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Wright Brothers' Invention of 1903 Propeller and Genesis of Modern Propeller Theory

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During the summers of 1900, 1901, and 1902, the Wright Brothers developed, tested, and implemented, on the sands of Kitty Hawk, one of the most critical components of heavier-than-air, powered flight, that is, three-axis control. Only the assembly of a propulsion system remained to complete the world's first successful heavier-than-air flying machine. The greatest challenge in designing and developing the propulsion system, which included an engine and transmission, was the invention of an efficient propeller. To develop the first aerial propeller, the brothers researched momentum and blade-element theory used to explain marine propeller performance. This paper discusses the fusion of momentum and blade-element theories required to invent the aerial propeller, the misconceptions of early aviators such as Langley and Maxim, and the contributions to propeller design provided by Rankine, Froude, and Drzewiecki. Also summarized are the results of the static tests the Wrights conducted on their first full-sized propeller. Additionally, the calculated performance for their 1903 propeller is quantified and summarized for the major components including thrust, drag, torque, throwdown, forward velocity, gross speed, and true slip. The paper provides the derivation of the 66% efficiency estimate for the 1903 propeller.

Nomenclature

A	=	area of propeller disk
C_D	=	drag coefficient
C_L	=	lift coefficient
C_R	=	resultant-force coefficient: $(C_L^2 + C_D^2)^{\frac{1}{2}}$
CP	=	center of pressure
D	=	drag
k	=	air-pressure coefficient
L	=	lift
P	=	pressure
Q	=	tangential force: $R \sin(\Phi' t)$
R	=	resultant pressure: $V^2 \times k \times S \times C_R$
S	=	blade area
T	=	thrust
t	=	tangential: C_D/C_L
V	=	velocity
v	=	forward velocity
z	=	throwdown
α	=	angle of attack
β	=	blade angle
Φ	=	pitch angle

Introduction and Historic Background

AFTER a difficult six-day voyage from Dayton, Ohio, Wilbur Wright (aged 33) first stepped onto the windswept dunes of Kitty Hawk, North Carolina, on the evening of 12 September 1900. He intended to test his theory that, if successful, would enable the pilot for the first time to bank a glider in the roll axis. His younger brother, Orville (aged 29), arrived two weeks later, and during the next month their enthusiasm soared as they realized they were making a critical contribution to the fledgling science of aeronautics—the greatest contribution since Leonardo da Vinci. It is almost inconceivable that in only three short years they would lift off from these same dunes in a powered, heavier-than-air, flying machine—the foremost technological achievement of the 20th century—and simultaneously realize man's ageless quest for flight. Neither Wilbur nor Orville received a high school diploma, attended college, or married. By 1908, however, they had become the most celebrated and famous men in the world.

They were gifted men of unusual intellect and talent—Wilbur the visionary, Orville the problem solver—neither of whom could have alone conquered the science, engineering, or mathematics of flight. Their brilliance was evident in their overall engineering and construction of the Wright *Flyer*, in their invention of a canard elevator, in their development of a movable rudder, and in their design and manufacture of the first successful aircraft engine. They separated themselves, however, from all previous aeronautic enthusiasts by their genius in conceiving wing warping, establishing the modern airfoil using their own wind-tunnel data, and in developing and implementing the complex theory of propeller design. By 1910, when the rest of the aeronautic world had finally caught up to the Wrights' accomplishments in flight, only their propeller remained unequaled.

A modern, piston-powered aircraft is manufactured by a corporation such as Cessna or Piper and is subsequently joined to an engine built by a second corporation such as Lycoming or Continental. A third corporation, for example Hartzell or McCauley, then designs and fabricates a propeller specifically for that unique aircraft/engine combination. The propeller is manufactured to maximize flight performance and takes into consideration engine horsepower, rpm, cruising airspeed, takeoff performance, and payload.[1] Modern propeller theory can be fully described only in lengthy books filled with endless, advanced mathematics. Consequently, it is astonishing that the Wrights' propellers equaled the efficiency of today's modern propellers. Indeed, if a modern pilot (not an aeronautical engineer) were to go back in time and approach the Wrights in their bicycle shop, the modern pilot would have much to contribute to the design of an airplane. The modern aviator would confirm the use of a teardrop wing foil, suggest a dihedral wing, discuss ailerons, and recommend a fuselage to prevent sideslips during turns. He would also be able to improve flight controls and, as flight speeds increased, suggest that the elevator be moved to the rear with

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the rudder and that both be attached to a stabilizer. But on the topic of propeller theory, the modern pilot would be forced to defer to the 1903 bicycle mechanics.

