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 Ivanovitch Sikorsky (1955)

1.1 Rising Vertically

Aerodynamics is the science of all flight. The role of aerodynamics in the engineering analysis and design of rotating-wing vertical lift aircraft, such as the helicopter, is the primary subject of this book. A helicopter can be defined as any flying machine using rotating wings (i.e., rotors) to provide lift, propulsion, and control forces. The rotor produces a lift force equal to the weight of the helicopter and because the generation of this lift force does not require any forward flight speed, the helicopter can rise vertically from the ground and hover. A simpler definition, therefore, is that a helicopter is an aircraft using a rotor (or rotors) that can hover – see Hafner (1954). Tilting the orientation of the rotor disk(s) provides the forces and moments to control the helicopter in flight. Tilting the rotor disk fore and aft provides pitch control, and tilting it left and right gives roll control. If a single main lifting rotor is used, then a sideward thrusting tail rotor provides anti-torque and directional (yaw) control. If the rotor disk is tilted progressively forward, the rotor provides a propulsive force, accelerating the helicopter into forward flight.

Although the helicopter has been described as an "ungainly, aerodynamic maverick" [Carlson (2002)], the modern helicopter is indeed a machine of considerable engineering sophistication and refinement (Fig. 1.1) and plays a unique role in modern aviation provided by no other aircraft. It is truly a unique form of aircraft and a mastery of modern aeronautical engineering. The helicopter can take off, fly forward or backward, climb and descend, and move in almost any direction at the whim of the pilot. This is the form of true flight that inspired humankind literally hundreds of years before the helicopter became a reality. Igor Sikorsky's vision of a rotating-wing aircraft that could "lift itself vertically" and safely perform all these desirable flight maneuvers under full control of a pilot was ultimately only to be achieved in the mid-1930s, some thirty years after fixed-wing aircraft (airplanes) were flying successfully. In the last seventy years, the helicopter has matured 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. Its modern civilian roles are almost limitless and encompass sea and land rescue, police surveillance, oil rig servicing, homeland defense, and other important missions. Without question, helicopters are an essential part of any modern military.

Rotating-wing aircraft are far more complicated than they might first appear. Aerodynamically, the airflow through the helicopter rotor is extremely difficult to define and even after many years of intense study it still defies a fully adequate description. The ability to define and predict the rotor aerodynamics, however, is key to the prediction of the performance of the helicopter as a whole. Mechanically, the helicopter is complicated as well. The long slender rotor blades twist and bend, flap up and down, and lead and lag about

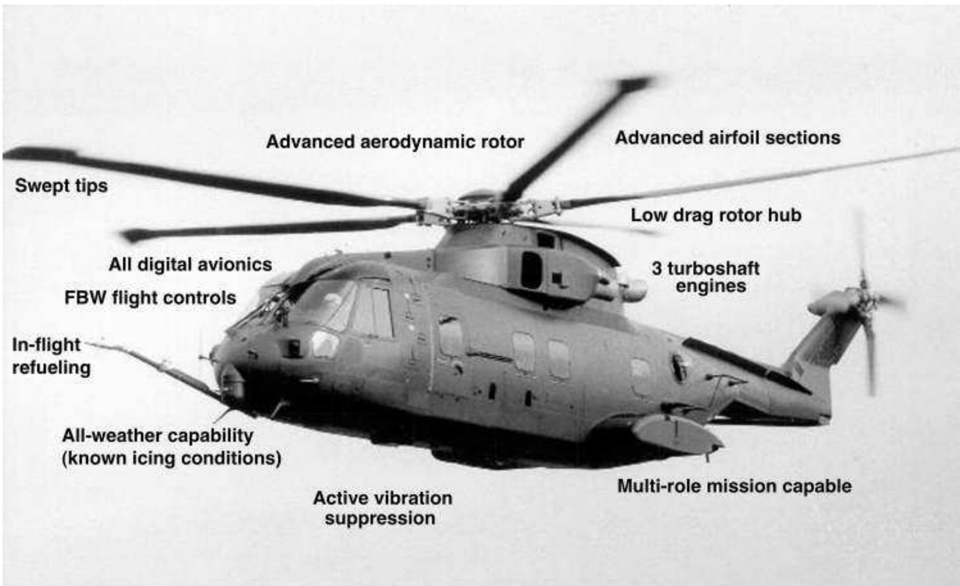

Figure 1.1 Modern helicopters have matured into sophisticated machines with extraordinary capability, which fulfill many civilian and military aviation roles. Agusta–Westland EH–Industries EH-101. (Photo by permission of Agusta–Westland.)

