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PART 1 : SECTION 1

CHAPTER 16

BASIC HELICOPTER AERODYNAMICS

Introduction

1. The aerodynamics of the helicopter are based on the same laws that govern the flight of fixed-wing aircraft, although the significance of the various considerations is changed to some extent.

2. Both the helicopter and the fixed-wing aircraft rely for their support on the reaction (lift) produced by the movement of the air over the lifting surfaces ; but whereas the fixed-wing aircraft needs to be moved bodily through the air to provide the necessary movement of air over the wings, the helicopter can move its blades (rotors) to obtain this airflow independently of fuselage movement.

3. **The Autogyro and the Helicopter.** Both these types of aircraft have rotating wings, but whereas those of the autogyro rotate freely in flight under the single influence of the airflow which passes through them (a windmill effect) those of the helicopter are engine driven in normal flying. Whereas a " pure " autogyro must be provided with a source of horizontal thrust by, for example, a propeller, the rotor of a " pure " helicopter provides both lift and horizontal thrust. Composite aircraft can be built having the features of both an autogyro and a helicopter and may be used in either role or both at once, *e.g.* the Gyrodyne and Rotodyne. Autogyros have some advantages over the helicopter in forward flight, but cannot take off vertically in still air. Consequently the " pure " autogyro, although comparatively simple in design, is now replaced by the more complex but much more versatile helicopter or composite helicopter/autogyro.

4. **Helicopter Configurations.** Hicopleters have one or more rotors, each made up of two, three, four, or five blades. A helicopter with a single rotor, driven by a power plant in the fuselage (*i.e.* torque driven) must be provided with a compensating device to prevent the fuselage from rotating in the opposite direction to that of the rotor (*i.e.* torque balance is required). The torque balancing device usually consists of a vertical rotor (tail rotor) which produces horizontal thrust normal to the aircraft's longitudinal axis and at a suitable distance (arm) from the source of power. In practice the length of this arm is dictated by the requirement to place the tail rotor outside the slipstream of the main rotor. Helicopters with a single rotor, the blades of which are driven by reaction, *e.g.* by tip-mounted jets, do not require torque balance since there is no torque reaction on the fuselage. Multi-rotor helicopters may have contra-rotating rotors on the same shaft, or on different shafts mounted at convenient points. If they are driven by torque applied at the hub, the torque reaction from one may be balanced by the torque reaction from another, without any additional purely torque balancing rotor. In the event of engine failure, helicopter rotor systems are provided with free-wheeling devices to permit free rotation of the rotor in the same way as in the autogyro.

THE SINGLE-ROTOR HELICOPTER

Lift and Thrust

5. The rotor can be caused to produce both lift and horizontal thrust. The drag of the rotors is balanced directly by engine power, and their torque by the tail rotor. The rotor thus has a single total reaction. The vertical component of this total reaction is lift, and the horizontal component (if any) is thrust. The magnitude of the total reaction depends on the amount of lift obtained from the blades, and therefore on the relative airspeed and angle of attack of the blades ; if the helicopter is hovering in still air " airspeed " means rotor r.p.m. and " angle of attack " means blade pitch angle. In most helicopters, the rotor r.p.m. are kept substantially constant and the magnitude of the total reaction is varied chiefly by altering the blade pitch angles collectively, *i.e.* all together, by the same amount. Thus the helicopter can be moved up and down vertically.

6. **Horizontal Movement of the Aircraft.** Since all the rotor blades go through identical motions in one revolution of the rotor, their tips all move in the same plane when the rotor is in equilibrium. The total reaction of the rotor acts through the point of attachment (the rotor hub) and is always normal to (at right angles to) the tip path plane. It follows that if the tip path plane is inclined from the horizontal the total reaction is similarly

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inclined from the vertical and thus acquires a horizontal component (Fig. 1). Since the tip path plane can be tilted from the horizontal in any direction, the helicopter can be given horizontal thrust in any direction, irrespective of the heading of the fuselage.

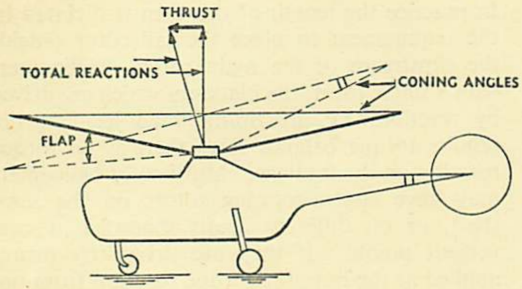


Fig. 1. Definitions

7. **Directional Control of the Aircraft.** Helicopters employing a tail rotor obtain directional control by varying the thrust of the tail rotor. Single-rotor helicopters not requiring a tail rotor sometimes use a rudder surface which operates either in the main rotor slipstream or in the jet efflux if a gas turbine is used in the fuselage to supply driving air to blade-tip jets.

Flight Controls

8. **Collective Pitch Lever.** The lever which controls the magnitude of the total reaction by altering the blade pitch angles collectively (increases or decreases the pitch angle of all the blades by the same amount) is called the *collective pitch lever*, or simply " the lever ". It is normally held in the left hand. Upward movement of the lever increases the blade pitch angles.

9. **Throttle.** Engine power is governed by a throttle control. The manual throttle control is usually in the form of a twist grip which is also the handle of the collective pitch lever.

10. **Rudder Pedals.** Directional control is obtained by the use of foot pedals which operate in the same sense as the rudder pedals in a fixed-wing aircraft; in the case of a helicopter with a tail rotor, they control direction by varying the thrust of the tail rotor.

11. **Cyclic Pitch Stick.** The lever which is used to incline the tip path plane, and thus tilt the total reaction in the desired direction, is called the *cyclic pitch stick*, or simply " the stick ". It is sometimes also referred to as the azimuth control, and is normally held in the right hand. Displacement of the cyclic stick in any direction from the central position causes the tip path plane, and thus the total reaction, to be inclined in a similar sense. The reason for the name *cyclic pitch* will be clear when the method of functioning of the controls is discussed.

Blade Flapping

12. To obtain horizontal thrust, the total reaction must be inclined away from the hub axis, in the required direction. To allow tilting of the tip path plane without tilting the mechanical rotor hub, which is inconvenient in practice with shaft-driven rotors, the blades are hinged in such a way as to allow them to rise and fall in the vertical plane under the influence of varying lift forces. (The way in which this is done is discussed later under the method of functioning of the cyclic stick.) If a two-bladed rotor is used the tip path plane may be inclined by giving the blades a see-saw motion on a gimbal mounting, but in rotors having more than two blades each one is mounted on a hinge (*flapping hinge*) allowing individual blade movement in the vertical plane. Movement *up and down* on this hinge during each revolution of the rotor is called flapping. (See Fig. 2.)

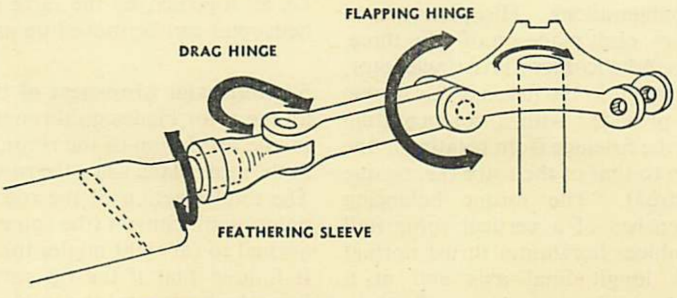


Fig. 2. A Fully Articulated Rotor Blade

Coning Angle

13. During rotation the forces acting on any section of a blade are: lift, centrifugal force, and drag. The lift and centrifugal force determine the angle that the hinged blade takes up. Fig. 3 shows that the blade, being free to flap in the vertical plane, lies along the resultant of these two forces. The angle between the blade and the tip path plane is called the *coning angle*. An increase in rotor speed reduces the coning angle through an increase in the centrifugal vector, and vice versa. An increase in lift increases the coning angle through an increase in the lift vector, and vice versa. It is important not to confuse coning and flapping. When the function of the cyclic stick is discussed it will be seen that when the blades are caused to flap upwards on one side of the disc so as to incline the tip path plane, downward flapping to exactly the same degree is induced on the opposite side of the disc. If the lift and r.p.m. remain unchanged the coning angle is unaffected by flapping. (See Fig. 1.)

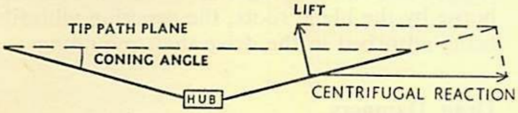


Fig. 3. Coning Angle

The Rotor Disc

14. The rotor disc is that disc whose edge is described by the tip path of the rotor blades. The rotor disc thus lies in the tip path plane. It will be seen that when coning occurs, the centre of the rotor disc is moved upwards inrelation to the rotor hub.

Blade Dragging

15. Besides being free to flap in the vertical plane, the blades of some helicopters are also free to move in relation to the rotor hub and to each other in the plane of rotation about *drag hinges* (Fig. 2). This freedom of movement, called *dragging*, is required to relieve the bending stresses at the blade root due to a tendency for the blades to move in the plane of rotation in relation to each other when flapping is taking place. Although the addition of yet another hinge for each blade further complicates the rotor head, it has proved preferable in all but very small helicopters to the alternative of strengthening the blade root with consequent weight and vibration penalties.

Reasons for Allowing Individual Blade Freedom of Movement

16. The reasons for these movements of the blades in the plane of rotation in relation to each other may be summed up in three ways :—

(*a*) *Varying Axis of Rotation.* In hovering flight the axes of the rotor hub and the cone formed by the rotor are coincident (Fig. 4(*a*)). When the tip path plane is tilted (by flapping) the axis of this cone inclines away from the axis of the rotor hub. Fig. 4(*b*) shows that the blades try to retain their position in relation to the axis of the displaced cone, *i.e.* the axis of rotation, and when viewed from above it will be seen that they must move on their drag hinges to do so.

(*b*) *Conservation of Energy.* The tendency for dragging can also be explained by the principle of conservation of energy. A blade that is flapped up has the C.G. brought nearer to the axis of rotation and therefore tends to accelerate, thus retaining a constant kinetic energy. The opposite occurs when the blade flaps down, for the same reason.

(*c*) *Periodic Drag Forces.* In forward flight, the blade passing from the rear of the disc towards the front is called the *advancing blade*, and the blade moving from the front to the rear the *retreating blade*. In all positions on the disc the blades have airspeed owing to rotation. The advancing blade has the forward speed of the helicopter added to the rotational airspeed while the retreating blade has it subtracted. It must not be imagined, however, that there is a very large change in the drag force on a blade during the change from the retreating side of the disc to the advancing side, since, as is explained later, lift is symmetrical over the whole rotor disc. There is merely a difference in the lift/drag ratio owing to the different airspeeds, and since the lift is constant throughout the rotation there must be a small residual variation in drag between the advancing and retreating blades.