While at Kitty Hawk during September and October 1902, the Wrights mastered the science of gliding. They established, or broke, all of the world records in gliding with their newly constructed machine.[2] The brothers designed the glider's wings using revolutionary airfoils scientifically developed with the aid of their November and December 1901 wind-tunnel data and research. The 1902 glider was so technologically advanced that the brothers applied for a U.S. patent on 23 March 1903. Wilbur and Orville were awarded both U.S. and international patents based on the technological developments of their glider that constituted, for the first time, the fundamentals required for heavier-than-air, manned flight. The patent documented the first-order principle that only the Wrights recognized would be essential for all future aircraft: three-axis control provided, in part, by their wing-warping and rudder systems.[3]

When the brothers left Kitty Hawk on 28 October 1902 to return to Dayton, they realized their dream of powered flight was now only a propulsion system away. Specifically, they simply needed to secure an engine, devise a transmission, and attach a propeller. The Wrights were not engine builders. Consequently, they sent letters to at least 10 manufacturers of gasoline engines asking for quotations on engines that could produce eight or nine horsepower and weigh less than 180 lbs. They received no bids. As a result, they proceeded to design and build the first successful aircraft engine in the world. The engine was designed by Orville and built by Charlie Taylor, the machinist employed by the Wrights in their bicycle shop. Work began in late December 1902, and the engine first fired to life six weeks later on 12 February 1903. The transmission consisted of sprockets and a chain drive.

But the design and fabrication of an efficient propeller proved to be the brothers' single-greatest challenge—and one essential for the invention of flight. The Wrights began work on propeller theory and design in December 1902 and completed much of the development by early March 1903. Revelation of the mathematics and physical principles central to the invention of an efficient aerial propeller did not appear in a "eureka moment" similar to the one that produced wing warping. The development of propeller theory was not as straightforward as the creation of lift tables from lengthy wind-tunnel measurements. In fact, the development of the 1903 propeller required the brothers' total aeronautical knowledge—knowledge that they alone possessed.

Propellers are an evolution of the screw that was first developed by Archimedes (c. 250 B.C.) to advance water up a hill. Over 1700 years later, Leonardo daVinci used screws to create lift in his drawings of a flying machine. An American, David Bushnell, developed the first effective use of a screw propeller for use in a primitive submarine during the Revolutionary War of 1776 (Ref. 4). The first person to conceive of an "aerial screw" for propulsion was the French mathematician J. P. Paucton. He devised a "Pterophore" consisting of two aerial screws attached to a light chair—one to lift and the other to propel.[5] In the early 1800s, however, balloonists modified the airscrew to produce more power by collapsing the screw into a "straight blade." The famous British aeronautical pioneer, Sir George Cayley, laid the groundwork for his countrymen, William Henson and John Stringfellow, in 1843 to construct the first, fixed-wing, twin airscrew propelled airplane referred to as the Aerial Steam Carriage. Later, in 1865, Thomas Moy built the Aerial Steamer consisting of two 12-ft propellers, each with six blades. In 1890, Sir Hiram Maxim built a four-ton biplane powered by twin 180-hp steam engines. The motors were attached to two-bladed propellers measuring 17 ft, 10 in. in diameter, 5 1/2 ft wide at the tips, and each weighing 135 lb. By that time, Maxim had developed the most advanced screw analysis derived from systematic experimentation. In 1891, James Means of Boston published a pamphlet claiming that it was possible to navigate the air using the screw principle. The article constituted the most widely distributed and comprehensive work on the potential use of the aerial screw for use in navigating the air. He summarized the state of the art at that time: "If you want to bore through the air, the best way is to set up your borer and bore." In 1897, France's Clement Ader used two bamboo propellers shaped like a bird's feather to power his unsuccessful Avion.[6] In 1898, the American secretary of the Smithsonian Institution, Samuel Pierpont Langley, was given a $50,000 government grant to build the Great Aerodrome. The failed Aerodrome used two 7-ft propellers constructed of cloth stretched between a wood frame secured by guy wires. Gustave Whitehead, an immigrant from Germany, claimed to have flown his Airplane No. 21 in 1901. The 965-lb machine was powered by a 20-hp engine driving two 6-ft-diam, flat-blade propellers.

Development of Modern Propeller Theory

The Wrights initially hoped marine-propeller theory would prove useful, but unfortunately they quickly discovered that there was little of marine-propeller theory that could be applied to air propellers. Because water is 800 times more dense than air and cannot be compressed, a propeller advances through water more like a screw through cork. Marine propellers were designed by trial and error and were only 50% efficient, but nonetheless sufficient for boats capable of carrying large motors.[7] During a 1949 interview, Charlie Taylor stated, "I think the hardest job Will and Orv had was with the propellers. I don't believe they ever were given enough credit for that development. They had read up on all that was published about boat propellers, but they couldn't find any formula for what they needed. So they had to develop their own."[8] In a June 1903 letter to George A. Spratt, Orville states, "We had been unable to find anything of value in any of the works to which we had access, so that we worked out a theory of our own on the subject, and soon discovered, as we usually do, that all propellers built heretofore are all wrong, and then built a pair of propellers 8 1/8 ft. in diameter, based on our theory, which were all right!"[9]

To characterize the complexity of propeller theory, Orville wrote in the December 1913 issue of *Flying* magazine,

> It is hard to find even a point from which to make a start; for nothing about a propeller, or the medium in which it acts, stands still for a moment. The thrust depends upon the speed and the angle at which the blade strikes the air; the angle at which the blade strikes the air depends upon the speed at which the propeller is turning, the speed the machine is traveling forward, and the speed at which the air is slipping backward; the slip of the air backward depends upon the thrust exerted by the propeller, and the amount of the air acted upon. When any of these changes, it changes all the rest, as they are all interdependent upon one another. But these are only a few of the many factors that must be considered and determined in calculating and designing propellers.

