"Aerodynamic Aspects of the Fairey Rotodyne"

By K T McKENZIE

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A Meeting of the Association was held in The Library, The Royal Aeronautical Society, 4 Hamilton Place, London, W 1, at 6 p m on Friday, 4th December, 1959

Professor J A J Bennett
in the Chair

The Chairman, in opening the meeting, said that one of the important aspects of aerodynamics was the study of the interaction between two component systems Thus much experimental work was devoted to the investigation of interference effects between, for example, a wing and a body, or one wing and another wing, or a wing with a jet stream issuing from its surface, or the effect of ground proximity

In the rotary wing field, it was necessary to have a knowledge of the aerodynamic interaction between two rotors for the successful design of tandem rotor helicopters With the modern trend for rotorcraft to have fixed wings and become more like aeroplanes, it was necessary now to have an accurate knowledge of the mutual interaction between a wing and a rotor Tonight, this aspect, as well as other aerodynamic aspects of the Fairey Rotodyne, was to be discussed by the lecturer, Mr K T McKenzie

From 1941 to 1944, Mr McKenzie had studied at the College of Technology, Belfast, after which he spent three years as Aerodynamicist at Handley Page In 1947 he joined the Fairey Aviation Company, where he became Deputy Chief Aerodynamicist in 1952 and Chief Aerodynamicist in 1956 Until he was appointed to his present position, he had been concerned primarily with fixed wing aircraft, including the supersonic Fairey Delta 2 Thus he was very conversant both supersonically and rotationally with the problems associated with high speed flight

Mr K T McKenzie

Introduction

As you are doubtless aware the main design purpose of the Fairey Rotodyne was to provide a vertical take-off passenger airliner capable of much higher cruising speeds than the conventional helicopter, and also capable of a payload potential which would make this aircraft an economic transport vehicle This statement of purpose is an essential qualification to our design processes and implies that we do not set out to find an optimum solution on any particular aspect, but rather an overall design balance

The general engineering aspects and principles of the Rotodyne have been the subject of many articles in the technical press (of which Ref 1 is probably the most comprehensive) In this paper I propose to confine myself as far as possible to the aerodynamic problems and processes which were encountered during the design and development In the main these are associated with behaviour in autorotation and as such are peculiar to a Rotodyne type configuration, but I also propose to include some other items of aerodynamics which we came across which may be of a more general interest

Before proceeding it may be worth recalling briefly the outline of the present Eland prototype Fig 1 This machine has a rotor diameter of 90 ft and has flown at take-off weights up to 38,500 lb and at forward speeds up to 170 knots

General Aerodynamic Design Processes

Helicopter

In the main the design of the rotor is dominated by low speed helicopter criteria The facility for obtaining forward propulsive thrust from the propellers instead of the rotor and to a lesser extent obtaining lift from the wing, removes " advancing blade compressibility—retreating blade stall " as a major design criterion

Since the method of tip jet propulsion used on the Rotodyne produces at the tip a thrust nearly constant with tip speed, rotor power available is increased by rotational speed So long as rotor profile power is a minor part of the total power required, a high tip speed is desirable, and on the Rotodyne the normal take-off tip speed is 720 feet per second Fortunately, with higher helicopter forward speeds (say above 40 knots) induced power is reduced and with the increased ratio of profile to induced power rotational speed is no longer critical in terms of performance

Apart from this novel feature of the tip jet propulsion and a further compromise associated with the tip jet air ducts, the rotor main aerodynamic design follows a conventional pattern based on the engine out performance at take-off, particularly endeavouring to keep profile power to a minimum to assist in the autorotation process The desire for large internal ducts for minimum tip jet thrust loss must be balanced against increased blade thickness which would aggravate the compressibility problems and make a larger solidity necessary

Autorotation—Rotor and Airframe Balance

If we are talking about a particular rotor configuration, we can, by ignoring compressibility variations and secondary interference effects, express many of the rotor characteristics in non-dimensional terms Figs 2, 3, 4 show the results analysed from Rotodyne flight testing of " tip path incidence*", control axis incidence ($\alpha_{SHAFT} - B_{1_s}$) and aerodynamic flapping (a_1), plotted against mechanical collective pitch input (θ_0) and tip speed ratio A similar plot could be derived for a rotor thrust coefficient C_T or in other words, a lift function

