Discussion

The Chairman I know you will all agree with me that the paper which Mr FITZWILLIAMS has laid before us is one of intense interest to the Services, naval and military, as it is also to the civil aircraft operators Therefore, I will invite Major-General BOWER to open the discussion

Major-General R H Bower (*War Office*) When I came here I did not realise in the least the scale of the project and I think everybody will agree with me that Mr FITZWILLIAMS' proposals are very remarkable indeed I do not know whether they have anything to do with the remarks I made at your Helicopter Association dinner On that occasion I said that the bigger the helicopter, the bigger the dividend, and there is no doubt that we should earn a dividend out of the one we have heard about this evening

In considering size and what we want to do with helicopters we have a very difficult problem In the case of the ordinary transport aircraft we say there is an optimum size—and I am speaking only for the Army—at which we get the best value for money If you are using very small transport aircraft you must have a lot of them, and that puts up the bill for the aircraft, for airfields, for training, and so on, and the total number of personnel required is large

We concluded that a transport aircraft of 25,000 lbs payload, having a radius of 550 miles, was the sort of thing which would suit the Army best When considering helicopters I think that we might arrive at much the same answer, because if we go to very big aircraft we cannot have a large number of them undoubtedly we would lose flexibility in operation, which is frightfully important It is worth noting that the main road transport vehicle in the Army is the 3-tonner, not the 10-tonner

We might say that we do not want the 50 ton helicopter at all if it were not for one thing, and that is, as our lecturer has already mentioned, the possibility of lifting the Centurion tank The advent of that tank has resulted in a demand for bridges which can carry a load of 80 tons, that is the weight of the Centurion and its transporter, and every bridge on a Centurion tank route has to be able to take that load It has meant the complete re-design and widening of the Army bridge, both here and in America If you can use a helicopter which can pick up the Centurion and put it down again on the other side of a river, for example a distance of possibly a 1,000 yards, you have certainly achieved something which might have a considerable effect on the bridging and ferrying policy of the Western nations

If it were not for the Centurion tank, I would say that a helicopter with a payload of 10—15 tons was the sort of thing we wanted for general use in the Army But with the possibility of lifting the Centurion tank the prospect has in some degree altered

Summarising, therefore, I say that we should certainly like to see the 50—60 ton helicopter for that specific purpose, but for general utility purposes I think that, all in all, we should get better value by having more of the 10—15 ton type

Mr H F Vessy (*Ministry of Supply*) I must congratulate Mr FITZWILLIAMS on a most stimulating and interesting paper I think he will be shot at, but he has asked for that

Helicopters, as we know, are growing up, and Mr FITZWILLIAMS has shown us one way of curing the growing pains I think it is quite true, as he has stated in the paper, that for the transmission the geared drive cannot grow up indefinitely, and that sooner or later we shall be forced to the tip drive Mr FITZWILLIAMS has shown a very interesting method of tip drive We have heard of a number of other methods of tip drive The Ariel is a ducted system burning air at the tips, and the Hughes is of the same type The Hiller Hornet is a ram jet, and then we have Mr FITZWILLIAMS' suggestion of the turbo jet engine

I think we might try to simplify the case for these various methods of tip drive, and I should like to suggest that as a start we should consider fuel consumption noise, cost and installed weight My personal opinion is that in respect of fuel consumption the order of merit would be the jet engine as suggested by Mr FITZWILLIAMS, the pressure jet and then the ram jet The order of merit in respect of noise might well be the same Noise probably does not matter very much, except in the civil aircraft market, where I think it will matter quite a lot The jet engine certainly ought to score there

In respect of cost and installed weight I think that possibly the order might be

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reversed, *i e*, the ram jet, the pressure jet and then the turbo jet I should certainly like to hear other people's views on the matter

That might lead us to the conclusion that of the two extremes—the turbo jet and the ram jet—the turbo jet would be the choice for the long range job and the ram jet for the very short range job, such as the lifting of a tank over a river, which has been mentioned by Major-General BOWER

Coming down to detail, in the last of the author's illustrations we saw the jet engine placed along the span of the rotor and giving us a 27 per cent thick aerofoil at the tip I think that 27 per cent for the normal type of aerofoil is a bit thick ! This is for the large giant, for the small giant, having the 100-ft rotor, it would be a good deal thicker than that, and I do not think the ordinary aerofoil would take it But if we have the Griffiths type, which is a suction aerofoil—it was described very well by Relf in a lecture some time ago in America—we can go up to quite large thicknesses by re-designing the aerofoil into a kind of tadpole shape and sucking towards the trailing edge You have the means of sucking in the jet engine, and I think that might be well worth considering

Finally, Mr FITZWILLIAMS has stuck his neck out, and I hope that speakers will not criticise too much in detail He has admitted that he is making assumptions, and I should like the criticism to be in the broad rather than in detail because those details just do not matter at this stage

Mr A McClements (*Founder Member—Ministry of Supply*) Mr FITZWILLIAMS is to be congratulated on presenting a paper full of novelty and ripe for discussion His approach to the problem of the large helicopter is a courageous one, he talks a great deal of common sense and he does it in a very entertaining way

