Principles of Helicopter Aerodynamics

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CHAPTER 1

Introduction: A History of Helicopter Flight

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 Sikorsky (1938)

1.1 Introduction

The science of aerodynamics is the fundament of all flight. It is the role of aerodynamics in the engineering analysis and design of rotating-wing vertical lift aircraft that is the subject of this book. Igor Sikorsky's vision of a rotating-wing aircraft that could safely hover and perform other desirable flight maneuvers under full control of the pilot was only to be achieved some thirty years after fixed-wing aircraft (airplanes) were flying successfully. This rotating-wing aircraft we know today as the helicopter. Although the helicopter is considered by some to be a basic and somewhat cumbersome looking aircraft, the modern helicopter is indeed a machine of considerable engineering sophistication and refinement and plays a unique role in modern aviation provided by no other aircraft.

In the introduction to this book, the technical evolution of the helicopter is traced from a cumbersome, vibrating contraption that could barely lift its own weight into a modern and efficient aircraft that has become an indispensable part of modern life. Compared to fixed-wing flight, the development of which can be clearly traced to Lilienthal, Langley, and the first fully controlled flight of a piloted powered aircraft by the Wright Brothers in 1903, the origins of successful helicopter flight are less clear. Nonetheless, there are many parallels in the development of the helicopter when compared to fixed-wing aircraft. However, the longer and perhaps more tumultuous gestation period of the helicopter is directly attributable to the greater depth of scientific and aeronautical knowledge that was required before all the various technical 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 suitable high power-to-weight engines and high-strength, low-weight materials for the rotor blades, hub, fuselage, and transmission.

A helicopter can be defined as any flying machine using rotating wings (i.e., rotors) 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. The thrust on the rotor(s) is generated by the aerodynamic lift forces created on the spinning blades. To turn the rotor, power from an engine must be transmitted to the rotor shaft. It is the relatively low amount of power required to lift the machine compared to other vertical take off and landing (VTOL) aircraft that makes the helicopter unique. Efficient hovering flight with low power requirements comes about by accelerating a large mass of air at a relatively low velocity; hence we have the large diameter rotors that are one obvious characteristic of helicopters. In addition, the helicopter must be able to fly forward, climb, cruise at speed, and then descend and come back into a hover for landing. This demanding flight capability comes at a price, including mechanical and aerodynamic complexity and higher power requirements than for a fixed-wing aircraft of the same gross weight. All of these factors influence the design, acquisition, and operational costs of the helicopter.

Besides generating all of the vertical lift, the rotor is also the primary source of control and propulsion for the helicopter, whereas these functions are separated on a fixed-wing aircraft. For forward flight, the rotor disk plane must be tilted so that the rotor thrust vector is inclined forward to provide a propulsive component to overcome rotor and airframe drag. The orientation of the rotor disk to the flow also provides the forces and moments to control the attitude and position of the aircraft. The pilot controls the magnitude and direction of the rotor thrust vector by changing the blade pitch angles (using collective and cyclic pitch inputs), which changes the blade lift and the distribution of thrust over the rotor disk. By incorporating articulation into the rotor design through the use of mechanical flapping and lead/lag hinges that are situated near the root of each blade, the rotor disk can be tilted in any direction in response to these blade pitch inputs. As the helicopter begins to move into forward flight, the blades on the side of the rotor disk that advance into the relative wind will experience a higher dynamic pressure and lift than the blades on the retreating side of the disk, and so asymmetric aerodynamic forces and moments will be produced on the rotor. Articulation helps allow the blades to naturally flap and lag so as to help balance out these asymmetric aerodynamic effects. However, the mechanical complexity of the rotor hub required to allow for articulation and pitch control leads to high design and maintenance costs. With the inherently asymmetric flow environment and the flapping and pitching blades, the aerodynamics of the rotor become relatively complicated and lead to unsteady forces. These forces are transmitted from the rotor to the airframe and can be a source of vibrations, resulting in not only crew and passenger discomfort, but also considerably reduced airframe component lives and higher maintenance costs. However, with a thorough knowledge of the aerodynamics and careful design, all these adverse factors can be minimized or overcome to produce a highly reliable and versatile aircraft.

