

An Experimental and Analytical Evaluation of the 1911 Wright Bent End Propeller

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Abstract

In an ongoing effort to research and build reproduction aircraft of the Wright Brothers, the Wright Experience® in Warrenton, VA has constructed Wright bent end propellers that were used from 1905 – 1915. Performance of this propeller has been evaluated by a wind tunnel test on an airfoil section representing the 70% station, as well as a full propeller test to measure thrust and torque characteristics. The airfoil was tested at Parks College in St. Louis, MO to obtain lift and drag coefficients. The propeller was tested at the low speed wind tunnel at NASA Langley, under the operation of Old Dominion University. The results of the testing indicate that the Wright aircraft were successful in large part due to their highly efficient propellers.

Nomenclature

C_l = lift coefficient
 C_d = drag coefficient
 C_f = skin friction coefficient
 c_s = thrust coefficient = $\frac{T}{\frac{1}{2}\rho V^2 \pi/4 D_o^2}$
 D = propeller diameter
 D_o = diameter of downstream helix
 J = advance ratio = $\frac{V}{nD}$
 $K(x)$ = Goldstein function
 n = rotational speed
 r = prop radius

Nomenclature cont'd

R = prop tip radius
 T = thrust
 x = nondimensional radius, r/R
 \bar{w} = nondimensional displacement velocity, w/V
 ε = axial loss factor
 κ = mass coefficient
 λ = helix advance ratio at ∞
 σ = prop solidity = $\frac{2c}{2\pi r}$
 ϕ = angle of incident velocity at blade section

Introduction

The Wright Brothers are most commonly noted for their development of the first powered aircraft in 1903, however little attention is given to the details of the design of their propellers. At the Wright Experience® in Warrenton, VA, these details are being explored to better understand the genius of the Wrights and how they triumphed in the race for powered flight. One of the more interesting aspects of their work was in the development of the propellers that enabled their aircraft to take off from level ground and fly with very low power. The Wrights developed an understanding of propeller performance through the development of theories and the verification of these theories using experimental testing. The successful flights of the Wright aircraft were, in part, due to the efficiency of their propellers which greatly exceeded that of other designs of the same period.

This paper presents the results of two wind tunnel tests involving the 1911 Wright “bent end” propeller. The first test measured the section lift and drag characteristics of the 70% radial station airfoil, and the second test was a full-scale propeller test that

measured thrust and torque. The 70% station section was chosen because it is a typical airfoil shape when compared to sections from 50% to 95%.

The results of the tests indicate that the Wright bent-end propeller was an efficient design that contributed greatly to their flying success. A comparison of the Wright design is made to an optimally designed propeller which shows little difference in the efficiencies.

Background

In December, 1902, the Wrights tested a 28 in. diameter fan as a precursor to full scale propeller design. The “bow-tie” shape of the prop was selected and used on the 1903 and 1904 aircraft most likely because they were taking advantage of the higher relative velocity at the larger radii to generate the largest possible thrust for a given tip radius. In addition, they maximized the diameter of their propellers to “...secure a reaction against a greater quantity of air...”¹. The development of their momentum theory equation was very similar to that used in contemporary propeller analysis and supported the fact that efficiency increases with propeller diameter. The 8.5 ft. diameter propellers used on many of their designs represented a maximum size that would safely fit on the machines.

It is noteworthy to point out that other propellers of the period did not attempt to maximize diameter, resulting in large induced losses. Despite the low-powered engines used by the Wrights, their high-efficiency propellers proved effective in generating adequate thrust for powered flight.

Development of their own propeller theory was necessary given the lack of unifying progress in this area in 1903. Although Rankine² and Froude³ had published the concept of a propeller imparting momentum to a moving column of fluid to generate thrust, they did not tie this idea to the lift and drag forces that are experienced by the propeller blade elements. The Wrights were able to combine momentum theory concepts with blade element theory to develop specific relationships between thrust and power, a necessary step in designing a propeller.

Part of their understanding of the interaction between induced velocity as the freestream air is accelerated into the propeller and how it affects blade angle of attack is revealed in a letter to Octave Chanute

dated June 18, 1903. Wilbur wrote “...Many writers seem to think there is some connection between the thrust per horsepower standing still and the real efficiency of the screw. This really has nothing to do with the efficiency except in flying machines built on vertical screws. In other machines the thrust must be adapted to the speed at which the machine flies.”⁴ It is this early intuition that led them to their rudimentary momentum theory/blade element theory that greatly aided their propeller design.