As I see it, the lecturer argues somewhat on the following lines He assumes a very large rotor and a conventional tip speed , he is therefore faced with a large coning angle unless he puts more weight into his blades than is necessary from structural considerations He must carry engines so he thinks it would be a good thing to use the engine weight to some advantage He can do this by installing the engines at the blade tips and by doing so he achieves further benefits by simplifying his overall gas system This is a very attractive argument and on its basis he makes an excellent case for the large helicopter I think, however, he raises engine problems of some magnitude and I hope some of the engine specialists will tell us later in the discussion how serious these problems are and what are the chances of their being overcome in a satisfactory manner

If we assume a solution to our engine problem we shall no doubt be left with quite a few problems in the airframe I wonder what they are ? One may be vibration in the case of power failure of one engine, *e g*, an unbalanced rotating thrust vector of some 10,000 lbs is surely something to be reckoned with Other problems may well be associated with the control of large rotors, particularly at low r p m such as are experienced during rotor starting and stopping It would be fruitful to hear more about these problems from Mr FITZWILLIAMS and from the other designers present and I hope we shall as this discussion develops

Group Captain J R Gordon-Finlayson (*Air Ministry*) I admit quite frankly that I cannot go as far as I would like with you in the discussion of technical detail However, I should like to thank the Helicopter Association for inviting me here and to thank Mr FITZWILLIAMS for a most stimulating lecture I like to hear this sort of lecture , it makes us look well into the future You are the pioneers in this technical sphere and we in the Services are very much in your hands Sometimes I am not so sure that I like that idea ! But I am confident it will all work out for the best

From the point of view of the Services, the army will obviously be the main user of the large helicopter and it will certainly be of enormous value Korea has shown that, and we will probably see a great deal more of that type of warfare It seems to me that any army which goes to war in the future without its airborne tail will be as out of date as a horse-drawn supply system would have been in the last war

You will all know a good deal about the economics of air transport in Burma and other areas That is looking back rather than looking forward but still there is much of interest At one point during the campaign in Burma it was estimated that 1 Dakota aircraft was worth 54 3-ton lorries on the army's lines of communication That is a good indication of the value of air movement in practical circumstances , and there are many other examples to show how extraordinary economical air supply can be

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I should now like to follow thel ecturer into the future for a moment and outline what might be a reasonable perspective in war Naturally, there is nothing official about this but a few comments may help to forge the link between the end and the means

The technical means of war change but the end remains much the same It seems to me that we can still find some useful parallel between the old-time procedure for attacking a fortress and modern warfare Generally speaking, the phases were the investment, the approach, the breaching, the assault and finally the occupation Although it is doubtless possible to win a war by total destruction, short of this it will still be necessary to occupy the enemy's territory That sounds straightforward enough But it raises the same old problems as in the old days For instance, when Napoleon invaded the expansive territories of Russia the biggest single factor that brought his plans to nought was the difficulty of supply and movement In World War II it is probably right to say that the biggest single factor that brought Hitler's plans in Russia to nought was this same problem of communications

Air movement is bringing about a fundamental change in the perspective of supply and movement in war Certainly, we shall have to go through all the phases of war as of old closing in upon the enemy and establishing bases from which to conduct breaching operations and ultimately the assault and occupation We all pray that we shall not have to go to war with any nation or peoples But if we do, we can now go far towards solving this vital problem—communications Indeed, the day is fast approaching when we can visualise armies on a huge scale being launched and maintained by air alone deep in the very heart of enemy territory That will be the time to exploit helicopters and all other means of air movement

There is just one more thing I would like to say Perhaps some of you wonder why the Services do not go in for helicopters in a really big way The answer to that is " timing " We are not at the assault stage of war, but are very much on the defensive We must therefore concentrate upon gaining air superiority for our own security and as the only condition in which we can exploit the air for all the purposes we have been discussing Until then priority must go to fighters and bombers

I am very glad to have attended this meeting and I thank you, Mr Chairman, for inviting me here It has been very interesting indeed

Dr Morley I believe Mr FITZWILLIAMS would like me to try and criticise the proposed use of turbo jet engines at the rotor tips so that we can perhaps see by discussion any fallacy there may be in the engine side of his proposal

With regard to the main advantages of the turbo jet I take it that these are obvious to us all, namely, light weight, high thrust and good thermal efficiency under the flight speed conditions at the rotor tip The question is whether the engine mechanical design which has proved so sound for more orthodox applications will be sufficiently robust to stand up to the extra centrifugal and gyroscopic forces

If we consider what seems at first sight to be the obvious way of using the turbo jet, that is with the engine axis chordwise across the rotor arm to face the way of rotation, we see immediately that the centrifugal field must enormously increase the main bearing loads of the motor Bearing loads are already critical as the high operating temperatures and high rotational speeds both impose severe restrictions on size of bearings and therefore on the permissible loads It might be possible in the future to design safely a 25g side acceleration but this would be a very unorthodox case by present standards Anything above 25g would be right outside present knowledge so that the possibility of ever withstanding 60 or 100g with a chordwise jet seems to me very remote indeed The bearing loads would not be the end of the problem by a long way, but they are sufficient to condemn the application of any existing jet engine in such a scheme

The use of an opposite rotating pair of engines does not help in any way

The transverse loads on the engine bearings are brought back into line with present practice if the jet unit is installed spanwise along the rotor arm There is then a spanwise gyroscopic couple to consider in addition, but this is relatively unimportant as regards additional bearing load A similar gyroscopic load has to be allowed for in normal engine design of about the same amount