Orville continues to write, "After long arguments we often found ourselves in the ludicrous position of each having been converted to the other's side, with no more agreement than when the discussion began." Their niece, Ivonette, age 7 at the time, clearly remembered during an interview the heated shouting matches between her two uncles. The uncles had promised their father they would not labor on Sundays so they would retreat to the parlor—Orv seated in the corner and Will positioned in the center. She remembered that one uncle would make a statement followed by a long pause—then utter "Tis!" Soon the other would shout, "Tisn't!" They argued aeronautical theory for hours every Sunday afternoon.

By mid-1903, the Wrights had easily surpassed Maxim, Langley, Whitehead, and other contemporary workers by a quantum level when they established the basis for modern propeller theory. They envisioned a propeller not as a simple, flat blade (e.g., found in ceiling fans or on Langley's Aerodromes) but as a revolving wing consisting of an airfoil with a helical twist to maintain an optimum angle of attack. They clearly recognized that a propeller would generate forward thrust (in the same way that lift is created above an airplane wing) as air accelerates over the front, chambered surface and, consequently, reduces the forward static pressure (i.e., the Bernoulli principle).

Unlike the development of three-axis-control and the wind-tunnel experiments, the Wrights' propeller theory is poorly documented in their surviving letters and writings. They refer to their propellers only briefly in a few of their letters. Two paragraphs in a 1908 *Century Magazine* article and three paragraphs in a 1913 *Flying* magazine article constitute their only formal writings on the subject. Five pocket notebooks containing mainly graphs, tables, formulas, and collected data encompass the remainder of what is known. The notebooks are as follows: 1) Wilbur's notebook H, 1902–1905, 2) Orville's notebook K, 1902–1905 (?), 3) Wilbur's notebook J, 1903–1909, 4) Wilbur and Orville's notebook O, 1908–1912, and 5) Orville's notes, 1916–1917.

Unfortunately, they did not leave an organized derivation or summary of their propeller theory used in their aircraft. Orville mentioned in a letter to F. R. Cordley, dated 13 November 1923, that he intended to publish their theory for propeller design, but the review was never completed.

Momentum Theory and Blade-Element Theory

When describing the motion of a propeller, there are two components that, when combined, make up a third. The first is rotational velocity and constitutes simply the speed at which a particular segment of the propeller revolves when the aircraft is standing still. The further from the center of the blade a given segment is, the greater its rotational velocity. The second is the forward velocity of both the aircraft and propeller. The third is resultant velocity. When the forward velocity is combined with the rotational velocity, the resultant velocity of a blade section can be obtained (Fig. 1.) The angle between the resultant velocity and the plane of rotation is the pitch angle. The angle between the chord line of the blade section and the relative airflow is the angle of attack. The pitch angle plus the angle of attack constitutes the blade angle (Fig. 2).

The Wrights were the first to identify and incorporate the two modern fundamental theories necessary to explain propeller performance. The first, attributed to W. J. M. Rankine (in 1881) and William Froude (in 1889), is referred to as momentum theory and uses Newton's second law of motion: force equals mass times acceleration. Momentum theory recognizes that a propeller establishes momentum in the column of air through which it travels, but the theory does not account for the shape of the blade segment. The second, developed by Polish marine pioneer Stefan K. Drzewiecki, is blade-element theory and incorporates the Bernoulli principle: static-pressure energy plus dynamic kinetic energy equals constant total energy. Blade-element theory establishes that a propeller is simply one continuous series of airfoil segments—or blade elements. Blade-element theory uses one representative blade segment, or element, at a given distance from the center of rotation to calculate forces acting on the entire blade. Propeller thrust is derived as if the dynamics of the blade element were consistent throughout the entire length of the blade (Fig. 2). The representative distance from the center used by the Wrights was $\frac{5}{6}$ of the blade length; however, modern theory uses either $\frac{7}{10}$ or $\frac{3}{4}$ (Ref. 10).