It is worth noting at this stage that the reduction in the backward tilt

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* More precisely the " tip path incidence " shown here is that derived from the measured flapping at the blade roots assuming the blade is infinitely stiff in bending

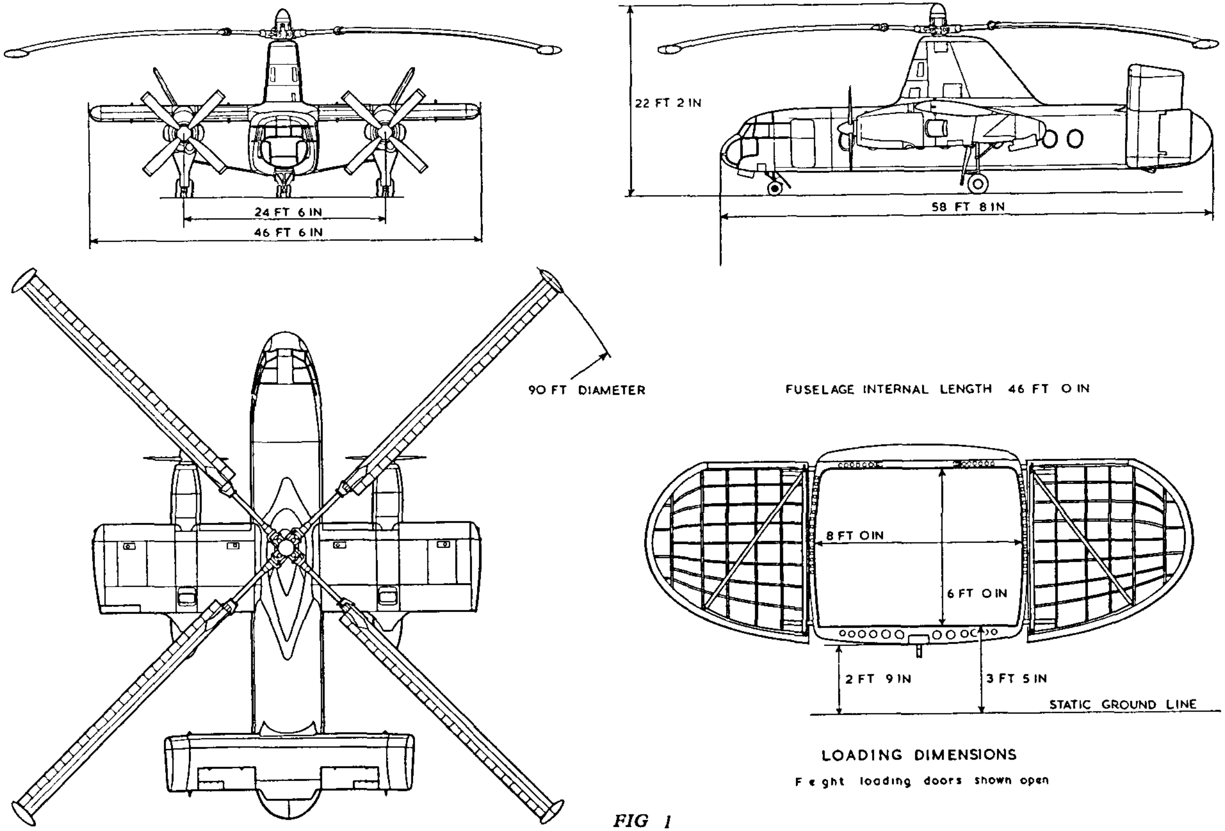
24 FT 6 IN
46 FT 6 IN
22 FT 2 IN
58 FT 8 IN
90 FT DIAMETER
FUSELAGE INTERNAL LENGTH 46 FT 0 IN
8 FT 0 IN
6 FT 0 IN
2 FT 9 IN
3 FT 5 IN
STATIC GROUND LINE
LOADING DIMENSIONS
Freight loading doors shown open