In the spanwise installation there is a great increase in axial end thrust on the engine rotor due to the c f which must be taken care of In theory this engine rotor end thrust can be balanced by means of pressure air from the compressor of the engine acting on one side of a suitable disc There are certain disadvantages in

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pneumatic balance because the sealing of the necessary diaphragm involves a loss of compressed air and therefore thrust, and also because the supporting diaphragm has to withstand the double load of centrifugal force plus air pressure However, it seems possible that with the necessary steps taken in design, the end thrust on the engine rotor can be balanced by some means or other The author has already taken care of this point

The centrifugal field will also produce a bending moment on the compressor blades and turbine blades If the compressor end of the engine faces inboard, this will load the blades axially in the outward direction The permissible bending stress of a compressor or turbine blade in relation to the ultimate strength at the operating temperature is usually kept low because it is additive to the centrifugal stress at the weakest point at the root of the blade However, gas pressure differential on the turbine blades helps to relieve the gas bending stress at the trailing edge and this is often the critical stressing point

Any bending stress due to helicopter rotor c f acts in the same direction as the gas pressure differential and thus tends to relieve the bending at the turbine blade trailing edge Gas bending and c f bending stresses will be of the same order and though they do appear partly to cancel in the case of the turbine it will be necessary in any particular engine to reconsider carefully the resultant blade stresses allowing for the bending due to c f The compressor blading must also be re-examined because the c f bending may increase the net bending stress and this may well be critical somewhere in the compressor To sum up the centrifugal field will introduce blade bending stresses which may or may not be critical in the turbine and compressor, but which will have to be taken into account in restressing the engine to clear it for the proposed application

Yet another factor to consider is the gyroscopic torque which tends to deflect the blades opposite ways at opposite ends of the disc vertical diameter This gyroscopic stress is periodic and for safety we would have to be quite sure that the blades of compressor or turbine would not suffer rapid fatigue through resonance at the running speed

Engine blade stresses are usually conservative by ordinary standards due to the big margin necessary for fatigue Each revolution of the engine infers a stress cycle and there are probably about a hundred or so cycles a second, so that if there is fluctuating stress the blades quickly approach the minimum fatigue stress limit Thus any extra stress on the blades must still come within the final fatigue limit of the material even for a relatively short engine life

Thus to me it seems that before an existing jet unit could be applied to the giant helicopter rotor even spanwise a careful restressing of the engine would be required to clear it for blade bending, rotor end loads, and the periodic effect of the steady gyroscopic couple on the turbine and compressor blades Other critical weaknesses for example in the fuel control system would no doubt also be brought to light, because no one has yet designed a turbo jet for this specific purpose As far as I can see without doing the actual detail work, these would not be serious

One imagines that if stresses turned out to be too high a moderate reduction in engine R P M would give sufficient relief of the engine c f stresses There would unfortunately be a corresponding sacrifice of thrust which would be equivalent at this stage to an increased engine specific weight But the existing jet engines are so good in respect of thrust weight ratio that the designer in the first instance can probably afford a reduction of stresses by these means in preference to waiting for a jet unit designed specifically for helicopter use

A main point is that the danger of increasing the engine stress is reduced as the rotor diameter is increased and rotor angular velocity reduced In other words the larger the helicopter the more suitable does the turbo jet unit become I think the author has made quite a good case for the use of the rotor tip turbo jet in the giant helicopter

Mr N E Rowe (*Member—British European Airways*) I have been very much impressed, as others have been, by the sweep of the imaginative powers of the lecturer, and I think he has done real service, at this stage in the development of rotary wing aircraft, by bringing us face to face with what he thinks are very real possibilities

I think that, in bringing the forward speed and the rotational speed down, he has made the conditions more suitable for what he wants to do In civil aviation, however, we want higher cruising speeds than 100 m p h , our recent specification, which I hope will reach the industry very soon, calls for a cruising speed of 150 m p h , and we want that speed because we have found in our operations that wind speeds in this country are such that, without that sort of speed, we cannot keep to a regular schedule , as time goes on and the possibilities are extended we shall want still higher speeds It seems to me, therefore, that the rotational speeds will have to be very much increased—I may be wrong in that respect—and the case may not be nearly so favourable for the engine at the tip of the blade

Mr VESSEY has hinted at the problem of noise, and that again is a cardinal factor in civil operation Helicopters will do what we think is possible and will revolutionise transport in this country only if they can go into the centres of cities Fixed wing aeroplanes can operate only outside cities and are unsatisfactory for inter-city transport in this country for that reason Helicopters, if they have a sufficiently low level of noise, can go into the centres, but I am perfectly certain that, if their noise is above a certain level, the city authorities will not allow them there However, I know that work is being done to reduce noise, and any remarks the lecturer may care to make on this matter I shall be glad to hear

Viewing the whole problem, it seems to me that the biggest point of all is that concerning the engines, and I would say that if, after examination, people are satisfied that Mr FITZWILLIAMS' suggestions lead to a good way of building military helicopters particularly, we want to hasten on the development of suitable engines It is perfectly clear that big changes will have to be made in the engine design, but I do not like the idea of the engines being spanwise It is true, as Mr VESSEY has said, that the suction aerofoil, if we can design it, will do the trick But the big point is the variation of the air flow into the engine as the blade sweeps round, which may cause difficult conditions inside the engine, and it seems to me, might lead to vibration troubles However, I think it should not be beyond the wit of man to take this lecture as a new starting point for the design of a range of engines specifically suitable to the operation envisaged which will make the engine go into its natural position, which is chordwise, at the tip of the blade , then we shall have what we want