17. It follows from the first two explanations (para. 16 (*a*) and (*b*)) that to produce blade dragging the blades must be free to flap independently of each other and also to take up the common coning angle. An increase in coning angle alone would cause all the blades to accelerate at once (constant kinetic energy) and would not tend to produce any movement relative to each other. A two-bladed rotor without individual blade flapping hinges, but

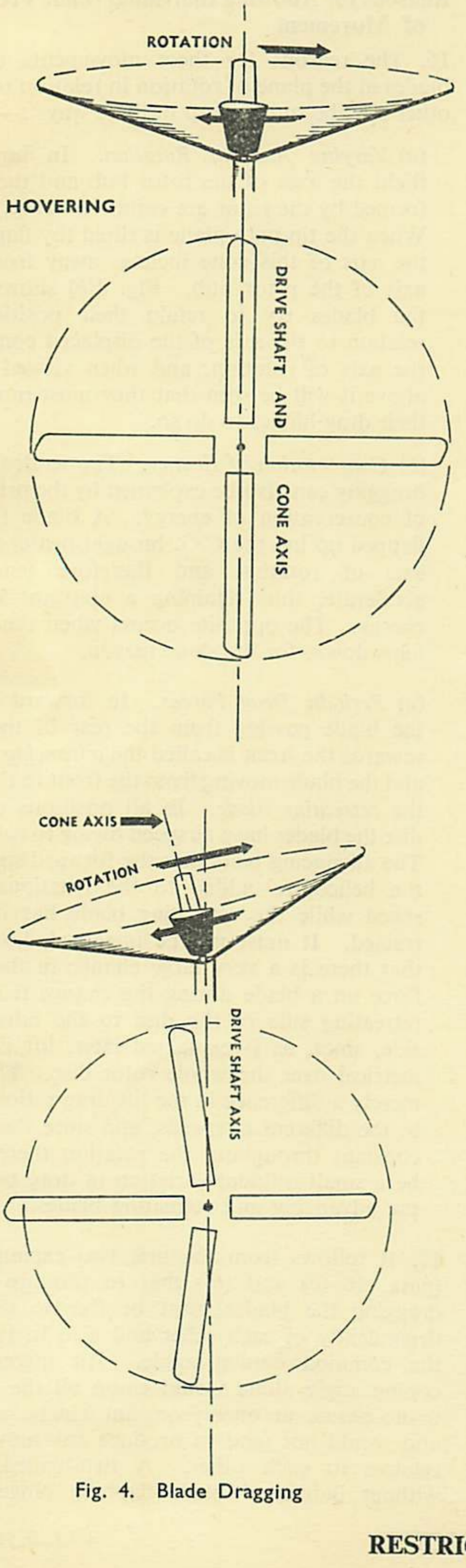


Fig. 4. Blade Dragging

with the blades able to see-saw on a gimbal mounting, produces the same effect as flapping by see-sawing, while a coning angle may be built in or partly provided by blade bending. When a small diameter rotor is used, the bending stresses due to dragging are, in some helicopters, borne by the blade roots, the resulting vibration being absorbed in the drive shaft mounting.

Drag Dampers

18. Blade movement on the drag hinges is controlled and restricted by dampers, in some cases working by friction and in others by hydraulic oil being forced through a constriction. To achieve balance between the blades it is essential that all the dampers work at the same rate.

METHOD OF FUNCTIONING OF CONTROLS

Collective Pitch Lever

19. Irrespective of rotor r.p.m., no lift is generated until the collective pitch lever is moved upwards to increase the blade pitch angles. The pitch angle is defined as being the acute angle between the rotor chord and the plane of the rotor hub ; the angle of attack is measured between the blade chord and the relative airflow. It will be appreciated therefore that the pitch angle and angle of attack are not necessarily equal during flight.

20. When the collective pitch has been increased sufficiently, and provided that the rotor r.p.m. are high enough, the air that is forced downwards gives a reaction (lift) greater than the weight of the helicopter. The amount of lift is controlled by changing the collective pitch and not the rotor r.p.m., since the inertia of the rotating blades is too high to allow the quick changes in r.p.m. which would be necessary for sudden changes in the amount of lift required, although this is not necessarily so in the case of small diameter rotors driven by jets at the blade tips.

21. The collective pitch lever can be made to change the pitch of the blades either by a mechanical linkage which twists each blade about an axis running through the length of the blade or by tabs, ailerons, or servo-tabs fitted to the trailing edge of the rotor blade so that when these are moved by the collective pitch lever the pitch is changed accordingly. The first method is that most commonly used and is further discussed below.

22. **The Control Orbit.** Two methods commonly used for controlling pitch angles are the *swash plate* (Fig. 5) and *spider* (Fig. 6) systems. The plane of the swash plate and the plane of the tips of the spider is called the *control orbit*, and the arms which control the pitch of each blade (pitch operating arms) are attached to it. While considering collective pitch changes only, we are not concerned with angular changes of the control orbit but only with movement up or down the central drive shaft. When the control orbit is raised, the pitch angles of the blades are all increased by the same amount. This is a collective pitch increase and is obtained by raising the collective pitch lever.

Throttle

23. To keep the rotor r.p.m. at the optimum value while pitch changes are made, power must be adjusted to counter the varying drag forces acting on the rotating blades. When lift is increased (collective pitch increased) the throttle must be opened and vice versa. Control of the power required is done through a cam and system of levers operated by the collective pitch

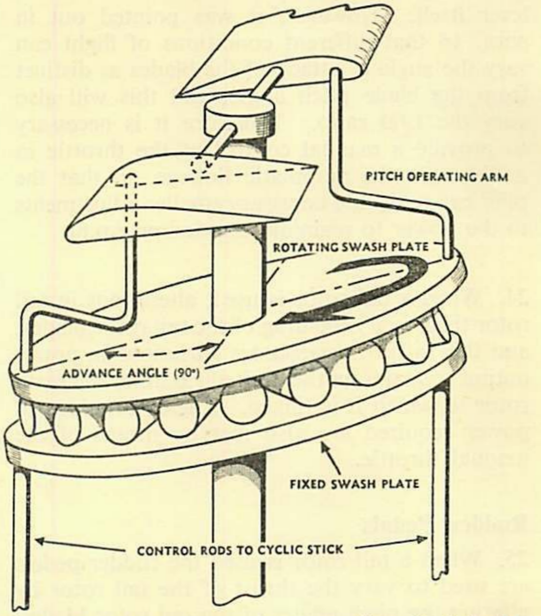


Fig. 5. Swash Plate System for Controlling Pitch Angle

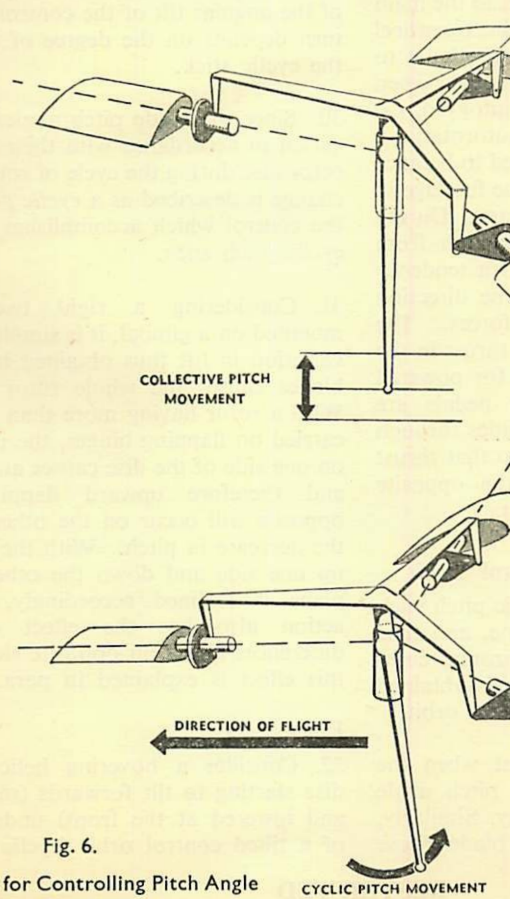


Fig. 6.

Spider System for Controlling Pitch Angle lever itself. However, it was pointed out in para. 16 that different conditions of flight can vary the angle of attack of the blades as distinct from the blade pitch angle, and this will also vary the L/D ratio. Therefore it is necessary to provide a manual control of the throttle in addition to the automatic linkage, so that the pilot can make the necessary smaller adjustments to the power to maintain the desired r.p.m.

24. When a tail rotor is used, alterations in tail rotor thrust vary the drag of the tail rotor blades, and this in turn necessitates variations in power output to maintain the desired r.p.m. of the main rotor to which it is linked. These variations in power required are also met by means of the manual throttle.

Rudder Pedals

25. When a tail rotor is used the rudder pedals are used to vary the thrust of the tail rotor by altering the pitch angles of the tail rotor blades. The rudder pedals are thus another pitch control.

26. The tail rotor is normally linked to the main rotor drive from the rotor side of the freewheel unit (para. 4) so that the tail rotor continues to turn and directional control is maintained when the helicopter is behaving like an autogyro, *i.e.* descending in engine-off flight (autorotation). In powered flight the tail rotor is used to balance the torque effect tending to rotate the fuselage in the opposite direction to the main rotor. During autorotation there is no torque reaction from the main rotor, but instead there is a tendency for the fuselage to turn in the same direction as the rotor owing to frictional forces. The tail rotor in this case must provide thrust in the opposite direction to that required for powered flight. Consequently, the rudder pedals are capable of turning the tail rotor blades through the angle of zero lift and beyond, so that thrust is obtained from the blades in the opposite direction to that of powered flight.

Cyclic Pitch Stick and the Control Orbit

27. It has been stated that the cyclic pitch stick is used to incline the tip path plane, and thus the total reaction, to obtain a horizontal component of thrust. The necessary tilt is obtained by inclining the plane of the control orbit.

28. In para. 22 it was stated that when the control orbit was moved up, the pitch angle of the blades was increased collectively. Similarly, when the control orbit is tilted, the blade whose pitch is controlled by the raised side of the control orbit has its pitch angle increased, while the blade whose pitch is controlled by the arm on the lower side has its pitch decreased. Blades in the intermediate positions are unaffected.

29. The control orbit may be moved by linking it directly to the collective lever and the cyclic stick (Skeeter and Sycamore), or by hydraulic jacks operated by the lever and the stick (Dragonfly and Whirlwind), or by using the air loads set up by small rotating aerofoils controlled by the lever and the stick (Hiller 360), or by the gyroscopic precessional forces supplied by rotating weights being displaced by the lever and stick (Bell 47). If the rotor is turned through 180° after inclining the control orbit, the control orbit turns with it through the same amount, but the plane of rotation (controlled by the cyclic stick) remains unchanged. The pitch angle change on the individual blades is thus reversed, but the positions on the *rotor disc* where the blades pass through the maximum and minimum pitch angles will have remained unchanged. The degree of pitch change is governedby the amount of the angular tilt of the control orbit, which in turn depends on the degree of displacement of the cyclic stick.

30. Since the blade pitch angles are now being varied in accordance with their position on the rotor disc during the cycle of rotation, this pitch change is described as a *cyclic pitch change*, and the control which accomplishes it is called the cyclic pitch stick.

31. Considering a rigid two-bladed rotor mounted on a gimbal, it is simple to see how the variation in lift thus obtained between the two blades causes the whole rotor system to tilt. With a rotor having more than two blades and carried on flapping hinges, the increase in pitch on one side of the disc causes an increase in lift, and therefore upward flapping, while the opposite will occur on the other side owing to the decrease in pitch. With the blades flapping up one side and down the other, the tip path plane is inclined accordingly. The flapping action also has the effect of neutralizing differences in lift on opposite sides of the disc ; this effect is explained in para. 61.

