DEVELOPMENT OF THE AUTOGIRO: A TECHNICAL PERSPECTIVE

J. Gordon Leishman[*]

Alfred Gessow Rotorcraft Center
Department of Aerospace Engineering
Glenn L. Martin Institute of Technology
University of Maryland
College Park, Maryland 20742

Abstract

The technical challenges and accomplishments in the development of the autogiro are described. Exactly eighty years ago, the autogiro was the first successful rotating-wing aircraft, and the first powered, heavier-than-air aircraft to fly other than an airplane. Unlike a helicopter, the rotor on an autogiro is not powered directly, but turns by the action of the relative airflow on the blades to produce a phenomenon known as autorotation. The aerodynamic principles of autorotation are explained, and are combined with the historic technical insights of Juan de la Cierva, who used the principle to successfully develop and produce the autogiro. It is shown that while the autogiro encountered many technical hurdles, its developers worked in a systematic, step-by-step approach to advance the state of knowledge. The autogiro did not have a long commercial or military life, but it was certainly a significant technical success. There were major scientific and engineering contributions from both practical and theoretical fronts. The most significant was the development of the articulated rotor hub with flapping and lead/lag hinges, and later the complete and precise control of the aircraft by tilting the rotor plane using cyclic blade feathering. The era also accomplished the first scientific understanding of rotor behavior, and the first mathematical theories of rotor aerodynamics, blade dynamics, structural dynamics and aeroelasticity. The success of the autogiro also paved the way for the helicopter, but pre-dating it by about 15-years, and providing fundamental technology that greatly accelerated its development.

Nomenclature

A	rotor disk area, πR^2
c	rotor blade chord
C_l	airfoil section lift coefficient
C_d	airfoil section drag coefficient
C_D	rotor drag coefficient
C_R	resultant rotor force coefficient
D	rotor drag force
I_b	blade inertia
L	rotor lift force
P	rotor shaft power
Q	rotor shaft torque
Q_h	rotor shaft torque in powered hovering flight
R	rotor radius
R	rotor resultant force
T	rotor thrust
V_c	climb velocity
V_d	descent velocity
v_h	reference (hovering) induced velocity
v_i	average induced velocity through the rotor
V_∞	free-stream velocity
W	weight of aircraft
x, y	Cartesian coordinate system
α	angle of attack
β	blade flapping angle
β_0	rotor coning angle
β_{1c}	rotor longitudinal flapping angle
β_{1s}	rotor lateral flapping angle
θ	blade section pitch angle
μ	advance ratio, $V_\infty/\Omega R$
ρ	air density
ϕ	induced inflow angle
ψ	azimuth angle
Ω	rotational velocity of rotor

Abbreviations

RAE	Royal Aircraft Establishment
NACA	National Advisory Committee for Aeronautics
RAeS	Royal Aeronautical Society
ARC	Aeronautical Research Council

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[*] Professor of Aerospace Engineering. E-mail contact: leishman@eng.umd.edu. Paper presented at the Hofstra University Conference *From Autogiro to Gyroplane – The Past, Present & Future of an Aviation History*, Hofstra University, NY, April 25 & 26, 2003. Copyright © 2003 by J. G. Leishman. All rights reserved.

Introduction

The autogiro often seems to be a half-forgotten machine that occupies a lower place in the history of aviation. Yet, the autogiro played such a fundamental role in the technological development of modern rotating-wing aircraft that its accomplishments must be properly recognized. An autogiro has a rotor that can freely turn on a vertical shaft. However, unlike a helicopter, the rotor on an autogiro is not powered directly. Instead, the rotor disk inclines backward at an angle of attack, and as the machine moves forward in level flight powered by a propeller, the resultant aerodynamic forces on the blades causes the necessary torque to spin the rotor and create lift. This phenomenon of “self-rotation” of the rotor is called *autorotation*. The autogiro was developed by Juan de la Cierva,[1,2] and in 1923 it was the very first type of rotating-wing aircraft to fly successfully and demonstrate a useful and practical role in aviation, pre-dating the first successful flights with helicopters by about 15-years. The autogiro was also the first powered, heavier-than-air aircraft to fly successfully other than a conventional airplane.

The principle of autorotation can be seen in nature in the flight of sycamore or maple seeds, which spin rapidly as they slowly descend, and are often carried on the wind for a considerable distance from the tree from whence they fall. The curious aerodynamic phenomenon of “autorotating bodies” had been observed in variety of experiments by the beginning of the 20th century, which probably date to earlier theoretical work by the Scottish physicist James Maxwell – see Tokaty.[3] The Italian, Gaetano Crocco, and also Boris Yur’ev (Your’yev) of Russia, examined the principle of autorotation on spinning rotors. In 1922, Max Munk of the NACA conducted experiments[4] with “helicopter propellers,” where the phenomenon of autorotation was again demonstrated. Yur’ev and his students probably made the most significant studies. They conducted experiments with model helicopter rotors, and showed that under some conditions of steeply descending and horizontal flight with the rotor at a positive angle of attack, a lifting rotor could be made to turn on its own accord. Yur’ev called this phenomenon “rotor gliding,” and he apparently realized that the ability of the rotor to self-rotate might even be used to bring a helicopter safely to the ground in the event of an engine failure. Today, of course, the ability to autorotate in an emergency condition such as power or transmission failure is a fundamental safety of flight capability designed into all helicopters.

At the beginning of the 20th century the development of the conventional airplane was well underway, and there had also been many attempts to build helicopters. In fact, toward the end of the 19th century there had been more attempts to build helicopters than fixed-wing aircraft (see Fig. 1, which is based on data contained in Ref. 5), although an unconscionable number of “tower jumpers” were still active even then. The first helicopters after 1903 included the Breguet-Richet[6,7] and Cornu[6,8] machines, and the Denny-Mumford machine,[6,9,10] all built around 1907. Yet, other than making short hops off the ground, none of these machines were successful in demonstrating sustained, fully controlled vertical flight. Many problems plagued the early attempts at powered vertical flight. These included the relatively poor understanding of rotating-wing aeromechanics to allow for efficient rotors, the lack of suitable engines, counteracting torque reaction from the shaft driven rotor(s), and also in providing the machine with enough stability and control.

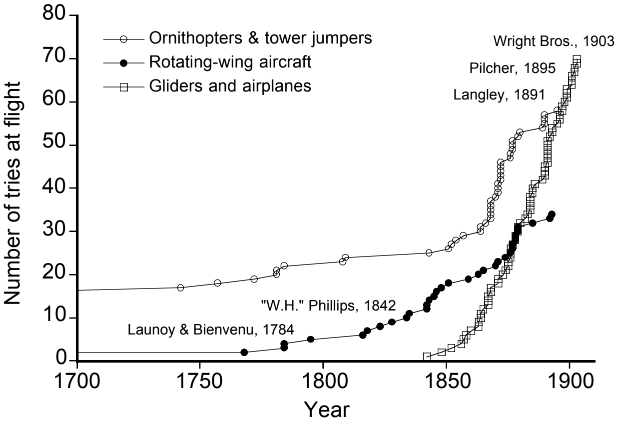


Figure 1: By the end of the 19th century more attempts had been made to build rotating-wing aircraft than fixed-wing aircraft.

The power required to sustain hovering flight was an unknown quantity to the earliest experimenters with rotating-wings, who were guided more by intuition than by science. More often, too much rather than too little power was installed to provide lift, making the machines unnecessarily heavy. The first application of aerodynamic theory to predict the power requirements of rotating-wings was not to happen until the early 1920s, inspired mostly by the rapid and sustained success of the early autogiros. This was despite the fact that the momentum theory describing the performance of lifting “propellers” had been published by William Rankine,[11] W. Froude,[12] and R. E. Froude,[13] in the late 19th century. The powerplant issue was not to be overcome fully until gasoline engines with higher power-to-weight ratios were developed in the 1920s.

The ability to provide an anti-torque device to counter the reaction of the torque driven rotor shaft was also a major hindrance in the development of the helicopter. The relatively simple idea of a tail rotor was not used, early designs being built with either coaxial or laterally side-by-side rotor configurations. The mechanical problems of building and powering multi-rotor helicopters proved too much, and the resulting vibrations were a source of many failures of the rotor and airframe. Providing stability and properly controlling helicopters was also a major obstacle to successful flight, including a means of defeating the unequal lift produced on the advancing and retreating sides of the rotor in forward flight. It was to be the development of the autogiro that was to provide the key for solving this latter problem.

The Idea of the Autogiro

Despite the numerous types of helicopters that were proposed and actually built in the period 1900–1920, nobody had previously considered the idea that a successful rotating-wing aircraft could be built such that the rotor was unpowered and always operated in the autorotative state during normal flight. In the spring of 1920, Juan de la Cierva of Spain built a small, free-flying model of a rotating wing aircraft, with the rotor free to spin on its vertical shaft. The model had a rotor with five wide-chord blades, with a horizontal and vertical tail to give it stability – see Fig. 2. Cierva launched the model from atop his home in Murcia, where the rotor spun freely of its own accord and the model slowly glided softly to the ground. He had rediscovered the principle of autorotation, which he was to call "autogiration." These first experiments with models were to pave the way for the design of a completely new aircraft that Juan de la Cierva was to call an "Autogiro."

Juan de la Cierva was a civil engineer by training, graduating with the title *Ingenero de Caminos Canales y Puertos* in 1918. He had become interested in aviation as early as 1908 when the Wright Brothers demonstrated their "Flyer" machine in Europe. Cierva was to subsequently build the first Spanish airplane in 1912. His C-3 airplane of 1919 was a large three-engined bomber. While the aircraft flew well, the test pilot became over ambitious, and the machine stalled and crashed during a demonstration flight. This tragedy motivated Cierva to think of a way of improving the flight safety of an aircraft when it operated at low airspeeds and, in particular, when it was flying close to the ground.

Cierva set out to design a safe flying machine that ensured "stability, uplift and control should remain independent from forward speed" and suggested further that it should be one that could be flown by a pilot with average skill.[1] Cierva goes on to point out that "the wings of such an aircraft should be moving in relation to the fuselage. The only mechanism able to satisfy this requirement is a circular motion [a rotor] and, moreover, in order to give adequate security to the aforementioned requirement it must be independent of the engine. It was thus necessary that these rotary wings were free-spinning and unpowered."

Thus was born the first ideas of an *autogiro*, a completely new aircraft with a unpowered rotor. The rotor provides the lift (or most of it), with forward propulsion being provided by a conventional tractor or pusher propeller arrangement – see Fig. 3. This is compared to the helicopter, where the rotor provides both lift and propulsion. The name "Autogiro" was later to be coined by Juan de la Cierva as a proprietary name for his machines, but when spelled starting with a small "a" it is normally used as a generic name for this class of aircraft. Today, "gyroplane" is the official term used to describe such an aircraft, although the names "autogiro," "autogyro," and "gyroplane" are often used synonymously.

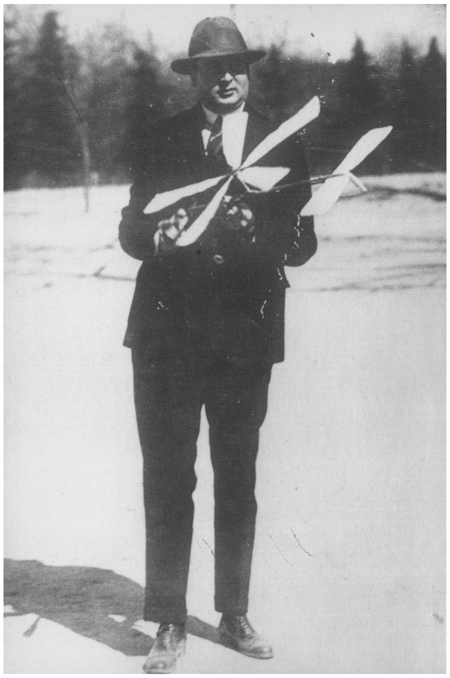
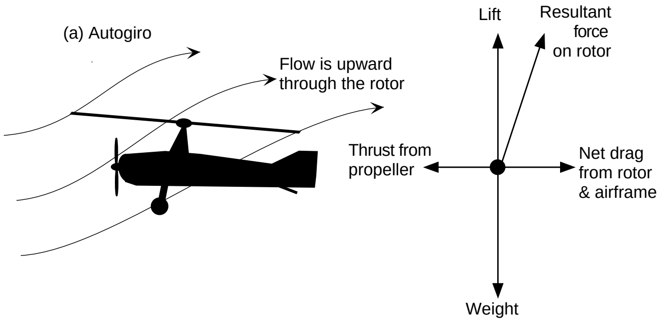


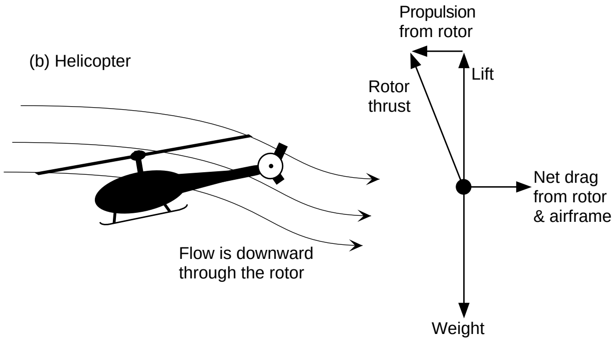
Figure 2: Photograph of Juan de la Cierva with his model autogiro, taken about 1920.

