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The Cierva Autodynamic Rotor

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March 2015

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THE CIERVA AUTODYNAMIC ROTOR

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"If any credit is due to me over the 'autodynamic' rotor head, it is only for having sensed that somewhere the perfect solution of the location in space of the blade axes exists." Juan de la Cierva (ref. 1) (fig. 1).

Figure 1: Juan de la Cierva.

In his invention and development of the Autogiro, Juan de la Cierva strived to simplify, and make as safe as possible, the practical task of flying by eliminating the pilot's ability to mishandle the aircraft. He was well aware of the swashplate/spider mechanism for providing cyclic pitch and collective pitch control of the rotor, but in the interest of what he considered mechanical and operational simplicity, he chose to develop the autodynamic system to automatically provide those same capabilities in the tilting hub rotor. His close associate, James Allan Jamieson Bennett, stated in response to Austrian engineer Raoul Hafner's development of a successful spider-actuated rotor control system (a variation of the swashplate rotor control), "It is considered that multiplication of manual controls is a retrograde step and that a manual control

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for effecting pitch change for take-off is undesirable, as consistent use of the control in the most effective manner is probably beyond the capacity even of an expert pilot” (ref. 2).

The tilting hub is rocked about longitudinally and laterally disposed hinges atop the rotor pylon to provide roll control and pitch control, respectively. The swashplate control system uses cams to translate linear motion into rotary motion acting through pitch links that change rotor blade pitch. The spider control system uses a vertical rod that raises, lowers, or inclines a system of levers attached to the rotor blades. Figure 2 illustrates these three control systems.

In 1922, Cierva attempted to provide lateral control of the C.4 (fig. 3), his first Autogiro fitted with flapping rotor blades, by hub tilt. Realizing that control of the Autogiro by tilting the rotor disk was too ambitious an undertaking at that primitive state of rotary-wing aircraft technology, he mounted the rotor to a fixed axis and used airplane control surfaces to maneuver the Autogiro in flight.

Cierva returned to the development of direct rotor control in mid-1932. He evaluated a swashplate-actuated control system (ref. 3) but decided to pursue development of the tilting hub because of its perceived simplicity and robustness (ref. 4). Hafner had been experimenting with a spider-actuated rotor control system since 1928, and in 1932 relocated to Britain after securing financial support from Scottish industrialist Jack Coates. In the following year, Hafner secured premises adjacent to those of the Cierva Autogiro Company, Ltd., at Hanworth Aerodrome, west of London. Hafner’s AR.III gyroplane was demonstrated in September 1935, and its control system was immediately recognized as a significant development. Unlike Cierva, who had conceived the Autogiro as a safer alternative to an airplane, Hafner regarded the former aircraft as “a proving tool for an improved helicopter which has always been my objective” (ref. 5). This approach dictated use of a fixed hub mounted atop a straight driveshaft with rotor control provided by a spider-actuated or swashplate-actuated system because a torque-driven tilting hub control system introduced significant mechanical complexity (as definitively proven with the Weir/Cierva W.9 helicopter in 1944–1946) (ref. 6).

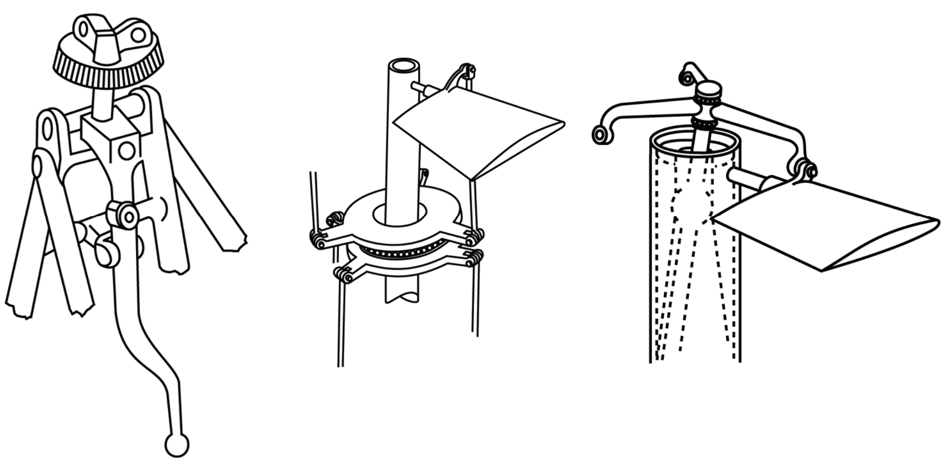


Figure 2: Tilting hub, swashplate, and spider rotor control systems.

Figure 3: The Cierva C-4 Autogiro with lateral control bellcrank below rotor hub.

Cierva developed the tilting hub rotor control on the C.19 Mk.V Autogiro with its fixed-wings and elevators removed. Early test flights without a horizontal stabilizer indicated inadequate stability about the pitch axis. The rudder was retained for yaw control and a dorsal fin added to suppress adverse roll with yaw. This experimental Autogiro led directly to the C.30, which entered production as the world's first practical direct-control rotorcraft.

During his third presentation to the Royal Aeronautical Society in December 1935, Cierva announced the successful development of an experimental jump-takeoff mechanism for the tilting hub controlled Autogiro, although he did not disclose any details other than mentioning tilt of the drag hinge to achieve the functionality (ref. 7). The jump-takeoff capability was part of what he termed "autodynamic rotor," this system providing various functionalities by means of torque, inertial, and aerodynamic forces acting on tailored rotor blades rotating about inclined flap, drag, and feather hinges. Additional functionality was provided by mechanical means within the hub actuated by those same forces or via a cockpit control. The autodynamic rotor achieved much of its functionality by coupling blade motion about two or more of the feather (x), drag (y), and flap (z) axes. The value of the coupling could be positive or negative relative to the respective axes. Figure 4 illustrates the hinge axes and possible couplings.

Cierva termed the hinge that primarily coupled flap and feather motions *delta* (δ), and the hinge that primarily coupled drag and feather motions *alpha* (α). A third hinge, which coupled drag-feather motions but was locked in flight, was termed *phi* (φ). The inclination of a hinge was designated as [hinge name]-[plane], e.g., δ-3, flap-feather hinge inclined in plane 3, and was characterized as positive (primary motion—damped) or negative (primary motion—amplified) (ref. 8). Table 1 shows the effects of coupled blade motion about each hinge.

The effects described above were dependent on the degree of coupled motion, with some undesirable behaviors occurring at high coupling ratios (defined as a hinge inclination greater than 45 degrees to the primary axis).

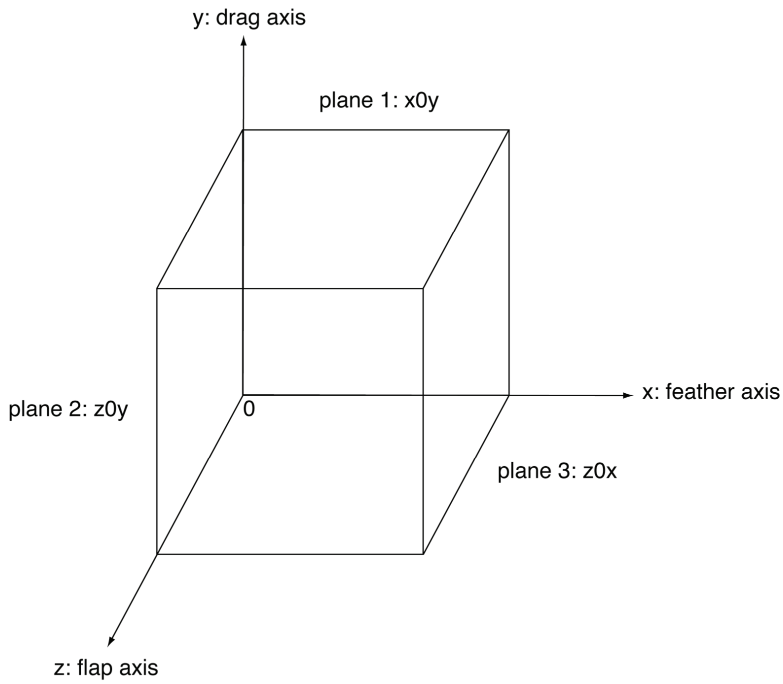


Figure 4: Rotor blade hinge axes.

TABLE 1: HINGE COUPLINGS

Coupled Blade Axes	Effects of Positive Coupling (secondary motion damps primary motion)	Effects of Negative Coupling (secondary motion magnifies primary motion)
Drag and feather (α-1) Primary motion: drag.	Forward drag causes pitch increase. Rearward drag causes pitch decrease. Unstable coupling of flap and drag motion resulting in self-excited vibration at high coupling ratios.	Forward drag causes pitch decrease. Rearward drag causes pitch increase. Stable coupling of flap and drag motion resulting in suppression of self-excited vibration at high coupling ratios.
Drag and flap (α-2, δ-2) Primary motion: drag.	Forward drag with flap up. Rearward drag with flap down. Drag damping required.	Forward drag with flap down. Rearward drag with flap up. Aerodynamic damping eliminates requirement for drag dampers.
Flap and feather (δ-3) Primary motion: flap.	Pitch decrease with flap up. Pitch increase with flap down. Decrease of drag amplitude. Suppression of lateral rotor disk tilt in flight.	Pitch increase with flap up. Pitch decrease with flap down. Eliminate flap-drag instability at low coupling ratios. Reduction of drag-feather instability at low coupling ratios. Flap instability at high coupling ratios.

The fundamental steps required for jump-takeoff in an Autogiro included:

1. Position aircraft upwind.
2. Lock wheel brakes.
3. Decrease rotor collective pitch.
4. Engage rotor drive.
5. Apply full engine throttle to drive rotor to rpm necessary for takeoff.
6. Disengage rotor drive.
7. Increase rotor collective pitch to angle to produce rotor thrust in excess of aircraft weight.
8. Set aircraft pitch attitude for shallow climb to transition rotor airflow from propeller state to autorotative state.
9. Depending on rotor design, decrease collective pitch to autorotative setting via pitch-cone coupling during jump takeoff.

The autodynamic system automatically combined items 3 and 4, and items 6 and 7 above.

Cierva had the following objectives for the autodynamic rotor:

1. Automatic control of rotor collective pitch for takeoff.
2. Automatic stabilization about the pitch and roll axes.
3. Automatic change of rotor collective pitch with airspeed and altitude.
4. Freedom from self-excited oscillations.
5. Absorption of bouncing (vertical oscillation of the rotor).
6. Automatic locking in flight of the *phi* hinge.
7. Automatic decrease in blade pitch with application of the rotor brake (ref. 9).

James G. Weir of the G&J Weir, Ltd. marine engineering firm in Glasgow, Scotland, provided the majority of funding for the Cierva Autogiro Company, Ltd. In 1932 he arranged an exclusive license to develop and market a single-place Autogiro for the firm's aircraft department. The Weir Aircraft Department's engineering staff included Cyril G. Pullin, Dr. James A.J. Bennett, G.E. Walker, F.L. Hodgess, and Kenneth Watson (fig. 5).

Following proof-of-concept work with the Weir W.1 Autogiro, the W.2 was successfully developed with a metal two-blade, fixed-pitch rotor, and an initial production run of 50 aircraft was planned. However, the aircraft was rendered obsolete due to Cierva's development of the autodynamic rotor, which had commenced in early 1933. Several months of mathematical analysis bore fruit with the first successful jump-takeoff of the C.30 prototype Autogiro G-ACFI (fig. 6), redesignated C.30 Mk.II, in August of that year. Bennett commented, "The calculation of the natural frequencies of oscillation of an articulated rotary-wing system presents considerable difficulties owing to the large number of variables which require to be taken into account… ." Cierva employed the mathematical resources of the Royal Naval College to expedite progress (ref. 10).

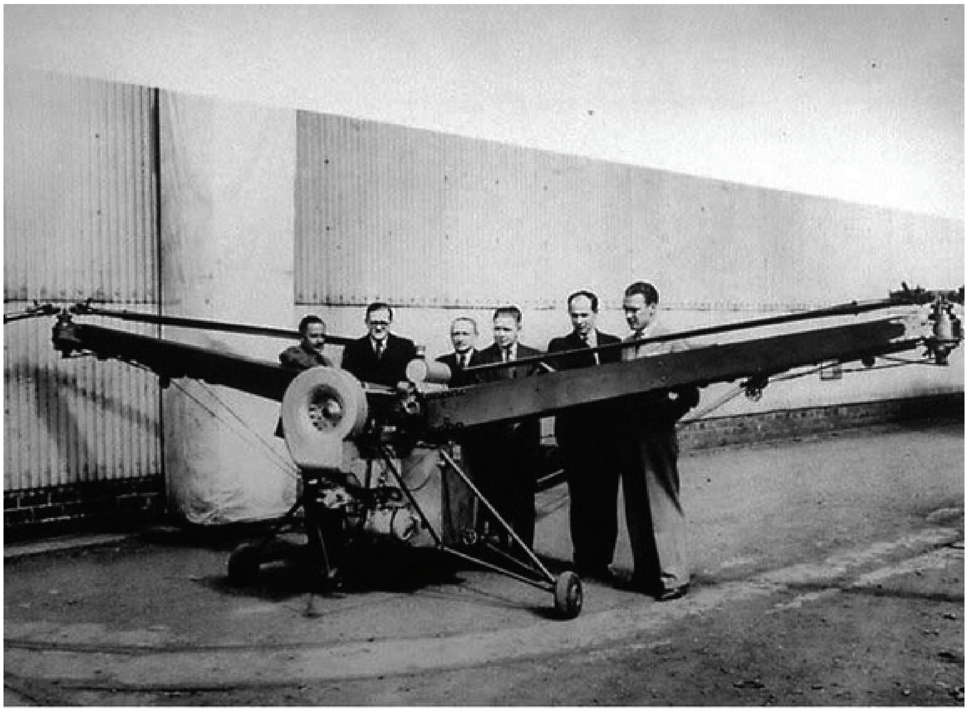


Figure 5: F.L. Hodgess, J.A.J. Bennett, Maurice Brennan, R.F. Bowyer, G.E. Walker, and R. Pullin with the Weir W-5 helicopter in 1938.

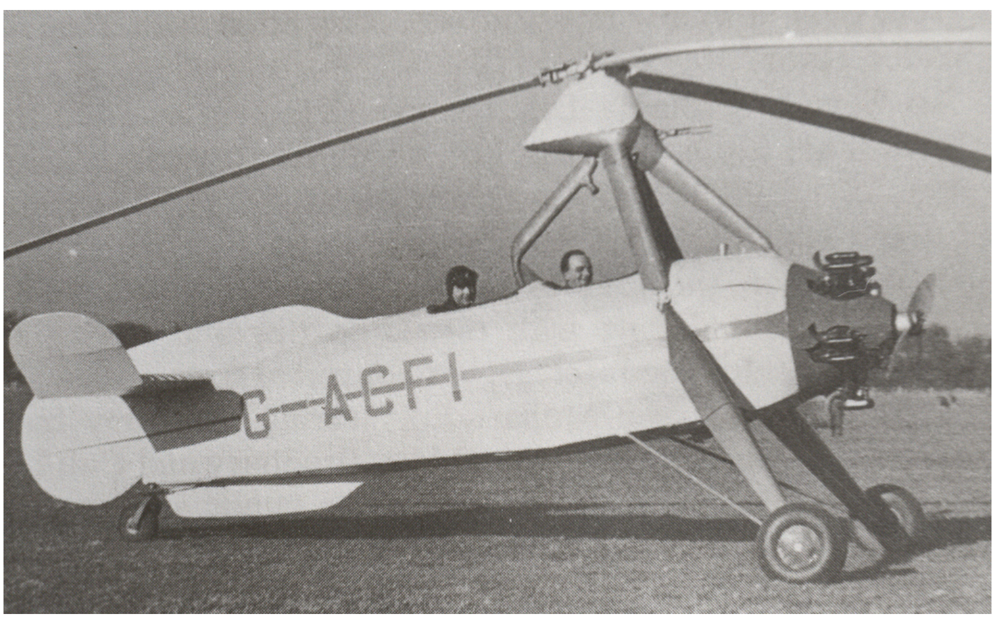


Figure 6: The C.30 Autogiro G-ACFI with standard fixed-pitch rotor before tests with autodynamic hub.

Cierva filed his first patent application for the autodynamic system in Great Britain on 5 August 1933 and included the following features:

1. Automatic reduction of blade pitch with application of driving torque by inclination of the drag hinge to include a feather component.
2. Automatic lock to maintain low collective pitch prior to takeoff until released by the pilot via a cockpit control.
3. Automatic collective pitch change in flight with variation of rotor rpm.
4. Mass balance of rotor blades to resist torsion acting on the blades and maximize rotor momentum.
5. Application of braking torque to increase rotor collective pitch prior to touchdown.
6. Maximum blade pitch angle for takeoff set at upper limit for autorotation since rotor initially operated in undisturbed air in contrast to the airflow developed by a helicopter rotor (ref. 11).

Cierva and Test Pilot Alan Marsh conducted flight tests of the G-ACFI fitted with various three-blade autodynamic rotors with positive alpha-1 drag-pitch couplings over a period of 16 months (fig. 7) (table 2). These flight tests disclosed conflicting requirements, persistent instability, and high vibration. Rapid collective pitch change required for takeoff was hindered by drag dampers necessary to avoid ground resonance. Consistent symmetrical motion of the blades about the alpha hinges was difficult to achieve with separate dampers (fig. 8) and was addressed by their replacement with a centralized damper stack to which each blade was connected by linkage. High positive alpha-1 drag-feather coupling ratios increased the magnitude of blade flapping by adding a second, independent, frequently out-of-phase blade pitch change that caused vibration, instability of the tip-path plane, and blade root pounding above a certain airspeed.