Phase Lag

32. Consider a hovering helicopter with the disc starting to tilt forwards (raised at the rear and lowered at the front) under the influence of a tilted control orbit (cyclic stick displaced

forwards). Viewed from the side, it will be seen that the vertical movement of the blades (flapping velocity) is zero in the fore-and-aft positions where the blades are at the highest and lowest positions, and maximum in the lateral positions where the blades are flapping towards the appropriate peak. (This motion may be represented as a sine curve.) The movement of the pitch operating arms, which are rotating with the control orbit, is a similar form of up-and-down motion following the inclination of the control orbit.

33. Consider now the vertical motion of one of the pitch operating arms connected to the control orbit which has been tilted forward by the cyclic stick. From the neutral position on one side of the control orbit on the athwartships axis of tilt the arm starts to move downwards as it moves round to the lowest point of the inclined control orbit, and then upwards again to the neutral position on the opposite side after an angular motion of 180°. It then starts to rise above the neutral position, passing the highest point of the control orbit after 90° motion and returning to its starting point in the neutral position after a further 90°.

34. If the blades were not free to flap, the highest and lowest positions of the pitch operating arms corresponding to the maximum and minimum blade pitch angle positions would be the positions of maximum and minimum lift. Since lift is equalized by flapping (see para. 61 and Fig. 10), maximum flapping velocity must occur at these positions.

35. In Fig. 7 the top curve represents the vertical movement of a pitch operating arm and therefore blade flapping velocity. The lower curve represents the consequent positions of the flapping blade tip during one cycle of rotation. A is a point of maximum pitch and therefore maximum upward flapping velocity. It therefore corresponds to A_1 (maximum upward slope on the lower sine curve). C is a point of minimum pitch and therefore corresponds to a point of maximum downward flapping velocity—C_1. Points of zero flapping velocity, B and D, correspond to the maximum and minimum flapped position of the blade, B_1 and D_1, and occur 90° later than the points of maximum and minimum pitch (A and C) respectively. The angular distance between points of application of maximum pitch and the consequent maximum flapped positions is thus 90° and is called the *phase lag*.

36. From the preceding paragraph it can be stated that the force which gives rise to a flapping motion " leads " the point of subsequent blade displacement by 90°, the force used being blade lift ; more concisely, the force leads the displacement by 90°. Note that phase lag is not caused by gyroscopic precession nor is it caused simply by blade inertia ; changes in the blade inertia would only change the amplitude of the blade motion and have no effect on the phase lag of 90°.

Advance Angle

37. If the pitch operating arms, rising and falling as they circulate on the inclined control orbit, were controlling the pitch angles of the blades in the same positions in the plane of rotation as themselves, then, owing to the *phase lag*, the tip path plane would be tilted on an axis at right angles to that on which the control orbit had been tilted. In practice it is desirable to cause the rotor disc to tilt in substantially the same direction as the control orbit. Consequently the pitch-operating arms are attached to the control orbit at points ahead (in the plane of rotation) of the blades they control, the angular distance being known as the *advance angle* (Fig. 5).

38. For various reasons the designer may select an advance angle which is slightly more or less than 90°, but if the disc is to be tilted in the same direction as the control orbit *in hovering flight* the advance angle must be the same as the phase lag. (This is not true in forward flight.)

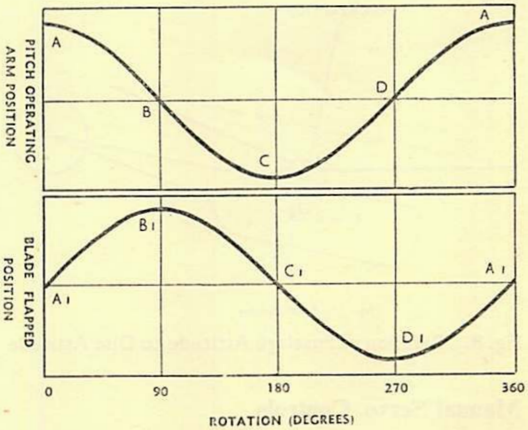
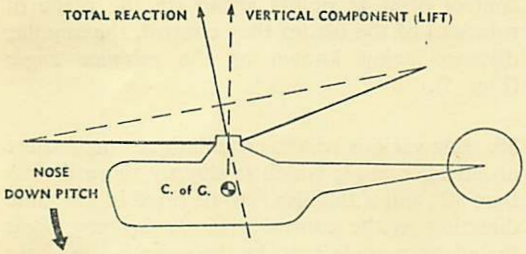


Fig. 7. Blade Pitch Change and Resulting Flapped Position during One Cycle

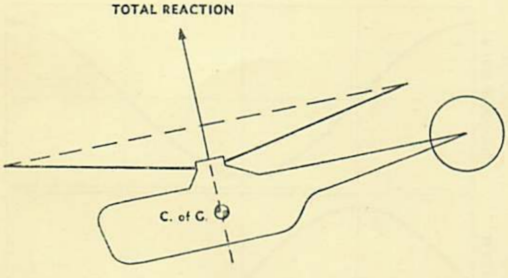
39. To sum up, when the cyclic stick is displaced the control orbit is tilted in substantially the same sense. The resulting cyclic pitch change then causes flapping of the blades, which in turn results in the tip path plane being inclined in substantially the same direction as the control orbit and the cyclic stick. Thus the inclination of the total reaction from the axis of the rotor hub is in the same direction as that in which the cyclic stick is displaced.

Relation of Fuselage Attitude to Disc Attitude

40. Tilting the control orbit forward causes the tip path plane and the total reaction to tilt in the same direction. Changing the tilt of the total reaction means that it no longer acts through the C.G. The moment of the shifted total reaction about the aircraft C.G. causes a nose-down pitching moment, and thus the fuselage tends to tilt until equilibrium is restored and the total reaction again passes through the C.G. (Fig.8(*a*) and (*b*)). In other words, the fuselage tends to follow the tilt of the rotor disc.



(*a*) *Tilting*



(*b*) *Equilibrium*

Fig. 8. Relation of Fuselage Attitude to Disc Attitude

Manual/Servo Controls

41. It has been explained that both the collective lever and the cyclic stick can move the control orbit, pushing it up or down, and tilting it respectively. In some helicopters this is done by a direct mechanical linkage, *e.g.* Sycamore and Skeeter, but in others hydraulic (servo) assistance is necessary, *e.g.* Dragonfly and Whirlwind. (See also paras. 80 to 83.)

HOVER AND TRANSITION

Ground Effect

42. While hovering the weight is balanced by the lift. Lift is obtained by the rotor displacing air downwards, the amount of lift depending on the mass flow and its acceleration through the rotor. The lift is also proportional to a further effect of this flow, *i.e.* the ratio of the reduced pressure above the rotor to the increased pressure below. When hovering just above smooth level ground, the free movement of the down-flowing air is restricted by the ground surface causing an increase in pressure below the disc. The changed total flow pattern has much the same effect on the rotor as a vertical descent with partial power, or alternatively, as a second rotor beneath the helicopter blowing air upwards. Since this upwards relative flow is induced by circumstances external to the aircraft, the same amount of lift may be obtained for less power output. Alternatively it may be said that the ratio of increased pressure beneath the disc to reduced pressure above the disc is increased by circumstances external to the aircraft. Note that ground effect is not due to re-circulation through the rotor. In so far as re-circulation occurs, *e.g.* in a very small jungle clearing, it has a detrimental effect on performance ; whereas the rotor experiencing ground effect may be likened to one descending vertically in free air, that experiencing a re-circulatory airflow may be regarded as one climbing vertically, *i.e.* one that is hovering in down-flowing air. Note also that a helicopter hovering very close to a tall obstruction, such as a hangar wall, is liable to experience re-circulation on the side nearest the obstruction. The lift is reduced on that side and the helicopter tends to tilt in the direction of the obstruction.

43. Since the magnitude of the ground effect depends on the efficiency with which the ground surface tends to return the downward slipstream in an upwards direction, ground effect is reduced as rotor distance from the ground increases and also when the ground surface dissipates the slipstream among bushes or very long grass, etc. When hovering over sloping ground, the return airflow from the ground is deflected laterally and ground effect may be lost completely. Hovering in a small deep depression in the ground may also induce re-circulation.

44. **Ground Cushion.** Ground cushion is a more picturesque name for the phenomenon of ground effect. It is descriptive in the sense that it relates to the behaviour of the aircraft when hovering near the ground. When the disc is tilted, not only does the inclined total reaction cause a horizontal movement of the helicopter together with loss of lift due to the reduction of the vertical component of total reaction, but the ground effect is deflected sideways causing further loss of lift, and the aircraft moves both horizontally and downwards, as though sliding off the convex surface of a hemispheric cushion.

Further Effects of the Tail Rotor

45. Torque is the result of a *couple*, *i.e.* a pair of equal and diametrically opposite forces acting in the same direction, which tend to produce rotation. The torque set up in driving the rotor through its hub is opposed by the moment of the tail rotor. The thrust of the tail rotor then results in an unbalanced side force acting on the whole aircraft, since the rotor thrust reacts on the structure on which it is situated. This side force causes the helicopter to drift sideways instead of hovering.

46. Drift may be countered by giving the tip path plane a permanent slight tilt in the opposite direction to the side force, either by mounting the rotor hub with its axis inclined from the vertical when the helicopter is level (as in the Sycamore) or by inclining the control orbit slightly when the cyclic stick is central and the helicopter level (as in the Dragonfly). In both cases, the setting is correct for only one power setting, *i.e.* one value of torque and tail rotor thrust. Further correction, if required, is made by inclining the tip path plane still more by means of the cyclic stick.

Transition to Forward Flight

47. To change from the hover into forward flight, the total reaction must be inclined forward to obtain forward thrust. The reduction in the vertical component of the total reaction, coupled with the loss of the ground cushion, causes a loss of height unless more power is applied.

48. **Translational Lift.** As the helicopter accelerates forward from the hover, more lift is obtained from the increased mass flow downwards through the rotor (inflow). As forward speed increases the inflow increases and so the mass flow through the rotor is greater, causing a larger total reaction. The increase in lift thus obtained is called *translational lift*.

Induced Power

49. The power required to produce a change of velocity of the air through the rotor is called *induced power*, and the air thus accelerated is said to have *induced velocity*. As the forward speed increases, the change in velocity imparted to the air by the rotor (induced velocity) becomes smaller and is replaced by inflow. Thus the induced power required is less.

Drag

50. **Fuselage Profile Drag.** As forward speed is gained the profile drag of the helicopter starts increasing (varying as the square of the speed). More power is then required to overcome this drag.

51. **Rotor Profile Drag.** Drag is produced on the blades as a component of blade total reaction, the other component being lift. If blade drag is considered purely in relation to forward speed, it is found that it increases only very slightly with increase in forward speed. The increase is due chiefly to the reduction of lift/drag ratio at high angles of attack and low speed on the rearward travelling blade, and the low angles of attack and high speed on the forward travelling blade (para. 65). Total blade drag is called *rotor profile drag*.