Early in their analysis of the propeller, the Wrights realized that a drag/lift ratio that was minimum would be desirable to minimize the power required for a given thrust. The airfoil chosen for the 1903 and 1904 propellers was an arc designated as “no. 9” that showed a minimum drag/lift ratio over a wide range of angles of attack. This airfoil was superseded by no. 12 in 1905 which was a parabolic shape with maximum curvature towards the forward edge. Although no. 12 did not have as low a drag/lift over the range of angles of attack, it did show higher lift and would thus produce more thrust which was a priority as the aircraft became heavier⁵.

In addition to a new airfoil in 1905, the propeller shape was modified to account for blade deformations occurring under the increased loads as the engine horsepower increased. With the elastic axis at approximately $0.5c$, the blades tended to twist such that the angle of attack was increasing, which in turn changed the thrust distribution on the blade. Originally, the Wrights tapered the outboard 16 inches of the propellers and added small trim tabs referred to as “little jokers.”⁶ to reduce the blade twist. This modification never flew, but it led to a variation of the design that effectively solved the twisting problem. By removing a wedge-shaped section of the propeller from 70% - 100% span only on the leading edge, the twisting was compensated for by the aft-sweeping shape of the blades.

The “bent-end” propeller design was used from 1905 – 1915 on the Model A and Model B aircraft and is shown in Figure 1. The propellers were covered from the 40% span to the tip with a linen fabric to reduce the likelihood of blade cracking. It will be noted that the metallic appearance of the propeller is due to the application of a petroleum paint base containing aluminum powder. A finishing coat of clear lacquer was also applied.



Figure 1 – 1911 Wright Bent End Propeller

In examining the literature on the Wright propellers, information concerning their performance is sometimes found to be incomplete or in conflict with other sources of information. To determine accurate performance measures for the bent-end design, two wind tunnel tests have been completed for the propeller. An airfoil section representative of the 70% station was tested at Parks College in St. Louis, MO to find section C_l and C_d , and the whole propeller was tested at the Full Scale Tunnel at NASA Langley to obtain performance over a range of advance ratios.

Propeller construction

At the Wright Experience® in Warrenton, VA, considerable effort has been expended in creating authentic bent-end propellers for a Model B aircraft under construction. Unfortunately, there is not one definitive source of information regarding the propeller geometry, and so data has been obtained from three sources: a.) a digitized image of two authentic propellers, b.) construction drawings of the propeller, and c.) the notes from the Wrights regarding blade angle as a function of radial station. Since these are very different sources, the authors and others have weighed the validity of all data to obtain the best possible representation of the true propeller design.

The surviving propellers came from Harry Atwood's Wright Model B Aircraft which crashed and burned in 1913, and from Grover Bergdoll's machine which resides in the Franklin Institute in Philadelphia, PA. The propeller from the Atwood machine was cracked on one end, so only data from the good side

was used. The Franklin Institute prop was in very good condition, although one side was slightly warped to a lower pitch which was only discovered after careful examination of the notes and drawings to determine correct blade angles. Both of these propellers were scanned using a three-axis measurement probe provided by Direct Dimensions, Inc. of Baltimore, MD.

This design has been captured in a master propeller carved from mahogany, which is being used to construct multiple replicas of the propeller. The pitch is nearly constant at 10.6 ft., and the chord length outboard of the 70% station remains nearly constant at 11.2 in. The diameter is 8.5 ft. and the weight is 9.0 lbs.

Test results for the 70% radial station section

The test section, also constructed by the Wright Experience®, is shown in Figure 2 installed in the Parks College Low Speed Wind Tunnel (LSWT). This tunnel had a width of 40 inches and a height of 26 inches with the section mounted vertically. An analysis performed on the section using a panel code showed that the wall effects would be negligible in the pre-stall region.