Wilbur's notebook H contains sketchy records of a fan-screw experiment conducted on 15 December 1902. They attached a wooden,

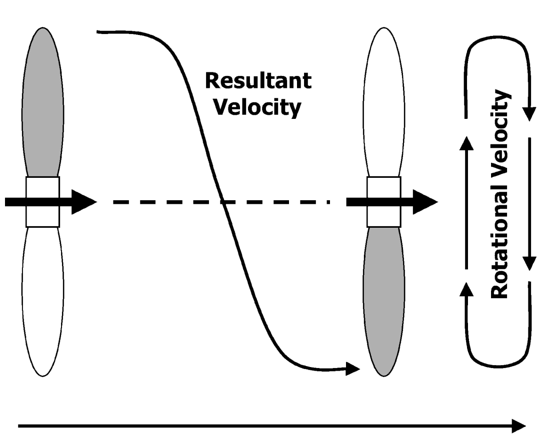

Fig. 1 Three velocities that describe a propeller's motion.

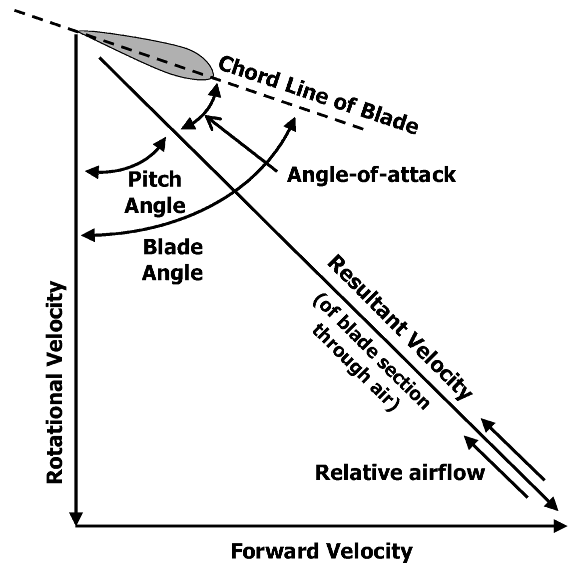

Fig. 2 Relationship of propeller blade, velocities, and angles.

hand-carved, 28-in. propeller to their bicycle shop's stationary motor that was routinely used to drive a line shaft for the shop's power tools. The power consumed was 26,400 ft-lb/min (determined by brake test) while the velocity of the slipstream was measured, using an anemometer, as 2200 ft/min. Propeller thrust could then be calculated as 12 lb.

Wilbur states in his notes that the blade element, which he refers to as the center of pressure (*CP*), had a speed of 160 ft/s. (How this was derived is unknown.) Knowing the velocity of rotation (160 ft/s) and the number of revolutions (26.7 rev/s), one can calculate, using Eq. (1), the *CP*:

$$CP = 160/2\pi 26.7 = 11.4 \text{ in.} \approx 5/6 \text{ blade radius} \qquad (1)$$

In 1900 and in 1901, Drzewiecki presented two papers on helical propulsion in Paris. Octave Chanute sent one of the two papers to Wilbur for review. Which paper Wilbur received from Chanute is unknown. Seven months after the fan-screw experiment in a letter to Chanute dated 2 July 1903, Wilbur is critical of Drzewiecki's blade-element theory for the same reasons its shortcomings are recognized today. Modern propeller theory must also incorporate momentum theory to explain performance. Wilbur writes,

> It shows a very clear understanding of some features of the question, but as the author seems unacquainted with negative tangential, and with the effect which weight of water acted by each part of the screw (marine) has in fixing the angle of incidence, the paper leaves much to be desired as a complete discussion of the subject. . . . Some of his conclusions seem to Orville and me to be rank heresy, but of course we are like the theologians and judge the "soundness" or "unsoundness" of others by the closeness of their agreements with ourselves.

In February 1903, the brothers built and analyzed a second test propeller. This propeller, however, was full-sized and measured 8.5 ft in diameter—the same length as the propellers used 10 months later for the first flight. By understanding momentum theory, the Wrights recognized the requirement for the largest propeller possible to efficiently move the largest volume of air possible. Given the low-powered engine (12 hp) they would later use in flight, they chose to use two large, slow-turning propellers instead of one small, faster rotating propeller. They understood that the advantage of using a longer propeller would result in a smaller proportion of the blade's inefficient hub and tip areas to the total blade area. For safety reasons, they selected a blade length of 8.5 ft given that the height of their machine was 8 ft. The brothers intended to use their newly manufactured motor for the static test on their second test propeller; however, on the second day of testing the motor broke and could not