FIG 1

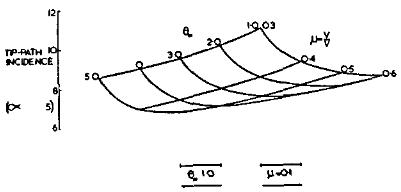

FIG.2 TIP PATH INCIDENCE

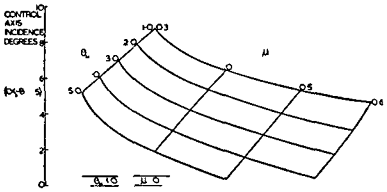

FIG.3 CONTROL AXIS INCIDENCE

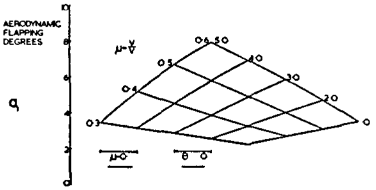

FIG.4 AERODYNAMIC FLAPPING

of the " tip path plane " with increase of tip speed ratio tends to slow up above a tip speed ratio of about 0 5 and also that in apparent contradiction to low speed autorotation experience, low collective pitch is less attractive since it requires a greater backward tilt

We can readily see that if we select a collective pitch and rotor rotational speed at a particular aircraft speed, we define the tip speed ratio and therefore a rotor state and a rotor lift Although the rotor state (tip path incidence or control axis incidence) can be obtained by various combinations of cyclic pitch and shaft incidence the unique value of rotor lift necessitates a complementary value of airframe lift to match the weight of the aircraft For a particular aircraft configuration this airframe lift in turn defines a shaft incidence and therefore the autorotational balance is met at a unique value of cyclic pitch Since the cyclic pitch is here used to obtain a selected rotor r p m it is no longer appropriate to consider it as a pure pitching moment control and some other control becomes necessary, namely, an elevator It should be noted that this additional control is necessary when we seek to operate at a selected value of rotor r p m and collective pitch

Still with the same conditions, this autorotational state defines a " tip path plane " and since the lift balance has defined a shaft incidence a unique value of mechanical flapping results

It is of importance to see what happens with change of r p m Recalling Fig 2 at least at moderate tip speed ratios an increase of r p m requires an increased tilt of the tip path plane , more important still with increase of r p m the rotor lift also increases , less airframe lift is required, consequently airframe or shaft incidence is reduced (nose down) The combined effect is that backward flapping is increased with increase of r p m

It is more difficult to generalise about the effect of collective pitch Certainly the backward tilt of the tip path plane is decreased with increase of collective pitch, but so also is the airframe lift and incidence, and the variation of flapping is very much a function of tip speed ratio and airframe aerodynamics At some values of tip speed ratio we can get a fairly flat minimum flapping over a band of collective pitch

IMPORTANCE OF FLAPPING AND ROTOR-STRUCTURAL STIFFNESS

This relationship of mechanical flapping to r p m , collective pitch, etc , may seem of interest, but of no direct importance However, with the design purpose of the Rotodyne, it assumes great and even critical significance

Briefly the mechanical flapping angles obtained represent an oscillatory load on the head system, and since the aim is to provide a very long fatigue life (quasi infinite) these angles must be kept very low The broad aim on the Rotodyne was to keep below 5 degrees, although during early flying beyond the original design speed values up to about 7° were attained in limiting manoeuvres Secondly, since we have a very large fuselage the directional stability solution is quite touchy and fin height above the fuselage is needed With any increase of backward flapping, preservation of the directional stability can only be achieved by increasing the pylon height which is not generally desirable from an engineering viewpoint

In the previous section it has been shown how the rotor r p m influences the flapping situation, lower r p m in general reducing backward flapping, although towards the high air speed end there would appear to be a limit where the gain is not significant below a certain r p m (say a tip speed ratio of 0 6)