Figure 2 – Test Section Installed in Wind Tunnel

The airfoil section has a chord of 11.3 in., an almost uniform thickness of 4.1% and a camber of 5.0%, with the maximum camber occurring at $0.46c$. Figure 3 shows the cross section as measured from the

Franklin Institute propeller, accurate in shape but exhibiting a 25% thicker section due to the effects of the measurement stylus. As mentioned, this section was representative of the 70% station of the propeller which is typical of the airfoils from 50% to 95%. This airfoil shows a slight reduction in thickness to the leading and trailing edges, with a leading edge radius of 0.21 in. and a trailing edge radius of 0.14 in. The trailing edge radius is large enough that a wake of significant depth is likely, creating more drag than what is common among modern airfoils.

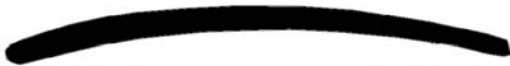


Figure 3 – 70% Airfoil Section (125% Thick)

The airfoil was tested at $V = 42.7$ MPH and $V = 54.5$ MPH. Higher speeds were attempted with a modified mounting system, but limitations of the balance prevented the acquisition of good data. This limited the Reynolds No. to $Re = 460,000$. The magnitude of the actual velocity of the propeller in operation at the 70% span was about 97 MPH, or $Re = 826,000$. Figures 4 and 5 show the results for section C_l and C_d . From the plot, it appears that the airfoil is fairly insensitive to Reynolds number, validating the data at the lower speeds. The assumption here is that enough turbulence was imparted to the flow upstream by the tunnel features to

cause a turbulent boundary layer over most of the airfoil. This effectively raises the Reynolds number on the section.

The maximum lift coefficient is $C_{l\max} = 1.43$, occurring at 11.0° angle of attack. The zero-lift angle of attack is -4.4° , referenced from a line across the bottom of the airfoil. The curve appears to show inflection points at -5° and 0° which is most likely attributable to the reattachment and separation of flow on the bottom and top sides of the airfoil, respectively. This is typical of a thin, highly cambered airfoil, and is responsible for the lift curve slope from -4.4° to 0° temporarily exceeding $2\pi / \text{rad}$.

The drag coefficient shows minimum drag at around 0.5° angle of attack with a value of $C_{d\min} = 0.029$. This is high for common airfoils⁷, but again is not unexpected due to the large trailing edge radius. It should be noted that skin friction will be lower at the operating Reynolds No. by the amount:

$$\Delta C_f = \frac{0.455}{(\log 3.61e5)^{2.58}} - \frac{0.455}{(\log 8.26e5)^{2.58}} = 0.00084 \quad (1)$$

This is a small contribution to the measured drag.

Figure 4 - Section Lift Coefficient vs. AOA

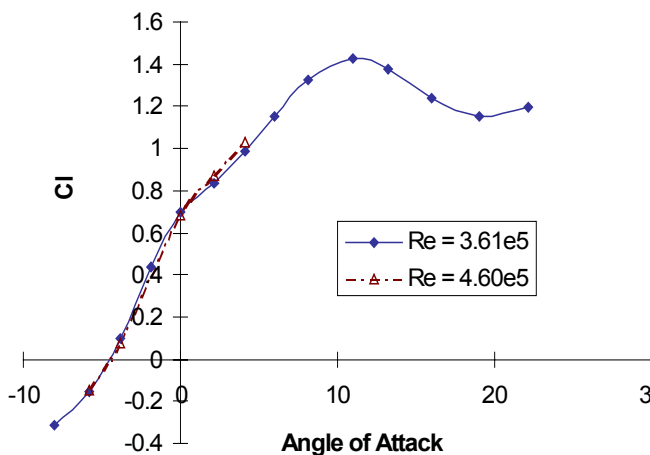
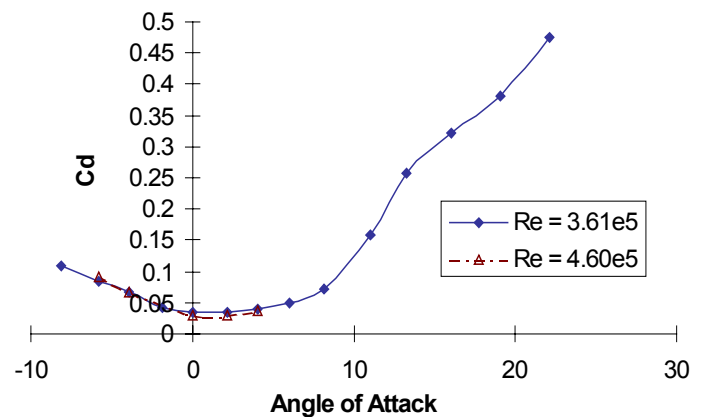