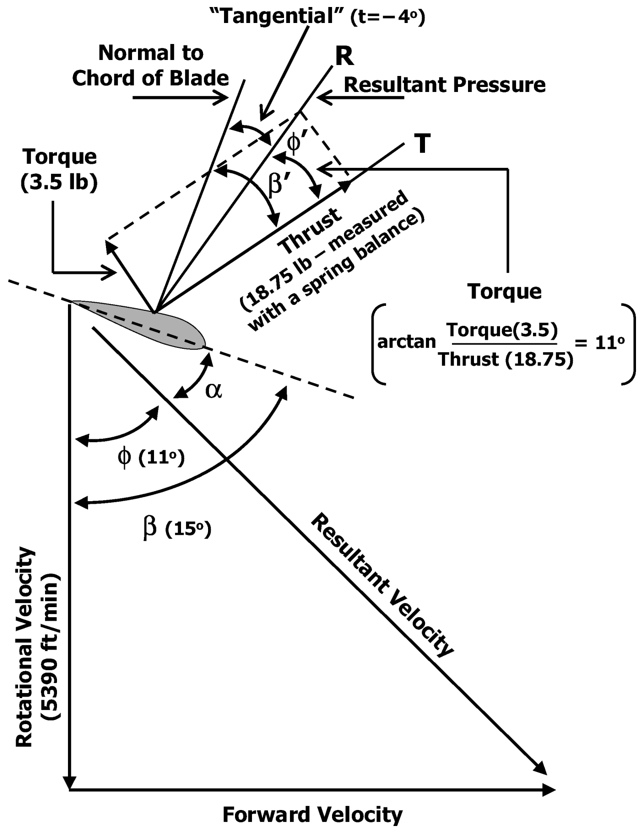

Fig. 3 Static test results of the Wright's full-sized propeller prototype—their second test propeller.

be recast for two months. The bicycle shop motor was used once again. The results of the static test are summarized in Fig. 3.

Propeller torque is the force generated in the plane of blade rotation and is calculated in Eq. 2 as

$$\text{Torque} = (19{,}140\ \text{ft-lb/min})/(5390\ \text{ft/min}) = 3.5\ \text{lb} \tag{2}$$

To calculate the angle of attack, the Wrights used the data derived from their 1901 wind-tunnel experiments and the lift formula of Eq. (3):

$$L = k \times V^2 \times S \times C_L \tag{3}$$

They solved for C_L, which could then be converted, using their table of rectangular pressures, to the angle-of-attack estimate of $7\frac{1}{4}$ deg. Wilbur, in a letter to Chanute dated 18 June 1903, outlined the limitation that had eluded all previous researchers performing static tests. The Wrights clearly knew that static thrust alone had little to do with propeller efficiency; one must also include forward velocity in the analysis.

The Wrights had to identify and to answer several design questions to transform the 1902 glider into a machine capable of powered flight. How much larger would the wings of the 1903 *Flyer* need to be to compensate for the addition of a 200-lb engine? What airspeed would be required to provide the lift necessary for the 1903 *Flyer*? How much thrust must the propellers generate to overcome the combined parasitic and aerodynamic drag? What sustained horsepower must the engine deliver to produce the required thrust? The Wrights estimated the total weight of the *Flyer* with pilot, engine, and propellers to be 625 lb. Therefore, the minimum lift necessary would also be 625 lb. Consequently, the wing surface of the 1902 glider would need to increase from 305 ft^2 to the *Flyer's* 500 ft^2. Using Eq. (3), the brothers estimated the necessary velocity to be 23 mph. C_L was derived from their wind-tunnel data on airfoil number 12—the airfoil selected for the *Flyer's* wings.[11]

The "k" (or Smeaton coefficient for air pressure) was established in 1752 to be 0.005. It remained the authoritative estimate until the Wrights derived the more correct value of 0.0033—the value they found necessary to explain the flight performance of their 1901 glider. Using the more accurate Smeaton coefficient, known only to the Wrights, was yet another advance that further distanced the brothers from their contemporaries.

To calculate the thrust necessary to overcome the total drag of the *Flyer*, the parasitic and aerodynamic drag must be computed. The drag component could be estimated because they now knew that the velocity required was 23 mph. The drag coefficients from their earlier wind-tunnel tests would be critical. The parasitic drag was calculated using Eq. 4:

$$D = k \times V^2 \times S \times C_D \tag{4}$$

where S is the total frontal surface area that they estimated to be 20 ft^2. The aerodynamic drag was estimated using the same drag equation but with S equal to 500 ft^2. They added the two drag components to give a total drag of 90 lb. Drag multiplied by velocity indicated that the engine must produce a minimum of 8 hp to produce 90 lb of thrust. Fortunately, the new engine developed 12 hp; however, the transmission would reduce the total power by 2.5 hp leaving only 9.5 hp to drive the propellers.

For a given airspeed (forward velocity), there is an optimum rpm (rotational velocity) that produces the most efficient blade angle-of-attack and consequently generates maximum thrust (Fig. 2). As airspeed increases, the blade angle of attack decreases; or if rpm decreases, the angle of attack decreases, either of which reduces thrust. Therefore, a propeller is designed to create maximum efficiency at only one airspeed/rpm combination. Any variation in airspeed or rpm markedly reduces propeller efficiency. By adjusting sprockets, the Wrights geared their engine to 23:8. Consequently, each propeller turned at 330 rpm providing the best blade angle of attack for 24 mph.