Power Required Curve

52. The total power required with increasing forward speed is the resultant of the induced power required and that required to overcome fuselage and rotor profile drag. In Fig. 9 these

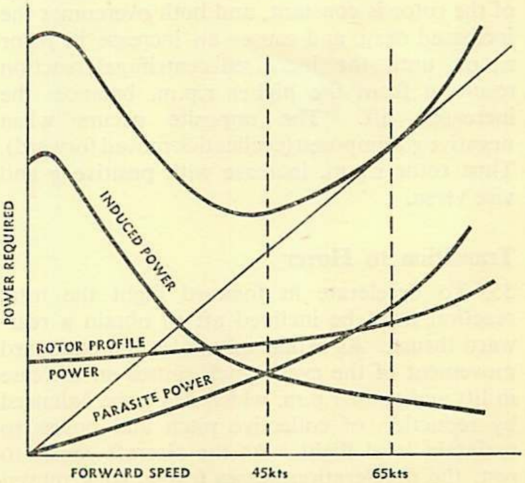


Fig. 9. Power Required Curves

effects are shown graphically. The upward slope at the beginning of the induced power required curve represents the increase of induced power needed to replace the loss of ground effect when moving into forward flight after hovering in the ground cushion.

Variation of r.p.m. with Airspeed

53. As the inflow increases, part of the total reaction which was previously produced entirely by engine power, *i.e.* induced power, is now provided by the increased mass flow through the rotor. The induced power required is therefore less. The surplus engine power thus made available results in an increase of rotor r.p.m. Looked at in another way, an increase in inflow downwards through the rotor has the same effect as reducing the blade angles of attack and so the drag ; if engine power is kept constant the r.p.m. increase. At constant pitch and power the r.p.m. therefore tend to vary directly with airspeed.

Variation of r.p.m. with Change of Attitude

54. During steep turns, recovery from dives, or in any manœuvre involving an increase in *g* without alteration in power or collective pitch (*i.e.* cyclic stick alone moved back while in forward flight) an increase in lift is obtained in the same way as with fixed-wing aircraft. It has been stated that the coning angle of the roto depends on the vectors of centrifugal force due to r.p.m. and lift. If the lift vector is increased by applying *g* then the coning angle immediately increases. The larger coning angle moves the C.G. of each blade closer to the rotor hub, thus reducing blade inertia. The kinetic energy of the rotor is constant, and both overcomes the increased drag, and causes an increase in rotor r.p.m. until the increased centrifugal reaction resulting from the higher r.p.m. balances the increased lift. The opposite occurs when negative *g* is imposed (cyclic stick moved forward). Thus rotor r.p.m. increase with positive *g* and vice versa.

Transition to Hover

55. To decelerate in forward flight the total reaction must be inclined aft to obtain a rearward thrust. As explained above, the backward movement of the cyclic stick causes an increase in lift and rotor r.p.m. which has to be balanced by reduction of collective pitch and power to maintain level flight. As the aircraft comes to rest, the deceleration ceases (cyclic stick moved forward to the central position) and the reductions in collective pitch and throttle previously made must be restored. Further, as the airspeed falls off the translational lift decreases, and so a further increase in collective pitch and power is necessary to prevent the helicopter from sinking. If the aircraft is close enough to the ground to experience ground effect, then after a pause while the hovering airflow pattern or ground cushion is established, the collective pitch and power required have to be reduced.

Overpitching

56. Through poor handling the hover may be established at a very high collective pitch setting, a low rotor r.p.m. and therefore a high coning angle. If the aircraft then has a tendency to sink, any attempt to check this by increasing the collective pitch may easily raise the blade drag so high that the rotor r.p.m. fall despite the use of full throttle. When full throttle is used and the rotor r.p.m. still fall *overpitching* has occurred.

Effect of Altitude, Temperature, and Humidity

57. The effect of increased altitude and/or temperature is to reduce air density, and this affects both engine and rotor performance. The effect of humidity is to reduce the weight of air taken in by the engine, *i.e.* an increase in humidity decreases the density of air. The effect of an increase in any or all of these variables is to cause a drop in engine power.

58. Since general practice is to allow only comparatively small variations in rotor r.p.m., the upper limit being set by the maximum engine r.p.m. (except when free turbines or tip jets are used) and the lower limit by the maximum permissible coning angle, the speed of the rotor blades is substantially constant. Thus the effect of reduced air density is to reduce lift, since density is proportional to lift in a given set of circumstances. To obtain the same amount of lift despite a lower density, higher blade pitch angles must be used ; the higher angles cause a less favourable lift/drag ratio, since the blade angle of attack moves away from the optimum angle, and increase the danger of overpitching in hovering or very slow flight. If the engine power is also reduced this danger is greater.

59. In extreme conditions of low air density and high humidity it may be impossible to hover. Even if it is possible to hover very close to the ground (maximum ground effect), if full power is already being used to do this there is no extra power available for transition to forward flight

and the helicopter will strike the ground as soon as it is moved off the ground cushion. The effect of reduced air density in forward flight will be discussed under the heading "Forward Flight".

FORWARD FLIGHT

Dissymmetry of Lift

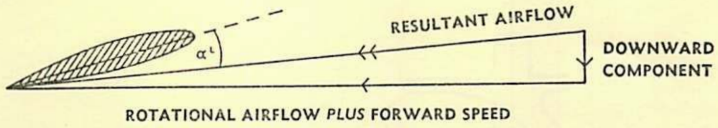
60. The differences in blade airspeed between the advancing blade and the retreating blade would, if uncorrected, produce more lift on the advancing blade and less on the retreating blade. The lift on the disc would thus be unsymmetrical and cause a rolling tendency. This applies both to the main and to the tail rotors.

61. **Compensation of Lift Dissymmetry by Flapping.** If the lift on the advancing blade increases owing to increase in the relative airspeed, then the blade starts rising on its flapping hinge in the same way as when lift is increased by increasing pitch. The upward flapping velocity has the effect of reducing the relative angle of attack of the blade (Fig. 10(*a*)), and so reducing lift until a balance is obtained. The retreating blade has a lower airspeed and a downward flapping velocity, and thus an increased relative angle of attack (Fig. 10(*b*)) so that its lift remains unchanged. The result is symmetry of lift over the disc.

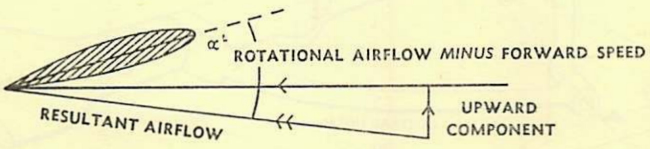
Flapping Back of the Disc in Forward Flight

62. Compensation of lift dissymmetry by flapping cannot be applied to a helicopter main rotor in forward flight since use of this method would involve an unwanted change in the tip path plane, and thus in the direction of the total reaction. Since in forward flight the blades are flapping up while traversing the whole of the advancing side of the disc and flapping down while traversing the retreating side, it follows that a point of maximum flapped position is reached at the front of the disc and a point of minimum flap at the rear. Referring back to Fig. 6, the upper curve (representing the variation in pitch and therefore lift during rotation at constant r.p.m.) may also be used to represent the increase in blade airspeed due to forward flight during rotation. A and C are points of maximum speed difference, and therefore lift difference, and lead the points of maximum and minimum flapped position by 90°. This means that the tip path plane and therefore the total reaction are tilted aft. The horizontal component of total reaction which previously was providing forward thrust is providing rearward thrust instead. This is known as flapping back of the disc with forward speed.

63. Compensation of lift dissymmetry by blade flapping in forward flight may be used in an autogyro where the forward thrust is provided independently of the main rotor, and is usually used in helicopter tail rotors where the inclination of the total reaction may be ignored. Tail rotor blades are therefore mounted on flapping hinges; the diameter is usually so small that the dragging forces can be borne by the blade roots, and so drag hinges are not required on the tail rotor.



(a) *Upward Flapping*



(b) *Downward Flapping*

Fig. 10. Compensation of Lift Dissymmetry by Flapping

Compensation of Lift Dissymmetry by Feathering

64. The tip path of the helicopter main rotor must be inclined forward in forward flight so that the horizontal component of the total reaction continues to provide thrust. It has already been explained that the cyclic stick controls the tip path plane by tilting the control orbit. Therefore any tendency for the disc to flap back in forward flight must be countered by tilting the control orbit forward, *i.e.* by moving the cyclic stick forward. This assumes that an advance angle equal to the phase lag has been used. Since the difference in airspeed between the advancing and retreating blades increases with forward speed so does the flapping and the tendency for the disc to flap back. Therefore with an increasing airspeed the control orbit must tilt progressively further forward to prevent flap-back of the disc, *i.e.* forward movement of the cyclic stick is required. The disc may be said to have flapped back in relation to the control orbit, but not in relation to the hub.

65. The main function of the cyclic stick in forward flight may therefore be described as to maintain a forward tilt of the rotor disc by preventing flapping due to forward flight from taking place. Since the cyclic pitch stick is moved forward to do this, it is reducing the pitch angle of the advancing blade and increasing the pitch angle of the retreating blade by the amount required to prevent flapping, *i.e.* by maintaining constant lift. It may therefore be said to be compensating for dissymmetry of lift by feathering the blades.

66. To restrict flapping due to forward flight, a certain degree of automatic feathering may be obtained by offsetting the control horn (through which the pitch-operating arm twists the blade) from the axis of the flapping hinge. As the blade flaps up, the control horn is held down by the pitch-operating arm, thus decreasing the blade pitch angle. It will be seen in Fig. 11 that this may be done by reducing the advance angle. This system is used in the Sycamore, and part of its effect is to reduce the amount of forward stick movement needed to correct flap-back of the disc in forward flight.

67. A further effect of reducing the advance angle is that the disc does not tilt in exactly the same direction as the cyclic stick. The result is that when the rotor hub is built with a permanent forward tilt in relation to the fuselage (*e.g.* as in the Sycamore), necessitating a backward movement of the cyclic stick to achieve a horizontal tip path plane when taking off to the hover, a small lateral rolling tendency is also induced as the disc tilts not only backwards but slightly down towards the advancing side. This effect occurs with backward movement of the cyclic stick in all helicopters having an advance angle less than the phase lag. Forward movement of the cyclic stick tilts the disc not only forwards but also downwards towards the retreating side.

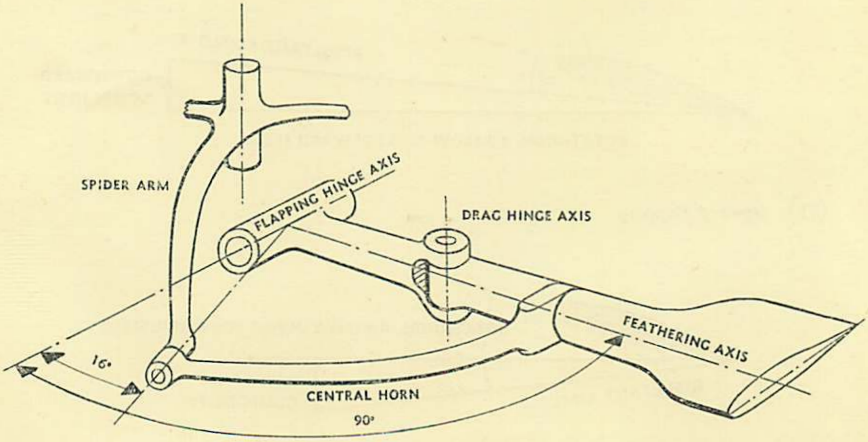


Fig. 11. Offset Control Horn

68. Fig. 12 shows that owing to inflow in forward flight the blade in the forward position has an effectively increased angle of attack, and in the rear position an effectively decreased angle of attack. Since "force leads displacement by 90°" these effective changes tend to produce an upward flapped position with the blade laterally on the retreating side, and a downward flapped position with the blade laterally on the advancing side.

