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Frank W. Caldwell and Variable-Pitch Propeller Development, 1918–1938

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The variable-pitch propeller was a critical propulsion technology to the aeronautical design revolution of the late 1920s and early 1930s. The new device bridged the gap between the two major advances of that revolution in the sky: aerodynamic drag reduction and increased engine power. The leader in this development was Frank Walker Caldwell (1889–1974). During his tenure as the government's chief propeller engineer (1917–1928) and his work in industry (1929–1938), Caldwell oversaw the invention, development, and innovation of the metal, multipiece propeller, the ground-adjustable pitch propeller, and the hydraulically actuated two-position controllable-pitch and constant-speed propellers. In the process, he made a major contribution to fundamental aeronautical engineering through his work on propeller testing facilities and techniques. Caldwell achieved this while recognizing the importance of the propeller within the synergy of the larger technical system of the airplane. This paper documents Caldwell's critical role in the development of the variable-pitch propeller in the United States from World War I to the outbreak of World War II.

Introduction: The Evolution of the "Gearshift of the Air"

IN the spring of 1933, United Air Lines began testing the first "modern" airliner, the Boeing Model 247, for service on its newly opened transcontinental routes. The new airplane incorporated the latest aeronautical developments—streamline design, monoplane wings, all-metal construction, and radial engines—but it could barely reach the altitude of 6000 ft (1828 m) needed to fly over the Rocky Mountains (Fig. 1). That obstacle is almost unthinkable in a time when six-hour transcontinental flights at over 30,000 ft (9144 m) are commonplace. The innovation that enabled the Model 247 to reach its desired performance and enter transcontinental service was the variable-pitch propeller developed by Frank W. Caldwell, chief engineer of the Hamilton Standard Propeller Company (Fig. 2). Hailed as the "gearshift of the air" by the aviation community, the new propeller allowed the angle, or pitch, at which each propeller blade rotated through the air to vary according to different flight conditions. The result was dramatic improvement in the overall operating efficiency of the Model 247 at both high and low speeds and at varying altitudes. For their contribution to the development of aeronautical technology, Caldwell and Hamilton Standard received the 1933 Collier Trophy for the "greatest achievement in aviation in America" for that year.[1]

The variable-pitch propeller was a critical propulsion technology to the aeronautical design revolution of the 1920s and 1930s in the United States. This revolution witnessed the transformation of the slow, fabric-covered, strut-and-wire-braced biplane of 1918 into the high-speed, streamline, cantilever monoplane of 1938. The new design bridged the gap between the two major advances of the aeronautical design revolution: aerodynamic drag reduction and increased engine power. It linked the innovations in streamline design, cantilever monoplane wings, and retractable landing gear with sophisticated engines, fuels, and supercharging to spearhead the onset of the new and modern airplane.

From 1918 to 1938, Frank W. Caldwell effectively guided and set the pace of innovation in the American propeller industry. He oversaw all of the major developments in propeller design and construction—the metal, multipiece propeller; the ground-adjustable pitch propeller; and the hydraulically actuated two-position controllable-pitch and constant-speed propellers—and was the first to make them practical. Caldwell pioneered the design of propeller testing facilities and techniques that were major contributions to fundamental aeronautical engineering. Despite his specialization, he recognized the importance of integrating the propeller within the synergy of the larger technical system of the airplane. This paper traces the evolution of the gearshift of the air through the career of its creator, Frank W. Caldwell.

Caldwell was born on 20 December 1889, at Lookout Mountain near Chattanooga, Tennessee. His father, Frank H. Caldwell, was president of the Cahill Iron Works and a former mayor of Chattanooga. He attended the Tome Preparatory School in North East, Maryland, and the University of Virginia before entering the mechanical engineering program at the Massachusetts Institute of Technology (MIT) in 1908 (Ref. 2). Exhibiting a strong interest in aviation, Caldwell and another student, Hans Frank Lehmann, designed and flew a contest-winning glider. They also collaborated on a bachelor's thesis in 1912 entitled, "Investigation of Air Propellers," which was one of the earliest attempts at a comprehensive propeller testing program in the world.[3]

Caldwell graduated from MIT in 1912 and served as foreman and process engineer for the propeller department of the Curtiss Aeroplane and Motor Company in Buffalo, New York. Curtiss sent him in 1916 to Columbus, New Mexico, near the Mexican border, to investigate and solve the problems with the wooden propellers used on the Pershing Expedition's Curtiss JN-2 aircraft. The propellers for these aircraft, which were manufactured in the American northeast, dried and split after exposure to the over 100°F (37.78°C) heat of the southwestern desert. Caldwell studied local furniture-making practices and found that the use of native woods and improved glues that could withstand the heat was the solution. He established a small factory and constructed 80 propellers for the expedition.[4] That would not be the last time Caldwell would be detailed to address the problems with wood as a propeller construction material.