The operating safety of the passenger vehicle makes it essential to achieve single engine en route safety This should preferably be in autorotation rather than in helicopter conditions because of the lower fuel consumption and the higher speed possible Over a considerable area the reduction of rotor r p m through the reduction of profile power results in an overall reduction in power required and hence aids single engine safety Eventually, however, the continued shedding of lift onto a small span wing by reducing rotor r p m would by the increase of airframe induced power outweigh the reduction of profile power

In addition because of the large size of rotor and its low rotational speed (105—150 r p m) the attainment of an unrestricted r p m band with no resonant speeds would demand a very careful and probably weighty rotor design from the point of view of stiffness (lag, torsion or bending) This might not be so important if comparatively short lives were adequate but again as with the head a long fatigue life is sought for the blades and hence any appreciable structural resonance amplification should be avoided

DESIGN RELATIONSHIP BETWEEN WING AND ROTOR

I have touched on the desire to control rotor speed and flapping angles for autorotational flight There are obviously a large number of possible combinations which at first sight would appear to meet the requirements In fact it tends to become too many for straightforward pilot controlling and we have simplified the procedure by virtually fixing the collective pitch Obviously, too low a collective pitch aggravates the backward flapping problem In practice we have chosen a value of 3½ to 4 degrees which tends to minimise flapping at the low speed end, and avoids vibration

The wing characteristics come into the picture when the collective pitch and r p m are chosen With an increase of weight at the low speed end in autorotation, since the rotor lift is fixed, the increased weight must be supplied by the airframe which results in an increased incidence and therefore a backward tilt of the rotor shaft and a change of flapping in a forward direction Equally increased "g" in a manoeuvre, or increased height (because the rotor lift is proportional to density) both mean increased forward flapping

The total range of backward and forward flap at low autorotational speeds is therefore determined by the variations in wing lift required, and as such the range here is inversely proportional to the rate of change of wing lift with incidence, ignoring second order effects Bearing in mind also the variation in tip path plane with speed shown in Fig 2 the change in speed does not require much change in wing lift but does of course mean a change in airframe incidence and therefore shaft tilt The variation in flapping resulting is directly influenced by wing lift characteristics

To briefly summarise the position we normally find that the forward flapping case comes from high weight, high altitude, low speed and the backward flapping case comes from low weight, low altitude, high speed The greater the wing lift slope the smaller will be the flapping range involved

INTERFERENCE BETWEEN WING AND ROTOR

I have spent a large part of this lecture in talking about the wing-rotor relationship because this is the fundamental issue in the aerodynamic design of the Rotodyne Bearing in mind the small angles of flapping which are involved it becomes quite critical to determine accurately the effects of interference between the wing and the rotor

While we initially, somewhat tongue in cheek, used classic biplane theory to derive a rotor wing interference relationship, we based our main design investigation on direct measurements on a wind tunnel model

A one-fifteenth model (six feet diameter rotor) was made and tested in our wind tunnel The rotor was in aerodynamic connection only (Reference 2 gives information on the mechanical side) Unfortunately at that stage we were a bit pessimistic in our judgment of the interference effects and concentrated thought too much on the low speed end When we set out to measure the interference effect corresponding to the cruise cases, we found it to be relatively small and we also found to our dismay that the mechanical design of the model rotor, in particular the support and large hub, produced a stream interference on the rotor of a magnitude greater than the airframe effects we were investigating To check against this fault we felt compelled to test the build up of the model through all its stages and the final interference effects were not measured directly from rotor out, to complete model, but rather as a difference between complete model and model with rig in place, head rotating but with no blades

We made measurements of the interference for various tip speed ratios and rotor thrust states (combinations of collective and shaft tilt) As an example of the results we obtained, at a tip speed ratio of 0 33 we measured an effective downwash angle (radians) at the wing equal to 5 C_T for an extreme helicopter case varying down to 2 C_T at the state representing our autorotation This would correspond to an estimated mean downwash value of 4 5 C_T, using simple momentum theory In real terms the effective downwash angles that we indirectly measure and are concerned with are of the order $\frac{1}{2}$ to $1\frac{1}{2}$ degrees