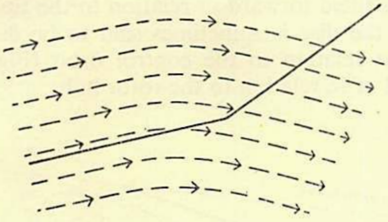


Fig. 12. Effect of Inflow on Blade Angle of Attack

69. This additional flapping effect is superimposed on the flap-back of the disc due to blade differential airspeed already described, and being a much smaller effect, only shifts the resultant maximum and minimum flapped positions by a small amount away from the front and rear positions of the disc.

70. Fig. 13 shows that owing to this effect of inflow, the disc not only tends to flap back in forward flight but also downwards towards the advancing side. Points A and B are maximum and minimum flapped positions due to blade differential airspeed. Points C and D are maximum and minimum flapped positions due to blade angles of attack variations due to inflow. Points X and Y are the resultant maximum and minimum flapped positions due to forward flight. As forward speed increases, therefore, the cyclic stick moves not only forward to prevent flapping but also laterally towards the retreating side as inflow increases.

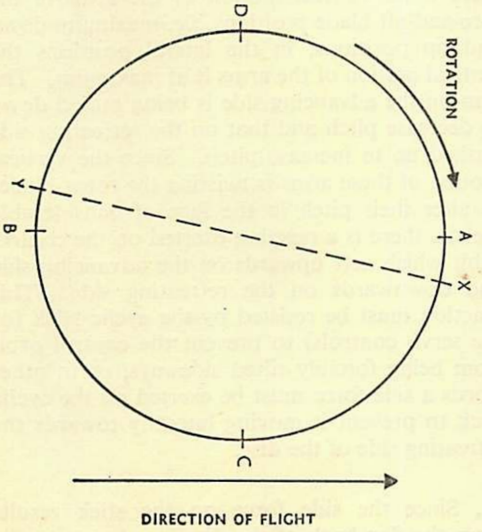


Fig. 13. Resultant Disc Flapping Tendency in Forward Flight

71. In para. 67 it was stated that in helicopters having an advance angle smaller than the phase lag, *i.e.* less than 90°, forward movement of the cyclic stick tilts the disc both forwards and downwards towards the retreating side. It follows that offsetting the control horn not only produces automatic feathering to some degree, but also tends to compensate for the lateral tilt (due to inflow) of the disc downwards on the advancing side.

LIMITS OF FORWARD SPEED

General Considerations

72. Basically the limit of forward speed is reached when the cyclic stick has been moved fully forward as far as it is allowed to go. Any further increase of speed causes flapping back of the disc which cannot be corrected by the cyclic stick which is already fully forward.

73. When the cyclic stick is pushed forward, the pitch angle of the retreating blade is increased; the amount of forward movement permissible is therefore restricted by the stalling angle of the retreating blade.

74. Since the effective speed of the airflow over the retreating blade is the forward speed of the aircraft subtracted from that given by rotation, the portion of the blade nearest the rotor hub, which has only a low rotational speed, has its resultant airflow reversed. As forward speed increases, the area of the blade affected by a reversed airflow extends along the blade away from the hub causing a progressive loss of lift on the retreating blade, and so causing downward flap at the rear of the disc (force leads displacement by 90°). Thus a further flap-back of the disc occurs which in turn requires forward movement of the cyclic stick to counter it.

75. If the forward speed is limited by the retreating blade approaching the stalling angle as the cyclic stick is moved forward, then the maximum permissible forward speed varies with the amount of collective pitch applied. The amount of collective pitch required must vary with the A.U.W., so as weight increases the maximum permissible speed decreases.

76. Since reducing the collective pitch relieves the stalling of the retreating blade, it follows that if the lift can be increased in some way without use of the collective pitch then a lower collective pitch setting can be used without loss of height ; this also permits a higher maximum forward speed, *e.g.* by the use of small fixed wings which produce useful lift at the higher forward speeds. (This is called "unloading the rotor".) Any attempt to increase lift by increasing rotor r.p.m. alone has a very limited application owing to the onset of compressibility effects at the tip of the advancing blade at the higher forward speeds.

Effect of Altitude on Forward Flight

77. The amount of flap-back of the disc in forward flight depends on the relation between the speed differential of the advancing and retreating blades and the rotor r.p.m. The speed differential between the advancing and retreating blades is twice the forward speed of the helicopter. For a given rotor r.p.m. then, the amount of flap-back of the disc varies with the forward speed. Since a constant rotor r.p.m. implies a constant T.A.S. for the blades, the forward speed must also be expressed as true airspeed.

78. For a given I.A.S. at sea level the cyclic stick is moved forward by a certain amount to prevent flapping back of the disc. For the same I.A.S. at greater altitude, the higher T.A.S. causes further flap-back of the disc. Therefore the cyclic stick has to move further forward to correct flap-back of the disc for the same I.A.S. as height is gained. This means that for a given I.A.S., as height is gained, the available forward displacement of the cyclic stick to correct nose-up pitching moments during manœuvre or in turbulence is progressively reduced.

79. As the rotational speed of the blades is true airspeed and is substantially constant, the falling density with gain in altitude causes loss of lift which has to be countered by an increased collective pitch. This immediately brings the retreating blade closer to its stalling angle and so the maximum permissible forward T.A.S. as well as I.A.S. is reduced as height is gained.

Cyclic Stick Forces

80. So far the indications are that the blades do not flap in relation to the rotor hub while in forward flight, *i.e.* there is no movement on the flapping hinges. However, since the control orbit is tilted forward in relation to the tip path plane, the disc is sometimes said to be flapped back in relation to the control orbit (Fig. 14) instead of in relation to the rotor hub.

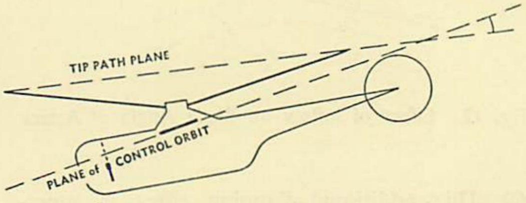


Fig. 14. Disc Flap in Relation to Control Orbit

81. When the control orbit is tilted in relation to the tip path plane, a cyclic pitch change is taking place (feathering). Consider the control orbit viewed from the side and tilted forwards in forward flight. The rate of movement up and down of the pitch-operating arms may be represented by a sine curve (para. 32). While there is no vertical motion of the arms in the fore-and-aft blade positions, *i.e.* maximum down and up positions, in the lateral positions the vertical motion of the arms is at maximum. The arm on the advancing side is being pulled down to decrease pitch and that on the retreating side pushed up to increase pitch. Since the vertical motion of these arms is twisting the rotor blades to alter their pitch in the face of considerable inertia, there is a reaction exerted on the control orbit which acts upwards on the advancing side and downwards on the retreating side. This reaction must be resisted by the cyclic stick (or the servo controls) to prevent the control orbit from being forcibly tilted sideways, or in other words a side force must be exerted on the cyclic stick to prevent it moving laterally towards the retreating side of the disc.

82. Since the side force on the stick results from the flap-back of the disc in relation to the control orbit and the amount of flap-back increases with the forward speed, the resultant

sideways stick force also increases with forward speed. Note that whereas actual forward *movement* of the stick is required to tilt the control orbit forwards, the sideways stick force resulting from forward flight is one which is merely *resisted* by the pilot.

83. As stated earlier, power-assisted controls are fitted to some helicopters to facilitate tilting the control orbit ; if the power assistance fails the resultant large sideways stick force required in manual control is a major factor in maintaining control. In other helicopters without power-assisted controls the pilot can " load " the cyclic stick by means of the trimmer controls which usually apply the load by means of springs.

STATIC STABILITY

Static Stability with Speed

84. It has been shown that the rotor disc tends to tilt back from the control orbit by an amount proportional to the forward speed. Thus an uncontrolled increase in speed causes the rotor to tilt backwards. The total reaction is tilted back causing a deceleration, returning the helicopter to its original speed. The helicopter is thus statically stable with speed.

Static Stability with Disc Angle of Attack

85. The disc angle of attack is the acute angle between the free airflow and the tip path plane. If the helicopter is displaced in pitch, say nose up, the tilt back of the control orbit causes an increased angle of attack on the advancing blade and a decrease on the retreating blade with corresponding changes in lift. Owing to the phase lag effect, maximum upwards flap is reached at the front of the disc and minimum flap at the rear. The disc has therefore flapped back and set up a further nose-up pitching moment (para. 40). Therefore the helicopter is statically unstable with change in disc angle of attack.

Methods of Increasing Stability

86. The arrangement of rotating weights used in the control system of the Bell 47 and the small rotating aerofoils in the Hiller 360 increase the stability by automatically applying corrective cyclic pitch changes when the rotor system is displaced (*e.g.* in turbulence). They also prevent any fuselage attitude displacements being felt directly in the rotor system.

87. The offset control horn system used in the Sycamore improves stability in turbulence by partly restricting blade flapping and therefore the amount of corrective cyclic stick movement required to maintain equilibrium (Fig. 11).

88. Offsetting the flapping hinges, *i.e.* positioning the flap hinges at some distance outwards from the rotor hub, has the same effect as moving the rotor hub vertically away from the centre of gravity (Fig. 15(*a*) and (*b*)). The pendulum effect of the fuselage about the rotor hub having been increased, greater stability is obtained.

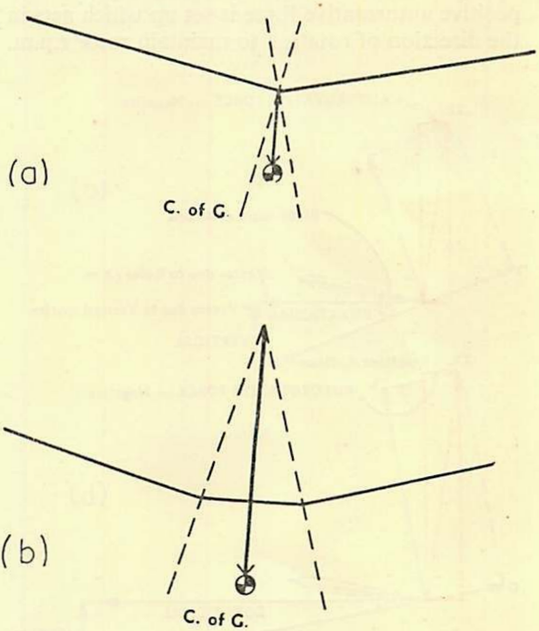


Fig. 15. Effect on Stability of Offsetting the Flapping Hinges

AUTOROTATION

Definition

89. Autorotation in the helicopter is defined as the free rotation of the rotor resulting from inflow induced upwards through the rotor disc. This upwards inflow is induced by the descending path of the helicopter.

Autorotative Force

90. The autorotative force is the force which, in the absence of engine power, is required to maintain rotor r.p.m. by balancing rotor drag. Fig. 16(*a*), (*b*), and (*c*) show a blade aerofoil section at various angles of attack. In each the total reaction has been resolved into horizontal and vertical components (shown in red). The usual lift and drag components are drawn at right angles and parallel respectively to the relative airflow.