When the United States entered World War I in 1917, it committed itself to an ambitious aviation production program supported by an unprecedented $640 million government appropriation. Part of that program was the establishment of an aeronautical research and development facility at McCook Field in Dayton, Ohio, to be operated by the newly formed Airplane Engineering Division of the U.S. Army Air Service beginning in December 1917. The division's specialized subdivisions cooperated in the modification of existing military aircraft to increase performance and the design, testing, and construction of new military aircraft. The Propeller Department, the first Engineering Division branch to open at McCook, dealt specifically with enhancing the efficiency and durability of airscrews for

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Fig. 1 First production Boeing Model 247 in flight, spring 1933.

Fig. 2 Frank W. Caldwell (1889–1974).

military aircraft.[5] Already recognized as a leading authority on propeller design in the United States as a result of his work at Curtiss, Caldwell came to McCook to become the civilian chief engineer of the Propeller Department. He would be responsible for the research, design, and testing of all aircraft propellers used by the Army and Navy in World War I.[6]

World War I was the catalyst for increased aeronautical development in the United States and Europe, and it directly stimulated the development of the variable-pitch propeller. The wooden, fixed-pitch propeller, which was efficient for only one predetermined flight condition, gave satisfactory performance for aircraft that operated at less than 100 mph (160 kph) and at low altitudes. The engine with the highest horsepower in the United States at the outbreak of the war was the 90 hp Curtiss OX-5 aircraft. The introduction of the 400 hp Liberty engine, four times more powerful than the OX-5, offered Caldwell a significant challenge regarding the design of propellers that could withstand this power and effectively transmit it to the air. Not only was there the increase in power, but there were also plans to supercharge the Liberty engine to increase high-altitude performance.[7] The need for higher performance at what were then unprecedented speeds and altitudes created the need for a practical variable-pitch propeller (Fig. 3).

As result, the American aeronautical community called for the development of a workable variable-pitch propeller. The chairman of the National Advisory Committee for Aeronautics (NACA—the modern day NASA), William F. Durand, asserted in 1918 that the invention of such a device was "of the highest order of importance" and "outstanding as one of the appliances for which the art of navigation is definitely in wanting."[8] The NACA went on to identify that the construction of a practical metal propeller was one of the "very important problems now confronting the air services of the nation." Specifically, the NACA issued a call for assistance in the development of a steel propeller that would be "coincident" with the introduction of a variable-pitch propeller.[9]

The NACA's request reflected the pursuit of two important and intertwined propeller design trends that began in the United States during World War I: the search for new materials used in the construction of propellers and the perfection of the mechanism for changing blade pitch. Before variable pitch could be a reality, engineers and designers had to develop a type of propeller that would facilitate controlled pitch variation. Aerodynamic forces could physically distort the blade angle of a rotating one-piece fixed-pitch propeller, but the change in pitch could not be controlled. Caldwell set the tone for developing a new multipiece propeller that consisted of separate detachable blades joined to a central hub that would allow deliberate pitch variation.

Before Caldwell and the Propeller Department could proceed with experimentation, they had to create the tools and practices necessary

Fig. 3 American-built de Havilland DH-4 with wood propeller and 400 hp Liberty engine.

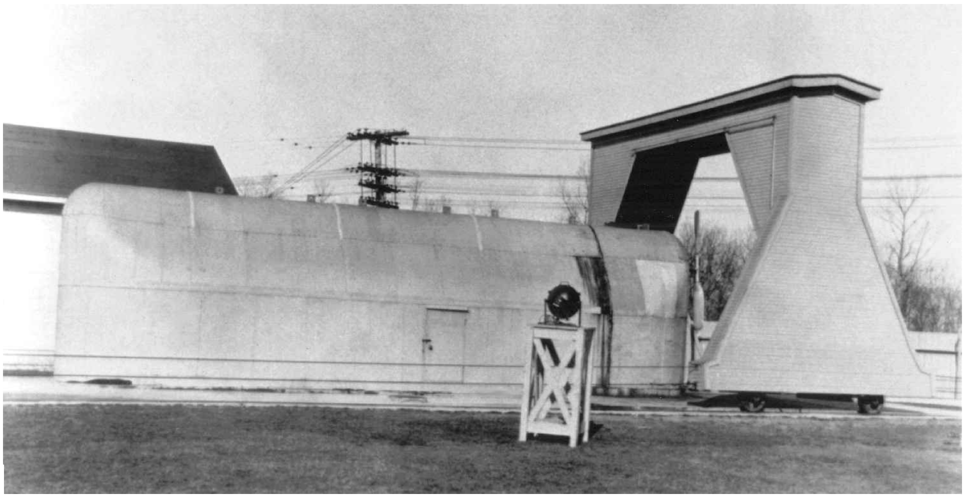

Fig. 4 McCook Field Propeller Whirl Testing Facility, 1918.

