DEVELOPMENTS IN ROTATING WING AIRCRAFT

by RAOUL HAFNER

Raoul Hafner came to this country in 1932 and continued his earlier helicopter experiments with the successful design and construction in 1937 of the Hafner AR. III Gyroplane. He is now Chief Designer of the Helicopter Department of the Bristol Aeroplane Company.

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Introduction

In the first instance, I should like to thank the President and the committee members of the Bristol branch of the Royal Aeronautical Society for the invitation which they have extended to me to speak here on rotating wing aircraft.

Secondly, I take this opportunity of thanking Captain Liptrot, of the M.A.P., for a film on helicopters which he kindly lent, and which will be shown later in the evening, and also the Bristol Aeroplane Co. for certain data and information which they have made available for this lecture.

Regarding the subject of the lecture, I must confess I am faced with considerable difficulties. Great advances have been made in the last few years in the rotating wing field, and today the art embraces practically all branches of science.

I believe I am not making an over statement when I say that the rotary wing today is a much bigger and more complicated subject than the fixed wing. There is hardly one aspect of the fixed wing, which does not equally well, perhaps in a slightly modified form, apply to the rotating wing. But on the other hand, there exist now a thousand and one headaches of the rotating wing variety, which the designer of fixed wing aircraft is very fortunate to miss altogether.

In deciding on tonight's subject, I had therefore the choice between a detailed analysis of a specific aspect of the rotating wing development, and a more general talk which, however, necessarily can only touch the fringe of the numerous problems.

I have been advised that the second course, that is a more general and popular discussion, would be the more appropriate one, as the majority of the audience is not likely to be sufficiently closely connected with this development to be interested in intricate technical details.

General Principles of Rotating Wing Flight

There are several forms of rotating wings which permit aerodynamic flight, but in tonight's discussion I have in mind only wings rotating in free air about a substantially vertical axis, and producing a force along this axis which is directly utilised to overcome gravitational and inertia forces. One or more such wings rotating about a common axis form a rotor, and the surface swept by the wings is

¶ *For printing purposes the Greek symbols within the text are reproduced in italics.*

known as the rotor disc. Let us at first consider the simple case of flight along the axis of rotation, or vertical ascent. This is the case of the propeller. We have a number of blades of suitable aerodynamic shape moving through air, due to their rotation about their common axis and their linear velocity along this axis. Propeller blades produce a steady lift which is a function of:—

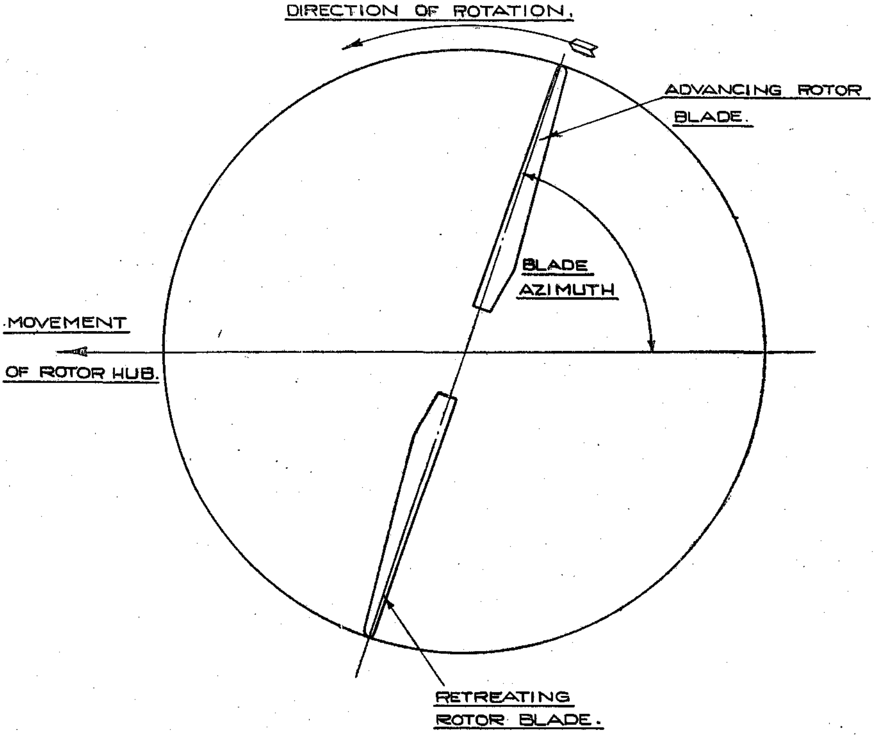
(1) The size and shape of the blades.
(2) Their incidence relative to the rotor disc.
(3) Their rotational velocity.
(4) Their axial velocity.

The lift, and this is important, does not depend on the *position* of the blade in the plane of rotation, or on the blade Azimuth.

The picture, however, changes if an additional velocity component is introduced, that is one in the plane of rotation.

To illustrate this, let us consider a rotor without axial velocity, but with a velocity component in the plane of rotation (Slide 1.)

In this form of flight, the Azimuth position of the blade is an important factor governing blade lift. It is easily seen that, on one side of the



SLIDE No 1.

rotor disc, where the blade may be said to be advancing relative to the rotor hub, the resultant velocity of the blade will be greater than that on the side of the disc where it is retreating. Thus we have here a cyclic change of speed. Unless, therefore, special arrangements are being made, this variable speed would result in a concentration of lift on the advancing side of the rotor, and consequently an undesirable rolling moment.

Quite apart from this there would be severe vibrations due to the cyclic lift change in the blades, which could not be tolerated.

A number of schemes have been proposed to overcome this difficulty. In the first instance, it would appear that the cyclic change of resultant blade velocity could be avoided, at the outset, by arranging for a cyclic variation of the rotational velocity of the blade, so that when advancing the blade would have a smaller angular velocity than when retreating.

Such cyclic change of angular velocity would involve, however, angular accelerations, which can be shown to be excessively high, and the solution of the problem in this form seems, therefore, unlikely.

Other schemes assume constant angular blade velocity, and consequently a cyclic changing blade velocity in forward flight, but propose to compensate by means of a cyclic change of other blade parameters governing lift.

Alternatively one could think of a variable blade area, or a telescoping blade, which would be retracted on the advancing side and extended at the retreating side. The technical difficulties of such arrangements, however, can be easily visualised. They are obviously impractical.

The next possibility is the cyclic variation of blade incidence. This is termed "cyclic blade feathering", and is of great practical importance, having been adopted in most modern rotary wing aircraft.

Its main advantage lies in the fact that only a few degrees of incidence change are necessary to supply the required compensation. This is performed by oscillating the blade about its longitudinal axis, which is characterised by a comparatively small mass moment of inertia. Hence, compensation by means of blade feathering involves only small inertia forces.