hinges that attach them to the rotor shaft. The need to control the aerodynamic forces on the rotor requires that the pitch of each blade be changed individually as the blades rotate about the shaft. Despite the relatively high aerodynamic and mechanical complexity of the rotor system and the helicopter as a whole, there are still many parallels in their development when compared to fixed-wing aircraft. However, the longer and more tumultuous

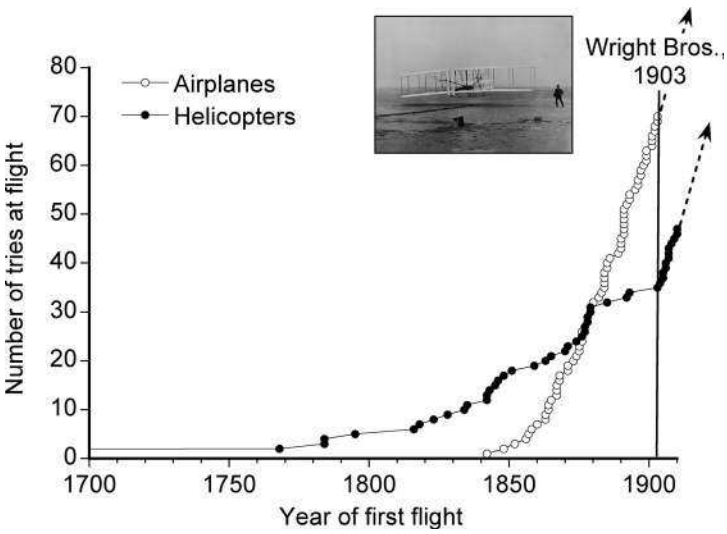

Figure 1.2 Until the middle of the nineteenth century, more attempts had been made to build rotating-wing aircraft than airplanes. Data source: Hafner (1954) and adapted from Harris (1994).