for rational engineering development. The increase in engine horsepower required heavier, larger, and more complicated propellers, which pushed the boundaries of engineering design knowledge. To ensure that a potential design was structurally sound and that experimentation and/or production should proceed, Caldwell pioneered the destructive whirl test, the ultimate check for the structural strength of any propeller. The test involved mounting a propeller to a stationary test stand where instruments measured the effective thrust of the propeller while it underwent long endurance runs at high speeds, usually 10 h using a 600 hp electric motor. The test destroyed the propeller to determine the ultimate material strengths of both experimental and production propellers under extreme aerodynamic loads (up to 200% beyond its design threshold) and to ascertain any specific design flaws. Destructive whirl testing was an empirical process that reflected Caldwell's and the Army's desire to "overengineer" aeronautical equipment for the rigors of aerial operations. Any manufacturer that wanted to sell a propeller to the U.S. government during the war or after had to have the design whirl tested by the Army. Caldwell's design of whirl-testing facilities at the Westinghouse Electric and Manufacturing Company of East Pittsburgh, Pennsylvania (1917); McCook Field (1918); Wright Field, Dayton, Ohio (1926); and his pioneering the testing procedures that made them indispensable to the development of all modern high-performance propellers would alone be a major contribution to fundamental aeronautical engineering (Fig. 4) (Ref. 10).

With the facilities and testing procedures clearly defined, the first technological step Caldwell addressed in the realization of a practical variable-pitch propeller involved the composition of the propeller. The primary material for propeller manufacture from the pioneer period to World War I was wood because it offered great strength and ease of fabrication. As Caldwell had learned in the New Mexico desert, however, wood possessed several disadvantages for propeller construction. Extreme variations in temperature and humidity as well as water, sand, and stone easily damaged the aerodynamic and structural integrity of solid and laminated wooden propellers, which had an average service life of only six months. In addition, wooden propellers deteriorated rapidly under the stress of high-output engines, making them unsuitable for use on new, higher-performance aircraft. Perceived wood shortages during the war also influenced a concerted effort to find a new construction material.[11]

The problems with wood resulted in Caldwell's search for an alternative material to wood. Caldwell first concentrated on the Bakelite micarta propeller, which was derived from the phenolic resin used as an insulator in electrical machinery. These "plastic" propellers marginally improved resistance to climatic conditions and were also proportionally heavier and more expensive than their wooden counterparts.[12]

It became increasingly clear that metal, specifically steel, offered the needed durability and strength required by the new commercial and military aircraft with large-horsepower engines. Caldwell also knew that metal offered a specific performance advantage. The use of thinner blades, or airfoil sections, toward the tip increased the propeller's efficiency. Propeller engineers well knew that thin blade sections were ideal for high-speed applications because they did not suffer from compressibility burble with its sharp increase in drag at high speeds. Much of that knowledge was the result of Caldwell's collaborative work with Elisha N. Fales in the McCook Field high-speed wind tunnel, which was one of the earliest fundamental investigations of airfoil efficiency at high speeds.[13] Wooden propellers and their thick airfoils for the purposes of structural integrity suffered severe drag limitations at high speeds. To turn faster, propellers needed to be thinner, which required the strength of metal.

The initial tests of steel propellers during the war, however, led Caldwell to reject metal temporarily and to state that "steel is not a suitable material for propeller construction," whereas "wood propellers may be designed for any number of R.P.M. as far as stress is concerned." Most of the wartime designs such as the Faehrmann steel propeller exhibited low resistance to torsional stresses and were expensive to fabricate.[14]

Caldwell soon recognized that it was not the inferiority of the material, but the type of construction, that stymied metal propeller development. The Propeller Department began work on a drop-forged steel propeller in 1918. Caldwell believed drop-forging was the best method for fabricating a metal propeller blade because it could economically produce a very strong metal part. In addition, the process allowed what he called a certain "freedom of selection" that allowed experimentation with the correct blade shape and form. In 1920, the army contracted the Standard Steel Propeller Company of Pittsburgh, Pennsylvania, an organization that had been unsuccessfully experimenting with metal propellers, to construct various forged-steel designs. The contract initiated a long-term partnership between Caldwell and Thomas A. Dicks, Standard Steel's chief engineer.[15]

The Propeller Department conducted destructive whirl tests on four different forged-steel designs. The early designs suffered from flutter. In an effort to solve the problem, Caldwell looked to existing knowledge on the stiffness of wooden propellers and devised a method of calculating the deflection of a propeller under load. He also attempted to make the tips flexible while stiffening the area near the blade root. These two new improvements would be major breakthroughs in the design of metal propeller blades. Despite those breakthroughs, the design was structurally weak where the blades were threaded to the solid machined hub. Experimentation with solid-steel forged blades continued until 1923. Caldwell and Dicks found the design of both hollow and forged-steel propeller blades to be initially impractical. Clearly, the destructive whirl tests showed that the "steel" in Standard Steel was impractical from the standpoint of structural integrity. (Propeller manufacturers would introduce practical steel blades later in the 1930s.)