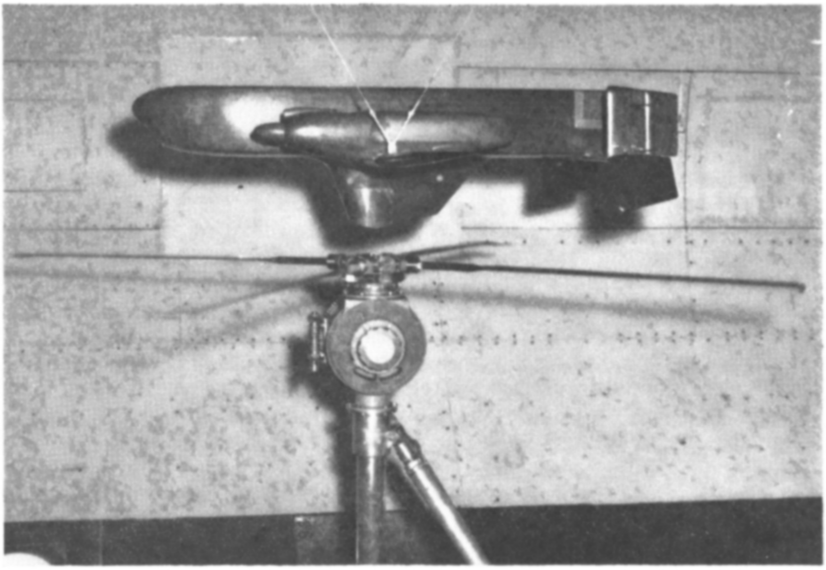

Fig 5 1/15th Scale Model in Wind Tunnel

AERODYNAMIC FEATURES IN FLIGHT TESTING

I have attempted to outline the broad relationship between the wing and the rotor This was our continuing anxiety through the design and flight testing A considerable change in aircraft attitude (and rotor state) must occur between pure helicopter flight (zero propeller thrust) where the wing lift is low and the autorotational state at lower r p.m where the wing lift is significant It seems unrealistic to assume that this could all be suddenly done with reasonable judgment by the pilot, so a step by step programme was laid down, in which once sufficient forward speed was attained for directional safety and wing lift (about 100 knots) propeller thrust was gradually increased and rotor power decreased until minimum rotor power was reached Collective pitch was adjusted to give an airframe incidence close to the autorotational value and power was then finally cut This in fact has remained the standard technique throughout the flying

The original design requirements had been to meet 130 knots cruising speed with plain jets The need for silencers had been shown during tip jet development work after the design had been stabilised, as also had been shown the desirability of increasing the cruising speed Both of these developments would have the effect of increasing the backward mechanical flapping of the rotor if nothing else were done The remedies open were to change the wing incidence or to reduce rotor r p m which would be a limited palliative In view of the big changes involved in a wing incidence change, it was decided to postpone this major change, and to obtain as much flying experience at high speeds as possible by tolerating larger flapping (reducing the clearance between blades and fins) and allowing the r p m to drop below the design values into a region approaching a lag plane resonant speed Having obtained high speed (170 knots) the wing incidence change took place this year with the expected decrease in flapping

Two other aerodynamic features were vindicated by the flight experience on the aircraft We had considered that lateral cyclic was inadequate for flight above 130 knots, and later design proposals for higher speeds had incorporated ailerons Initial flying, however, had to take place without ailerons and at high speed the response in roll was both too small and sluggish for satisfactory control The introduction of ailerons coupled to the lateral cyclic completely cured this trouble and the control available at all speeds was more than adequate

In the process of endeavouring to obtain satisfactory directional stability we had added upper folding fins which in order to also increase longitudinal stability we had placed at a dihedral angle of 60 degrees Later it was realised that the total airframe dihedral effect was too high , at first the pylon was suspected and it was not until rather later that it was realised that most of the dihedral effect (rolling moment due to sideslip) came from the sloping fins Again because of the changes involved and lack of experience on this type of aircraft, it was felt worth while to explore this effect in flight For normal flying the pilot was not too critical of this characteristic, presumably because at moderate speeds he had crisp rolling control without any stick force He only complained when he had to carry out deliberate sideslip manoeuvres above 100 knots, which used up most of the lateral cyclic for moderate amounts of sideslip