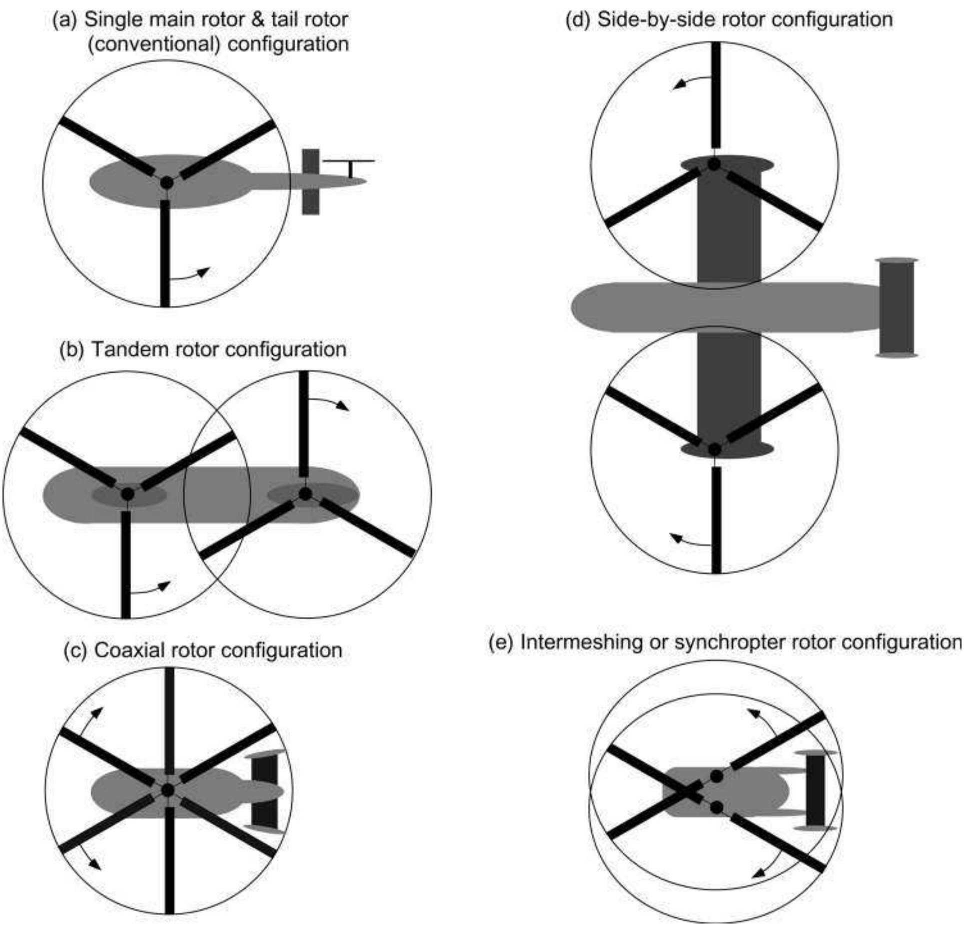

Figure 1.3 Types of helicopter. (a) Single main rotor/tail rotor (conventional) configuration. (b) Tandem rotors. (c) Coaxial rotors. (d) Side-by-side rotors. (e) Intermeshing rotors.

gestation period of the helicopter is clearly attributable to the greater depth of scientific and aeronautical knowledge that was required before all the various technical problems could be understood and overcome. Along with the need to understand the basic aerodynamics of vertical flight and improve upon the aerodynamic efficiency of the helicopter, technical barriers included the need to develop suitable high power-to-weight ratio engines and high strength-to-weight ratio materials for the rotor blades, hub, fuselage, and transmission.

Compared to airplanes – the development of which can be clearly traced to Lilienthal in Germany, Pilcher in Britain, Langley in the United States, and the first controlled flight of a piloted powered aircraft by the Wright Brothers in 1903 – the origins of successful helicopter flight are less clear. It may seem surprising that until the middle of the nineteenth century there had been more attempts to build helicopters than fixed-wing aircraft (see Fig. 1.2). Yet the early preference of helicopters over airplanes is perhaps not so surprising given the rapid adoption of the marine propeller during the same time period. Therefore it would seem that the preferred means of vertical-rising locomotion through a fluid would be a propeller of some type. Yet, other than making short hops off the ground, none of these early machines were successful in demonstrating sustained, fully controlled vertical and hovering flight.

Many problems plagued the early attempts at powered vertical flight with rotating wings. This included the relatively poor understanding of rotating-wing aeromechanics[1] to allow for efficient rotors, the lack of suitable engines, counteracting torque reaction from the shaft driven rotor(s), and providing the machine with enough stability and control. Many of the early machines were of the coaxial or side-by-side (lateral) rotor configuration – see Fig. 1.3. Contrarotating rotors – one rotor above the other on a concentric shaft – automatically balance torque reaction on the airframe, despite the greater mechanical complexity involved in gearing and controlling the two rotors. Side-by-side rotors, especially if the shafts were inclined inwards, gave the early machines somewhat better lateral stability, but again there was a greater level of mechanical complexity associated with this type of design. The intermeshing rotor design has outward tilted contrarotating shafts. The simplest idea of using a single rotor with a sideward thrusting tail rotor to compensate for torque reaction was not used until much later in the initial development of the helicopter.

1.2 Producing Thrust

In its simplest terms, the thrust on the helicopter rotor 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. It is clear that much has been accomplished over the last sixty years in improving the capabilities and efficiency of the helicopter, but one must wonder what would really be possible with future helicopters if these complex aerodynamics could be fully understood and controlled to harness its maximum efficiency!