1.2 Early Attempts at Vertical Flight

There are many authoritative sources that record the development of helicopters and other rotating-wing aircraft such as autogiros. These 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) takes a unique approach in that he gives a first-hand account of the early helicopter developments through interviews with the pioneers, constructors, and pilots of the machines. A remarkably detailed history of early helicopter developments is given by Liberatore (1950, 1988, 1998). For original publications documenting early 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 distinct 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. Prior to the nineteenth century there were few scientific investigations of flight or the science of aerodynamics. The inherent mechanical and aerodynamic complexities in building a practical helicopter that had adequate power and control, and did not vibrate itself to pieces, resisted many ambitious efforts. The history of flight documents literally hundreds of failed helicopter projects, which, at most, made only brief uncontrolled hops into the air. Some designs provided a contribution to new knowledge that ultimately led to the successful development of the modern helicopter. Yet, it was not until the more scientific contributions of engineers such as Juan de la Cierva, Heinrich Focke, Raoul Hafner, Igor Sikorsky, Arthur Young, and others did the design of a truly safe and practical helicopter become a reality.

Six fundamental technical problems can be identified that limited early experiments with helicopters. These problems are expounded by Sikorsky (1938, and various editions) in his autobiography. In summary, these problems were:

1. Understanding the 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.[1]
2. The lack of a suitable engine. This was a problem that was not to be overcome until the beginning of the twentieth century, through the development of internal combustion engines.
3. Keeping structural weight and engine weight down so the machine could lift a pilot and a payload. Early power plants were made of cast iron and were heavy.[2]
4. Counteracting rotor torque reaction. A tail rotor was not used on most early designs; these machines were either coaxial or laterally side-by-side rotor configurations. Yet, building and controlling two rotors was even more difficult than for one rotor.
5. Providing stability and properly controlling the machine, including a means of defeating the unequal lift produced on the advancing and retreating blades in forward flight. These were problems that were only to be fully overcome with the use of blade articulation, ideas that were pioneered by Cierva, Breguet, and others, and with the development of blade cyclic pitch control.
6. Conquering the problem of vibrations. This was a source of many mechanical failures of the rotor and airframe, because of an insufficient understanding of the dynamic and aerodynamic behavior of rotating wings.

The relatively high weight of the structure, engine, and transmission was mainly responsible for the painfully slow development of the helicopter until about 1920. However, by then gasoline powered piston engines with higher power-to-weight ratios were more widely available, and the antitorque and control problems of achieving successful vertical flight were at the forefront. This resulted in the development of a vast number of prototype helicopters. 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 II years, it was not until the late inter war period that significant technical advances were made and more practical helicopter designs began to appear. The most important advances of all were in engine technology, both piston and gas turbines, the latter of which revolutionized both fixed-wing and rotating-wing flight.

A time-line documenting the evolution of rotating-wing aircraft through 1950 is shown in Fig. 1.1. The ideas of vertical flight 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

[1] The first significant application of aerodynamic theory to helicopter rotors came about in the early 1920s.

[2] Aluminum was not available commercially until about 1890 and was inordinately expensive. It was not used in aeronautical applications until about 1915.

