A History of Helicopter Flight

J. Gordon Leishman

Professor of Aerospace Engineering,

University of Maryland, College Park.

"The idea of a vehicle that could lift itself vertically from the ground and hover motionless in the air was probably born at the same time that man first dreamed of flying."

Igor Ivanovitch Sikorsky

Contents

Text on all pages © J. G. Leishman 2000, with extracts from the author's book "Principles of Helicopter Aerodynamics" © Cambridge University Press 2000.

Overview

During the past sixty years since their first successful flights, helicopters have matured from unstable, vibrating contraptions that could barely lift the pilot off the ground, into sophisticated machines of extraordinary flying capability. They are able to hover, fly forward, backward and sideward, and perform other desirable maneuvers. Igor Sikorsky lived long enough to have the satisfaction of seeing his vision of a flying machine "that could lift itself vertically from the ground and hover motionless in the air" come true in many more ways than he could have initially imagined. At the beginning of the new Millennium, there were in excess of 40,000 helicopters flying worldwide. Its civilian roles encompass air ambulance, sea and mountain rescue, crop dusting, fire fighting, police surveillance, corporate services, and oil-rig servicing. Military roles of the helicopter are extensive, including troop transport, mine-sweeping, battlefield surveillance, assault and anti-tank missions. In various air-ground and air-sea rescue operations, the helicopter has saved the lives of over a million people. Over the last forty years, sustained scientific research and development in many different aeronautical disciplines has allowed for large increases in helicopter performance, lifting capability of the main rotor, high speed cruise efficiencies, and mechanical reliability. Continuous aerodynamic improvements to the efficiency of the rotor have allowed the helicopter to lift more than its empty weight and to fly in level flight at speeds in excess of 200 kts (370 km/h; 229 mi/h). Since the 1980s, there has been an accelerating scientific effort to understand and overcome some of the most difficult technical problems associated with helicopter flight, particularly in regard to aerodynamic limitations imposed by the main rotor. The improved design of the helicopter and the increasing viability of other vertical lift aircraft such as the tilt-rotor continue to advance as a result of the revolution in computer-aided design and manufacturing and the advent of new lightweight composite materials. The helicopter today is a safe, versatile, and reliable aircraft, that plays a unique role in modern aviation provided by no other aircraft.

Back to Contents

The Dream of True Flight

Compared to airplanes, the development of which can be clearly traced to Otto Lilienthal, Samuel Langley, and the first fully controlled flight of a piloted powered aircraft by Orville and Wilbur Wright in 1903, the origins of successful helicopter flight are considerably less clear. A pure helicopter can be defined as any flying machine using rotating wings (i.e., a rotor with blades that spin about a shaft) to provide lift, propulsion, and control forces that enable the aircraft to hover relative to the ground without forward flight speed to generate these forces. In addition, to be practical, the machine must also be able to fly forward, climb, cruise at speed, and then descend and come back into a hover for landing. This is the dream of true flight, a feat only achieved in nature by the hummingbird or dragonfly. Nature has inspired humankind for literally hundreds of years before the vertical flight machine we now know as a helicopter became a practical reality.

The price of an aircraft that could safely and efficiently perform these very demanding flight maneuvers under full control of a pilot is significant mechanical and aerodynamic complexity. While one can draw several parallels in the technical development of the helicopter when compared to fixed-wing aircraft, the longer and more tumultuous gestation of vertical flight aircraft is a result of the greater depth of knowledge required before all the various aerodynamic and mechanical problems could be understood and overcome. Besides the need to understand the basic aerodynamics of vertical flight and improve upon the aerodynamic efficiency of the helicopter, other technical barriers included the need to develop powerplants (engines) with high power-to-weight ratios, as well as high-strength, low-weight materials for the rotor and airframe. As these key technologies have matured during the last seventy years, the helicopter has grown from a vibrating rickety contraption that was barely able to lift its own weight into a modern and efficient aircraft of considerable engineering sophistication.

Back to Contents

Key Problems in Attaining Vertical Flight

There are several authoritative sources that document the development of helicopters and other rotating-wing aircraft such as autogiros. These authors include Gregory (1944), Lambermont (1958), Gablehouse (1967), Gunston (1983), Apostolo (1984), Boulet (1984), Lopez & Boyne (1984), Taylor (1984), Everett-Heath (1986), Fay (1987) and Spenser (1999), amongst others. Boulet (1984) has a unique perspective, giving a first-hand account of the early helicopter developments though interviews with the pioneers, constructors, and pilots of the machines. A detailed history of very early, and perhaps even obscure, helicopter developments is given by Liberatore (1950, 1988, 1998). For original publications documenting the earliest technical developments of the autogiro and helicopter, see Warner (1920), von Kármán (1921), Balaban (1923), Moreno-Caracciolo (1923), Klemin (1925), Wimperis (1926) and Seiferth (1927).

As described by Liberatore (1998), the early work on the development of the helicopter can be placed into two categories: inventive and scientific. The former is one where intuition is used in lieu of formal technical training, whereas the latter is one where a trained, systematic approach is used. At the beginning of the twentieth century nearly all prior attempts at vertical flight can be considered as inventive, the inherent aerodynamic and mechanical complexities of building a vertical flight aircraft resisting many ambitious efforts. A contributing factor was the relatively few scientific investigations of flight or studies into the science of aerodynamics -- see Anderson (1997). The history of flight documents literally hundreds of failed helicopter inventions, which either had inadequate installed power or limited control capability, or more often than not, the machine just vibrated itself to pieces. Some of the better designed early machines made brief hops into the air, but control of the aircraft was limited. Yet, the quest for true mastery of the air continued to inspire many inventors and, in time, their work led to sustained technical efforts by trained engineers and, ultimately, to the successful development of the modern helicopter. The technical contributions of Juan de la Cierva, Louis Breguet, Heinrich Focke, Raoul Hafner, Igor Sikorsky and Arthur Young stand out, and their work was instrumental in the design of truly safe and practical helicopters.

Six fundamental technical problems can be identified that limited early experiments with helicopters. These problems have been described by Igor Sikorsky (1938) and other sources. In summary, these problems were:

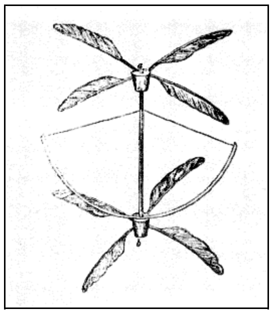
1. ***Understanding the basic aerodynamics of vertical flight:*** The theoretical power required to produce a fixed amount of lift was an unknown quantity to the earliest experimenters, who were guided more by intuition than by science. While basic theories describing the operation of thrusting rotors had been established by the end of the nineteenth century by William Rankine (1855), W. Froude (1878) and R. E. Froude (1889), the first significant application of aerodynamic theory to helicopter rotors came about in the early 1920s.
2. ***The lack of a suitable powerplant (engine):*** This was a problem that was not to be overcome until the beginning of the twentieth century by the development of internal combustion (gasoline) powered engines. Yet, it was not until the mid-1920s that engines with sufficient power and with the high power to weight ratios suitable for vertical flight became more widely available.
3. ***Minimizing structural weight and engine weight:*** Early power plants were made of cast iron and were relatively heavy. Aluminum, a common material used on modern aircraft, was not available commercially until about 1890, but even then was inordinately expensive. Aluminum was not widely used in aeronautical applications until 1920.
4. ***Counteracting rotor torque reaction:*** The idea of a tail rotor to counter torque reaction and provide directional control was not used on most early designs. Most early machines were built with either coaxial or laterally side-by-side rotor configurations. Yet, building and controlling two rotors was even more difficult that for one rotor. Igor Sikorsky was the first to successfully use the tail rotor in the single rotor helicopter configuration we know today.
5. ***Providing stability and properly controlling the machine:*** A primary concern was to devise a means of defeating the unequal lift produced on the blades advancing into and retreating from the relative wind when in forward flight. These were problems that were only to be fully overcome with the use of blade articulation in the form of flapping and lead/lag hinges, ideas that were pioneered by Cierva, Breguet, and others, and with the development of blade cyclic pitch control.
6. ***Conquering the problem of high vibrations:*** Vibration was a source of many mechanical failures of the rotor and airframe, and reflected an insufficient understanding of the dynamic and aerodynamic behavior of rotating-wings.

While all of the factors listed above contributed in some way to the lack of initial progress in achieving successful vertical flight, the development of a practical helicopter had to wait until engine technology could be refined to the point that lightweight engines with considerable power could be built. By 1920, gasoline powered piston engines with higher power-to-weight ratios were more widely available, and the control problems of achieving successful vertical flight were at the forefront. This era is marked by the development of a vast number of prototype helicopters throughout the world. Most of these machines made short hops into the air or flying slowly in ground effect. Many of the early designs were built in Great Britain, France, Germany, Italy, and the United States, who led the field in several technical areas. However, with all the various incremental improvements that had been made to the basic helicopter concept during the pre-World War 2 years, it was not until the late interwar period that significant technical advances were made, and more practical helicopter designs that could lift both a pilot and a substantial payload began to appear.

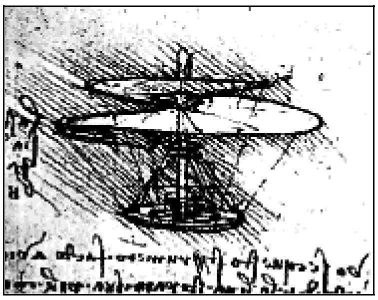
Back to Contents

Early Thinking

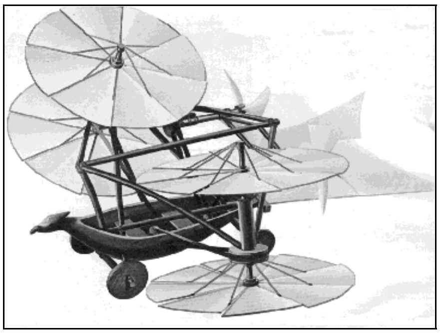
The ideas of vertical flight aircraft can be traced back to early Chinese tops, a toy first used about 400 BC. Everett-Heath (1986) and Liberatore (1998) give a detailed history of such devices. The earliest versions of the Chinese top consisted of feathers at the end of a stick, which was rapidly spun between the hands to generate lift and then released into free flight. These toys were probably inspired by observations of the seeds of trees such as the sycamore, whose whirling, autorotating seeds can be seen to carry on the breeze. More than 2,000 years later, about 1754, Mikhail Lomonosov of Russia had developed a small coaxial rotor modeled after the Chinese top but powered by a wound-up spring device. The device flew freely and climbed to a good altitude.



In 1783, the French naturalist Launoy, with the assistance of Bienvenu, his mechanic, used a coaxial version of the Chinese top in a model consisting of a counterrotating set of turkey feathers. This relatively large device was powered by a string wound around the rotor shaft and tensioned by a crossbow. When the tension was released, the blades whirled and the device climbed high into the air. Launoy & Bienvenu's invention created quite a stir in scientific circles. Inspired by the early success with these and other such whirling tops, the French mathematician A. J. P. Paucton published in 1786 one of the first scientific papers on the problem of rotating wings entitled "Theorie de la vis D'Archimede."

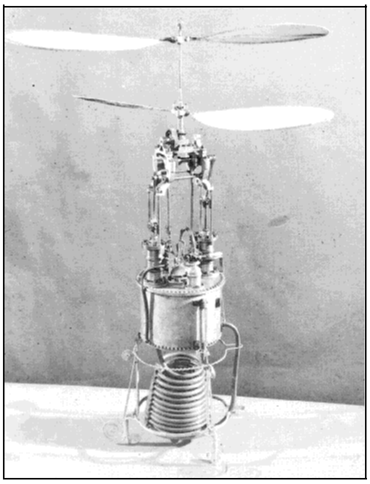


Amongst his many elaborate drawings, the Renaissance visionary Leonardo da Vinci shows what is a basic human-carrying helicopterlike machine. His sketch of the "aerial-screw" or "air gyroscope" device is dated to 1483 but it was first published nearly three centuries later. (Da Vinci's original drawing is MS 2173 of Manuscript (codex) B, folio 83 verso, in the collection of the Bibliotheque L'Institute de France, Paris.) Da Vinci's idea was an obvious elaboration of an Archimedes water-screw, but with keen insight to the problem of flight. His proposed device comprised a helical surface formed out of iron wire, with linen surfaces made "airtight with starch." Da Vinci describes that the machine should be "rotated with speed that said screw bores through the air and climbs high." He obviously realized that the density of air was much less than that of water, so da Vinci describes how the device needed to be relatively large to accomplish this feat -- the number "8" in his backward mirror image script and to the left of the sketch indicates that the size of the rotor is eight braccia. (A braccia is an old Florentine unit of measure approximately equal to one arm's length, which translates into a rotor of roughly 20-feet in diameter.) Da Vinci clearly did not build his machine, except perhaps for some small models, but his idea was clearly far ahead of its time. See Hart (1961) or Giacomelli (1930) for further reading on da Vinci's aeronautical inventions. Although da Vinci worked on various concepts of engines, turbines, and gears, his sketches did not seem to unite the ideas of his aerial-screw machine to an engine. Nor did da Vinci seem to appreciate the concept of torque-reaction -- a well-known problem to all rotary-wing engineers where a torque applied to the rotor shaft will result in a reaction torque tending to rotate the platform from which the torque is applied.

