The Application of the Jet Flap to Helicopter Rotors*

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INTRODUCTION

During the course of fundamental research into noise suppression on jet engines, the need for a jet system which embodies quick mixing has become apparent , one way of doing this is by the use of a long thin peripheral slot in place of the usual circular nozzle Indeed noise measurements on such a jet unit[1] indicate a reduction such as to make the use of pressure jets on helicopters once more feasible from the noise point of view

If this need for a long thin slot is taken to its ultimate conclusion, we arrive at the concept of a long two-dimensional pressure (or gas) jet whose nozzle consists of a long slit positioned at the trailing edge of some considerable portion of the rotor and integral with it Thus if a tip pressure jet with a circular 6 in diameter nozzle is replaced by such a two-dimensional unit of eight feet length, say, with the same thrust and exit velocity, the slit will be about 0 3 in wide and the noise reduction to be expected will be of the type shown in Fig 1 This possible reduction of 30 decibels in all but the highest frequency range is unlikely to be obtainable to anything like the same extent in any other way and presents a very different picture from that painted hitherto of the noise problems of high pressure jets The high frequency noise is troublesome but is attenuated by relaxation effects[2] to a far greater degree with distance than is the low frequency element This is discussed in more detail in Ref 1

This obvious advantage of the two-dimensional jet leads to the thought that is now foremost in the minds of fixed wing aircraft designers, that it is wrong to design the engine and airframe separately but that one must aim at an integrated system which uses the power available in the optimum way Thus the practice of blowing over flaps with air taken from the engine compressor is becoming an accepted feature in both the U S A and in this country Further steps in the move along the line of optimization involve the use of deflecting jets, of vertical take off, and the " jet flap " put forward by N G T E [3] This paper confines itself strictly to the application of this last system to the helicopter rotor design , it must be pointed out, however, that in the authors' views the practice of blowing over flaps may be equally or more advantageous, and that this system should be included in any detailed analysis of the acceptability of these new systems in helicopter rotor design

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https://doi.org/10.1017/S2753447200002766 Published online by Cambridge University Press

Lift

The principle and theory of the jet flap is dealt with in Ref 3 It is shown that if a high velocity jet is emitted from the trailing edge of an aerofoil at an appreciable angle to the stream, the lift on the aerofoil is augmented by an amount not equal to the downward momentum but by an amount greatly in excess of this The exact amount varies but can be as much as twenty or thirty times the downwards component of the jet thrust This only occurs when the jet thrust is small, and the lift is not great even when thus augmented A more reasonable augmentation figure is of the order of 5 obtainable for high values of the thrust coefficient

A better idea of the lift coefficient to be obtained with varying values of the downward thrust of the jet is given in Fig 2 taken from Ref 3 If we define J as the momentum of the jet, which blows at an angle of $\theta°$ to the wing chord line,