Mr J S Shapiro (*Founder Member*) Mr FITZWILLIAMS told me some time ago that he would " talk big " when delivering this lecture, and he asked that all his remarks should not be taken too seriously I think he has succeeded in both respects, but in boldly putting forward his ideas, he has given us a truly magnificent lecture

I was particularly interested to hear what Maj -Gen BOWER had to say, because it is very important to be assured that we really want these giants General experience teaches us that nature has a horror of giants, and most giants are problematical, to say the least Many experts hold that aeroplanes have already been made which are too big for practical operation

Having decided nevertheless that very large helicopters are really necessary, it is fascinating to examine the limits of the single rotor Some designers have regarded the transmission of torque as the effective limitiation to the mechanically driven rotor Mr Sikorsky in a lecture to this Association last summer has used his great authority to question this view All the same even if tip drive is not the only solution, it is undoubtedly an attractive solution for a large rotor, and it is the solution we are discussing to-night

I shall try to review this matter on broad lines The most startling result of the paper is that if we go on drawing bigger circles, the area increases quadratically and we get enormous disc areas supporting enormous weights We now multiply by two the disc loading to which we are accustomed and we get still bigger weights Now, we all know that when the disc loading goes up we need more power to hover The answer to the search for more power without excessive weight penalty is jet propulsion in any one of its forms, but particularly in its association with the tip drive in the pressure jet system and the tip mounted turbo jet units

That is one aspect of the line of thought which leads to this staggering machine of the future The other is that which Mr McCLEMENTS has re-emphasised The difficulty with very large rotors is that we need an increasing percentage of weight in the blades to keep them down if they are articulated and we must therefore put something useful there to avoid excessive structural weight , the most obvious thing is the engine

We have the very attractive proposition of putting the turbo jet engine there , Mr FITZWILLIAMS has shown us that we do not know how to do it ! Whilst I agree fully with Mr VESSEY that we must speak broadly, on this matter I think that any really useful contribution to the discussion should deal with the question of how we are going to put the engines on blade tips and operate them

On this matter I can only make another criticism, though I cannot offer a solution The idea of a bearing of 1 ft diameter rotating at 7,000 or 9,000 or 10,000 r p m is a very revolutionary one! I just cannot visualise this jump in the development of bearings However, the attraction is there and we must await developments

In my opinion it is premature to scrutinise too closely the lecturer's assumption until the possibility and manner of operating turbo jet engines in a field of 50 to 100 g are established

The attraction of this configuration is undeniable though it does not preclude the attractions of others

Mr R Hafner (*Member—Bristol Aeroplane Company*) I have had the pleasure of knowing Mr FITZWILLIAMS for a number of years and I have found him to be a man of no ordinary qualities He enjoys throwing a challenge into the arena and sitting back and watching the consequences Sometimes he says things which shock simple, peace and compromise loving people

On this occasion he has thrown a gigantic challenge amongst us, the general effect of which I cannot fathom as yet, but as regards myself I confess, even though I do not count myself into the class of peace and compromise loving people, that for a moment I lost the ground under my feet However, on regaining my balance I came to the conclusion that the best thing to do was to write myself a little paper on giant Helicopters

My objective is, to present the problem in the proper perspective or, if you like, in my perspective I will show a few figures relating to typical Helicopters and I hope Mr FITZWILLIAMS will tell me whether or not I have gone too far in presenting my case

May I start with Mr FITZWILLIAMS' assumption of a forward speed of 120 m p h The maximum permissible coning angle of a rotor is a function of the forward speed and the permissible level of vibration In our case this angle β is 5° to 6° Thus we can see from Fig 3 in his paper that

$$\tan \beta = \frac{nL - b}{C_F} = \frac{1}{10}$$

where $nL = W$ = all-up-weight of aircraft

b = total weight of rotor blades
C_F = total centrifugal force acting on the rotor blades

I agree with Mr FITZWILLIAMS that a tip speed of 550 ft /sec appears to be about the optimum speed for this kind of Helicopter Therefore, the centripetal acceleration at the blade tip will be

$$a_t = \frac{550^2}{R}$$

where R = Rotor radius

In conventional designs the centre of gravity of the blade is at a distance of about $\frac{R}{2}$ from the rotor centre With blades carrying a jet engine at the tip there will be a need for additional structure weight at the blade root, to take care of the greater loads, thus the c g of such a blade will not differ materially from that of a conventional one

The total centrifugal force acting on the blade will thus be

$$C_F = \frac{b}{g} \times \frac{1}{2} \times \frac{550^2}{R} = 4700 \frac{b}{R}$$

If we substitute F_C in the previous equation by the above expression we obtain the simple relationship between blade weight and all-up-weight of the aircraft

$$\frac{b}{W} = \frac{R}{470 + R}$$

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In the table below values for $\frac{b}{W}$ are given in Line 2 for a few selected values for R Thus, as the rotor increases in size, its weight increases in relation to the all-up-weight of the aircraft This is the fundamental scale effect in rotors