Unlike the helicopter, the autogiro rotor always operates in the autorotative working state, where the power to turn the rotor comes from a relative flow directed upward through the rotor disk. The low disk loading (T/A) of an autogiro rotor (and, therefore, its low induced velocity) means that only a small upward flow normal to the tip-path-plane is necessary to produce autorotation. Therefore, in straight-and-level forward flight, the rotor disk need operate only with a slight positive angle of attack (backward tilt). As long as the machine keeps moving forward though the air, the rotor will continue to turn and produce lift. Reducing engine power will cause the machine to slowly descend, and increasing power will cause it to climb. The loss of the engine is never a problem on an autogiro because the rotor is always in the autorotative state, and so the machine will descend safely.

The autogiro is mechanically simpler than a shaft driven helicopter because the engine gearbox and rotor transmis-



(a) Autogiro



(b) Helicopter

Figure 3: The autogiro rotor (a) provides lift, with forward propulsion being provided by a conventional propeller, compared to the helicopter (b) where the rotor provides both lift and propulsion.

sion can be dispensed with. Furthermore, it is not necessary to develop a separate means of countering torque reaction, as on the helicopter. This all significantly reduces weight, and also reduces design, production, and capital costs. While the autogiro is not a direct-lift machine and cannot not hover (nor was it designed to be), it requires only minimal forward airspeed to maintain flight. Through a series of over thirty designs that spanned more than ten years of development, Juan de la Cierva proved that his Autogiros were very safe and essentially "stall-proof," and because of their low speed, they could be landed in confined areas. Take-offs required a short runway to build-up airspeed, but this was rectified later with the advent of the "jump" take-off technique. This gave the autogiro a capability that was to rival the future helicopter in terms of overall performance.

Basic Physics of Autorotation

As previously mentioned, Juan de la Cierva was not the first to observe the phenomenon of autorotation, but he was certainly the first to better understand the aerodynamic principles and to put the phenomenon toward serving a useful purpose. He was to make some of the first theoretical studies on rotors, and conducted a series of wind tunnel tests[1] "with valuable results, among them the determination of the fact that the rotor would continue to turn at every possible angle of flight – a point that was somewhat disputed by critics of my earlier experiments."

Autorotation can be defined as a self-sustained rotation of the rotor without the application of any shaft torque, i.e., the net shaft torque, $Q = 0$. Under these conditions, the energy to drive the rotor comes from the relative airstream, which is directed upward through the rotor. To see why, the problem can first be approached from an integral method applied to a powered rotor in vertical descent.[14,15] The use of the integral method affords considerable mathematical simplification, but means only the properties of the flow into and out of the rotor are considered, and the theory does not give any information about what is actually happening at the blades.

From this rotor theory applied to a vertical climb or descent, the torque ratio (the shaft torque required to produce a given thrust, Q, relative to the power required for a shaft driven rotor to hover, Q_h) is

$$\frac{Q}{Q_h} = \frac{V_c}{v_h} + \frac{v_i}{v_h}, \tag{1}$$

where V_c is the climb velocity, v_i is the induced velocity through the rotor, and v_h is the induced velocity in shaft powered hovering flight (used as a reference). The two terms on the right-hand-side of the prior equation represent the torque required to change the potential energy of the rotor and the aerodynamic (induced) losses, respectively. The solution for v_i/v_h depends on the rotor operating state. For a climb, the solution is

$$\frac{v_i}{v_h} = -\left(\frac{V_c}{2v_h}\right) + \sqrt{\left(\frac{V_c}{2v_h}\right)^2 + 1}, \tag{2}$$

and for descending flight

$$\frac{v_i}{v_h} = -\left(\frac{V_c}{2v_h}\right) - \sqrt{\left(\frac{V_c}{2v_h}\right)^2 - 1}, \tag{3}$$

the latter equation being valid only for $V_c/v_h \leq -2$. The results for Q/Q_h are shown in Fig. 4 in the form of a non-dimensional curve. Notice that there is no exact theory to describe the flow in the region $-2 \leq V_c/v_h \leq 0$ (which includes the autorotative state), and the nature of the curve is obtained empirically.

It is significant that the results in Fig. 4 show that in a descent, at least when established above a certain rate, the rotor is driven by the air. Notice also that there is a value of V_c/v_h for which no net torque is required at the rotor, i.e., when the curve crosses the autorotational line $V_c + v_i = 0$ so that $P = Q\Omega = T(V_c + v_i) = 0$ or $Q/Q_h = 0$. This condition is usually called *ideal autorotation*, although because

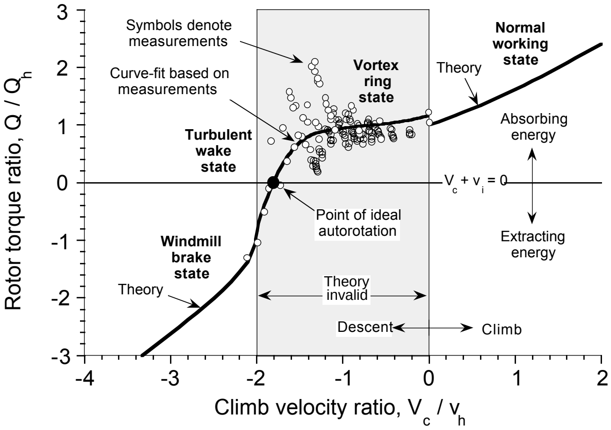


Figure 4: Universal power curve for a rotor in vertical climb and descent.

the nature of the curve is empirical, it includes *non-ideal losses*. It will be apparent that this condition occurs when the rotor is descending vertically at $V_c/v_h \approxeq -1.75$. In practice, a *real autorotation* in vertical flight occurs at a slightly higher rate than this because, in addition to induced losses at the rotor, there are also profile losses to overcome. Therefore, in an actual autorotational condition

$$Q = \frac{T}{\Omega}(V_c + v_i) + Q_0 = 0. \tag{4}$$

It will be apparent then that when in a stable "gliding" autorotation with a constant airspeed and constant rotor rpm, there is an energy balance[*] where the decrease in potential energy of the rotor TV_c just balances the sum of the induced *and* the profile losses of the rotor. Using Eq. 4, this condition is achieved when

$$\frac{V_c}{v_h} = -\frac{v_i}{v_h} - \frac{Q_0\Omega}{Tv_h}. \tag{5}$$

The second term on the right-hand side of the latter equation will vary in magnitude from between 0.04 to 0.09, depending on the rotor efficiency, i.e., the profile drag of the rotor. The profile drag depends on the rotor solidity and the drag of the airfoil sections used on the blades.[14,15] Compared to the first term, however, which is all induced in nature and is defined by the curve in Fig. 4, the extra rate-of-descent required to overcome profile losses is relatively small. Therefore, on the basis of the foregoing, it is apparent that a real vertical autorotation of the rotor will occur for values of V_c/v_h between -1.8 and -1.85. For the larger value, this is equivalent to the rate-of-descent

$$V_d \approxeq 1.85\sqrt{\frac{T}{2\rho A}} = 26.83\sqrt{\frac{T}{A}} \tag{6}$$

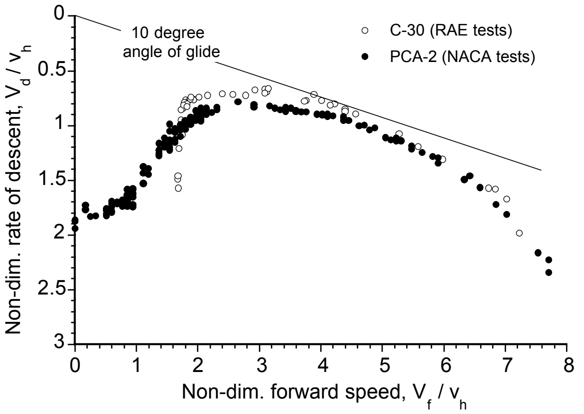


Figure 5: Non-dimensional rate-of-descent in autorotational "gliding" flight versus non-dimensional forward speed.

at sea-level. This latter equation shows that the autorotational descent rate is proportional to the square root of the rotor disk loading, $T/A(= W/A)$. Cierva's early autogiros all had a disk loading of about 2 lb/ft^2 (95.76 N/m^2) (which is also typical of modern autogiro designs), so this would give a *vertical* autorotative rate-of-descent at sea-level of only about 38 ft/s (11.58 m/s).

Measurements documenting the performance of autogiros are rare, but detailed in-flight measurements were conducted by the RAE using a Cierva C-30,[17] and by NACA using a Pitcairn PCA-2.[18] The autorotational rate-of-descent, V_d, for both machines is plotted in Fig. 5 as a function of forward speed, V_f, both parameters being non-dimensionalized by the average induced velocity in shaft powered hovering flight, $v_h(= \sqrt{T/2\rho A})$, which removes the effects of disk loading from the results. It is apparent that the measured vertical rate-of-descent occurs about $V_d/v_h = 1.9$, which is in good agreement with the result given previously. As also previously mentioned, there is no *exact* theory describing the rotor aerodynamics in an autorotation, even with forward speed, but the measurements clearly show a rapid decrease in the autorotational rate-of-descent as forward speed builds. A minimum rate-of-descent is reached at about $V_f/v_h = 2$ (which corresponds to about 35 to 40 kts), and the rate-of-descent slowly increases again thereafter. There is good agreement between the independent measurements for the C-30 and PCA-2 autogiros, as there should be because the machines used essentially identical rotors.

Also of interest, is the autorotational rate-of-descent versus the rotor disk angle of attack. While the forgoing measurements were performed in "gliding" flight, autorotation is also possible in level flight with propulsion to drive the autogiro forward. All that is required is that the rotor disk be held at a sufficient angle of attack such that the component of the relative wind upwards through the disk causes the rotor to autorotate. In the words of Juan de

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[*] The ideas of an energy balance in autorotation were first explored by Cierva[16]

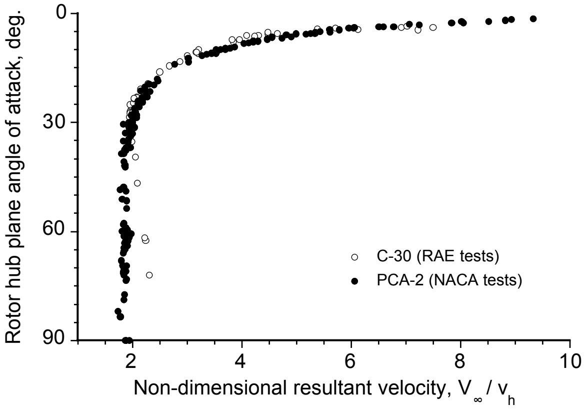


Figure 6: Rotor hub angle of attack versus resultant non-dimensional speed showing that the disk must only be held at a small angle of attack to produce lift and autorotate at higher airspeeds.

la Cierva[1] "It makes no difference at what angle the Autogiro is climbing or flying. The blades are always gliding toward a point a little below the focus of forward flight. Its is impossible, therefore, for autorotation to stop while the machine is going anywhere."

The results in Fig. 6 show the measured hub plane angle of attack as a function of the resultant non-dimensional velocity of the aircraft. In a pure vertical descent it is apparent that the tip-path-plane and hub plane angles of attack are both 90° (the resultant wind is perpendicular to the disk). As forward speed builds, the hub plane needs to make a progressively smaller angle to the relative wind to enable autorotation, until at higher speeds the rotor must be held only at a shallow angle to produce enough lift in the autorotational state. The rotor tip-path-plane angle is also inclined back, but is not equal to the hub plane angle of attack because of blade flapping (see Fig. 7 and also later discussion). The natural tendency to produce longitudinal flapping (β_{1c}) with forward speed increases the component of velocity upward through the disk, which means the hub plane angle is always small in forward flight. The tip-path-plane has a positive angle of attack much like a wing under these conditions, and as Glauert was to show,[19,20] the rotor acts very much like a fixed-wing of circular planform under these conditions.

