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| Thierry M. Faure. The quest of vertical flight: the development of helicopter. 2015. hal-01192627v1

HAL Id: hal-01192627

<https://hal.science/hal-01192627v1>

Submitted on 3 Sep 2015 (v1), last revised 3 May 2016 (v2)

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The quest of vertical flight: the development of helicopter

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The idea of vertical flight

The dream of flight, first developed by the observation of nature, was inspired from birds and insects. However, the whirling fall and glide of seeds from trees like the sycamore, allowing a wide dissemination of the specie, is an alternative way of flight. That is probably the origin of conception of the Chinese top (reported by Ge Hong circa 400 BC), which is a small toy consisting in two blades attached to a stick, which rotation between the hands of an operator, generates lift and its vertical flight [1]. The idea of using blade rotation, to fly a machine carrying a man, was developed by Leonardo da Vinci at the end of the XVth Century. His thinking was to adapt the Archimedes' screw, which is a device for raising water from the ground level, to the vertical translation of a machine in the air (Figure 1). If no light and high-strength material existed at that time and no engine was available to provide enough power to fly that machine, its design was wrong in its mechanical concept. Contrary to the seeds falling from a tree, or the Chinese top, the shaft-driven rotor generates a torque which is transmitted to the nacelle making it swirl and leads to a loss of control. Thus, the lack of a proper counter-reacting torque system is the main drawback of that design. In addition, the rotor shape is far from an optimum use in the air.

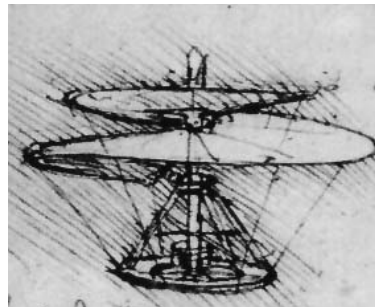


Figure 1 : Aerial screw.

In Russia, Mikhail Lomonosov realized in 1754 a model inspired by the Chinese top to raise a charge from the ground [1]. That model consisted in two rotors powered by a wound-up spring device; the charge was inside a box in translation between two vertical poles. That model did not require counter-reacting torque system since it was linked to the floor. In France in 1784, Launoy and Bienvenu developed an evolution of the Chinese top including a power source, a string wound around the rotor shaft and tensioned by a crossbow [2]. For the first time, torque reaction was cancelled using two counter-rotating rotors (Figure 2). That device was successfully demonstrated before the French Academy of Sciences and renewed the interest of rotor vertical flight in the scientific community.



Figure 2 : Launoy and Bienvenu's invention (1784).

First designs and models

During the XIXth Century, the cancellation of torque reaction was well understood and solved by counter-rotating rotors. Many vertical motioned rotor-driven machines were designed and sometimes tested. They were generally moved by spring or steam power, but the lack of engines developing sufficient power-to-weight ratios did not lead these machines to success. Following the flights of a hot-air balloon, by Pilatre de Rozier and the Marquis d'Arlandes, and of a hydrogen balloon, by Charles and Robert, in 1783, a key issue was to control the trajectory. That period was then marked by the struggle between the “lighter than air” and “heavier than air” flight supporters, the latter being dominated by the defendant of vertical rotor propulsion. It is reported [2] that in England William Henry Phillips, the inventor of the extinguisher, developed and flew in 1842 a miniature model of vertical rotor-driven machine powered by steam ejected at the tip of the blades. Because that rotor was not driven by shaft rotation, a torque reaction system was useless. After making a four-bladed version of Launoy and Bienvenu's model in 1796 [3], Sir George Cayley developed the concept of Convertiplane in 1843 [4] (Figure 3). That kind of gyrodyne was intended to take-off vertically with two pairs of counter-rotating rotors, then to fly horizontally by the conversion of the rotors into lifting circular wings, the horizontal propulsion being addressed by two vertical rear propellers. That machine was never built.