then if $\triangle C_L$ = lift coefficient at zero geometrical incidence

$$\triangle C_L = \mu C_J \sin \theta$$

where $C_J = J/\frac{1}{2}\rho U^2_0 c$

and c and U_0 are the wing chord and velocity at infinity respectively

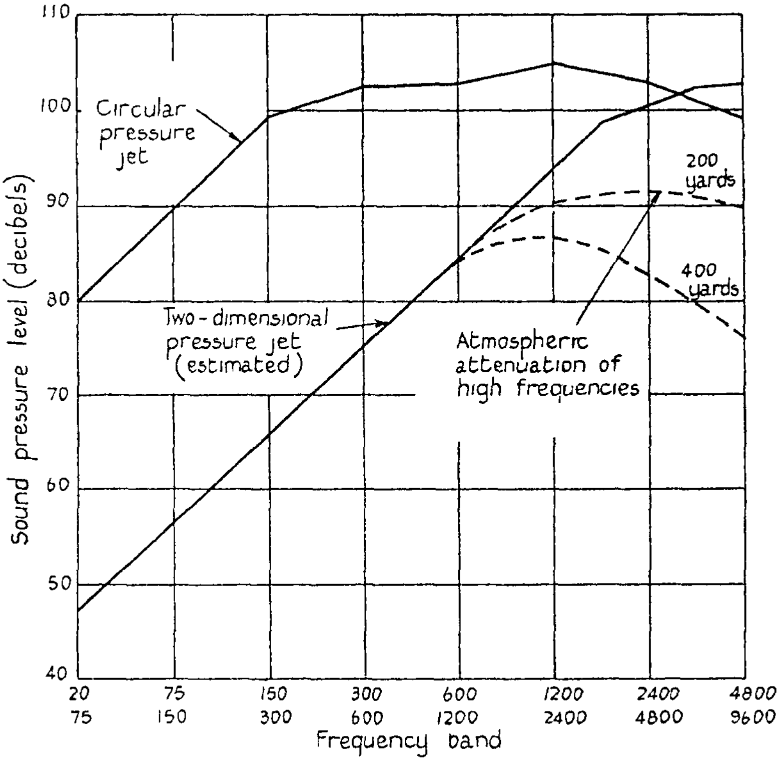

Fig 1

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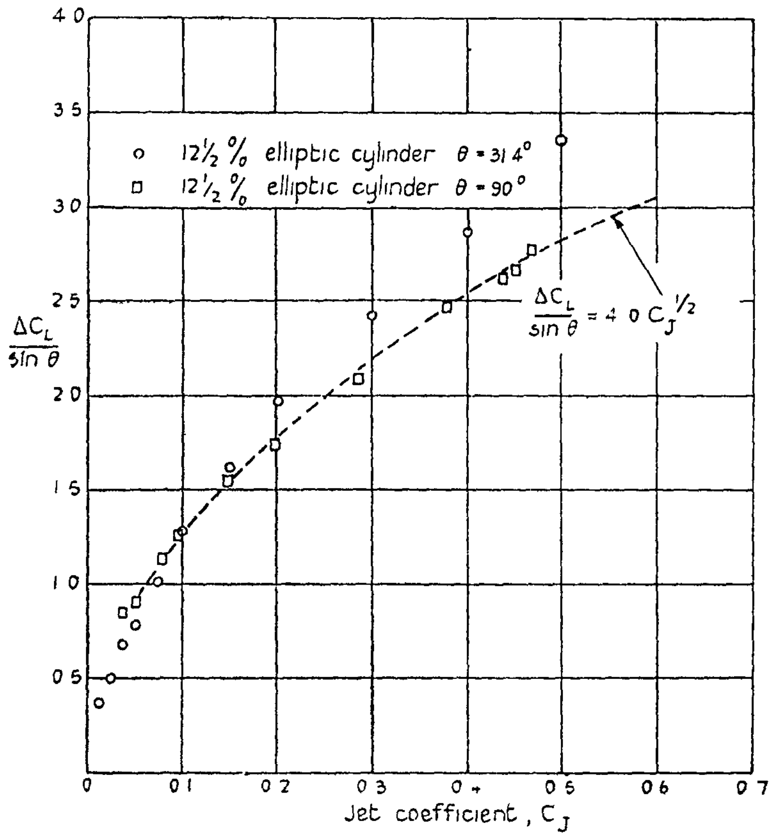
For purposes of this discussion the important thing to notice is that at a value of C_J of 0 15 the lift coefficient at zero incidence is augmented by as much as 1 5 and at a C_J of 0 40 it is augmented by about 2 5   In fact for this particular case at least (with the jet at 90° to the chord line and a slot width of 0 0022 c) we can write in practice

$$\triangle C_L = 4 \; C_J^{\frac{1}{2}}$$

while for a jet at an angle $\theta°$ to the chord line we can write conservatively,

$$\triangle C_L = 4 \; C_J^{\frac{1}{2}} \sin \theta$$

For high values of C_J this latter formula gives a result about 5-10% less than in experiment   While more accurate formulae are given in the section, "Application to the Helicopter," these formulae are sufficient for the purposes of the present discussion