Detailed Aerodynamics of Autorotation

Cierva was to juggle with the parameters affecting the magnitude and direction of the aerodynamic forces acting on the rotating blades, and concluded that there could be number of combinations of rotor operating conditions where the net torque on the rotor shaft could be zero. Consider the flow environment encountered at a blade element on the rotor during autorotation, as shown in Fig. 8. For autorotational equilibrium at that section the inflow angle, ϕ, must be such that there is no net in-plane force and, therefore, no contribution to rotor torque, i.e., for force equilibrium

$$dQ = (D - \phi L) y dy = 0, \tag{7}$$

or simply

$$(D - \phi L) = 0 = C_d - \phi C_l. \tag{8}$$

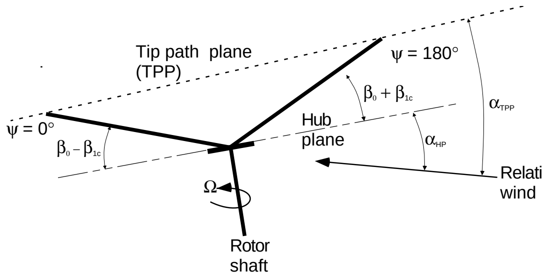


Figure 7: Definition of the rotor hub plane and rotor tip-path-plane angles of attack.

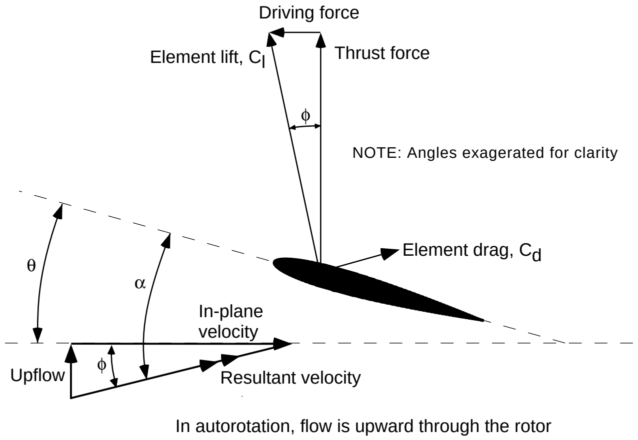


Figure 8: Detail of the flow at the blade element in autorotational flight.

However, this is an equilibrium condition that cannot exist over all parts of the blade, and only *one* radial station on the blade can actually be in autorotational equilibrium. In general, some portions on the rotor will absorb power from the relative airstream and some portions will consume power, such that the *net* torque at the rotor shaft is zero, i.e., $\int dQ = 0$. With the assumption of uniform inflow over the disk, the induced angle of attack at a blade element is given by

$$\phi = \frac{\text{Upflow velocity}}{\text{In-plane velocity}} = \tan^{-1}\left(\frac{|V_c + v_i|}{\Omega y}\right). \tag{9}$$

It follows that for autorotational equilibrium the induced angles of attack over the inboard stations of the blade are

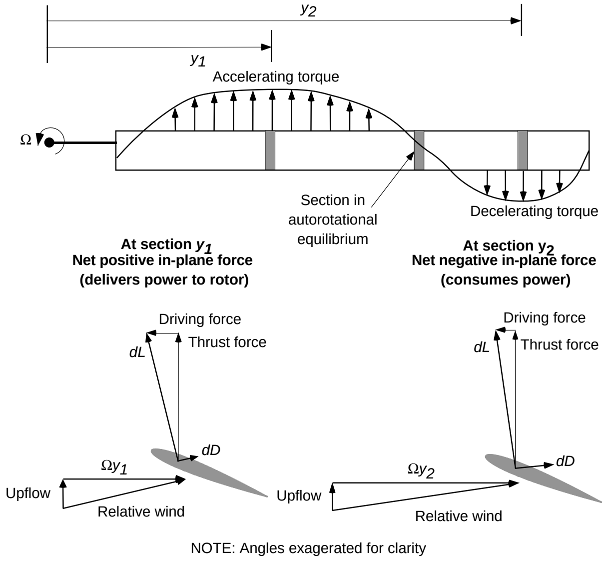


Figure 9: The various forces acting on the blades in autorotational flight form a balance such that the net torque on the rotor shaft is zero.

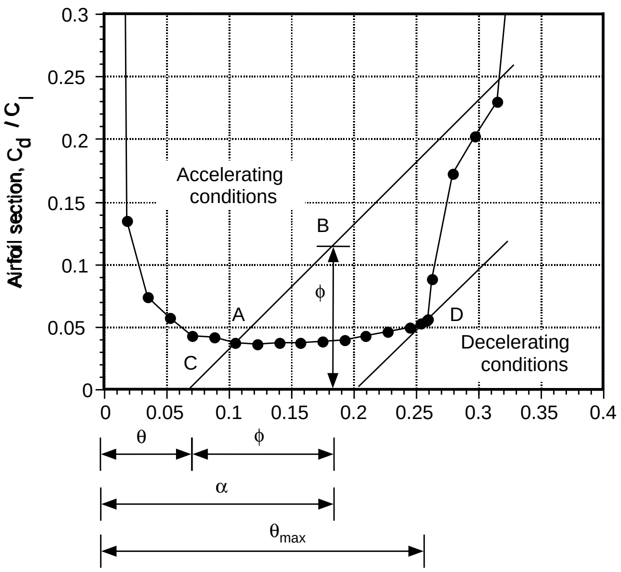


Figure 10: Autorotational diagram in the form first suggested by Wimperis.

relatively high, and near the tip the values of ϕ are relatively low – see Fig. 9. One finds that at the inboard part of the blade the net angle of attack results in a forward inclination of the sectional lift vector, providing a propulsive component greater than the profile drag and creating an accelerating torque. This blade element can be said to *absorb* energy from the relative airstream. Toward the tip of the blade where ϕ is lower, these sections of the blades *consume* energy because the propulsive component as a result of the forward inclination of the lift vector is insufficient to overcome the profile drag there, i.e., a decelerating torque is produced.

In the fully established autorotational state, the rotor rpm will adjust itself until a zero torque equilibrium is obtained. This is a *stable* equilibrium point because it can be deduced from Fig. 9 that if Ω increases, ϕ will decrease and the region of accelerating torque will decrease inboard, and this tends to decrease rotor rpm again. Conversely, if the rotor rpm decreases, then ϕ will increase and the region of accelerating torque will grow outward. Therefore, when fully established in the autorotative state, the rotor naturally seeks to find its own equilibrium rpm to any changing flight conditions. This is an inherent characteristic of the rotor that gives the autogiro very safe flight characteristics.

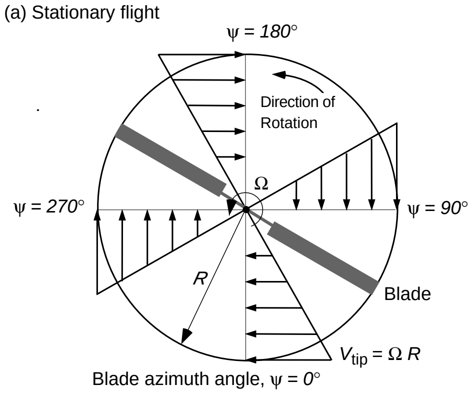
However, in the autorotational state the blade pitch must always be at a low value and the disk angle of attack must be positive to ensure that the inboard blade sections never reach high enough angles of attack to stall. If stall does occur,[†] then the outward propagation of stall from the blade root region will tend to quickly further decrease rotor rpm because of the associated high profile drag.

The phenomenon of autorotation is often explained at a technical level using an *autorotational diagram*. This is shown in Fig. 10, where the blade section C_d/C_l is plotted versus angle of attack at the blade section. This is a form originally used by Wimperis.[21] Both Nikolsky[22] and Gessow & Myers[23] describe rotor equilibrium at the blade element in terms of this interpretation. For a single section in equilibrium

$$C_d - \phi C_l = 0 \quad \text{or} \quad \frac{C_d}{C_l} = \phi = \alpha - \theta, \qquad (10)$$

where θ is the blade pitch angle and α is the aerodynamic angle of attack. For a given value of blade pitch angle, θ, and inflow angle ϕ the previous equation represents a series of points that form a straight line, which is plotted on Fig. 10. The intersection of this line with the measured C_d/C_l data for the airfoil sections comprising the rotor blades at point A corresponds to the equilibrium condition where $\phi = C_d/C_l$. Above this point, say at point B, $\phi > C_d/C_l$, so this represents an accelerating torque condition. Point C is where $\phi < C_d/C_l$ so this represents a decelerating torque condition. Note that above a certain pitch angle, say θ_{max}, equilibrium conditions is not possible, so for point D, stall will occur causing the rotor rpm to quickly decay, an issue alluded to previously.

[†] Stall may occur if the rotor rpm decays below an acceptable threshold, such as when the disk angle of attack becomes negative, or a negative load factor is produced. These are flight conditions to be avoided.


(a) Stationary flight

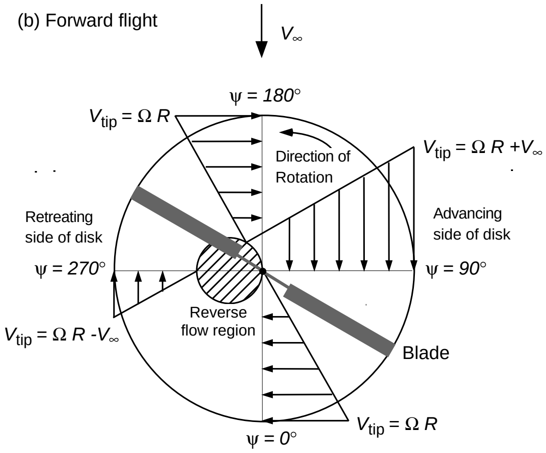

(b) Forward flight

Figure 11: An unequal lift on the rotor is produced in forward flight because of the dissymmetry in the aerodynamic environment between the advancing and retreating side of the rotor.

The Asymmetric Lift Dilemma

When a rotor operates in forward flight with the rotor passing edgewise through the air, the rotor blades encounter an asymmetric velocity field – see Fig. 11. The blade position can be defined in terms of an azimuth angle, ψ, which is defined as zero when the blade is pointing downstream. The local dynamic pressure and the blade airloads now vary in magnitude with respect to blade azimuth, and they become periodic (primarily) at the rotational speed of the rotor, i.e., once per revolution or 1/rev. It will be apparent that the aerodynamic forces must reach a maximum on the blade that advances into the relative wind (i.e., at $\psi = 90^\circ$), and will be minimum on the blade that retreats away from the relative wind (i.e., at $\psi = 270^\circ$). For blades that are rigidly attached to the shaft, the net effect of these asymmetric aerodynamic forces is an upsetting moment on the rotor. This was Cierva's first dilemma in developing the autogiro.

It will be evident that the distribution of lift and induced inflow through the rotor will affect the inflow angles, ϕ, and angles of attack at blade sections and, therefore, the detailed distribution of aerodynamic lift and drag forces over the rotor. This subsequently affects the blade flapping response, and so the aerodynamic loads. This coupled behavior is a complication with a rotating-wing that makes its thorough analysis relatively difficult.[14,15] Notice also from Fig. 11 that at higher forward speeds,[‡] a region of reverse flow (and stall) will form at the root of the retreating blade, increasing rotor profile drag and reducing aircraft performance.

Cierva's first Autogiro, the C-1, was built in 1920 and had a co-axial rotor design. He was to build two more machines, both with single rotors, before he achieved final success with the C-4 in January 1923. The problem of asymmetric lift between the advancing and retreating blades was well-known to Cierva. His first idea of using a counter-rotating co-axial design, was that the lower rotor would counteract the asymmetry of lift produced on the upper rotor, thereby balancing out any moments on the aircraft. However, when flight tests began, it was found that the aerodynamic interference between the rotors resulted in different autorotational rotor speeds. This spoiled the required aerodynamic moment balance, and the C-1 capsized before becoming airborne. Cierva considered the possibility of mechanically coupling the rotors to circumvent the problem, but this was quickly rejected because of the obvious mechanical complexity and significant weight penalty. Despite its failure to fly, however, the C-1 proved that the rotors would freely autorotate when the machine was taxied with sufficient forward speed.

The next Cierva design was the *compensating rotor*, which was tested in three-bladed form on the C-3 in 1921, and in five-bladed form on the C-2 in 1922 (the C-2 actually followed the C-3). This idea used blade twisting in an attempt to compensate for the undesirable characteristic of asymmetric lift, i.e., by using nose-down twist on the advancing blade and nose-up twist on the retreating blade. Photographs of these two machines[2] show a series of cables attached to the trailing-edges of the blades, with the idea that the blade twist could be changed in a cyclic sense as the blades rotated about the shaft. However, while the basic principle was correct, the concept proved impractical, and both the C-2 and C-3 were only to achieve short hops off the ground. Perhaps the use of cyclic blade feathering (as opposed to blade twisting) might have been more successful, but it was not to be until 1931 that E. Burke Wilford in the USA demonstrated this concept on an autogiro.[24,25] The NACA was also to study this type of rotor in the wind-tunnel.[26]

[‡] To be precise, at higher advance ratios, $\mu = V_\infty / \Omega R$.