Finally, Wilbur and Orville used their 1901 wind-tunnel data once again to determine the best possible airfoil with which to design the propeller. As just mentioned, they settled on airfoil no. 12 for the wings of the *Flyer* because it provided the greatest lift at the least angle of attack. They chose airfoil no. 9, however, to design the propeller because it was the most efficient (lift/drag ratio or thrust/torque ratio) over the widest range of angles of attack. This efficiency would be critical when either the forward velocity (airspeed) or rotational velocity (rpm) varied. The brothers reversed the rotation of one of the propellers on the Flyer by twisting its chain drive into a figure eight. The counter rotation of the propellers eliminated any gyroscopic influence.

When an aircraft propeller rotates through air, two additional concepts are needed to describe its performance, both of which add to the forward velocity. The terminology is somewhat confusing because the Wrights used their own jargon to characterize these effects. The first is throwdown (Fig. 4). Throwdown accounts for the fact that air in front of a propeller (a propeller advancing at a steady forward velocity) is accelerated before it strikes the blades. Throwdown is the difference between the forward velocity of the airplane and the forward velocity of the air striking the blade. Combining forward velocity and throwdown results in gross speed: the propeller's velocity relative to air. The Wrights not only refer to this as throwdown in their notebooks, but also as loss from moving air, as throwdown of air, or most often as slip. Modern terminology refers to the concept as inflow, indraft, velocity, slipstream, or induced velocity.

The second concept used by the Wrights to describe propeller performance is referred to as true slip, or loss through angle of pitch, which, in modern terminology, is slip. True slip is the difference between the effective pitch of a blade and its geometric pitch. It is the difference between the chord line of the blade and the resultant velocity. Both throwdown and true slip are dynamic causes that account for a propeller's loss of efficiency (Fig. 4).

Using momentum theory, Newton's second law, and an estimate for air density of 0.075 lb/ft^3, the Wrights calculated the loss of efficiency caused by throwdown as

$$z = 426P/(z + v) \tag{5}$$

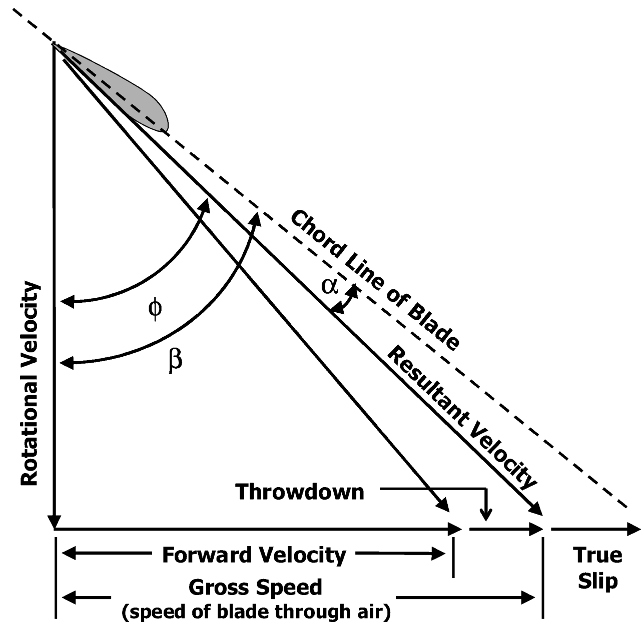

Fig. 4 Throwdown and true slip relative to propeller velocities and angles.

Using Eq. (5), the Wrights estimated throwdown at 8.2 ft/s, which, when added to the forward velocity of 33.3 ft/s (24 mph), gave a gross speed of 44 ft/s.

We now realize the value for the throwdown estimate should have been reduced by half because only half of the slipstream velocity reaches the propellers. Either the Wrights unknowingly neglected this issue, chose not to use it, or were unaware that Froude had published the concept in 1889. Years later, Orville corrected this mistake in notebook entries. Nonetheless, the Wrights had successfully combined blade and momentum theory.

An efficient propeller, by definition, converts a large proportion of the engine's power to thrust by effectively transferring the engine's brake horsepower to thrust horsepower.

$$\text{Propeller efficiency} = \text{thrust horsepower/brake horsepower}$$

As shown later, the Wrights calculated the torque of the propellers to be 40 lb. Torque multiplied by the velocity of rotation (121 ft/s) equals 8.73 engine-break horsepower. The thrust horsepower is calculated by multiplying the 90 lb of thrust by 24 mph and equals 5.76 hp. The Wrights' 1903 propeller efficiency can now be estimated at 66% (5.76 hp/8.73 hp) with a throwdown loss of 14% and a true slip loss of 20% (Fig. 5).

Remarkably, the calculated efficiency and the empirically tested efficiency of the 1903 propellers varied by only 1%! The high efficiency of 66% made it possible for the Wrights to succeed in flight years before other aviation pioneers; pioneers burdened with heavier, more powerful engines, which, in turn, produced proportionally less thrust.