Paradoxically the pilot used this high dihedral effect as a rolling aid at high speed by deliberately sideslipping Eventually the fins were moved to vertical and with the ailerons already referred to, satisfactory rolling characteristics were obtained The lesson again learnt here is how surprisingly flexible good research pilots are in adjusting themselves to whatever aircraft system the engineers offer up, but also that this adjustment sometimes occurs without the pilots being able to precisely define what they do

DRAG ASPECTS

For fuel economy and for the ability to fly on one engine in autorotation, drag assumes more critical proportions on the Rotodyne than on most conventional helicopters, and we have devoted a considerable amount of effort to studying this problem Although the lessons we learned were not necessarily novel, it may be worth recalling them to illustrate the regions in which effort is worth while with an increased operating speed

In addition to the normal methods of drag estimation we used our large 1/6 scale wind tunnel model to break down component and interference effect As a general principle we kept this up to date with all the modifications which occurred during flight testing Obviously no simple representation of the rotating system was possible but we considered that a static simulation of the non blade part of the entire rotor system would give us a valuable approximation of the forward flight drag and enable us to plan development work

I have prepared a diagram to show how the drag at 130 knots (corresponding roughly to the single engine speed) of the prototype Eland in its current development is approximately broken up, based on corrected wind tunnel results and estimates It should be remembered that the aircraft is

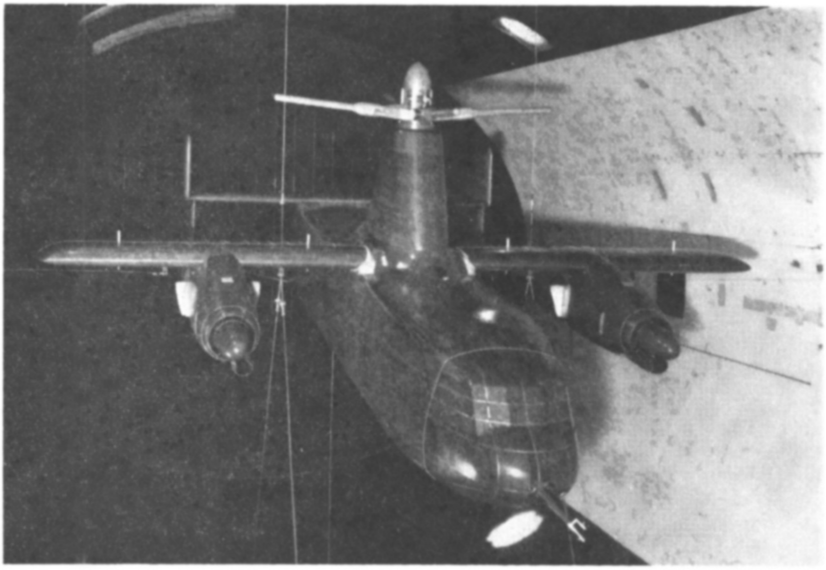

Fig 6 1/6 Scale Wind Tunnel Model

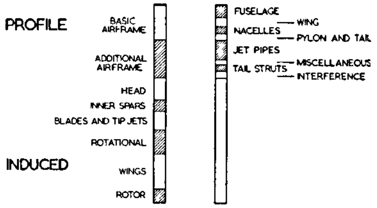

Fig 7 Drag Breakdown—130 knots

here at a stage representing suitability for mechanical testing and has not yet had the maximum effort incorporated to reduce the drag

The high drag features glare out of this picture , some are completely tractable, some can be avoided by re-design and some can only be relatively improved If we look at them in turn we can see what improvements must be made