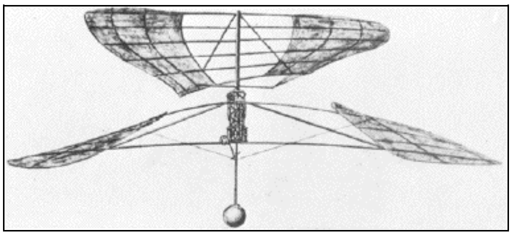


Sir George Cayley is famous for his work on the basic principles of flight, which dates from the 1790s -- see Pritchard (1961). As a young boy, Cayley had been fascinated by the Chinese top, and by the end of the eighteenth century had constructed several successful vertical-flight models with rotors made of sheets of tin and driven by wound-up clock springs. As a young man, his fascination with flight led him to design and construct a whirling-arm device in 1804, which was probably one of the first scientific attempts to study the aerodynamic forces produced by lifting wings. Cayley (1809-10) published a three-part paper that was to lay down the foundations of modern aerodynamics -- see Anderson (1997). In a later paper, published in 1843, Cayley gives details of a relatively large vertical flight aircraft design that he called an "Aerial Carriage." The machine had two pairs of lateral side-by-side rotors to provide lift, and were pushed forward by propellers. His idea seemed to be that the disks flattened down in forward flight, becoming circular wings. However, Cayley's device only remained an idea because the only powerplants available at the time were steam engines, and these were much too heavy to allow for successful powered flight.

The lack of a suitable powerplant continued to stifle aeronautical progress, both for fixed and rotating wing applications, but the use of miniature lightweight steam engines met with some success. In the 1840s, another Englishman, Horatio Phillips, constructed a steam-driven vertical flight machine where steam generated by a miniature boiler was ejected out of the blade tips. Although impractical to build at full-scale, Phillips's machine was significant in that it marked the first time that a model helicopter had flown under the power of an engine rather than stored energy devices such as wound-up springs.



In the early 1860s, Ponton d'Amecourt of France flew a number of small steam-powered helicopter models. He called his machines helicopteres, which is a word derived from the Greek adjective "elikoeioas" meaning spiral or winding, and the noun "pteron" meaning feather or wing -- see Wolf (1974) and Liberatore (1998). However, the novelist Jules Verne was still impressed with d'Amecourt's attempts, and in 1886 he wrote "The Clipper of the Clouds" where the hero of the novel cruised around the skies in a giant helicopterlike machine that was lifted by thirty-seven small coaxial rotors and pulled through the air by two propellers.



Other notable vertical flight models that were constructed at about this time include the coaxial design of Bright in 1861 and the twin-rotor steam-driven model of Dieuaide in 1877. Wilhelm von Achenbach of Germany built a single rotor model in 1874, and he was probably the first to use the idea of a sideward thrusting tail rotor to counteract the torque reaction from the main rotor. Later, Achenbach conducted experiments with propellers, the results of which were published by NACA -- see Achenbach (1923). About 1869 a Russian helicopter concept was developed by Lodygin, using a rotor for lift and a propeller for propulsion and control. Around 1878, Enrico Forlanini of Italy also built another type of flying steam-driven helicopter model. This model had dual counterrotating rotors, and it is recorded that it flew freely at heights of over forty feet for as much as twenty seconds.

In the 1880s, the well-known scientist and inventor Thomas Alva Edison experimented with small helicopter models in the United States. He tested several rotor configurations driven by a gun cotton engine, which was an early form of internal combustion engine. A series of explosions deterred further efforts with these engines. Later, Edison used an electric motor for power, and he was one of the first to realize from his experiments the need for a large diameter rotor with low blade area to give good hovering efficiency. Unlike other inventors and experimenters of the times, Edison's more scientific approach to the vertical flight problem proved that both high aerodynamic efficiency of the rotor and high power from an engine were required if successful flight was to be achieved. In 1910, Edison patented a rather cumbersome looking full-scale helicopter concept with boxkite-like blades, but there is no record that it was ever constructed. Edison, however, was to remain a staunch supporter of helicopter concepts for the rest of his life.

Back to Contents

Engines: A Key Enabling Technology

The development of the engine (powerplant) is fundamental to any form of flight. While airplanes could fly with engines of relatively lower power, the success of the helicopter had to wait until aircraft engine technology could be refined to the point that much more powerful and lightweight engines could be built. A look at the historical record shows that the need for engines of sufficient power-to-weight ratio was really a key enabling technology for the success of the helicopter.

To the early pioneers, the power required for successful vertical flight was an unknown quantity and an understanding of the problem proceeded mostly on a trial and error basis. The early rotor systems had extremely poor aerodynamic performance, with efficiencies (figures of merit) of no more than 50%. This is reflected in the engines used in some of the helicopter concepts designed in the early 1900s, which were significantly overpowered and overweight. Prior to 1870, the steam engine was the only powerplant available for use in most mechanical devices. The steam engine is an external combustion engine and, relatively speaking, it is quite a primitive form of powerplant. It requires a separate boiler, combustor, recirculating pump, condenser, power producing piston and cylinder and well as a fuel and an ample supply of water. All of these components would make it very difficult to raise the power to weight/ratio of a steam engine to a level suitable for aeronautical use. Nonetheless, until the internal combustion engine was developed, the performance of steam engines was to be steadily improved upon, being brought to a high level of practicality by the innovations of James Watt.

The state-of-the-art of aeronautical steam engine technology in the mid-nineteenth century is reflected in the works of British engineers Stringfellow and Hensen and also the American, Charles Manly. The Hensen steam engine weighed about 16lb (7.26kg) andproduced about 1hp (0.746kW), giving a power-to-weight ratio of about 0.06, which as about three times that of a traditional steam plant of the era. Fueled by methyl alcohol, this was also a more practical fuel for use in aeronautical applications. However, to save weight the engine lacked a condenser and so ran on a fixed supply of water. With a representative steam consumption of30lb/hp/hr (18.25kg/kW/hr) this was too high for aircraft use. A steam engine of this type was also used by Erico Forlanini of Italy in about 1878 for his experiments with coaxial helicopter rotor models.

In the United States, Charles Manly built a relatively sophisticated five cylinder steam engine for use on Langley's Aerodrome. The cylinders were arranged radially around the crankcase, a form of construction that was later to become a basis for the popular air-cooled radial reciprocating internal combustion aircraft engine. Manly's engine produced about 52hp (36.76kW) and weighed about 151lb (68.5kg), giving a power-to-weight ratio of 0.34hp/lb (0.56kW/kg). The Australian, Lawrence Hargreve, worked on many different engine concepts, including those powered by steam and gasoline. Hargreve was probably the first to devise the concept of a rotary engine, where the cylinders rotated about a fixed crankshaft, another popular design that was later to be used on many different types of aircraft including helicopters

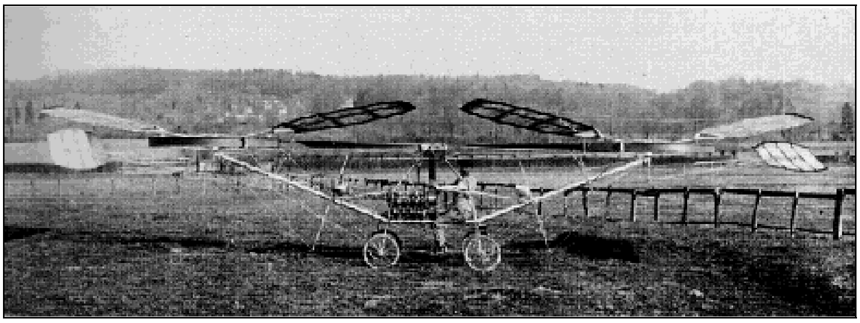
The internal-combustion engine came about in the mid-20th century and was a result of the scientific contributions from many individuals. Realizing the limitations of the steam engine, there was gradual accumulation of knowledge in thermodynamics, mechanics, materials and liquid fuels science. One of the earliest studies of the thermodynamic principles was by Sadi Carnot in 1824 in his famous paper "Reflections on the Motive Power of Heat." In 1862, Alphose Beau de Rochas published the first theory describing the 4-stroke cycle. In 1876, Nikolaus Otto was to use Rochas's theory to design an engine that was to form the basis for the modern gasoline powered reciprocating engine. The development of the internal combustion engine eliminated many parts, simplified the overall powerplant system and for the first time enabled the construction of a compact powerplant of high power/weight ratio.

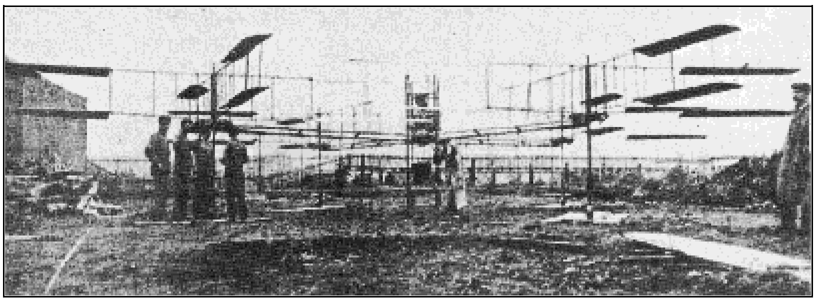
The earliest gasoline powered aircraft engines were of the air-cooled rotary type. The popular French "Gnome" and "Le Rhone" rotary engines had power-to-weight ratios of 0.35hp/lb (0.576kW/kg) and were probably the most advanced lightweight engines of their time. This type engine was used by many helicopter pioneers of the era, including Igor Sikorsk in his test rig of 1910. The rotary engine suffered from inherent disadvantages, but compared to other types of engines that were available at the time, they were smooth running and sufficiently lightweight to be suitable for aircraft use. The technology to enable vertical flight was now finally at hand.

Back to Contents

The First Hoppers

In 1907, about four years after the Wright brothers' first successful powered flights in fixed-wing airplanes at Kitty Hawk in the United States, a French bicycle make named Paul Cornu constructed a vertical flight machine that was reported to have carried a human off the ground for the first time. Boulet (1984) gives a good account of the work. The airframe was very simple, with a rotor at each end. Power was supplied to the rotors by a gasoline motor and belt transmission. Each rotor had two relatively large but low aspect ratio blades set at the periphery of a large spoked wheel. The rotors rotated in opposite directions to cancel torque reaction. A primitive means of control was achieved by placing auxiliary wings in the slipstream below the rotors. The machine was reported to have made several tethered flights of

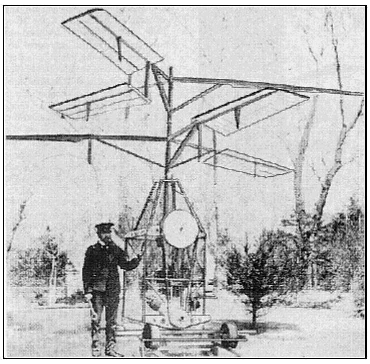




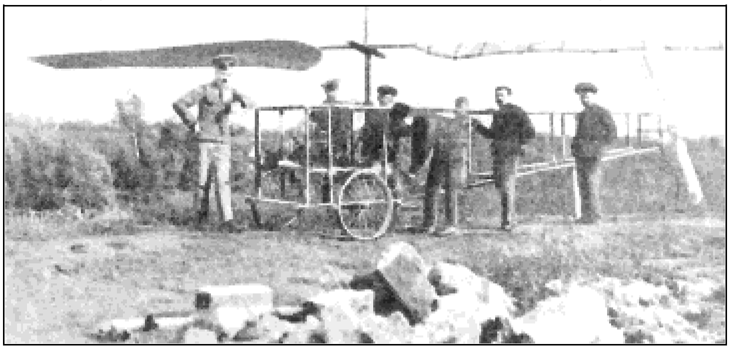
a few seconds at low altitude, but this has never been satisfactorily verified. Certainly, the 24-hp engine used in the machine was hardly powerful enough to have sustained hovering flight out of ground effect.