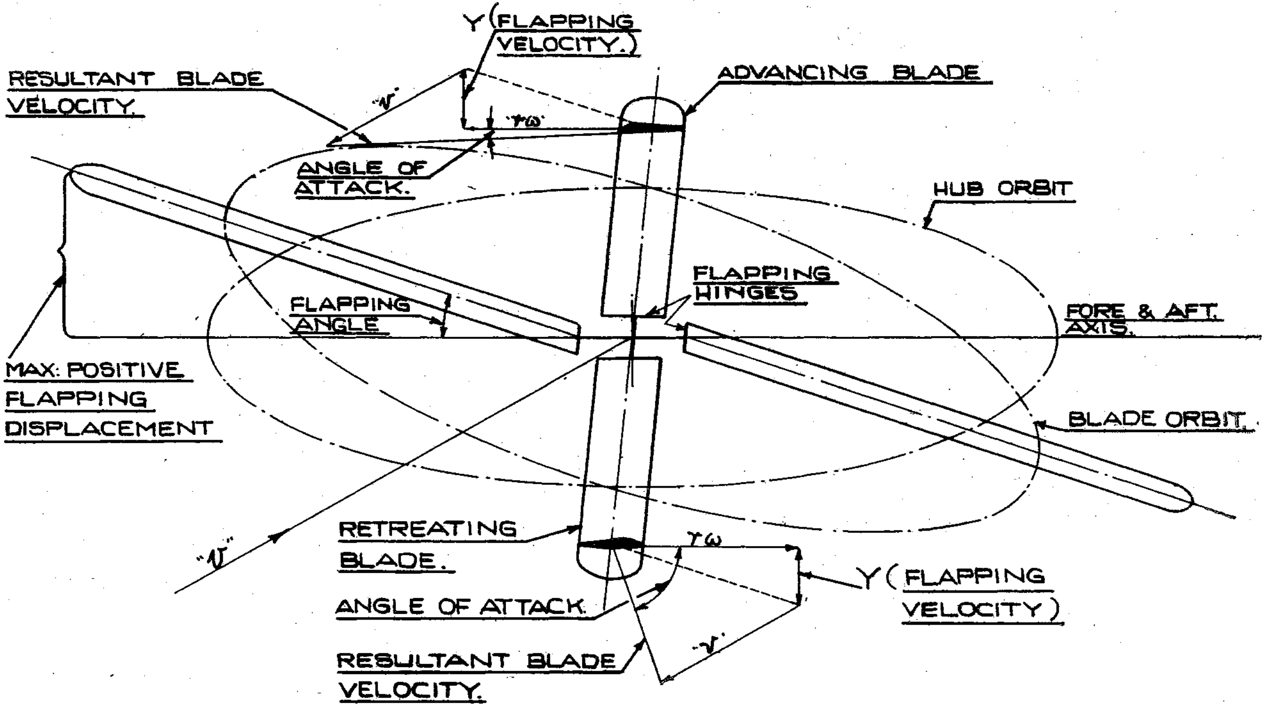
Another form of compensation is obtained through blade flapping. In this case the blade is articulated at the root, to enable it to oscillate, or flap, in a plane at right angles to the plane of rotation. The tip of the blade has therefore, apart from its rotational speed a cyclic velocity component at right angles to it. (Slide 2.)

From this diagram it will be seen that, whilst the blade incidence remains constant, the effective angle of attack is decreased when the blade has a positive or upward flapping velocity, and alternatively it is increased when the flapping velocity "y" is downwards. We see, therefore, that blade flapping in forward flight performs the same function as blade feathering. Both are, in fact, identical in aero dynamic respects.

To sum up, the feathering blade reaches a minimum incidence at the advancing side, and a maximum at the retreating side. At the fore and aft positions the incidence is at an average value.

In order to achieve the same object, the flapping blade must have a maximum upward velocity at the advancing side, and a maximum downward velocity at the retreating side. At the fore and aft positions the flapping velocity is nil.

The maximum positive, or upward, flapping displacement, however, occurs forward of the rotor, and the maximum downward flapping displacement is aft of the rotor hub.


Y (FLAPPING VELOCITY.)
RESULTANT BLADE VELOCITY.
"V"
"rω"
ADVANCING BLADE
ANGLE OF ATTACK.
HUB ORBIT
FLAPPING HINGES
FLAPPING ANGLE
FORE & AFT. AXIS.
MAX: POSITIVE FLAPPING DISPLACEMENT
BLADE ORBIT.
"V"
RETREATING BLADE.
rω
Y (FLAPPING VELOCITY)
ANGLE OF ATTACK.
"V"
RESULTANT BLADE VELOCITY.

SLIDE No 2

I would like to add that this blade flapping in forward flight is quite an automatic movement—in no way controlled—so that articulated blades which are free to flap, automatically retain the equilibrium of lift in the rotor within a considerable speed range, and tend to suppress rotor vibrations.

Flapping blades have, however, another important property. During rotation the blade is subject to a considerable centripetal acceleration, causing a centrifugal inertia force.

In conventional designs this centrifugal force acting on the blade is approximately 12 times the blade lift.

The articulated blade will therefore assume a position of equilibrium where lift, centrifugal and centripetal forces are in balance.

This will be the case when the angle between the plane of rotation and the longitudinal axis of the blade, is approximately 1 in 12, or about 5°. This angle is termed the "coning angle" of the rotor, and the surface swept by articulated blades is therefore a very flat cone.

The important feature in this arrangement is the avoidance of bending moment at the blade root, and even at other points of the blade; the resultant bending moment is only of negligible proportions compared with that of a straight cantilever blade. This feature permits slender and, aerodynamically, very efficient blades, and has been the main reason for its almost universal adaptation in contemporary rotating wing design.

Indeed, this method of reducing bending moments due to blade lift has been extended to blade drag, which is intimately connected with lift, and we find today, in rotary wing practice, fully articulated blades which are not only free to flap, but are also free, to a certain extent, to oscillate individually in the plane of rotation.

These oscillations are termed "drag oscillations", and the operative hinges are called "drag hinges".

The Aero-Dynamics of the Rotor

The aero-dynamics of the rotor are considerably more complicated than those of the fixed wing, for the following reasons:—

In the study of the air forces on the fixed wing, it has been found expedient to regard the wing as stationary, and to observe the pattern of the airflow and the forces around it. The essence of this procedure is, that we are dealing with a static problem, and are concerned only with the components of space and force. There is not involved—and this is important—a variation in respect of time.

The theory of the potential flow, as well as the wing theory concerned with the lift over a finite span, are based entirely on this conception. The picture developed in these theories represents the static equilibrium of forces which is obtained once the wing has been in a certain attitude for a length of time, and there are no more changes with respect to time.

But for the rotor, such a conception is strictly not permissible. Consider in the first instance, the potential flow around the aerofoil.

The blades in their flight through air carry out a composite movement, consisting of rotation and translation. The resultant air speed, angle of attack and circulation around the aerofoil, change rapidly with time. In the modern rotor this cyclic variation has a frequency of the order of four to five cycles per second, so that the rate of change of magnitudes in respect of time is considerable.

A certain amount of investigation in this direction has been carried out in connection with flutter problems, in order to provide the necessary aero dynamic derivatives for the dynamic equations, but there remains still a good deal to be done.

I would have liked to say more about this interesting subject, but unfortunately time doesn't permit, and so I confine myself to a few observations:—

We have today, for aerofoils, such data as the change of lift and drag with respect to speed, or with respect to incidence, or to Reynolds numbers, but for the rotor blade, in addition to this, the changes of air force in respect of v. or a. and a.. are of importance, that is:—

$$\frac{\partial C_L}{\partial \dot{v}}, \quad \frac{\partial C_L}{\partial \dot{\alpha}}, \quad \frac{\partial C_L}{\partial \ddot{\alpha}}, \quad \frac{\partial C_D}{\partial \dot{v}} \quad \text{etc.}$$

Until we know more about these derivatives we cannot, with confidence, attempt rotor calculations.

Let us consider next the air space close to the aero-foil, which is known as the boundary layer.

Skin friction comes from the shearing of air within this boundary layer, and is the result of the rate at which momentum is exhausted from this air. This layer is trailed behind the fixed wing as a turbulent wake, and once it has passed the wing—has no further effect on the aircraft.

This is not so in the rotor blade. Here the air, as soon as it loses momentum, becomes subject to centrifugal force, which moves it radially away from the centre of the rotor.

In addition to this, when the pitch setting of the rotor is close to zero, the wake of the blade is cut by the following blades, which amplifies the effect that I have just mentioned. This phenomenon can be studied in practice on any helicopter or autogiro rotor.

At zero pitch there is a very powerful radial flow in the plane of rotation of the rotor, consisting entirely of an from the boundary layer, which is fed by inflowing air from both sides of the rotor disc.