91. In Fig. 16(*a*) and (*b*) the flight conditions have given the total reaction a rearwards tilt. Notice that in these cases the autorotative force is negative, *i.e.* it opposes rotation of the blade and thus would cause the rotor r.p.m. to fall. In Fig. 16(*c*) the flight conditions have resulted in a forward tilt to the total reaction, so that a positive autorotative force is set up which acts in the direction of rotation to maintain rotor r.p.m.

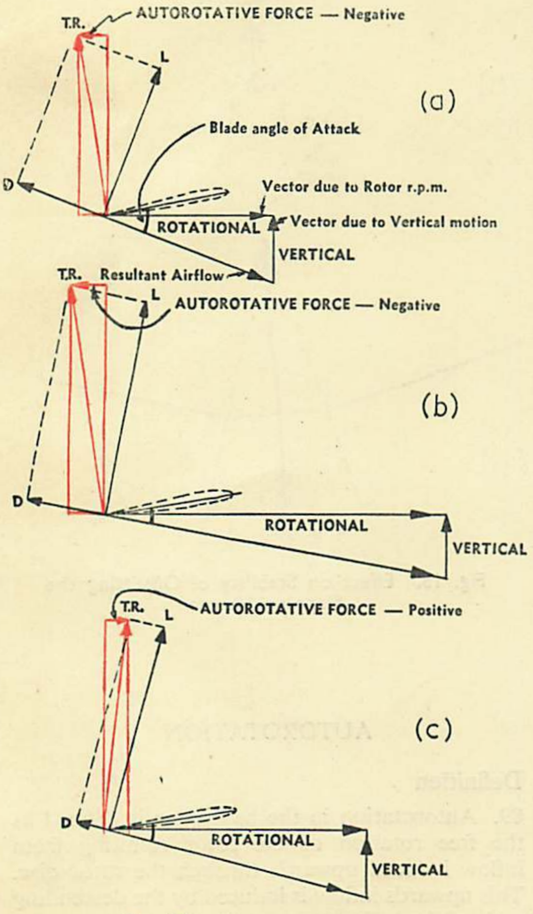


Fig. 16. Autorotative Force

92. From the dimensions of the lift and drag vectors it can be seen that when drag is high (L/D ratio is low) the autorotative force is negative. Only when the blade angle of attack gives a high L/D ratio (low drag) can a positive autorotative force be obtained.

93. The angle of attack of the blades for a given rotational speed depends on the speed and direction (velocity) of the inflow, and on the pitch angles selected by the pilot. In powered flight the movement of the inflow is downwards through the rotor but in autorotation it is upwards, therefore the collective lever must be lowered considerably in autorotation to obtain the same angles of attack and must then be lowered still further to obtain a favourable blade lift/drag ratio and so a positive autorotative force to balance rotor profile drag.

94. For a given inflow velocity, pitch angle setting, and r.p.m., the rotational speed and therefore blade angle of attack varies along the length of the blades, the angle being largest near the rotor hub, and decreases to a minimum at the tips. There is therefore only one section of the blade over which the autorotative force opposes the blade drag; this is the range giving the highest L/D ratio.

95. Fig. 17 shows how the L/D ratio of an aerofoil varies with angle of attack, and the rotor blade imposed on it is assumed to experience the change in angle of attack along its length that is indicated by the scale beneath. Note that in the areas outside the small band of angles producing useful autorotative force, the tip portion has a lower average L/D ratio than the remainder of the blade.

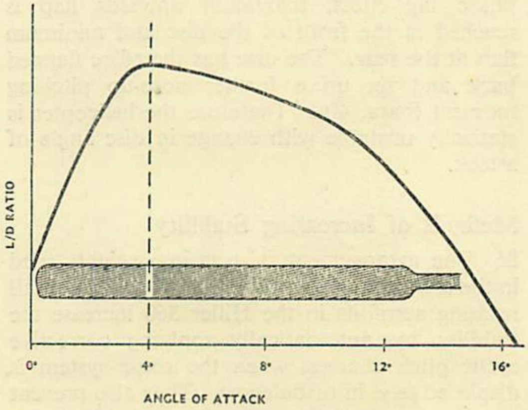


Fig. 17. Variation of L/D Ratio along the Blade Length in Autorotation

Stability of r.p.m. in Autorotation

96. Consider the rotor blade in Fig. 17 when autorotating at a steady r.p.m. If the r.p.m. increase, the angle of attack is decreased along the whole blade and the portion producing useful autorotative force moves towards the hub thus decreasing the arm through which it is acting and consequently its moment about the hub axis. The r.p.m. therefore decrease. In addition, the areas of the blade which have a lower L/D ratio change position and effectiveness in relation to each other, that nearest the tip (with the lowest mean L/D ratio) becoming larger than that near the hub. The total mean L/D ratio for the blade has thus been reduced and for this reason also the r.p.m. are reduced. If the rotor r.p.m. decrease initially, all these effects are reversed, and the rotor tends to speed up until the original speed and thus equilibrium are regained. *Rotor r.p.m. are therefore stable with constant pitch and inflow velocity*, as long as the portion of the blade producing useful autorotative force does not extend to the blade tip. This fixes the minimum practicable rotor r.p.m. in autorotation (unless the maximum permissible coning angle has been reached first). Any further reduction in r.p.m. causes the portion of the blade producing useful autorotative force to move still further outwards, so causing a further loss of r.p.m.

Controlling Rate of Descent with r.p.m. during Autorotation

97. When the portion of the blade producing positive autorotative force is near the blade tip, the moment about the rotor axis is at a maximum. Also the area of blade with the lowest L/D ratio is at a minimum. The L/D ratio for the whole blade is therefore at its highest and the blade is working most efficiently. This condition is achieved by increasing collective pitch and so reducing r.p.m. It follows that rate of descent is least when the collective pitch is raised to give minimum safe r.p.m.

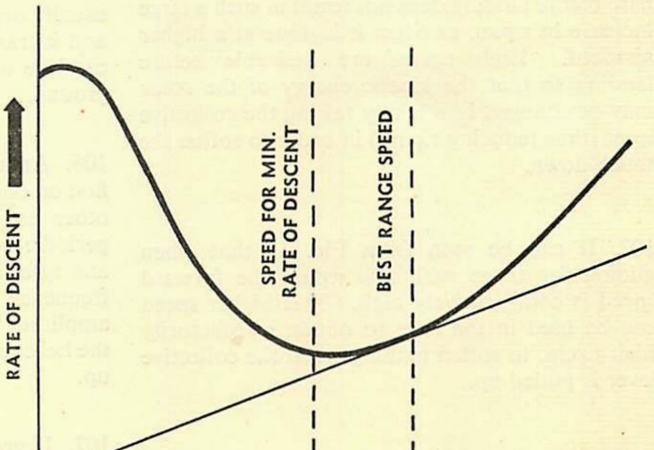


Fig. 18. Effect of Airspeed on Rate of Descent in Autorotation

Controlling Rate of Descent with Airspeed during Autorotation

98. An increasing airspeed increases the inflow (airflow past the lifting surfaces) in the same way as for powered flight. In autorotation the inflow is providing all the power to turn the rotor and so the r.p.m. tend to increase. There is a complete analogy between the helicopter descending vertically in autorotation and then translating into forward flight and the hovering helicopter translating into powered forward flight (see "Power Required" curve, Fig. 9). As the autorotating helicopter starts to move forward by tilting its rotor disc, inflow from beneath is initially reduced (just as ground effect was lost by the hovering helicopter) and thereafter the inflow increases. The work required to be done by gravity reduces just as the engine power required was reduced in powered level flight, until it is required to increase again to overcome fuselage drag. The rate of descent of the helicopter with varying forward speed may therefore be represented by a curve similar to the power required curve but with rate of descent represented on the vertical axis of the graph (Fig. 18).

Varying Rate of Descent with Change of Disc Angle of Attack during Autorotation

99. If the cyclic stick is pulled back during autorotative forward flight, the motion resulting from the subsequent increase in the disc angle of attack, the aft inclination of the total reaction, the nose-up attitude, and the deceleration, is called a *flare*. The increased blade angle of attack causes an increase in lift, coning angle, and therefore r.p.m.; while this is true in both

powered and autorotative flight the effect is much more marked when autorotating as the inflow has been increased as well. Further, the portion of the blade providing most autorotative force is moved along the blade towards the tip and so accelerates the rotor because of its increased moment about the hub axis. Therefore when an autorotating helicopter is flared, the total reaction is inclined aft and increased, thus reducing the forward speed and the vertical speed and markedly increasing the rotor r.p.m. When the disc angle of attack is decreased by pushing the cyclic stick forward in forward flight, the opposite of these effects occurs. The flare is used to reduce vertical speed and forward speed and increase the r.p.m. prior to an engine-off landing.

Best Gliding Conditions in Autorotation

100. Fig. 18 shows the variation in rate of descent with forward speed in autorotation. The minimum rate of descent occurs at the airspeed corresponding to the lowest point of the curve, and the best range is obtained at the speed corresponding to the point on the curve touched by a line passing through the origin and tangential to the curve. To obtain maximum gliding range the most efficient disc condition is also required, *i.e.* lowest safe rotor r.p.m.

101. When maximum range is not required, a lower airspeed and rate of descent may be more comfortable and also a higher r.p.m., since the flare before landing does not result in such a large increase in r.p.m. as when it is done at a higher airspeed. High r.p.m. are desirable before landing so that the kinetic energy of the rotor may be changed into lift by raising the collective lever (thus reducing r.p.m.) in order to soften the touch-down.

102. It can be seen from Fig. 18 that when gliding for range with low r.p.m. the forward speed is comparatively high. This higher speed can be used in the flare to obtain satisfactorily high r.p.m. to soften landing when the collective lever is pulled up.

103. Higher forward speeds may be used for maximum range when autorotating into wind, in the same way as the best range gliding speed for fixed-wing aircraft is varied with wind speed.

Effect of A.U.W. on Autorotation

104. During autorotation the rotor is kept turning by the autorotative force obtained while the aircraft is descending under the effect of gravity. For a given pitch setting, the higher the A.U.W. the greater is the rate of descent, the inflow, and therefore the rotor r.p.m. If at a high weight the pitch setting is increased to keep a constant rotor r.p.m., more lift is obtained to offset the high weight. In this condition, when the rotor r.p.m. are the same as for a lower weight, the increased blade angle of attack causes more blade drag but this is countered by a stronger autorotative force proportional to the increase in A.U.W. It follows that when *minimum* pitch is selected there must be a minimum A.U.W. for autorotation from the point of view of rotor r.p.m. As the A.U.W. is increased, if the pitch is progressively increased to keep the same rotor r.p.m., the rate of descent is almost constant until an A.U.W. is reached at which the blade angle of attack has been increased to the point at which the portion of the blades giving useful autorotative force is the blade tip. Any further increase in A.U.W. requires a reduction in collective pitch to maintain autorotation and entails an increased rate of descent.

GROUND RESONANCE

Sources of Ground Resonance

105. **Definition.** Ground resonance is a vibration of large amplitude resulting from a forced or self-induced vibration of the helicopter in contact with the ground. A self-induced vibration usually originates from disturbances on the rotor and is transmitted via the fuselage to the undercarriage oleo legs and tyres in contact with the ground.

106. An unbalanced force on the rotor is felt first on one side of the helicopter and then on the other as the rotor turns. If the rhythm of periodic compression of the undercarriage legs and tyres happens to coincide with their natural frequency in compression and rebound, the amplitude of the vibration rapidly increases until the helicopter either bounces right over or breaks up.