Caldwell and Dicks placed a new emphasis on drop-forged propeller blades made from duralumin, an aluminum alloy generally known as "dural." Composed of aluminum, copper, manganese, and lesser amounts of iron, magnesium, and silicon, dural permitted a closer following of wooden-propeller practice, a practice Caldwell knew very well. He recognized that dural's lower density allowed a stiffer blade with a greater area than corresponding steel ones. Through a comparison of the blade deflections under load of wood and steel propellers, he attempted to construct a propeller with the flexibility between the two and with a weight slightly above wooden propellers. As a result, Caldwell concluded that he could emulate wooden-propeller design practice.

Meanwhile, Dicks and the engineers at Standard Steel developed a split, or two-piece, steel hub that used retaining shoulders to secure the blades at the blade root and a clamping ring to fasten the complete unit together. This assembly compensated for small errors in the vertical balance of the blades, allowed interchangeability of parts, and permitted the aircraft operator to adjust pitch angle on the ground for anticipated performance regimes. Through the use of detachable drop-forged duralumin blades and the split hub, retaining shoulders, and clamping ring, a major milestone in propeller design and construction was achieved by 1925: the introduction of a standardized metal ground-adjustable pitch propeller.

The appearance of the new propeller in the mid-1920s came at just the right time for military and commercial aircraft. During a routine takeoff exercise at the Norfolk Navy Yard in Virginia, one of the Martin T3M torpedo-bomber scouts slated for use on the new aircraft carriers Saratoga and Lexington lost its wooden propeller on takeoff because of the high power of its 575 hp Wright T-3B Typhoon 12-cylinder inline engine. After investigation, the Navy authorized procurement of 100 duralumin propellers for use on an improved variant of the T3M, the T4M, which would have equally powerful and lighter radial engines (Fig. 5). The contract with Standard Steel marked the first use of the metal ground-adjustable propeller by the U.S. government.

The lessons Caldwell learned with the ground-adjustable propeller provided valuable design knowledge toward the realization of a practical variable-pitch propeller. Moreover, the ground-adjustable

Fig. 5 Martin T4M-1 torpedo-bomber scout with Standard Steel dural ground-adjustable pitch propeller.

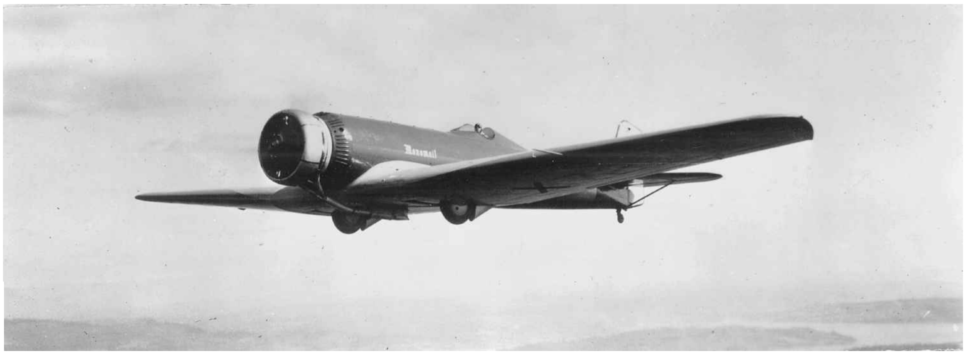

Fig. 6 The performance of the Boeing Monomail suffered from the use of a ground-adjustable pitch propeller.