In 1904 French scientist and academician Charles Richet built a small, unpiloted helicopter. While the machine was unsuccessful, one of Richet's students was the future famous aviation pioneer, Louis Breguet. During the latter part of 1906, the brothers Louis and Jacques Breguet had begun to conduct helicopter experiments of their own under the guidance of Professor Richet. The Breguet Brothers were of an affluent famous clock making family, and were subsequently to become pioneers in French aviation. Louis Breguet made meticulous tests of airfoil shapes, paralleling those of the Wright Brothers [see Anderson (1997)], and without a doubt understood the essential aerodynamic theory of the helicopter. In 1907, the Breguet Brothers built their first helicopter. Their ungainly quad-rotor Gyroplane No.~1 consisted of four long girders made of steel tubes and arranged in the form of a horizontal cross. A rotor consisting of four biplane blades was placed at each of the four corners of the cross, giving a total of 32 separate lifting surfaces. The pilot sat in the center of the cross next to a 40-hp engine. The machine is reported to have carried a pilot off the ground, albeit briefly. Photographs show the assistance of several men stabilizing and perhaps even lifting the machine. Clearly, the machine never flew completely freely because, like the Cornu machine, it lacked stability and a proper means of control. However, the Breguet machine was more sophisticated and probably closer to achieving proper vertical flight than the machine built about the same time by Paul Cornu.

In the early 1900s, Igor Ivanovitch Sikorsky and Boris Yur'ev independently began to design and build vertical-lift machines in Czarist Russia. By 1909, inspired by the work of Cornu and other French aviators, Sikorsky had built a nonpiloted coaxial

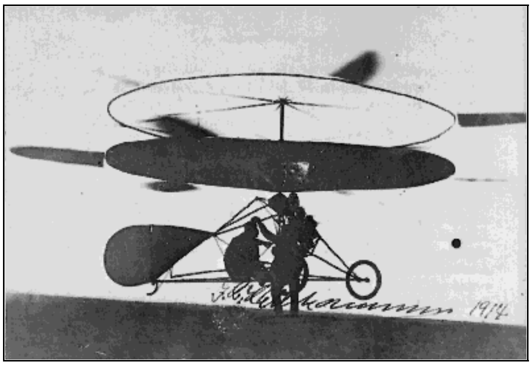


helicopter prototype. This machine did not fly because of vibration problems and the lack of a powerful enough engine. Sikorsky (1938) stated that he had to await "better engines, lighter materials, and experienced mechanics." His first design, the S-1, was unable to lift its own weight, and the second machine, the S-2, only made short (nonpiloted) hops even with a more powerful engine. Discouraged, Sikorsky abandoned the helicopter idea and devoted his skills to fixed-wing (conventional airplane) designs at which he was very successful. Although he never gave up his vision of the helicopter, it was not until the 1930s after he had emigrated to the United States that he again pursued his ideas of vertical flight. Good accounts of the life and work of Igor Sikorsky are documented by Bartlett (1947), Delear (1969), Sikorsky (1964, 1971), Sikorsky & Andrews (1984), Finne (1987), and Cochrane et al. (1989).



Unbeknown to Igor Sikorsky, Boris Yur'ev had also tried to build a helicopter in Russia around 1912. This machine had a very modern looking single rotor and tail rotor configuration. The large diameter, high aspect ratio blades suggested some knowledge that this was the configuration for high aerodynamic efficiency. Yet, like Sikorsky's S-1 and S-2, Yur'ev's aircraft lacked a powerful enough engine. Good accounts of Yur'ev's machine are given by Gablehouse (1967) and Liberatore (1998). The machine never flew properly, being plagued with mechnical failures. Yet, besides being one of the first to use a tail rotor design, Yur'ev was another one of several firsts to propose the concepts of cyclic pitch for rotor control. In this vein, another early cyclic pitch design was patented by Gaetano A. Crocco of Italy in 1906. Crocco, who pioneered the ideas of hydrofoil boats, recognized that if a helicopter was to work properly when in forward flight, a means of changing the pitch on the blades would be needed to account for the dissymmetry in the aerodynamic loads between the side of the rotor advancing into the relative wind and the side retreating away from the wind. As mentioned earlier, the concept of cyclic pitch was one key to attaining full control of the helicopter.

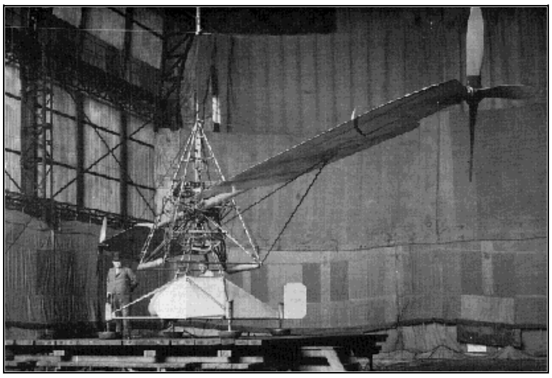
There is also evidence of the construction of a primitive coaxial helicopter by Professor Zhukovskii (Joukowski) and his students at Moscow University in 1910 -- see Gablehouse (1967). Joukowski is well known for his theoretical contributions to aerodynamics, and besides other contributions to the field he published several papers on the subject of rotating wings and helicopters -- see Margoulis (1922) and Tokaty (1971). While prior to 1900 Rankine and Froude had already established the general theory of propellers and rotors using momentum theory, there were a number of rapid developments in the basic aerodynamic theory. For example, the Frenchman Drzewiecky had developed a hybrid momentum/blade element concept about 1900. In 1909 Drzewiecky published a book entitled "Des Helices Aeriennes Theorie Generale des Propulseurs." In 1904, Joukowski published a paper entitled "On the Useful Load Lifted by a Helicopter." In 1906, Joukowski's well-known work "About Connected Vortices" was published. A year later, a paper entitled "A Multi-Bladed Propeller-Screw" appeared. In 1909 Joukowski began to investigate the theory of the effects of forward flight speed on a rotor. This paper was entitled "Experiments on the Theoretical Determination of the Effect of the Airflow on the Surface of a Propeller." Here, like Crocco, Joukowski proved that because of the non-axisymmetric distribution of velocity and airloads, asymmetric forces and moments must act on a propeller when in edgewise (forward) flight. Of course, this implied that to control a helicopter such that it could fly forward would be a difficult task indeed. Although this problem was later to be solved with the invention of cyclic blade pitch and blade flapping hinges, Joukowski offered no method of solution in his 1909 paper.



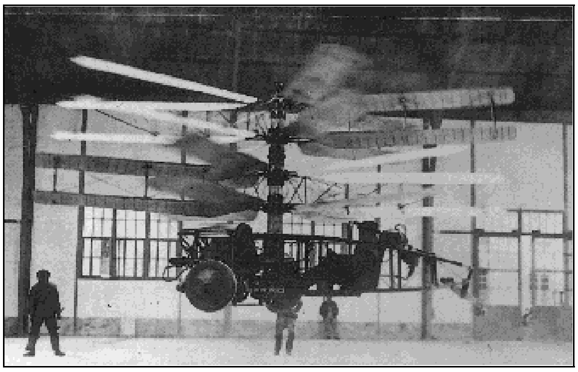
About 1914, the Danish aviation pioneer Jen C. Ellehammer designed a coaxial rotor helicopter. Boulet (1984) gives a good description of the machine. The rotor blades themselves were very short; six of these were attached to the periphery of each of two large circular aluminum rings of about 20-ft in diameter, with the wings extending out about another 5-feet. The lower disk was covered with fabric and was intended to serve as a parachute in the event the blades or the engine failed. A cyclic pitch mechanism was used to change the pitch of the rotating wings and to effect control, this being another one of many early applications of the cyclic pitch concept. The pilot was supported in a seat that could be moved forward and sideways below the rotor, allowing for additional kinesthetic control. The aircraft made many short hops into the air but never made a properly controlled free flight. It was finally destroyed in a crash in 1916.

An Austrian, Stephan Petroczy, with the assistance of the well-known aerodynamicist Theodore von Kármán, built and flew a coaxial rotor helicopter during 1917-20. Interesting design features of this machine included a pilot/observer position above the rotors, inflated bags for landing gear, and a quick-opening parachute. The machine was powered by three rotary engines. While the machine never really flew freely, it accomplished numerous limited tethered vertical flights restrained by cables. The work is summarized in a report by von Kármán (1921) and published by the NACA. It is significant that von Kármán also gives results of laboratory tests on the "rotors," which were really oversize propellers. With the work of William F. Durand [see Warner (1920) and the analysis of the measurements by Max Munk (1923)] these were some of the first laboratory experiments to study rotor performance and the power required for vertical flight.

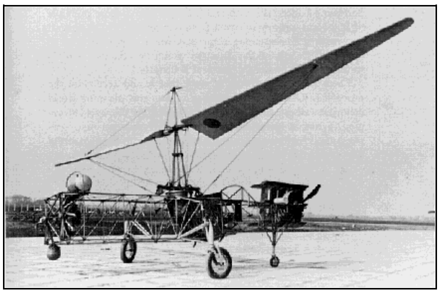
In the United States, Emile and Henry Berliner (a father and son) were interested in vertical flight aircraft. As early as 1909, they had designed and built a helicopter based on pioneering forward flight experiments with a wheeled test rig. They were one of the first to observe the fact that the rotor power required for hovering flight was substantially greater than for flight at low forward speeds. In 1918 the Berliners patented a single-rotor helicopter design, but there is no record that this machine was built. Instead, by about 1919, Henry Berliner had built a counterrotating coaxial rotor machine, which made brief uncontrolled hops into the air and reached a height of about four feet. By the early 1920s at the College Park airport, which is close to the University of Maryland, the Berliners were flying an aircraft with side-by-side rotors. The rotors were oversized wooden propellers, but with special airfoil profiles and twist distributions. Differential longitudinal tilt of the rotor shafts provided directional control. Lateral control was aided by cascades of wings located in the slipstream of the rotors. All variants used a conventional elevator and rudder assembly at the tail, with a small vertically thrusting auxiliary rotor on the rear of the fuselage. This machine made only short hops into the air, and because the true vertical flight capability was limited, the Berliners abandoned the pure helicopter in favor of another hybrid machine they called a "helicoplane." This still used the rotors for vertical lift but incorporated a set of triplane wings and a larger oversized rudder. The Berliner's final hybrid machine of 1924 was a biplane wing configuration with side-by-side rotors. However, the Berliner's early flights with the coaxial rotor and side-by-side rotor machines are credited as some of the first rudimentary piloted helicopter developments in the United States. See also Berliner (1908, 1915). The Berliner's subsequently went on to form the Erco Company or Riverdale, Maryland, which became a well-known manufacturer of light planes and propellers.



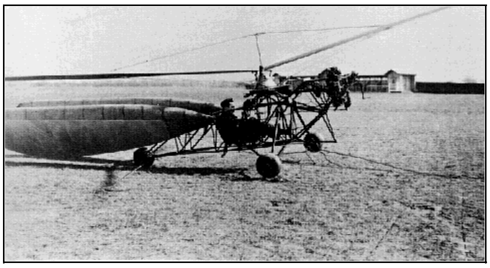
In Britain during the late 1910's and early 1920's, Louis Brennan worked on a helicopter concept with an unusually large single two-bladed rotor. Fay (1987) gives a good account of Brennan's work. Brennan, who was an inventor of some notoriety, had a different approach to solving the problem of torque reaction by powering the single rotor with propellers mounted on the blades themselves. Control was achieved by the use of servo-flaps or "ailerons" inboard of the propellers. The machine was powered by 230-hp Bentley rotary. While Brennan's work was initially carried out with considerable secrecy, in 1921 the machine was moved to the Royal Aircraft Establishment (RAE) at Farnborough. In 1922, the machine flew successfully inside a balloon shed. Further flights outdoors were undertaken through 1925, where the machine made flights at low altitude. The machine crashed on its seventh flight, and official interest in the Brennan machine quickly faded because of increasing interest in the autogiro.



During the early 1920s, Raul Pescara, an Argentinan living and working in Spain and France, was building and attempting to fly a coaxial helicopter with biplane-type rotors. On his first machines, each rotor had four sets of biplane blades that were mounted rigidly to the rotor shaft, and this was later increased to a remarkable five sets per rotor, giving a total of 20 lifting surfaces. As described by Boulet (1984), Pescara's work focused on the need for complete control of the machine, which was achieved through cyclic-pitch changes that could be obtained by warping the blades periodically as they rotated. This was one of the first successful applications of cyclic pitch. Yaw was controlled by differential collective pitch. Early versions of Pescara's machine were underpowered, which may not be surprising considering the high drag of the bracing wires of his rotor, and the aircraft did not fly. With a later version of his helicopter using a more powerful engine, some successful flights were accomplished, albeit under limited control. However, most flights resulted in damage or serious crashes followed by long periods of rebuilding. By 1925, Raul Pescara had abandoned his helicopter projects.



Between 1924 and 1930, a Dutchman named A. G. Von Baumhauer designed and built one of the first single-rotor helicopters with a sideward thrusting tail rotor to counteract the torque reaction from the main rotor. Boulet (1984) gives a good description of Von Baumhauer's machine. The fuselage consisted essentially of a tubular truss, with an engine mounted on one end. The other end carried a smaller engine turning a conventional propeller to provide a thrust force, which with the long moment arm, counter the main rotor torque reaction. The main rotor had two blades, which were restrained by cables so that the blades flapped about a hinge like a seesaw or teeter board. Control was achieved by a swashplate and cyclic-pitch mechanism, which was another very early application of this mechanism. Unfortunately, the main and tail rotors were in no way connected, and this caused considerable difficulties in achieving proper directional control. Nevertheless, the machine was reported to have made numerous short, semi-controlled flights.