Development of the Flapping Hinge

Based on his many experiments with small models, Cierva noticed that the flexibility of the rattan spars on his models provided different aerodynamic effects compared to the relatively rigid blade structure used on his full-scale machines. This was the key Cierva needed, and his "secret of success."[1] His fourth machine (the C-4), therefore, incorporated blades with mechanical hinges (horizontal pins) at the root, which allowed the blades to freely flap up and down in response to the changing asymmetric aerodynamic lift forces during each rotor revolution – see schematic in Fig. 12. Also acting on the blades are centrifugal and gravitational forces, and as a result of free flapping there are inertia and Coriolis forces to contend with, all of which act through the center of gravity of the blade. The blades on the C-4 were retrained by cables attached to the shaft to limit both lower and upper flapping angles, and also so the blades would not droop to the ground when the rotor was stopped.

The principle of flapping blades had actually first been suggested for the application to propellers,[27] apparently by Charles Renard, but the idea of hinged blades was formally patented by Louis Breguet in 1908 and then by Max Bartha & Josef Madzer[28] in 1913 – see also Liberatore.[29] Juan de la Cierva,[§] however, must be credited with the first successful practical application of the flapping hinge to a rotor. Cierva noticed that the incorporation of the flapping hinge eliminated any adverse gyroscopic effects and also allowed the lift forces on the two sides of the rotor to become more equalized in forward flight. However, Cierva's initial avoidance of using a lead-lag hinge to alleviate the in-plane blade Coriolis forces (resulting from the flapping motion) and in-plane blade motion was an oversight that he was ultimately to come to terms with (see later).

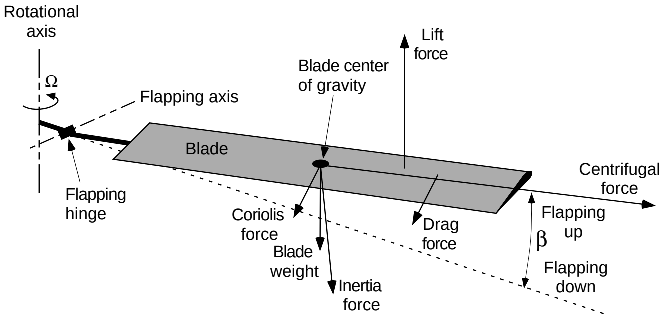


Figure 12: The principle of the flapping hinge allowed the blades to freely flap up and down in response to the changing asymmetric aerodynamic loads on the blades.

Figure 13: The Cierva C-4 Autogiro first flew successfully on January 9, 1923. It was the first rotating-wing aircraft to fly, and also the first type of heavier-than-air aircraft to fly successfully other than a conventional airplane.

In Cierva's C-4 Autogiro of 1923, a single rotor with four independent, freely flapping blades was mounted on a long shaft above an Avro airplane fuselage. The blades were of high aspect ratio, similar to those of modern helicopter blades, and used a relatively efficient Göttingen 429 airfoil shape. A propeller, powered by a Le Rhone gasoline engine, provided propulsion. The first model of the C-4 used a lateral tilting of the entire rotor disk[2] to provide roll control, and without the use of any auxiliary "fixed" wings, which were later to be characteristic of most of his Autogiros. However, taxiing tests showed that the control forces involved in tilting the rotor were too high for the pilot, and the control response also proved very ineffective. The machine was subsequently fitted with a non-tilting rotor and a set of ailerons mounted on a stub spar projecting from the sides of the fuselage. Pitch and directional (yaw) control on the C-4 was then achieved by conventional airplane surfaces, with an elevator and a rudder used at the tail.

The C-4 Autogiro first flew successfully on January 9, 1923, and made its first official flight demonstrations at the Getafe Aerodrome in Madrid on January 21, 1923. On January 31, 1923 at the Quatro Vientos Aerodrome, the C-4 was flown around a 4 km closed circuit, and this was to be the first time any flying machine other than a conventional airplane had accomplished this feat.[30] It is significant to note that it took Cierva just over a year between conceiving the idea of the flapping hinge and using it to successfully fly the first autogiro.

Physics of Blade Flapping

The technical details of the rotor response must now be considered further. Without forward motion, the flow field at the rotor is azimuthally axisymmetric, and so each blade encounters the same aerodynamic environment. The rotating blades then will simply flap and "cone" up to form a

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[§] It does not seem that Cierva was aware of any of the earlier ideas of flapping blades.

static equilibrium between the aerodynamic lift forces and the centrifugal forces – see Fig. 12. The rotor disk plane (the tip-path-plane) then takes on a natural orientation in inertial space. Even with lightweight blades, centrifugal forces are dominant over the aerodynamic and gravitational forces, so the coning angles of the blades, β_0, always remain relatively small (just a few degrees).

Because the centrifugal loads remain constant for a given rotor speed (rpm), the blade coning angle varies with both the magnitude and distribution of lift across the blade. For example, a higher aircraft weight requires a higher blade lift, which tends to increase the aerodynamic moment about the hinge resulting in a higher coning angle. Varying the rate-of-descent also changes the coning angle; with higher rates of descent (or higher disk angles of attack) the coning angle is reduced because of the redistribution of lift on the blades. In addition to flapping, the aerodynamic drag forces on the blades cause them to lag back. However, the drag forces are only a fraction of the lift forces, and if the rotor is only lightly loaded, they are almost completely overpowered by centrifugal forces.

With the rotor set into forward motion, and the rotor disk now moving edgewise through the air, the asymmetry of the onset flow and dynamic pressure over the disk produces aerodynamic forces on the blades that are a function of blade azimuth position, i.e., cyclically varying airloads on the spinning blades are now produced – see Fig. 11. The use of a flapping hinge allows each blade to independently flap up and down in a periodic manner with respect to azimuth angle under the action of these varying aerodynamic loads. The blades reach an equilibrium condition when the local changes in angle of attack and the aerodynamic loads produced as a result of blade flapping are sufficient to compensate for local changes in the airloads resulting from cyclic variations in the dynamic pressure. In the words of Cierva,[1] the blades were “free to move in a sort of flapping motion wherever they liked according to the effects of the air upon them.” The rotor disk, therefore, begins to tilt with respect to the shaft, and takes up a new orientation in inertial space.

The amount of the rotor tilt can be predicted by using the equation of motion for a freely flapping blade spinning about a vertical shaft. The hinge is placed at the shaft axis for mathematical simplicity. By considering the distribution of the elemental forces acting on the blade (see Fig. 14), the flapping equation can be written as

$$I_b \Omega^2 \frac{\partial^2 \beta}{\partial \psi^2} + I_b \Omega^2 \beta = \int_0^R L y \, dy, \tag{11}$$

or in short-hand notation

$$\overset{**}{\beta} + \beta = \frac{1}{I_b \Omega^2} \int_0^R L y \, dy. \tag{12}$$

The right-hand side of Eq. 12 under the integral sign is just the moment abut the hinge produced by the aerodynamic lift forces. It is also apparent that Eq. 12 mimics equation of motion of a simple single degree-of-freedom system, for which undamped natural frequency of the flapping blade about the rotational axis is Ω rad/sec or once-per-revolution (1/rev).

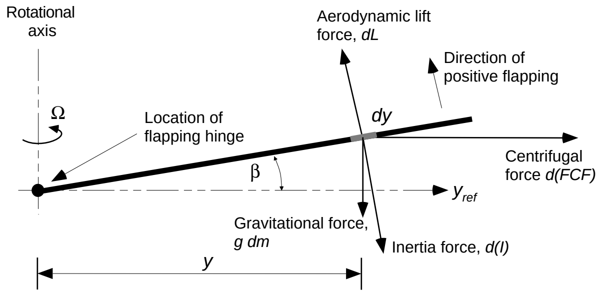

Figure 14: Forces acting on an element of a freely flapping blade.

Consider first the case where the rotor operates in a vacuum, so there are no aerodynamic forces present. The flapping equation reduces to

$$\overset{**}{\beta} + \beta = 0, \tag{13}$$

and this equation has the general solution

$$\beta(\psi) = \beta_0 + \beta_{1c} \cos\psi + \beta_{1s} \sin\psi, \tag{14}$$

where β_{1c} and β_{1s} are arbitrary coefficients. Thus, in the absence of aerodynamic forces, the rotor takes up an arbitrary orientation in space, somewhat like a gyroscope.

In forward flight, the aerodynamic forces now provide the excitation to the flapping blade (primarily at 1/rev) and constitute a periodic forcing to the right-hand side of Eq. 12. The introduction of new aerodynamic forces produces an aerodynamic flapping moment about the hinge, which causes the rotor blades to precess to a new orientation in space. It is significant to note that the flapping response must lag the blade pitch (aerodynamic) inputs by 90°, which is always the behavior of a single degree-of-freedom system excited at its natural frequency.[¶]

The upward and downward flapping of the blade tends to reduce and increase the angle of attack at the blade elements, respectively. For example, as a result of the flapping upward, the blade lift tends to decrease relative to the lift that would have been produced if there was no flapping hinge – see Fig. 15. As a result of the higher dynamic pressure on the advancing side of the rotor disk, the blade lift is increased over that obtained at $\psi = 0^\circ$ and $\psi = 180^\circ$. Therefore, as the blade rotates into the advancing side of the disk, the excess lift causes the blade to flap upward.

[¶] Strictly speaking this is for a rotor with a flapping hinge at the rotational axis, but even with a hinge offset, the essential physics of the blade flapping response are the same.

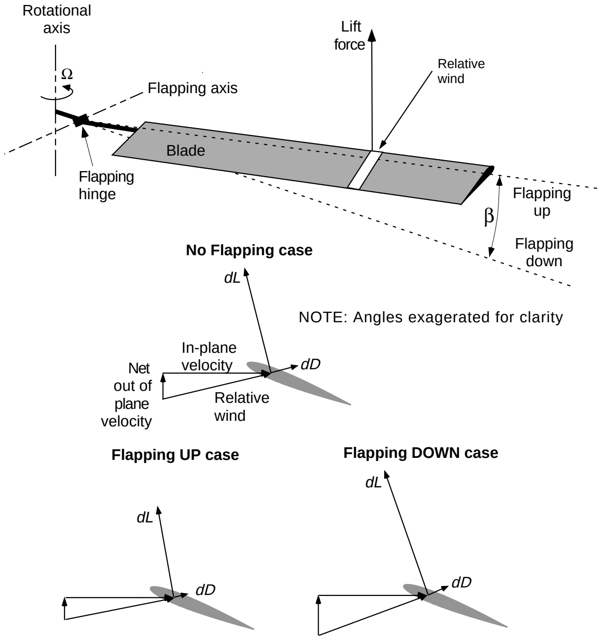

Figure 15: The effect of flapping serves to reduce or increase the lift on the blade.

Over the front of the disk, the dynamic pressure reduces progressively, and the blade reaches a maximum displacement at $\psi = 180^\circ$. As the blade rotates into the retreating side of the rotor disk, the deficiency in dynamic pressure now causes the blade to flap downward. This downward flapping motion increases the angle of attack at the blade element, which tends to increase blade lift over the lift that would have been obtained without flapping motion – see Fig. 15 again. Therefore, the main effect of the dissymmetry in lift over the rotor is to cause the rotor disk to tilt back, giving it a natural angle of attack – see Fig. 7 shown previously.

In addition, the rotor disk also has a tendency to tilt laterally slightly to the right.[‖] This effect arises because of blade flapping displacement (coning). For the coned rotor, the blade angle of attack is decreased when the blade is at $\psi = 0^\circ$ and increased when $\psi = 180^\circ$. Again, another source of periodic forcing is produced, but now this is phased 90° out of phase compared to the effect discussed previously. Because of the 90° force/displacement lag of the blade flapping response, this results in a lateral tilt of the rotor disk. Therefore, as the rotor moves into forward flight, the disk will begin to be tilted back longitudinally with respect to the hub, i.e., a $-\beta_{1c}$ blade flapping motion, with a small lateral tilt to the right when viewed from behind, i.e., a $-\beta_{1s}$ blade flapping motion.

The upshot of all this flapping motion is that the rotor blades again reach an equilibrium condition when the local changes in angle of attack and aerodynamic loads as a result of blade flapping become sufficient to compensate for local changes in the airloads resulting from variations in dynamic pressure over the disk. The natural tilting of the rotor tip-path-plane tilts the rotor lift vector and produces forces and moments on the autogiro, which must be compensated for to maintain trimmed flight and proper control. On a helicopter, this is done by using cyclic pitch inputs to the blades, which alters both the magnitude and phasing of the 1/rev aerodynamic lift forces over the disk, and so can be used to maintain a desirable orientation of the rotor disk to meet propulsion and control requirements. On Cierva's first machines, the rotor disk was uncontrolled and conventional "fixed-wing" aerodynamic control surfaces (ailerons, elevator and rudder) were used to provide the necessary forces and moments on the aircraft to compensate for the effects produced by rotor tilting. While not an ideal solution to satisfy force and moment equilibrium in forward flight, Cierva was satisfied with the simplicity of his interim solution to the problem. Later autogiro designs incorporated the ability to tilt the rotor disk, either by tilting the rotor shaft directly, or with the use of a "spider" mechanism or a swashplate (see later).