Figure 5 - Section Drag Coefficient vs. AOA



Test results for the full scale propeller

On October 15 - 18, 1999, the bent end propeller was tested at the Langley Full Scale Tunnel (LFST) under the operation of the Aerospace Engineering Department of Old Dominion University in Norfolk, VA. Figure 6 shows the test configuration with the propeller mounted to a propeller dyno. The test specification covered rotational speeds from 50 RPM to 420 RPM and freestream velocities from $V = 0$ to $V = 96$ ft./sec.

This covered the operating range of the propeller based on published data concerning the operation of the engine and aircraft. Recent testing of the engine has not been completed at the time of this publication, however the Wright Notes and published articles indicate that the motor produced somewhere between 28 HP and 42 HP, depending on the specific configuration⁸. Since the engine drove two propellers, one-half of this power would be delivered to each propeller, minus transmission losses. The propellers were reported to turn at around 420 rpm statically⁹, and information about the speed in flight indicates that they operated at around 450 rpm. The Model B aircraft flight speed has been reported to be around 40 MPH¹⁰.



Figure 6 – Bent End Propeller Mounted for Test

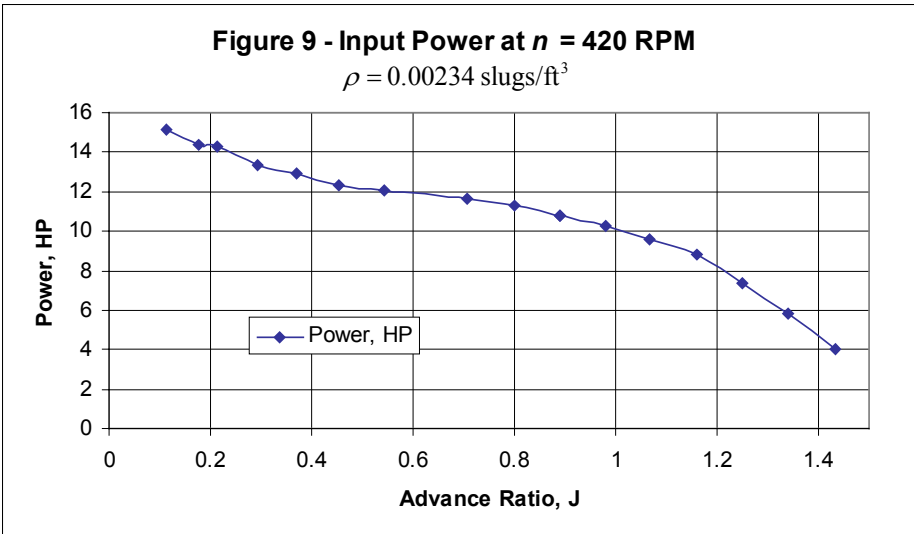
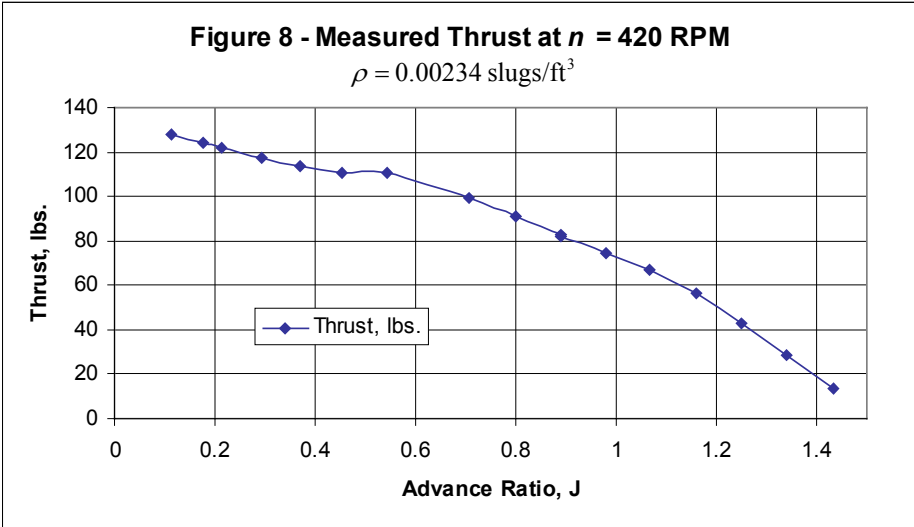
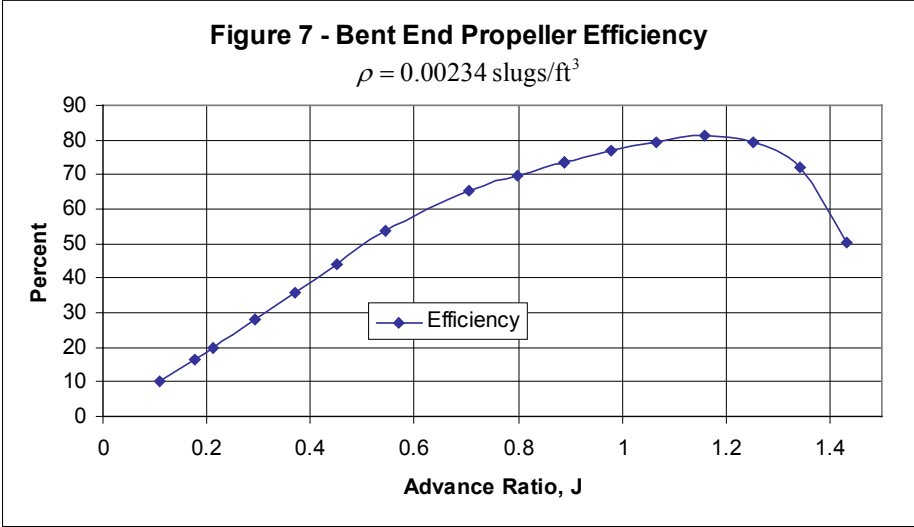
The test data for 17 runs is summarized in Figures 7, 8 and 9. Testing was conducted at 420 RPM because of the numerous references to this speed in the literature. At 40 MPH, the propellers were operating at an advance ratio of $J = 0.986$, corresponding to an efficiency of 77%. In the event that the propellers actually turned faster, such as 450 RPM, then $J = 0.920$ and the resulting efficiency would decrease to 74%. This is still a high efficiency for an early design propeller.