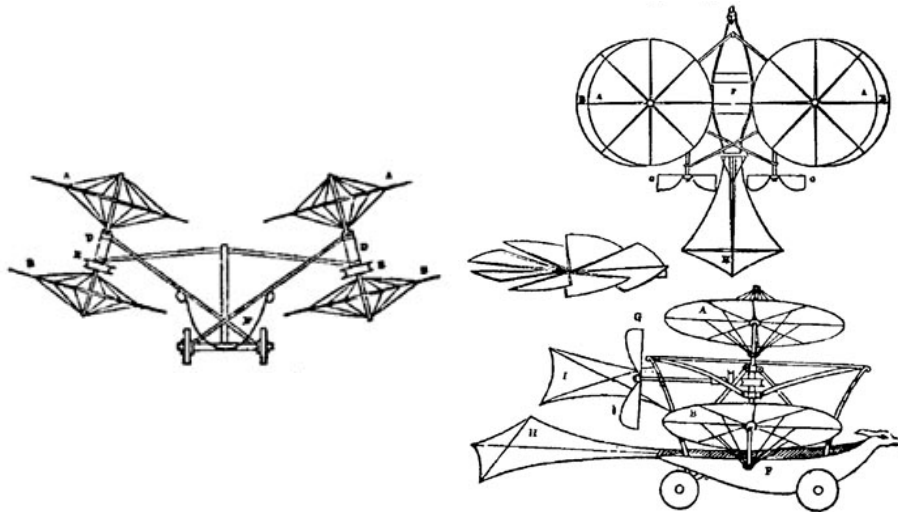


Figure 3 : George Cayley's Convertiplane (1843) [4].

In France, Gustave de Ponton d'Amécourt (1861) made a steamed engine model called for the first time “helicopter” [5]. To save weight, that coaxial counter-rotating rotors machine was the first to use aluminum, which was a new light material at that time (Figure 4). A rise of different helicopter designs and models followed, and many thought that heavier-than-air flight would be realized very soon. The literature with Jules Verne's novel “The Clipper of the Clouds” (« Robur le Conquérant ») published in 1886 [6] inspired that standpoint.



Figure 4 : Helicopter of de Ponton d'Amécourt (1861).

In 1878, the Italian Enrico Forlanini flew during 20 s a miniature model, using steam power, which reached the height of 13 m [1]. Up to 1880, all the helicopter models employed short blades. Thomas Alva Edison developed small helicopter models and was the first to found the need for a large rotor diameter with low blade area to give good hovering efficiency. Unfortunately, the engines tested did not provide a sufficient power-to-weight ratio.

Theoretical developments

During this period, in the field of theoretical approach, the Scottish William Rankine in 1865 [7] and the British William Froude in 1878 [8] and his son Robert Edmund Froude in 1889 [9], developed the propeller theory. First applied to naval propulsion, this theory was then adapted to vertical flight dynamics from the beginning of the XXth Century. Many improvements followed, with Drelie's concept of a hybrid momentum-blade element (1900) [10] and other approaches including tip vortices dynamics by Joukowski (1906) [11]. A practical helicopter would not limit its operating range to vertical translation, but has to combine vertical and horizontal motions. The forward flight of a helicopter is an important issue which produces a non-uniform velocity distribution on the rotor and creates a rolling moment. The way to suppress that rolling moment is the principle of flapping propeller blades, suggested in 1904 by Colonel Charles Renard. An operational system of flapping blades was patented in 1908 by Louis Charles Bréguet [1]. He built a whirling arm test rig in 1905 and found the way of producing a forward thrust by tilting the rotor blades. The effects of forward flight speed on the rotor flow were also analyzed by Joukowski in 1909 [12]. He proved that the asymmetry of velocity and pressure on the main rotor generates asymmetry in forces and moments on the propeller in forward flight. But, unless Bréguet, Joukowski did not propose a technical solution to address this issue. The concept of cyclic pitch was one way for attaining full horizontal control and was patented in 1906 by the Italian Gaetano Arturo Crocco. He recognized that, in order to operate properly in forward flight, a helicopter needed a change of the blades pitch, to take into account the dissymmetry in the aerodynamic loads between the advancing blade into the relative wind, and the blade retreating away from the wind. Other torque-reaction systems were also suggested, as the synchropter, which consisted in two counter-rotating side-by-side intermeshing rotors, and was patented by Max Bourcart in 1902 [13].