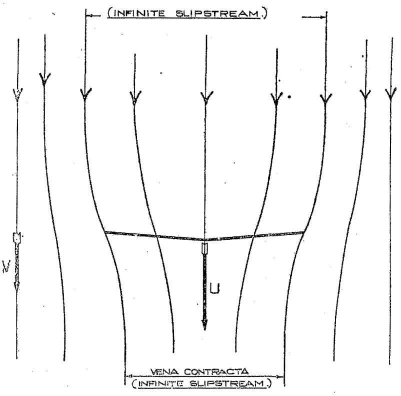
The work involved in this movement of air is very considerable, and all conditions of flight connected with pitch settings close to zero are, therefore, materially affected by this radial flow.

The next item on the list of specific rotor problems is the fact that rotary wing aircraft, slow though they are in the eyes of the pilot, fly really exceedingly fast. With this I mean that, in modern designs, the wing surface supporting the main weight of the aircraft moves at a rate of anything between 500 and 700 ft/sec.

This is a speed range where aero elasticity already plays an important part, and the design of the blade tip, from the point of view of flutter, as well as performance at these high speeds, requires special consideration.

To complete the list of rotary problems (which appear to be problems which have the habit of indefinitely turning up again and again) we come to consider the induced flow.

The calculation of the induced flow of a rotor in vertical ascent is relatively simple. It is similar to that of the pro-



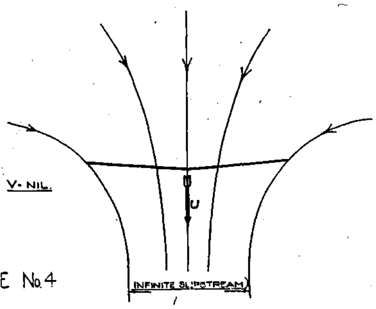
SLIDE No3

peller, which is well established, and the formulae which have been evolved for the propeller, equally apply to the rotor.

The induced flow for this flight case can be seen on the diagram. (Slide 3.)

The picture becomes, however, very different for other modes of flight.

The propeller Vortex theory breaks down already in the case of the hovering rotor. The strip theory, and the assumption of the induced velocity at the actuator disc being half of that in the vena contracta, is not valid any longer. The induced flow for the hovering helicopter is shown by this diagram. (Slide 4.)

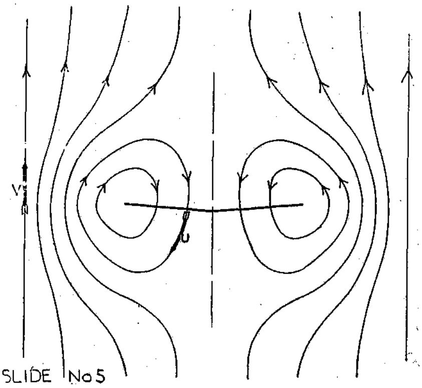


SLIDE No. 4

Empirical extensions of the propeller Vortex theory, with limited validity, have been made, but we are still in need of a satisfactory theoretical investigation on this mode of flight.

The picture becomes still more complicated when we enter into the Vortex ring state. The rotor is in this condition of flight when the direction of the flow, passing through the actuator disc, is opposite to that of the outer air flow. The flow pattern for this case is shown in this slide. (Slide 5.)

We see here that the infinite slip stream has disappeared, and is replaced by a Vortex ring of air which completely envelops the rotor, and the outer laminar flow passes around this Vortex ring, without coming in contact with the rotor itself.

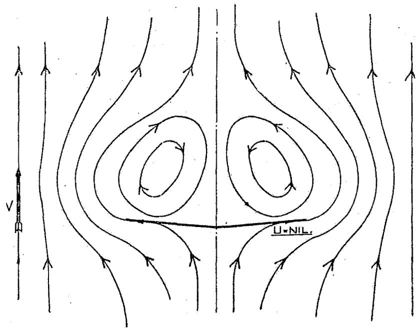


SLIDE No 5

There is, however, no clear demarkation between the outer air and that forming the Vortex ring. Considerable turbulence is in evidence, and there seems to be a continuous exchange of air between these two regions, resulting in a transfer of energy from the Vortex ring to the outer air. Such a transfer is, of course, essential for fundamental reasons, as otherwise the velocity of the finite mass of air within the Vortex ring, which continuously receives momentum from the rotor, would increase to infinity. The form of this energy transfer, and its behaviour, is therefore, a very interesting study, and requires to be analysed before a more exact calculation of the induced flow in the Vortex ring state can be attempted.

The Vortex ring state is bounded by two conditions. The first, which I have already mentioned, is the hovering condition. The other is the free wind-milling condition. In this condition the flow through the rotor disc is nil, or in other words, the rotor behaves like a solid disc.

There is a Vortex ring of smaller proportions immediately above the rotor. (Slide 6.)



SLIDE No6

Going a step further, we enter into the wind-mill-brake state. (Slide 7.)

In this condition the flow through the rotor disc is directed upwards, like that of the outer air flow. There is still a small Vortex ring situated above the rotor which, however, diminishes as the speed through the rotor disc increases.

The characteristic feature of the wind-mill-brake state, as distinct from the previous conditions of flight, is that energy is transmitted to the rotor from the air flow, passing through the disc. In other words, the rotor is receiving energy like a wind-mill.

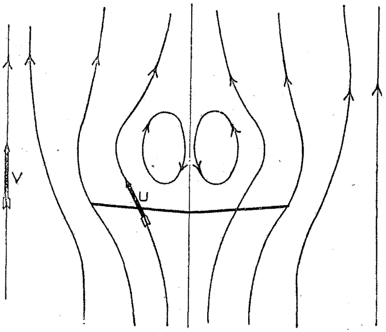
There is one particular point in the wind-mill-brake state which deserves special attention.

Every rotating rotor absorbs a certain amount of power, which is expended on the profile drag of the blades.

If, now, a point in the wind-mill-brake state of the rotor is found, where the work extracted from the air flow passing through the disc is exactly equal to the profile work expended on the blades, then the rotor is maintained in rotation without any power passing through the mechanical rotor drive. In other words, the rotor is free-wheeling, or is in auto-rotation. This feature is employed in aircraft known as rota planes or autogiros. The rotor of such aircraft is not power driven, but is auto-rotating in the manner which I have described. The rota-plane represents, therefore, one specific form of helicopter flight; one point, so to say, on the line extending from the power driven rotor to the power receiving wind-mill.

The helicopter can consequently descend with its rotor in auto rotation, and without the use of engine, provided appropriate adjustments have been made to the blade pitch.

We come now to the induced flow in forward flight.



SLIDE No7

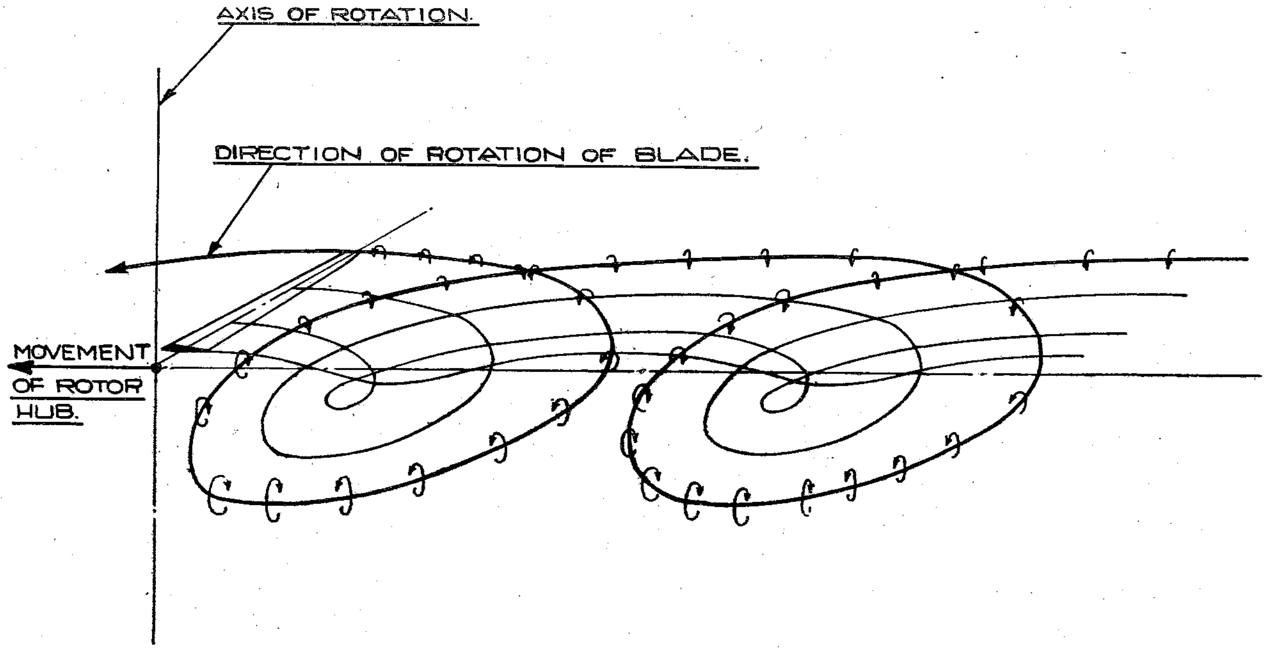
Lift of the rotor originates, of course, along the blade, exactly like along the span of a wing.