Basic Airframe

The basic airframe, despite the apparently bulky square fuselage and the addition of the wings, contributes only about 1/6 of the total drag Admittedly this does not mean that we would not seek reductions there, but rather only that any significant improvement would be exceptionally difficult to achieve

Tail Unit Struts

These do not require much thought but it is interesting to see what damage they do They started life as faired struts, but a resonant damage caused them to be replaced by larger round struts These will eventually be faired

Miscellaneous Wing Excrescences

The worst item here came in during development as unfaired fuel vent pipes to accommodate large tilt angles Because of their position on the wing they can cause surprisingly great harm out of proportion to their size They would be designed out on future designs

Jet Pipe Fairings

Since these lie in the propeller slipstream there is an increased effect due to the higher local velocity Although exhaust drag was well known in piston engine days, in this era of jet engined aircraft the effect of exhausts tends to be under emphasised On the Rotodyne our main difficulty stemmed from having a bifurcated jet pipe The inboard exhaust tended to heat the side of the fuselage with the variation in propeller slipstream associated with thrust directional control at low airspeeds This heating was only cured by extension of the jet pipes with the consequential drag penalty On later designs this obstacle was avoided by choosing a single sided jet pipe exhausting outboard which would enable a nearly flush jet pipe to be used

Rotor Head and Stub Arms

On the Rotodyne the head is essentially a cruciform structure about two feet across with a central pillar or dome housing the virtual swashplate and a long shaft to mount slip rings, etc , for tip ignition and strain gauges The inner blade spars (or " lamp-posts ") are circular tubes to provide defined lag-plane elasticity

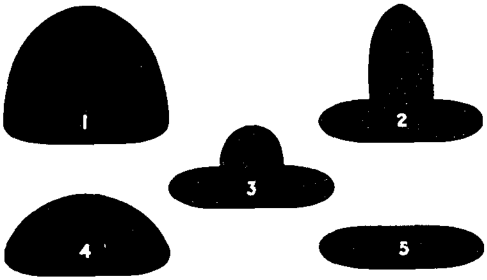

Fig 8 Rotor Head Fairings used for Drag Tests

The drag measured in the tunnel due to these items was very high, but conformed fairly well to conventional flat plate or circular cylinder data Although the principles involved seemed clear, a series of fairing shapes for the head were tested on the tunnel model (Fig 8) The results did indeed confirm that with the near vertical body of revolution defined by the rotor requirement, the cross stream area of the head fairing was the most important item and our development line is to enclose the cruciform portion of the head in a " mushroom " fairing out to the flapping hinge and eventually to reduce the pillar excrescence

Now that the mechanical integrity of the head is proven, this " mushroom " fairing will shortly be tested in flight along with streamwise fairing cuffs on the blade inner spars

Rotor Profile Drag

At these speeds rotor profile drag constitutes a large proportion of the total drag I have divided the rest of the rotor profile drag into that due to forward speed and that due to rotational speed Even at the rotor r p m assumed here (70% of take-off) the drag due to rotation is about 10% of the total aircraft drag Unfortunately, further reduction in rotor speed does not help much as it will only increase the lift on the wing and therefore put up the induced drag It is obviously worth a considerable effort to clean up the blade profile drag

CONCLUSION

I have set out in this paper to present the highlights of the aerodynamic problems of the Rotodyne While it might have been desirable to concentrate on one isolated aspect and treat that in very great detail with its full technical treatment, I felt it much more appropriate to try to establish the broad treatment with which we proceeded with the design and development, and to define our philosophy of the relationship between the airframe and rotor

Obviously the permutations and combinations of a compound configuration are somewhat colossal and it is virtually impossible to generally determine an absolute optimum from first principles and we have instead tried to isolate the main critical regions and come in from there to a " good " solution in our particular context

Although I have mentioned several of the main aerodynamic areas, we have had to concern ourselves with many others, *e g*, the external design of the silencers, which affects flapping and drag, or the efficiency of the fin system limited as it is by rotor above and the ground below, and almost all of these are complex joint engineering problems which feed back elsewhere into the system