In a 1 June 1934 letter to Cierva, Harold F. Pitcairn (fig. 9), whose Autogiro Company of America was U.S. licensee of the Autogiro patents, commented:

> “ I am concerned over the fact that quite a few people here know that you have been experimenting with a ‘jump-off’ machine. I have the impression that you have discarded the inclined hinges as impractical, and therefore assume that temporary direct lift will have to be accomplished in some other way [ref. 12].”

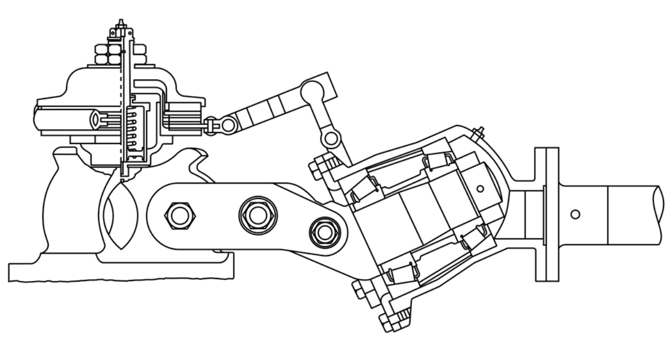
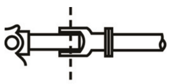
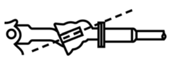
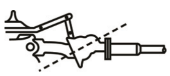
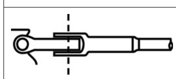
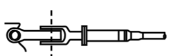
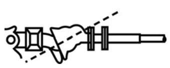
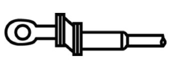
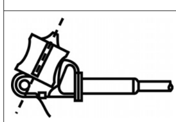
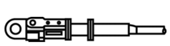
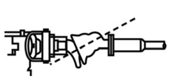
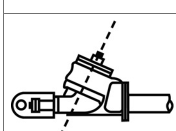
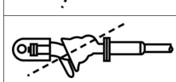
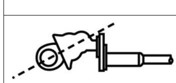


Figure 7: Autodynamic rotor with positive drag-feather coupling and single central drag damper. Tested on the C.30 G-ACFI (U.S. Patent 2,380,583).

TABLE 2. DETAILS OF AUTODYNAMIC ROTOR HUBS (REF. 9)

Hub	Aircraft	Number of Rotor Blades	Rotor Direction of Rotation	Main Features
	C.30P	3	Clockwise	Standard hub with drag hinge friction dampers.
	C.30P	3	Clockwise	Standard hub with alpha-1/α-1 hinge.
	C.30 (G-ACFI)	3	Clockwise	Negative alpha-1/α-1 inclination at 26º to horizontal.
	C.30 (G-ACFI)	3	Clockwise	Negative alpha-1/α-1 inclination at 26º to horizontal and fitted with central friction damper.
	C.30A	3	Clockwise	Standard hub with friction dampers.
	C.30A	3	Clockwise	Standard hub with friction dampers and adapters to accept oval blade spars.
	C.30 (G-ACFI)	3	Clockwise	Adjustable alpha-1/α-1 hinge.
	C.30A	3	Clockwise	Standard hub with adapters to accept oval blade spars and offset block.
	C.30P	3	Clockwise	Standard hub fitted with inclined drag hinge and needle races.
	C.30 Mk.II	3	Anticlockwise	Friction damped alpha hinge.
	C.30 Mk.II	3	Anticlockwise	Positive alpha-2/α-2 hinge inclination of 50º.
	C.30 (G-ACFI)	3	Clockwise	Adjustable delta hinge and negative alpha-1/α-1 hinge inclination.
	C.30 Mk.II	3	Anticlockwise	Adjustable negative alpha-2/α-2 hinge inclination.
	C.30 Mk.II	3	Anticlockwise	Adjustable negative or positive alpha-2/α-2 hinge inclination.
	C.30 Mk.II	3	Anticlockwise	Alpha hinge mounted directly to delta hinge.

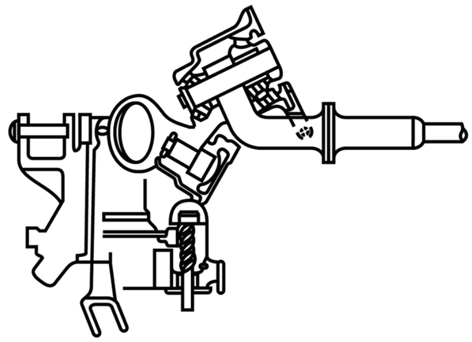


Figure 8: Autodynamic rotor with negative drag-feather alpha-1 coupling and individual drag dampers. Tested on the C.30 Mk.II (ref. 9).

Figure 9: Harold F. Pitcairn (photo from author's collection).

Cierva attempted to develop the autodynamic rotor covertly, but because testing was being conducted at Hanworth Aerodrome, adjacent as it was to a residential area and a large hotel, it was not possible to maintain absolute secrecy. Despite Pitcairn's comment, Cierva continued development of the autodynamic rotor using inclined hinges.

J.A.J. Bennett commented on testing of the first autodynamic rotors:

> "Cierva soon discovered that the simple angled drag hinge was not a practical solution of the direct take-off problem. To utilize effectively the kinetic energy of the rotor for an inertia take-off, he could not allow friction or hydraulic dampers to act as a brake, a quick change of pitch being required, yet dampers were necessary to prevent 'ground resonance'. Consequently, a hinge arrangement like the 'alpha-two' had to be selected that provided an alternative to friction dampers and allowed the blades to oscillate freely, but unlike the alpha-two hinge, provided the required change of pitch in response to torque. Such an arrangement, applicable only to two-blade rotors, was found. A negative α-1 inclination gave freedom from ground resonance without dampers in a

two-bladed rotor but not a three-bladed one. The blades, however, had to be driven against their forward stops before takeoff instead of being allowed simply to swing back naturally as in the case of positive α-1 [ref. 9].”

The intractability of the problems with the three-blade rotor prompted development of a two-blade autodynamic rotor that, although possessing an inherent two-per-rev vibration characteristic in addition to the blade oscillatory phenomena arising from the coupled blade motions, offered a practical development path. This compounded the development problems because, except for various tests of two-blade rotors starting with the Cierva C.8R in 1927 (fig. 10) and abandoned due to vibration problems, all Autogiro rotors had included three or four blades. The use of a two-blade rotor mandated solution of the previously unsolved problems in addition to those posed by the autodynamic system.

To Pitcairn’s dismay (and caused by poor business relations), Kellett Autogiro Company Chief Engineer Richard H. Prewitt made an unannounced visit to Hanworth Aerodrome to observe autodynamic rotor developments. In a 17 October 1934 report, Prewitt noted:

“The [Cierva jump-off giro], having a two-bladed rotor which incorporates cocked horizontal [positive flap-feather] and vertical [positive drag-feather] hinges, jumps off up to 25 to 40 feet. The hub mechanism is apparently complicated and weighs approximately 200 [lb]. The ship cannot be flown more than 60 m.p.h. due to ‘bottoming’ of the blades at higher speeds. The bouncing in this rotor is supposed to decrease with increase of forward speed but according to Ray, it would have to be reduced to ¼ its present value to be commercially passable. Cierva claims to be able to reduce this bouncing to half its present value.

Cierva claims this rotor has increased efficiency and stability [ref. 13].”

Figure 10: The Cierva C.8R, 1927.

On 28 October 1934 Pitcairn, accompanied by his engineers, Agnew E. Larsen and Paul H. Stanley, and pilot, James G. Ray, observed test flights of G-ACFI with the positive delta-3 flap-feather and positive alpha-2 drag-flap coupled autodynamic rotor hub during which he executed climbs from the top of 10-foot jumps.

On 19 November 1934 the C.30 Mk.II was demonstrated at Hanworth Aerodome for Air Ministry officials:

> "After one preliminary attempt Señor Cierva caused the machine to rise vertically from the ground to a height of five or six feet and then to proceed forward and begin to climb without subsequently touching the ground. The rotor was speeded up to a higher rotational rate than would ordinarily be customary, and the pitch angle was automatically changed from about zero to the normal amount for an autogiro, by tilting the azimuth axis of the three blades outwards to about 45° [sic]. It was noticed that the inventor took much trouble beforehand to adjust the damping mechanism [ref. 14]."

Bennett later summarized some of the mathematical analysis accomplished with the two-blade autodynamic rotor:

> "An approximate method will now be described of obtaining the natural vibrations of a two-bladed rotor in which the drag hinges are inclined downwardly and outwardly. This approximation requires the solution of fourth degree equations. Later a more accurate method is considered in which eighth degree equations have to be solved, and it will be seen that an accurate analysis of a three-bladed rotor would be extremely laborious owing to the increased number of variables and therefore of simultaneous differential equations.
>
> [...] Stability with reference to pendular oscillations is attainable in a two-bladed rotor without frictional damping of the drag hinge when tan α-1 is negative, i.e. when the drag hinge is inclined outwards and downwards. This result is due to aerodynamic damping alone […] .
>
> It is found that this theoretical result is confirmed in practice and that whenever tan α-1 is made positive it is impossible to drive the blades up to their take-off speed owing to the uncontrolled motion of the rotor tip-path plane as predicted by the theory. These results apply, of course, only to a two-bladed rotor and it is found by experiment that a negative value of tan α-1 does not give stability in the case of a rotor having three blades.
>
> Frictional damping and its associated maintenance troubles can, however, be avoided by tilting the axis of the drag hinge through an angle (alpha-2) in a plane perpendicular to the radial axis of the blade so that displacements about the drag hinge have both flapping and rotational [drag] components but have only a negligible feathering component. Provided [alpha-2] is designed in accordance with a requirement to be discussed later, the blades may be allowed to oscillate smoothly about their drag hinges without friction dampers, yet without becoming unstable either in flight or on the ground [ref. 10]."

In February 1935 Walker and Bennett were assigned to Hanworth to assist Cierva; Pullin, Hodgess, and Watson remained in Glasgow. By August Cierva claimed to have achieved conclusive results in his analysis. In June the Weir Aircraft Department started design of a single-place Autogiro designated W.3 (figs. 11, 12, and 13). This aircraft was to test autodynamic rotors developed independently but in cooperation with Cierva and Bennett. The Weir W-2 was used for testing until the W-3 became available.

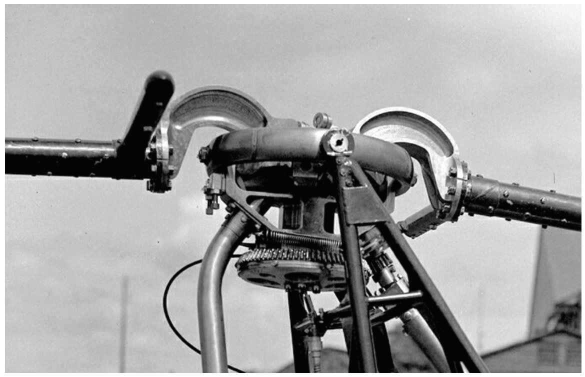


Figure 11: The Weir W-3 rotor hub.

Figure 12: The Weir W-3 with engine cowl removed.

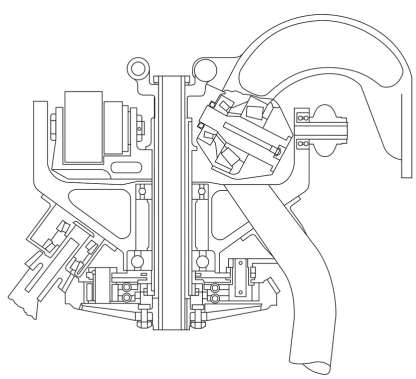


Figure 13: The Weir W.3 two-blade autodynamic rotor hub with high-ratio negative drag-feather alpha-1 coupling and low-ratio flap-drag delta-2 coupling. No drag dampers (U.S. Patent 2,216,768).

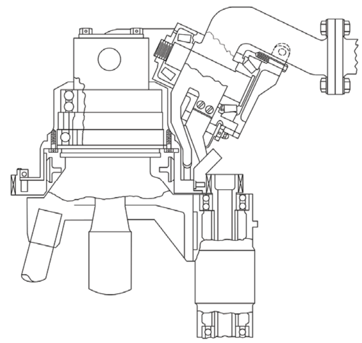


Figure 14: The C.30 Mk.III two-blade autodynamic rotor hub with low-ratio negative drag-feather alpha-1 coupling and positive delta-3 coupling. No drag dampers (U.S. Patent 2,216,768).

In addition to any delta-3 flap-feather coupling, the two-blade autodynamic rotor hubs fitted to the W.3 and C.30 Mk.III could be biased by giving each flapping hinge a negative delta-2 flap-drag coupling of up to 10 degrees to swing the blades onto their forward stops when at rest.

G-ACFI had suffered damage to its landing gear in October 1935 and the C.30A G-ACWF, redesignated C.30 Mk.III, was modified for testing duties (fig. 14).

The following are excerpts from flight test reports (ref. 15) filed by Marsh (fig. 15):

"13 December 1935, C.30 Mk.II:

- [Rotor] rotates out-of-balance at very low revs but OK about 50 rpm onwards.
- Declutching at 100 rpm and taxying forward.
- Blades appear to track well and nothing felt in stick.
- Rough surface affects machine badly.
- After about 120 rpm machine appears to get light on the tail, and starts fore-and-aft oscillating which lurches onto front wheels and starts intense wobble.

14 December 1935, C.30 Mk.II:

- Machine becomes unstable with rotor rpm about 120 over rough [ground]. Trouble starts in tail and throws [machine] forward and sideways as before.
- Cierva impression that machine is getting light at 140 rpm.
- Rotor seems perfectly smooth, and also controls.

Flight tests disclosed 'vertical bouncing about as good as on any tests, but definitely developed a greater intensity after being a few minutes in the air. Also, I had the impression that at certain times it increased quite a bit and then settled back to normal.

Very little difference in bouncing but should say it was slightly worse. Did not notice quite the same phenomenon re machine increase in vibration as on previous tests – possibly due to smoother air. Even so bouncing or vibration still increases the longer one stays in the air.'

5 January 1936: C.30 Mk.II:

- Rotor drive works quite well, also clutch and rotor brake. One has to pause a short while after releasing rotor brake and before engaging clutch.
- Taxying and takeoff as usual after obtaining 115-120 rpm.
- Vertical bouncing about as good as in any tests, but definitely developed a greater intensity after a few minutes in the air. Also I had the impression that at certain times it increased quite a bit and then settled back to normal.

- After weights added to blades, initially very little difference in bouncing, but should say it was slightly worse. Did not notice quite the same phenomena re. sudden increase in vibration as on previous tests – possibly due to smoother air. Even so bouncing or vibration still increases the longer one stays in the air.
- Motion of fore-and-aft control does not appear to vary with speed as one notices in the C.30. Lateral control is still 2-2½" to the right at 40 mph. Will check this for different speeds on next test. Slight pull forward on control for all conditions of flight so far obtained, except for tail heaviness after taxying off.

2 February 1936: C.30 Mk.II:
- Fitted with fabric-covered Mk.III blades.
- Starting up and taxying off as usual. Starting up not as rough as in higher winds. Clutch will only give 140 rpm with blades at this setting.
- Rotor rpm 145-150 at takeoff, 150 in vertical descent, 160 at 50-55 mph.
- Blades tracking not at all well. Vertical vibration in worse than at any previous time on these blades, and as bad as at any time on previous blades. 'Building up' of vibration also was quite bad in spite of smooth conditions.
- Motion of fore-and-aft control does not appear to vary with speed as one notices in the C.30. Lateral control is still 2-2½" to the right at 40 mph. Will check this for different speeds on next test. Slight pull forward on control for all conditions of flight so far obtained, except for tail heaviness after taxying off..
- Later test, during runup engine coughed at 65-70 rotor rpm. There was a loud noise in the head as if the Bendix drive threw out and back in again, and on looking up I saw that the hub had taken up a set to port. I applied the rotor brake, and when the blades had stopped discovered that [I] could not move the control.

11 March 1936: C.30 Mk.III:
- Fitted with fabric-covered blades.
- Change of incidence quite definite when quick release is thrown. Machine gives a small jump (not clear of the ground) at about 120 rpm.
- Rotor brake works satisfactorily by throwing blades on front stop, but is not very powerful.

14 March 1936: C.30 Mk.III:
- Head has been dismantled since previous tests, and examined at Mollarts to try and discover cause of unequal drive on blades while starting, and also the thrust bearing of the alpha hinge has been altered.
- Two starts up to 150 rpm – one with alpha hinge free and one with blades locked forward against front stops.
- In both cases there was a distinct 'wobble' on machine when revving up, and it was impossible to hold the stick against the movement. The movement on the stick was mostly in a lateral sense, and when the clutch was released the control was quite smooth.

11 June 1936: C.30 Mk.II:
- Inching bearing installed in rotor hub.
- Starting and running up to 120 rpm machine is still quite rough and sets up an unpleasant lateral and slightly vertical movement in tail.
- Certain amount of building up and once per rev movement to stick.
- Jump at maximum rpm. Height about 25-30 feet, and flew off quite well with little loss of height."