We know, however, that the movement of a blade is a composite one, and speed, direction and circulation, change continuously, with regard to place as well as time.

The Vortex sheet shed by such a blade is, therefore, necessarily of a complicated shape.

This diagram perhaps gives a rough picture of its geometry. (Slide 8.)

There is increased vorticity at certain points, due to the cyclic conditions to which the blade is subject, and these regions of increased vorticity are left behind in the path of the aircraft, similar, perhaps, to the Vortex pools from the oars of a moving rowing boat.


AXIS OF ROTATION.
DIRECTION OF ROTATION OF BLADE.
MOVEMENT OF ROTOR HUB.

SLIDE No 8.

There is usually more than one blade in a rotor, so that the Vortex sheet produced by a rotor is a pattern of N interwoven Vortex sheets, from N rotor blades.

It will be appreciated that a rigorous analysis of such a complex configuration is impossible, and far going simplifications must be applied to this picture in order to make it amenable to mathematical treatise.

Fortunately, there is a good deal of justification for simplifying the picture. The blades in a modern rotor rotate at a high rate compared with the forward speed.

This produces a tight pattern of coils formed by the Vortex sheets of the individual blades, which tends to level out the moving pattern in the Vortex sheet of the rotor.

Thus, the individual Vortices moving down stream merge more or less into a continuous Vortex sheet, which is trailed by the rotor as a whole, and which is acceptable to calculation. We make, therefore, the assumption, notwithstanding the fact that the lift originates from the rotor blades, that it is formed at the rotor disc as a whole, or simpler still, along the lateral rotor diameter or span of the rotor.

This assumption permits the calculation of the induced flow in the span wise direction by the orthodox manner known in fixed wing design. As regards the fore and aft distribution of induced flow, one assumes a slight curvature of airflow, which is confirmed by experience.

Having made allowance for the induced flow in this manner, the further calculations for the rotor blade itself are made on the assumption of two-dimensional-flow conditions.

Let us now make a brief investigation into the aero dynamics of the blade.

We have seen that a blade element in forward flight is subject to speed variation, which depends on the ratio between forward speed and the speed component due to rotation. Thus, it varies directly with forward speed, and indirectly with the rate of rotation, and the distance of the blade element from the rotor centre, i.e. the smaller the radius the larger the speed ratio.

We have seen that, in order to maintain a constant lift throughout rotation, this speed variation is compensated by a cyclic change of angle of attack. As there is a larger speed ratio near the root than near the tip of the blade, it might be desirable to arrange for a larger cyclic change of blade incidence near the root than near the tip. This clearly means cyclic twisting of the blade, which for obvious reasons cannot easily be done. As a compromise arrangement, a mean cyclic change of incidence, which is the same for all blade elements, is usually provided for by means of blade feathering or flapping. This meets exactly the requirements of the most important portion of the blade around three quarters radius from the root, and all the other blade elements, inwards and outwards of this region, receive only an approximate speed compensation.

In order to meet the conditions for various ratios between forward speed and rotational speed of the rotor, the mean cyclic change of incidence can be varied by increased or decreased blade feathering. Thus for instance, on a rotor moving at slow forward speed but at a high rotational speed, the blade feathering needed is very little, whereas, on the other hand, considerable feathering is required for a small and slow rotating rotor moving at high forward speed. From this it will be seen that, in a rotor in forward flight, the conditions in the rotor disc vary from point to point, i.e. with respect to radius as well as Azimuth, and analytical calculations for this reason tend to be rather cumbersome. However, in order to obtain a convenient datum for performance calculations, which do not involve analytical treatment, but are based on semi-empirical data, the definition "tip speed ratio" has been found expedient. This is the ratio between the forward speed and the velocity component due to rotation of the blade tip, or, in mathematical terms, the tip speed ratio is

$$\frac{V}{R\,w}$$

where V is the forward speed in the plane of rotation, R the blade radius, and w the angular velocity of the rotor.

I will show now that there are definite limits in the tip speed ratio of a rotor, beyond which satisfactory operation is not possible.

Let us assume a rotor with a blade tip speed of 600 ft/sec, and in the hovering condition, an average lift coefficient of .4.

Take now this same rotor at the forward speed of 225 ft/sec, or at a tip speed ratio of 225/600, or .375. For the working portion of the blade at ¾ radius the rotational speed component is ¾ of 600=450 ft/sec., so that the speed ratio in this region is of the order of 225/450 which is ½.

On the advancing side of the rotor, the resultant blade speed in the working region is therefore 1½ times its normal rotational speed, whereas on the retreating side it is only half of it. If no speed compensation was provided for, the lift on the advancing side would consequently be 3 half squared, or nine quarter times that of the lift when hovering. In order to compensate for this, the lift coefficient on the advancing side is reduced to four ninths of the original value, i.e. it is reduced from .4 to .17, whereas on the retreating side the lift coefficient will be 4 times that of the original value, or 1.6.

A lift coefficient of 1.6 is a fairly high value for an aerofoil, which, in this condition, is probably near the stalling point.

This brief analysis has shown, therefore, that the tip speed ratio of .375 has brought the working portion of the blade on the retreating side close to stalling point. A further increase of tip speed ratio is obviously not possible, and we may regard, therefore, this figure as a limiting value. Any further increase of forward speed can, therefore, only be achieved by increasing the tip speed of the rotor proportionally, so that the tip speed ratio remains at the value of .375, but, in the present case, the resultant speed of the blade tip on the advancing side is already about 600+225 ft., equalling 825 ft/sec. This velocity at sea level represents a Mach number of .73. We are here, therefore, fairly close to a critical speed, in view of aero compressibility, so that we have, with 225 ft/sec. or 150 m.p.h., indeed come close to the maximum forward speed at which our helicopter can safely be flown. Exact investigations, allowing for finesse in design, show that, with today's knowledge, we could fly helicopters up to speeds of approximately 180 miles an hour. Beyond such speeds there would be either stalling on the retreating side, or alternatively, at the advancing blade tip, difficulties due to aero elasticity.

Control of Rotary Wing Aircraft

A few words now about control. The most general movement of a body in space is defined by its 6 degrees of freedom. 3 degrees of translational freedom of movement and 3 degrees of angular freedom of movement. Such a body can turn about all possible axes, and, quite independently from this movement, can trace any path in space. If such a body were controlled, its control would comprise at least six independent control components. However, controlled flight is possible with less degrees of freedom, and therefore, not all of the 6 control components are necessary. As we require a minimum of one control for one dimensional movement, and 2 control components for two dimensional movement, so, by analogy, we require a minimum of three dimensional control components for movement in space. In the conventional aeroplane there are the throttle control, pitching control, and, as the third control, either the Yawing or the rolling control. The throttle or power control provides for linear acceleration along the longitudinal axis of the aircraft. The two other controls determine angular accelerations of the aircraft. There remain, consequently, three degrees of freedom of movement, which are not independent, but which, in one form or another, are coupled with the directly controlled movements. Thus, the aeroplane cannot, for instance, perform a rotation in pitch or roll, without these angular movements affecting the flight path, or, in short; into whatever direction the aeroplane turns, there it has to go.