1	Rotor Radius R	25 ft	50 ft	100 ft	150 ft
2	Blade $\frac{b}{W}$	05	10	18	24
3	Fuselage	36	36	36	36
4	Power Unit (piston engines)	18	16	14	13
5	Transmission	05	06	07	08
6	Empty weight of piston engined Helicopter with mechanical transmission	64	68	75	81
7	Power Unit (jet engine)	08	07	06	06
8	Empty weight of jet engined Helicopter with mechanical transmission	54	59	67	74
9	Empty weight of jet engined Helicopter without mechanical transmission	49	53	60	66
10	Weights of blade & structure	04	05	07	09
11	Weight of blade ballast	01	05	11	15
12	Empty weight of Fitzwilliams' Helicopter	No solution	48	54	60
13	Empty weight of Aerial Crane	No solution	48	49	51

Weights expressed as fractions of all-up-weight of aircraft

My next item (Line 3) is the weight of the fuselage, again expressed as a fraction of the A U W My figure for this item, which is somewhat higher than Mr Fitzwillaims', includes an allowance for safety and other gadgets, without which—I am told by competent authorities—a Helicopter cannot fly, I suspect Mr Fitzwilliams has not made such allowances

Line 4 gives the weight of the complete power unit for a piston engine installation, expressed as a fraction of the A U W

Line 5 similarly represents transmission weight It is significant that this item increases markedly with rotor size

Line 6 is the sum of Lines 2 to 5 inclusive and represents the empty weight of the aircraft The differences between these figures and unity corresponds to the useful load including the weight of fuel This line shows clearly the weight penalty paid in increasing the size of the rotor

Line 7 gives the power unit weights of jet engines The figures quoted are probably optimistic

Line 8 is the sum of Lines 2, 3, 5 and 7 and represents the empty weight of the jet engined aircraft with mechanical transmission The weight savings made here by comparison with Line 6 are obvious It should be borne in mind, though, that the specific fuel consumption of the jet engine is higher than that of the piston engine,

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a factor which, in the case of long flights, may obviate the apparent gain However, for short journeys the jet engine offers a clear advantage

Line 9 gives the empty weight of a jet engined Helicopter without mechanical transmission, an example of which is Hughes large experimental Helicopter The saving of the whole of the transmission weight is obviously beneficial, but this simple analysis does not make allowance for the weight of air ducts and power losses therein and consequently the figures quoted are optimistic

Lines 10 and 11 bring us to Mr FITZWILLIAMS' proposals We have here the weight of the blades broken up into two components, *i e*

b_s, the minimum weight necessary to meet structural requirements

and

b_b, the ballast weight necessary in order to bring the total blade weight up to the figures in Line 2

The ballast weight b_b, which is wholly parasitic weight, increases considerably with the size of rotor By placing jet engines into the tips of rotor blades, Mr FITZWILLIAMS has been able to utilise some or all of this parasitic weight, and thereby reduced the fundamental inefficiency of the large rotor

Line 12 represents a series of his type of Helicopter, *i e*, it is the sum of Lines 3, 7 and 10 and in addition blade ballast b_a is sufficient to bring the blade weight (including that of the jet engine) up to the figure in Line 2 It is evident that a small rotor does not permit a solution of this type

Line 13 represents the case of a large aerial crane In this case there is no requirement for a high forward speed and the coning angle of the rotor is thus of little significance Therefore, ballast of rotor blades is not necessary This line contains the elements of Line 12 without however the additional blade ballast b_b

The table clearly shows two tendencies

(1) Weight penalties are generally involved in moving across the table from left to right, *i e*, from the small to the large rotor

(2) Weight savings are generally obtained in moving along the table in the downward direction

There appears to me to be an attractive solution for a large aerial crane

I congratulate Mr FITZWILLIAMS on a stimulating paper

Dr J A J Bennett (*Founder Member—Fairey Aviation Company*) I am sure we have all enjoyed listening to Mr FITZWILLIAMS this evening discussing his ideas on helicopters of the future There is no doubt that the jet-powered rotor opens up many interesting possibilities in helicopter design and, in particular, enables relatively large helicopters to be built with only one rotor, thereby avoiding the complexity of two or more rotors with their heavy transmissions and high maintenance costs

The feature which Mr FITZWILLIAMS has exploited in his paper is the advantage gained by helicopters with blade-mounted power plants in operating at greatly reduced coning angles The upper limit of rotor size is thereby extended well beyond that of the hub-driven helicopter

This problem was discussed in my paper (Ref 1) to this Association nearly five years ago, in which I made a brief survey of limitations in helicopter design The basic limitation in rotor size was shown to be dependent on three factors

(*a*) angular speed, (*b*) blade-tip speed, and (*c*) coning angle

The ratio of rotor weight to gross weight is inversely proportional to the product of these three quantities An increase in rotor diameter, therefore, without a simultaneous increase in either blade-tip speed or coning angle, would increase the ratio of rotor weight to gross weight, thereby imposing a limitation on useful load If, however, as Mr FITZWILLIAMS proposes, the rotor weight includes the weight of the power plant, the basic limit of rotor size applies to very much larger diameters There is no doubt that this is one avenue of approach to the "giant helicopter"

As happens very often in engineering development, alternative avenues of approach may tend to converge and eventually reach the same destination A supersonic rotor may appear to be an entirely different proposition to that of Mr FITZWILLIAMS, yet there is a basic similarity The mass of the blade-mounted turbo-jet rotating with the blade at sub-sonic speed maintains the coning angle within its

(Ref 1 Journal of the Hel Assoc, Vol 1, No 1, 1947) limiting value. The supersonic blade achieves the same result, though the mass of a ram jet located at the blade tip is only a fraction of that of the turbo-jet.