Coriolis Forces and the Drag Hinge

On the first lightly loaded Cierva rotor designs, the in-plane forces were balanced by sets of wires connected between the blades, such that as one blade lagged back or forward, the motion was easily resisted by the other blades. However, by Cierva's own admission,[1] the flight of his early Autogiros were "rather rough in flight owing to a sort of whipping action of the rotor blades which jerked at the mast as they turned in their circle." Cierva was noticing Coriolis effects, which produce forces in the plane of rotation of the rotor. These forces are larger than any drag forces, and appear whenever there is a radial lengthening or shortening of the radius of gyration of the blade about the rotational axis (which can be a result of blade flapping and/or elastic bending.) In other words, Coriolis terms are a result of conservation of angular momentum, and introduce an important dynamic coupling between blade flapping or out-of-plane motion and the lead/lag or in-plane motion of rotor blades. With later bigger and heavier machines, the combination of higher drag forces and higher Coriolis acceleration forces set up relatively high in-plane cyclic stresses at the blade roots.

Flight tests with Cierva's bigger C-6 showed evidence of structural in-plane bending overloads and the onset of fatigue damage, the latter phenomenon being poorly understood in the 1930s. Yet, Cierva initially resisted the use of a second hinge to relieve these Coriolis loads. Eventually, on a version of the C-6 Autogiro that was being flight

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[‖] For a rotor turning in a counter-clockwise direction.

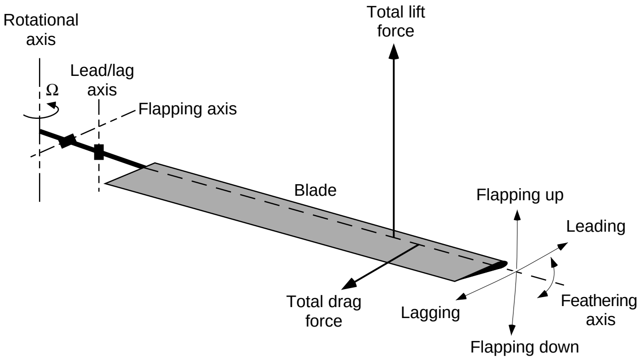

Figure 16: The incorporation of both a flapping hinge and a lead/lag (or "drag") hinge was an important step in the development of the fully articulated rotor hub.

tested in Britain, a blade failed and flew off as the aircraft settled in for a landing. The resulting crash caused the British Air Ministry to immediately ground all autogiros. The episode finally convinced Cierva that another hinge, a lead/lag or "drag hinge," was required on the blades – see Fig. 16. Cierva tried out the idea of two hinges per blade on his model C-7, which was tested in Spain, and he then returned to England to modify the C-6. After convincing the British Air Ministry of the renewed airworthiness, Cierva went on to develop the C-8. The incorporation of both a flapping hinge *and* a lead/lag hinge was an important step in the development of the *fully articulated rotor hub*, which is used today for many helicopters. Amongst other successes, the C-8 was to go on to demonstrate international acclaim, including the first flight from Paris to London across the English Channel on September 18, 1928, and a European tour of over 1,500 miles.

The Cierva-Glauert Technical Debate

In 1925, Juan de la Cierva was invited to Britain by H. E. Wimperis of the British Air Ministry and also by the industrialist James G. Weir of the Weir Company in Glasgow, who provided financial backing. Cierva was shortly thereafter to found the Cierva Autogiro Company Ltd., and Britain was then to become the home for Cierva's work. His company was not set up for manufacturing, however, but for technical studies, management of patents, and awarding of licenses to build his Autogiros. His Autogiros were built by established aircraft manufacturers, and mostly by the A.V. Roe (Avro) Company in Britain. Pitcairn and Kellett in the USA were later to become major licensees, and were to produce various derivatives of the Cierva machines in some numbers.

Cierva's C-6 Autogiro was demonstrated at the Royal Aircraft Establishment (RAE) during October 1925, and on 22 October 1925, Cierva gave the first of three historical technical lectures[**] to the membership of the Royal Aeronautical Society (RAeS). This lecture, which documented his early development of the Autogiro, was subsequently published as Ref. 16. His next paper[31] was given on 13 February 1930, at a time when over 100 autogiros were flying in Britain and the USA, and he was to document the rapid technical developments of the autogiro that had taken place during the preceding five years. His final lecture and paper[32] to the RAeS was on 28 October 1934, and he then described in detail the "jump" take-off technique and the direct rotor control device (described later).

Juan de la Cierva's first demonstration flights and lectures in Britain stimulated early experimental and theoretical work on rotating-wing aerodynamics at the RAE. This work was conducted under the auspices of the eminent aerodynamicists H. Glauert and C. Lock. The theoretical work was pioneering, and the names Glauert and Lock still occur in routine discussions of rotating-wing aerodynamics and blade dynamics. Their theoretical work was supported by relatively advanced wind tunnel measurements on model rotors.[33] In 1926, Glauert published a classic paper,[19] which was the first theoretical treatise on induced inflow and rotor performance, a summary of which was also presented in a lecture to the RAeS.[34] Glauert's analysis quantified rotor performance in horizontal, climbing, and descending flight, and set down the basic equations that could be used to relate performance to certain rotor design parameters. However, in descent or in autorotation the theory was not exact, and even since then there has been no *exact* theory derived from first principles to fully describe the aerodynamics of a rotor in the autorotative state.

Cierva vehemently disagreed with Glauert's analysis, based on his own theories and also his practical flight testing experience with the C-6. In a letter to the RAeS, Cierva wrote:[35] "In the first place I must, with respect, record my protest against the manner in which Mr. Glauert has made assertions in an almost axiomatic form, from which the evident conclusion must be drawn that the autogiro is, in effect, useless." In part, Cierva disagreed with Glauert's estimation of the vertical autorotative rate-of-descent, claiming values for "practically vertical descents" that were half of Glauert's estimate. He goes on to state: "Such assertions are based only on very incomplete and uncertain calculations which I am able to state are not at all in agreement with experimental results." One of Cierva's other concerns with Glauert's results was with the possibly large aerodynamic scaling effects from the measurements made on relatively small model rotors, which Cierva refers to as "puzzling results." He goes on further to draw concerns "with almost every point con-

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[**] At the end of all the lectures, there was considerable debate on the merits of the autogiro, including contributions from Mr. Handley-Page, Prof. Bairstow, Dr. Lock, and others.

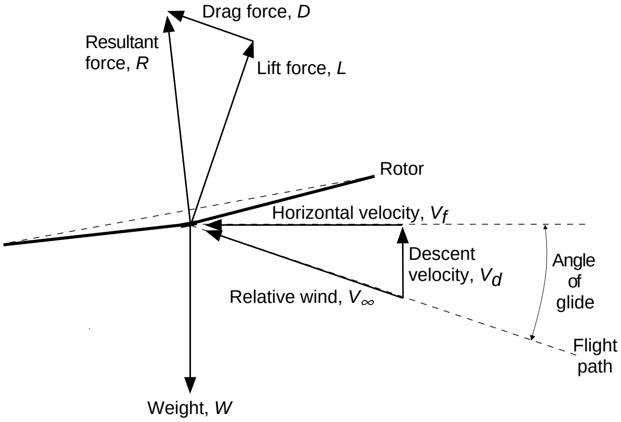


Figure 17: Forces acting on the autogiro in "gliding" flight.

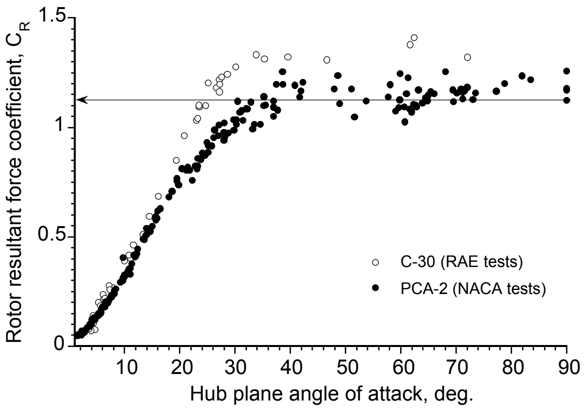


Figure 18: Resultant force coefficient on a rotor in autorotation showing that the force is large and relatively constant over a wide range of angles of attack.

tained in Mr. Glauert's developments." Glauert did not consider the autogiro as "useless" and seems to have been unruffled by such harsh criticism standing confidently behind his theoretical studies – see post-lecture discussion.[34]

With hindsight, Glauert was probably closer to the truth of the matter than Cierva might have first suggested. The analysis conducted previously had shown that the vertical rate-of-descent can be related to the rotor disk loading. The same result can be approached using measurements of the resultant force acting on the autorotating rotor, which are shown in Fig. 18. The resultant force coefficient acting on the rotor is defined as

$$C_R = \frac{R}{\frac{1}{2}\rho {V_\infty}^2 A}, \tag{15}$$

where R is the resultant force on the rotor as given by $R = \sqrt{L^2 + D^2}$, with L as the rotor lift force and D as the rotor drag force – see Fig. 17. It is significant to notice that the resultant force coefficient on the rotor at steep angles (greater than 30°) is about 1.25 and nearly equivalent to the drag coefficient, C_D, of a circular disk[36] with a flow normal to its surface,[††] i.e., the rotor acts like a bluff body with the attendant turbulent downstream wake. It is also close to the drag coefficient of a hemispherical shell, which means that aerodynamically the rotor produces a resultant force equivalent to a parachute when in the autorotative state. Herein lie the difficulties in the aerodynamic analysis of the rotor, because the rotor in its autorotative flow state creates turbulence and is often said to operate in the *turbulent wake state* – see also Fig. 4.

The following analysis parallels that of Harris.[37] For larger disk angles of attack it is possible to equate the resultant force on the rotor to the weight of the autogiro, i.e., $R \approxeq W$, so that

$$C_R = \frac{W}{\frac{1}{2}\rho {V_\infty}^2 A}. \tag{16}$$

Furthermore, the resultant velocity, V_∞, can be written as $V_\infty = \sqrt{V_f + V_d}$ so that

$$C_R = \frac{W}{\frac{1}{2}\rho (V_d^2 + V_d^2) A}. \tag{17}$$

In pure vertical autorotation the disk angle of attack is 90 degrees, which according to the experimental measurements in Fig. 18, gives a resultant force coefficient of about 1.25, i.e., $C_R = C_D = 1.25$. Therefore, for larger operational angles of attack it is possible to write

$$V_f^2 + V_d^2 = \frac{2W}{\rho A C_D}. \tag{18}$$

In pure vertical descent $V_f = 0$, so the vertical rate-of-descent in autorotation will be

$$V_d = \sqrt{\frac{2W}{\rho A C_D}} = 25.94\sqrt{\frac{W}{A}} \tag{19}$$

at sea-level, which compares favorably with the result given previously in Eq. 6, and also with Glauert's published result[19] of $25\sqrt{W/A}$, which was also determined empirically. The autorotative rate-of-descent, however, drops off quickly with increasing forward speed, to a point, as has been shown previously in Fig. 5.

For a series of horizontal velocities, V_f, at the steeper angles of attack where $C_R = C_D = 1.25$, the rate-of-descent V_d can be solved for using

$$V_d = \sqrt{\frac{2}{\rho A C_D}\left(\frac{W}{A}\right) - V_f^2}, \tag{20}$$

[††] $C_D = 1.11$ for a disk, $C_D = 1.2$ for a closed hemisphere, and $C_D = 1.33$ for an open hemisphere.

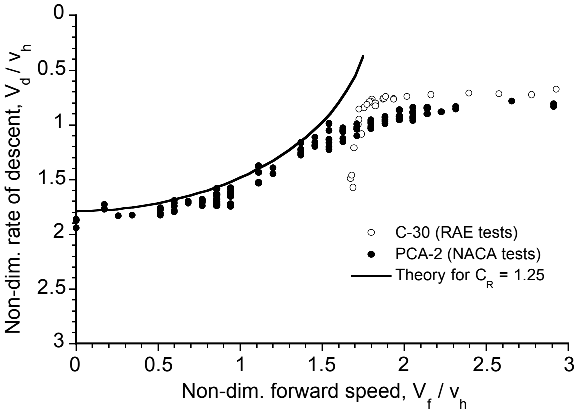


Figure 19: Non-dimensional rate-of-descent in autorotational "gliding" flight with forward speed.

or in non-dimensional terms

$$\frac{V_d}{v_h} = \sqrt{\frac{4}{C_D} - \left(\frac{V_f}{v_h}\right)^2}, \tag{21}$$

for which the predictions made using this latter equation are shown in Fig. 19. While not exact, it does give a result for the rate-of-descent in an autorotation, V_d, as a function of forward speed, V_f, when the rotor disk is at relatively steep angles of attack to the relative wind.