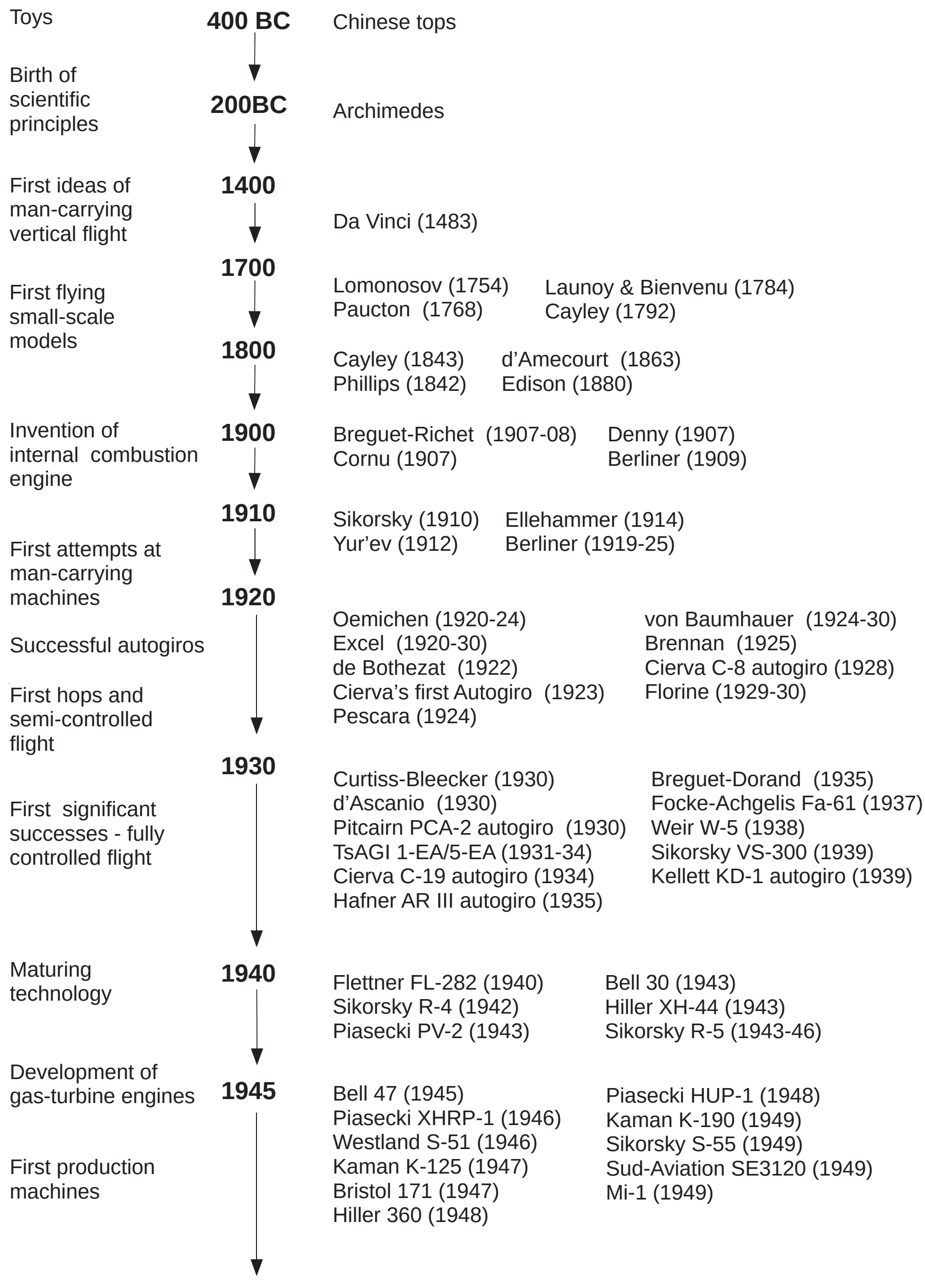

Figure 1.1 Time-line showing development of helicopters and autogiros prior to 1950.

a stick, which was rapidly spun between the hands to generate lift and then released into flight. More than 2,000 years later in 1784, Launoy & Bienvenu used a coaxial version of the Chinese top in a model consisting of a counterrotating set of turkey feathers, powered by a string wound around its shaft and tensioned by a crossbow. It is also recorded that Mikhail Lomonosov of Russia had developed, as early as 1754, a small coaxial rotor modeled after the Chinese top but powered by a wound-up spring device. In 1786, the French mathematician

A. J. P. Paucton published a paper entitled "Théorie de la vis D'Archimèdes," where he proposed a human-carrying flying machine, with one rotor to provide lift and another for propulsion.