The lift ΔC_L of a jet flap aerofoil at 0° incidence

Fig 2

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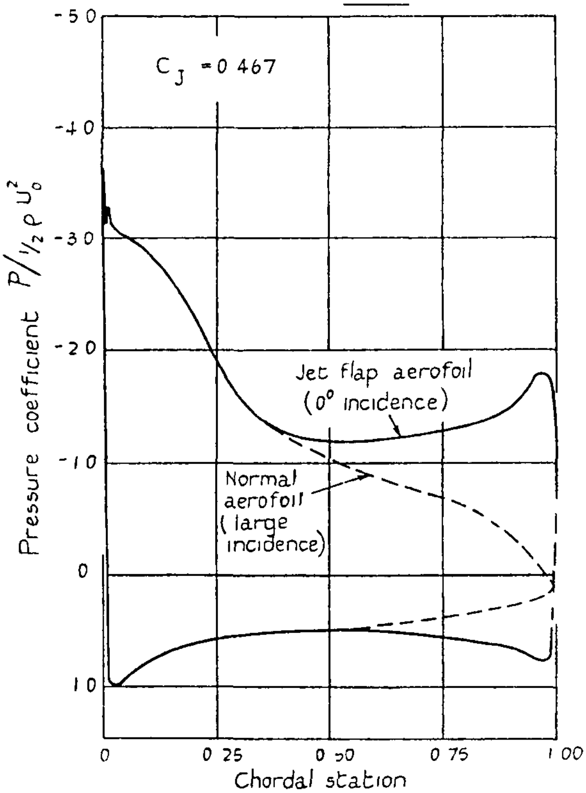
The above relationship for $\triangle C_L$ gives the increment in lift coefficient arising at zero geometrical incidence In practice, we would aim at setting the blades at some incidence such that with the jet operating, the blades would just remain unstalled Little information is available to show whether the normal C_L increment due to incidence can be added to $\triangle C_L$ This will certainly be true for small values of C_J in which the induced suction peaks are small For large values of C_J one can see from Fig 3, which shows a typical pressure distribution over an aerofoil, that the overall C_{Lmax} can only be increased in so far as the rear of the aerofoil carries lift and prevents any extensive chordwise region of separation from occurring Until more work is done on this, it is best to assume that for the moderate values of C_J involved, the basic effect of incidence can be added in part, let us say, at the Reynolds numbers of helicopter blades by $C_L = 0\ 6$

Thus C_{Lmax} would be written $C_{Lmax} = 0\ 6 + 4\ C_J^{\frac{1}{2}} \sin\theta$ The aspect ratio in this instance will be very large (of the order of 15 or so) and the change of lift slope arising from this may be neglected

FIG 3



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Thrust

Much controversy has arisen regarding the amount of thrust that is obtained in flight from a jet blowing at an angle θ to the chordline Experience with circular jets would suggest that the forward thrust is simply the component of the jet thrust J in that direction Theory indicates, however, that on a two-dimensional unit, the forward thrust will be equal to the full value of J, whatever the downward inclination of the jet While such theories do not allow for mixing of the jet with the surrounding stream, experiments[3] carried out with a jet set at an angle of 90° to the chord indicate that at least a quarter to one half of the theoretical thrust is obtainable even in this extreme case For the more practical arrangement of the jet set at a moderate angle, say 45°, it appears likely that little thrust will be lost by the inclined angle This is assumed in the analysis below although more work is needed to elucidate this controversial point

Application to the Helicopter

Before examining the advantages of any jet flap application, it is worthwhile to point out the present limitations now imposed on design These may be listed as follows —