May I ask Mr. FITZWILLIAMS if he would not prefer a ram jet to a turbo-jet owing to the absence of rotating parts within the jet unit and the great reduction in power plant weight? The ram jet would not be much of a burden on the blade and would not object to being whirled at supersonic speed. On the other hand, the turbo-jet would be a very heavy partner to whirl around and would not particularly enjoy the experience even at sub-sonic speeds. Does Mr. FITZWILLIAMS not think that the supersonic ram jet rotor would be a preferable approach to the "giant helicopter?"

Miss A. Kennedy: What does Mr. FITZWILLIAMS anticipate will be the maximum ceiling of the giant helicopter? That would seem to be important in enemy country. Also, can he tell us about the vulnerable parts which could suffer damage if shot at?

Dr. Henry Roberts (*Founder Member*): I should like to say a few words about the tip speeds for rotors and the maximum coning angles of rotors having flapping hinges.

Mr. FITZWILLIAMS would appear to be in favour of conventional tip speeds and disc loadings. There is a tendency to judge tip speeds by the Sissingh criterion $\frac{C_T}{\sigma} = 0.2$. This criterion has its uses, but I have a very strong suspicion that it was not derived for a rotor having tip propulsion. It has, in fact, been pointed out by Stepan (J. H. Ass. G.B. Vol. 3 No. 3) that $\frac{C_T}{\sigma} = 0.11$ gives a more efficient rotor for this case. The optimum tip speed for hovering may be derived from the equation

$$P = kW \left[\frac{W}{2\pi\rho B^2 R^2}\right]^{\frac{1}{2}} + \tfrac{1}{8}\rho\delta\sigma\pi\,\Omega^3 R^5$$

P	=	power required for hovering
k	=	factor to allow for non-uniformity of the induced velocity
W	=	helicopter weight
B	=	tip loss factor
R	=	rotor radius
δ	=	blade profile drag coefficient
ρ	=	air density
σ	=	solidity of the rotor
Ω	=	angular velocity of the rotor

Noting that for tip jets $P = T_j\Omega R$ where T_j = total jet thrust and putting

$$C_T = \frac{W}{\frac{1}{2}\rho\,\Omega^2\pi R^4}$$

the equation becomes

$$\frac{T_j}{W} = \frac{k}{2B}\left[C_T\right]^{\frac{1}{2}} + \frac{1}{4}\frac{\delta\sigma}{C_T}$$

When $\delta\sigma$ is assumed constant this gives a minimum sized jet unit when

$$C_T^{3/2} = B\delta\sigma/R$$

for which

$$\left(T_j/W\right)_{opt} = \frac{3}{4}\left(\frac{k^2\sigma\delta}{B^2}\right)^{\frac{1}{3}}$$

These relations give us quite independently of fuel consumption considerations, tip speeds for normal disc loadings, which are higher than the 550 ft./sec. that has been mentioned tonight, tip speeds that are far less liable to give us tip stalling troubles in fast forward flight.

The equations, however, can be used to give us a family of supersonic rotors which are going to solve a great many of our current problems once we get to the larger sizes. These have increasing disc loadings as the tip speed increases. This is just what we want both in view of the power plant we shall be using (probably ram

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jets) and the necessity to turn the " large giants " into " little giants " The price we have to pay for supersonic tip speeds is shown by the equation for $(Tj/W)_{opt}$ It is that the weight that can be lifted per unit thrust (which is conventionally 16 to 18) drops off rapidly and at a Mach number of 2 is about half the usual value It is, however, still worth while to carry 6 to 8 lbs for every lb of thrust Regarding the question of coning angles, Mr FITZWILLIAMS has referred to 8°, Mr HAFNER to 6°, Dr BENNETT to 10° and it is difficult when this parameter assumes such fundamental importance in fixing the overall weight allocation to decide what value it should have In fact, it is very difficult to see the source of the limitation indeed, I just cannot see it We have had helicopters operating at coning angles in excess of 10° The main effect of increasing forward speed is to give a lateral tilt to the rotor which is proportional to the coning angle This must be eliminated and results in a certain loss of control movement, generally of the order of half the coning angle This effect is not very important once it is allowed for in the design So far, as tip stalling is concerned, I am not sure there will be much effect there either The only possible cause of the limitation seems to be the amplification of vibration with speed, which need not arise if the original vibration is kept down The use of light blades does, of course, give higher engine-off landing speeds when used in conjunction with piston engines On the other hand, when used with jet units and mechanical drives, the high inertias of the engines is such that the fly wheel effect lost by using a high coning angle criterion, is recovered by virtue of the engine I feel that until we know more about this criterion, it seems dangerous to fix our ideas especially when looking forward, as we are, tonight

What we have to go in for is that supersonic helicopter with reduced coning angles coming automatically If you are worried about centrifugal forces, you can always put the jet engine inboard instead of at the blade tip , indeeed, I think that offers a good solution to the engine installation problem