Amongst his many intricate drawings, Leonardo da Vinci shows what is a basic human-carrying helicopterlike machine, an obvious elaboration of an Archimedes water-screw. His sketch of the "aerial-screw" device, which is shown in Fig. 1.2, is dated to 1483 but was first published nearly three centuries later. The device comprises a helical surface that da Vinci describes should be "rotated with speed that said screw bores through the air and climbs high." He realized that the density of air is much less than that of water, and so da Vinci describes how the device needed to be relatively large to accomplish this feat (the number "8" in his writing to the left of the sketch indicates that the size of the rotor is 8 *braccia* or arm lengths). He also describes in some detail how the machine should be built using wood, wire, and linen cloth. Although da Vinci worked on various concepts of

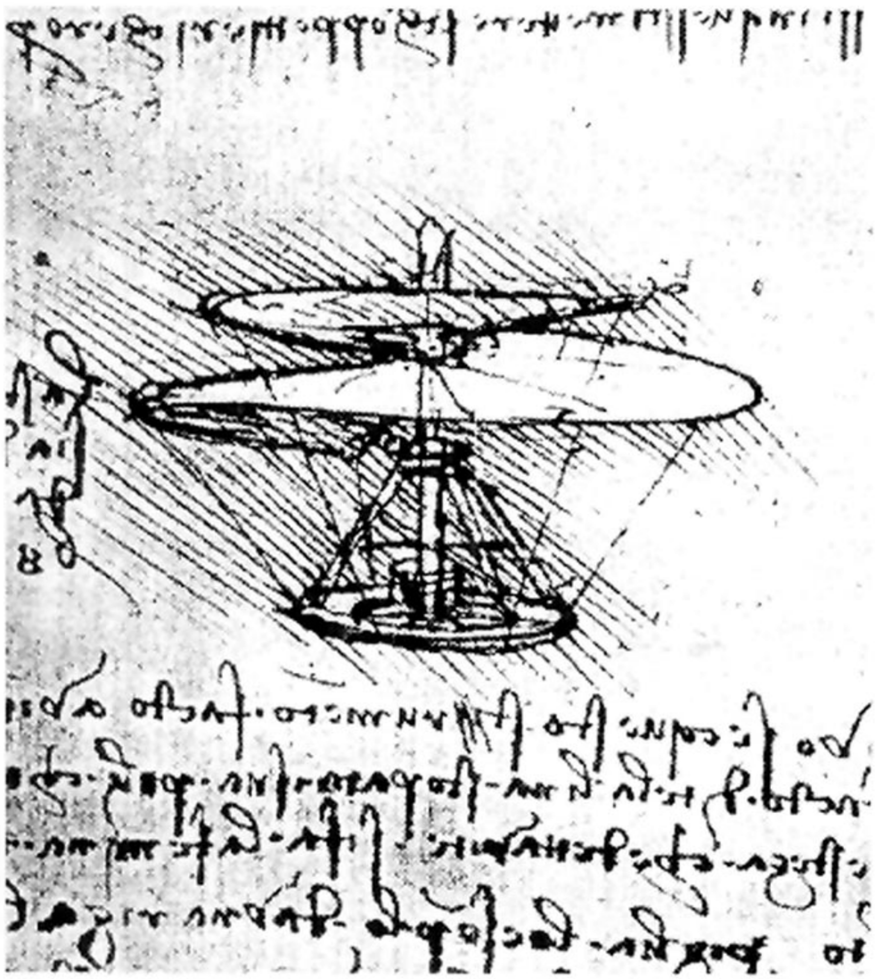

Figure 1.2 Leonardo da Vinci's aerial screw machine, dated to 1483. Original drawing is MS 2173 of Manuscript (codex) B, folio 83 verso, in the collection of the Bibliothèque L'Institut de France (Paris).

engines, turbines, and gears, he did not unite the ideas of his aerial-screw machine to an engine nor did he appreciate the problems of torque reaction. See Hart (1961) or Giacomelli (1930) for further details of da Vinci's aeronautical work.