First attempts of piloted vertical flights

The better performance of the internal combustion engine obtained at that time is linked to the development of airplanes, but that gain was not large enough to see a successful helicopter flight. However, that new type of engine and the increase of their power-to-weight ratio provided to helicopter pioneers, a way of building machines able to carry a man. France was the main workshop of the research on helicopter. It is said that Paul Cornu, a bicycle maker, was the first one to make a vertical flight of 30 cm from the ground during 20 s on 13 November 1907 (Figure 5). However, the engine power was limited to 24 hp, and would not be enough to sustain hovering flight out of ground effect. The frame of the helicopter consisted in tandem rotors to cancel torque reaction. Note the short rotor blade shape, which was not the best aerodynamic design.



Figure 5 : Helicopter of Cornu (1907).

Previously the same year, brothers Louis Charles and Jacques Bréguet tested the Gyroplane No. 1, which was under development since 1905 and based on the work of Professor Charles Richet. The

machine consisted in four double four-bladed rotors arranged at the end of each branch of a cross, this geometry is called quad-rotor, and was driven by a 40 hp engine (Figure 6). It is reported that the Gyroplane No. 1 lifted off and reached 60 cm during 1 min on 14 August and 29 September 1907. Because of its absence of stability system, it was secured by ropes tighten by operators on the ground. This is probably the reason why it is not mentioned as the first helicopter flight. Again, the machine took advantage of ground effect. Nevertheless, the Bréguet brothers had a good knowledge of aerodynamics as they used rotors with long blades and low area.

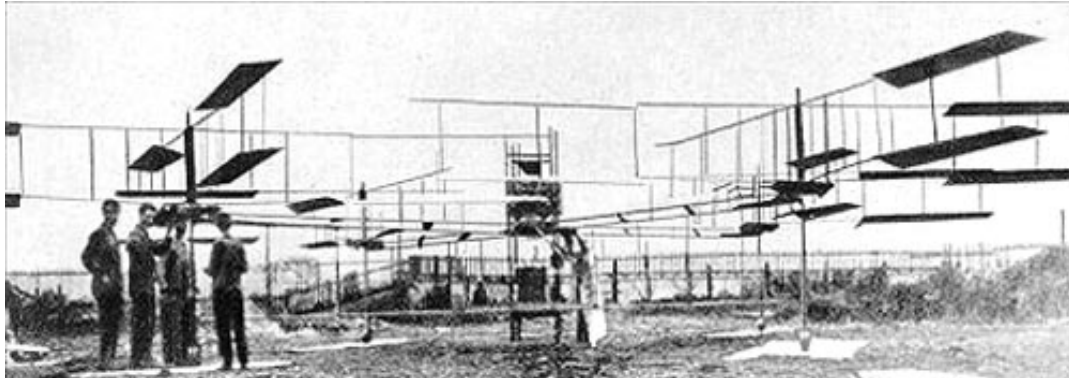


Figure 6 : Gyroplane No. 1 (1907).

In Russia, Igor Ivanovitch Sikorsky (1910) built vertical flight models. After the failure of the S-1 helicopter, the S-2 was fitted with a more powerful engine. It consisted in two three-bladed counter-rotating rotors and made only small hops from the ground. Discouraged, Sikorsky turned his mind to fixed-wing airplanes.

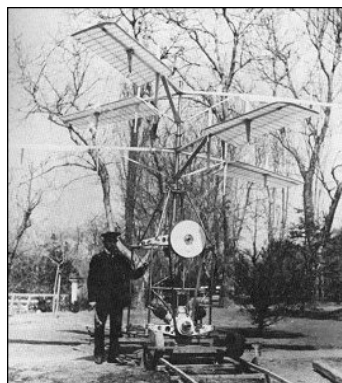


Figure 7 : Sikorsky S-2 (1910).