The Rotodyne is essentially an aircraft demanding an " integrated " design team and new exchange rates between mechanical and aerodynamic features have had to be learned by the engineers concerned In everything I have said here, it is as a member of that team and although my views may not necessarily be wholly accepted by the aerodynamic purists, I should like you to receive them in the tone in which they have been put forward, namely our aerodynamic solution appropriate to offering an operational vertical take-off airliner

In conclusion may I record my appreciation to the Chairman and Directors of Fairey Aviation Limited for permission to give this paper and to my colleagues for their help in the preparation

REFERENCES

1 G S HISLOP The Fairey Rotodyne
Journal H A G B, Vol 13, No 1, February, 1959

2 M S HOOPER On the Wind Tunnel Testing of Helicopter Models
Journal H A G B, Vol 12, No 3, June, 1958

SYMBOLS

a_1 = Fore and aft aerodynamic flapping
a_{1s} = Fore and aft mechanical flapping
B_1 = Fore and aft cyclic pitch

C_T = $\frac{T}{\rho A V_T^2}$ = thrust coefficient
V = Aircraft flight path speed, ft per sec
V_T = Rotor rotational tip speed, ft per sec
α_f = Fuselage datum incidence, degrees
α_{sh} = Rotor shaft incidence, degrees = $\alpha_f + 1\ 5^\circ$
θ_0 — Mechanical Collective Pitch (Pitch lever input) degrees
μ = Tip speed ratio

Discussion

The **Chairman** invited Mr Austin to open the discussion

Mr R G Austin (*Bristol Aircraft Limited*) (*Member*), who thanked the author for his paper, said that the addition of fixed wings to the rotary wing aircraft was of undeniable advantage and a lot of work obviously had yet to be done before a complete understanding was reached of the aerodynamic effects involved The wing, however, only delayed the onset of compressibility and retreating blade stall troubles Could the author say whether information was available as to how close they had got to the compressibility " barrier " and the retreating blade stall " barrier " ? That is Tip Mach No and retreating blade incidence

The Rotodyne, like all aircraft, was an aerodynamic compromise and the advancing blade compressibility limit was no doubt of significance in that in order to achieve a compromise between the aerodynamic efficiency of the rotor blade and the thermodynamic efficiency of the tip jet system, a rather thick aerofoil section was used At the high μ values when the Rotodyne was operating at high speeds, in common with any other form of rotor plane, the area of the retreating blade that was actually doing any work was quite small , and the stall lift coefficient that was achieved on the section must be very little different whether one used a rotor in the autogyro or helicopter state Information therefore obtained from one type in this respect is applicable to the other The only difference between the two types was that the helicopter might have the advantage on the advancing blade compressibility limitation due to thinner tip sections, whereas the Rotodyne type of machine had possibly a small advantage with the retreating blade stall Hence the actual forward speed available in both types was similar

He was rather puzzled about the use of airscrews for forward propulsion because (apart from the added weight of the hardware involved), one imagined that their power transmission efficiency was of the order possibly of about 80 per cent , whereas using the power by a shaft drive directly to a rotor system was probably of the order of 95 per cent efficient

Mr McKenzie, in reply, said that he did not know whether he spoke a different language, but he found it difficult to put together Mr AUSTIN'S questions Mr Austin was probably uneasy in his mind about the whole business of the retreating blade stall, and one tended to agree with him in his uneasiness

In the particular problem with the Rotodyne, the tip speed of the rotor in autorotation was being reduced to such relatively low value that it was possible to accept high forward speeds of the order of 200 knots without getting into a significant compressibility on the tip of the advancing blade

On the question of retreating blade stall, again in the ultimate autorotational configuration of the Rotodyne one was not dependent on the rotor for providing a large proportion of lift In the ultimate solution, therefore, one was removed completely from the questions raised by Mr AUSTIN Exactly what he was trying to convey in his question, however, remained obscure—or was he talking about a helicopter configuration ?

Mr Austin said that summing up to his way of thinking, the limitations imposed on the rotor by compressibility effects on the advancing blade and the stall of the retreating blade, was independent of the direction in which the rotor was tilting