Testing disclosed problems with the W-3 rotor due to inconsistent friction about the alpha hinges. The cause was traced to false brinelling due to the very small reciprocating oscillation of each rotor blade shaft about its bearing. Watson solved the problem by developing an "inching bearing" that eliminated localized wear by rotating the bearing around slightly with each blade oscillation. During development of the W.3 autodynamic rotor, Pullin later noted: "In the case of the Autogiro angled hinge system, reasonable control effort was only possible when the plain

Figure 15: Autodynamic rotor test pilot Alan Marsh (photo courtesy of John T. Bent).

bearings had been replaced by ball or roller bearings [ref. 16].” Another problem, excessive weight variation between rotor blade metal spars, was solved by a chemical milling process developed by Jack Arnott, Chief Chemist of G&J Weir, Ltd. (ref. 17).

On 18 February 1935 Cierva asked the Air Ministry for a contract to build two direct takeoff Autogiros based on the C.30A and including “…a new design of rotor blade with improved all round characteristics, new method of blade attachment which provides the automatic pitch variation necessary for taking off, and new undercarriage with considerably improved shock absorbing characteristics, and the latest version of the Genet Major engine which develops appreciably higher power.” This led to the issuance of Air Ministry contract 404378/35 that left all decisions regarding design of the aircraft to the Cierva Autogiro Company providing it carried two persons and could execute direct-takeoffs. A 23 March 1936 letter to the company discussed

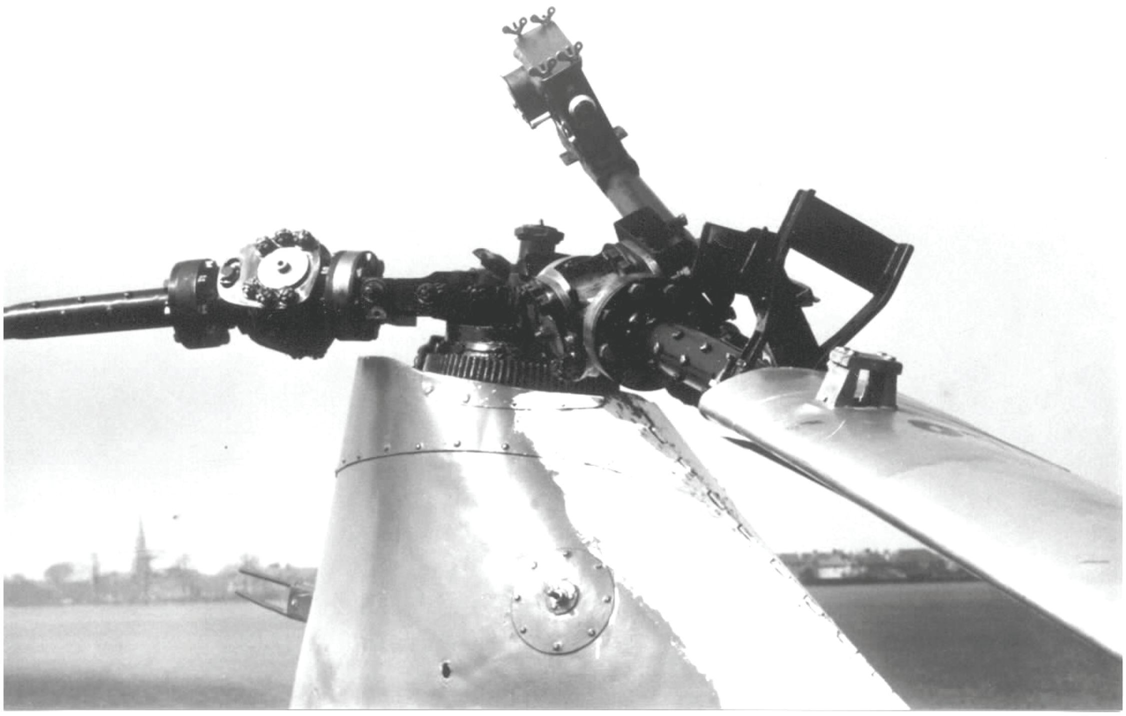


Figure 16: Autodynamic rotor hub fitted with camera to record coupled negative alpha-2 drag-flap blade motion, G-ACWF (clockwise-turning rotor), 1936 (photo courtesy of John T. Bent).

the danger to the pilot posed by the hanging stick rotor control in the event of an accident, and included a request for either a panel-mounted or floor-mounted rotor control "…in one of the direct lift autogiros that you have in construction for the Air Ministry." The company responded that the rate of progress with development mitigated against such modification and recommended retrofit of the feature at a later date (ref. 14). The Air Ministry issued Specification 43/36 for two Autogiros designated C.40 in July 1936 (ref. 18). Design of the aircraft commenced under engineer Otto Reder while autodynamic rotor development continued on the C.30 Mk.III (figs. 16 and 17).

Further flight test reports (ref. 15) from Marsh:

"3 July 1936: C.30 Mk.III:

- Fitted with blades with special finish, stiffened trailing edge but now too thick. ¾ lb. weight fitted at ¾ radius but fitting now not sufficiently strong for jump-off and flying tests. Drain holes not provided for so delay necessary while these were added.
- Blades fitted at normal incidence and test run locked to 107 rpm.
- Different blades fitted and run up to 190 rpm. Machine very rough when running up and also one-per-rev vibration in stick very bad. This has been the case since the crown wheel was allowed greater clearance.
- Jumped about 10 feet and flew off quite well.
- General vibration about normal for idle thrust bearings, and also building up and once-per-rev in stick.
- Blade pull-off 13-14 lb. When stopping into wind they came off front stops at low rpm.

- Demonstration at Hounslow Heath to Dobson and Chadwick of A.V. Roe. Rolling takeoff at

Hanworth; jump takeoff at Hounslow.
- Demonstration to Petter of Westland. Rolling takeoff at Hanworth; two jump-takeoffs and landings at Hounslow Heath.

14 July 1936: C.30 Mk.III:
- Since the demonstration to Petter at Hounslow [Heath] on 3 July, a good deal of trouble has been experienced with the hydraulic system. This has been dismantled and thoroughly cleaned. 19 July jump-takeoff demonstration to RAF officials canceled due to doubtful state of system.
- Starting and running up to maximum rpm with blades locked, the machine is very smooth, but when running up with blades free it is very rough indeed.
- Jump was made at maximum rpm about 210 – 220 and was about 25-30 feet – flew off quite well.
- General vibration is better than with previous idle pins, but not as good as with 'inching round' bearings.
- Brake pull-off 15 lb. approximately but not enough for any appreciable amount of wind.
- Demonstration to Pearson and Nellie of Vickers at Hanworth.
- One jump about 20 feet and one circuit.
- Machine being left as-is for further demonstrations. We are trying to discover the source of the roughness while running up, and also cleaning the machine up a little."

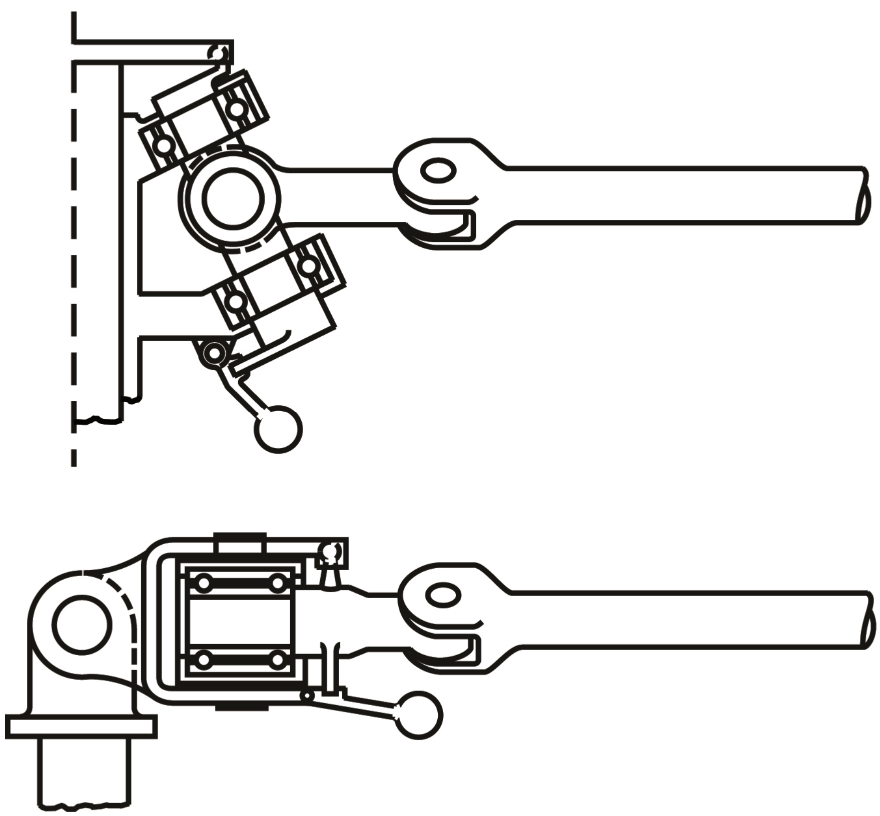


Figure 17: Autodynamic hubs of the type tested on G-ACWF (U.S. Patent 2,197,677).

Marsh conducted the first flight of Weir W-3 in Glasgow on 9 July 1936 after which it was transported to Hanworth Aerodrome. He conducted further test flights of the W-3 on 14 and 15 July. His report states:

"• Starting and running up to 220 r.p.m. and taxying off.
- Rotor r.p.m. 200–205 in vertical descent.
- [Rotor r.p.m.] 210–215 at 40 m.p.h.
- General vibration appears to be increasing steadily. "Building up" quite bad in gusty conditions. Stick is free from once per rev. movement, but has slight twice per rev. movement, which, I think, is in sympathy with the vibration in the machine.
- The carburetter has been tuned by changing the "changeover or bridging" jet (from slow running to main). This has been increased in size. The engine picks up better, but still has a flat spot about 1800 r.p.m. running free, and about 1400 r.p.m. when driving the rotor.
- First jump at 310–315 r.p.m. appeared to b the maximum r.p.m., and machine jumped about 4–6 ft., and flew off. After this, the blades, etc. were checked over, and I tried again and obtained just under 340 r.p.m. for two jumps. On each occasion the machine jumped about 12 ft. or so, and flew off quite well. It must have been my fault in the first case in allowing the clutch to slip, but even so we are still 10–12 r.p.m. down from the last test in Glasgow. One jump was made on the morning of July 15th in a wind of about 5–6 m.p.h., and the machine jumped about 10 ft. and flew off.
- The fore-and-aft "hunting" is more pronounced in gusty weather, and also the peculiar turning characteristic [ref. 19].

17 July 1936: C.30 Mk.III [fig. 18]:
- Demonstration to *Flight*, *Aeroplane*, Sir Robert Kindersley, etc. at Hounslow Heath.
- Cowlings have been made and fitted to cover the link mechanism.
- One jump at Hanworth, flight to Hounslow Heath, two jumps there and return to Hanworth.
- Starting and running up to maximum r.p.m. in each case 210 r.p.m.
- General vibration and "building up" not quite so bad in these conditions.
- Rotor r.p.m. normal.
- Rotor brake will have to be improved [ref. 15].

19 July 1936 C.30 Mk.III:
- Demonstration to Secretary of State for the Air and Lord Weir at Hounslow Heath.
- 18 lb weight reduction by removing extraneous equipment, added fairings to pylon struts. Cierva practicing jumps, and idle pins inspected on two occasions.
- Jump takeoff at Hanworth; two jump takeoffs at Hounslow Heath.
- 210 rotor rpm. All jumps quite good and flies off without any appreciable loss of height.
- General vibration is distinctly bad and appears to be more of type experienced before. i.e. heavy on one beat and light on the other. Building up quite appreciable too. Blades hitting [droop] stops at 60 mph.
- Rotor brake barely strong enough for gusty 10-15 mph wind.
- Machine stands up very well to vertical drop of 6-8 feet (during landing) as long as it does not drift backwards.
- A fairing is being made to cover up as much of the hub mechanism as possible. The hydraulic gear is behaving very well now, but the quick release lever is really loose and must be stiffened up. Something should be done to try and make the machine smoother when starting up, but it actually looks worse than it feels [ref. 15]."

The W-3 direct takeoff procedure was actuated through a gated lever system operated by the pilot. The mechanism comprised a single lever that, when moved to its first gate, engaged the rotor drive. Moving the lever to the second gate engaged the clutch, and the third gate applied the main wheel brakes. Once the required rotor rpm was gained by advancing the throttle fully, pressing a button below the gated lever released the rotor drive, clutch, and main wheel brakes simultaneously. The pilot held the control stick slightly aft as the Autogiro jumped, and the propeller accelerated it into translational flight. Because a rotor controlled by hub tilt cannot directly control the fuselage attitude, the W-3 pointed slightly nose-down during the jump due to the location of the center of gravity until sufficient airflow passed over the horizontal stabilizer to align the fuselage with the flightpath (fig. 19).

Figure 18: The C.30 Mk.III executing jump-takeoff at Hounslow Heath, 17 July 1936.

Figure 19: The Weir W-3 executing jump-takeoff at Hanworth Aerodrome.

Marsh flight test report (ref. 15):

> "23 July 1936: C.30 Mk.III:
> - Shorter quick release lever fitted.
> - Three jumps to see what could be accomplished in calm wind conditions. First jump to 15 feet and pull away not very good.
>
> Rotor rpm and vibration almost normal. Rotor brake very bad and one blade came off front stop when slowing down.
> 23 July 1936: C.30 Mk.III
> - At rotor runup to 200 rpm, machine jumped and held height quite well.
> - General vibration and building up quite bad in gusty 15-20 mph conditions and also hit droop stop a number of times.
> - Jumps and pull-away quite good in these conditions.
> - Speed must not exceed 60 mph to avoid blades hitting droop stops or even 50 mph in gusty conditions.
>
> 14 September 1936, C.30 Mk.III:
> - Rotor head sent to Mollarts for installation of knife-edge bearings in place of the roller races of the alpha hinge, and also inching bearing thrust races.
> - The general vibration is definitely much better than I have ever had it, and I should say the bouncing has been cut by approximately half. This must be taken with a certain reservation as the speed never exceeded about 35 mph and the conditions were excellent. Also, it must also be borne in mind that there is a great deal of room for improvement.
> - The once-per-rev movement on the stick has not been altered and is quite pronounced.
> - Rotor rpm 175 at 35 mph airspeed."

Table 3 shows the results of two-blade autodynamic rotor tests conducted on the C.30 Mk.III with various alpha-2 drag-flap inclinations and bearing combinations.

Watson made the following observation regarding tests conducted with the Weir W-3: "The autodynamic rotor system … didn't quite meet expectations; sometimes it was rough and sometimes smooth. It was discovered [that] friction in the alpha-1 hinge played a big part in whether the system functioned in step or out of step. The hinge motion required a low and consistent friction if [it] was to function properly" (ref. 17). The alpha hinge torsion bearing was replaced with preloaded stranded steel cable in an attempt to address this problem (fig. 20).

TABLE 3: RESULTS OF TWO-BLADE AUTODYNAMIC ROTOR TESTS (REF. 20)

Test Number	Alpha-2 Angle (deg)	Distance of Drag Hinge Axis From Rotor Axis of Rotation (in.)	Distance of Drag Hinge Axis From Flapping Hinge Axis (in.)	Type of Bearing in Drag Hinge	Flight Test Results
1	60	10.64	8.84	Plain bushes	No air resonance or ground resonance.
2	60	4.3	2.5	Plain bushes	Ground resonance.
3	50	10.64	8.84	Plain bushes	Ground resonance.
4	65	10.64	8.84	Needle bearing	Incipient air resonance and bad ground resonance.
5	65	10.64	8.84	Plain bushes	No air resonance or ground resonance.

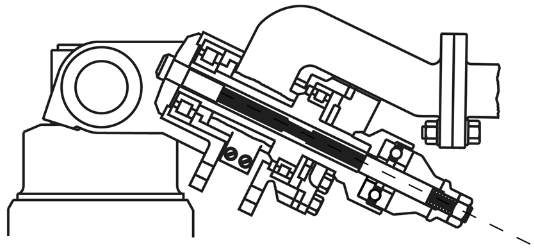


Figure 20: The C.30 Mk.III autodynamic hub with alpha hinge torsion bearing replaced by stranded cable (U.S. Patent 2,173,153).

Marsh flight test report (ref. 15):

"12 November 1936 C.30 Mk.III:

- Since last tests on 25 September 1936, various tests made at [the G&J Weir, Ltd., facility in] Cathcart to test a cable attachment to take the axial load, the radial load being taken by roller bearings.
- Two takeoffs and straights.
- Machine very rough when running up.
- Very bad once per rev vibration in machine but not in stick. Blades badly out of track. Both of these results to be expected when bad blade incidence setting considered.
- Quite impossible to get any impression of two-per-rev vibration due to magnitude of once per rev vibration.
- Cables were taken out and examined, and it appears that both heart wires are badly broken, more so in one than in the others."