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 both rotor and airframe drag. The orientation of the rotor disk to the airflow also provides the forces and moments to control the attitude and position of the helicopter. The pilot controls the magnitude and direction of the rotor thrust vector by changing the blade pitch angles (using collective and cyclic pitch inputs through the controls), which changes the blade lift and the distribution of lift forces 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. However, the mechanical complexity of the rotor hub required to allow for articulation and pitch control leads to high design and maintenance costs. 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 as a result asymmetric aerodynamic forces and moments will be

[1] A branch of mechanics that deals with the motion of air and the effects on bodies.

produced on the rotor. Articulation helps allow the blades to naturally flap and lag so as to help balance out these asymmetric aerodynamic effects. With the inherently asymmetric airflow 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 are 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.

1.3 Key Technical Problems in Attaining 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), among others. Boulet (1984) takes a unique approach in that he gives a first-hand account of the early helicopter developments though 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 Liberatore (1998) described, 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, and 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. Clearly, 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, Henrich Focke, Raoul Hafner, Harold Pitcairn, Igor Sikorsky, Arthur Young, and others did the design of a truly safe and practical helicopter become a reality.

Seven fundamental technical problems can be identified that limited early experiments with helicopters. These problems are described by Sikorsky (1938 and various editions) and in many 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. The first significant application of aerodynamic theory to helicopter rotors came about in the early 1920s. [See also Liberatore (1998) for a historical discussion of this point.]
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 practical internal combustion (gasoline-powered) engines. The steam engine was never a viable concept for any type of aircraft. However, the development of internal

combustion engines with sufficient power-to-weight ratios suitable for use on a helicopter did not occur until the 1920s.

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. Aluminum was not available commercially until about 1890 and was inordinately expensive, it not being used as a construction material for airframes and aircraft engines until about 1915.
4. Counteracting rotor–torque reaction. The relatively simple idea of a tail rotor to counter torque reaction was not used on most early helicopter designs, these machines were either coaxial or side-by-side rotor configurations. Yet, building and controlling two or more primary lifting rotors was even more difficult than controlling one rotor, a fact that seemed to evade many inventors and constructors.
5. Providing stability and properly controlling the machine, including 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, ideas that were pioneered by Cierva, Breguet, and others, and with the development of practical forms of cyclic blade pitch control by Hafner and others.
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. It was to be many years before such problems could be reduced to the thresholds where the helicopter was to become as reliable as a fixed-wing aircraft.
7. The capability to recover safely to the ground in the event of engine failure (i.e., a “gliding” or autorotational requirement – see page 28). It is fair to say that this capability is critical to the success of any practical helicopter or other type of rotorcraft because it would simply not be accepted otherwise.

The relatively high weight of the structure, engine, and transmission was mainly responsible for the painfully slow initial development of the helicopter. In particular, the success of the helicopter had to wait until aircraft engine technology could be refined to the point that lightweight engines with considerable power could be built. By 1920, gasoline-powered reciprocating engines with higher power-to-weight ratios were more widely available and the anti-torque 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 Britain, France, Germany, and Italy, which 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–WW2 years, it was not until the late interwar period that significant technical advances were made and more practical helicopter designs began to appear. One of the most important advances of all was in engine technology, with powerful reciprocating and gas turbine (turboshaft) engines, the latter of which revolutionized both fixed-wing and rotating-wing borne flight.

1.4 Early Thinking

A timeline documenting the evolution of some key rotating-wing aircraft through 1950 is shown in Fig. 1.4, the year 1950 being the onset of large-scale commercial success for the helicopter. 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