In the late 1920s, the Austrian engineer Raoul Hafner designed and built a single-seat helicopter called the R-2 Revoplane -- see Everett-Heath (1986) and Fey (1987). The flights were mostly unsuccessful despite some brief tethered flights of up to a minute. His early machines used a single-rotor configuration with a pair of wings located in the rotor downwash to provide an antitorque moment. For rotor control, Hafner's machine in notable in that it used a swashplate for blade pitch, which was a very early application of the final mechanism that was to become the standard means of providing pitch control on the modern helicopter. Hafner later emigrated to England, where he and Juan de la Cierva independently continued work on blade articulation and rotor control for autogiros, and later, for helicopters.

Back to Contents

Not Quite a Helicopter

The Spanish engineer Juan de la Cierva had built and flown another type of rotating-wing aircraft as early as 1923 -- see Juan de la Cierva (1926, 1930). This aircraft looked a lot like a hybrid between a fixed-wing airplane and a helicopter, with a set of conventional wings and a tail but with a rotor mounted on a vertical shaft above the fuselage. However, unlike a helicopter, this rotor was not powered directly and was completely free to turn on the shaft. It was found that when the rotor disk was inclined backward at a small angle of attack and as the machine was pulled forward by a propeller, the rotor was turned by the action of the airflow on the blades. This aerodynamic phenomenon, called "autorotation," had been understood by Crocco and Yur'ev before 1910, but the idea of pulling the rotor horizontally through the air to generate lift was clearly that of de la Cierva. Juan de la Cierva called his rotating-wing aircraft an "Autogiro." The name Autogiro was registered by de la Cierva as a proprietary name, but when spelled with a small "a" it is used as a generic name for this class of rotorcraft. Today, we might call this type of aircraft an "autogyro" or a "gyroplane."

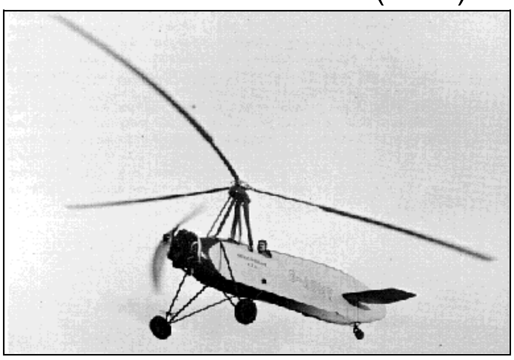
De la Cierva's C-1 Autogiro of 1923 was a coaxial design, the airframe being from a converted wartime fixed-wing aircraft. The problem of asymmetric lift (decribed earlier) was well known to de la Cierva, and his first idea of using a counter rotating coaxial design was that the lower rotor would counteract the asymmetry of lift produced on the upper rotor, thereby balancing the net rolling moment on the aircraft. However, the aerodynamic interference produced between the rotors resulted in different rotor speeds, spoiling the required aerodynamic roll balance, and the aircraft crashed. Undeterred, De la Cierva conducted basic wind tunnel experiments on model rotors at Quatro Vientos airport near Madrid, and was one of the first to establish a scientific understanding of their aerodynamic behavior.

De la Cierva built two more full-scale machines with single rotors before he achieved final success in January 1923 with the C-4. Based on his tests with small models, this fourth machine incorporated blades with mechanical "flapping" hinges at the root, which de a Cierva used as a means of equalizing the lift on the two sides of the rotor in forward flight -- see de la Cierva & Rose (1931). This novel solution to the problem of asymmetric aerodynamic forces allowed the blades to flap up or down about these hinges, responding to the changing airloads during each blade revolution. Although the principle of flapping propeller blades had actually been suggested by Charles Renard in 1904 and the idea of flapping hinges was also patented by Louis Breguet in 1908, Juan de la Cierva is credited with the first successful practical application to an rotating-wing aircraft.

In all of de la Cierva's early Autogiros, the engine drove only the propeller. Starting the rotor required a team of helpers to pull a rope wound around the rotor shaft. Alternatively, taxiing around on the ground could get the rotor spinning. Thereafter, the pilot opened the throttle and the thrusting propeller pulled the machine forward until it quickly lifted off into flight. The freely spinning rotor, or "windmills" as de la Cierva called them, turned relatively slowly in flight. His blades were of a distinctive planform, with a constant chord outer portion and a well rounded tip, tapering inboard to a spar. Metal ties with turnbuckles located near the mid-span linked each of the blades together.

With the success of his Auotgiros, in 1925 Juan de la Cierva was invited to Great Britain by the Weir Company. His C-6 Autogiro was demonstrated at the RAE, and these flights stimulated early theoretical work on rotating-wing aerodynamics at the RAE, mainly by Glauert and Lock. Early theoretical developments were also conducted at NACA by Munk. De la Cierva himself was to write two books for the fledgling rotorcraft industry, albeit formally unpublished, called "Engineering Theory of the Autogiro" and "Theory of Stresses in Autogiro Rotor Blades." In later models of his Autogiro, de la Cierva added a lag hinge to the blades, which alleviated stresses caused by in-plane Coriolis forces and completed the development of the articulated rotor hub for autogiros. A control stick was also connected to the rotor hub, which allowed the rotor disk to be tilted for control purposes. De la Cierva called this the "orientable direct rotor control." While this allowed the ailerons to be dispensed with, the rudder and elevator on the machine were retained. The Cierva Autogiro Company went on to build many more versions of the Autogiro, including the highly successful C-19, the development of which is described by de la Cierva (1935).

Although de la Cierva's autogiro was still not a direct-lift machine and could not hover, it required only minimal forward airspeed to maintain flight. Juan de la Cierva proved that his autogiros were very safe and essentially stall-proof, and because of their low speed handling capability, they could be landed in confined areas. Takeoffs required a short runway, but this problem was solved with the advent of the so-called "jump" take-off technique. In the jump take-off technique, the blades are set to flat pitch and the rotor rpm is increased above the normal flight rpm using the engine. This is followed by the rapid application of collective blade pitch, while simultaneously declutching the rotor and thereby avoiding any torque reaction on the fuselage. This technique lifts the aircraft rapidly off the ground, powered only by the stored kinetic energy in the rotor system. As forward speed builds, the rotor settles into its normal autorotative state -- see also Prewitt (1938). To achieve jump takeoffs, in 1935 Cierva introduced a pitch change mechanism into the rotor design in later versions of the C-30 model.

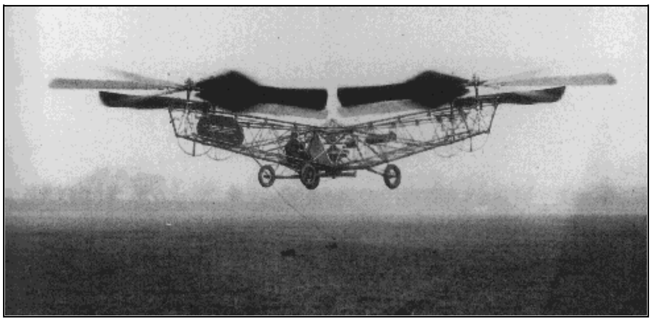


About the same time, Raul Hafner introduced the "spider" cyclic-pitch control system to autogiros; see Fay (1987). This provided a means of increasing collective pitch and also tilting the rotor disk without tilting the rotor shaft with a control stick as in de la Cierva's direct control system. Hafner used this design in his third autogiro, the AR-3, which flew in 1935. With its jump take-off capability, the autogiro was to closely rival the helicopter in performance capability. Several other British companies including Weir, Avro, Parnall, de Havilland, and Westland went on to build variants of the de la Cierva Autogiro designs. The first Weir designs were developments of de la Cierva's models and used the orientable direct rotor control system. The Weir W-1 through W-4 models were all autogiros and were some of the first machines to use a clutch to help bring up the rotor rpm prior to takeoff. The de Havilland and Westland companies built a few larger prototype autogiros. The Westland C-29 was a five-seat cabin autogiro built in 1934. The aircraft was never flown because it exhibited serious ground resonance problems, and the project was canceled with the untimely death of Juan de la Cierva in 1936. However, de la Cierva's work was carried on by designers from Weir, and another Westland designed autogiro called the CL-20 was flown just before World War 2; see Monday (1982).

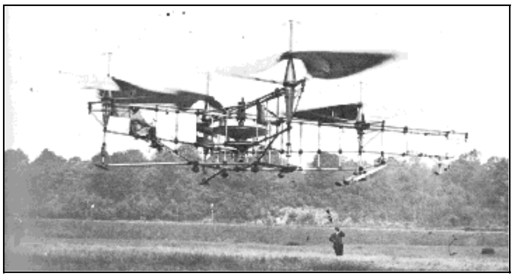
In the United States, the Kellett and Pictairn companies entered into licensing agreements with de la Cierva, resulting in the first flight of an autogiro in the USA in 1928. Picairn went on to design and patent many improvements into the de la Cierva rotor system [see Smith (1985)], but it became clear that it was a true helicopter with power delivered to the rotor shaft that was required. The autogiro was extensively tested in the United States by the NACA. Gustafson (1971) gives an authoritative account of the early NACA technical work on autogiros and helicopters. In addition, the entire first issue of the Journal of the American Helicopter Society, published in January 1956, was devoted to the early autogiro and helicopter developments in the United States. In Russia, the TsAGI built autogiros derived from the de la Cierva designs. Kuznetsov and Mil built the 2-EA, which was derived from the Cierva C-19 -- see Everett-Heath (1988). Later developments of this design led to the first Russian helicopters built with the assistance of Vittorio Isacco, who had led basic helicopter developments in Italy during the 1920s.

Back to Contents

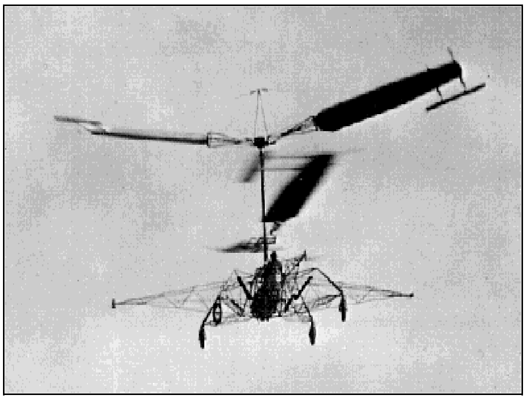
First Successes with Helicopters



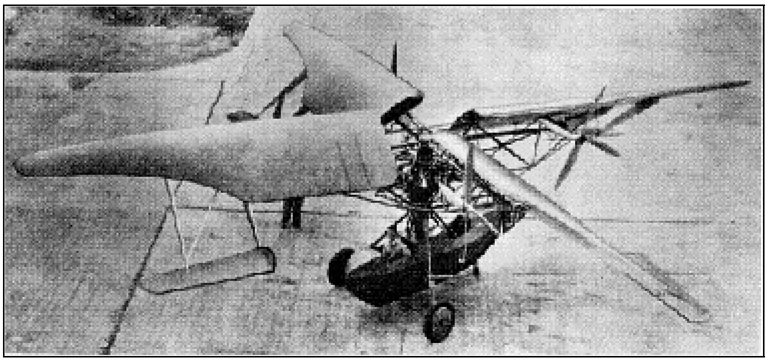
In 1922, a Russian émigré to the United States by the name of Georges de Bothezat built one of the largest helicopters of the time under contract to the US Army. De Bothezat had been a student of Professor Zhukowski in Russia and had written one of the first technical manuscripts on rotating-wing aerodynamics -- see de Bothezat (1919). De Bothezat's machine was a quadrotor with a rotor located at each end of a truss structure of intersecting beams, placed in the shape of a cross. Ivan Jerome was the codesigner. Each rotor had six wide chord blades. Control of the machine was achieved by collective, differential collective and cyclic blade pitch variations, and the blade pitch design likely derived directly from those of Yur'ev. A set of four smaller rotors served to help control the machine. In 1922, the ungainly Jerome-de Bothezat quad-rotor or "Flying Octopus" flew successfully many times, albeit at low altitudes and slow forward speeds. However, because of insufficient performance, high financial costs, and the increasing military interest in autogiros at the time, the project was canceled. Surprisingly, it was to be fifteen or more years before a pure helicopter was again to fly again in the United States and better de Bothezat's accomplishments.



In 1920, Etienne Oemichen, an employee of the French Peugeot car company, built a quad-rotor machine in a similar style to that of de Bothezat, but with eight additional rotors for control and propulsion. His machine typified the cumbrous mechanical complexity of the various helicopters of that time. His initial design was under-powered, and it had to have a hydrogen balloon attached to provide additional lift and stability. Nevertheless, Oemichen went on to design a pure helicopter that was flown between 1923 and 1924. By 1924, Oemichen was making reasonable flights and his machine proved that a vertical flight machine could be stable and somewhat maneuverable, although cumbersome. In May 1924 he was awarded a prize by the FAI for demonstrating the first helicopter to fly a standard closed 1 km circuit, which took 7 minutes 40 seconds at an average speed of only 7.8 km/hr (4.9 mph). The machine, however, was impractical for any realistic use. See also NACA (1921) and Oemichen (1923).