Cierva's Technical Books

In 1929, Juan de la Cierva arrived in New York for his second visit to the USA, this time at the invitation of Harold F. Pitcairn. Pitcairn had previously become acquainted with Cierva during a visit to Europe, and had brought a Cierva C-8 model Autogiro to the USA in 1928. Pitcairn was a wealthy engineer from Philadelphia, and owner of Pitcairn Aviation Inc. The main work of his company was the manufacture of airplanes, for which his PA-5 "Mailwing" was to gain much acclaim. In the early 1920s Pitcairn had already experimented with several designs of model helicopters with the assistance of Agnew Larsen. While the details of this work are not well known, a good summary is given by Larsen himself[24] and by Liberatore.[29]

In a lecture to the Franklin Institute in 1929 (Ref. 38), Pitcairn was to expound the benefits of the autogiro. Subsequently, he obtained the rights to Cierva's patents, and in 1929 this saw the beginning of the Pitcairn-Cierva Autogiro Company of America. In 1933, this enterprise was to become simply the Autogiro Company of America. Pitcairn went on to design and patent many improvements into the Cierva rotor system (see Smith[39]), and in time the company was to patent many new ideas related to rotor design, much of which was applicable to helicopters and subsequently used by the future industry.

Pitcairn urged Cierva to consolidate his vast engineering knowledge of the autogiro, and in 1929 commissioned him to write a reference book for American engineers. The first Cierva book was entitled *Engineering Theory of the Autogiro*. Sufficient data had been measured and analysis conducted that "a theory could be developed covering many probabilities of performance and possibilities of design beyond the actual achievement in construction to that time."[1] Later, Cierva wrote a comprehensive design manual entitled *Theory of Stresses in Autogiro Rotor Blades.* Neither document was formally published, but they were copyrighted and made available to engineers at Pitcairn, the Kellett Autogiro Company, the NACA, the U.S. Air Force and the Bureau of Aeronautics. These engineering documents helped greatly in the certification of autogiros manufactured (and later designed) in the USA.

Airfoil Profiles for Autogiros

The choice of airfoil section on a rotating wing aircraft is never an easy one because of the diverse range of Reynolds numbers and Mach numbers found along the length of the blade. Moreover, rotor airfoil designs are never "point" designs and no one single airfoil will give the benefits of maximum aerodynamic efficiency over the entire operational flight envelope. Overall, airfoils with good lift-to-drag ratios are required to ensure low autorotative rates of descent. Low pitching moments are also essential to maintain low torsional loads on the blades to prevent aeroelastic twisting, and to give low control forces. Compressibility issues on the advancing blade can be an issue for an autogiro, although somewhat less so than for a helicopter (because the autogiro operates at lower mean lift coefficients), so there is some need to use airfoils with good characteristics at high subsonic Mach numbers.

Cierva was well aware of the importance of airfoil shape in improving the performance of his autogiros. He wrote[1] in reference to the twisting moment produced on autogiro blades by the use of a cambered airfoil versus a symmetric airfoil: "It [the Göttingen-429] is a reasonably efficient airfoil, although others give greater lift and a great many different curves are used for designing [fixed-wing] airplanes. But, the important advantage of this particular type is that its center of lift or pressure is approximately the same at all angles which it may assume in flight. This is not true of other types of airfoil, so that center of pressure travel is a factor to be reckoned with in using them." In essence, Cierva is referring here to the connection between aerodynamic performance (better maximum lift coefficient and improved lift-to-drag ratios) through the use of camber and the corresponding increase in pitching moments caused by that camber.

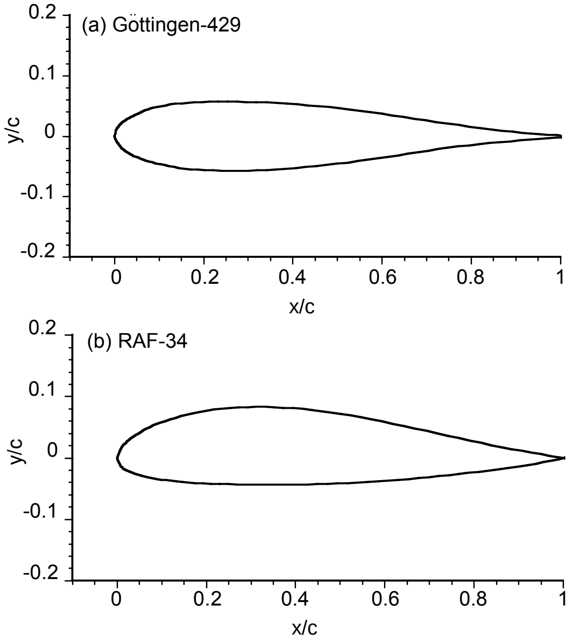


Figure 20: Two types of airfoils that were used on the Cierva Autogiros: (a) the symmetric Göttingen-429, (b) the reflexed cambered RAF-34.

Cierva had many airfoil sections to choose from, but the aerodynamic characteristics of most were not well documented. However, as early as 1920, various research institutions had begun to examine the characteristics of various airfoils and organize the results into families of airfoils, basically in an effort to determine the profile shapes that were best suited for specific purposes. The aerodynamic properties were studied at Göttingen in Germany, and later by the NACA in the USA. On the C-4, Cierva used the Eiffel 106 airfoil section, later switching to the Göttingen-429 airfoil (see Fig. 20). Some years later, Cierva was again to reconsider the choice of the airfoil section for his Autogiros, but limiting his study to ten candidate airfoil sections he decided to replace the symmetric Göttingen-429 airfoil, which had "abrupt stalling" characteristics,[31] with the reflexed cambered RAF-34 airfoil of 17% thickness-to-chord ratio. The new blades were first tested on the C-19 Mk-IV, which became one of the most successful Cierva Autogiro designs.

On the C-30 Autogiro, Juan de la Cierva switched the airfoil again, this time to the cambered Göttingen-606 airfoil. In some flight conditions, mainly at high speeds, the higher pitching moments resulted in blade twisting and control problems. These aeroelastic effects arose because of the generally low torsional stiffness of early wood and fabric rotor blades. Finally, a crash of a C-30 Autogiro was tied to the use of this cambered airfoil section – see Beavan & Lock.[40] The NACA also had noticed such aeroelastic problems and had analytically analyzed the effects of blade twisting.[41,42] On the Kellett YG-1 (which also used the Göttingen-606 airfoil), the NACA replaced the blades with a reflexed airfoil based on the NACA 230 series. Yet, these airfoils were not successful and were found to have poor characteristics at high lift and at high speeds.[25,43]

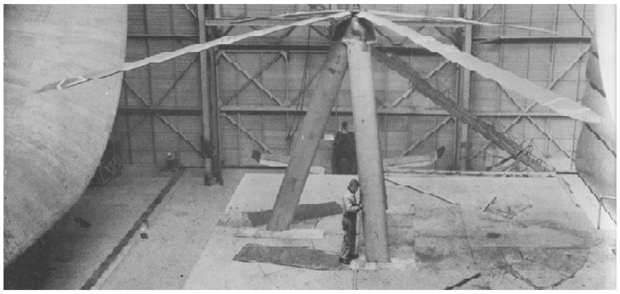


Figure 21: A Pitcairn PCA-2 autogiro rotor was to form the basis for the first NACA wind tunnel tests of a rotating-wing.

The aforementioned events led to such widespread concerns about the uncertainty of cambered airfoil sections for rotors that later it resulted in the almost universal use of "safe" symmetric airfoil sections for the first helicopter designs. However, while symmetric airfoils offered an overall compromise in terms of maximum lift coefficients, low pitching moments, and high drag divergence Mach numbers, they were by no means optimal for attaining maximum performance from future helicopter rotors. It was not to be until the early 1960s, however, that a serious effort came about to improve airfoil sections to give helicopters better performance, and cambered rotor airfoils were used once again.

NACA's Technical Contributions

While the RAE in Britain had conducted experiments with autogiros and developed a theoretical basis for their analysis as early as 1926, it was not until the early 1930s that the extensive resources of the NACA were turned toward the science of rotating-wings. Over the next ten or more years, the autogiro was to be extensively tested by the NACA, with the work forming a solid foundation for later work on helicopters. In 1931, the NACA purchased a Pitcairn PCA-2 autogiro, and this platform became the basis for extensive flight and wind tunnel testing (see Fig. 21) for almost 8 years, until the helicopter appeared. Gustafson[25] gives a first hand summary of the early NACA technical work on both autogiros and helicopters, and Gessow[44] gives a complete technical bibliography.

The first published NACA report on the autogiro was authored by Wheatley,[18] which provided the first authoritative baseline measurements on the performance of the PCA-2 autogiro. Measurements of rates of descents and glide angles were obtained (see Fig. 5 previously), along with estimates of rotor lift-to-drag ratio. Separate tests of the rotor were also conducted in the wind-tunnel,[45] allowing quantification of the rotor performance alone compared to the complete PCA-2 aircraft. As shown in Fig. 22, the aerodynamic efficiency of the autogiro was relatively poor, with a maximum L/D of only about 4.5. The differences between the rotor alone and the complete aircraft reflects the high parasitic drag of the airframe. However, to put results in perspective, the rotor alone performance, which had a maximum L/D of about 7, is comparable to that of a modern helicopter rotor – see Fig. 23. Notice that for higher advance ratios (or tip speed ratio) the helicopter rotor L/D drops off markedly because of retreating blade stall and advancing blade compressibility effects, whereas the autogiro rotor retains a L/D of 5 at $\mu = 0.7$.

In another report,[46] Wheatley goes on to study the load sharing between the rotor and the wing, and also examines the maneuver characteristics of the autogiro. One of the most remarkable findings in this work was a sustained maximum maneuver load factor of 4.3, which is high for any kind of rotorcraft, and rarely obtained even on modern combat helicopters during transient maneuvers. The main reason was the relatively low blade loading and low mean lift coefficients of the autogiro rotor, which led to good stall margins. The role of the wing was also important in off-loading the rotor at higher airspeeds. Flight tests with the PCA-2 demonstrated forward speeds of 140 mph, with an advance ratio in excess of $\mu = 0.70$; this was an advance ratio about three times that possible with the earliest helicopters, and also exceeding that possible with a modern helicopter.

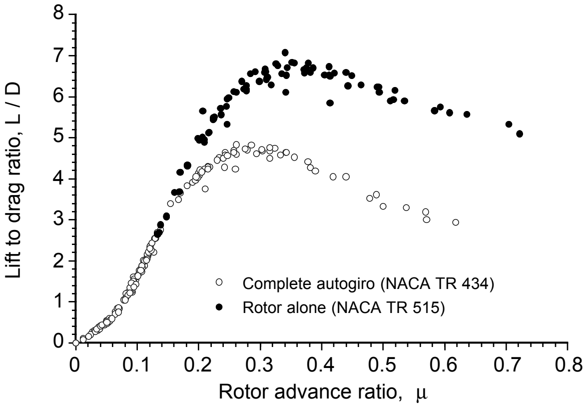


Figure 22: Lift-to-drag ratio in autorotation for complete autogiro (PCA-2) versus the rotor alone.

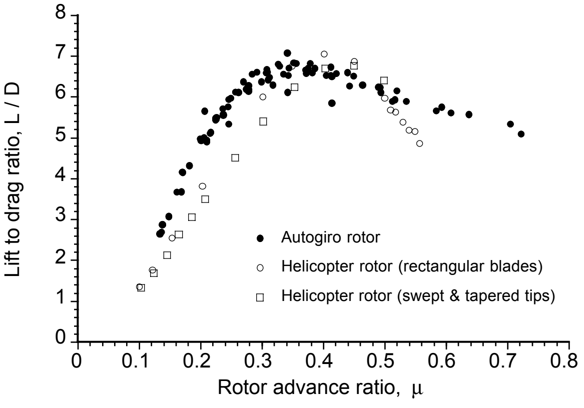


Figure 23: The lift-to-drag ratio of a rotor in autorotation is comparable to a modern helicopter rotor.

The earliest theoretical studies of the autogiro at NACA resulted a number of reports, including one of the first aerodynamic analysis of the rotor.[47,48] Later, a now classic report by Bailey,[49] extended the earlier work of Glauert[19,20] and Lock[50,51] at the RAE, and included the treatment of blade twist, reverse flow, non-uniform inflow, and "tip loss" effects on the aerodynamics of the rotor. The predictions were shown to be in good agreement with both flight and wind tunnel measurements. The NACA worked extensively on several other technical problems (both from an experimental and theoretical perspective) that were to occur during the maturation process of the autogiro. This included work on rotor dynamics, vibration, airfoil sections, jump take-offs, and ground resonance. Again, much of this is detailed by Gustafson.[25]

Orientable Autogiro Rotors

Landing tests with the autogiro were conducted at the NACA in 1934 by Peck,[52] and helped quantify the poor roll control response autogiros at very low airspeed. This was a direct result of the use of conventional "airplane" control surfaces (ailerons). Because the autogiro could be landed at almost zero airspeed, the ineffectiveness of the ailerons under these conditions was a serious deficiency in the machine's handling qualities. The problem resulted in numerous mishaps, where inexperienced pilots would land the machine on one wheel only, and a wing tip or blade tip would strike the ground. While Cierva had initially investigated a disk tilting mechanism on the C-4 to provide roll (see previously), the control forces were found to be too heavy for the pilot.