The peak efficiency of 81.5% was measured at $J = 1.16$. This would correspond to a flight speed of 50.4 MPH if the propellers were turning at 450 RPM. Again, it should be noted that most modern wood propellers see efficiencies near 84 – 85%, giving credibility to the Wright design.

Figures 8 and 9 show the thrust and power characteristics of the propeller. There is a slight increase in thrust at $J = 0.5$, and a small inflection of the power curve at the same point. This may be a result of the blade sections operating at a near-stall condition. As J increases, the angle of attack is reduced, resulting in a momentary higher lift coefficient. Use of a momentum theory / blade element theory program validates the potential for stall angles of attack on blade sections $x < 0.6$ for $J = 0.5$.

Comparison of the Wright Design to an Optimal Design

The propellers designed by the Wrights were based on their understanding of momentum theory and blade element theory, and the use of simplifying equations to compensate for their lack of computational power in a very complicated analysis. One of the simplifying assumptions made in their analysis was to consider the $5/6R$ radial position as representative of the entire propeller¹¹. They made calculations for the chord and angle only at this point, and then determined the angles for the rest of the blade from the pitch at $5/6R$. In light of these simplifying assumptions, it is desired to see what an optimally designed propeller would look like if the Wrights had access to the vortex theory developed for propellers.



Betz¹² first presented the concept of a minimum energy loss propeller design which applied to lightly loaded propellers. The basic result of the theory was that the helicoidal vortex sheet that originates from the propeller should have a uniform displacement velocity with respect to radius in the trailing vortex. From the hub to the tip to minimize losses. This velocity should not be confused with the induced velocity that will vary with the radius of the propeller disk. The displacement velocity can be visualized as the apparent motion of the surfaces in a rotating Archimedian screw.

Theodorsen¹³ expanded this theory to heavily loaded propellers, and although this work was first published in 1944, it is still used today for obtaining optimal designs.