Sir George Cayley is famous for his work on the basic principles of flight, which dates from the 1790s – see Pritchard (1961). By the end of the eighteenth century, Cayley had constructed several successful vertical-flight models based on Chinese tops driven by wound-up clock springs. He designed and constructed 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 aerodynamics – see Anderson (1997). In a later paper, published in 1843, Cayley gives details of a vertical flight aircraft design that he called an "Aerial Carriage," which had two pairs of lateral side-by-side rotors. Also, 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, 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'Amécourt of France flew a number of small helicopter models. He called his machines *hélicoptères*, 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). In 1863, d'Amécourt built a steam propelled model helicopter, but it could not generate enough lift to fly. However, the novelist Jules Verne was still impressed with d'Amécourt's attempts, and in 1886 he wrote "The Clipper of the Clouds" where the hero 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 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 a flying steam-driven helicopter model. This model had dual counterrotating rotors, but like many other model helicopters of the time, it had no means of control.

In the 1880s, Thomas Alva Edison experimented with small helicopter models in the United States. He tested several rotor configurations driven by a guncotton engine, which was an early form of internal combustion engine. 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 solidity to give good hovering efficiency [Liberatore (1998)]. Unlike other experimenters of the time, Edison's more scientific approach to the problem proved that both high aerodynamic efficiency of the rotor and high power from an engine were required if successful vertical 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.

In 1907, about four years after the Wright brothers' first successful powered flights in fixed-wing airplanes at Kitty Hawk in the United States, Paul Cornu of France constructed a vertical flight machine that 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

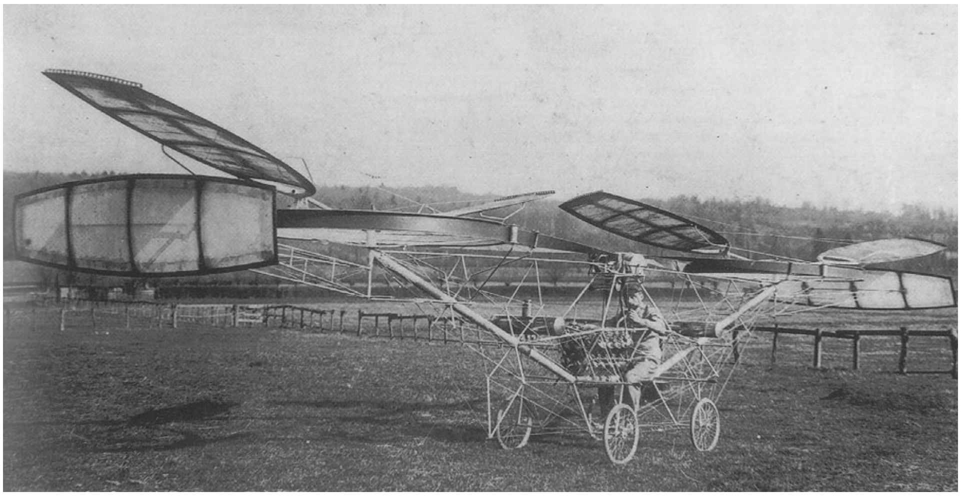

Figure 1.3 The Cornu helicopter, circa 1907. (Courtesy NASM, Smithsonian Institution, SI Neg. No. 74-8533.)

(Fig. 1.3). Power was supplied to the rotors by a gasoline motor and belt transmission. Each rotor had two blades, and the rotors rotated in opposite directions to cancel torque reaction. A primitive means of control was achieved by placing small wings in the slipstream below the rotor. The machine was reported to have made several tethered flights of a few seconds at low altitude. Also in France, the Breguet brothers had begun to conduct helicopter experiments about 1907. Their complicated quadrotor "Gyroplane" carried a pilot off the ground, albeit briefly, but like the Cornu machine it was underpowered, and it lacked stability and a proper means of control.