107. If ground resonance develops, the remedy is either to take off immediately or change the rotor r.p.m. Rotor speed has a direct relationship with the frequency with which the unbalanced force moves from side to side.

108. Common Reasons for Out-of-Balance Forces on the Rotor. Some common reasons for out-of-balance forces on the rotor are :—

(*a*) A faulty drag damper or insufficient drag damping causing blade pattern unbalance (Fig. 19(*a*) and (*b*)).

(*b*) Rapid forced tilting of the helicopter and therefore the rotor hub as when landing heavily on one wheel, bouncing lightly from one wheel to the other, or taxying on rough ground. All these cause blade pattern unbalance owing to the sudden change in the plane of rotation of the blades which take time to re-adjust their positions on the drag hinges.

(*c*) Control unbalance due to rapid cyclic stick movement by the pilot and sometimes when landing on sloping ground (Fig. 20).

Precautions Required to Avoid Ground Resonance

109. Ground resonance is taken into account in the design of a helicopter and the undercarriage is arranged to minimize the chances of ground resonance. However, the characteristics of the undercarriage in resonance depend to a great extent on tyre and oleo pressures, and for this reason it is most important that the correct pressures should be maintained.

110. Blade drag dampers have to be thoroughly checked for correct operation, since partial failure of one causes blade pattern unbalance which the pilot is powerless to control.

111. It can be seen that two of the common causes of ground resonance given in para. 108 are

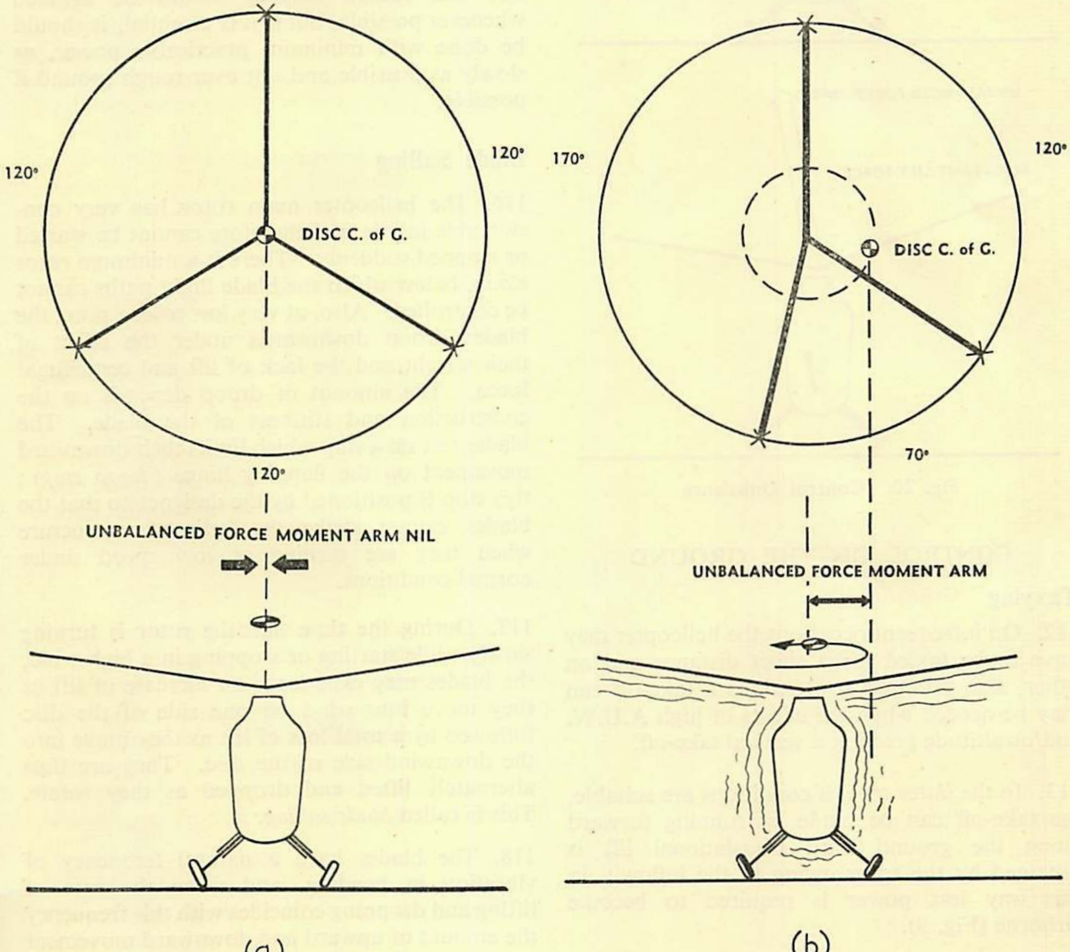


Fig. 19. Blade Pattern Unbalance

caused by faulty flying techniques and are the sources of resonance considered in Vol. 2, Part 2, Sect. 4, Chap. 12 (Helicopter Basic Flying Techniques).

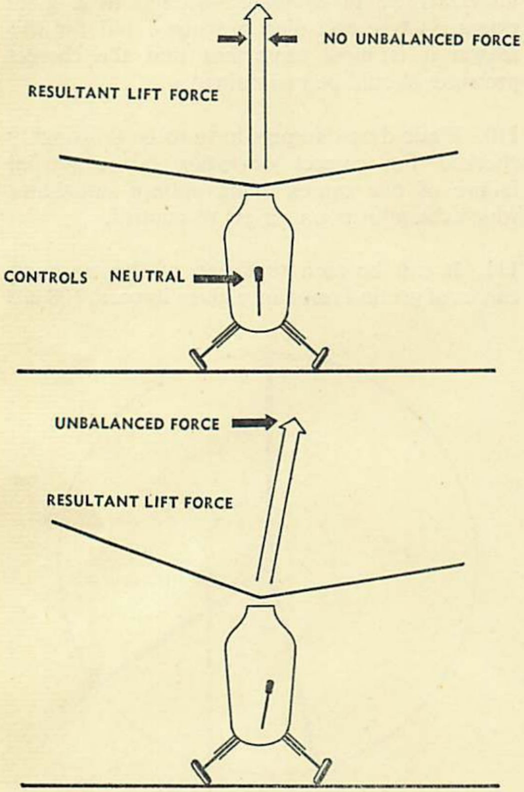


Fig. 20. Control Unbalance

CONTROL ON THE GROUND

Taxying

112. On infrequent occasions the helicopter may have to be taxied for a short distance and on other, also infrequent, occasions a take-off run may be needed when the effects of high A.U.W. and/or altitude prohibit a vertical take-off.

113. In the latter case, if conditions are suitable, the take-off can be made by running forward along the ground until translational lift is obtained by the rotor owing to the inflow; in this way less power is required to become airborne (Fig. 9).

114. Having attained the operating rotor r.p.m., the helicopter can be taxied by moving the cyclic stick forward to tilt the disc in the required direction and then raising the collective pitch lever until the horizontal vector of the total reaction becomes large enough to move the aircraft forward. Directional control is provided by the tail rotor which, being linked with the main rotor, has the same r.p.m. and thus degree of effectiveness as in forward flight.

115. When the collective lever is raised to provide horizontal thrust, vertical lift is produced at the same time. The lift has the effect of reducing the compression of the undercarriage legs, thus changing the conditions for ground resonance; further, because the wheels are carrying less weight they are more likely to bounce on rough ground and tilt the aircraft from side to side and so excite ground resonance. For this reason taxying should be avoided whenever possible, but if it is essential, it should be done with minimum practicable power, as slowly as possible and not over rough ground if possible.

Blade Sailing

116. The helicopter main rotor has very considerable inertia and therefore cannot be started or stopped suddenly. There is a minimum rotor r.p.m. below which the blade flight paths cannot be controlled. Also, at very low rotor r.p.m., the blades droop downwards under the effect of their weight and the lack of lift and centrifugal force. The amount of droop depends on the construction and stiffness of the blade. The blades rest on a stop which limits their downward movement on the flapping hinge (*droop stop*); this stop is positioned by the designer so that the blades cannot strike the helicopter structure when they are turning at low speed under normal conditions.

117. During the time that the rotor is turning slowly while starting or stopping in a high wind, the blades may experience an increase of lift as they move into wind on one side of the disc followed by a total loss of lift as they move into the downwind side of the disc. They are thus alternately lifted and dropped as they rotate. This is called *blade sailing*.

118. The blades have a natural frequency of vibration in bending, and when the rate of lifting and dropping coincides with this frequency the amount of upward and downward movement greatly increases. If the blades are passing over the fuselage during large downward movements they are liable to strike it.

119. Blades with a large natural droop when at rest are particularly prone to blade sailing, since they acquire a relatively high angle of attack when they are pointing downwind and a correspondingly low angle of attack when they point into wind, and thus acquire an increased periodic change of lift. In addition, their flexibility produces a whip effect which causes a greater amount of movement than with stiffer blades.

120. **Centrifugal Droop Stops.** In some helicopters the risk of blades striking the fuselage during blade sailing can be reduced by restricting the downward movement of the blades on their flapping hinges as they slow down. The restriction has to be withdrawn before flying to permit free movement on the flapping hinges, and replaced after landing before the rotor has slowed down sufficiently to make blade sailing possible.

121. The restriction usually takes the form of movable wedges held in position by springs. The wedges prevent downward blade movement on the flapping hinge and are moved outwards by centrifugal reaction when the rotor r.p.m. rise above a set figure.

122. **Conditions Favourable to Blade Sailing.** Strong winds, particularly when combined with turbulence (*e.g.* in the lee of hangars), are the main causes of blade sailing because of the varying upward component of flow and the consequent effect of periodic lift changes on the rotor blades. To avoid the worst effect of blade sailing it is important that the critical stages of rotor r.p.m. should be passed through as quickly as possible. A faulty rotor brake can thus lead to a dangerous situation in conditions of high wind.

CENTRE OF GRAVITY AND LOADING

C.G. Range

123. Neglecting the effects of rotor slipstream on the fuselage, the total reaction must pass through the C.G. to achieve hovering flight. Fig. 21 shows that with a forward C.G. the fuselage tilts nose down to achieve this and with a rearward C.G. it tilts nose up. Since in both cases the tip path plane must be horizontal to maintain the hover, the rotor disc becomes tilted in relation to the fuselage. The single-rotor helicopter has a fixed angular range through which its rotor can be tilted both fore-and-aft and laterally; the fore-and-aft and lateral ranges of C.G. movement are therefore decided by the product of the maximum angular rotor disc tilt and the vertical height of the rotor above the C.G. (Fig. 22).