During most of 1936, Cierva was distracted by the deteriorating political situation in Spain, which adversely affected his development work and hitherto excellent relationship with Pitcairn. In June he arranged for an aircraft to fly General Francisco Franco from the Canary Islands to Morocco, which precipitated a military coup against the Republican Government in Madrid. On 9 December 1936 Cierva boarded a KLM DC-2 at fog-shrouded Croydon Aerodrome. At 10:30 a.m. the aircraft took off and, drifting slightly off course, headed towards gently rising terrain where it slammed into a house at 25 Hillcrest Road, Purley. Cierva and 13 other passengers died in the ensuing fireball. Three passengers survived and, through great fortune, no one on the ground was injured (ref. 21).

Cierva's death has been considered a major cause of the eventual decline of the Autogiro and rise of the helicopter. However, Wynn Lawrence LePage, a British engineer long associated with Autogiro development in the United States, quite unequivocally stated Cierva had accepted that the limitations of the Autogiro would be solved by the helicopter (ref. 22). Design study of a two-three-seat hovering Autogiro designated C.39 had been made prior to Cierva's death. The design, termed *Gyrodyne* (gyratory aerodyne), employed a powered rotor and propeller laterally offset from the longitudinal axis to provide anti-torque control and forward thrust. Power delivered to the rotor and propeller varied differentially with airspeed, respectively. Bennett was appointed Technical Director upon Cierva's death, and would eventually supervise development of the Gyrodyne into a viable aircraft as well as successfully complete work on the direct-takeoff Autogiro.

Paul Stanley reported the following regarding a 20 December 1936 test of the C.30 Mk.III at Hanworth Aerodrome (ref. 15):

> "Jim Ray flew 10 minutes; Marsh flew 15 minutes. At 70 mph droop stops hit three times. It was agreed that this machine was pretty rough at all times, and became rougher with increased forward speed. It was agreed that this machine is too rough for any comfort in flying, with the roughness a minimum in vertical descent. Bouncing and other disturbances were present with a tendency to build up and subside. Roughness increased in both right and left turns. The blued shanks of the cables were inspected but it was impossible to determine whether the few marks found were obtained in flight or during the assembly of the cables.
>
> Both inner and outer cable shanks were blued, and the root weights were moved out to the extreme distance from the center of the spar. After both March and Ray had tested the machine in these conditions, it was felt that any changes in the roughness were slight, but there possibly had been a little decrease in roughness. Marsh observed that rotor rpm had increased slightly. Roughness still increases with increase in forward speed, and still seems to be a beating phenomena. The fore-and-aft pylon wobble seems to be a little stronger than the lateral wobble. Marsh also thinks the increase of roughness in turns is about the same in right or left turns, or possibly even a little more in left than right turns.
>
> No information was obtained from an inspection of the blued cable shanks.
>
> The original 140 cwt. cables, in which the heart strands had failed, were then installed, and tests conducted."

Pitcairn engineers worked on an alternate method of providing automatic collective pitch change that did not employ the alpha-1 drag-feather coupling used by Cierva. As reported by Harris S. Campbell and Paul Stanley (ref. 23):

> "Experiments have been conducted by the Autogiro Company of America for the past nine months on one form of direct take-off mechanism as applied to the PA-22 Autogiro. This mechanism consists of steep-pitch threaded extension blocks which permit changes of blade pitch angle between two limits, determined by stops. The lower limit used during rotor acceleration for direct take off is now slightly below the pitch angle of zero lift, and the blades are held in this position by force applied from hydraulic cylinders. When the pressure is released in these cylinders, centrifugal force in each blade draws the blade out along the steep thread of the extension block until this action is stopped by the stops limiting the 'up' angles of the blades."

The PA-22 prototype Autogiro (fig. 21), built as a technology demonstrator in 1933, was used extensively for development of the Pitcairn tilting-hub direct control system. From July to September 1936, Jim Ray tested the aircraft with a two-blade jump takeoff rotor that permitted 15-degree incremental variation of the flap-feather delta-3 angle from 0 to 45 degrees. The alpha hinges were fitted vertically with oscillation of the blades controlled by friction dampers. Though this system was subject to vibration inherent in a two-blade rotor, it did not suffer from the vibration and droop stop pounding in flight caused by inclined alpha-1 hinges, and Ray considered this rotor to be superior to that of the C.30 Mk.III (ref. 24).

Marsh flight test report (ref. 15):

> "20 January 1937: C.30 Mk.III
>
> - Since the tests yesterday another type of cable has been fitted. Also an arrangement of lamps is mounted to show the movement about the alpha links.
> - Intensity of bouncing about the same as for some time past, but a form of periodical "build-up" is again noticeable as apart from building up in parts. Links just begin to hit droop stops at a

speed of 65-70 mph. The lights did not shine at all during flight. After landing it was quite an appreciable time before the lights came on after applying rotor brake, and then only one. The other lamps came on when the blades had almost stopped. Ray did about 10 minutes flying with approximately the same results.

- Stick positionmeters are now being fitted."

The Cierva Autogiro Company had made known to H.E. Wimperis of the Air Ministry its problems in identifying sources of vibration in the W-3. On 22 January 1937, the aircraft was fitted with two vibrographs, loaned by the Royal Aircraft Establishment, to measure and record rotor pylon vibration. The results were generated and reviewed by F.G. Barlow, a Royal Aircraft Establishment engineer, J.A.J. Bennett, and Paul Stanley. Two flights were made with a vibrograph mounted on each side of the rotor pylon, both flights conducted at 2,600 engine rpm, 220 rotor rpm, and 30 mph indicated airspeed (IAS). For both flights the port vibrograph recorded longitudinal vibrations. During the first flight the starboard vibrograph recorded transverse vibrations, and during the second flight it recorded vertical vibrations.

The first test flight disclosed a regular transverse vibration at twice rotor rpm of 0.070" amplitude with occasional reduction of amplitude to 0.017" for a period of 0.1–0.2 second. The report noted, "It is possible that such decrease would give an impression of shock to the pilot." Longitudinal vibrations at a frequency of twice rotor rpm occurred at an average amplitude of 0.020–0.025" with an occasional gradual increase to 0.040–0.045". A periodic vibration at a frequency of four times rotor rpm superimposed on a second order vibration with the amplitude varying between 0.016–0.040" was noted. The report stated "…reasons for the occurrence of this vibration with a two-blade rotor are not immediately apparent."

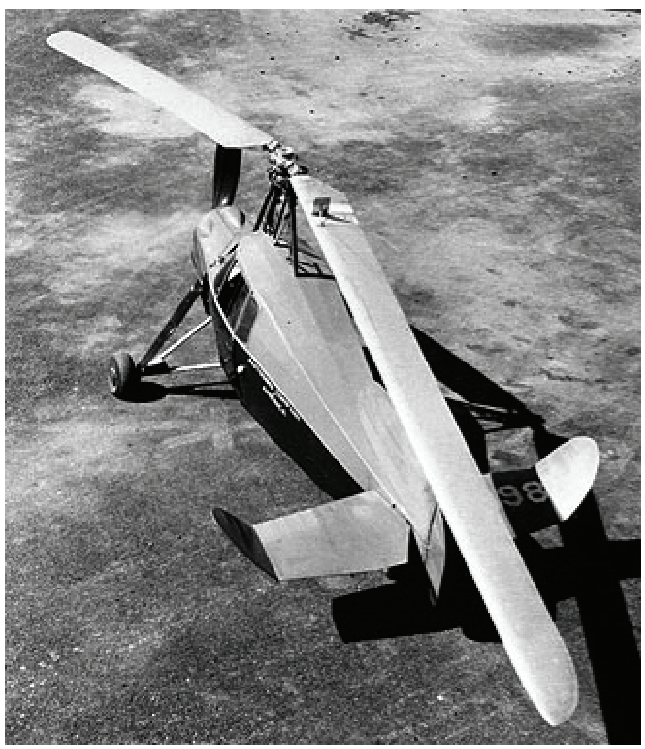


Figure 21: The Pitcairn PA-22 with two-blade autodynamic rotor (photo courtesy of the National Air and Space Museum).

The second test flight disclosed a regular [vertical] vibration at twice rotor rpm and fairly constant amplitude of 0.016" with a maximum amplitude of 0.024". The report stated, "It is of interest to note that this vibration is at the threshold of unpleasantness with an amplitude of 0.016" and would cause distinct discomfort with 0.024" amplitude." The longitudinal results were found to be essentially identical to those recorded on the first flight except for the absence of the fourth-order rotor vibrations.

The resultant of all measured pylon vibrations was resolved to an ellipse with its major axis aligned along the longitudinal axis and inclined 27 degrees down towards the nose (ref. 14).

Marsh flight test reports (ref. 15):

"15 February 1937: C.30 Mk.III

- Two arm vibration absorber fitted on rotor hub at Cathcart [Glasgow] in attempt to reduce bouncing vibration. Unsuccessful.

17 March 1937: C.30 Mk.III

- Since the tests on 5 March various things have been done to the head. A central friction damper has been fitted to the alpha links and the delta 3 hinges again fitted between the blade flange and alpha link, but this time they will be set to work in the opposite direction to tests on 27 February. With all this outfit rigged up the machine was tested off the ground but was so very bad – out of track and very bad vertical movement – that we started again. The friction damper was disconnected and the delta 3 hinges locked and we concentrated on getting the blades in track. Two or three days were spent on this and then it was discovered that the blade incidence was all wrong and somehow the blade structure had become misformed.
- Generally speaking a great deal more unpleasant to fly.

25 May 1937: C.30J

- Blade incidence adjusted.
- Ten minutes flying to check for trim and general smoothness, etc. Machine is fairly tail heavy, but flyable. Control is quite definitely rougher but out of track not appreciable. Flight bias to right noticeable at low speed. Rotor down by 3–4 rpm.

26 May 1937: C.30J

- Blade incidence increased a further ½°.
- Five minutes flying to check trim, etc. Machine very tail heavy. Control even rougher than previously and out of track noticeable. Bias to right a little more pronounced but not enough to worry about for general flying. Rotor down by 3–4 rpm again and now reads approx 140 in vertical descent with usual corresponding increase in speed.
- Tail altered 1°30″ and now reads 3° plus. Bias spring tightened.
- Ten minutes flying to check trim, etc. Tail heaviness less pronounced. Other remains as before.
- One jump at maximum rpm but cannot give the figures. The machine ran up quite alright to approx. 130 rpm and then a very bad shake developed (almost like a resonance) but which is probably due to some out of balance. Even so it was quite alarming as I opened full out and let go—hoping for the best! The jump was quite reasonable, but there was quite a good wind of at least 20 mph."

During a 4 January 1937 conference with Agnew Larsen, G.B.L. Ellis, A.G. Harrison of the Air Ministry, and Farnborough metallurgical engineers, British manufactured blade spars were compared to "gas pipe" and the desire was expressed for C.40 blades to be obtained from Pitcairn Autogiro Company due to their high quality and because "We have had so much trouble with the ROTA (C.30A) that I do not feel like taking any chances with a possibly imperfectly developed article if we can get the genuine thing from America [ref. 14]." Ellis agreed to use

American spars but not the manufacture of blades by Pitcairn Autogiro Company, due, if nothing else, to the impracticality of such a long-distance arrangement when conducting rotor development.

In August 1937 the Air Ministry issued the Cierva Autogiro Company, Ltd., an order for five C.40s. Three machines were intended for the Fleet Air Arm, one for the Army, and one for research at Farnborough. Development of the two-blade autodynamic rotor was not successful in reducing vibration to an acceptable level, and the C.40 hub design included three blades secured to the hub through a low-ratio positive drag-feather alpha-1 hinge and a positive flap-feather delta-3 hinge inclined at 20 degrees. The blades were particularly flexible in the flapping plane to minimize bouncing in flight. The C.40 was built by British Aircraft Manufacturing Company, Ltd., at Hanworth Aerodrome, and Marsh conducted the first tests of the prototype on 4–5 January 1938. While executing a running takeoff, the C.40 was badly damaged by ground resonance.

In early 1937, Jim Ray reported progress with the autodynamic rotor to Pitcairn (ref. 25):

> "On the Mark IV the 'bell setup' [bell-shaped housing around alpha hinge] referred to last week will probably be ready for the middle of this week. It has been assembled for several days but they are having trouble with the central friction damper. One tightening nut clamps down on all three plates evenly but because the plates and discs naturally have unequal coefficients of friction the pull off at the blade tips cannot be adjusted the same for all three blades. On any rotor with alpha hinges, giving as it does an incidence change for blade movement in the plane of rotation, if frictional restraint is imposed, it must be equal on all blades. The greater the tilt of the alpha hinge from the vertical, the more sensitive this becomes. In the bell arrangement the hinge is 25 degrees from the horizontal and it will be interesting to see if a central damper can be made to work.
>
> Various rumors are floating around that the W-4 is nearly ready. Its earlier trials will be at Glasgow. […] Some of the engineers seem to doubt that the job will fly well enough to bring down here."

A production version of the W-3, designated the W-4 (fig. 22), was designed in mid-1937. It resembled the W-3 but routed the rotor drive through the fuselage and pylon, which was faired to minimize adverse roll with yaw. The landing gear was streamlined and simplified over that of the W-3. The Weir Pixie engine, now type tested, drove a wood two-blade fixed-pitch propeller. Designed by Bennett, the two-blade rotor system differed from that of the W-3, using low-ratio positively coupled alpha-1 drag-feather hinges mounted outboard of low-ratio positively coupled delta-3 flap-feather hinges that intersected the rotor axis of rotation. The hub also incorporated a mechanism to reduce blade collective pitch with application of the rotor brake. Various functionalities intended for incorporation in the autodynamic rotor were abandoned on the W-4 due to conflicting requirements and persistent vibration. Development of the system since late 1933 had not succeeded in producing a smooth rotor. Prior to the first flight, Bennett decided to change the blade drag-feather coupling ratio, and accordingly, a rotor hub with an adjustable positive alpha-1 hinge was built and fitted. During the first attempts at test flight in Glasgow during December 1937, the W-4 refused to lift-off despite various combinations of rotor rpm and takeoff run. According to Marsh, "[an engineer] just climbed the pylon, altered two screws and, taking off, I turned straight over on my back without any effort [ref. 26]." The W-4 was not pursued further due to a G&J Weir, Ltd., board decision to pursue helicopter development. The Cierva Autogiro Company was to continue development of the C.40 direct takeoff Autogiro to fulfill the Air Ministry contract for the aircraft.

Figure 22: The Weir W-4 with adjustable direct-takeoff rotor hub (photo courtesy of the Weir Group).

During a 29 December 1937 telephone conversation with James Weir, Pitcairn enquired:

> "Would there be any objection to telling [Kellett] that you are very much discouraged on the Cierva line of autodynamic rotor and discouraged from the standpoint of producing a smooth autogiro rotor?"

Weir replied (ref. 27):

> "I think we have to admit complete failure on this line."

As with the W-4, Bennett abandoned the autodynamic rotor for the C.40 (fig. 23). The resulting rotor system included three blades, each attached to the hub with a low-ratio positively coupled flap-feather delta-3 hinge that intersected a low-ratio positively coupled drag-feather alpha-1 hinge. The latter feature required several degrees aft displacement of the blades when the rotor was driven for takeoff but minimized blade pitch change with normal drag oscillation (±1.5°) in flight. Each was connected to a central damper through two links to maintain correct angular spacing between them but permitted undamped symmetrical oscillation of the blades.

By the end of January 1938, a C.40 pylon and blades had been fitted to the C.30 Mk.III and successfully test flown. A C.40 rotor hub was added in mid-February for demonstration to Pitcairn and his associates. Marsh conducted taxying tests of the rebuilt C.40 on 24 February and successfully completed a normal takeoff followed by a circuit around Hanworth Aerodrome the following day. On 1 March he executed a jump-takeoff but found the hanging stick biased by the angled rotor-drive coupling. The C.30 Mk.III experienced excessive vibration during rotor runup

Figure 23: The Cierva C.40.

for a jump takeoff on 16 March. Two days later, Marsh completed a circuit around Hanworth Aerodrome after a takeoff in which no more than 220 rotor rpm could be attained due to excessive swaying of the aircraft. On 28 March C.40 blades covered in three-ply wood were fitted to the C.30 Mk.III and locked at 120-degree spacing from each other. Tests of the C.30 Mk.III and C.40 the following day disclosed resonance in both aircraft. On 31 March standard C.30A blades were tested on the C.30 Mk.III with no sign of vibration. Bennett considered that the C.40 blades were too flexible in flapping and had a new set constructed with increased rigidity. These were installed on the C.30 Mk.III in May and tested successfully over several days without occurrence of vibration. The C.40 rotor hub was disassembled and inspected in June after which it flew successfully when refitted onto the aircraft. New design C.40 blades installed on the C.30 Mk.III resulted in severe ground resonance on 23 August. Inspection of the aircraft two days later disclosed that the butt end of one blade did not solidly fit its fork-end attachment . Installation of new fork ends to the C.40 hubs solved the vibration problems, and by December Royal Navy pilots were undergoing training on the aircraft (ref. 15).

Marsh flight test report (ref. 15):

> “C.30J: 27 Jan 1938 to 7 February 1938
> - Fitted with C.40 rotor head.
> - Machine fitted with C.40 blades 44 feet diameter. First tests carried out by ‘taxying off’ and a total of 1 hr. 05 of flying. General feel of control is not as nice as it was when part of test flown on the machine previously (i.e., prototype). It appears heavier and there is a distinct backward bias on the control all the time. Up to 90 m.p.h. there was no sign of vibration but beyond that speed a slight quick vibration (3 times per rev) is noticeable. Have not been beyond 100 m.p.h. so far. A once per rev vibration has been noticeable in the control all the time and this is transmitted to the machine at higher speeds. One blade is slightly out of track which is probably due to the tip being out. A light spring was fitted and improved the feel of the control quite a bit. Control travels approximately 1-3 inches. Actually with speed from slightly left at slow speed to about1.5-2 inches right at high speed.