Mr J L C Briscoe (*Ministry of Civil Aviation*) Said he had noticed the mention of rotor diameters up to 280 ft and was relieved to hear that such helicopters were proposed only for military use as there would be great difficulty in finding sites in city centres large enough for such machines

He went on to ask whether Mr FITZWILLIAMS would explain, and if the military might like to consider; how such a helicopter would be loaded, since it is hard to find unprepared ground strong enough to bear a helicopter weighing 250 tons on ten wheels

MR FITZWILLIAMS' REPLY TO DISCUSSION

I am most grateful to all those who, by taking part in the discussion, have made the giving of this lecture such a great pleasure

GENERAL BOWER's discussion of Army requirements is of great interest I accept his ruling on the optimum size for general transport duties and hope it may be possible to give him the sort of thing he wants in a helicopter designed around four modified Viper engines On the other hand I do not believe it can be true that bigger helicopters would be used solely for lifting tanks plus their transporters over rivers Why not take the tank all the way and leave the transporter behind ? For transport to and salvage from the combat area the big helicopter has considerable advantages as well as many other uses The special crane helicopter, also advocated by Mr HAFNER, is likely to have so short a range as to be almost immobile and I cannot think this is a profitable line of development if something better can be done

I am in agreement with Mr VESSEY's view that the geared drive cannot grow up indefinitely but we have Mr Sikorsky's assurance that it can successfully be applied up to at least 100 passenger capacity and this already reaches the lower limit of General Bower's optimum size

Among tip drive systems the pressure and turbo jets should, I think, be reversed in the order of merit suggested by Mr Vessey in respect of installed weight, as far as this affects disposable load Also the turbo jet should not be more expensive unless development charges are disproportionately large Noise should not be too serious a problem with these helicopters because airline performance standards link high power with rapid purposeful movement Low powered approaches, landing without hovering, negligible warm-up and rapid climb away should make the noise much less objectionable than on a test tower

The Griffiths aerofoils suggested by Mr VESSEY might be awkward in the event of engine (and therefore suction) failure but without them I agree that the smaller engines would present a formidable problem if mounted spanwise However, a further look at the spanwise installation shows, perhaps fortunately, that it does not really provide the intended solution to the bearing problem The gyroscopic couples plus the transverse accelerations—*e g* , from rapid control movements and in manoeuvres, seem to combine to produce journal loads approaching those found in the chordwise installation

As suggested by Mr McCLEMENTS there will undoubtedly be " quite a few " problems in the airframe ! However, I am inclined to think that most of them will be frightening, because of the unaccustomed scale of forces, rather than involving real difficulty Even a rotating thrust vector of 10,000 lb becomes less alarming when one remembers that the corresponding helicopter has a gross weight of about a quarter of a million pounds, and that a small movement of the throttle can reduce or eliminate the vibration while the rotor is being re-balanced

Group Captain GORDON-FINLAYSON's important contribution began with a discussion of the economics of military air transport and we would welcome more information on this subject to aid in assessing and comparing the performance of aircraft intended for Army use

With regard to timing, it is difficult to appreciate the delays imposed by present conditions and official procedure and one wonders whether the matter is not already quite urgent Also it is natural to think of the helicopter as a transport vehicle required simply for bringing up supplies and evacuating wounded, but the carriage of certain classes of equipment almost transforms it into an offensive weapon—*e g* , in bringing up tanks, in siting and supplying guided missile launching points, and perhaps in giving mobility to heavy mortars for atomic shells If the helicopter is suited to such offensive roles it may be required at a somewhat earlier stage

I am very grateful to Dr MORLEY for his lucid and comprehensive review of the difficulties which are likely to arise in the development of suitable engines and it is very encouraging to know that our jet engine industry is represented by men who are able to give such fairminded attention even to the most unorthodox proposals My question was at first very incompletely defined and although the spanwise installation does not now appear to offer a solution, it might well have proved a valid answer to the original question

On the other hand I hope that Dr Morley's views on the limits of bearing capacity are not correct My own impression, after further inquiry, is that even normal ball and roller bearings may well be suitable Alternatively, Michell journal bearings seem very promising in spite of the rather elaborate oil system which they would require for heat dissipation in such a high speed application although this heat can be recovered by using the incoming fuel as the cooling medium Broadly, I believe the bearing problem to be no worse than the other undoubtedly severe stressing difficulties throughout the engine

Mr ROWE suggests that I am guilty of special pleading in assuming low forward and tip speeds but my choice of a three blade rotor and low tip speed ratio was made simply to put the examples on a conventional basis I do not agree with the commonly accepted view of blade stalling as a limiting factor in helicopter speeds and would base a real design case on a different conception, of which the most obvious feature would be the use of a four-blade rotor In such a case a tip speed of 550 ft /sec would suffice for any forward speed likely to be required for the airline helicopter operation I sympathise with Mr Rowe's anxiety in respect of noise and hope my reply to Mr Vessey will satisfy him on that point

From what Mr SHAPIRO has said I gather that Nature agrees with General Bower in disliking giantism ! Perhaps he will be satisfied on reflecting that the 10—15 ton lift helicopter which is apparently wanted, suffers least from this defect

Mr HAFNER has made a commendable effort to knock the load carrying capacity of my examples down to what he considers more reasonable proportions, but his arguments seem to reflect a somewhat hurried preparation They are based on a number of assertions, of which the most important is his statement that if a jet engine is added to the tip of a blade, additional structure weight will be required at the root to such an extent that the spanwise C G position of the blade plus engine will not differ materially from that of the original blade