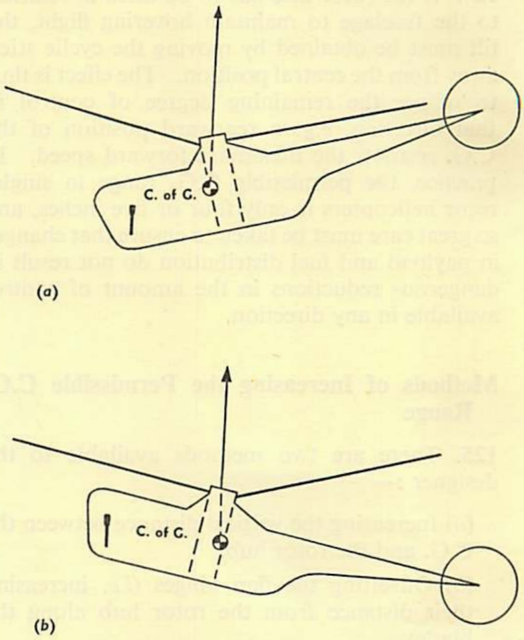
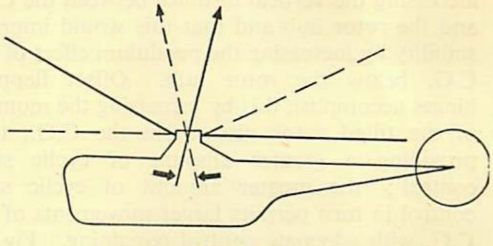
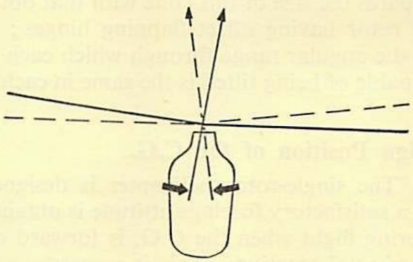


Fig. 21. Effect of C.G. Movement on Fuselage Attitude



(a) *Fore and Aft Range*



(b) *Lateral Range*

Fig. 22. Ranges of C.G. Movement

124. If the rotor disc has to be tilted in relation to the fuselage to maintain hovering flight, the tilt must be obtained by moving the cyclic stick away from the central position. The effect is thus to reduce the remaining degree of control in that direction, *e.g.* a rearward position of the C.G. restricts the maximum forward speed. In practice, the permissible C.G. range in single-rotor helicopters is only four or five inches, and so great care must be taken to ensure that changes in payload and fuel distribution do not result in dangerous reductions in the amount of control available in any direction.

Methods of Increasing the Permissible C.G. Range

125. There are two methods available to the designer :—

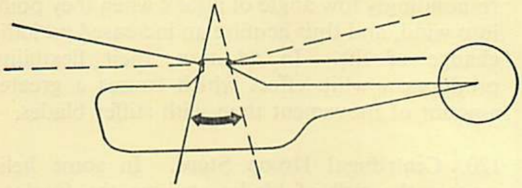
(*a*) Increasing the vertical distance between the C.G. and the rotor hub.

(*b*) Offsetting the flap hinges (*i.e.* increasing their distance from the rotor hub along the blade).

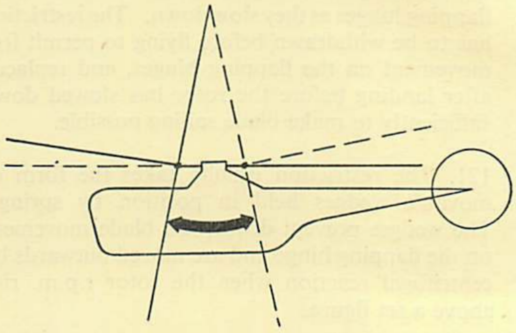
126. It was mentioned in para. 88 that the effect of using offset flapping hinges was equivalent to increasing the vertical distance between the C.G. and the rotor hub and that this would improve stability by increasing the pendulum effect of the C.G. below the rotor hub. Offset flapping hinges accomplish this by increasing the moment of the tilted rotor disc about the C.G., thus providing a greater amount of cyclic stick control ; the greater amount of cyclic stick control in turn permits larger movements of the C.G. with adequate control remaining. Fig. 22 shows the cone in which C.G. must lie, the permissible movement increasing as distance from the apex of the cone increases. Fig. 23 compares the size of this cone with that obtained in a rotor having offset flapping hinges ; note that the angular range through which each rotor is capable of being tilted is the same in each case.

Design Position of the C.G.

127. The single-rotor helicopter is designed so that a satisfactory fuselage attitude is obtained in hovering flight when the C.G. is forward of the line of total reaction. This is necessary so that the moment of the total reaction about the C.G. opposes the moment caused by the rotor downwash acting on the tail cone (Fig. 24). It is also necessary to have a greater control range in the forward direction to correct flap-back of the disc in forward flight. Backward flight is therefore possible only at much lower speeds than forward flight.



(*a*) **No Offset Flapping Hinge**



(*b*) **With Offset Flapping Hinge**

Fig. 23. Effect of Offset Flapping Hinges on C.G. Range

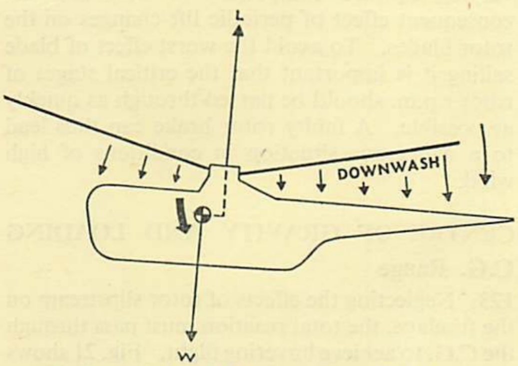


Fig. 24. Effect of Downwash on Tail Cone and Fuselage Attitude

THE VORTEX RING

Definition

128. The vortex ring is the turbulent vortex found at the periphery of the rotor disc in powered flight when the normal downwards induced velocity of the air through the rotor is

opposed by an upward inflow. Fig. 25 shows the airflow pattern of the fully developed vortex ring. Two conditions are required to establish the vortex ring :—

(*a*) Powered flight to produce a downward rotor slipstream.

(*b*) Movement of the helicopter to produce inflow at right angles to the tip path plane from below the rotor disc.

These two requirements can be obtained by descending with zero airspeed under partial power or by applying power during a steep flare.

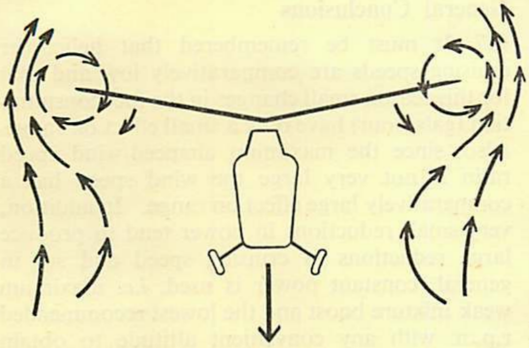


Fig. 25. The Vortex Ring State

Main Effects of the Vortex Ring

129. Whenever an induced downward velocity of the air is necessary to produce the required lift and the downward velocity is opposed by an inflow from the opposite direction, the total flow through the rotor and the lift is decreased. The loss of lift causes a gain in speed in the direction of movement (at right angles to the tip path plane). The higher speed increases the upward inflow and this in turn causes a further loss of lift. The condition thus tends to exaggerate itself until all downward flow through the rotor is completely blocked and the rotor disc becomes analogous to a parachute having no central vent, *i.e.* the column of air beneath the disc spills alternately round one side and then the other.

130. In practice, before the advanced stage is reached, either the pilot inclines the tip path plane with the cyclic stick (thus changing the angle of the disc to the inflow so that it is no longer a right angle) or else the upward flow past the tail cone becomes strong enough to produce a sharp nose-down pitch which has the same effect.

Other Effects of the Vortex Ring

131. The vortex ring is extremely turbulent when established and considerable vibration is felt ; further, as the inflow increases, the higher blade angles of attack cause a large increase in blade drag which reduces the rotor r.p.m. The increase in torque due to higher blade drag causes the aircraft heading to change and this effect is further exaggerated since the loss of r.p.m. reduces the torque compensation provided by the tail rotor. The effects of the vortex ring occur in this sequence :—

(*a*) Reduction of rotor r.p.m.

(*b*) Onset of marked vibration.

(*c*) Sharp change of aircraft heading in the opposite direction to that of rotor rotation.

(*d*) Uncontrolled acceleration in the direction of flight.

(*e*) Sharp nose-down pitch resulting in loss of the vortex ring.

The last occurs after a very considerable loss of height.

RANGE AND ENDURANCE

Introduction

132. When flying for range or endurance the same engine considerations apply as for fixed-wing aircraft, *i.e.* minimum practicable r.p.m. for both range and endurance with, for range flying, maximum weak mixture boost and, for endurance, minimum boost required to maintain height. The minimum practicable rotor r.p.m. and the I.A.S. are determined by the rotor characteristics, while the best height to fly depends on the balance between the reducing efficiency of the rotor as height increases and the varying efficiency of the engine at the same time.

Choice of Rotor r.p.m.

133. Low rotor r.p.m. and higher pitch angles are preferable, as a better blade lift/drag ratio is obtained and therefore a lower rotor profile drag. Below a certain rotor r.p.m. any further reduction causes a significant increase in coning angle and loss of rotor efficiency ; these minimum rotor r.p.m. are usually indicated on the r.p.m. gauge as the minimum permissible r.p.m. for powered flight. The best r.p.m. for range or endurance flying are this figure plus a small safety margin.

Choice of Airspeed

134. The most economical airspeed is obtained from the power required curve (Fig. 9) in the

same way as for fixed-wing aircraft. The best speed for endurance corresponds to the lowest point on the curve and that for range to the point touched by a line tangential to the curve drawn through the origin. (Note that the lowest point on the curve, endurance speed, is also the airspeed giving the best rate of climb for a set power.) When flying for range the maximum weak mixture boost and a minimum recommended engine r.p.m. are used, the airspeed given by this engine setting being accepted as the range speed in most cases. However, if the fuselage drag is high at this speed, it may be found by experiment that the range can be substantially increased by reducing the airspeed through the use of a lower boost.

Effect of Weight

135. At constant rotor r.p.m. a decrease in weight requires a lower pitch angle setting and therefore gives less drag and decreases the power required. The power required curve is thus shifted downwards on the graph and it can be seen that the best airspeed for range is thereby decreased. In practice the effect is very small in most helicopters and is usually ignored.

Choice of Altitude

136. As altitude increases, pitch must be increased to maintain constant rotor r.p.m.; the higher pitch increases the rotor drag and the power required at given rotor r.p.m. Therefore in helicopters with unsupercharged engines the range decreases with height. In helicopters with supercharged engines the range increases with altitude only while the increased efficiency of the engine with gain in altitude is sufficient to counter the falling rotor efficiency (higher rotor drag), *i.e.* up to full throttle height. In practice, the increase in engine efficiency as altitude is increased towards the full-throttle height is largely offset by the increase in rotor drag, and so range does not vary appreciably with height even with a supercharged engine. In these circumstances it is wasteful to use fuel in climbing to the full throttle height. The lowest practicable height is used for endurance.

General Conclusions

137. It must be remembered that helicopter cruising speeds are comparatively low and that for this reason small changes in the fuel consumption (gals/hour) have only a small effect on range. Also, since the maximum airspeed/wind speed ratio is not very large the wind speed has a comparatively large effect on range. In addition, very small reductions in power tend to produce large reductions in cruising speed and so, in general, constant power is used, *i.e.* maximum weak mixture boost and the lowest recommended r.p.m. with any convenient altitude to obtain maximum range. When a helicopter has characteristics which differ markedly from these generalizations the Pilots' Notes will detail the techniques for range flying. Flying for endurance always requires the use of the minimum recommended r.p.m., minimum practicable height, and minimum boost required to maintain height at the recommended best endurance speed.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