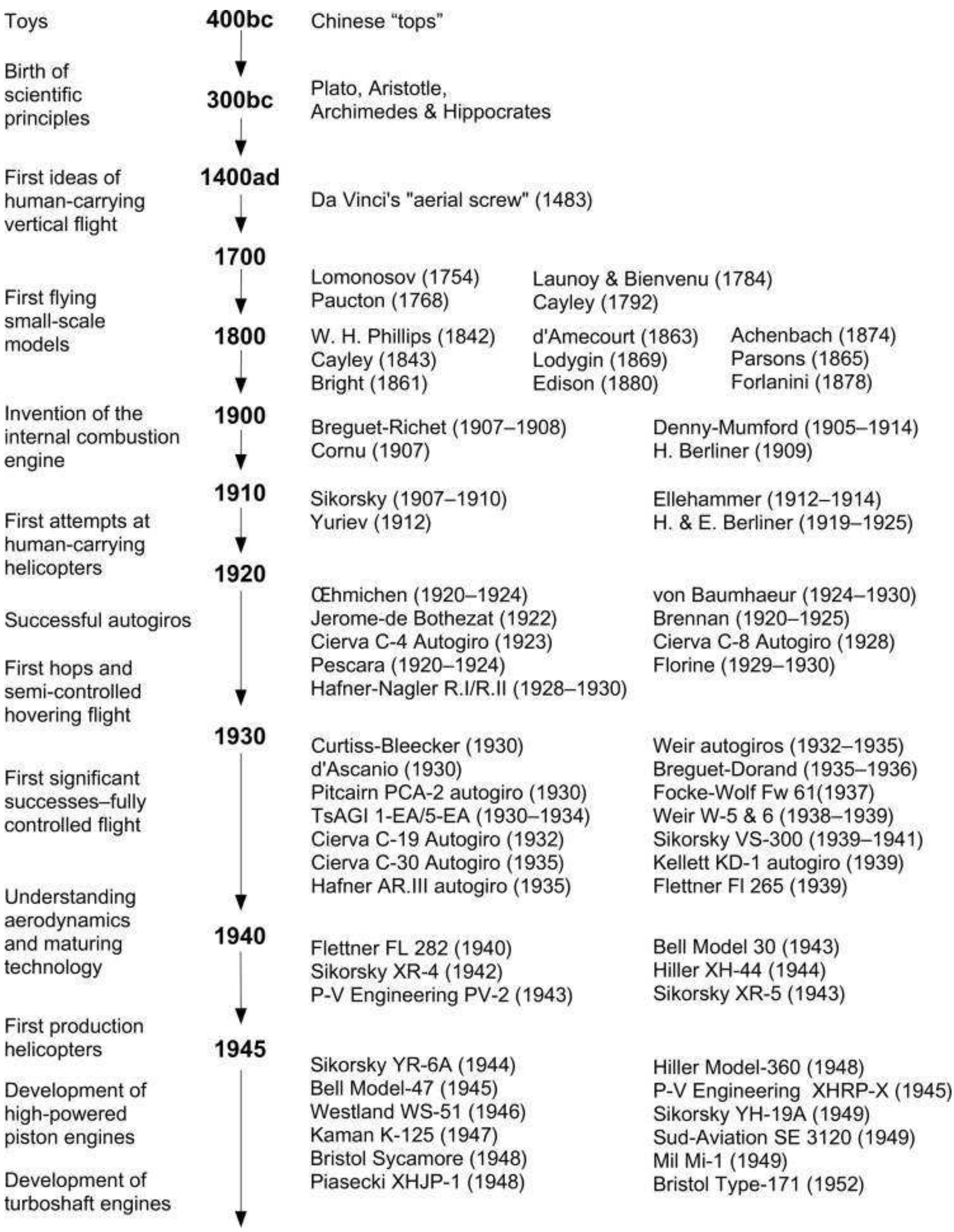

Figure 1.4 Timeline showing the development of helicopters and autogiros up to 1950.

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 maple and sycamore, whose whirling, autorotating seeds carry far on the breeze. While the Chinese top was no more than a toy, it is perhaps the first tangible device of what we may understand as a helicopter. The Chinese top is still a popular toy today.