Stability control and horizontal flight

The theoretical improvements on rotor wing dynamics were rapidly followed by the development of innovative technologies. In Denmark, Jen C. Ellehammer built a co-axial rotors helicopter in 1914 which made many hops into the air. Each rotor was fitted with six short blades and a lower disk covered with fabric, to serve as a parachute in case of an engine failure. The main innovation of that helicopter is the first use of a rotor cyclic pitch mechanism.

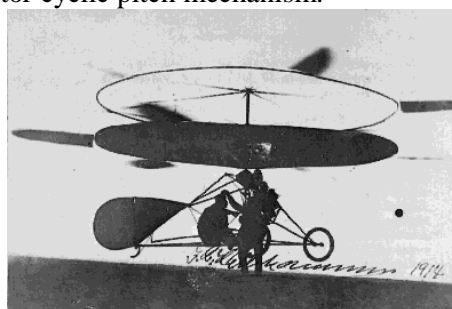


Figure 8 : Ellehammer's helicopter (1914).

In the United States, a Russian émigré expert in rotor-wing theories [14], Georges de Bothezat, built for the U.S. Army a quad-rotor helicopter (Figure 9). It was fitted with collective and cyclic blade pitch variations and four smaller rotors to help control. That machine flew successfully at a low altitude and a low forward speed in 1922, but the performances were not sufficient and the Army stopped its funding in 1924.

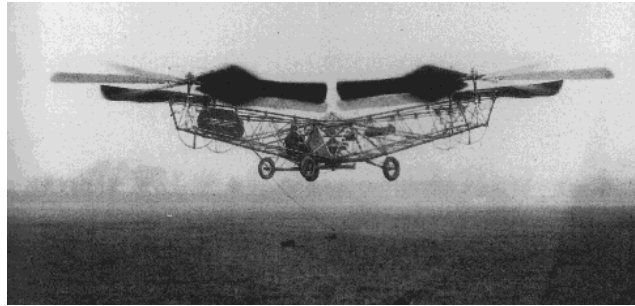


Figure 9 : de Bothezat's helicopter (1924).

Raúl Pateras Pescara, from Argentina, worked in France and Spain and focused on the design of the rotor, the key element of the helicopter, which he transformed into a complex mechanical system. He developed many co-axial rotors helicopter. Each rotor was made with five biplane blades with a cyclic pitch and control mechanism; yaw was controlled by differential collective pitch. The biplane blade design of the rotor needed bracing wire and generated a large drag, and the first models were underpowered [1]. A new version with a more powerful engine was the Pescara 2F (Figure 10) which established on 18 April 1924 a world record of flight distance in straight line of 736 m with an altitude of 1.8 m in 4 min 11 s recorded by the Fédération Aéronautique Internationale (FAI), but the helicopter control was limited.



Figure 10 : Pescara 2R (1921) and 2F (1923).

Again in France, Étienne Œhmichen, funded by the Peugeot car company, developed a quad-rotor helicopter with eight additional rotors for horizontal direction control (Figure 11). That machine was the first one with flight capabilities not limited to vertical and straight line motion, but demonstrated some maneuverability [15]. In May 1924 Œhmichen was awarded a prize of the FAI for a closed-loop circuit of one kilometer in 7 min 40 s.

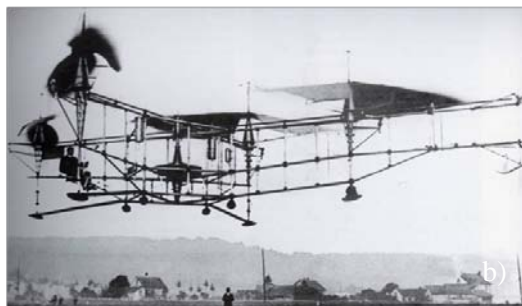


Figure 11 : Œhmichen's helicopter No. 2 (1924).