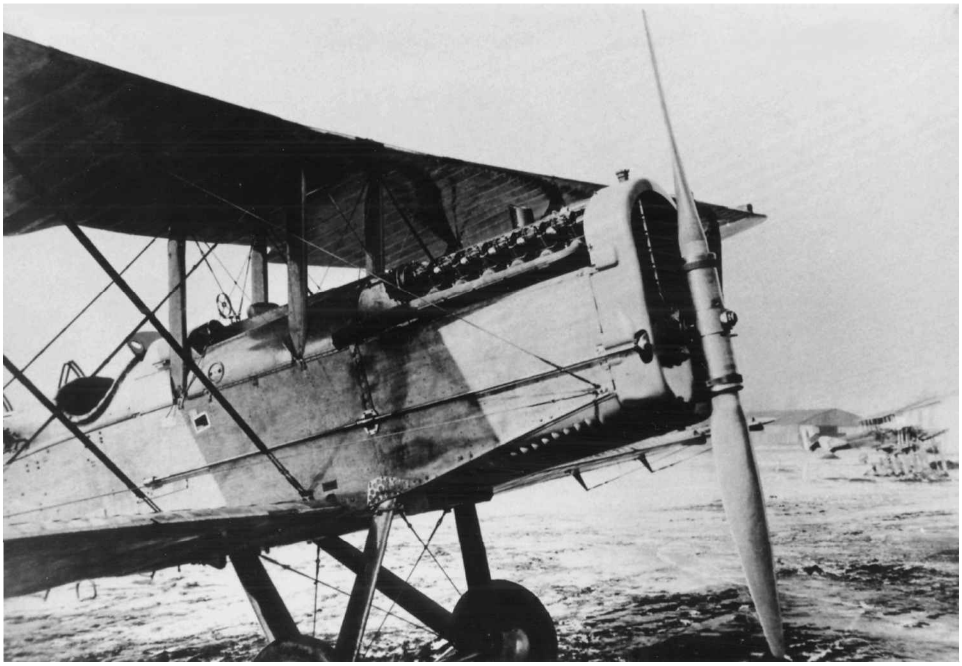

Fig. 7 Hart and Eustis controllable- and reversible-pitch propeller mounted on de Havilland DH-4, 1918.

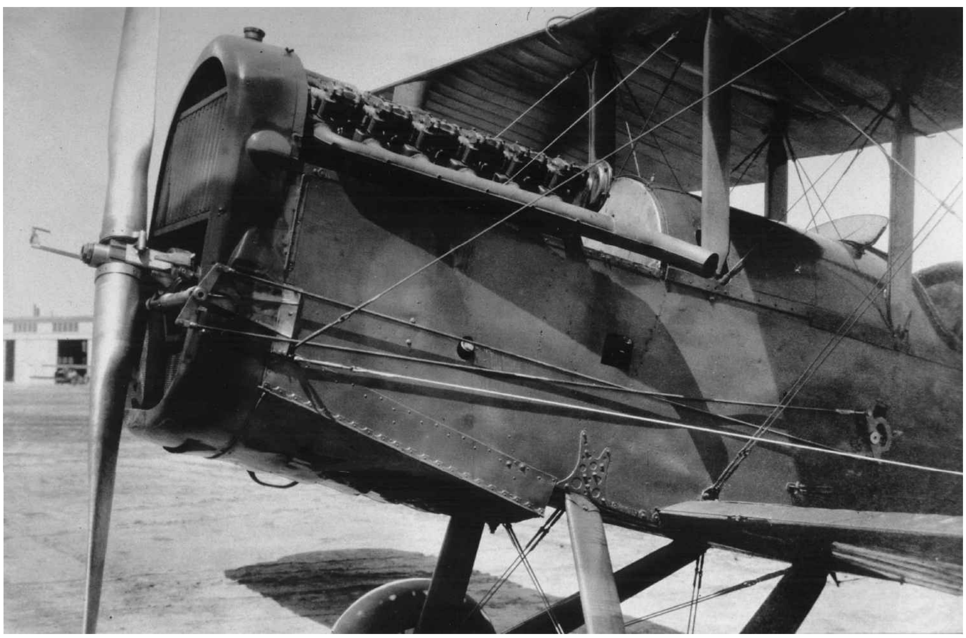

Fig. 8 Standard Steel controllable- and reversible-pitch propeller mounted on de Havilland DH-4, 1920.

propeller's multipiece construction offered valuable experience in working with metal, a new and important material for propeller manufacturing. The stage was set for the next technological plateau for the American propeller community—the perfection of the variable-pitch mechanism in the early 1930s. Even though there were no significant breakthroughs in the 1920s, Caldwell presented the potential performance and economic benefits of variable pitch to the aviation community through professional presentations and publications.[16,17]

Regardless of the rhetoric, nothing illustrated the need for variable pitch more than the suffering performance of the new low-wing monoplanes with high wing loadings influenced by advances brought forth by the aeronautical design revolution. With its ground-adjustable propeller set for cruise, the revolutionary Boeing Monomail of 1930 could not even take off for its first test flight (Fig. 6). Its test pilot, Eddie Allen, had to adopt a compromise propeller setting that did not generate full performance in either regime. Even then, the new mail plane used every inch of runway to get off the ground.[18]

Caldwell had been directing work on variable-pitch mechanisms since the opening of McCook Field in late 1917, even though it was not a priority program for the Army during World War I and on through the 1920s. The Army saw no real need for variable pitch on biplanes with low wing loadings. The most successful of the early designs was a mechanically actuated, controllable—meaning the pilot controlled the change in pitch—and reversible propeller submitted by Seth Hart and Robert I. Eustis of Los Angeles in 1917 (Fig. 7). The pilot controlled pitch variation through cables connected to the propeller's steel hub. Caldwell identified the Hart and Eustis propeller as a promising design, but it suffered from rapid wear of its mechanical control mechanism and there was considerable difficulty with adequate retention of its wooden blades. The Army abandoned the project in the mid-1920s. Standard Steel designed and built a