I have spoken of either the rudder or aileron control as a minimum requirement for controlled flight.

Conventional aircraft, however, possess rudder *and* aileron control, and have thus four independent controls, and four degrees of freedom of movement.

There is, therefore, one redundant control above the absolute minimum which enables the aircraft to carry out assymetric flight manoeuvres.

If rotating wing aircraft were required only to possess the limited degree of freedom of the aeroplane, the same controls would suffice. But the outstanding manoeuvrability of the helicopter is due to an additional degree of freedom of movement, making five in all.

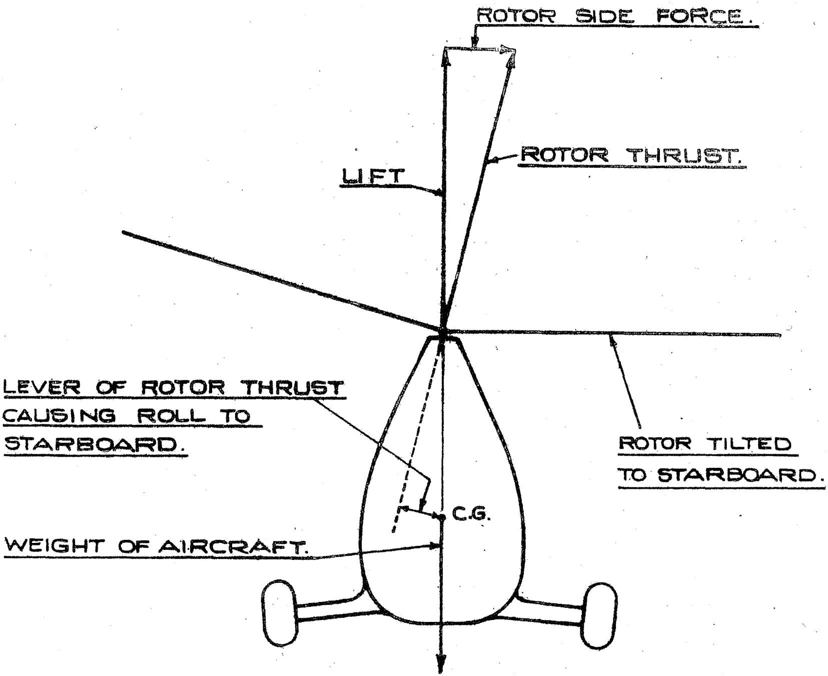
The helicopter distinguishes itself from the fixed wing aircraft by the fact that it is not forced to fly in the direction where its nose points. We have seen that the aeroplane, which possesses rudder and aileron control, can already divorce rotational from translational movement.

The helicopter in slow flight can move in any direction in space, without noticeable change of attitude relative to the ground.

The additional freedom of movement of the helicopter would not be possible without a further independent control component. This additional control component is the height control, and determines the linear accelerations in the vertical axis of the aircraft. The remaining controls of the helicopter are analogous to the respective controls in the aeroplane, but they are not quite identical in operation. The control components served by the control column are, in the helicopter, termed the Azimuth control. In the low speed range they determine linear accelerations in lateral and fore and aft direction. Therefore pulling the control column back does not result in a climb, as one would think, nor pushing it forward in a loss of height, but merely in a change of speed in the horizontal plane. Only when higher speeds are attained does the control column effect movements in the vertical direction, like in the aeroplane.

As I have already mentioned, rotary wing aircraft are required to operate at a speed range commencing at zero speed. It is, therefore, obvious that the conventional type of control in the fixed wing aircraft, that is by means of adjustable control surfaces, is unsatisfactory, as it would become inoperative at zero flying speed.

A variation of this principle is obtained by utilising the induced air flow which is always present where a load is carried aero-dynamically. Although all possibilities of this nature are by no means exhausted, the general impression from the various attempts made is that the available air flow is not powerful enough to give effective control. The control surfaces would



SLIDE No 9

be rather large, and the control cumbersome, so that apart, perhaps, from the control in yawing, the deflection of the slip stream of the rotor is unlikely to be used for the purpose of controlling the aircraft.

A more important argument, however, for not controlling roll and pitch in this way, is that this can be done, very much easier and more effectively, by the rotor itself.

The rotor produces an aero-dynamic force carrying the entire weight of the aircraft, and this force lies along the axis of rotation. By moving the axis of rotation, and with it the rotor thrust relative to the aircraft, a very powerful control can be obtained, which is independent of any translational speed of the aircraft. The most elementary form of control, in this way, would be the shifting of the rotor bodily in its plane of rotation. (Slide 9.)

The second possibility, which is of great practical importance, is the angular displacement of the rotor relative to the aircraft. If the rotor is tilted to starboard, the aircraft will at first accelerate in this direction and, as the rotor is usually placed above the C.G. of the aircraft, eventually roll to starboard, and similarly, if the rotor is tilted backwards, the aircraft will accelerate backwards, and eventually pitch in the positive sense.

There are various methods of tilting a rotor. The most simple form comprises a rigid rotor like a propeller, which is spherically hinged about its centre of rotation, and is connected to a suitable control gear, in order to permit inclinations in all directions. This form represents a direct control, and consequently the work to overcome inertia and gyroscopic forces must be provided by the pilot, or another external source of power. Such a control is necessarily very heavy in operation, and larger rotors would be quite unmanageable by this method.

Another method of control is by means of cyclic pitch variation. In this form a cantilever rotor blade is rotated about the longitudinal axis, like the blade in a variable pitch propeller, but the pitch change is of a cyclic nature, so that there is more incidence, and consequently more lift, on one side of the rotor than on the opposite. In this way the air is made to do the work of tilting the rotor. The serious drawback to this scheme, however, is the gyroscopic couple due to the rate of change of rotation of the rotor, which is not catered for in the control, and which is making itself felt as a disturbing element during control movements.

The third, *and most important,* method of control, is that of the articulated rotor. Two forms can be distinguished which are aero-dynamically identical. There is, in the first instance, the direct hub control which we find in the autogiro. We have here a set of flapping blades which are articulated to a central hub. This hub, in turn, is pivoted at the top of the pylon, and connected with a control gear enabling it to be tilted in any Azimuth direction.

Let us assume a hub and rotor rotating in the same plane. Tilting of the hub, i.e. angular displacement of it relative to the momentary plane of rotation of the rotor, causes, in the first place, a cyclic pitch change in the blades, which produces an aero-dynamic couple on the rotor. This couple performs the change of rotation of the rotor which as before induces a gyroscopic couple. Owing to the articulation of the blades however, the gyroscopic couple cannot be transmitted to the hub and control, but is balanced by air forces set up by the flapping of the blades. The control is therefore free from all severe rotor forces, and the only indication by which these forces are experienced is a time lag in the control. In this way, any angular movement of the hub, after a brief time lag, is followed up by the rotor disc, which always tends to align itself with the plane of rotation of the hub.

The second form of control for the articulated rotor was demonstrated in the Hafner gyroplane, and is used in most helicopters.

The rotor blades which, apart from flapping can be feathered about a longitudinal axis, are linked suitably to a spider or swash plate, or the like, which in turn is connected to the pilot's controls, and can be tilted in any Azimuth direction. The tilting of the control spider, like the tilting of the hub in the autogiro, causes, in the first place, a cyclic pitch change in the rotor, which produces an aero-dynamic couple, including the rotor disc, and all further reactions are exactly as in the tilting hub control.