In the early 1900s, Igor Sikorsky and Boris Yur'ev independently began to design and build vertical-lift machines in Czarist Russia. By 1909, Sikorsky had built a nonpiloted coaxial 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 was unable to lift its own weight, and the second, even with a more powerful engine, only made short (nonpiloted) hops. 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 pursued his ideas again. 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 Sikorsky, Boris Yur'ev had also tried to build a helicopter in Russia around 1912, but with a single rotor and tail rotor configuration. Like Sikorsky's machine, the aircraft lacked a powerful enough engine. Besides being one of the first to use a tail rotor design, Yur'ev was one of the first to propose the concept of cyclic pitch for rotor control. (Another early design was patented by Gaetano Crocco of Italy in 1906). Good accounts of Yur'ev's machine are given by Gablehouse (1967) and Liberatore (1998). 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 he published several papers on the subject of rotating wings and helicopters; see also Margoulis (1922) and Tokaty (1971).

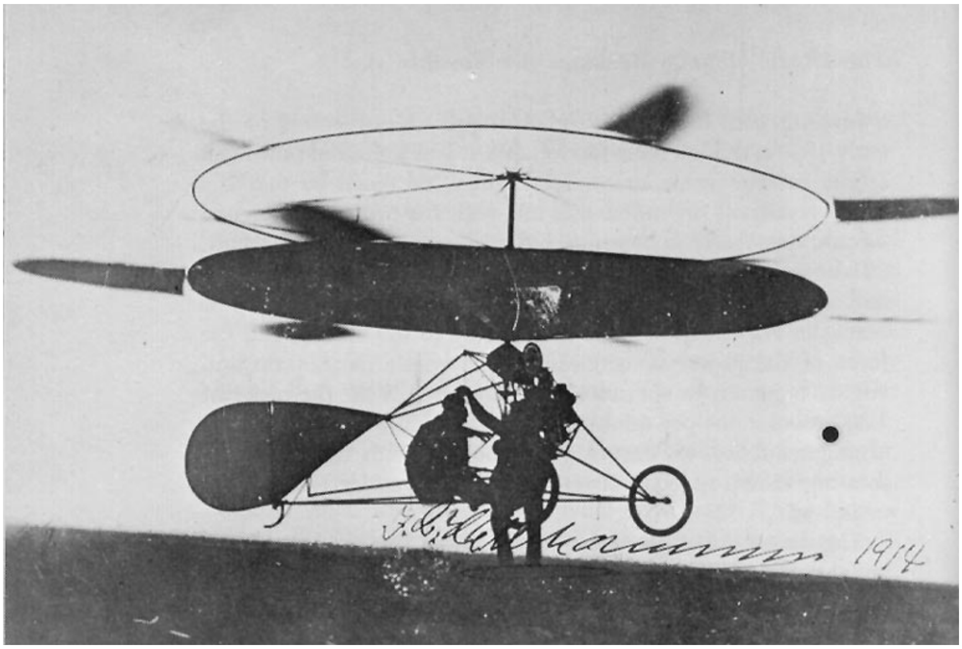

Figure 1.4 Danish aviation pioneer Jens Ellehammer flew a coaxial rotor helicopter design in 1914.

About 1914, the Danish aviation pioneer Jens Ellehammer designed a coaxial rotor helicopter. Boulet (1984) gives a good description of the machine, which is shown in Fig. 1.4. The rotor blades themselves were very short; six of these were attached to each of two large circular aluminum rings. The lower disk was covered with fabric and was intended to serve as a parachute in the event the rotors failed. A cyclic pitch mechanism was used to provide control, this being another one of many early applications of the 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.

An Austrian, Stephan Petroczy, with the assistance of the well-known aerodynamicist Theodore von Kármán, built and flew a coaxial rotor helicopter during 1917–1920. Interesting design features of this machine included a pilot/observer position above the rotors, inflated bags for landing gear, and a quick-opening parachute. While the machine never really flew freely, it accomplished numerous limited tethered vertical flights. 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 by Munk (1923)] these were some of the first attempts to scientifically 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. 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. By the early 1920s at the College

Figure 1.5 This Berliner helicopter with side-by-side rotors made short flights at College Park airport in Maryland in 1922. (Courtesy of College Park Airport Museum.)