Now one does not add structure weight at the blade root unless the forces acting there are increased, and the fact is that as between two blades producing equal lift at equal coning angles, the one with a concentrated tip weight is not only lighter overall but it exerts less centrifugal pull on the root and even has a lower static bending moment when stationary About two thirds of the discrepancy between Mr Hafner's estimate and my own arise from his error on this point

He also asserts that at 120 m p h the coning angle must not exceed 6° In a three-blade rotor certain fundamental vibrations might exceed the threshold of discomfort in the conditions he mentions but such a standard is not a good basis for so firm an assertion, particularly as the reasoning behind it could not be applied to other rotors in a general sense, except at very much higher speeds In a properly designed rotor I see no objection to coning angles at least up to the limits assumed in my examples Mr Hafner's assertion on this point is responsible for most of the remaining discrepancy

He also draws a number of other conclusions which are at least questionable For instance, he allots 36% of the gross weight to the fuselage My corresponding 28% may be on the low side but is it really necessary to allot 8% of the gross weight (about 7½ to 8 tons in the case of the Medium Giant) to "safety and other gadgets"? His final conclusion favouring the specialized crane helicopter is one with which I heartily disagree

I am in agreement with Dr BENNETT's views as to the general desirability of retaining a single rotor but he is not entirely correct in linking the advantages of the blade mounted power plant so firmly to the reduction in coning angle Concentration of weight at the blade tip can effect a reduction in blade weight equal to about 5% of the gross weight, and a further important reduction of the same order can be achieved by replacing the tip weight by something useful such as the engine, but even more important is the relatively low fuel consumption of the tip mounted turbo jet which has such a strikingly favourable influence on the Range/Payload characteristics as compared with other subsonic jet systems

Dr BENNETT'S suggested supersonic ram jet powered rotor is a most interesting possibility and I am prepared to believe that the two apparently very different systems may both tend toward similar increases in size It seems to me likely, however, that the way of the ram jet may be as hard as the way of the turbo jet Broadly, the supersonic rotor must tend to have very thin narrow blades, with possible flutter troubles and perhaps inability to control the blade from the root so that some new system of control may be needed Difficulties in fuel distribution, in maintaining the ram jet shape, in very high tensile stresses in the blades, in noise, and even in the formation of vapour in the shock waves (so that the pilot may sit like Moses in the midst of a cloud !) all seem to me to add up to rather more than the homely stressing problems of the turbo jet

Miss KENNEDY has asked about the maximum ceiling I have given my examples a mean lift coefficient of 0 45 which ought to take them up to 20,000 ft at normal load, but, of course, they could go much higher if fitted with bigger blades or if flown at reduced weights I do not know what the highest possible ceiling would be but at half load my examples might reach, say, 40,000 ft

Miss Kennedy also asked about vulnerability First, the aircraft is by no means a lumbering thing The proposed helicopter, when fully loaded, has a performance similar to that of any present-day helicopter, but at half load, and especially at no load, it is extremely agile I do not know whether it would be possible for the pilot, simply by pulling up the pitch lever, to black himself out, but I think the machine will have an agility of that order at light loadings, so that from the manoeuvrability point of view I do not think it is vulnerable The shaft would be of about 18 ins diameter, and quite thick-walled , the pieces of metal in the upper and bottom hub plates would be perhaps 6 ins thick, so that I do not think that any light fire would harm them very much Most of these things are also shaped, so that a shell would have to make an extremely lucky hit in order to penetrate The tail rotor is about the only really vulnerable part of the aircraft and that is duplicated

Dr ROBERTS is fully justified in pointing out my rather odd application of Sissingh's criterion to a jet rotor, but in this case it was permissible since the tip speed was fixed at 550 ft /sec , which converts thrust into horsepower I agree that higher tip speeds would give greater power plant efficiency but apart from their effect on the turbine and a tendency to Mach No troubles at high speed, they would lead away from the broad-bladed slowly turning rotor which I find rather attractive

In following the tip speed argument to the point of advocating supersonic tip speeds, it seems to me that both Dr Roberts and Dr Bennett may be attaching too much importance to the efficiency symbol η as a design criterion So long as the turbo jet can be considered a possibility, my 550 ft /sec seems to me a comfortable and quite efficient compromise

I agree with Dr Robert's view on coning angles and, as a sidelight, he may be interested to note that my smaller examples have small coning angles simply because in those cases large angles give no advantage, as shewn in Figs 5, 6 and 7 The larger examples reach nearly 10° (at 100 m p h) in the overload case

Mr BRISCOE's difficulties in finding city sites deserve sympathy but a 50-passenger twin tandem helicopter is likely to be about 120 ft overall—in fact the Piasecki of this capacity is nearly 170 ft overall Against this a 100 passenger helicopter with tip mounted turbo-jets would not exceed 120 ft so this type really offers a big reduction in size for a given passenger capacity

By the time traffic justifies a 280 ft helicopter I think we may hope that operating techniques will permit smaller landing areas than are now thought necessary on the basis of present experience Mr Briscoe's query about unprepared ground in military operations should not be too difficult to answer because for such special uses one can fit around the lower part of the wheels a kind of broad foot to spread the load