The Wrights used three separate approaches to estimate the thrust of the propeller. One of the methods to estimate thrust, as well as torque, is represented in Fig. 5 and Eq. (6):

$$T = R\cos(\Phi' t) \tag{6}$$

1903, 1904, and 1905 Wright Propellers

Wilbur and Orville's notebook O documents that the propellers used on the 1903 *Flyer* were $3\frac{3}{8}$ in. thick at the hub and suggests that the propellers were made from three $1\frac{1}{8}$ in. spruce boards laminated together. The two 1903 Wright propellers in existence, however, were constructed using only two boards. One propeller is on display at the Smithsonian Institution; the other at the National Park Wright Brothers National Memorial in Kill Devil Hills, North Carolina. Two sets of Smithsonian Institution engineering drawings of

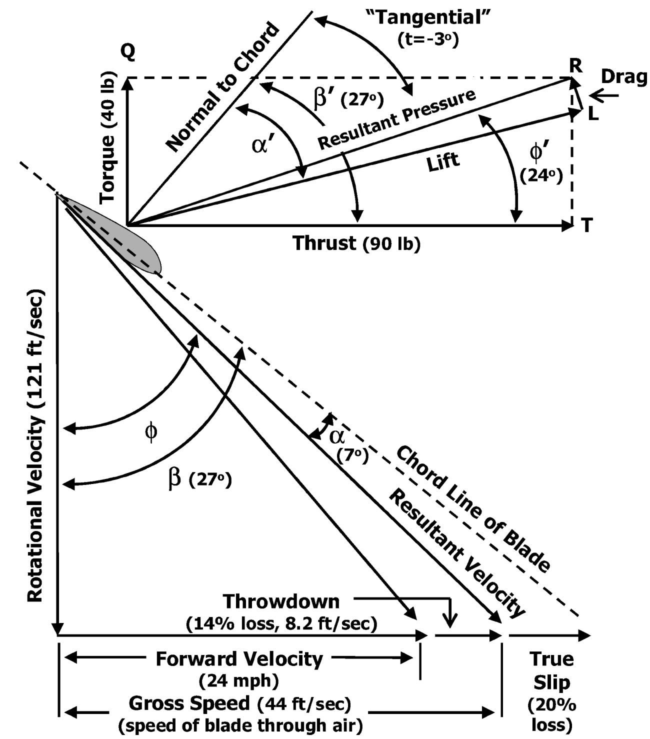

Fig. 5 Wright's calculated performance for their 1903 propeller.

the 1903 *Flyer* (one by Bostrom, 1996, and the other by Christman, 1950) indicate that three boards were used to construct the 1903 propellers. A third set of drawings (by Mikesh, 1987) indicates that only two boards were used. The drawings by Mikesh also show a more rounded blade tip than the two sets of drawings that indicate three boards were used. A hatchet and drawknife were used by the brothers to carve each of the two propellers. A modern reproduction of the 1903 propeller by Larry Parks from "The Wright Experience" required 39 hours to complete using the original construction methods and tools.

The Wrights fully tested the 1903 *Flyer's* engine, transmission, and propeller combination for the first time at Kill Devil Hills on 5 November 1903. The 1903 photographs of the *Flyer* taken in November and December clearly show the rounded-tip, two-board-propeller design with a natural finish and without canvas covered tips. On 17 December after Wilbur's last flight of the day, the *Flyer* was overturned by a gust of wind and severely damaged. When Wilbur later summarized the extent of the damage, he did not indicate that the propellers were damaged on 17 December. In 1904, the Wrights made several test flights at Huffman prairie outside of Dayton using the old 1903 propellers with their new 1904 machine. In 1904 the brothers covered the tips of the 1903 propellers with fabric to prevent splintering. Additionally, they coated each propeller with aluminum paint, perhaps to confuse others on the construction material. Remnants of the fabric-covered tips and aluminum paint can be seen today on both the Smithsonian and National Park Service propellers. Marvin McFarland states in his 1960 letter to the National Park Service that the 1903 propellers were likely broken (as they now appear) during test fight no. 26 on 10 August 1904 or flight no. 72 on 26 October 1904. In 1916, under Orville's direction, two new propellers were made for the exhibition of the 1903 *Flyer* at the Massachusetts Institute of Technology. Interestingly, the propellers were painted a dull gray green, carved from two boards, have rounded tips, and are currently on the original 1903 *Flyer* displayed in the Smithsonian.

In a 1931 letter to C. A. Carlisle, Orville stated, "We are able to calculate in advance the width a propeller blade should be to give the greatest efficiency. It is the width of the blade that determines the angle-of-attack. The wider the blade, the smaller the angle-of-attack." In other words, for every different blade width there is a corresponding different angle of attack that produces the greatest efficiency. Therefore, in 1904, the Wrights built three additional sets of propellers with increasing blade width. Two of the remaining 1904 propellers are on display at Carillon Historical Park in Dayton, Ohio.

In 1905, the brothers dramatically altered their propeller design. They used their most efficient airfoil, number 12 (parabolic shape), instead of number 9 (arc shape), perhaps because they now felt the blades would have a reduced range of potential angles of attack. They first experimented with a "taper tip" propeller that had a taper in both the leading and trailing edges at the tip. Although it was never flight tested, the taper tip is now on display at the Wright State University library.