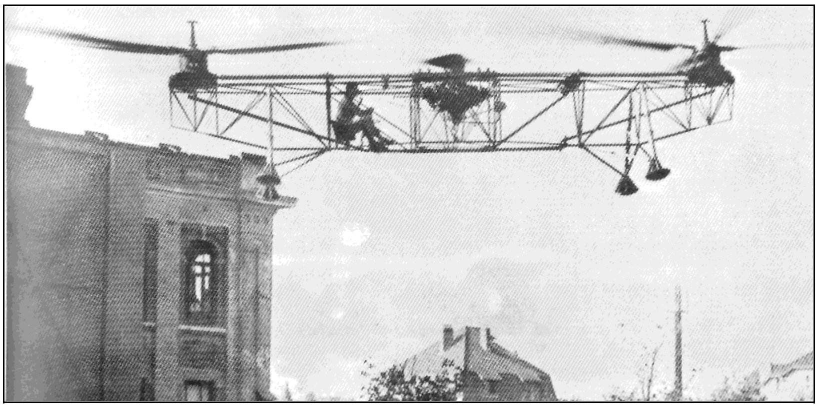


In 1930, Corradino d'Ascanio of Italy built a relatively successful coaxial helicopter, which flew under good control. His relatively large machine had two, two-bladed, counterrotating rotors. Following the work of de la Cierva, the blades had hinges that allowed for flapping and a feathering capability to change blade pitch. Control was achieved by using auxiliary wings or servo-tabs on the trailing edges of the blades, a concept that was later adopted by others, including Bleeker and Kaman in the United States. D'Ascanio designed these servo-tabs so that they could be deflected cyclically by a system of cables and pulleys, thereby cyclically changing the lift on the blade as it swept around the rotor disk. For vertical flight, the tabs on all the blades moved collectively to increase the rotor thrust. Three small propellers mounted to the airframe were used for additional pitch, roll, and yaw control. This machine



held modest FAI speed and altitude records for the time, including altitude (57 ft, 17.4 m), duration (8 minutes 45 seconds) and distance flown (3,589 ft, 1,078 m).

In 1930, Maitland Bleeker of the United States followed Brennan's approach to the torque reaction problem by using a single rotor and delivering power to propellers that were mounted on each rotor blade. Power was supplied through a system of chains and gears from an engine mounted at the center of the machine. Like d'Ascanio's machine, Bleeker's helicopter was controlled by auxiliary aerodynamic surfaces he called "stabovators" that were fastened to the trailing edges of each of the four blades. Both collective and cyclic pitch capability were incorporated into the design. Bleeker's machine accomplished numerous precarious hovers in ground effect. It was not as successful as d'Ascanio's machine and high vibration levels and control problems caused the project to be abandoned during 1933. Liberatore (1998) gives one of the best accounts of the project.



In Belgium during 1929-30, the Russian born engineer Nicolas Florine built one of the first successful tandem rotor helicopters. The rotors turned in the same direction but were tilted in opposite directions to cancel torque reaction. Boulet (1984) describes the various mechanical aspects of the machine. Florine's first aircraft was destroyed in 1930, but he had a second design flying successfully by 1933, which made a flight of over 9 minutes to an altitude of 15-feet. This exceeded d'Ascanio's modest flight duration record of the time. Yet, Florine's designs suffered many setbacks, and work was discontinued into the pre-World War 2 years. His machines were ultimately destroyed during the war.

Back to Contents

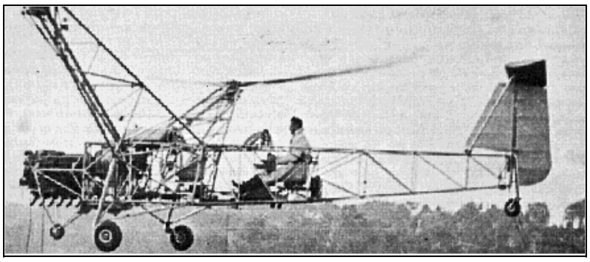
Success at Last

During the period 1930--1936, the famous French aviation pioneers Louis Breguet and Rene Dorand made particularly notable advances in the development of a practical helicopter. Their machine of 1935 was relatively large for the era, with a coaxial rotor configuration. Boulet (1984) and Kretz (1987) give an excellent account of the work. Each rotor had two modern looking tapered blades that were mounted to the hub with flap and lag hinges. The blades were controlled in cyclic pitch using a swashplate design. Yaw control was achieved by differential torque on one rotor with respect to the other rotor. Horizontal and vertical tails were used for increased stability. For its time, the aircraft had held several FAI records, including a duration flight of 62 minutes and distance flown of 44 km (27 mi). Further work on the Breguet-Dorand machine was stopped prior to the outbreak of World War 2.

While helicopters were becoming more and more successful, the safety of the machine was still an issue. They were difficult to fly, and the possibilities of loss of power was always present. All aircraft must possess safe flight characteristics after a loss of power, the helicopter being no exception. While a fixed-wing aircraft can glide, the helicopter can take advantage of autorotation with the rotor unpowered as a means of maintaining rotor rpm, lift, and control in the event of engine failure. In this mode, the helicopter behaves very much like an autogiro so that the relative wind comes upward through the rotor disk. However, with the higher disk loadings (the thrust carried per unit disk area) found on helicopters, to get the rotor to autorotate the helicopter must descend at a relatively high rate. The pilot, in effect, gives up altitude (potential energy) at a controlled rate for kinetic energy to drive the rotor and with care, can autorotate the aircraft safely onto the ground. The ability to "autorotate" can be viewed as one distinguishing feature of a safe and successful helicopter.

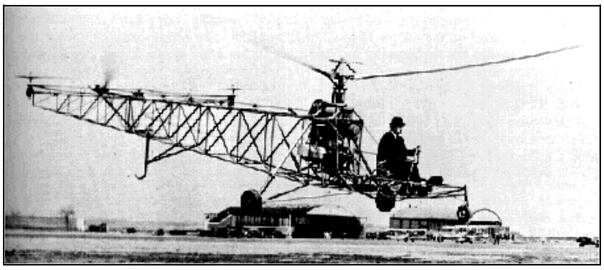
Heinrich Focke of the Focke-Wulf Company began his work on rotating-wing aircraft as early as 1933. He acquired a license to build de la Cierva's autogyros, and successfully manufactured the C-19 and the C-30 models. From the experience he gained by working on these machines and after many wind tunnel tests with small models, Focke began developing the FW-61 helicopter in 1934, named after his current company, Focke-Wulf. Later, in early 1936, Focke and Gert Achgelis finally built and demonstrated a successful side-by-side, two-rotor machine, called the Fa-61. The details of this machine are described by Focke (1938, 1965) and Boulet (1984). This machine was constructed from the fuselage of a small biplane trainer with rotor components provided by the Weir-Cierva company. The rotors were mounted on outriggers and were inclined slightly inward to provide lateral stability. The blades were tapered in planform and were attached to the rotor hub by both flapping and lagging hinges. Longitudinal control was achieved by tilting the rotors forward and aft by means of a swashplate mechanism, while yaw control was gained by tilting the rotors differentially. The rotors had no variable collective pitch, instead using a slow and clumsy system of changing rotor speed to change the rotor thrust. A vertical rudder and horizontal tail provided for additional directional stability. The cut-down propeller on the front of the machine served only to cool the radial engine.

The Fa-61 machine is significant in that it was the first helicopter to show fully controlled flight and also to demonstrate successful autorotations. To this end, provision was made in the design for a fixed low collective pitch setting to keep the rotor from stalling during the descent. It also set records at the time for duration, climb to altitude (3,427 m, 11,243 ft), forward speed (122 km/h, 76 mph), and distance flown in a straight line (233 km, 143 miles). The machine gained a certain amount of notoriety prior to the outbreak of World War 2 when the famous German test-pilot Flugkapitan Hanna Reitsch flew it inside Berlin's Deutschlandhalle sports arena. The Fa-61 aircraft was used as a basis to develop the first German production helicopter, the Fa-266 (Fa-233E), which first flew in 1940. This was a fairly large aircraft, with two three-bladed rotors, and could carry up to four crew. Yet, the machine saw limited production during the Second World War. Boulet (1984) gives a good account of the later helicopter work of Focke. After the War, some of the German machines were used as a basis to develop helicopters in Russia [see Everett-Heath (1988)] and France.



With the assistance of Juan de la Cierva, the Weir Company had formed an aircraft department in Scotland in 1932. The W-5 was the Weir Company's first true helicopter design. Initially, the W-5 was a coaxial design, but concerns about stability and control as well as the success of the Fa-61 led to the redevelopment as a lateral side-by-side configuration, which flew successfully in June 1938. Control was achieved with cyclic pitch but there was no collective pitch; vertical control was obtained by altering the rotor speed, a cumbersome feature used also on the Fa-61. The W-5 reached speeds of 70 mph in forward flight. The Weir W-5 (and later the W-6) and the Fa-61 were technically ahead of Sikorsky's VS-300 in terms of flight capability, but the VS-300 was ultimately to set the new standard for helicopter design. The Weir W-6, which first flew in 1939, was a much larger version of the W-5 but still used the lateral side-by-side rotor configuration. Further work on the Weir designs was suspended at the outbreak of World War 2.

During the period 1938-43, Antoine Flettner, also of Germany, developed several helicopter designs. Flettner's success came with using a side-by-side intermeshing rotor configuration, which became known as a synchcropter. This rotor idea was first patented to Bourcart in 1903 and by Mees in 1910, and the synchropter configuration was pursued by other developers in other countries. In the synchropter design, the rotor shafts are close together but arranged so that they are at a significant outward angle with the overlapping rotors turning in opposite directions. A gearing system ensures the exact phasing of the rotors. In 1939, Flettner's Fl-265 synchropter flew successfully and was the first helicopter to demonstrate transition into autorotation and then back again into powered flight. Flettner built several other machines, including the Fl-282 Hummingbird. With the Focke Fa-266 (Fa-233E) , the Fl-282 was one of the first helicopters to enter into production. However, production was limited because of World War 2. After the war, in the United States, the Kellett Aircraft Company (which, as mentioned earlier, also built autogiros as a licensee to Pitcairn) adopted Flettner's synchropter configuration but used three-bladed instead of two-bladed intermeshing rotors. The aircraft flew very successfully, but it never went into production. The synchropter concept was also adopted by Charles Kaman, who's company Kaman Aircraft Corp. was later to put the type into successful production.



As described earlier, Igor Sikorsky had experimented in Czarist Russia with primitive vertical lift aircraft as early as 1907 -- see Sikorsky (1938) and Finne (1987). After Sikorsky had emigrated to the United States, he went on to design and build giant flying boats. In 1935, Sikorsky was issued a patent, which showed a relatively modern looking single rotor/tail rotor helicopter design with flapping hinges and a form of cyclic pitch control. Although Sikorsky encountered many technical challenges, he tackled them systematically and carefully. To the workers at the Sikorsky plant in Connecticut, the machine was known as "Igor's nightmare" and reflected the mechanical complexity of his early prototypes. Sikorsky's first helicopter, the VS-300, was flying by May 1940. A good summary of the technical design is given by Sikorsky (1941, 1942, 1943). His first machine had one main rotor and three auxiliary tail rotors, with longitudinal and lateral control being obtained by means of pitch variations on the two vertically thrusting horizontal tail rotors. Powered only with a 75 hp engine, the machine could hover, fly sidewards and backwards, and perform many other maneuvers. Yet it could not easily fly forward, exhibiting a sudden nose-up pitching characteristic at low forward speeds. This phenomenon was to be traced to the downwash of the main rotor wake, which as airspeed built, blew back onto the two vertically thrusting tail rotors and destroyed their lift. The main lifting rotor of the VS-300 was used in the later VS-300A with a more powerful 90 hp engine, but only the vertical (sideward thrusting) tail rotor was retained out of the original three auxiliary rotors. In this configuration, longitudinal and lateral control was achieved by tilting the main rotor by means of cyclic-pitch inputs; the single tail rotor was used for antitorque and directional control purposes. This configuration was to become the standard for most modern helicopters.