- Very bad vibration and left bias in control when revving up at the start of the tests. Clutch position has been altered twice and now the driving shaft is vertical, the control is very much better but not quite smooth.
- Jump tests were started on 5 March. One jump at 210 rpm another at 220 and another at 230 and flying away from each one. Resonance was felt very slightly on the latter but damped out after landing. Further "run ups" were attempted with the idea of jumping but resonance developed and on one occasion the machine went up into the air in this state. Afterwards I did not risk jumping on account of this so did not release dog-clutch. Various tyre pressures were tried without any marked difference and the blades were also locked rigidly. Another set of blades of 45 feet diameter and a good deal more flexible were also tried, but in this case the resonance was worse. In each case the resonance is worse after declutching for a few seconds.
- The hub has been stripped for examination and all three driving arms are cracked."

R.N. Liptrot of the Air Ministry reported his impressions of his flight in the C.40 on 27 July 1938 (ref. 28):

> "I flew in the C.40 on Monday [25 July] and consider it to be a great improvement in every way over all previous autogiros. Not only is it the first piece of sound engineering which we have had on autogiros, but its handling qualities are greatly improved. I found that there is little or no vibration in the rotor and that the control is light and effective. I was particularly pleased with the 'jump' take off. The 'jump' is very smooth and there is no sense of extreme acceleration on to its climb without any loss of height at the top of the 'jump'. Take-off on this aircraft is extremely simple; with the rotor up to takeoff r.p.m. one simply holds the stick centrally, turns a button and at the top of the 'jump' takes control in the ordinary way. Landing is also very much simplified, since immediately on touching down another button is turned which applies the rotor brakes and, through an epicyclic gear, positively drives the blades into low incidence, so that the lift is killed and the old tendency to blow over is eliminated."

During 1938 tests on the Pitcairn PA-22, a two-blade rotor with positive alpha-2 drag-flap coupling produced less vibration in flight than vertical drag hinge with friction dampers. Further testing in 1939 of the aircraft fitted with two-blade jump takeoff rotor hub with adjustable alpha and delta hinges resulted in smooth operation except for high sensitivity to gusts. The PA-22 was thereafter tested with a three-blade rotor for the PA-36 then under development (figs. 24 and 25) (ref. 29). This rotor incorporated positive delta-three flap-feather coupling, positive alpha-2 drag-flap coupling, and threaded blade roots that allowed pitch increase of the blades when a hydraulic lock was released for takeoff by the pilot.

In a 1939 letter to Bennett, Pitcairn stated (ref. 30):

> "…you will be interested to know that under certain conditions quite different results were found with the alpha-2 hinge tilted one way than when it was tilted the other. When the top of the hinge was tilted forward there was a pronounced increase or decrease of lift from skidding or certain kinds of bumps, whereas when the top of the hinge was tilted back, this was much less pronounced. However, a most surprising phenomenon developed in revving the rotor previous to takeoff.
>
> Our analysis indicates that with the top of the alpha hinge tilted forward, the incidence of the blades should be reduced under influence of torque, and therefore, the engine should be able to bring the rotor to a higher rotational speed. The opposite was the case, since the rotational speed was reduced 20 rpm. On the other hand, when the top of the hinge was tilted back, our analysis showed that there should be an increase of incidence in the blades, but we were able get 20 rpm more than with the [forwardly tilted] alpha-2 hinge."

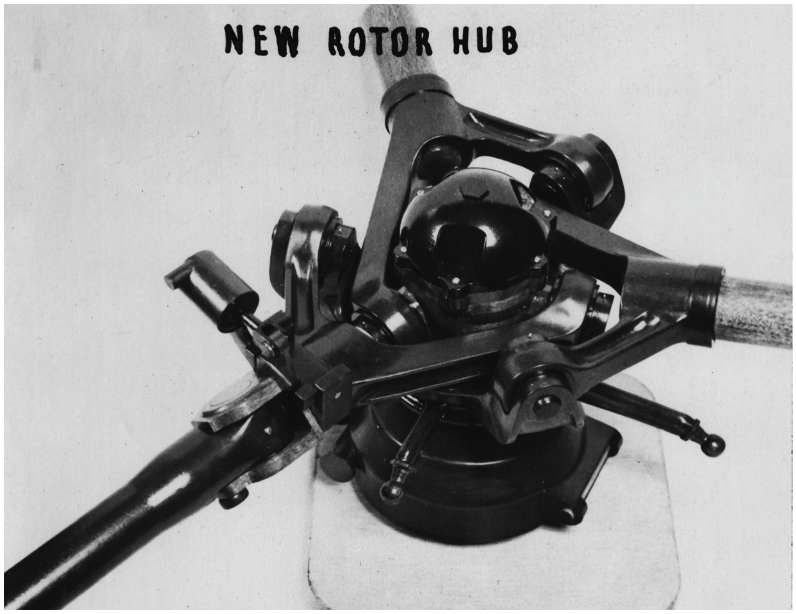


Figure 24: The Pitcairn PA-36 hub (photo courtesy of the National Air and Space Museum).

Figure 25: The Pitcairn PA-36 (photo courtesy of the U.S. Army Signal Corps).

Pitcairn later stated to Weir:

> "Apparently with the combination of alpha-2 and delta-3 [on the PA-36 rotor], a rapidly intermittent fluctuation in the power will cause the rotor to become rough. It is interesting and encouraging that none of this roughness has occurred during flight. By attention to mechanical details, we have reduced the roughness of the rotor and expect within a very few days to have eliminated it [ref. 31].
>
> In view of Marsh's reaction in revving up the PA-36 while he was here, we were afraid that we were troubled with flapping resonance as you have been with some blades on the C.40. In view of our experience, it occurs to me that you might eliminate the resonance in your flexible blades if you allow the blade complete freedom in flapping and in plane of rotation, but held their incidence very rigidly. It took us a long time to realize we were actually getting a certain amount of incidence oscillation, due primarily to a slight amount of flexibility in the structure that determined the incidence.

> Also, we were not able to secure smooth rev-ups until we eliminated even the least contact of the blade with the droop stops and alpha hinge stops. We went through a long period of uncertainty owing to the erratic motion of the rotor, but when the points mentioned above were taken care of, every trace of resonance disappeared.
>
> We have been doing quite a little flying with the machine to find ways and means of giving it complete (airplane) stability. So far there has been no indication of roughness from the alpha hinge in turbulent air which March cautioned us against, although we have not flown it in extremely rough air so far. I believe the trouble that was experienced on your machine from the alpha hinge has been eliminated in our configuration by the introduction of delta-2 [ref. 32]."

Pitcairn summarized the difference between the autodynamic rotor and the system developed by his engineers (ref. 33):

> "[Cierva] devised a jump take-off, permitting the machine to rise vertically from the ground, and was successful in jumping autogiros over 30 feet, but his mechanism produced some roughness in forward flight operation after the jump was completed, owing to other rotor functions that he was attempting to achieve in the same mechanism.
>
> Recognizing the vital importance of the jump take-off, in our approach to this problem we concentrated on devising a mechanism which would accomplish the jump without affecting the usual functioning of the rotor in forward flight. We solved this problem with a satisfactory mechanism, as was demonstrated by innumerable successful jumps."

On 2 January 1939, G.B.L. Ellis was conducting experiments with a C.40 to eliminate the central friction damper from the hub. Later that month, the Air Ministry granted authority for fitting of variable pitch propeller, new, flexible rotor blades, and landing gear redesign to the C.40 (ref. 28). Though 200 pounds over design weight and less than ideal regarding maintenance, the C.40 was accepted for service by the British Army and Royal Navy. However, as a result of the outbreak of World War II, G&J Weir, Ltd., suspended operations of its Aircraft Department and the Cierva Autogiro Company in late 1939 but maintained the legal structure of the latter as a patent holding entity. Sales of the Cierva C.40 Autogiro were limited to five units because of bankruptcy of the construction firm, British Aircraft Manufacturing Company, Ltd., difficulties in obtaining rotor blade spars from the supplier in Sweden, and persistent problems with the French Salmson engine. The French firm, Société Nationale de Constructions Aeronautiques du Sud-Est (SNCASE), had obtained the agreement of the Cierva Autogiro Company for the purchase of 300 to 400 Kellett KD-1A Autogiros to meet French Army requirements. However, this suggestion was dismissed by the British Government due to reluctance to spend credits on an obsolete Autogiro that required substantial modification for provision of direct takeoff capability. The Cierva Autogiro Company flight operations staff joined the Royal Air Force while the engineering staff was assigned to various development projects deemed important to the war effort. Bennett joined the Air Ministry as Chief Technical Officer specializing in rotary-wing aircraft.

In 1941 Pitcairn received an order from the British Air Commission for seven jump-takeoff Autogiros. The resulting PA-39 (fig. 26), built on obsolete PA-18 airframes, used the rotor system developed for the PA-36. Though delivered, none of these aircraft entered service due to sinking of the ship carrying them across the Atlantic Ocean to Britain.

In 1945, Bennett joined Fairey Aviation Company, Ltd., to undertake development of the Cierva C.39. This aircraft, realized as the Fairey Gyrodyne (fig. 27), used a rotor system that incorporated many of the principles developed for the autodynamic rotor. A swashplate controlled the rotor hub that articulated about a straight driveshaft to avoid problems with transmitting torque through a bend. Three blades were attached to low-ratio negatively coupled alpha-1 drag-feather hinges connected via a radial link to low-ratio positively coupled delta-3 flap-feather hinges that intersected the rotor axis of rotation. Blade drag angle varied with driveshaft torque to automatically govern rotor collective pitch via the drag-feather alpha-1 coupling and the change in flap-feather delta-3 coupling.

In 1949 the Gyrodyne was fitted with a rotor hub (fig. 28) that used vertical drag hinges and provided rotor collective pitch change via variation of the flap-feather delta-3 coupling with blade drag angle. Poor machining caused failure of this hub in flight on 9 April 1949, resulting in the deaths of the pilot and observer.

Figure 26: The Pitcairn PA-39.

Figure 27: The Fairey Gyrodyne.

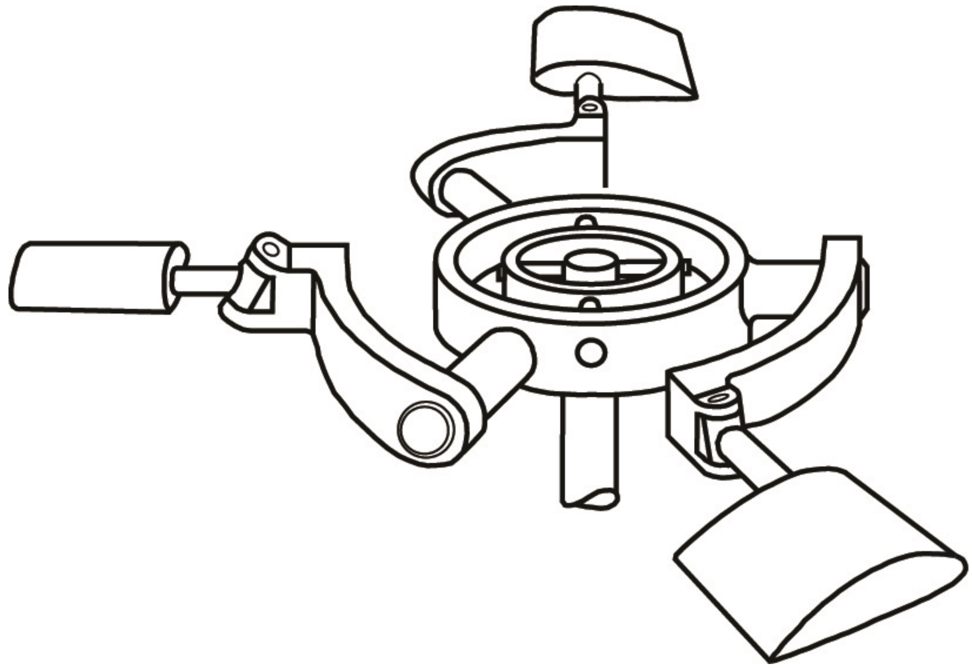


Figure 28: The Fairey Gyrodyne rotor hub.

Conclusion

There are many examples of Cierva reacting defensively to legitimate criticism of the Autogiro. He did not readily accept suggestions and often exhibited what his first British test pilot, Frank T. Courtney, characterized as *hidalgo* pride (ref. 34); nevertheless he was a brilliant, practical engineer who would change his mind when confronted with a sound argument, such as when, towards the end of his life, he accepted that significant operational limitations of the Autogiro were eliminated by the helicopter. These limitations were elegantly summarized by Cyril Pullin who, in a memorandum, stated, "The limitations of a sustaining rotor towed by a propeller are so great as to offset the advantages of the rotor as compared to a fixed wing except for a limited number of special applications [ref. 35]." Also, Cierva claimed that the Autogiro would eventually attain efficiencies approaching those of the airplane. In his first volume (ref. 36) Franklin D. Harris commented: "I cannot help but feel that Cierva knew—as he spoke to the Royal Aeronautical Society that Friday in 1935—that further rotor system improvements were not going to close the [efficiency gap between the rotor and fixed wing]." Similarly, the autodynamic rotor was a complicated system requiring secondary mechanisms to provide the desired operations and to cater to conflicting requirements, and was subject to inherent limitations of which he must have been aware. Cierva worked on the autodynamic rotor from 1933 until his death in late 1936 without satisfactory result. Compared to the rapidity with which he introduced and refined technical advances to the Autogiro prior to 1933, one can speculate that the primary reasons Cierva continued with the autodynamic rotor were pride and overconfidence in his ability to make it work. Pitcairn's early skepticism was borne out and Bennett was only able to make the angled hinge system practical by minimizing coupling ratios and foregoing almost all of the features intended for the autodynamic rotor. Cierva's motivation in developing this system was to eliminate pilot error as much as possible. The result, however, was an unwieldy, complicated, overly sensitive mechanism whose disadvantages were convincingly avoided by Raoul Hafner's manually operated spider-actuated cyclic/collective pitch rotor control system as demonstrated on the AR.III gyroplane in 1935. Though the autodynamic rotor was unsuccessful as a system, its lessons were relearned in the 1950s with the advent of hingeless rotors that exhibited behaviors arising from coupling of blade motions. The Cierva Autogiro Company and its licensees did not disclose technical details of their work, for as pioneers in the rotary-wing field, intellectual property considerations were of major concern. Their efforts gave them a thorough understanding of blade motion coupling phenomena that was withheld from the rotary-wing aircraft industry, particularly in the case of Pitcairn who was then involved in a lawsuit against the U.S. Government for infringement of his rotary-wing patent rights. The publicly available body of knowledge now built up in this area of rotary-wing engineering permits the manufacture and operation of hingeless rotor helicopters possessing performance and agility inconceivable when work on the autodynamic rotor commenced in 1933.

Appendix A: C.40 Rotor Hub Details

Description of the C.40 rotor hub extracted from its maintenance manual:

"The hub consists of an outer shell surrounded by a gimbal ring which forms the attachment of the hub to the pylon, an inner rotating sleeve located in the outer [shell] by ball bearings and having a flange at its upper end, a blade articulation or hinge assembly bolted to the flange of the inner sleeve, a central driving shaft passing through, and free to rotate in, the inner sleeve and hinge assembly, terminating at its upper end in a head carrying three radial driving areas and having the main driving gear keyed to its lower end. Attached to the top of the hinge assembly is a friction damper, one third of the plates of which are connected to each blade. Pressure on these plates is adjusted by nuts. The inner rotating sleeve at its lower end passes through a brake drum which is free to rotate, and has the main driving gear keyed to it.

In flight the hub rotates anticlockwise in plan under the influence of the autorotative force from the blades, these being attached to the hub through the articulations in the vertical and horizontal planes. The articulations allow freedom to the blade in the vertical and horizontal planes as in the normal Autogiro.

In the direct takeoff the central shaft is driven from the back of the engine through a single plate dry clutch in the cockpit via a vertical transmission shaft. This central shaft being free to rotate does so until the three driving arms at its upper end engage with extensions formed on the blade attachments on the hub side of the vertical plane articulation or drag hinge.

Further rotation of the central shaft causes movement of the blades about the drag hinges which, by virtue of tilt of these hinges, results in a decrease of blade incidence. Movement of the blades about the drag hinges is restricted by stops so that when the blade reaches its stop the central driving shaft is virtually solid with the hub and drives it. The leverage of the radial driving arm on the central shaft and of the extensions to the blade attachments is such that the blades area held on the drag stops against the centrifugal force resulting from the relatively high rate of rotation necessary for direct takeoff.

Drive to the hub is continued until its speed is about 50% above that obtained in flight, when the torque is removed by releasing the friction clutch. Upon so doing the blades become free to take up their natural position in the drag plane. Such movement, since it takes place about the tilted drag hinge, results in a rapid increase of blade incidence and a consequent excess of lift sufficient to lift the machine direct from the ground, after which airscrew thrust gives the machine its forward motion.