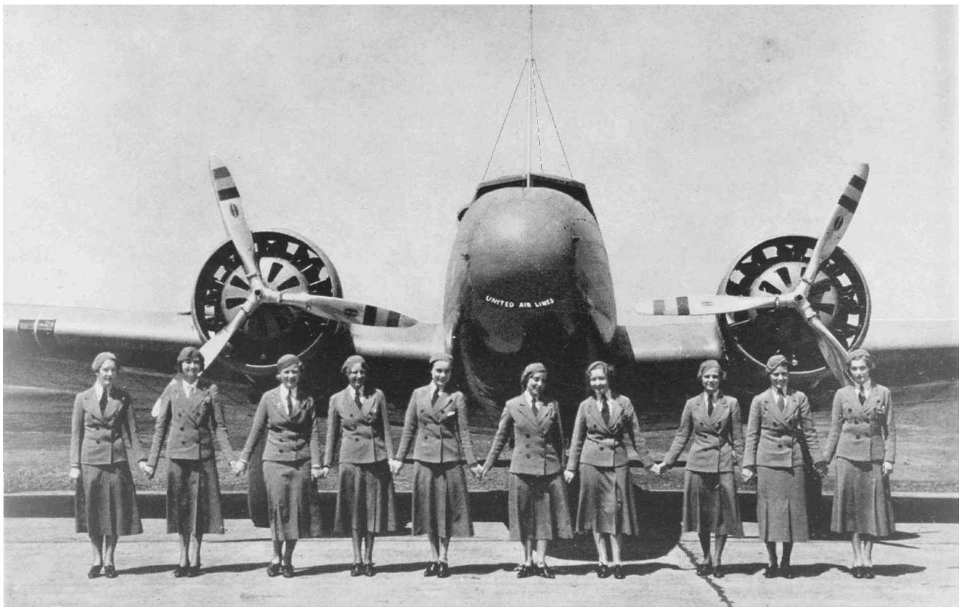

Fig. 9 Boeing Model 247 with three-blade, ground-adjustable pitch propellers.

Fig. 10 Modified Boeing Model 247 with two-blade, two-position, controllable-pitch propellers.

mechanically actuated, controllable, and reversible propeller with hollow steel blades in 1920 (Fig. 8). In 1922, Caldwell patented his own mechanically actuated, two-position, controllable-pitch propeller that featured a better system of blade retention than the Hart and Eustis.[19]

Caldwell's experience with the Hart and Eustis design influenced his decision to concentrate on hydraulic rather than mechanical actuation. He also decided that he would develop the new device privately and without the sponsorship of the Army. As a result, he left government service in August 1928, worked for a brief period as a consulting engineer, and joined Standard Steel as the company's chief engineer in June 1929. That same year, he patented a hydraulically actuated variable-pitch propeller.

With almost 10 years of experience in the field, Caldwell was in the best position to invent a successful variable-pitch propeller.

Fig. 11 Caldwell receiving the 1935 Sylvanus A. Reed Award from Glenn A. Martin.

Unfortunately, the small propeller company he joined lacked the financial resources and staff required for success. The creation of large aviation holding companies, primarily the United Aircraft and Transport Corporation (UATC—the modern-day United Technologies), marked the emergence of large-scale propeller companies able to conduct the necessary research and development needed in the development of the variable-pitch propeller. UATC merged the two leading American propeller manufacturers, Hamilton Aero Manufacturing and Standard Steel, to create the Hamilton Standard Corporation in November 1929, which became the world's premier manufacturer of propellers.[20] As a result, Caldwell became an important contributing member to one of the most powerful aviation corporations in the United States.

Despite the promise of UATC's corporate momentum, Hamilton Standard was suffering from dwindling government contracts and the economic upheaval of the Great Depression. Looking for something that would sustain the young corporation, Eugene E. Wilson, the president of Hamilton Standard, went to Caldwell to see if he had any ideas for new products. Caldwell unveiled a drawing of the two-position controllable-pitch propeller he had patented in 1929. His design used the engine's oil supply and centrifugal force exerted by counterweights to keep the propeller blades at the desired pitch during flight. Caldwell visualized his new design as the aeronautical equivalent of a manual automobile transmission—the gearshift of the air—where "low" gear (a low angle of pitch) provided efficiency at takeoff and "high" gear (a high angle of pitch) provided efficiency at cruise. Wilson believed the propeller was "the answer to a maiden's prayer" and quickly ordered the development of the two-position controllable-counterweight design, which would be an extreme financial undertaking during the Great Depression.[21] Caldwell built the first propeller based on his design in 1930 and tested it on an airplane with a 150 hp engine. For two years, Hamilton Standard tested controllable-counterweight designs on engines rated to 700 hp and on various aircraft in the UATC family. The new propeller was ready for production for both military and commercial aircraft at the end of 1932.