Thus, the spider performs the function of the tilting hub, and the rotor orbit will always tend to align itself with the plane of rotation of the control spider or the control orbit, and any movement of it, subject to a very brief time lag, is copied by the rotor.

To sum up, the rotor control means essentially tilting of the rotor thrust. This produces horizontal aero-dynamic force components, which accelerate the aircraft in this direction. Further, owing to the fact that the rotor is above the C.G. of the aircraft, this side force, acting at the rotor head, induces a rotation of the aircraft.

Types of Rotary Wing Aircraft

I have pointed out that the autorotating rotor, which we find in the rotor plane, does not absorb power, but performs merely the function of a wing. This type of aircraft is, therefore, very similar in principle to the aeroplane, and flies in the same manner.

Rotor planes are usually fitted with an auxiliary drive for the rotor, which permits initial acceleration of the rotor prior to take off. In certain designs the speeding up of the rotor on the ground is carried beyond normal flying rotor speed, in order to utilise kinetic energy stored in the rotor, and obtain a direct or jumping take off.

Many versions of this type of aircraft have been constructed, but since the renaissance of the helicopter, the autogiro has lost most of its selling points.

Today the helicopter is in the centre of the rotary wing development. There are many forms of helicopters. Let us first consider the single rotor helicopter.

Its characteristic feature is the compensation of the aero-dynamic rotor torque, which is done in various ways. There is the jet driven rotor, which carries power jets at the tip of the blades, and the fuselage is consequently free from torque. The high velocity of the blade tip is particularly suitable to give high jet efficiency.

The most simple arrangement would be one where the whole power unit is confined to the blade tip, with only fuel pipes and controls leading to the rotor centre. There are, however, a number of serious problems connected with this arrangement, and its solution must be left to the future.

The second possibility is the combination of blade tip jets, with a central power unit supplying compressed air, which is fed through the hollow blade to the tip.

This arrangement suffers from frictional losses at the walls of the tunnel, which contains at least two 90 degree turns.

Another arrangement comprises a conventionally driven rotor and a jet, arranged at the tail of the fuselage, so that its thrust produces a moment about the axis of rotation of the rotor. This is not strictly a power jet, but a static thrust producing device. As such its efficiency is not very high, because, the jet cross sectional area being relatively small, the static thrust can only be obtained at the expense of high jet velocities and, consequently, power.

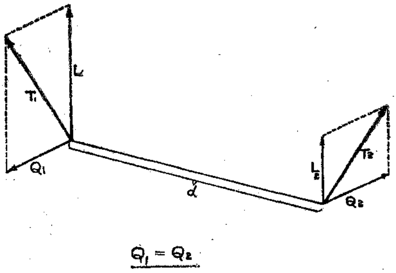
Another form of torque compensation utilises the induced flow of the rotor. Suitably shaped vanes are placed in this flow which produce the required compensating torque. This scheme has a valuable feature, in that it recovers the rotational momentum and energy, which otherwise is lost in the slip stream.

Considering now the twin rotor helicopter, we have first the type where the rotors rotate about parallel axes, but in opposite directions. It can be shown that two counter rotating rotors are most efficient if they are identical in geometry. That is, equal in size, tip speed, lift etc. They can be arranged, side by side, or behind one another.

Alternatively, the rotor discs can over-lap, partially in the case of intermeshing rotors, or fully when they are co-axially one above the other. Any over-lapping of rotor area, means, however, a reduction in supporting surface which results in increased induced losses. On the other hand, non overlapping rotors necessitate always relatively heavy supporting structures.

An example for a side by side rotor helicopter is the Focke Wulf, whereas the Breguet helicopter represents the co-axial type.

So far we have considered parallel axes of rotation.



SLIDE No 10

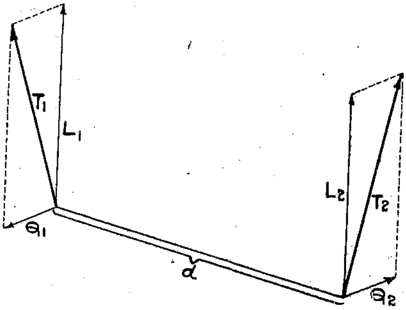
Now we come to twin rotors, the axes of which are inclined to one another, and do not intersect. The torque compensation of such rotors is based on very different principles. In the first instance, the torques of such rotors, do not add to zero, but leave a resultant torque, which is compensated in the following manner. (Slide 10.)

The thrusts T1 and T2, of the rotors which lie along the respective axes of rotation, can be resolved in two-components, L1 and Q1 and L2 and Q2.

L1 and L2 represent together the total lift of the helicopter, whereas Q1 and Q2 form a couple with the lever *d*, which is the distance between the two rotor axes, and this couple is adjusted to provide the torque compensation for these two rotors.

It is obvious that the components Q1 Q2, which don't contribute towards lift, should be as small as possible, and this can be done by making *d* large.

There are a number of configurations on this principle.



$T_1 \simeq L_1 = L_2 \simeq T_2$

$Q_1 = Q_2$

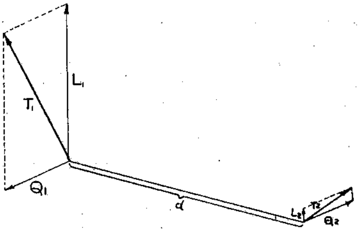
SLIDE No 11

Consider two rotors of equal thrusts. *d* being large, and consequently Q being relatively small, we can see from this diagram that the angle between the axes of the two rotors is quite small, and both lie in the general direction of lift. (Slide 11.)

The Florine helicoper is an example of this arrangement.

Now let us consider 2 rotors of different size. (Slide 12.)

In this case the large rotor with the large thrust determines the general direction of lift, as we can see in the diagram, whereas the small rotor is mostly concerned with producing the force Q2.



$T_1 \simeq L_1 \simeq$ TOTAL LIFT OF HELICOPTER

$L_2 \simeq$ NIL

$T_2 \simeq Q_2 = Q_1.$

SLIDE No. 12

The well known Sikorsky helicopter is an example of this type.

One could make a long list of possible helicopter lay outs, and what the future helicopter will look like we frankly do not know today. There are so many factors which will be thrown into the scales in the coming years, that it would be futile today, to attempt a prophecy on this development.

There are, however, a few indications based on general principles and natural laws, which permit a limited statement. In my opinion, the small helicopter which carries the equivalent of a car load, will be of the single rotor type, or at least, have only one rotor to supply the main lift. In the larger helicopter, which carries something like a bus load, the lift will be equally shared between 2 rotors.

The Helicopter as a means of Transportation

After this short description of the rotary wing aircraft and its most important representative, the helicopter, I should like to say a few words on its possible uses in the future.

I have made reference already to the size of helicopters.

I would add that it can hover and manoeuvre exceedingly well in confined spaces, and, on the other hand, can travel at speeds up to 180 miles per hour. Regarding cruising speed for the near future, a figure of perhaps 100 m.p.h. is near a practical mark.

The helicopter can operate at day and night, and can fly in very adverse weather conditions. We know that, in the case of an engine failure, controlled flight can be maintained, and a safe landing can be performed. For such an emergency landing, an area of 100 yards in diameter is ample, the actual landing run being of a length of 10 to 20 yards only.

There will, of course, be many specific uses for the helicopter, for instance, as weight lifting gear in ports and mines, and in Civil Engineering works, where cranes are not practicable; also for police and military uses.

A seemingly unlimited range of proposals of this sort have already been made, and it is not my intention to add here to this list.

What I have in mind, however, is the helicopter as a means of transportation in competition with already existing forms of transport.

Let us consider a probable ground organisation for such helicopter service.

This sketch shows a typical helicopter landing and parking place, as I visualise it. The landing pitch itself is a circular area of 100 yards in diameter. There is no reason why such a place should not be situated in a built up area, providing there are no high obstacles in the vicinity, preventing an approach along a flying path of 30 degrees slope. (Slide 13).