To prevent an inadvertent takeoff due to any cause such as a sudden removal of torque due to engine failure or partial failure, a locking sleeve is incorporated in the design which locks the centre shaft to the rotating hub when this shaft is in that position where the blades are held at no lift. This locking sleeve is operated by a thumb lever on the control column and is interconnected with a control column lock also operated by the same thumb lever. This interconnection is so adjusted that the center shaft locking sleeve always is in the locked position when the control column is locked.

Since the control column is allowed to remain locked until a second or so before the friction clutch is released, direct takeoff cannot take place except at the will of the pilot.

In flight the machine behaves and is controlled in just the same way as the normal Autogiro but the landing is accomplished without forward run and the whole of the lift of the rotor is removed immediately after touching down.

This latter is brought about by means of a system of gearing housed in the brake drum at the bottom of the hub. The hub inner sleeve has a gear at its lower end as has also the central driving shaft. Double pinions whose spindles are housed in the brake drum mesh with these two gears. The application of braking torque to the brake drum, which is not rotationally locked to the hub, causes it to stop rotating for a short time thus holding the pinions spindles stationary. Energy from the rotating inner sleeve and rotor system then drives the central driving shaft via the double pinions, the gear ration being such that the central driving shaft rotates in the same direction and faster than the hub, thus causing the blades to move about the tilted drag hinge and decrease their incidence [ref. 37]."

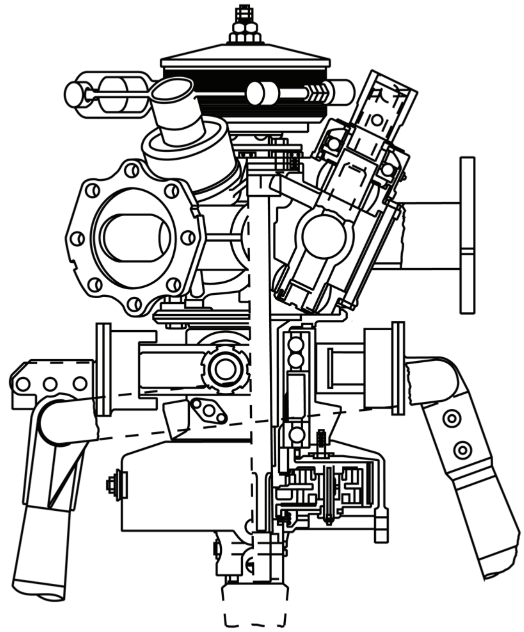


Figure A-1: The C.40 rotor hub, side view (U.S. Patent 2,252,544).

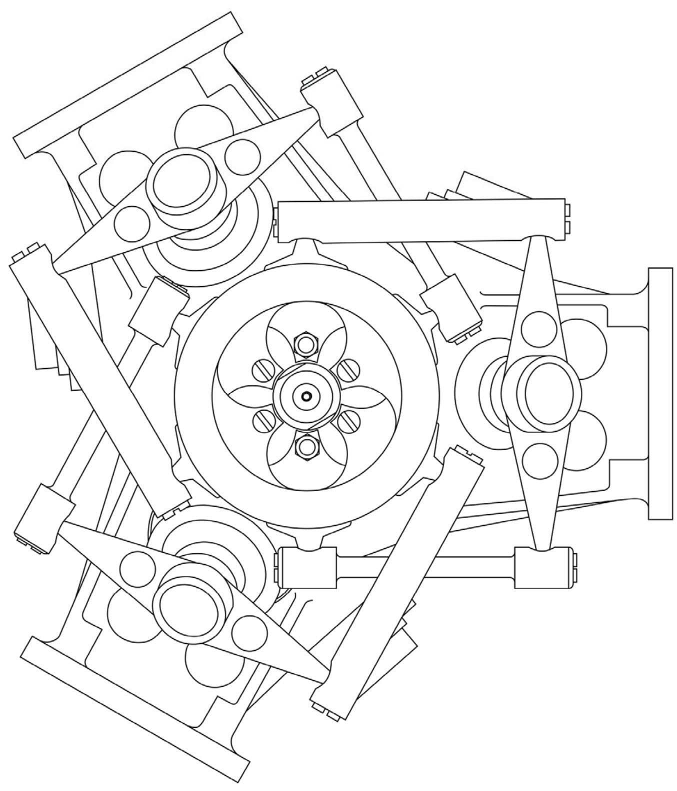


Figure A-2: The C.40 rotor hub, top view (U.S. Patent 2,252,544).

Appendix B: Autogiros Used for Autodynamic Rotor Tests

Aircraft Model Designation	Registration	Dates Used	Main Features	Airfoils
C.30 prototype	G-ACFI	August 1933–November 1935	Three-blade autodynamic rotor development and test.	Göttingen 606
C.30 Mk.II	G-ACWF	December 1935–February 1936	Two-blade and three-blade autodynamic rotor development and test.	Göttingen 606
C.30 Mk.III	G-ACWF	March 1936–November 1936	Two-blade autodynamic rotor development and test.	Göttingen 606
C.30 Mk.IV	G-ACWF	December 1936–December 1937	Three-blade autodynamic rotor with central friction damper development and test.	Göttingen 606
C.30 Mk.V / C.30J	G-ACWF	January 1938–August 1938	C.40 three-blade autodynamic rotor with central friction damper and pylon development and test.	Göttingen 606 NACA 230XX
C.40	G-AFDP	January 1938	Production jump takeoff Autogiro.	NACA 230XX
PA-22		November 1935–June 1940	Two and three-blade autodynamic rotor development and test.	Unknown
PA-36		April 1938–June 1941	Prototype production jump takeoff Autogiro.	Unknown
PA-39		October 1941–January 1942	Production jump takeoff Autogiro using PA-36 rotor system.	Unknown
W-3	N/A	May 1935–July 1936	Two-blade autodynamic rotor development and test.	Göttingen 606
W-4	N/A	December 1937	Production jump takeoff Autogiro prototype.	Göttingen 606

Appendix C: Autodynamic Rotor Patents

U.S. Patent Number	Application Date	Issuance Date	Inventor	Main Features
2,105,682	13 September 1935 (USA) 17 September 1934 (UK)	18 January 1938 (USA)	J.A.J. Bennett, F.L. Hodgess	• Independent flapping of blades in a two-blade rotor. • Suppression of vibration due to flapping, particularly in a two-blade rotor. • Coincidence or blade flapping axes, hub tilt axes, and rotor lift line.
2,121,536	14 September 1935 (USA) 17 September 1934 (UK)	21 June 1938 (USA)	J.A.J. Bennett	• Elimination of drag hinge friction dampers. • Coupling of drag and flapping notions to dampen inplane oscillation of the blade.
2,135,700	15 January 1936 (USA) 16 January 1935 (UK)	8 November 1938 (USA)	Juan de la Cierva	• Use of two or more airfoil section in rotor blades to minimize aeroelastic effects in flight. • Use of aerodynamic devices at the rotor blade tip to provide stable aeroelastic characteristics with movement of the airfoil center of pressure. • Use of various planforms and/or airfoil sections at the rotor blade rip to maximize aerodynamic efficiency.
2,154,601	14 May 1935 (USA) 16 May 1934 (UK)	18 April 1939 (USA)	J.A.J. Bennett	• Reduction of rotor collective pitch with application of driving torque to hub. • Increase of rotor collective pitch with cessation of driving torque to hub. • Provision of jump-takeoff capability by means of overspeeding rotor when collective pitch reduced. • Provision of dedicated third hinge to provide variation of rotor collective pitch with torque. • Dedicated third hinge inclined at angle to minimize its effects on blade motion in normal flight. • Application of rotor brake in flight increases rotor collective pitch.
2,155,409	15 January 1936 (USA) 16 January 1935 (UK)	25 April 1939	Juan de la Cierva	• Means to prevent automatic increase of rotor collective pitch due to interruption of torque when driving the rotor for takeoff. • Means to prevent reapplication of driving torque when the rotor collective pitch is at high collective pitch or the aircraft is airborne. • Means to disconnect the transmission upon reduction or loss of driving torque. • Squat switch means to disengage the rotor drive if the autogiro is airborne. • Means to reduce rotor collective pitch upon application of the rotor brake.
2,161,699	29 April 1937 (USA) 1 May 1936 (UK)	6 June 1939 (USA)	Juan de la Cierva	• Addition of nonstructural masses to rotor blade for stability and performance purposes. • Placement of nonstructural masses at radius positions to minimize any changes to blade natural frequency and reduce static bending loads.

Appendix C: Autodynamic Rotor Patents (cont.)

U.S. Patent Number	Application Date	Issuance Date	Inventor	Main Features
2,173,153	10 November 1937 (USA) 12 November 1936 (UK)	19 September 1939 (USA)	J.A.J. Bennett, G.B.L. Ellis	• Pivot mechanism adapted to sustain heavy end loading and whose moment of resistance to relative rotation of its parts, when so loaded, is smaller than that of any ordinary thrust bearing, at least for small relative displacements of the pivot parts from their normal position. • Preloaded stranded cable inside pitch change pivot to sustain tension and feathering forces.
2,192,492	31 March 1938 (USA) 6 April 1937 (UK)	5 March 1940 (USA)	J.A.J. Bennett	• Means to provide differential and non-differential flapping freedom to rotor blades. • Two flapping hinges per blade, both of which are inclined to include a feathering component but at differing ratios.
2,197,677	31 March 1935 (USA) 6 April 1937 (UK)	16 April 1940 (USA)	J.A.J. Bennett	• A pitch change pivot that is effective to change the blade pitch under the different conditions of takeoff and flight but which is rendered inoperative or ineffective during normal autorotational flight. • Accommodation of lead and lag displacements incidental to autorotational flight operation by means of a separate drag hinge. • Automatic locking of the pitch change pivot during normal flight operation, and automatic release of the locking device for purposes of direct or jump takeoff. • Automatic reduction of blade pitch upon application of the starting or driving torque and movement of the blade on the pitch change pivot from the lower to the higher pitch position automatically under the influence of centrifugal force of rotation.
2,201,810	7 March 1938 (USA)	21 May 1940 (USA)	Harris S. Campbell	• Means to reduce rotor collective pitch upon application of driving torque, and means to increase rotor collective pitch upon cessation of driving torque. • Means to render the pitch change hinge inoperative in flight but operative under the influence of driving torque. • Means to increase rotor collective pitch to higher than autorotative pitch setting at higher than normal rotor rpm, and means to adjust rotor collective pitch to normal autorotative setting at normal rotor rpm. • Means to lock rotor collective pitch at the desired setting for various flight conditions.

Appendix C: Autodynamic Rotor Patents (cont.)

U.S. Patent Number	Application Date	Issuance Date	Inventor	Main Features
2,216,768	29 April 1937 (USA) 4 May 1936 (UK)	8 October 1940 (USA)	Juan de la Cierva	• Amelioration of undesirable qualities and complications in rotors with pronounced positive drag-feather coupling. • Application of negative drag-feather coupling particularly in two-blade rotors. • Means of providing vertical takeoff capability to an autogiro fitted with a rotor with negative drag-feather coupling. • Means for automatically locking rotor blades in no-lift position when driving torque is applied. • Means for automatic decrease of rotor collective pitch with application of driving torque. • Automatic reduction of rotor collective pitch with application of rotor brake. • Additional vertical pivot (drag hinge) to relieve in-plane loads when torque is applied to the rotor. Relief pivot is automatically locked during normal flight. • Means to automatically position the blades to the leading (zero pitch) position on the pitch-change pivot when the rotor is at rest.
2,217,663	21 March 1938 (USA) 6 April 1937 (UK)	15 October 1940 (USA)	J.A.J. Bennett	• Drag-feather coupling set at acute angle to hub axis to eliminate blade instability in flight. • Drag-flap coupling to eliminate requirement for drag dampers. • Use of flap-feather coupling to reduce blade in-plane motion, increase smoothness of rotor operation, and minimize shift of rotor thrust line.
2,247,053	9 January 1939 (USA) 13 January 1938 (UK)	24 June 1941 (USA)	G.B.L. Ellis	• Means to lock rotor collective pitch at its minimum value until intentionally released by the pilot while driving the rotor prior to takeoff. • Means to couple reduction of rotor collective pitch to rotor flight control when said control is locked in its most forward position.
2,252,544	30 April 1938 (USA) 30 April 1937 (UK)	12 August 1941 (USA)	J.A.J. Bennett	• Positive drag-feather blade coupling. • Application of torque to rotor causes blades to drag and decrease pitch to no-lift value. • Offset of drag-pitch change hinge to provide centrifugal restoring moment to maintain blade pitch at value required for autorotative flight. • Acute angle between drag-pitch change hinge to provide stable drag oscillation. • Means associated with the rotor drive to impose drag motion on rotor blades to overcome restoring centrifugal force. • Means to apply braking torque to rotor after landing, which simultaneously imposes a drag motion on the blades to reduce collective pitch to the no-lift value. • Means to limit differential drag motion between rotor blades while allowing non-differential drag motion of all blades.

Appendix C: Autodynamic Rotor Patents (cont.)

U.S. Patent Number	Application Date	Issuance Date	Inventor	Main Features
2,296,250	23 August 1940 (USA) 5 January 1939 (UK)	22 September 1942 (USA)	J.A.J. Bennett	• Means of providing collective pitch control and cyclic pitch control to a rotor. • Use of double flapping hinges or double drag hinges, one of each pair inclined to provide pitch change. • Use of double flapping hinges is accompanied by a single drag hinge that may or may not be inclined to provide pitch change. • Use of double drag hinges is accompanied by a single flapping hinge that may or may not be inclined to provide pitch change. • Means to control rotor collective pitch with applied torque or a swashplate.
2,296,251	23 August 1940 (USA) 1 December 1938 (UK)	22 September 1942 (USA)	J.A.J. Bennett	• Use of double flapping hinges, at least one of which is inclined to provide pitch change. • Means to effect automatic change of rotor collective pitch with application of driving torque. • Means for automatically changing rotor collective pitch with cessation of driving torque.
2,380,583	3 August 1934 (USA) 5 August 1933 (UK)	31 July 1945 (USA)	Juan de la Cierva	• Provide an autogiro with the capability of executing a vertical takeoff and landing. • Transmission system capable of driving rotor to an initial rotational speed considerably in excess of the mean autorotative speed in flight. • Means for automatically decreasing rotor collective pitch to minimize rotor drag during application of driving torque. • Automatic increase of rotor collective pitch to a value at least equal to the minimum value required for flight immediately upon cessation of driving torque to the rotor. • Automatic increase of rotor collective pitch with increase in rotor rpm and vice-versa to enable rotor to operate at optimal collective pitch value corresponding to airspeed or aircraft acceleration loading. • Effect of driving torque when the rotor rpm is at or below the minimum required for flight predominates over the effects of centrifugal force to maintain rotor collective pitch at substantially no-lift setting. • Combined effect of cessation of driving torque with high rpm results in centrifugal force changing rotor collective pitch to a setting higher than that required for normal flight, generating excess rotor thrust for good vertical takeoff performance. • Automatic reduction of rotor collective pitch to a value required for normal flight as rotor rpm decays after takeoff.

Appendix C: Autodynamic Rotor Patents (concluded)

U.S. Patent Number	Application Date	Issuance Date	Inventor	Main Features
2,380,583	3 August 1934 (USA) 5 August 1933 (UK)	31 July 1945 (USA)	Juan de la Cierva	• Means to prevent automatic increase of rotor collective pitch due to interruption of torque when driving the rotor for takeoff. • Negative pitch-drag blade motion coupling by means of inclined drag hinge with application of driving torque. • Means to limit blade pitch when under the influence of driving torque and/or centrifugal force. • Blade mass distribution with respect to the aerodynamic center to provide automatic rotor collective pitch variation with changes in centrifugal force. • Application of braking torque to rotor to increase rotor collective pitch as necessary for landing.
2,311,247	24 September 1941 (USA)	16 February 1943 (USA)	H.F. Pitcairn	• Application of drag-flap coupling in rotors subject to a wide range of torque drive inputs. • Use of coupled flap-feather hinge, vertical drag hinge, and coupled drag flap hinge.

Appendix D: Autodynamic Rotor Patent Illustrations

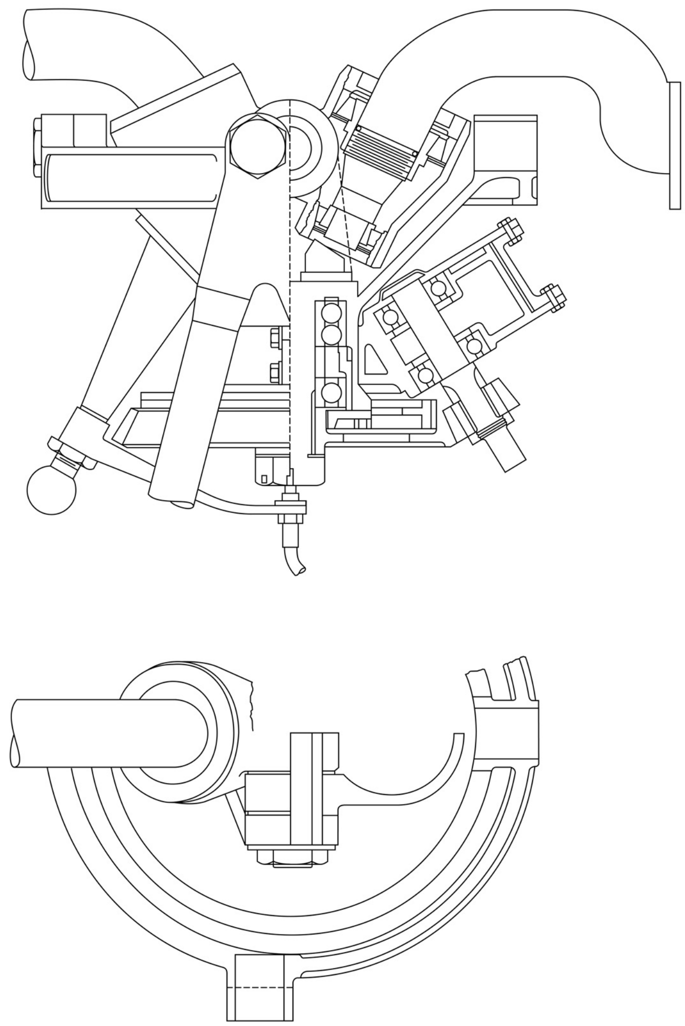


Figure D-1: U.S. Patent 2,105,682.