The autogiro

An important milestone in the elaboration of an operational helicopter is the autogiro. That gyroplane consists in a traditional airplane with a propeller and fixed wing, with the addition of a non-powered

horizontal rotor above the fuselage, freely rotating on its shaft by the action of the forward speed. It was unable of vertical take-off and landing, but take-off and landing distances were largely shortened in comparison with a traditional airplane. That design was developed by the Spanish Juan de la Cierva in order to provide additional lift by the autorotation of the horizontal rotor, to prevent an eventual engine failure. The first model C-4 flew in 1923 (Figure 12-a). De la Cierva elaborated and realized new technical solutions as the first practical application of flapping hinges as a means of equalizing the lift on the parts of the rotor in forward flight [16]. De la Cierva was invited to Great Britain in 1925 by the Weir Company and a first autogiro model, the C-19, was produced from 1932 to 1936 (Figure 12-b). In later models, de la Cierva added a lag hinge to each blade to cancel stresses caused by centrifugal forces, completing the articulated rotor hub design. The autogiro was very popular in the 1930s and was produced by many companies. The Austrian-born British engineer Raul Hafner developed the cyclic pitch control on its autogiro AR-3 in 1935, which 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 [1]. Ironically, although motivated by air safety, Juan de la Cierva died in an airplane crash in 1936. The autogiro development was then stopped and the helicopter was preferred.

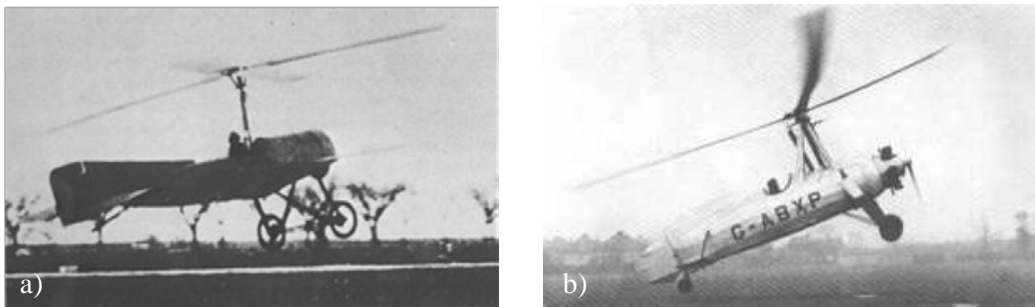


Figure 12 : de la Cierva's autogiros: a) C-4 (1923), b) C-19 (1932).

The first reliable helicopters

With the maturation of the key technologies in rotor control, like the cyclic and collective pitch control, the flapping and lagging hinges and anti-torque reaction rotors, the emergence of a useful helicopter was possible in the years 1930s. Many rotor configurations emerged at that time (Figure 13), and they are still in use by present helicopter manufacturers.