By 1931, Juan de la Cierva had introduced the *directly orientable* rotor control. This "rocking head" design solved the control problem by tilting the entire rotor shaft in any direction and inclining the rotor lift force. This innovation allowed him to finally dispense with the stub wings and the elevator. During 1932, the new device was tested on a C-19, which had no conventional airplane features except for a vertical tail and a rudder, and over 100 test flights proved the success of this new form of rotor control. The controls for the original tilting shaft design was later replaced by a "hanging stick" from the rotor hub to the cockpit, which gave the pilot both good control authority and also relatively light forces in both roll and pitch. The device was quickly incorporated on all new autogiros manufactured after 1932, including the C-30, which became one of the most famous autogiros, with nearly 200 being built in Britain, the USA, and France.

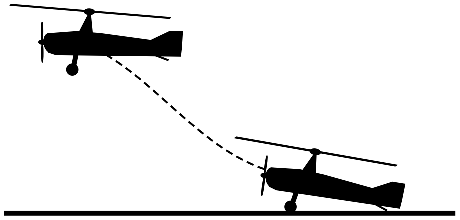
In 1934, Raoul Hafner introduced the "spider" blade pitch control system to autogiros. Hafner was a competitor to Cierva, and the Hafner Gyroplane Company built and flew their first machine, the A.R. III, in September 1935. The novel spider mechanism provided a means of increasing collective pitch on the rotor blades and also using cyclic pitch to simultaneously tilt the rotor disk. This was done without tilting the rotor shaft with a control stick, as was used in Cierva's direct control system. Hafner's mechanism was a significant advance on Cierva's system, and in addition to enabling "jump" or "towering" take-offs, it offered the pilot light and responsive flight controls. With this feature, the autogiro was to closely rival future helicopters in handling and performance capability. Hafner was later to be a leader in the British helicopter industry, first at Bristol Helicopters and then at Westland Helicopters. He subsequently published a number of technical papers on rotorcraft, including Ref. 53.

The "Jump" Take-off

Because the rotor of the autogiro is unpowered in flight, the rotor needs to be brought up to speed by some means before take-off. On the earliest machines this was done by taxiing the aircraft around on the ground, but this was not very effective. Later, a "spinning top" method was used where a rope was wound around pegs mounted on the bottom of the blades, the other end of the rope being fixed to the ground. As the machine moved away and picked up speed, the rotor speed was increased. Alternatively, the rope could be pulled manually to start the rotor. Although Cierva had previously patented a mechanical starter for his Autogiros, he had resisted its use because it was too heavy. In 1929, the Cierva Model C-12 used a biplane tail, which could deflect the propeller slipstream to help spin the rotor. Eventually, Pitcairn engineers developed a lightweight mechanical pre-rotator, and from 1930 onward nearly all autogiros were equipped with one.

In 1933, Cierva had started work on a vertical "jump" take-off capability for the C-30 with James Bennett, who was the chief aerodynamicist of the Weir Company in Glasgow. In this system, the rotor could be clutched to the engine through a lightweight transmission when the autogiro was on the ground. The weight of the autogiro on its wheels prevented it turning in response to rotor torque reaction. In the *First Cierva Memorial Lecture* to the RAeS in February 1961, Bennett explained how no fewer than fifteen different hinge assemblies were tried.[56] The modified C-30 used blades with a kinematic *pitch/lag coupling*. When the rotor was clutched and driven by the engine, the blades lagged back and pitch was reduced to nearly zero by the coupling. The rotor rpm was then increased well above the normal flight value by revving the engine. When the rotor was declutched, the blades lagged forward and pitch was simultaneously increased. This lifted the aircraft rapidly off the ground (Fig. 24). While the jump take-off capability is partly a result of the stored kinetic energy in the rotor system, there are also large aerodynamic benefits of thrust overshoot because of the lag in the developing rotor wake dynamics.[54,55] As forward speed builds, the rotor speed decays, and the rotor settles into its normal autorotative working state.

(a) Towering take-off



(b) Jump take-off

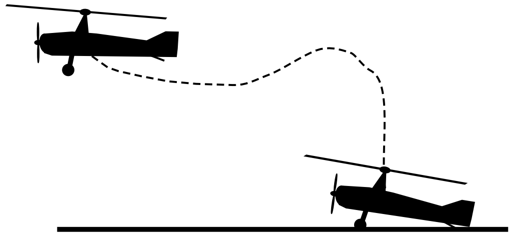


Figure 24: The towering (a) and jump (b) take-off capability gave the autogiro a capability rivaling a helicopter.

Cierva's jump take-off system, which was known as the "Auto-dynamic rotor," was installed on a modified C-30 and first demonstrated successfully on March 15, 1935. This was the year, however, when the Bréguet-Dorand helicopter made its first flights, and the otherwise significant advance in the performance of the autogiro received only minimal attention.[‡‡] The C-30 eventually became the production C-40, with both the C-30 and the C-40 seeing some military service during WWII.

[‡‡] The jump take-off of an autogiro was first publicly demonstrated by Weir's W-3 autogiro on July 23, 1936.

In later developments of the autogiro, a variable pitch system was used such that the blades could be set to flat pitch when the autogiro was on the ground, and increased to a fixed pitch for normal flight. To perform a jump take-off with this system, the pilot first over-sped the rotor, then rapidly applied collective pitch while simultaneously de-clutching the rotor to avoid any torque reaction. Prewitt[57] gives a technical discussion of the jump take-off technique. The jump take-off was also studied experimentally by the NACA using model rotors,[58] and later by means of theory.[54]

Ground Resonance

It has already been mentioned that on the first Autogiros, the in-plane Coriolis and drag forces on the blades were balanced by interconnected sets of wires between the blades. The blades were also restrained in flap by cables so that they could not "droop" when the rotor was stopped. Cierva found this interim solution rather unsatisfactory because the cables created high parasitic drag, reducing overall aircraft performance. Eventually, Cierva incorporated support stops instead of suspension cables, and friction disks at the drag hinges to damp out any in-plane blade motion. He called these "cantilevered" blades, although the name is somewhat of a misnomer because the blades were still articulated with mechanical hinges in the conventional sense.

While these ideas seemed to work fine on the lighter weight autogiros, a crop of new problems arose when they were applied to the bigger and heavier machines. These problems included high vibrations in the control system, large control forces, and a susceptibility to a destructive aeromechanical problem known as *ground resonance.* Ground resonance is associated with the out of pattern in-plane motion of the blades and a coupling with the dynamics of the undercarriage and wheels on the ground. This causes the net center of gravity of the rotor system to spiral outward away from the rotor hub, resulting in a severe shaking of the machine and quickly to a catastrophic resonance. "Sympathetic" pilot inputs through the flight controls usually provides the initial excitation to the rotor system, but not always. There were also a number of reported instances of *air resonance*, which occurs in flight and can also be disastrous.

There were some limited technical efforts to understand the ground resonance problem on autogiros, but the "trial-and-error" approach meant it was never satisfactorily resolved until much later when the same problems occurred on helicopters. In the 1930s, NACA made an attempt to study the ground resonance problem by mounting a camera high above the autogiro while the rotor was revved up on the ground. Another camera was mounted on the rotating hub to study the motion of one blade. The NACA was to have a special interest in the phenomenon; because of resonance on the mounting hardware, a specially instrumented autogiro that was being tested in the Langley full-scale wind tunnel was completely destroyed.[25] In later years, helicopters were to suffer similar "resonance" problems, which was cured for the most part by the addition of dampers to the in-plane blade motion and changes to the undercarriage design. It was not until the 1950s however, that the first mathematical theory to predict and cure the problem of ground resonance became available.[59]

Other Technical Developments

The role of the Pitcairn and Kellett Companies in the technical development of the autogiro has already been mentioned. The Buhl Aircraft Corp. of Detroit, Michigan was another company involved in autogiros. They designed and built a small two-seater autogiro with a pusher propeller, the first of its kind, which had no fixed aerodynamic surfaces other than a tail. The unrestricted downward visibility saw its use in aerial photography.

In 1931, Harold Pitcairn received the highly prized Collier Trophy for his technical contributions, the events of the day cumulating in a PCA-2 landing on the White House lawn. Pitcairn made over 100 patented concepts in rotor blade design and rotor control, some of which were later licensed to Sikorsky.[39] Other helicopter manufacturers were be relieved from patent licensing requirements by the U.S. Government, under the banner of "military procurement expediency." This move led to litigation, which Pitcairn's estate subsequently won 26 years later.[39]

After WWII, Kellett adopted an intermeshing or "synchropter" helicopter configuration, which had been developed in Germany by Flettner.[60] The aircraft flew successfully, but it never went into production. Rotor design patents from the Weir and Cierva companies in Britain were transferred to the Picairn-Larsen Company (as it was later known), and then to the G&A (Gliders & Aircraft) Division of the Firestone Tire & Rubber Company. They subsequently built a small prototype helicopter, first flown in 1946, called the G&A XR-9, which was designed by Harold Pitcairn.

In Europe, the Cierva Autogiro Company issued production licenses to three companies in France and Germany. The Weymann-Lepère Company of France was to build an enclosed four-seater derivative of the C-18, and a two-seater called the model CTW-20. The Lioré-et-Olivier Company, also of France, built a derivative of the Wier W-1 (C-27), and later derivatives of the C-30 called the C-301 and C-302. In 1931, Focke-Wulf Flugzeugbau A.G. of Germany produced versions of the C-19 and C-30. All of these machines were basically license built, and incorporated no new advances in autogiro design.

From the mechanical experience gained from the Cierva autogiros, and after systematic wind tunnel tests with rotors and free-flight models,[61] Henrich Focke began to develop a helicopter – which was to become the now famous Focke-Wolf Fw-61 (later the Focke-Achgelis Fa-61). Focke was later to state in a RAeS lecture[62] that "[he] was brought to the task of making the first practical helicopter because Cierva did not do it himself." Focke's machine used lateral side-by-side rotors, and first flew in June 1936. This was one year after the Breguet-Dorand *Gyroplane Laborotatoire* helicopter had flown successfully. Yet, the Fa-61 machine is significant in that it smashed all existing altitude and speed records for a helicopter, and also was the first helicopter to demonstrate successful autorotations from powered flight, the first autorotation being performed on May 10, 1937. Provision was made in the Fa-61 rotor design for a fixed low collective pitch setting to keep the rotor from stalling during the descent. This low pitch setting was automatically engaged if the rotor rpm dropped below a predefined value, a novel safety feature also used on helicopter designs by Weir.

During WWII the Focke-Achelis company also built the Fa-330 "Bachstelze" kite. This aircraft was a pure autogiro with a relatively simple lightweight skeletal construction, and was designed as an observation platform for one man while being towed behind a surfaced submarine. The Hafner Rotachute[63] was built along similar lines, but never saw operational use. The simplicity of both these platforms later formed the inspiration for inexpensive amateur homebuilt autogiros, many of which are still popular today.

In the 1930s, several British companies including Weir, A.V. Roe (Avro), de Havilland and Westland built variants and/or developments of the Cierva Autogiro designs. The first Weir design (the W-1 or C-28) was designed by Juan de la Cierva, and used the first form of orientable direct rotor control system. The Weir W-2 through W-4 models were some of the first machines to use a clutch to help bring up the rotor rpm prior to take-off. 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, but it was never flown because of serious ground resonance. Another Westland designed autogiro called the CL-20 was flown just before WWII, but with limited success – see Mondey.[64]

In Russia, the TsAGI built autogiros derived from the Cierva designs. The Ka-Skr I and II were copies of the Cierva C-8. Kuznetsov and Mil built the TsAGI 2-EA, which was derived from the Cierva C-19 – see Everett-Heath[63] for details. Later developments of this design led to the first Russian helicopters. The Japanese made copies of the Cierva and Kellett autogiro designs, and used them as submarine spotters during WWII – see Gablehouse.[65]

End of an Era: Autogiros Give Way to Helicopters

The timing of autogiro development led to only limited success with the military. The Cierva C-30 machines saw some military service with the British Royal Air Force during WWII.[9] They were mainly used for radar calibration missions, vital in helping to give early warning of raids by the *Luftwaffe*. The U.S. Navy had high hopes for the autogiro in shipborne use for submarine detection and convoy defense. Initial trials of the Pitcairn XOP-1 autogiro, however, were less than impressive, with the Navy citing poor range, insufficient payload capability, and limited center of gravity travel. While later models of the autogiro had much improved capabilities, the Navy remained unconvinced. The U.S. Army later tested both the Kellett and Pitcairn machines in a variety of roles, including reconnaissance and battlefield observation. The low-speed loiter capability of the autogiro seemed particularly promising for artillery spotting roles, but the Army concluded that the autogiro could perform well in only a few areas and would be largely outclassed by conventional airplanes. Later, the U.S. forces, however, did buy some autogiros built by Kellett.