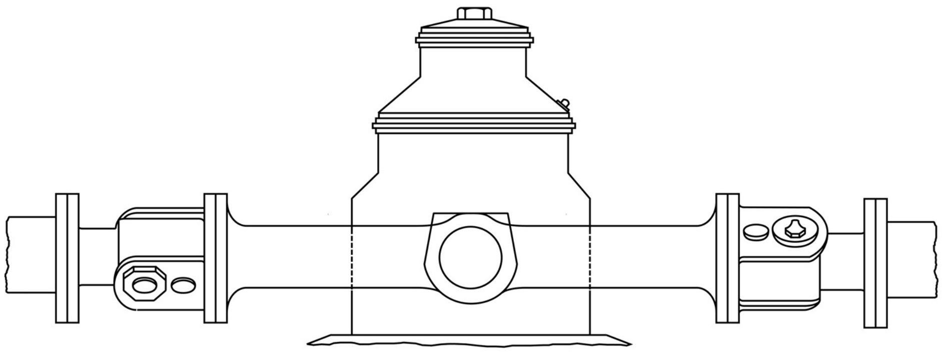


Figure D-2: U.S. Patent 2,121,536.

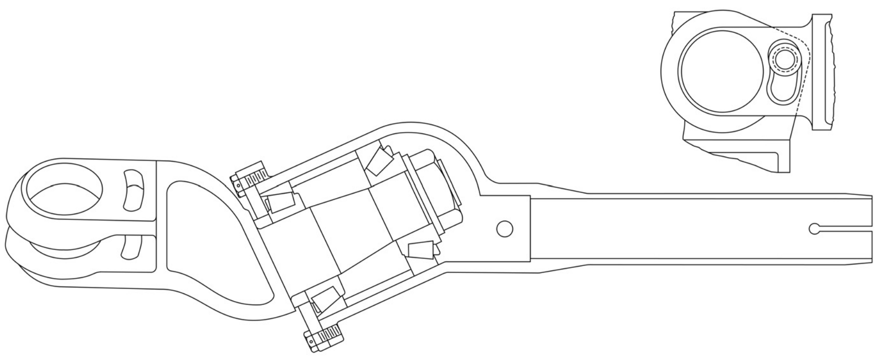


Figure D-3: U.S. Patent 2,121,536.

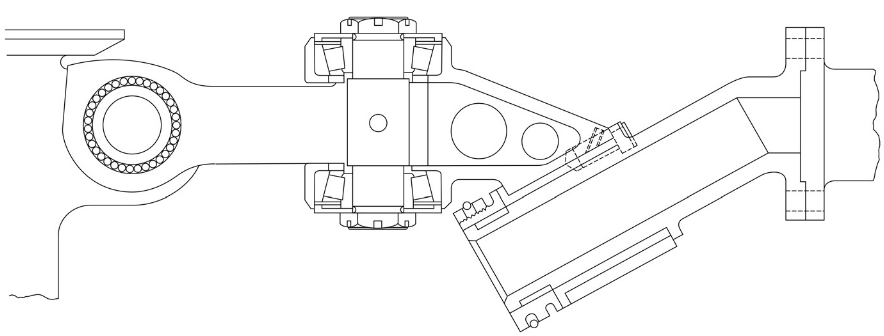


Figure D-4: U.S. Patent 2,154,601.

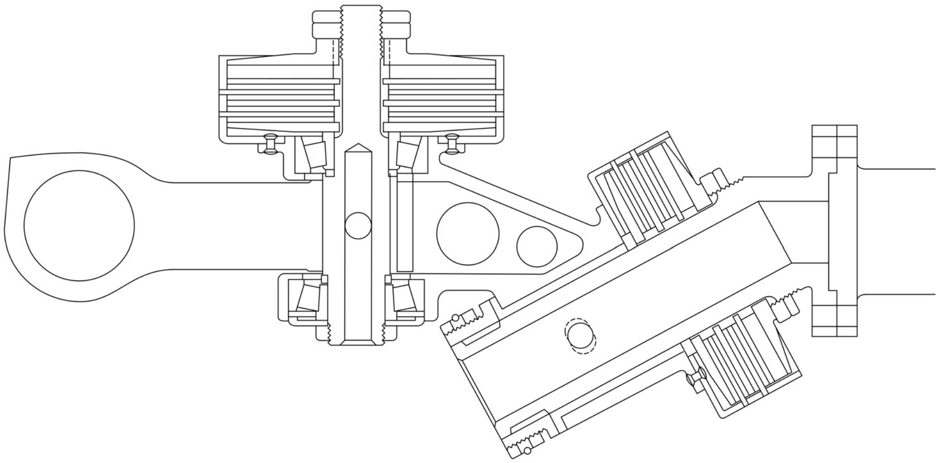


Figure D-5: U.S. Patent 2,154,601.

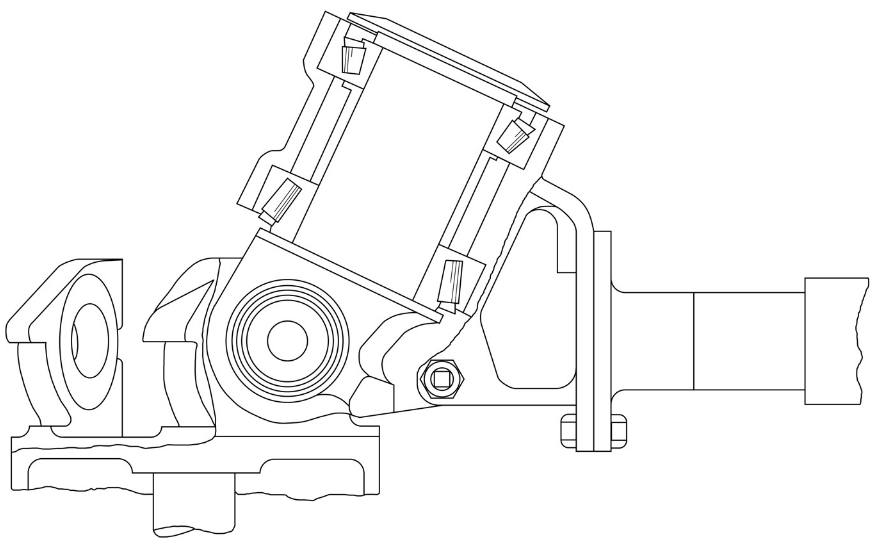


Figure D-6: U.S. Patent 2,155,409.

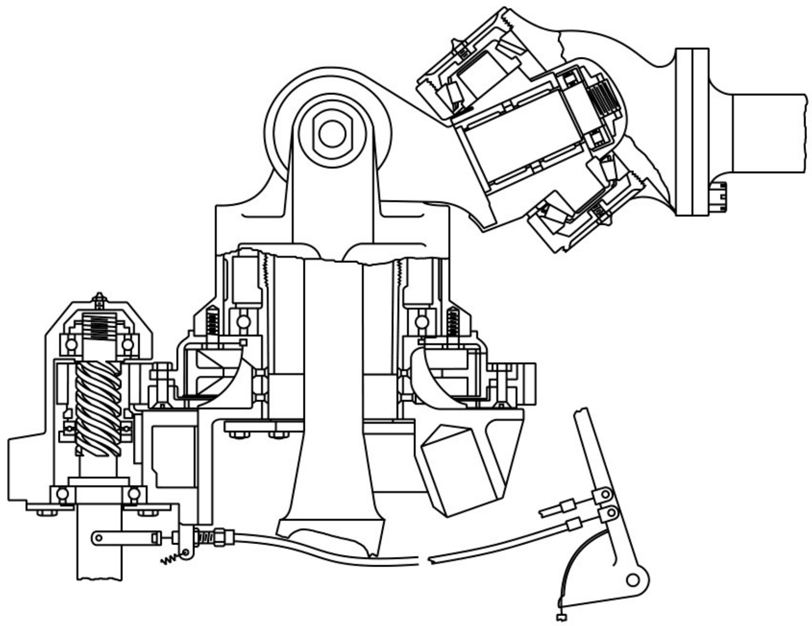


Figure D-7: U.S. Patent 2,155,409.

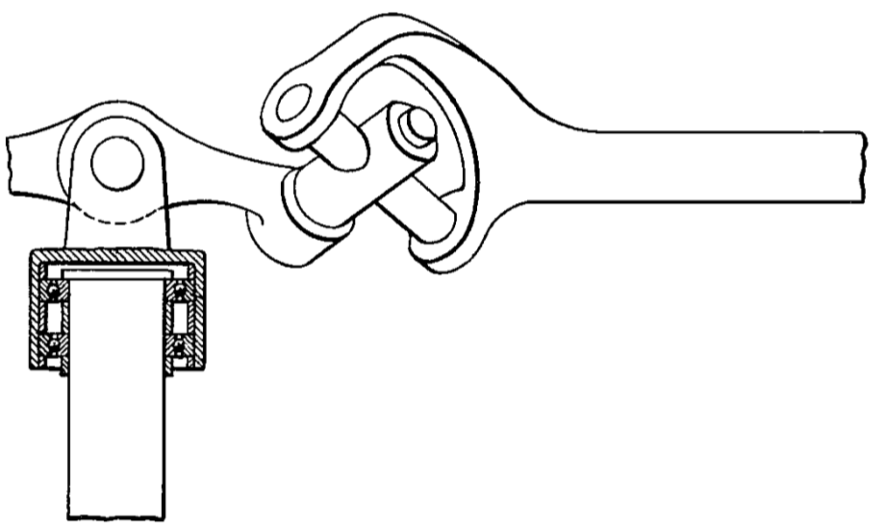


Figure D-8: U.S. Patent 2,155,409.

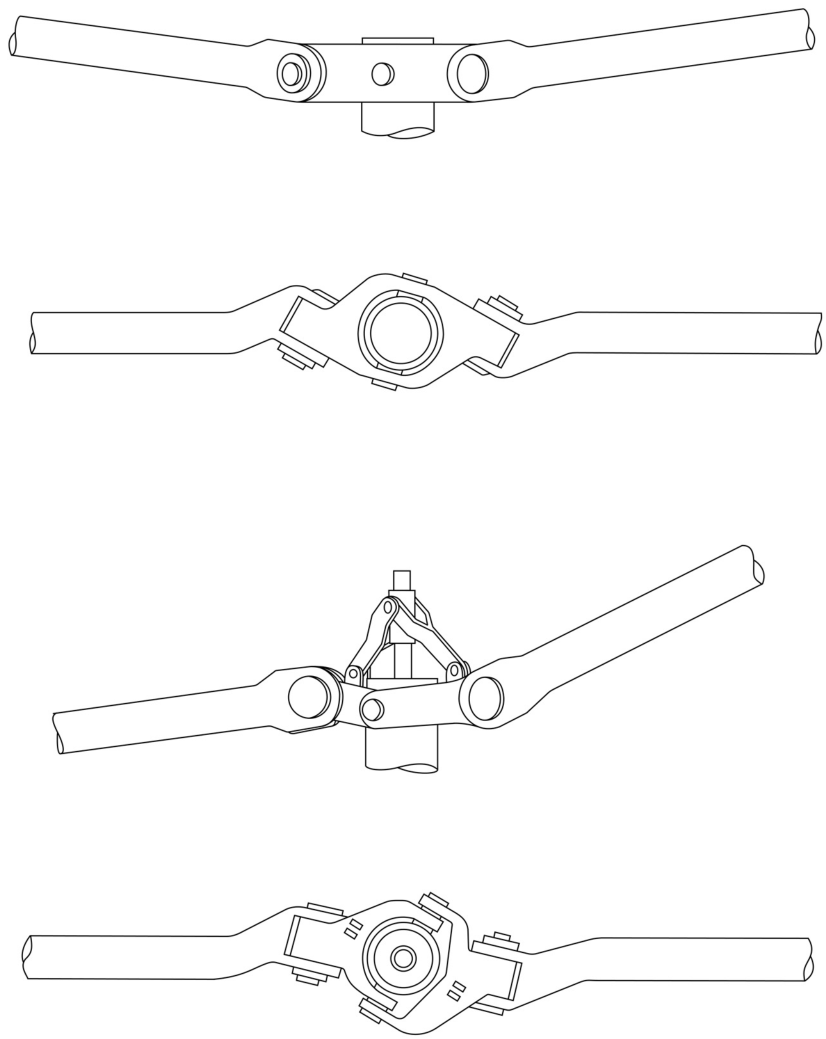


Figure D-9: U.S. Patent 2,192,492.

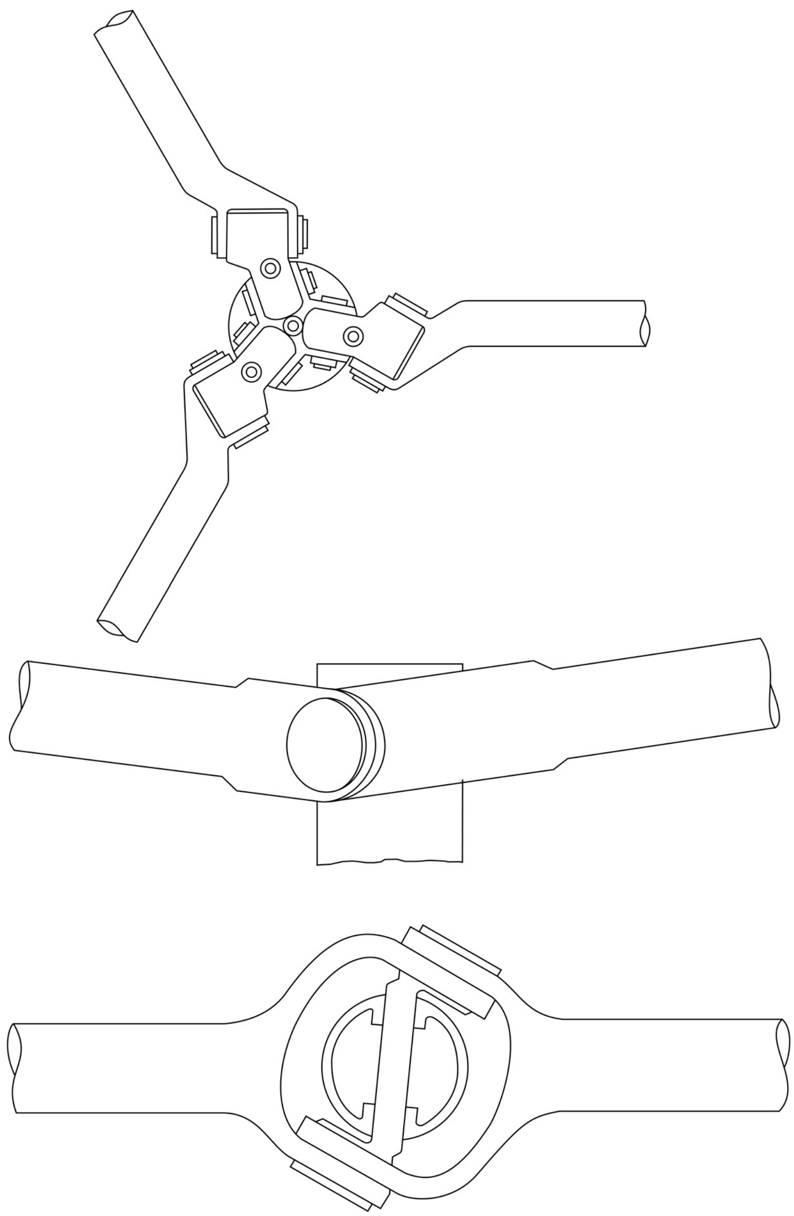


Figure D-10: U.S. Patent 2,192,492.