This provision is necessary to enable emergency landings. Normal take off and landing are made in such a manner that, at any instance during the manoeuvre—should an engine failure occur—the pilot is in a position to force land on this landing pitch. For this reason take off and landings are made facing into wind, and the flight path during take off is in the direction upwards and backwards.

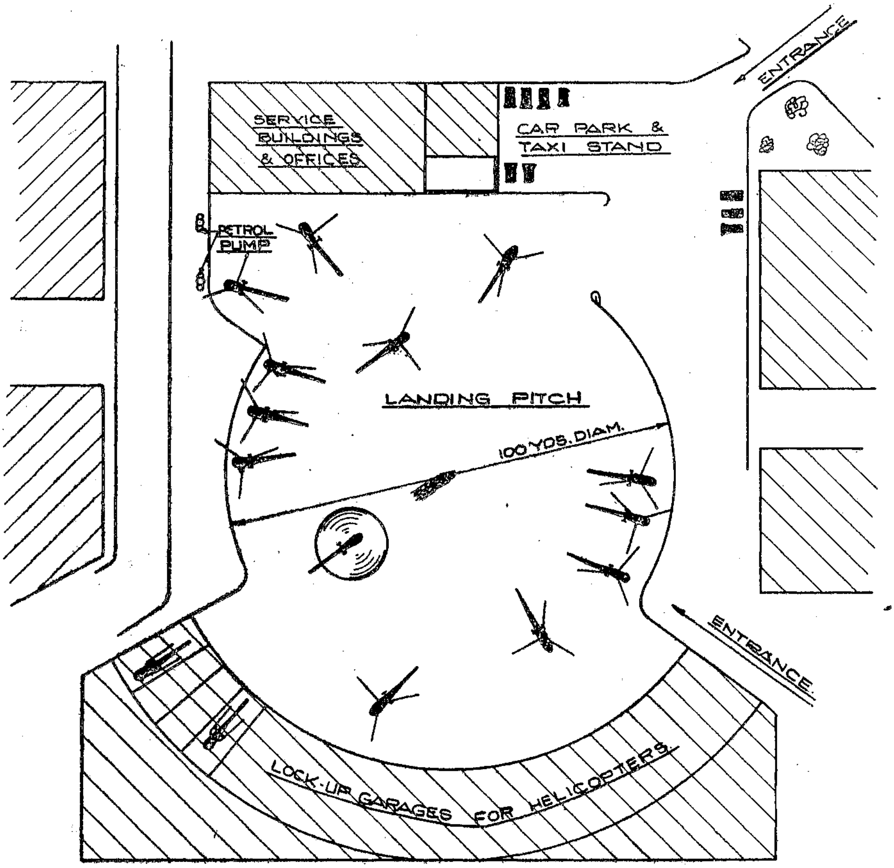
A diametrical strip of the landing pitch in the direction of wind is always kept free for take off and landing, and the remainder of the area is used as a parking place for helicopters. Adjoining the pitch we have lock up garages for helicopters, petrol pumps and service buildings, and the necessary office accommodation, with telephone facilities etc.

Preferably, such a helicopter station should be combined with a car service station, and a taxi stand and car park should be included.

There is nothing elaborate about this lay out, and the initial expense and maintenance costs should be very moderate.

I visualise these helicopter stations distributed densely over the countryside, as well as in towns. They are really only a glorified road-side car service station, and I feel, therefore, that once the helicopter is available, and subject to suitable guidance from the appropriate authorities, private enterprise will see to it that they grow like mushrooms.

I am afraid I had not time to discuss the efficiency of the helicopter, and therefore have no basis for its running costs.



SLIDE No 13

From investigations which have been made on these lines, we know today that it is possible to build helicopters which will be able to operate at a cost of approximately one and a half times that of taxis. This estimate is subject to a fair taxation policy, that is low taxes on aviation fuel, and no direct taxation on the helicopter, at least in the early stages of its development.

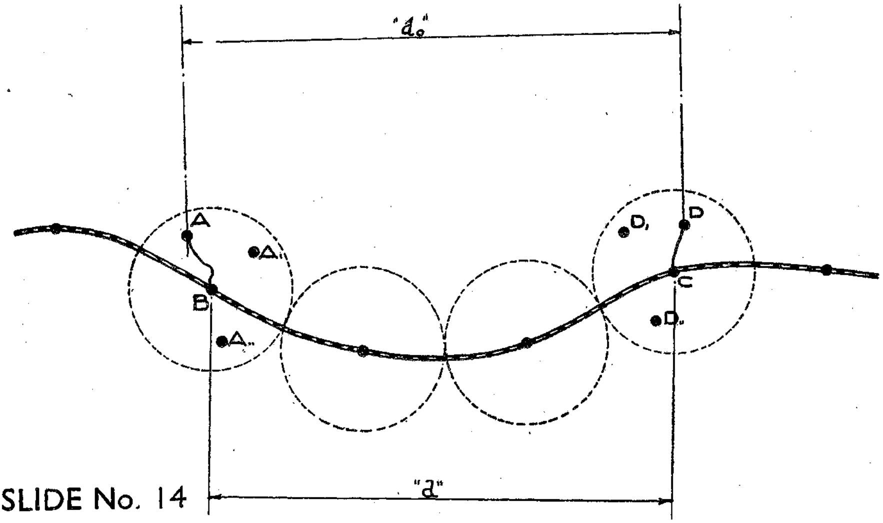
Assuming now a helicopter service based on these lines; what would be its chances in competition with other means of transport?

It is necessary here to establish a few definitions which apply to any form of transportation or travel.

A journey has a starting point A, and a point of destination D. (Slide 14)

The distance of transporting *d*o is the length of the straight line connecting A and D.

The major part of the journey is performed by the selected form of transport i.e. by air, road, rail etc. It commences at B, the nearest practical point to A for embarkation, and terminates at C, the nearest practical point to D for disembarkation. The distance between these points, the straight line BC, is defined as *d*.



SLIDE No. 14

This leaves short distances AB and CD at the ends of the journey. Their length varies, of course, with the circumstances, and depends mostly on the form of service employed over BC. They may be nil in the case of a direct " door to door " service. Alternatively they are covered by another, usually inferior, form of service to that selected for the main distance BC.

The difference between AD and BC is :—

$$\triangle d = d_o - d$$

$\triangle d$ may be positive or negative, as can be seen by moving the points A and D, and is usally small compared with the total distance. For a large number of journeys $\triangle d$ averages zero, which will be appreciated if a large number of points, A1, A2, A3 etc., are assumed in the neighbourhood of B, and a similar number of points D1, D2 D3 around C. The mean journey distance for all combinations of A and D is clearly equal to BC, which means

$$\triangle d \longrightarrow \text{nil}$$

The time needed to travel from A to D is t_o, and the time for the journey from B to C is *t*, the difference is defined as

$$\triangle t = t_o - t$$

Now $\triangle t$ varies with circumstances, depending on the length of the subsidiary journeys AB and CD, on the time for embarkation and disembarkation, and other factors.

It is clear, however, that for a large number of journeys, the average $\triangle$ does not approach zero, but has a definite value. This value can be shown to be a constant for a given form of service, and is practically independent of the length *d* of journey. It is therefore, suitably termed the " marginal time loss ".

Now the rate of progress along BC, or the mean cruising speed along this line is defined as :—

$$V_m = \frac{d}{t}$$

In a similar manner the mean effective speed of the whole journey from A to D is

$$V_e = \frac{d_o}{t} = \frac{d + \triangle d}{t + \triangle t_o}$$

however, because $\triangle d$ averages zero.

We can write

$$V_e = \frac{d}{t + \triangle t}$$

which, with substitutions, gives the following expression

$$V_e = \frac{V_m}{1 + \triangle t\,(V_m/d)}$$

We see, therefore, that the mean effective speed depends on the mean cruising speed, the length of the journey, and the marginal time loss.

The mean cruising speed, in turn, depends on a number of factors.