The design point is specified as:

$$\begin{aligned} V &= 40 \text{ MPH} \\ n &= 7 \text{ rev./sec.} \\ T &= 76 \text{ lbs.} \\ D &= 8.5 \text{ ft.} \end{aligned}$$

The thrust was selected from the wind tunnel data for the corresponding V and n . From these values, the advance ratio and thrust coefficient c_s are obtained:

$$\begin{aligned} J &= \frac{V}{nD} = 0.986 \\ c_s &= \frac{T}{0.5 \rho V^2 \frac{\pi}{4} D_o^2} = 0.33 \end{aligned} \quad (2)$$

Note that this design point has really been chosen to find an optimal propeller for the wind tunnel test conditions. As of this writing, the actual speed of the propellers and the aircraft in flight are not known.

A value of the displacement velocity \bar{w} is chosen to give a downstream helix advance ratio, λ :

$$\lambda = \frac{1}{\pi} \frac{V(1+\bar{w})}{nD_o} \quad (3)$$

From this, the mass coefficient κ is determined:

$$\begin{aligned} \kappa &= 2 \int_0^1 K(x) x dx \\ &= 1 - \lambda^2 \log \left(1 + \frac{1}{\lambda^2} \right) \end{aligned} \quad (4)$$

where $K(x)$ is the Goldstein function.

The axial loss factor is related to the total loss factor by:

$$\frac{\varepsilon}{\kappa} = \kappa + \frac{1}{2} \lambda \frac{d\kappa}{d\lambda} \quad (5)$$

And these equations are used to iteratively find the original thrust coefficient:

$$c_s = 2\kappa\bar{w} \left[1 + \bar{w} \left(\frac{1}{2} + \frac{\varepsilon}{\kappa} \right) \right] \quad (6)$$

The displacement velocity is determined to be $\bar{w} = 0.38$. The Goldstein function for the corresponding λ is found in Tibery and Wrench¹⁴ which contains an accurate compilation of $K(x)$ for

$\frac{1}{12} \leq \lambda \leq 4$. Finally, the chord lengths are determined from:

$$\sigma C_l = \frac{(1+\bar{w})2\bar{w}K(x)\sin\phi\tan\phi}{\left(1+\frac{1}{2}\bar{w}\right)\left(1+\frac{1}{2}\bar{w}\cos^2\phi\right)} \quad (7)$$

where σ is the solidity of the propeller.