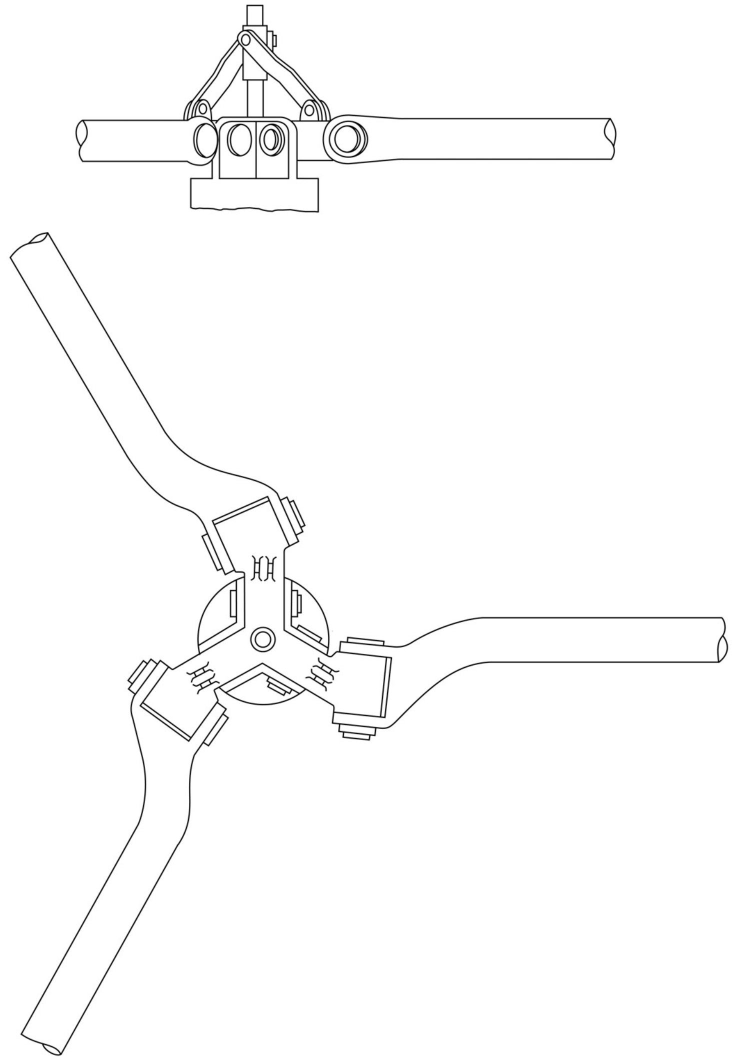


Figure D-11: U.S. Patent 2,192,492.

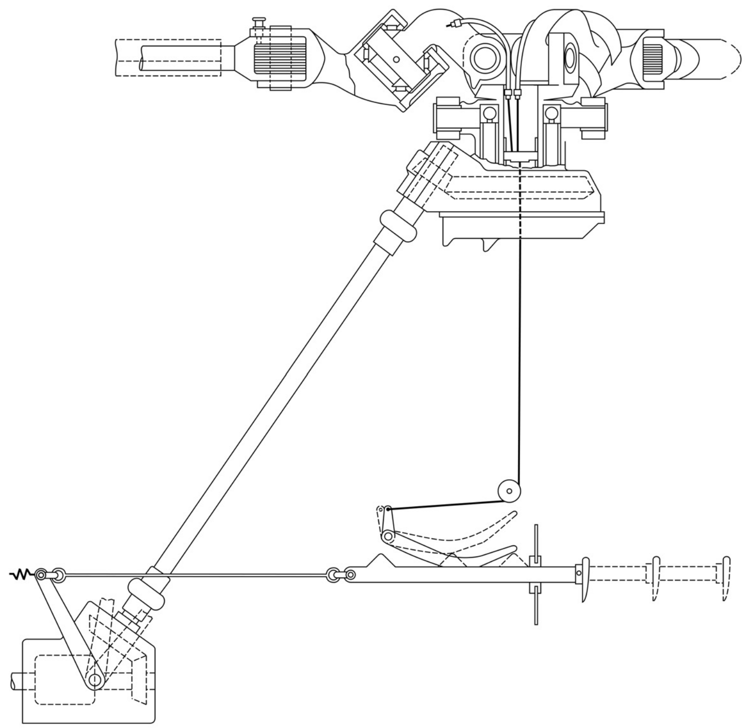


Figure D-12: U.S. Patent 2,201,810.

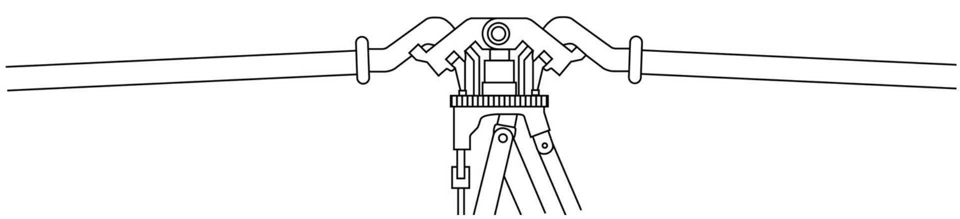


Figure D-13: U.S. Patent 2,216,768.

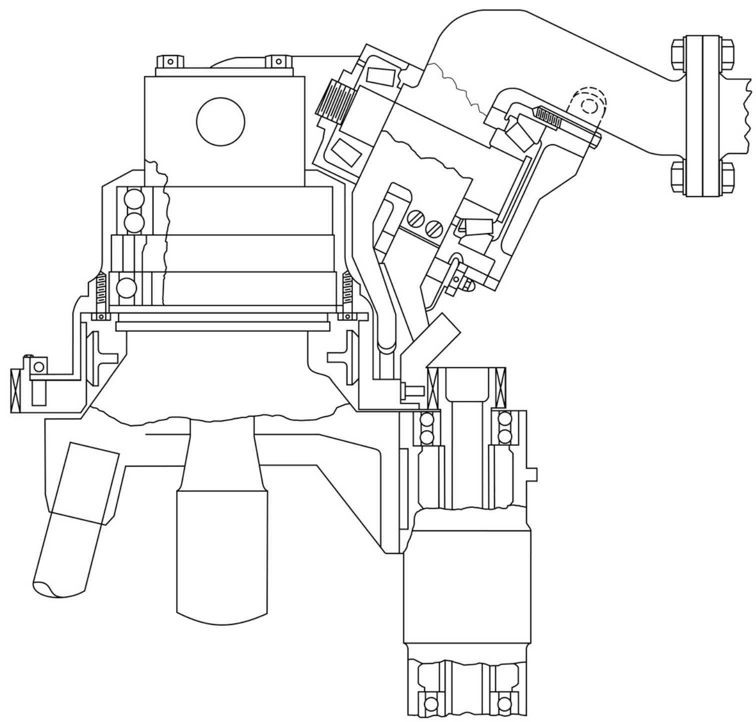


Figure D-14: U.S. Patent 2,216,768.

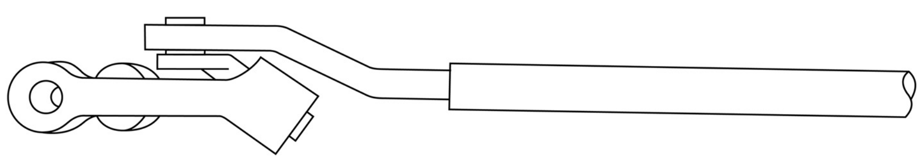


Figure D-15: U.S. Patent 2,216,768.

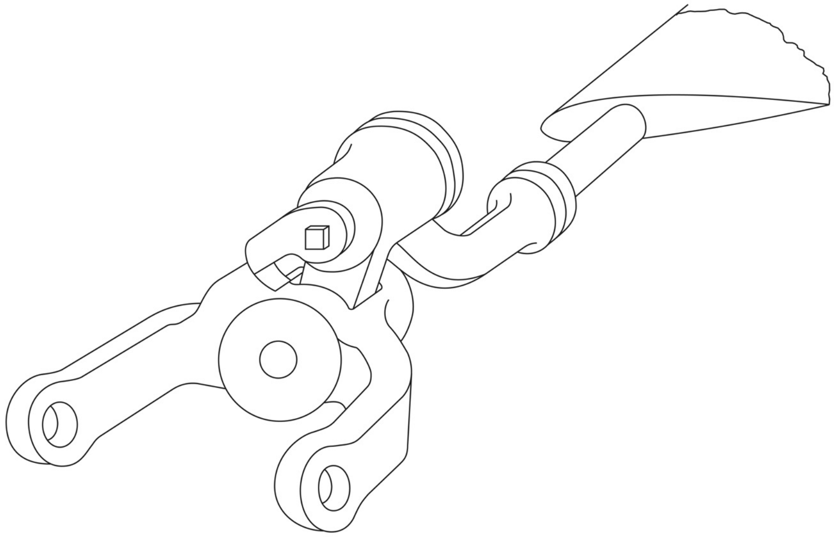


Figure D-16: U.S. Patent 2,216,768.

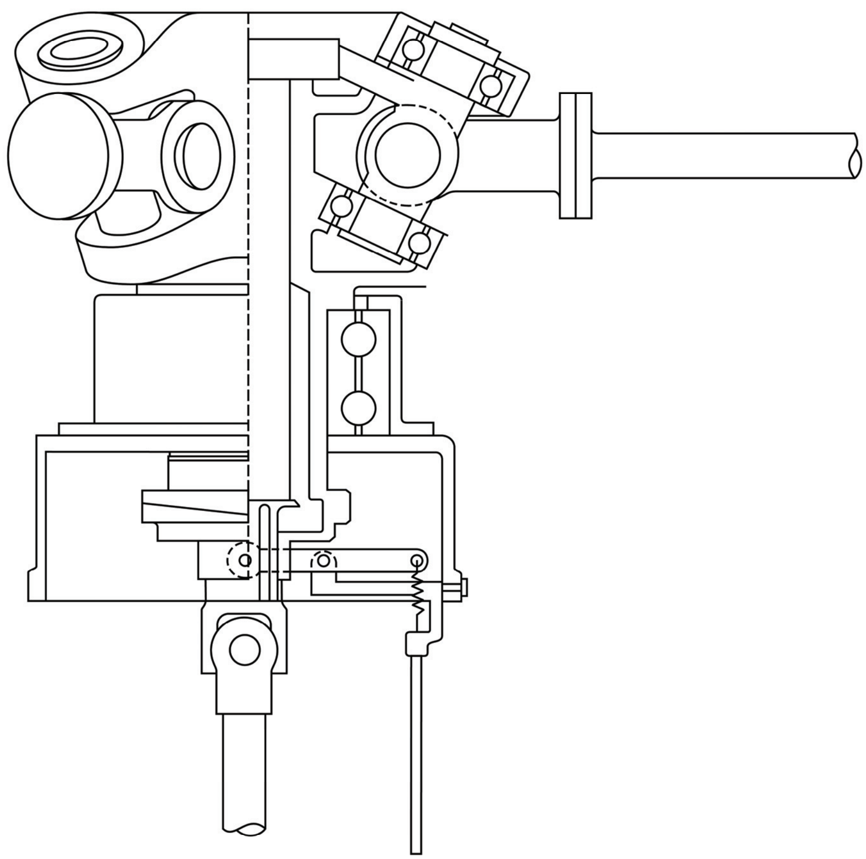


Figure D-17: U.S. Patent 2,247,053.

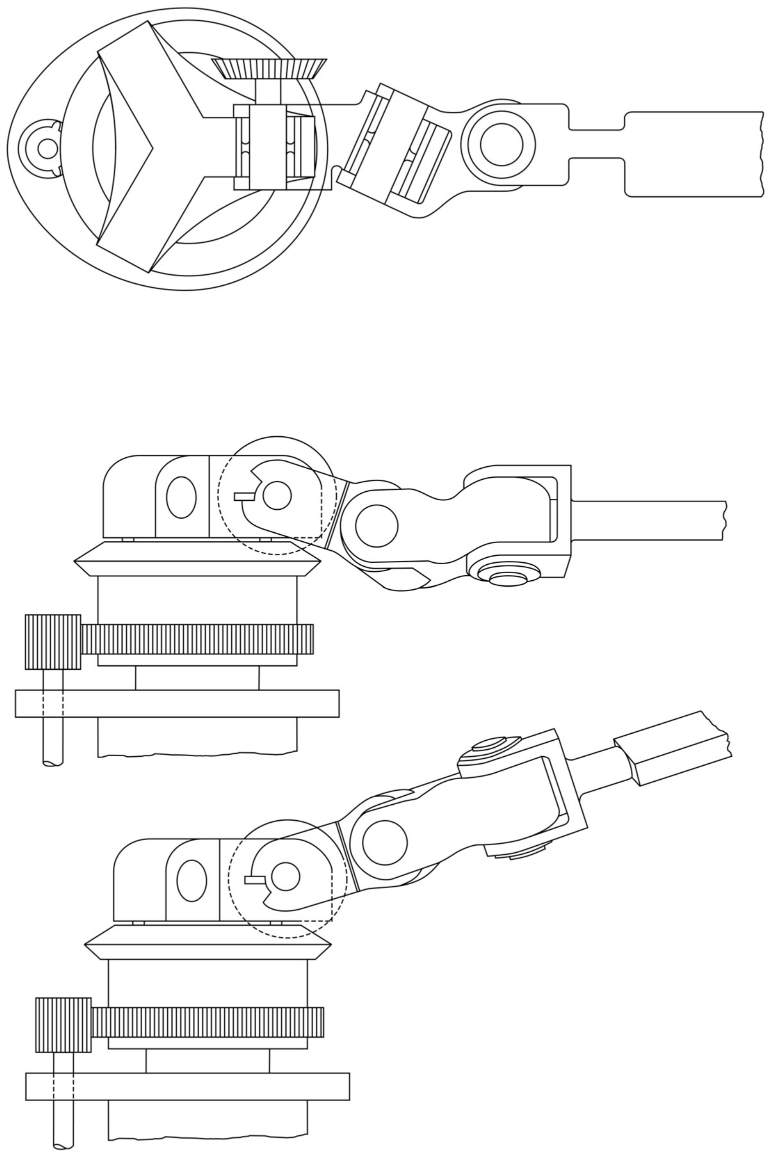


Figure D-18: U.S. Patent 2,296,250.

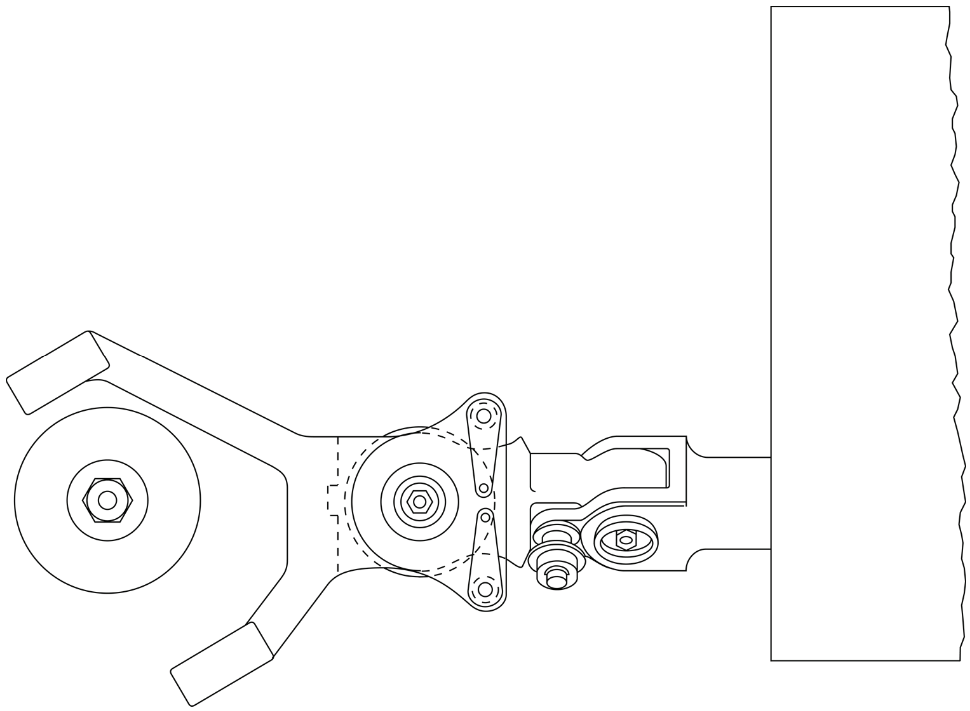


Figure D-19: U.S. Patent 2,311,247.

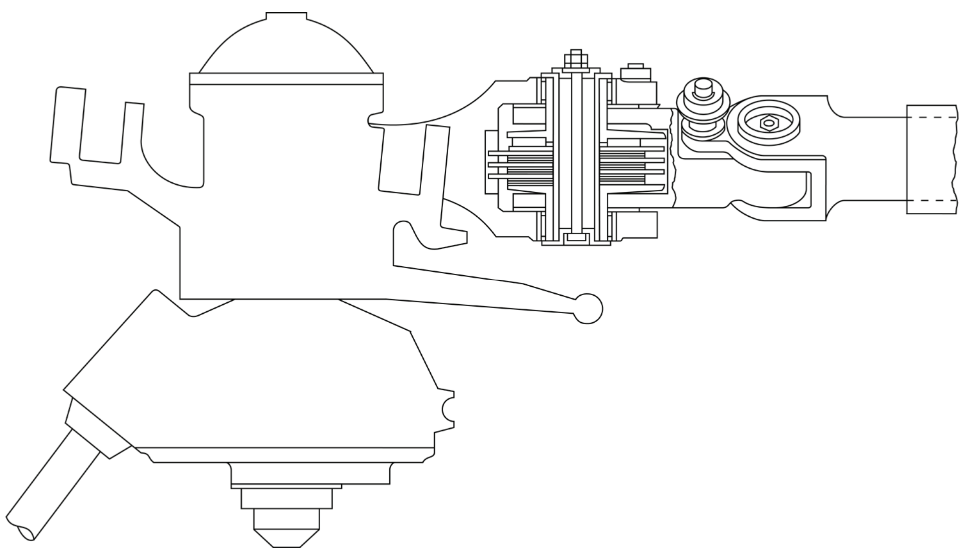


Figure D-20: U.S. Patent 2,311,247.

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