Park airport, the Berliners were flying an aircraft with side-by-side rotors (Fig. 1.5). The rotors were oversized wooden propellers, but with special airfoil profiles and twist distributions. Differential longitudinal tilt of the rotor shafts provided yaw control. On later variants, 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, also with a small vertically thrusting auxiliary rotor on the rear of the fuselage. 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. However, because true vertical flight capability with these machines was limited, the Berliners abandoned the pure helicopter in favor of a 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. See also Berliner (1908, 1915).

In Britain during the 1920s, 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 rotor with propellers mounted on the blades (Fig. 1.6). Control was achieved by the use of "ailerons" inboard of the propellers. In 1922, the machine lifted off inside a balloon shed. Further brief low altitude flights outdoors were undertaken through 1925, but the machine crashed, and further work stopped because of increasing interest in the autogiro (see Section 1.3).

During the early 1920s, Raul Pescara, an Argentinian living and working in Spain and France, was building and attempting to fly a coaxial helicopter with biplane-type rotors (Fig. 1.7). As described by Boulet (1984), each rotor had a remarkable five sets of biplane blades that were mounted rigidly to the rotor shaft. Pescara's work focused on the need

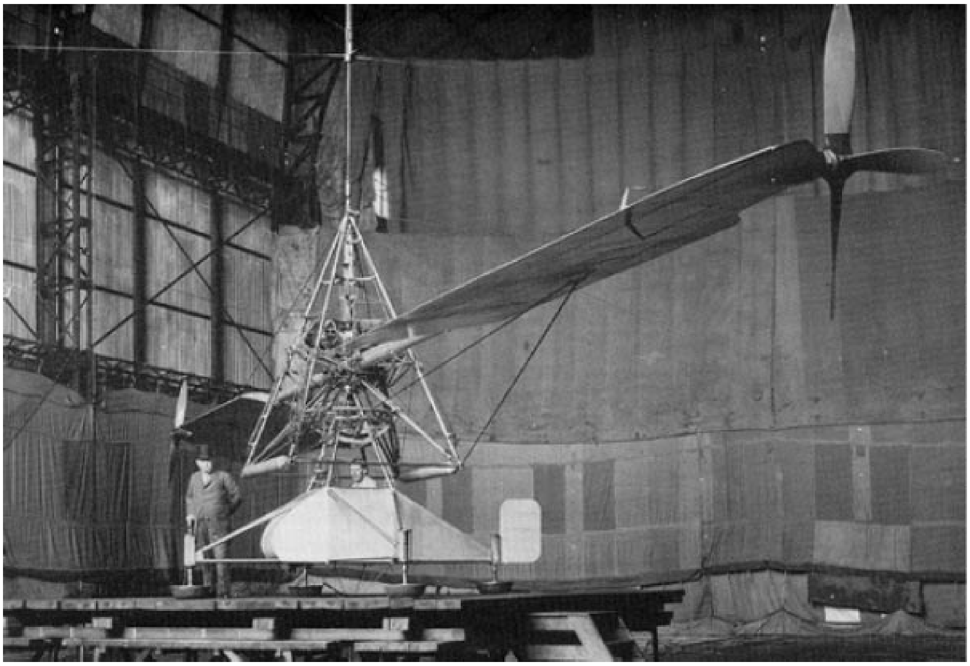

Figure 1.6 The Brennan helicopter suspended in the balloon shed at RAE Farnborough, circa 1922.