Hamilton Standard's new product faced design conservatism throughout the aeronautical community. The Army, Navy, industry, and even the UATC corporate leadership rejected outright the idea of a variable-pitch propeller, especially Caldwell's hydraulic design, in the early 1930s. To many aircraft designers and engineers who did not recognize the value of variable pitch, hydraulic control was excessively heavy and expensive, and it was the most complicated method of pitch actuation. The most prolific example of this design conservatism concerned the development of the Boeing 247, considered the first "modern airliner."[22] Boeing engineers specifically rejected variable-pitch propellers for the reasons cited and because they felt that other innovations in aerodynamics, structures, and power plants would provide the desired performance. Consequently, the new airliners performed poorly during their United Air

Fig. 12 Curtiss Y1P-36 with Hamilton Standard constant-speed counterweight propeller, 1937.

Lines acceptance flights over the Rocky Mountains at Cheyenne, Wyoming, in February 1933 (Fig. 9). The Boeing engineers would quickly learn that all of the innovations of the aeronautical design revolution, including variable-pitch propellers, would need to act in synergy before their new design could make it over the Rockies.

Hamilton Standard, to prove the value of its new product, sent Caldwell to Cheyenne to investigate the problem. His tests concluded that incorporation of variable-pitch propellers would reduce the 247's takeoff run by 20% and increase the rate of climb by 22% and cruising speed by 5.5%, from 165 to 171 mph (265 to 275 kph)[23] (Fig. 10). Caldwell's invention maximized the performance of an already revolutionary design. As a result, Boeing placed the first production order for the Hamilton Standard two-position, controllable-pitch propellers for use on all of its transport aircraft, not just the refined Model 247D.[24]

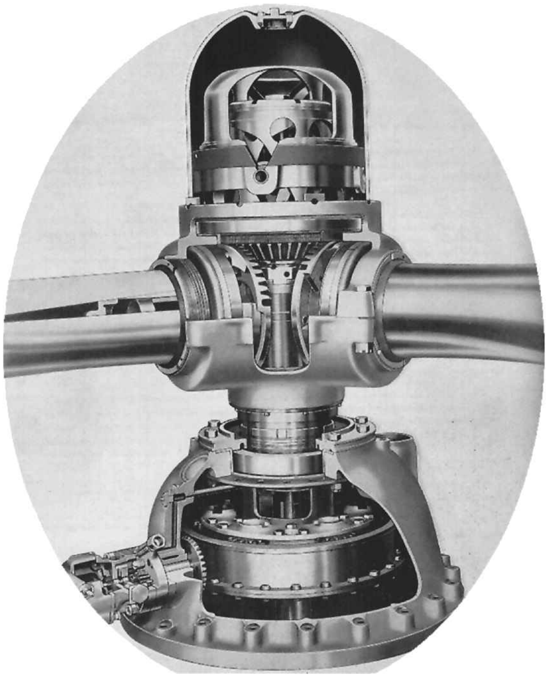

Fig. 13 Hamilton Standard Hydromatic constant-speed propeller mechanism.

After the demonstration of the extreme utility of the variable-pitch propeller on the Model 247, the larger aviation community learned that the new propeller was a vital component of any new airplane design. The Army, Navy, and industry removed their objections. The Douglas Company consciously incorporated Hamilton Standard controllable-pitch propellers into the design of their revolutionary DC-1 transport before its first flight in July 1933. The high performance and long range of the highly successful DC-series transports benefited from the use of variable-pitch propellers.[25]

The introduction of the variable-pitch propeller on the Boeing 247 and Douglas DC-series transports paved the way for the expansion of air transport and performance in the United States. By the spring of 1934, Hamilton Standard had manufactured or had orders for 1000 controllable-counterweight propellers, which was indicative of their importance and the revolutionary nature of the new device. The corporation would sell the foreign rights to manufacture the propeller to Britain (de Havilland), France (Hispano-Suiza), and Germany (Junkers) in 1934 and 1935. By 1939, Hamilton Standard and its licensees had produced more than 25,000 controllable-pitch propellers for the international commercial and military market.

The dramatic improvement in performance offered by the variable-pitch propeller won Caldwell and Hamilton Standard the 1933 Collier Trophy. President Franklin D. Roosevelt bestowed the honor on behalf of the National Aeronautics Association because the new device enabled "modern planes and engines to realize to the full the improvements in design" brought about by the aeronautical design revolution.[26] Roosevelt emphasized that "The success of [Caldwell's] propeller has revealed a new horizon of aeronautics and taken the limits off speed. Henceforth, our pace through the air will be as fast as the daring and imagination of the engineers."[27] Other honors Caldwell received for his invention included the Sylvanus A. Reed Award (1935) and an honorary fellowship (1946) from the Institute of Aeronautical Sciences (the present-day AIAA) (Fig. 11). He also served as the society's president in 1941.

