propeller design methods has shown that their bent-end design was a pioneering approach to increasing propeller efficiency while minimizing the effects of aerodynamic forced blade twisting. Measurements on two reproduction, bent-end, Model B 1911 propellers have shown that by 1911, and probably as early as 1905, the Wright brothers had developed high-efficiency, slowly rotating (<450 rpm), large-diameter wooden propellers of radically new design, with efficiency levels approaching modern human-powered-flight propeller performance. They utilized a primitive type of composite material construction to reinforce their thin, laminated spruce propeller blades, achieving surprisingly stiff blade tips, with a maximum measured propeller efficiency of 86+% at an advance ratio of 1.13.

Appendix: Uncertainty Analysis

An analysis based on Ref. 35 was performed to determine the uncertainty in measuring propeller efficiency at the peak value. Precision limits were obtained through repeated evaluations of the peak efficiency. Using a 95% confidence limit the precision P was found to be 0.00133. The bias limits for the measured values were estimated based on calibrations. The data reduction equation is given in terms of the measured values. With the exception of the gas constant (error accepted as negligible) the bias of all variables was estimated for a 95% confidence limit:

$$\eta = \frac{TV}{P} = \frac{TV}{Q\omega} = \frac{T\sqrt{2qR\theta/P}}{Q\omega}$$

The torque and thrust bias limits were the greatest contribution to the total uncertainty. These values were derived from the 95% confidence limit specifications obtained during the balance calibration and could perhaps be reduced for future investigations through a more detailed calibration. Table A1 catalogs the component bias contributions to the total bias obtained using the sensitivity derivatives and the elemental bias values.

Table A1 Bias Contribution Summary

Variable X_i	Element bias limit B_i	Component bias limit $(d\eta/dx_i)B_i$
Thrust, N	6.672	0.022
Torque, N · m	1.959	0.011
Angular velocity, rad/s	0.1047	0.001933
Dynamic pressure, Pa	0.6583	0.001017
Temperature, K	1	0.001384
Atmospheric pressure, Pa	168.8	0.0006798

The total bias limit was obtained using the root sum square of all component bias values, and the total uncertainty is reported as the root sum square of the total bias and the measured precision. The total experimental uncertainty of the peak efficiency with 95% confidence was found to be 0.025:

$$B = \sqrt{\sum \frac{d\eta}{dx_i} B_i} \qquad U = \sqrt{B^2 + P^2}$$

Acknowledgments

This research is now supported partially by the NASA Langley Research Center under Educational Cooperative Agreement NASA CA NCC-1-369. The authors would like to thank NASA Langley Research Center and, specifically, A. Gary Price and Susan Althoff Gorton, for their assistance and support in performing these tests. In addition, the assistance of Modern Machine and Tool Company in recalibrating the thrust-torque balance is gratefully acknowledged.

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