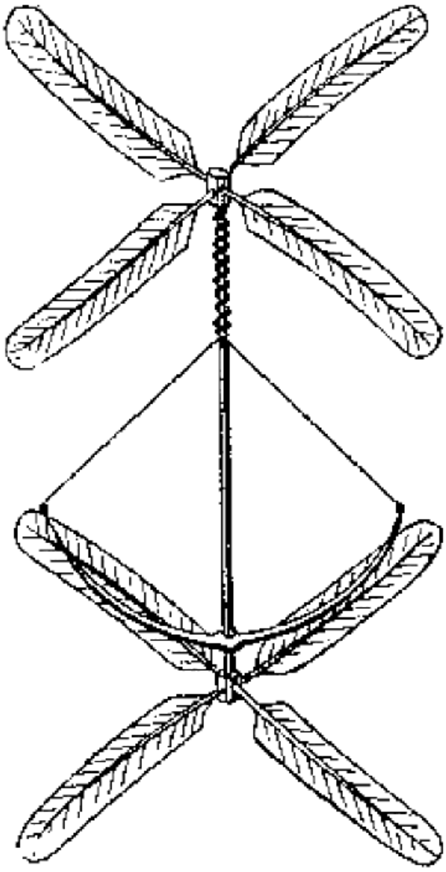

Figure 1.5 A facsimile of the "Chinese Top" built by Launoy & Bienvenu in 1783.

More than two millennia 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. In 1783, the French naturalist Launoy, with the assistance of a mechanic named Bienvenu, used a coaxial version of the Chinese top in a model consisting of a contrarotating set of turkey feathers. Their device was powered by a string wound around the rotor shaft that was tensioned by a crossbow (Fig. 1.5). When the tension was released, the rotor spun and the device climbed high into the air. Launoy & Bienvenu's invention flew well and its success even created quite a stir in scientific circles. Inspired by the early success with these whirling tops, in 1786 the French mathematician A. J. P. Paucton (1768) published a scientific paper titled "Théorie de la vis D'Archimède," where he proposed one of the first concepts of a human-carrying helicopter.

Among his many hundreds of intricate drawings, the Renaissance visionary Leonardo da Vinci shows what is a basic human-carrying helicopter-like machine, which was an obvious elaboration of an Archemedes water-screw. His sketch of the "aerial-screw" or "air gyroscope" device (Fig. 1.6) is dated to 1483, but it was not published until the end of the eighteenth century. The device comprises 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 realized that the density of air was much less than that of water and so da Vinci describes how the device

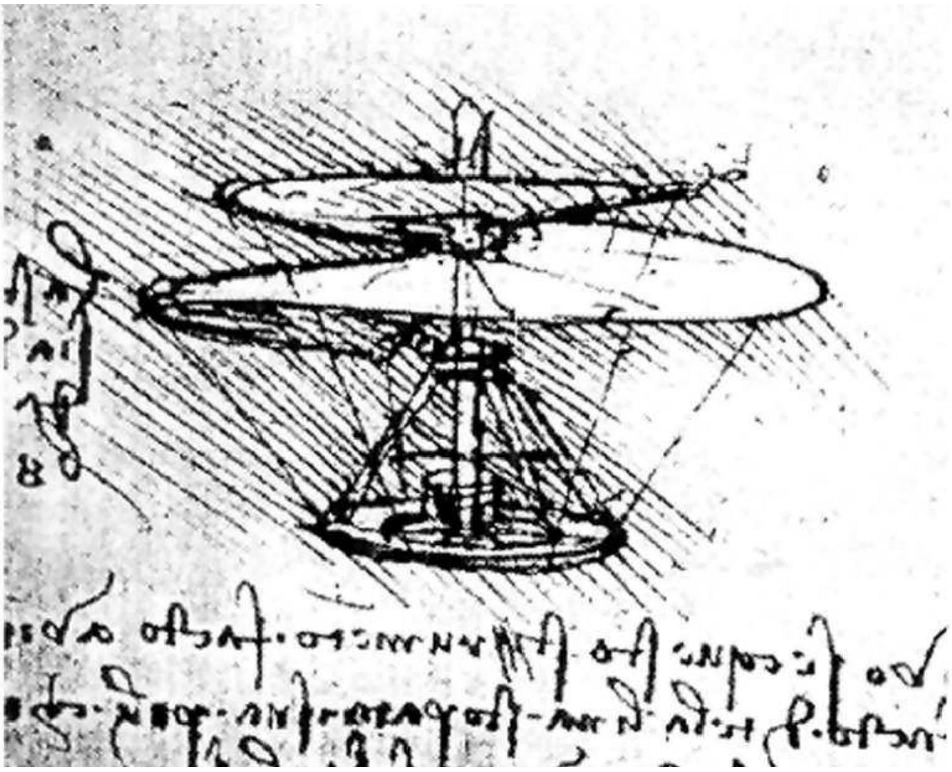

Figure 1.6 Leonardo da Vinci's aerial screw machine, dated to 1483. Original drawing is MS 2173 of Manuscript (codex) B, folio 83 verso, in the collection of the Biblothèque L'Institute de France (Paris).