While the autogiro did see some commercial success, mainly in the USA, it was never on a large scale. During the 1930s and 1940s it was used by the U.S. Post Office for regular mail service between Washington D.C. and Philadelphia, as well as in other cities, including Chicago and New Orleans. The 1920s and 1930s were an exciting and adventurous time for aviation despite the Great Depression, and the autogiro was widely popularized as a super-safe, easy-to-fly aircraft, which it was for the most part. It subsequently found its way into the private market, where it gained good popularity with pilots and some level of public acceptance, despite being fairly odd in appearance. It was also used for aerial photography and advertising, the latter role giving it good public exposure.

One practical limitation (and often the most popularized reason for the loss of interest in the autogiro) was that it cannot hover stationary in the air. While the efficient hovering flight capability of the helicopter is certainly a very desirable attribute, the autogiro still has the ability to take off vertically using the "jump" technique, and can land almost vertically, especially into a wind. However, the autogiro's vertical jump and towering take-off capability was not to be demonstrated publicly until after the Breguet-Dorand and Fa-61 helicopters were successfully flying, and this otherwise significant advance in its capability received only passing attention.

The autogiro is an efficient machine at low to moderate airspeeds, and can outperform both the airplane and the helicopter under these conditions in terms of economics and also safety of flight. Unlike a helicopter, the autogiro has no "Deadman's Curve,"[14,15] and so can operate much more safely at lower altitudes and airspeeds. However, several early flying mishaps with the autogiro in the hands of inexperienced pilots led initially to a poor perception of the machine. Flight control was drastically improved by the use of "orientable" rotors. While efficient at low speeds, autogiros did not have the higher speed capability of airplanes designed in same time period, mainly because of its high parasitic drag. While much was done on later models of autogiros to increase streamlining and reduce rotor profile drag, especially by eliminating blade bracing wires, they were never to match the higher speed capabilities of airplanes. Furthermore, autogiros were mostly single or dual-seater aircraft, at a time when airplanes in the same weight and engine class (and also for a significantly lower capital cost) could carry several passengers. As alluded to earlier, scaling up the machine resulted in ground resonance issues, and these were not completely understood at the time.

While the autogiro was well-engineered, the high cyclic stresses imposed on rotating components meant that mechanical failures of the rotor system were not uncommon. Yet, it is unfair to over-emphasize any mechanical shortcomings of the autogiro at a time when all types of aircraft structural analysis was in its infancy. Autogiro designers worked steadily to improve the mechanical reliability and efficiency of the rotor design, and with the later designs they were extremely robust and reliable. These technical accomplishments were to serve well the future designers of helicopters. By the early 1930s, helicopter pioneers, who for the most part were working independently to those developing the autogiro, suddenly realized that the autogiro had served to help work out all the problems of achieving proper control with helicopters. Thereafter, the progress with the helicopter accelerated rapidly, and interest in the autogiro dwindled. It is ironic that all of the innovative technical developments that led to the perfection of the autogiro brought the helicopter to the threshold of its own success.

There were several other factors contributing to the loss of interest in the autogiro in the 1940s. In the USA, military interest in the helicopter increased, and in 1938 the Congress passed the Dorsey Bill, allocating (but not immediately providing) to the Army the sum of $2M "for the purpose of rotary-wing and other aircraft research, development, procurement, experimentation, and operation for flight testing." The Bill made possible the 1938 Rotating-Wing Aircraft Conference at the Franklin Institute in Philadelphia,[66] and brought together most of the pioneers and technical specialists in the rotating-wing field. Igor Sikorsky was already working toward the first flight of his VS-300, and in his paper[67] at the subsequent Rotating-Wing Aircraft Conference in 1939, he was to extol the future potential of the helicopter. The imminent success of Sikorsky and his VS-300, funding from the Dorsey Bill, and the pressures of making technological advances during wartime, eventually led to the successful development of a military helicopter in the USA.

In December 1936, Juan de la Cierva was killed at the age of only 41 years in the crash of an airliner. Shortly thereafter, the British Government attempted to centralize rotating-wing engineering by trying to get the Cierva and Hafner companies to merge, but this initiative was unsuccessful. Raoul Hafner saw the autogiro only as an interim step toward the development of the helicopter; Juan de la Cierva did not. Nevertheless, both Cierva and Hafner saw the important future role of rotating-wing aircraft in both military and civil aviation. At the end of a lecture[68] to the RAeS in 1938, Hafner stated: "We cannot afford to disregard the clear indications towards progress offered by the rotative wing. We can see the limitations with fixed wings – we must be aware of the limitation of fixed ideas; and if are to avoid flying and thinking in circles we must make the *wing* rotate."

The imminent outbreak of WWII ended all research and development on British rotorcraft, there being a need to devote resources and skilled labor to "more important war work." The British Government's moratorium on rotorcraft development, albeit only for a few years, was to be a serious blow to the Cierva, Weir and Hafner companies. It was not to be until 1943, in response to the first official British government design specification for a helicopter, that British rotorcraft development was to start again. By that time, the USA had accelerated into the technical lead. With the rapid advances by Igor Sikorsky in 1939 and early 1940s, engineers in the USA were to shelve any further technical development of the autogiro and were to focus work on helicopters. Much of the future technical work on rotorcraft, both experimental and theoretical, took up where the autogiro had left off. For a detailed account of this, see Gustafson.[25]

A New Era: Autogiros After Helicopters

In the 1950s, there was some revival of interest in the gyroplane or "convertiplane" concept, with a series of protoypes being designed by the Fairey Company in Britain and McDonnell in the USA. These machines were designed to help overcome the inherent forward flight speed limitations of a conventional helicopter. Gyroplanes can take-off vertically and hover with the rotor powered directly, but the rotor is then off-loaded (for the most part) by a conventional wing in forward flight. With the shaft torque being removed from the rotor, it enters into the autorotative state. McDonnell developed the XV-1,[70] but its performance was disappointing. Two Fairey *Gyrodyne* prototypes led to the *Rotodyne*, which was the world's biggest gyroplane with a cabin big enough for 40 passengers – see Hislop.[69] The aircraft set a world speed record for a convertiplane in 1959 before the project was cancelled "for the usual reasons."[6]

During the late 1950s and early 1960s, single and two-seater commercial autogiros were developed in North America for the private aviation market by three companies: Umbaugh (later Air & Space), Avian, and McCulloch. While Umbaugh and McCulloch delivered over 100 machines, they had limited performance and the lack of sustained orders put the companies out of business. Single and two-seat autogiros were also built in Britain by Kenneth Wallis, with one of his machines gaining a starring role in a 1967 James Bond film. In the 1950s, Igor Bensen developed a homebuilt autogiro with an open airframe, based to some extent on the simplicity of the German Fa-330 kite, which he called a "Gyrocopter." A thriving amateur homebuilt autogiro market is still active today, with at least a dozen manufacturers in business.[71]

From a scientific perspective, there have been few recent studies of autogiros. However, work in the UK by researchers at Glasgow University,[72] has begun to reexamine the stability, control and handling qualities of autogiros, mainly from a flight safety and certification standpoint.[73–76] Advanced mathematical models of the autogiro were developed, and validated by flight testing measurements conducted on a specially instrumented two-seater autogiro. This work represents the first significant scientific interest in autogiros in over five decades, and perhaps points the way forward to improved future autogiro and gyroplane designs.

Recently, there have been two companies in the USA that have resurrected the idea of the autogiro or gyroplane, and have begun to exploit its capabilities using modern technologies. These companies are Carter Aviation Technologies,[77] and Groen Bothers Aviation, Inc.[78] The Carter test platform[77] incorporates both a rotor and a large, high aspect ratio fixed-wing. It is a hybrid aircraft using some of the underlying principles of the Fairey compound machines of the 1950s. While the rotor provides all of the lift during take-off and landing, the wing produces most of the lift at higher airspeeds, with the rotor almost completely offloaded and operating in its autorotational state. The high inertia rotor has a bearingless hub, with a tilting spindle to control the orientation of the rotor disk (much like in the original Cierva designs) with collective pitch to control rotor rpm. The machine is made almost entirely of composites, and is powered by a lightweight propeller driven by a piston engine. Conventional flight control surfaces (ailerons, elevator and rudder) are used, again much as on the original Cierva designs.

The Groen Bothers Aviation (GBA) have developed the world's first turbine powered autogiro (gyroplane).[78] Their *Hawk 4* gyroplane has been designed and tested for pending civil certification. The GBA machine provides all of the short take-off and nearly vertical landing capabilities of the autogiro, with a demonstrated level flight speed of 148 mph. Among other innovations, the two bladed articulated rotor incorporates a patented cone/pitch coupling for excellent rotor rpm stability. It uses a swashplate with collective and cyclic pitch, which gives the aircraft excellent control and maneuverability, and also allows for extremely short take-offs. The all-metal blades use a series of advanced airfoil sections, designed specifically to meet the unique aerodynamic requirements of sustained autorotational flight. Unlike the Carter machine, there are no conventional flight control surfaces on the GBA machine for roll or pitch, this all being achieved through rotor control, but with rudder for directional (yaw) control.

While current work on gyroplanes may lead to larger and much more capable machines, the technical challenges involved in building larger gyroplanes are yet to be fully understood. As past experience with large rotorcraft has shown, they will likely confront the analysts and engineers of the future with many technical and engineering problems that will need to be overcome. This time, however, it will be the gyroplane that will benefit from the helicopter, in part, by using the powerful analytic design tools that have evolved over 50 years of helicopter development. Clearly, significant gains in the performance of the autogiro are possible using optimized airfoil sections, blade shapes and planforms, composite structures, advanced flight controls and efficient new engines. If these new technologies can be used to advance the previous technical success of large commercial gyroplanes along the lines of the Fairey *Rotodyne*, then this gives much confidence in the future role that new gyroplanes could play in modern aviation.

Concluding Remarks

This article has summarized the technical challenges in the development of the autogiro or gyroplane. A truly remarkable aircraft, exactly eighty years ago it was the first powered, heavier-than-air aircraft to fly successfully other than a conventional airplane. It was also the very first type of successful rotating-wing aircraft. The success of the autogiro paved the way for the development of the helicopter, its roots being anchored in the pioneering technical accomplishments of Juan de la Cierva and Harold Pitcairn. While it is surprising that the autogiro is often viewed as occupying a rather lowly place in the history of aviation, it played such a fundamental role in the technological development of modern rotating-wing aircraft that its proper place must be fully recognized.

It is often said by some that the autogiro was not a significant success, perhaps an "ugly duckling" and only a makeshift hybrid between the airplane and the helicopter. While the earliest autogiros certainly had many shortcomings and encountered many technical hurdles, the developers worked in a systematic, step-by-step approach to overcome each hurdle and advance the state of engineering knowledge. It was a technical success, and in ways that are really quite remarkable when viewed in hindsight. The autogiro led to scientific discovery and many engineering contributions to rotorcraft technology on both practical and theoretical fronts. The most significant was clearly development of the articulated rotor hub, with the incorporation of flap and lead/lag hinges, and later the complete control of the aircraft by tilting the rotor plane by using cyclic blade feathering. The autogiro era also produced the first theories of rotor aerodynamics, rotating blade dynamics, structural dynamics and aeroelasticity, and provided the foundation for much of the rotating-wing analyses that are used today.

At the end of WWII, when interest in the autogiro was waning and practical helicopters were coming to fruition, the industry had created nearly 50 variations of autogiros and had delivered about 450 production machines. It also familiarized the public with rotating-wing aircraft, which led to much quicker public acceptance of the helicopter when it finally appeared in significant numbers. It is amazing that nearly all of the technical development of the autogiro was done with limited funds. Little government money went into its development, and nearly all the innovative technical progress was achieved by a few individuals working within a few small companies using their private capital. This is quite unlike the situation today, when the established rotorcraft industry depends on massive amounts of sustained government spending.

The autogiro is still with us today, its principles being combined with current (and future) technology and innovative forward thinking toward ambitious new designs. This work also continues largely with private funds. However, this fabled ugly duckling may be getting a new lease on life, and the modern autogiro and gyroplane may have very important future roles to play in large military and commercial applications. If the innovations of the autogiro can be successfully combined with the capabilities of helicopters and also the speed and range attributes of fixed-wing aircraft, then modern gyroplanes could be used to meet an almost limitless variety of military missions and civil applications. Only time will tell, but the renewed interest in the unique capabilities of the gyroplane can clearly benefit from both the technical knowledge and the powerful mathematical models and analytic design tools that have evolved over the last 50 years of helicopter development.

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