Back to Contents

More Successes - First Production Machines

Before long, Sikorsky had refined his first machines and by 1941 he had already started production of the R-4. In 1943 Sikorsky developed the R-5, which, although still only a two-seater helicopter, was much larger, more powerful, and more capable than the R-4, which became used extensively for pilot training. The R-5 was produced in substantial numbers, and while it had a limited payload and forward speed capability, several hundred of them saw military service in the Pacific during World War 2. Find out more about the history of Sikorsky Aircraft by checking out the Sikorsky Archives or the Sikorsky Timeline at the Helicopter History Site. In 1946 Westland Helicopters in Great Britain obtained a license to build models of the

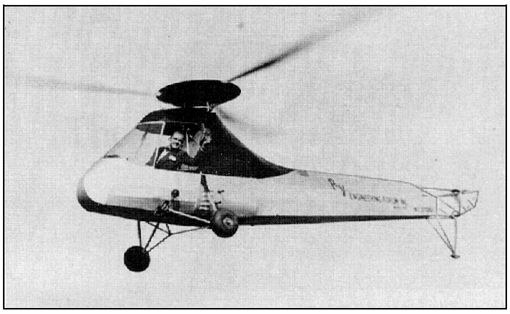
Sikorsky machines. Westland already had a history as a successful fixed-wing manufacturer. Their first machine was designated as the WS-51 after the S-51, which was a development of the R-5 and the first commercial helicopter designed by Sikorsky. This post-War period was the start of a long relationship between the two companies. After significantly reengineering the Sikorsky machine to meet British airworthiness standards, Westland called the aircraft the Dragonfly. The Westland Widgeon later followed, and this was a very modern looking and powerful version of the Dragonfly with a larger passenger cabin. Find out more about the history of Westland Aircraft by checking out the Westland Timeline at the Helicopter History Site.

During 1944, the Cierva-Weir Company, prompted by the initial success of Sikorsky's R-4 and R-5, proposed a rather large single-rotor machine called the W-9. This machine was rather unique in its use of jet thrust to counteract rotor torque reaction -- see Everett-Heath (1986). However, because the rotor lacked any collective pitch control, rotor thrust was controlled by changing rotor speed as in the pre-war Weir W-5/6 models. The W-9 crashed during a test flight in 1946, and the project was subsequently abandoned. Subsequently, the Weir and Cierva companies went on to design the W-11 Air-Horse, which was a unorthodox three-rotor helicopter of considerable lifting capability. Mainly designed for crop dusting, the machine crashed during a test flight and any further work was terminated. The final helicopter of the Cierva--Weir line was the diminutive W-14 Skeeter used by the British armed forces. This was a two-seater training helicopter designed in 1948, but it saw only a limited production run through 1960.

Several other young helicopter design pioneers were working in the United States during the 1940s. These included Arthur Young, Frank Piasecki, Stanley Hiller, and Charles Kaman. In the late 1930s, Arthur Young began a series of experiments with model helicopters that were ultimately to lead to the design of the renowned Bell-47 helicopter. After much research Young invented a teetering rotor with a stabilizer bar; see Young (1948, 1979). The bar had bob weights attached to each end and was directly linked to the rotor blades through the pitch control linkages. The idea was that if the rotor was disturbed in pitch or roll, the gyroscopic inertia of the bar could be used to introduce cyclic pitch into the main rotor system, increasing the effective damping to disturbances and giving stability to the entire rotor system -- see also Kelly (1954). Young received financial support from Lawrence Bell of the Bell Aircraft Corporation and their first prototype, the Bell-30, was built in 1942. This two-place machine had a single main teetering rotor with Young's stabilizer bar. The first

untethered flights of the Bell-30 took place in 1943, and the machine was soon flying at speeds in excess of 70 mph.

The Bell-30 formed the technical foundation for the famous Bell Model 47, which became the world's first commercially certified helicopter. During its nearly thirty-year manufacturing period over 5,000 were produced in the United States alone, and at least another 1,000 were license built in more than twenty other countries. Tipton (1989), Brown (1995) and Spenser (1999) give a good historical overview of the enormously successful Bell helicopters. Schneider (1995) gives a brief biography of Arthur Young and his novel teetering rotor design. To find out more about Arthur Young go to his website. To find out more about the history of Bell Helicopter, check out the Bell Timeline at the Helicopter History Site.



In 1943, Frank Piasecki designed and flew a tiny single-seater helicopter that was called the PV-2. This was the second successful prototype helicopter to fly in the United States, the first being Sikorsky's VS-300. Piasecki's company went on to develop the overlapping tandem rotor configuration, a concept patented by Gish Javanovitch and demonstrated with a flying prototype as early as 1944. Piasecki immediately turned to larger helicopters, and in 1945 the Piasecki Helicopter Corporation built a tandem rotor helicopter called the PV-3 Dogship. Further details are given by The Piasecki Corporation (1967) and Spenser (1999). This aircraft was popularly called the "Flying Banana" because of its long, distinctive, curved fuselage shape. Despite its nickname, however, the aircraft was very successful and larger and more powerful versions of the tandem rotor design quickly followed, including the H-16 and H-21 "Workhorse" model of 1952. To find out more about the history of the Piasecki, Vertol and Boeing Helicopters, check out the Boeing Timeline at the Helicopter History Site.

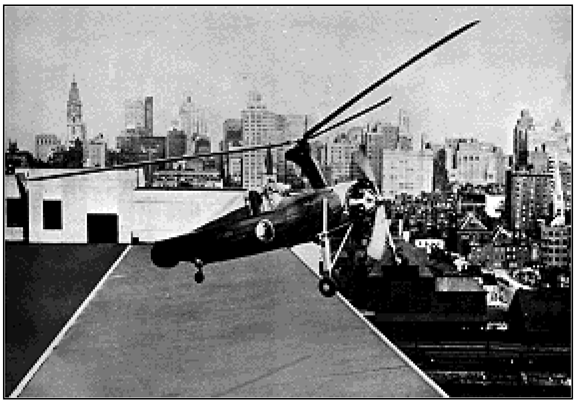
Despite the success of the tandem rotor design, the only other company in the United States to build a tandem helicopter was Bell Helicopter who manufactured the XSL-1 during the 1950s. The British company, Bristol Helicopters, had designed and built a tandem helicopter during the late 1940s under the leadership of the helicopter pioneer Raoul Hafner -- see Hobbs (1984) and Everett-Heath (1986). The Bristol Type-173 had a long, slim fuselage with two three-bladed rotors at each end, similar to the Piasecki machines. The Bristol Type-192 Belvedere was an improved tandem rotor design, which followed in 1958 with more powerful engines. While it saw service with the British forces, it was not as successful as the American machines. The other Bristol helicopter design of note was the single rotor Type 171 Sycamore, which had a well streamlined fuselage and quite good performance -- see Hafner (1949). However, the Bristol company found it difficult to compete with helicopters being produced by Sikorsky, Bell and Westland, and limited numbers of their machines were produced.

In the United States, Charles Kaman adopted Antoine Flettner's synchropter rotor design. One of Kaman's innovations was the use of torsionally compliant solid spar spruce rotor blades with servo-flaps. The servo-flaps were mounted at the three-quarter rotor radius, some distance behind the elastic axis of the blade -- a system first used by d'Ascanio. When these flaps were deflected cyclically, the aerodynamic moments caused the blades to twist, changing their angle of attack and thus introducing a cyclic rotor control capability. The first Kaman helicopter, the K-125A, flew in 1947. An improved version, the K-225, became the first helicopter to fly powered by a gas turbine engine. A family of larger Kaman machines, known as the H-43 Husky and its derivatives, were produced through 1964. While Kaman reverted to conventional single-rotor helicopter designs in the later 1950s, the servo-flap concept continued to be a trademark of the Kaman helicopters. The H-2 Seasprite first flew in 1959 and has been produced in considerable numbers. Kaman has recently returned to the synchropter concept with the design of the K-Max, which first flew in 1991. See Kaman Aircraft Corp. for further details of their helicopter lineage. To find out more about the history of Kaman Aircraft, check out the Kaman Timeline at the Helicopter History Site.

Stanley Hiller is another well-known pioneer who contributed to the development of the modern helicopter [see Straubel (1964) and Spenser (1992, 1999)]. Hiller built several helicopter prototypes, including the coaxial XH-44, which flew successfully in 1944. Although Hiller pursued various other coaxial and tip-jet driven rotor machines, his later helicopters used a conventional main rotor and tail rotor configuration. His main breakthrough was the "Rotormatic" main rotor design, where the cyclic pitch controls were connected to a set of small auxiliary blades set at ninety degrees to the main rotor blades. These auxiliary blades provided damping in pitch and roll helping to augment the hovering stability of the machine. While today this can be done electronically by an automatic flight control system, the "Hiller paddle" concept continues to be used for flying scale model helicopters. It is significant to note that both Hiller and Young designed in stability-producing mechanisms for their helicopters from the outset, whereas the Sikorsky machines had none and so they had a reputation for being harder to fly. While the Hiller machines are probably less well known than those of Sikorsky or Bell, the Hiller company went on to build many thousands of helicopters, including the Model 360 and later the UH-12A and H-23. To find out more about the history of Hiller helicopters, check out the Hiller Timeline at the Helicopter History Site.

Back to Contents

Don't Forget Autogiros



It is significant to note that while helicopters were becoming more and more successful throughout the 1950's, the development of the autogiro continued in Europe and the United States. Considerable development work was undertaken by the Pitcairn Company [see Pitcairn (1930) and Smith (1985)] and the Kellett Aircraft Company in the United States. Harold Pitcairn patented many basic concepts in rotor design, many of which were licensed and used by other helicopter manufacturers. The Pitcairn and Kellett autogiros or "Mailwings" flew on part of Eastern Airlines' network delivering mail from the top of the United States Post Office in Philadelphia to the nearby Camden Airport in New Jersey.

In Great Britain during the 1940s and 50s, the autogiro concept was pursued to some significant end by the Fairey Aviation Company. The Fairey Girodyne compound aircraft used a propeller set on the end of a stub wing to provide both propulsion and antitorque; see Everett-Heath (1986). The Fairey Company went on to develop the Jet Girodyne in which the rotor system was driven by tip jets. This ultimately led to the Rotodyne, which was the world's biggest giroplane with a cabin big enough for forty passengers -- see Hislop (1958). The aircraft set a world speed record for a convertiplane in 1959 before the project was canceled, for reasons that were perceived by many as political rather than technical.

During the 1960s small single- and two-seat autogiro designs were developed in the United States by Umbaugh and McCulloch for the private market. Similar single- and two-seat autogiros were later built in Britain by the Wallis company. Today, there is a strong interest in autogiros by the amatuer aircraft builder, mainly because of its mechanical simplicity, light weight, and forgiving flight characteristics. There is only a limited interest in autogyros for other commercial uses, mainly because it cannot compete with either a fixed-wing aircraft or the helicopter. However, the autogiro concept continues to be pursued by a number of enthusiasts, including the Groen Brothers Company in the United States.

Back to Contents

Maturing Technology

The early 1950s saw helicopters quickly maturing into safe, successful, and highly viable aircraft that were easier to fly and more comfortable for crew and passengers alike. This era is marked by significant mass production of helicopters by various manufacturers in the United States and also in Europe. The Sikorsky S-55 and S-58 models made great advances in helicopter design. These aircraft had a large cabin under the rotor, and to give a wide allowable center of gravity position, the engine was placed in the nose. Westland also maintained their relationship with Sikorsky and built versions called the S-55 Whirlwind and S-58 Wessex.

The 1960s saw the development of the Sikorsky S-61 Sea King, the heavy-lift S-64 Sky Crane, and the larger five- and seven-bladed CH-53 models. Later, the S-70 (UH-60) Blackhawk was to become the mainstay of the Sikorsky company, and the machine is expected to remain in production well into the twenty-first century. The civilian S-76 has been successful in its role as an executive transport and air ambulance, amongst other roles. In the 1970s, Sikorsky and Boeing teamed to build the military RAH-66 Comanche, which will be a scout/attack helicopter for the new millennium. The latest Sikorsky machine, the civilian medium lift S-92 Helibus, flew for the first time in 1998. For more information, check out the Sikorsky Aircraft home page, or the Sikorsky Timeline at the Helicopter History Site.

The success with the Model-47 led Bell Helicopter to develop the UH-1 Huey, which were delivered starting in 1959. The Bell 212 was a two-engine development of the UH-1D, and proved to be a successful military and civilian machine. The Huey-Cobra also grew out of the UH-1 series, retaining the same rotor components, but having a more streamlined fuselage with the crew seated in tandem. The type is still in production in 1999 as the AH-1W Super-Cobra, which uses an advanced composite four-bladed rotor. The Bell 412 is basically a 212 model, but with a four-bladed composite rotor replacing the two-bladed teetering rotor. Bell also conquered the civilian market with its 206 Jet-Ranger and variants, which first flew in 1966 and has become one of the most widely used helicopters. The OH-58 military version was sold in considerable numbers and with sustained improvements over the years, with the OH-58D having an advanced four-bladed rotor with mast mounted sight. One of most recent civilian models is the Bell 427, which is an eight-place light twin. See also Bell Helicopter Textron and the Bell Timeline at the Helicopter History Site.