As the brothers increased the propeller widths in 1904, the blades had a tendency to flatten, or untwist, under the stress of flight for two reasons: 1) centrifugal loading and 2) increased kinetic air pressure. To reduce the pressures that cause the loss of performance by flattening, or untwisting, the blade, they attached "little jokers" in 1905. The little jokers were upturned, flat surfaces attached to the trailing edge near the blade tip. As performance increased, they eliminated the need for the little jokers by adding a backward sweep to the leading and trailing edge of the blade. The backward sweep was obtained in the leading edge by removing a pie-shaped wedge near the tip. This resulted in a constant blade width for the outer third of the propeller. They referred to their new design as the "bent-end" propeller. These modifications increased the 1903 propeller efficiency of 66% to an astonishing 81.5% efficiency by 1905. "The Wright Experience" recently confirmed this remarkable propeller efficiency using contemporary measurement technology on an exact reproduction of the 1905 blade. This level of efficiency was not achieved by others until after World War I and is outstanding even by today's standards![12] The original 1905 propellers are on the original 1905 airplane, rebuilt under Orville's direction in 1947, and permanently on display at Carillon Historical Park.

Summary

This brief review of the Wrights' foremost aeronautical challenge reveals only a portion of the work they did to initiate the development of modern propeller theory. This paper traces only one of the possible pathways the Wrights might have used in obtaining the solution to the aircraft propeller problem. Revealed in their notebooks are many alternative methods they used to navigate their way through the fog of uncharted territory—not to mention dead-end approaches that were addressed with equal vigor.

The Wrights' odyssey with the propeller began with the hope that marine-propeller theory could easily be converted to aerial-propeller theory by simply substituting air pressure for water pressure. After all, marine propellers were 50% efficient, but not by design, rather by trial and error because marine propellers of varying morphology could easily be interchanged and evaluated. The Wrights did not have the luxury of trial and error. Either the propeller worked as predicted or the airplane would not fly. If the airplane did not fly, there was no way of knowing if their calculations were off by 1% or a much greater percentage. Their hot-tempered arguments between December 1902 and June 1903 were critical to their scientific method. Each brother not only envisioned the proof of a theory, but also was forced to articulate and defended its merits against his equally passionate sibling. The only trial and error took place during their frequent and spirited intellectual exchanges.

Rankine and Froude described a form of momentum theory in the 1880s. This marine-based information would have been available to aviation pioneers such as Hiram Maxim and Samuel Langley. Using momentum theory (or Newton's second law of motion), Maxim and Langley were able to construct flat, paddle-blade propellers with about 45% efficiency. Consequently, they invested in what they thought must be the primary solution to manned, powered flight: powerful engines producing abundant horsepower. To the contrary, the Wrights believed that an aircraft propeller would be the key to thrust by substituting the traditionally flat-blade propeller for one that incorporates a helical twist and uses the airfoil of a wing. By introducing lift coefficients derived from their revolutionary wind-tunnel data, the Wrights were able to substantially augment and improve upon Drzewiecki's marine blade-element theory. Drzewiecki's untested, new theory was published in 1901—a year before Wilbur tackled the aerial screw problem. The Wrights were the first to reason, even before Drzewiecki, that this theory was incomplete and must be combined with momentum theory, incorporating throwdown, to fully explain—and more importantly, to predict—propeller thrust. For the *Flyer* to produce enough lift to carry 625 lb, the brothers calculated it must maintain a flying speed of 24 mph. At 24 mph they estimated the total drag to be 90 lb. They calculated that it would require an 8-hp motor to produce the necessary 90 lb of thrust. Many alternative propeller shapes could have delivered the required thrust but they settled on 8.5-ft propellers with an 8-in. blade width (giving a total blade area of 5.4 ft^2) designed to turn at 330 rpm. Both the calculated and measured efficiencies of the screws are within 1% of the 66% propeller efficiency. This is an amazing validation of their airfoil coefficients, mathematical derivations, and their development of modern propeller theory.

The Wrights' ingenious invention of the aerial screw was the last of the brothers' pioneering breakthroughs to be understood and replicated by others. Not for seven more years would others, inspired by the Wrights' achievement, be able to produce propellers with the efficiency equal to their 1903 design. As Peter Jakab notes in *Visions of a Flying Machine*, "As with so many aspects of their aeronautical work, before the Wright propeller there were none like it, and after it there were none that were different."[13]

When the two bicycle mechanics, with only a high school education, stepped onto the stage in 1899, manned flight used only gliders—gliders balanced and maneuvered solely by the shifting of the rider's weight. Only the Wrights recognized the necessity for 1) three-axis control, 2) precise airfoil data, and 3) modern propeller theory. They completely solved these complex requirements before other "researchers" had even identified them as the three essential pillars of flight. When they stepped off the stage, six years later, they had delivered to the world man's greatest invention.

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