needed to be relatively large to produce enough lift to accomplish this feat – the number '8' in his backward mirror image script and to the left of the sketch (Fig. 1.6) indicates that the size of the rotor is 8 *braccia*,[2] which translates into a rotor of up to 26 ft (7.9 m) in diameter. Da Vinci clearly did not build his proposed machine except perhaps for some small models, but his idea was far ahead of its time. Although da Vinci worked on various concepts for engines, turbines, and gears, he did not seem to unite the ideas of his aerial-screw machine with an engine, nor did he seem to appreciate the concept of *torque-reaction*.[3] Therefore, a torque applied to the rotor shaft will result in a reaction torque tending to rotate the platform from which the torque is applied. See Hart (1961) or Giacomelli (1930) for further details of da Vinci's aeronautical inventions.

The great polymath, 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 he had constructed several successful vertical-flight models with rotors made of sheets of tin and driven by wound-up clock springs. 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 (1809–1910) published

[2] A *braccia* is an old Florentine unit of measure, approximately equal to one arm's length, although it has been defined variously between 15 and 39 in (0.28 to 1 m).
[3] Newton's third law states that for every action (force) there is an equal and opposite reaction (force).

a three-part paper that was to lay down the scientific principles of 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 rotors, arranged side by side, to provide lift. However, the device 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. Cayley's convertiplane is, nevertheless, an interesting concept. The issue of torque reaction was solved by using contrarotating rotors and two propellers provided horizontal thrust to push the aircraft through the air. The design of the rotors was such that they flattened down to become solid disks and act as wings in forward flight, an idea possibly gleaned from the American Robert Taylor – see Liberatore (1998). Cayley suggested that an engine with considerable power would be needed to accomplish this feat and he even mentioned in his paper that "very great power, in proportion to the weight of the engine, is necessary." While Cayley worked on engine concepts, it is not clear, however, if he ever actually attempted to establish the power requirements for vertical flight by means of theoretical calculations.

The lack of a suitable powerplant continued to stifle aeronautical progress, but the use of miniature, lightweight steam engines met with some success in powering smaller free-flying model helicopters. In the 1840s, another Englishman, W. H. Phillips, constructed a steam-driven vertical flight machine, where steam generated by boiling water in a miniature boiler was ejected out of the blade tips. Although impractical on a larger 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 bowstrings or other types of wound-up springs. In the early 1860s, Ponton d'Amécourt of France attempted to fly a number of small steam-powered 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). The novelist Jules Verne was impressed with d'Amécourt's attempts at vertical flight and in 1886 he wrote "Robur le Conquerant" (later published in English as "The Clipper of the Clouds") where the hero cruised around the skies in a giant helicopter-like machine that was lifted by thirty-seven small coaxial rotors and pulled through the air by two propellers. It was probably Jules Verne rather than d'Amécourt who is responsible for the word *helicopter* entering the standard lexicon.

Other notable vertical flight models that were constructed at about this time include Bright's coaxial design in 1861 and Dieuaide's twin-rotor steam-driven model in 1877. In 1865 Sir Charles Parsons of England built another type of helicopter model driven by a steam engine. Wilheim 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. 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 contrarotating rotors, and it flew freely at heights of over 40 ft (12.2 m) for as much as twenty seconds.

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 blade area to give good hovering efficiency [see Liberatore (1998)]. Edison was to say: "I got the motor and put it on the scales and tried a number of different things and contrivances [rotors] connected to the motor to see how it would lighten itself on the scale. I got some data and made up my mind that what was needed was a very powerful