Piasecki's corporation became The Vertol Company in 1956, which went on to develop the civilian Vertol 107 and two highly successful military tandem rotor models, the CH-46 and CH-47. The company finally became Boeing Helicopters. An overview of the Boeing-Vertol machines produced up to the mid-1970s is given by Grina (1975). In the late 1980s, the Boeing Company produced a demonstrator of an advanced technology tandem rotor helicopter called the Model 360, which was made almost entirely of composite materials. Production and remaunfacturing of the Boeing CH-47 continues today, and in 1998 Boeing announced the launch of the CH-47F and the CH-47SD "Super-D" Chinook. See also The Boeing Company and the Boeing Timeline at the Helicopter History Site.

Hughes built the military TH-55 and later the Hughes-500 series, which has seen extensive civilian use in various models. However, the AH-64 Apache, which was designed in 1976, proved to be the biggest success story for the Hughes company. The AH-64D Longbow model is still in production over twenty years later. It is also produced under license in the UK by GKN-Westland, where it is called the WAH-64. McDonnell Douglas have also produced a line of light commercial helicopters including the MD 500 and 600 series, and most recently it has marketed the MD-900 Explorer. This aircraft uses a new bearingless rotor design and the "No Tail Rotor" (NOTAR) circulation control antitorque concept. To find out more about the history of Hughes and McDonnell-Douglas helicopters, check out the McDonnell-Douglas Timeline at the Helicopter History Site.

Although the bulk of helicopters produced are for the military, several manufacturers produce training helicopters or helicopters aimed at the general aviation market, including Robinson, Schweizer, and Enstrom. In the United States, Robinson produces the R-22 two-seat and R-44 four-seat helicopters. Both are powered by piston engines. Schweizer produces an updated version of the two-seat Hughes 300 for the training market, and a larger derivative, designated as the Model-330, has a gas turbine.

The European manufactures Aerospatiale, Agusta, MBB, and Westland have produced many successful helicopter designs since the 1960s. Augusta and Westland have also license-produced helicopters designed in the United States, such as those of Sikorsky and Bell. The Aerospatiale (formally Sud-Aviation) Alouette was one of the most successful European helicopters, and in 1955 it was one of the first machines to be powered by a gas turbine. The Aerospatiale Super Frelon was a large transport machine, first flown in 1962. In the early 1970s the Aerospatiale/Westland SA330 Puma became Europe's best selling transport helicopter. The Aerospatiale/Westland Gazelle was a successful successor to the Alouette, first flown in 1967, and it introduced the fenestron tail rotor. The fenestron is a ducted tail rotor design, fully integrated into the fuselage and vertical fin. The Dauphin, first flown in 1972, used an improved fenestron tail rotor and a composite main rotor hub. Messerschmitt-Bolkow-Blohm (MBB) introduced the BO105 in 1967 with a hingeless titanium rotor, with the larger and more capable BK117 machine first flying in 1979. In the 1990s, Aerospatiale and MBB joined resources to form Eurocopter, which produces a large number of civilian and military helicopter models -- see Eurocopter. To find out more about the history of Aerospatiale, check out the Aerospatiale Timeline at the Helicopter History Site.

In 1952, Agusta purchased a license to build the Bell Model-47, and through 1965 it built several variants of the Bell machine to their own specifications. Agusta also began to design their own machines, with the large three-engined A-101 flying in 1964, but it never went into production. The Agusta A-109 was one of the most aerodynamically attractive helicopters. First flown in 1971, this high-speed transport and multirole helicopter has been very successful and is used in both civilian and military roles. The A-129 Mangusta, first flown in 1983, is a militarized version of the A109 with a different fuselage. To find out more about the history of Agusta, check out the Agusta Timeline at the Helicopter History Site.

Westland Helicopters (now GKN-Westland) has been a key player in British aviation since the 1930s -- see Mondey (1982). The earliest helicopters built by Westland were under license from Sikorsky, but these were significantly modified to meet British airworthiness standards. During 1959--60, Westland took over the operation of the Bristol, Saunders-Roe, and Fairey companies. Saunders-Roe (SARO) had previously taken over the Cierva Company in 1951.The

Westland/SARO/Cierva Skeeter was a small two-seat trainer, which led to the bigger and relatively successful Wasp in 1962. The Westland Wessex was a development of the Sikorsky S-58, which was built in many configurations through 1970. The Sea King and Commando were derived from the S-61, which were steadily improved upon since the first models flew in the late 1960s. The latest versions of the Sea King sold through 1990 have used composite rotor blades and various airframe improvements. Westland designed its own line of helicopters, starting with the military Lynx, which first flew in 1971. The Westland WG-30 was a larger multirole transport version of the Lynx. Although this aircraft saw some civilian use, production was limited. New versions of the Lynx (Super Lynx) are fitted with the Westland/RAE British Experimental Rotor Program (BERP) blade, which has improved airfoil sections and special tip shape. A Lynx with the BERP rotor currently holds the absolute straight-line speed record for a single-rotor helicopter at some 250-kts (400-km/hr; 287-mi/h). The BERP blade design is also used on the Westland-Agusta built EH Industries EH-101, which is a medium-lift helicopter that entered production in 1996 in both civilian and military variants. Westland also have a license agreement with Sikorsky to build the WS-70 Blackhawk. See also GKN-Westland for more information on the current lineage, and also the the Westland Timeline at the Helicopter History Site.

Significant numbers of helicopters have also been built in the former Soviet Union. In the 1930s, the TsAGI Technical Institute in Moscow built a series of autogiros based on the de la Cierva designs. Everett-Heath (1988) gives a good account of the early work. Later, work with the Focke-Achgelis company of Germany resulted in a number of prototype helicopter designs with a lateral side-by-side rotor configuration. The Mil, Kamov, and Yak companies all went on to build successful helicopter lines. An overview of the early Russian machines is given by Free (1970). Mikhail Mil adopted the single main rotor tail rotor configuration, with the Mi-1 flying in 1950. The Mi-2 was a turbine-powered version. The more efficient Mi-3 and larger Mi-4 machines quickly followed. The Mi-4 looked very much like the S-55, but it was much bigger and more capable. The Mi-2 was also built in significant numbers in Poland, with the Mi-4 being produced in China. The Mi-6 of 1957 was one of the largest helicopters ever built, with a rotor diameter of 35-m (115-ft) and a gross weight of over 42,500-kg (93,700-lb). This was followed by the smaller Mi-8 (similar to the Mi-4) which went into civilian service. The Mi-10 of 1961 was a flying crane development of the Mi-6, with a tall, wide, quadricycle landing gear. However, the credit for the world's largest and heaviest helicopter goes to the Russian Mil Mi-12. This aircraft had a side-by-side rotor configuration, with the span of the aircraft from rotor tip to rotor tip exceeding that of the wing span of the Boeing 747. Power was provided by four gas turbines, installed as pairs at the end of each wing pylon. The Mi-24 assault/transport helicopter was designed in 1972, and it has been produced in large numbers. The Mi-26 entered service in 1982 and is the largest helicopter currently flying. The Mi-28 is an attack helicopter, similar in configuration to the AH-64 Apache. The latest Mil design, the Mi-38, is planned as a successor to the Mi-8/17 and is similar in size and weight to the EH-101. To find out more about the history of Mil, check out the Mil Timeline at the Helicopter History Site.

The Kamov Company built a series of very successful light and medium weight coaxial rotor helicopter designs, including the Ka-15 and Ka-18 in 1956 and the Ka-20 in 1961. Kamov was the only company to ever put the coaxial helicopter design into mass production. The Ka-25 and most of the later models were all gas-turbine powered. The Ka-27 and the civilian model Ka-32 have been in production since 1972. One of the most recent Kamov designs is the Ka-50, which is a lightweight attack helicopter of considerable performance. One exception to the Kamov coaxial line was the Ka-22 convertiplane of 1961. Another new prototype design is the Kamov Ka-62, which is a conventional light utility helicopter design incorporating a fenestron. Alexander Yakolev built many successful fixed-wing designs, but with the assistance of Mil designed the large tandem Yak-24 helicopter in the early 1950s. This helicopter was produced from about 1952 to 1959, but it was not very successful. Further information on Russian helicopter developments is given by Anoschenko (1968) and Everett-Heath (1988). To find out more about the history of Kamov, check out the Kamov Timeline at the Helicopter History Site.

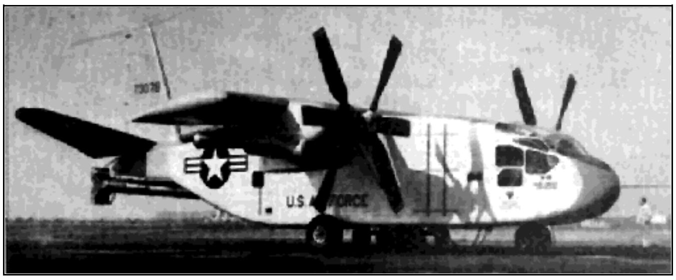
Back to Contents

Compounds, Tilt-Wings and Tilt-Rotors

The conventional helicopter is limited in forward flight performance by the aerodynamic lift and propulsion limitations of the main rotor. These rotor limits arise because of compressibility effects on the advancing blade, as well as stall on the retreating blade. In addition, the high parasitic drag of the rotor hub and other airframe components leads to a relatively poor overall lift-to-drag ratio of the helicopter. This generally limits performance of conventional helicopters to level-flight cruise speeds in the range of 150 kts (278 km/h; 172 mi/h), with dash speeds up to 200 kts (370 km/h; 230 mi/h). Although somewhat higher flight speeds are possible with compound designs, which use auxiliary propulsion devices and wings to offload the rotor. The idea is to enhance the basic performance metrics of the helicopter, such as lift-to-drag ratio, propulsive efficiency, and maneuverability. The general benefits are an expansion of the flight envelope compared to conventional helicopter, but this is always at the expense of much higher power required and fuel burn than would be necessary with a fixed-wing aircraft of the same gross-weight and cruise speed. Furthermore, compound designs suffer from an increase in empty weight and loss of payload capability, download penalties in hover, and reduced vertical rate of climb. The Lockheed Cheyenne is an example of a helicopter that used both lift compounding and propulsion compounding. While technically successful, it did not enter into production. While there are no compound helicopter designs in current production (although many prototypes have been built), except from a few Russian designs such as the Mi-6 that have an element of lift compounding. One of the first experimental compound helicopter designs was the McDonnell XV-1. This was a pressure jet driven rotor, with a wing and a pusher propeller. After a vertical take-off, the power was shifted from supplying the tip jets to driving the propeller, and the rotor continued to turn in autorotation. In 1954, the aircraft was flown at speeds approaching 200 mph. The Sikorsky NH-3A was based on the S-61, and used a wing mounted with two turbo-jets for auxiliary propulsion. It achieved speeds of up to 230 kts. The Bell UH-1 compound also had a wing and two turbo-jets, and reached a speed of 275 kts in level flight. Boeing-Vertol flew the tandem Model 347 with relatively large wings. The ideas of compounding have recently received renewed attention by some helicopter manufacturers. It remains to be seen, however, if the compound helicopter design will re-emerge as a viable design concept for the 21st century.

The need for a machine that could combine the benefits of vertical takeoff and landing (VTOL) capability with the high speed cruise of a fixed-wing aircraft has also led to the evolution of tilt-wing and tilt-rotor concepts. A history of the many VTOL designs, including tilt-wings and tilt-rotors, is given by Hirschberg (1997). However, this potential capability comes at an even greater price than for a conventional helicopter, including increased mechanical complexity, increased weight, and the susceptibility for the rotors and wing to exhibit various aeroelastic problems. The tilt-wing is basically a convertiplane concept, but it never became a viable rotating-wing concept to replace or surpass the helicopter. The idea is that the wing can be tilted from its normal flying position with the propellers providing forward thrust, to a vertical position with the propellers providing vertical lift. Several companies seriously considered the tilt-wing concept in the 1950s, with Boeing, Hiller, Vought-Hiller-Ryan, and Canadair all producing flying prototype aircraft. The Boeing-Vertol VZ-2 first flew in 1957 and went on to make many successful conversions from hover into forward flight. However, flow separation produced by the wing during the conversion flight regime resulted in some difficult piloting, and these issues were never satisfactorily resolved.

The Hiller X-18 was a large tilt-wing aircraft compared to the VZ-2. The aircraft used two large diameter, counterrotating propellers (from the earlier Ryan Pogo concept) -- see Straubel (1964). The aircraft underwent flight testing in 1960, but the program was canceled in 1961 after the aircraft suffered a loss of control. In the 1980s, the Ishida Co. developed the TW-68 tilt-wing aircraft as a private venture, but the company went into bankruptcy before the aircraft could be completed.