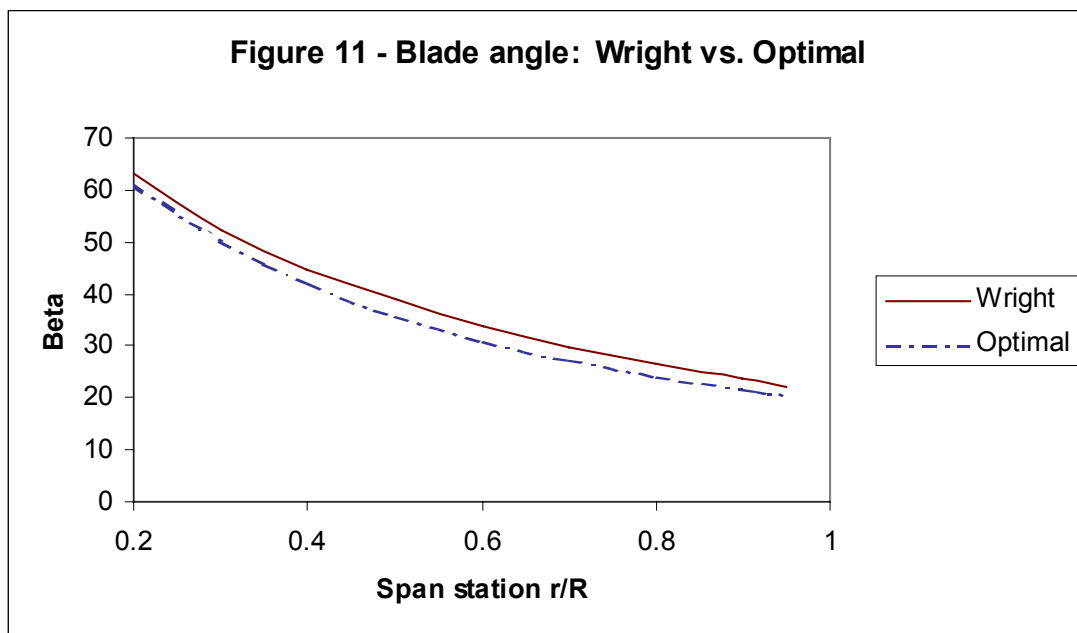
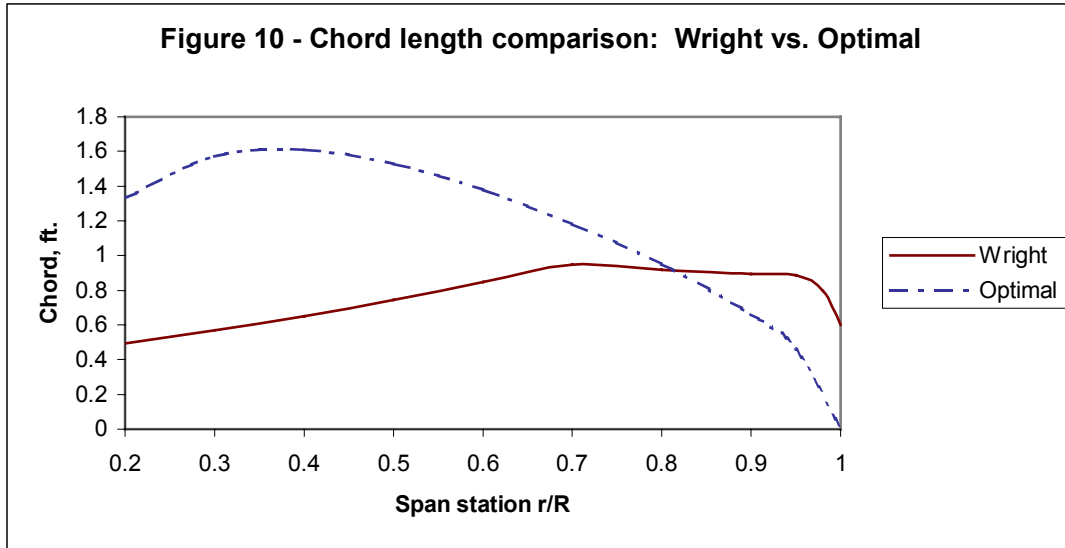
Figure 10 shows the distribution of chord lengths using a design $C_l = 0.6$ for the optimal prop. The chord lengths for the Wright prop are also shown. Figure 11 shows the distribution of blade angles (measured off the bottom of the propeller) for the Wright prop and the optimal design

The large chord lengths in the optimal design are a direct result of the slow turning speed which is not common in modern aircraft design. Despite the large difference in chord lengths, the ideal efficiency is not significantly higher at 84%, when drag is neglected. This would indicate that the Wright design was far from inferior with a measured efficiency of 77%. Furthermore, the ideal design would not be practical from a weight and strength

standpoint, given the material technology of the period.

small amount considering the differences in analysis. This fact alone is convincing evidence that the propeller designs were anything but trial and error.

The blade angles are about 2° greater on the Wright design than on the optimal design, a relatively



Conclusions

An often-overlooked achievement of the Wright Brothers was their development of the momentum and blade element theories for analyzing propellers. It was through this understanding of the physical principles of propeller operation that led them to develop highly efficient designs which enabled powered flight.

The results of two tests involving the Wright bent-end propeller have validated their designs. A test of the 70% station airfoil section designated as no. 12 is capable of a $C_{l\max} = 1.43$ and a $C_{d\min} = 0.029$. These results are in line with other highly cambered airfoils, although the drag coefficient is larger which is likely attributed to the rounded trailing edge causing flow separation.

The propeller showed a peak efficiency of 81.5% at $J = 1.16$, a remarkable result given the fact that most modern wooden propellers see efficiency in the range of 84 – 85%.

Finally, an optimal propeller design based on the Model B Aircraft performance parameters showed that ideal efficiency would be 84% at $J = 0.92$. The Wright propeller showed a value of 77% at the same J which was not significantly less than optimal. Furthermore, the optimal design was impractical from the standpoint that chord lengths at less than 50% radial station were excessively large.

Acknowledgements

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