Caldwell and Hamilton Standard went on to develop what would be the ultimate form of the variable-pitch mechanism, the constant-speed propeller, or the "automatic gearshift of the air."

Fig. 14 Boeing B-29s over Japan.

Fig. 15 The crew of this Boeing B-29 was able to be feather the propeller and get safely home.

Caldwell originally intended his first propeller in 1930 to incorporate constant-speed operation, which changed blade pitch automatically according to varying flight conditions while the engine speed remained the same. The immediate need for a variable-pitch propeller, however, influenced his first developing the two-position controllable. Nevertheless, development of a dedicated constant-speed propeller started in 1932. The key to the constant-speed unit was to design a control responsive enough to frequent changes in engine speed. Experiencing difficulty, Caldwell solicited the assistance of the Woodward Governor Company of Rockford, Illinois, a manufacturer of hydraulic governors for diesel engines. Caldwell and his engineering staff at Hamilton Standard, in conjunction with Woodward, worked on the new control unit for two years. They first tested the unit on an airplane in 1934 and placed it into production in late 1935[28] (Fig. 12) (Ref. 28).

While the first constant-speed propeller still employed counterweights to vary pitch in one direction, Caldwell and his engineering team at Hamilton Standard developed a new propeller that relied on hydraulic pressure for all pitch actuation and, as a result, utilized engine power more efficiently.[29] Introduced in 1938, the Hydromatic propeller employed three major improvements over the earlier Hamilton Standard variable designs (Fig. 13). First, the new design incorporated a new safety feature called "quick-feathering," which prevented propeller windmilling after engine failure. Second, the propeller's "quick-acting" cams provided more responsive control of pitch variation, facilitated multi-engine synchronization, and removed the risk of "over-speeding" the engine while diving. Finally, because its operating mechanism was sealed and operated under constant engine oil pressure, the Hydromatic was easier to maintain and operate while in service. All three improvements were major developments for high-performance aircraft that would soon be key weapons in the upcoming world war.[30] The Hydromatic propeller was essentially the modern hydraulic propeller.

During the pivotal years of World War II and the early Cold War (1940–1955), Caldwell was the corporate director of the United Aircraft Research Division at Hartford, Connecticut, where he supervised the design and construction of one of the world's leading industrial propeller and wind-tunnel testing facilities. As jet engine technology supplanted the propeller–piston engine propulsion system, Caldwell became active in turbine research. He retired in 1955 as vice president for research at United Aircraft. On December 23, 1974, Caldwell passed away at his home in West Hartford, Connecticut, at the age of 85.[31]

Conclusions

Frank W. Caldwell was America's leading propeller engineer and designer during the aeronautical design revolution of the 1920s and 1930s. The importance of his work can be gauged at various levels. From the military and political viewpoint, his inventions contributed to the victorious American aerial campaigns of World War II. Virtually the entire Air Force inventory, from multi-engine bombers to fighter and transport aircraft, employed Hydromatic propellers. The full-feathering feature alone was crucial to the safety of American bomber crews over Germany and Japan during World War II (Figs. 14, 15). At the end of the war, Daniel Adam Dickey, a Caldwell protégé and the civilian head of the Army's propeller program in the 1930s and 1940s, traveled to Germany with other Wright Field engineers to inspect and evaluate German aeronautical developments. In a 1983 interview, Dickey concluded that although the Germans were ahead of the Americans in many areas, they were dramatically behind the United States in propeller development. Dickey believed that the "early vision" of Caldwell and his propeller engineers at McCook Field were responsible for that achievement.

At the technical level, Caldwell recognized the synergistic balance that existed between the internal issues of variable-pitch propeller design and external technical issues related to overall aircraft design. He placed propeller shape, structures, and materials, as well as efforts to perfect the mechanism of variable pitch, in the context of their positive effect on the aerodynamic, propulsive, and economic efficiency of the airplane. That approach raises in turn larger questions pertinent to the history of technology. The introduction of an important and new aeronautical device illustrates the nature of evolutionary and revolutionary technological change during a period of unprecedented innovation.

Caldwell was but one of several key technologists who contributed to the development of the modern airplane. Their coincident advances in aerodynamics, structures, and power plants resulted in the synergy of innovation that shaped the aeronautical design revolution. That commitment to the continued improvement of the airplane reflected a strong cultural undercurrent in early 20th century America that emphasized technology as a harbinger of progress. The aeronautical design revolution resulted from a communal response to a technological challenge—to make the airplane go higher, faster, and farther—and a history of Caldwell's individual accomplishment can illustrate what that achievement meant to American society and culture. As a result, the story of the gearshift of the air and its creator, Frank W. Caldwell, can provide a broader understanding of 1920s and 1930s American society as a culture of progress.

Acknowledgments

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