(1) The maximum cruising speed obtainable with the type of transport employed.

(2) The ratio between the lengths of the straight line BC and that of the actual path of travel.

(3) The number of intermediate stops, or points, which for reasons of safety or otherwise, must be passed at a speed which is less than the maximum cruising speed.

(4) Weather conditions, etc.

The marginal time loss depends mostly on the density of the points of embarkation or disembarkation, which determines the length of the subsidiary journeys. Further, the speed of transportation on subsidiary journeys, the time lost in changing vehicles at B and C, and finally, the average time table loss, which is the average time needed to wait for connections.

On this basis let us now consider air transport by air liner.

I assume, in a future service, an economical cruising speed of the order of 300 miles per hour.

In a country like England, there will be air ports at average distances of 65 miles. They cannot, of course, owing to their size and the nature of the air service, be in towns or centres of activity, which results in an average of 39 miles, for both subsidiary journeys to and from the air port.

These figures substituted in the formula for mean effective speed give now the very interesting curve A. (Slide 15.) The remarkable fact arising from this curve, is a pronounced decrease of mean effective speed of transportation with the length *d* of the journey.

We see here, that even under conditions of an efficient air service, which, it is hoped, will be attained at some future date, the mean effective speed of a journey of, for instance, 100 miles, would only be of the order of 30 miles per hour. It is obvious, therefore, that the air liner, is quite unsuited for short journeys.

Let us now see how rail transport compares. The Railway Companies have lately issued a statement, which, amongst other points of information, hinted at possible future speeds on railways.

I have taken some of their figures.

Usually, for short distances below 60 miles, the journey is made by a local train, and for distances of more than 60 miles, by express trains, with the use of local trains at the end of the journey.

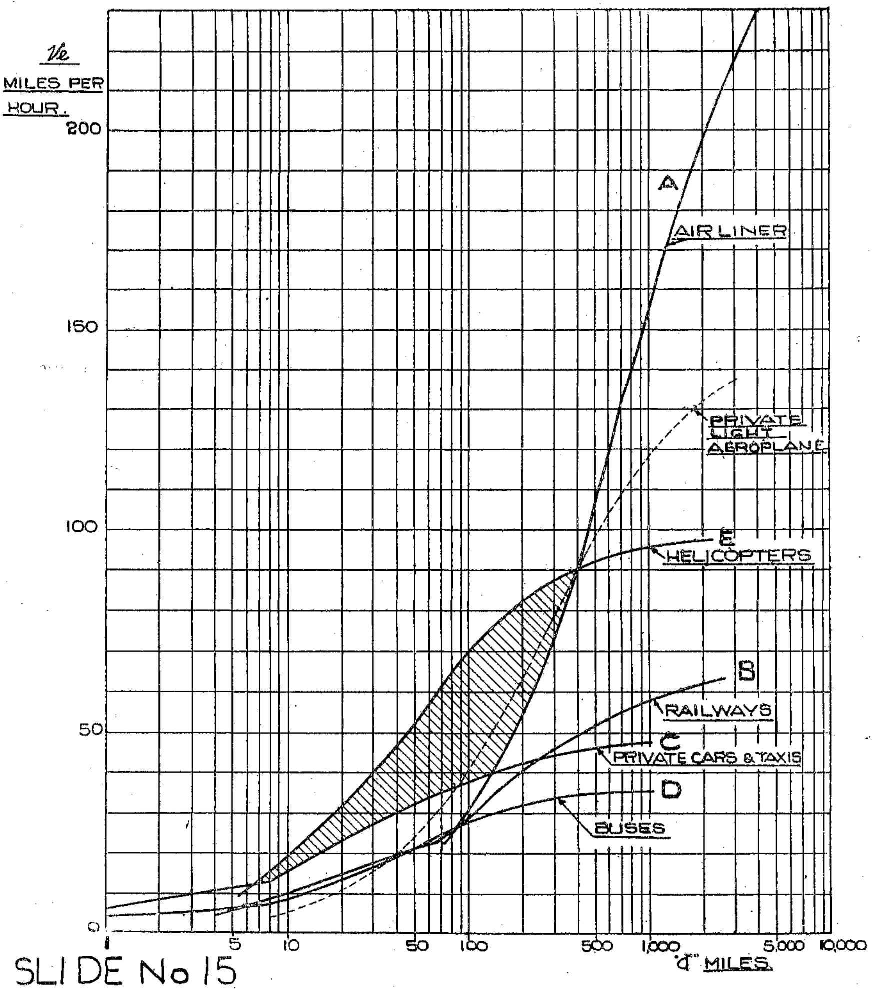
I have assumed a mean cruising speed for express trains of 65 miles an hour.

To attain this the train would have to run at a speed of over 80 miles per hour, for a good deal of the journey.

Owing to the great density of railway stations, and the fact that they are suitably placed with regard to centres of activity, the average marginal time loss for rail travel is better than for air travel.

It works out at approximately 40 minutes.

These figures give the curve B for the mean effective speed of rail transport.



SLIDE No 15

As regards motor road transport, we face the following facts :—

The private car and the taxi represent a "door to door" service. There is, therefore, no marginal time loss in this case.

As regards bus services, and under this category I would put the special railway services which are provided in densely built up areas, such as the underground and suburban lines, there is only a very small marginal time loss, of the order of 20 minutes.

On the other hand, however, the mean cruising speeds for these forms of transportation are low, due to the frequent stops or delays, which are necessary in the interests of safety.

As regards road transport, I have read with interest the proposals for roads and highways, which have been forwarded by the Post War reconstruction Committee, of the British Road Federation, and which indicate a scheme of motor highways for fast motor road travel, and a number of schemes for road traffic in built up areas.

On this basis I have assumed, as a mean cruising speed for cars, 45 m.p.h. on motor highways, which includes occasional stops, and a mean cruising speed, in built up areas, of 16 m.p.h.

The corresponding cruising speeds for buses are assumed to be slightly less.

Substituting, now, these figures in our formula for a mean effective speed of transportation, we obtain two curves C and D.

As regards air travel by helicopter, I have assumed a taxi service.

This means essentially, that aircraft do not fly to time tables, but meet exactly the wishes of the traveller. This would apply, of course, equally to the private owner's helicopter.

I have assumed twice as many helicopter stations as railway stations, excluding those of Urban and Suburban lines.

Thus, for instance, Bristol and district would have 15 to 20 helicopter stations, and a smaller town, like Weston-s-Mare, 2 or 3.

On this basis, the average marginal time loss works out to approximately 20 minutes.

The cruising speed of the helicopter is of the order of 100 miles per hour.

The mean effective speed of helicopter travel, on this basis, is given by curve E.

We are faced now with a very interesting comparison between the various forms of transportation.

The curves intersect each other, and it can be seen that the private car, or the taxi, is clearly the fastest form of transportation for short journeys, whereas on the other side of the scale, the air liner is unchallenged.

I have excluded from this comparison the private owner's aeroplane, because it cannot fly at night—at least I would not—and it is too much dependent on weather conditions.

However, a representative curve for mean effective speed is shown dotted in the diagram.

If we observe the curve for the helicopter, we find that it is faster than any other form of transport for journeys between 10 and 400 miles. In particular, if we consider journeys of the order of 120 miles, we find that it is nearly twice as fast as any of its competitors.

To sum up.

I believe the helicopter will be more expensive to run that the car or the taxi, but it will be by far the quickest means of communication for typical journeys in this country. For instance, from here to London, or from London to Birmingham, or from everywhere in England to Newmarket, or the sea-side.

There is no need for me to stress the fact that all the figures which I have quoted, have been, of course, to use the popular phrase, "cooked" to a considerable extent, and the conclusions at which I have arrived are highly optimistic.

Nevertheless, think of the possibilities! the chance to free yourself of cross-roads and roundabouts, of speed limits and stop lights, of time tables and waiting rooms! Think of the wing that flies in circles, but will give you the pleasure of travelling straight!