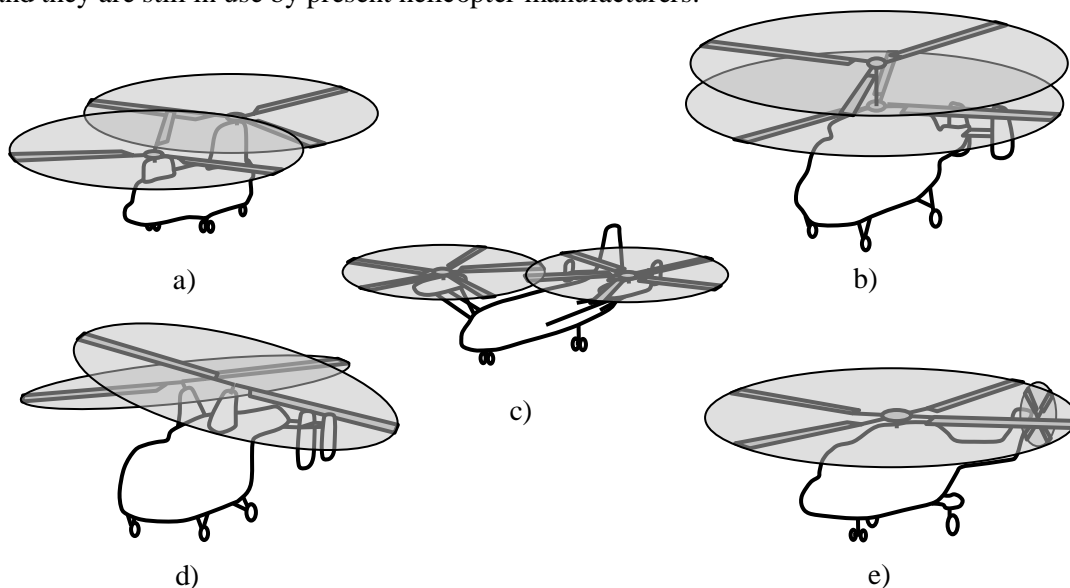


Figure 13 : Rotor configurations: a) tandem rotors, b) co-axial rotors, c) lateral side-by-side rotors, d) synchropter, e) main rotor with tail anti-torque rotor.

In Belgium, the Russian émigré Nicolas Florine was the first to fly a tandem rotor helicopter (Figure 13-a). That rotor configuration is more compact than the quad-rotor machines previously tested by Bréguet, de Bothezat and Cehmichen. In 1933, it reached the altitude of 5 m during a flight of 9 min (Figure 14).

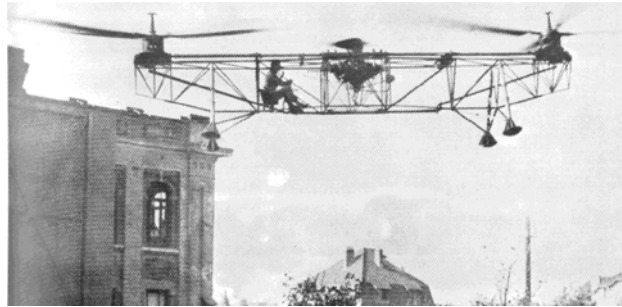


Figure 14 : Florine's tandem rotor helicopter (1930).

After establishing a noted aircraft company, Louis Charles Bréguet came back to the helicopter development with René Dorand. They improved the coaxial counter-rotating rotors concept (Figure 13-b) with a cyclic pitch control. The yaw angle control was obtained by applying a differential torque on a rotor. In 1936 the helicopter established a 62 min flight of 44 km (Figure 15).



Figure 15 : Bréguet-Dorand (1936).

In Germany, Henrich Focke began building rotor wing aircrafts acquiring a license of de la Cierva's autogiro in 1933. He built in 1936, the Fa-61 (Figure 16-a), made from the fuselage of a biplane with two side-by-side counter-rotating rotors (Figure 13-c). The rotor blades 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 obtained by tilting the rotors differentially. The rotors had no variable collective pitch, and used a slow system changing the rotor speed in order to change the thrust [1]. The Fa-61 was the first helicopter to sustain a controlled flight and to demonstrate autorotation. In 1937 it sets records of flight duration of 1 h 20 min, altitude with 3427 m, velocity of 122 km/h and distance in straight line with 233 km. On that model, the front propeller is only devoted to engine cooling. A later model, the Fa-223 (Figure 16-b), reached in 1940, the altitude of 7135 m and the velocity of 185 km/h. Its payload capability was one ton at low altitude and velocity.

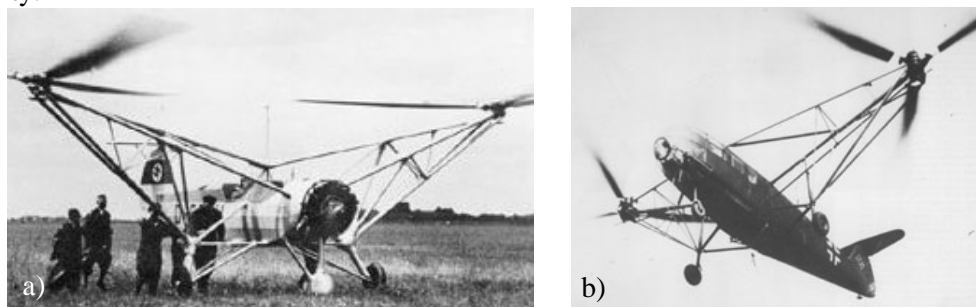


Figure 16 : Focke's helicopters: a) Fa-61 (1936), b) Fa-223 (1940).