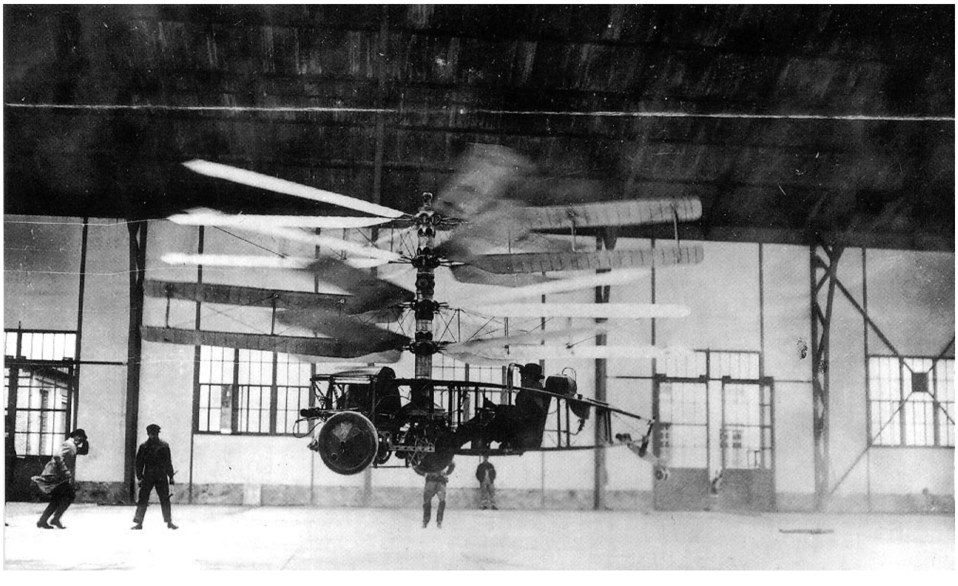

Figure 1.7 Pescara's helicopter hovering in a hanger about 1923. (Courtesy NASM Smithsonian Institution, SI Neg. No. 83-16343.)

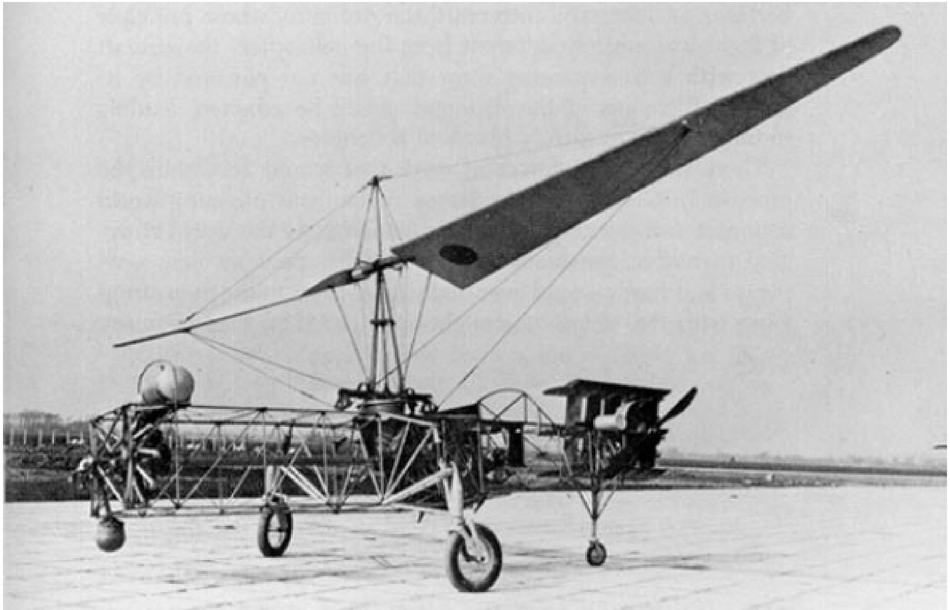

Figure 1.8 Between 1924 and 1930, A. G. von Baumhauer made attempts to fly a single main rotor helicopter with a separately powered tail rotor. (Courtesy of NASM, Smithsonian Institution, Neg. No. 77-721.)

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 between the two rotors. Early versions of his 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, 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 tail rotor to counteract torque reaction. Boulet (1984) gives a good description of the machine. Figure 1.8 shows that the fuselage consisted essentially of a tubular truss, with an engine mounted on one end. The other end carried a smaller engine mounted at right angles to the main rotor, which turned a conventional propeller to 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 control. Nevertheless, the machine was reported to have made numerous short, semicontrolled 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 fixed wings located in the rotor