The tilt-rotor aircraft takes off and lands vertically with the rotors pointed vertically upward like a helicopter. For forward flight, the wing tip-mounted rotors are progressively tilted to convert the aircraft into something that looks like a fixed-wing turboprop airplane. In this mode, the tilt-rotor is able to achieve considerably higher flight speeds (about 300-kts; 555-km/h; 344-mi/h) than would be possible with a helicopter. Therefore, the tilt-rotor combines some attributes of the conventional helicopter with those of a fixed-wing aircraft. Because the rotors of a tilt-rotor are not large, the hovering efficiency of the tilt-rotor is not as high as that of a helicopter. In the design of the Bell-Boeing V-22 Osprey, the rotor diameter was also limited by the need to operate and hanger the aircraft on board an aircraft carrier. The tilt-rotor concept was first demonstrated in a joint project between the Transcendental Aircraft Corporation and Bell in 1954.The first aircraft, the Model 1-G, had two three-bladed fully articulated rotors. Various technical problems were encountered, especially in the conversion from helicopter mode to fixed-wing flight. Bell later led the development of the XV-3 in 1951, which had two fully articulated 3-bladed rotors. The XV-3 was damaged in an accident in 1956 after an aeroelastic problem with the rotor. The second XV-3 used a two-bladed teetering rotor system, and the aircraft was successfully flown in 1958. However, several aeromechanical problems were again encountered, including pylon whirl flutter.

By the late 1960s, Bell had developed the Model 266 tilt-rotor and later the Model 300. Various wind-tunnel tests of scaled models led to an improved understanding of the rotor and wing aeroelastic issues involved with tilt-rotors, especially during the conversion mode, and Bell continued to develop the Model 301. This aircraft later became the XV-15, which fully demonstrated the viability of the tilt-rotor concept; but the aircraft was never designed for production. However, in 1983 the much larger V-

22 Osprey tilt-rotor program was begun. This joint Bell/Boeing project has resulted in several test and preproduction aircraft, and in 1997 the decision was made to put the aircraft into production for the United States Navy and Marines. In 1997, Bell announced the development of the Model 609 civilian tiltrotor, which will be capable of transporting 9 passengers at 275-kts (509-km/h; 315-mi/h) over 750-nm (1,390-km; 860-mi) sectors. See Bell Helicopter Textron for further information.

Back to Contents

References

1. Achenbach, W. 1923. "Variation in the Number of Revolutions of Air Propellers," NACA Technical Note 131.
2. Anderson, J. D., Jr. 1997. *A History of Aerodynamics: And Its Impact on Flying Machines*, Cambridge University Press, Cambridge, England.
3. Anoshchenko, N. D. (ed.) 1968. "History of Aviation and Cosmonautics, Vol. 5," NASA TT F-11851.
4. Apostolo, G. 1984. *The Illustrated Encyclopedia of Helicopters*, Bonanza, New York.
5. Balaban, K. 1923. "Evolution of the Helicopter," NACA TN 196.
6. Bartlett, R. M. 1947. *Sky Pioneer: The Story of Igor I. Sikorsky*, Charles Scribner's & Sons, New York.
7. Berliner, E. 1908. "The Berliner Helicopter," *Aeronautics*, Vol. 3.
8. Berliner, E. 1915. "Elements of a Girocopter," *Aeronautics*, Vol. 10. See also *Scientific American*, 27 May 1921.
9. Boulet, J. 1984. *The History of the Helicopter as Told by its Pioneers 1907-1956*, Editions France-Empire, Paris.
10. Brown, D. A. 1995. *The Bell Helicopter Textron Story*, Aerofax, Arlington, TX.
11. Cayley, G. 1809--10. "On Aerial Navigation," *Nicholson's Journal of Natural Philosophy, Chemistry and the Arts*, Nov. 1809, Feb. 1810 & Mar. 1810.
12. de la Cierva, J. 1926. "The Development of the Autogiro," *J. Royal Aeronaut. Soc.*, 30 (181), pp. 8--29.
13. de la Cierva, J. 1930. "The Autogiro," *J. Royal Aeronaut. Soc.*, 39 (239), pp. 902--921.
14. de la Cierva, J. and Rose, D. 1931. *Wings of Tomorrow: The Story of the Autogiro*, Brewer, Warren & Putnam, New York.
15. de la Cierva, J. 1935. "New Developments of the Autogiro," *J. Royal Aeronaut. Soc.*, 39, Dec., pp. 1125--1143.
16. Cochrane, D., Hardesty, V., and Lee, R. 1989. *The Aviation Careers of Igor Sikorsky*, University of Washington Press, Seattle &London.
17. de Bothezat, G. 1919. "The General Theory of Blade Screws," NACA TR 29.
18. Delear, F. J. 1969. *Igor Sikorsky: His Three Careers in Aviation*, Dodd, Mead & Co., New York.
19. Everett-Heath, J. 1986. *British Military Helicopters*, Arms and Armour Press,London.
20. Everett-Heath, J. 1988. *Soviet Helicopters -- Design, Development and Tactics*, Jane's Information Group, London.

21. Fay, J. 1987. *The Helicopter: History, Piloting and How It Flies*, Hippocrene, New York.
22. Finne, K. N. 1987. *Igor Sikorsky: The Russian Years*, edited by C. J. Brobrow and Von Hardesty, Smithsonian Institution Press, Washington DC.
23. Focke, H. 1938. "The Focke Helicopter," NACA TM 858.
24. Focke, E. H. H. 1965. "German Thinking on Rotary Wing Development," *J. Royal Aeronaut. Soc.*, 69 (653), pp. 293--305.
25. Free, F. W. 1970. "Russian Helicopters," *The Aeronaut. J.*, 74 (717), Sept., pp. 767--785.
26. Froude, R. E. 1889. "On the Part Played in Propulsion by Differences of Fluid Pressure," *Trans. Inst. Naval Architects*, 30, p. 390.
27. Froude, W. (1878), "On the Elementary Relation Between Pitch, Slip and Propulsive Efficiency," *Trans. Inst. Naval Arch.*,19, pp. 47-57.
28. Gablehouse, C. 1967. *Helicopters and Autogiros: A Chronicle of Rotating Wing Aircraft*, Lippincott, Philadelphia & New York.
29. Giacomelli, R. 1930. "The Aerodynamics of Leonardo da Vinci," *J. Royal Aeronaut. Soc.*, 34 (240), pp. 1016--1038.
30. Gregory, H. F. 1944. *Anything a Horse Can Do: The Story of the Helicopter*, Introduction by Igor Sikorsky. Reynal & Hitchcock, New York.
31. Grina, K. I. 1975. "Helicopter Development at Boeing Vertol Company," *The Aeronaut. J.*, 79 (777), pp. 401--416.
32. Gunston, B. 1983. *Helicopters of the World*, Crescent, New York.
33. Gustafson, F. B. 1971. "A History of NACA/NASA Rotating-Wing Aircraft Research, 1915-1970," Limited-Edition Reprint (VF-70) from *Vertiflite*, American Helicopter Soc., Alexandria, VA.
34. Hafner, R. 1949. "The Bristol 171 Helicopter," *J. Royal Aeronaut. Soc.*, 53, April, pp. 324--333.
35. Hart, I. B. 1961. *The World of Leonardo da Vinci*, MacDonald, London.
36. Hirschberg, M. J. 1997. "V/STOL: The First Half-Century," *Vertica*, 43 (2), pp. 34--54.
37. Hislop, G. S. 1958. "The Fairey Rotodyne," Meetings of The Helicopter Assoc. of Great Britain &The Royal Aeronaut. Soc., London, 7th Nov.
38. Hobbs, J. 1984. *Bristol Helicopters: A Tribute to Raoul Hafner*, Frenchay Publications, Bristol, UK.
39. Kelly, B. 1954. "Helicopter Stability and Young's Lifting Rotor," *SAE J.*, 53 (12), pp. 685--690.
40. Klemin, A. 1925. "An Introduction to the Helicopter," NACA TM 340.
41. Kretz, M. 1987. "Rene Dorand: The Life of a Pioneer," 13th European Rotorcraft Forum, Arles, France, Sept. 8--11.
42. Lambermont, P. (with Price, A.) 1958. *Helicopters and Autogiros of the World*, Cassell &Co., London.
43. Liberatore, E. K. (ed.) 1950. *Rotary Wing Handbooks and History*, United States Air Force Air Materiel Command. 18 volumes.
44. Liberatore, E. K. 1988. "An Eclectic Bibliography of Rotorcraft," *Vertiflite*, 34 (1), pp. 50--59.
45. Liberatore, E. K. 1998. *Helicopters Before Helicopters*, Krieger Publishing, Malabar, FL.
46. Lopez, D. S. and Boyne, W. J. (eds.) 1984. *Vertical Flight: The Age of the Helicopter*, Smithsonian Institution Press, Washington DC.

47. Margoulis, W. 1922. "Propeller Theory of Professor Joukowski and His Pupils," NACA TM 79.
48. Mondey, D., 1982. *Planemakers 2: Westland*, Janes Publishing, London.
49. Moreno-Caracciolo, M. 1923. "The Autogiro" NACA TM 218.
50. Munk, M. M. 1923. "Analysis of Dr. Schaffran's Propeller Model Tests," NACA TN 153.
51. NACA. 1921. "The Oehmichen--Peugeot Helicopter," NACA TM 13.
52. Oemichen, E. 1923. "My Experiments with Helicopters," NACA TM 199.
53. Piasecki Aircraft Corp. 1967. *The Piasecki Story of Vertical Lift: Pioneers in Progress for Over Forty Years*, Lakehurst, NJ.
54. Pitcairn, H. F. 1930. "The Autogiro: Its Characteristics anf Accomplishments," Annual Report of the Board of Regents to the Smithsonian Institution.
55. Prewitt, R. H. 1938. "Possibilities of the Jump-Off Autogiro," *J. Aeronaut. Sci.*, 6 (1), pp. 10--14.
56. Pritchard, J. L. 1961. *Sir George Cayley: The Inventor of the Airplane*, Max Parrish & Co., London.
57. Rankine, W. J. M. 1865. "On the Mechanical Principles of the Action of Propellers," *Trans. Inst. Naval Architects*, 6, p. 13--39.
58. Schnieder, J. 1995. "Arthur Young -- Inventor, Developer and Metaphysicist, the Developer of the Bell Teetering Rotor," *Vertiflite*, 41 (2), March/April, pp. 36--39.
59. Seiferth, R. 1927. "Testing a Windmill Airplane (Autogiro)," NACA TM 394.
60. Sikorsky, I. I. 1938 (Rev. 1958, 1967). *The Story of the Winged-S: An Autobiography*, Dodd, Mead & Co., New York.
61. Sikorsky, I. I. 1941. "Development of the VS-300 Helicopter," Paper presented at the Rotating Wing Aircraft Meeting of the Inst. of the Aeronaut. Sci., Jan. 29.
62. Sikorsky, I. I. 1942. "Technical Development of the VS-300 Helicopter During 1941," *J. Aeronaut. Sci.*, 9 (8), pp. 309--311.
63. Sikorsky, I. I. 1943. "Progress of the Vought--Sikorsky Helicopter Program in 1942," *Aeronaut. Eng. Rev.*, 2 (4), pp. 41--43.
64. Sikorsky, I. I. 1964. "Recollections and Thoughts of a Pioneer," Lecture Presented to the Wings Club, New York, Nov. 16.
65. Sikorsky, I. I. 1971. "Sixty Years of Flying." *The Aeronaut. J.*, 75 (731), Nov., pp. 761-768.
66. Sikorsky, S. and Andrews, A. 1984. *Straight Up*, Sikorsky Aircraft, United Technologies Corp.
67. Smith, F. K. 1985. *Legacy of Wings: The Story of Harold Pitcairn*, Jason Aronson, New York.
68. Spenser, J. P. 1992. *Vertical Challenge: The Hiller Aircraft Story*, University of Washington Press, Seattle and London.
69. Spenser, J. P. 1999. *Whirlybirds: A History of the U.S. Helicopter Pioneers*, University of Washington Press, Seattle and London.
70. Straubel, J. F. 1964. *One Way Up*, Hiller Aircraft Co., Palo Alto, CA.
71. Taylor, M. J. 1984. *History of the Helicopter*, Hamlyn Publishing, London.
72. Tipton, R. S. 1989. *They Filled the Skies*, Bell Helicopter Textron, Fort Worth, TX.
73. Tokaty, G. A. 1971. *A History and Philosophy of Fluid Mechanics*, Foulis & Co., Henley-on-Thames, England.
74. von Kármán, Th. 1921. "Tests Made With Captive Helicopters." In the report: "Recent European Developments in Helicopters," NACA TN 47.

75. Warner, E. P. 1920. "The Problem of the Helicopter," NACA TN 4.
76. Wimperis, H. E. 1926. "The Rotating Wing in Aircraft," ARC R & M 1108.
77. Wolf, A. L. 1974. "The Vision of D'Amecourt," *Vertiflite*, 20 (5), pp. 2--6.
78. Young, A. M. 1948. "The Helicopter and Stability," *American Helicopter Magazine*, March, pp. 6--25.
79. Young, A. M. 1979. *The Bell Notes: A Journey from Metaphysics to Physics*, Delacorte Press/Seymour Lawrence, New York.

Back to Contents

Text on all pages © J. G. Leishman 2000, with extracts from the author's book "Principles of Helicopter Aerodynamics" © Cambridge University Press 2000.