Anton Flettner built an autogiro in 1935, and then developed the synchropter Fl-265 in 1939 (Figure 17). This type of helicopter possesses two counter-rotating side-by-side intermeshing rotors (Figure

13-d). The FI-265 was much easier to control than the Fa-223, and was the first helicopter to demonstrate transition into autorotation and then back again into powered flight. An improved version, the FI-282 Kolibri (Figure 18), was produced.



Figure 17 : Flettner FI-265 (1939).

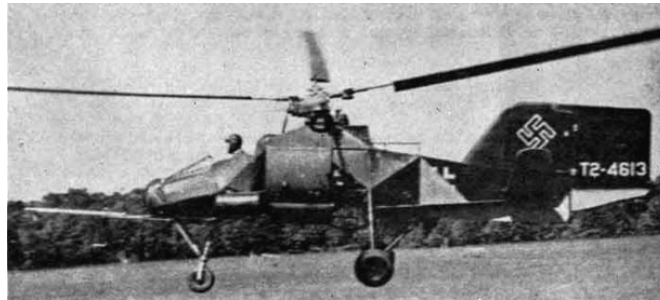


Figure 18 : Flettner FI-282 Kolibri (1942).

After having emigrated to the United States, where he developed a noted aircraft company, Igor Ivanovitch Sikorsky turned back to the study of helicopter in the 1930s. He developed in 1939 the VS-300 (Figure 19-a) with one main rotor and three auxiliary tail rotor for longitudinal and lateral control. The control of that first version was difficult and Sikorsky built in 1940 an improved one, the VS-300A (Figure 19-b), with a main rotor and a single vertical auxiliary tail rotor (Figure 13-e). Longitudinal and lateral control was achieved by cyclic pitch [17]. This concept was to become the standard for most helicopters and initiated with the industrial production of the R-4 in 1941 followed by the R-5 in 1943 (Figure 20).

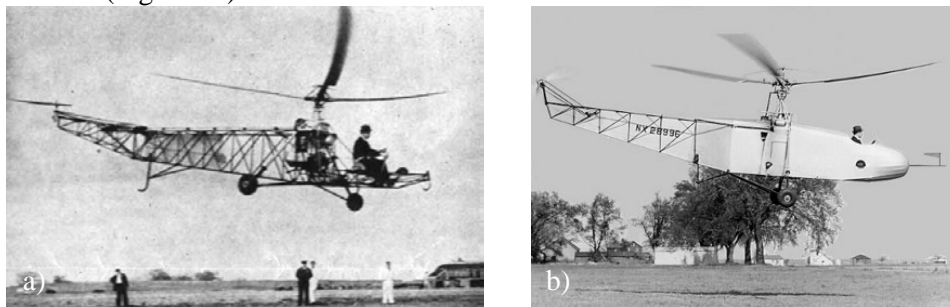


Figure 19 : Igor Sikorsky testing his helicopters a) VS-300 (1939), b) VS-300A (1940).



Figure 20 : Sikorsky R-4 (1941).

Conclusion

The development of the helicopter is a step-by-step story resulting from original design ideas, fundamental aerodynamics theories and innovative technical solutions. That course benefitted the internal combustion engine improvements, because of the large power-to-weight ratios needed, and the emergence of light and high-strength materials, but the key of a practical helicopter relied in its control, addressed by the elaboration of the complex mechanical system of the rotor head. That long time development of knowledge and technology, in the first decades of the XXth Century, led many pioneers interested in helicopter development, like Bréguet and Sikorsky, to bring a contribution, to turn their mind to other aeronautical fields before achieving a successful helicopter. It is worth noticing that the funding provided by their own aircraft company, together with their skills in aeronautics, were important elements of success.

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