(1) The maximum power involved is during hovering and vertical climbing Thus the maximum weight that a helicopter can lift is governed by the maximum lift obtainable, and also by the blade drag, part of which is profile drag and part due to the induced component arising from the backward inclination of the lift in a field of downwash

(2) In forward flight the reduction of airspeed on the retreating blade is compensated by an increase of incidence, provided that the stalling angle is not exceeded This limits the maximum forward speed of the conventional helicopter

(3) A collective pitch change arrangement is required to allow the lift to be varied for an effectively constant rotor r p m The significant conditions that must be covered are those of (*a*) lift in hovering flight (high C_L), (*b*) autorotation, with a negative C_L over some parts of the rotor and (*c*) ground running or zero overall lift coefficient

(4) The need for collective and cyclic pitch change mechanisms together with a driving system or tip jets causes serious design inconveniences

(5) The elimination by the use of the tip jet of the need to drive through the rotor is only replaced by the noise problem of the tip jet The only system at present acceptable is the low pressure jet which in turn requires large ducts

Basic Concept

Once we accept the basic concept that lift may be modified independently of geometrical incidence by varying the jet thrust coefficient collectively and cyclically, we can immediately conjure up jet flap helicopters in which the rotor head possesses neither a means of varying the geometric collective pitch nor the cyclic pitch of the blades, but relies rather on " sleeve valve " air or fuel systems in the head to vary both collectively and cyclically the jet efflux to obtain the same characteristics Thus if the value of C_J is altered

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from almost zero for ground running to 0 5 say on the retreating blade in forward flight, the concept is feasible although clearly presenting serious and possibly insurmountable difficulties These are —

(1) Since a variable direction jet is inadvisable on the score of complication, reduced lift implies reduced torque It would then be necessary to modify our concept of constant rotational speed

(2) If the system of control of the jet momentum is by the variation of the air flow at the rotor head, lag difficulties arise owing to the rapidity with which the jet efflux has to fluctuate On the other hand, as will be seen later, the cyclic system is to quite an extent self compensating, the reduced velocity on the retreating blade automatically increasing C_J The alternative of using a cyclically variable fuel feed system is probably simpler, the control system being then a single variable air valve controlling the air flow to the blades (equivalent to collective pitch), the cyclic variation of C_J being obtained by the variation of the air-fuel ratio and by the self compensation mentioned above

(3) Provision must be made for the blades to autorotate in the event of failure of the compressed air or fuel supply Since this is normally not the zero pitch required for ground running, a collective pitch change may be necessary to overcome this difficulty Since the requirements of flying and autorotation are contradictory on normal rotors and result in any case in a compromise design, this may also be true on the jet flap type of rotor discussed here

All in all, the possibilities of obtaining a fundamental new approach to the rotor problem by the introduction of the jet flap does not look very favourable However, the improvements obtained in the noise pattern are so great that it would be well worthwhile for a progressive helicopter designer to be asked to make a design study using such an approach It is clear that this can only be done if all preconceptions are eliminated and the design tackled from a fundamental viewpoint

Hovering

If we now discard the long term concept, and confine ourselves to the problem of how best we can integrate a two-dimensional pressure jet, or gas jet, into our design to give an optimum performance as well as noise reduction, it is clear that the jet flap principle has great possibilities Consider a helicopter in hovering flight with a tip jet of 0 30 semispan and inclined at an angle of say 45° Since we may argue that the jet momentum is fully utilized in thrust, and since a typical torque coefficient for a helicopter may be taken as say $C_Q = 0\ 0003$, we will require a C_J in hovering flight of about 0 13 to overcome the blade and induced drag In this condition

$$C_{L\max} = 0\ 6 + 4\ C_J^{\frac{1}{2}} \sin\theta$$
$$= 0\ 6 + 1\ 02 = 1\ 62$$

It is probable that for the low values of C_J used in this instance, the peak suction built up by the induced flow due to the jet is not very large, and that possibly a higher value than 0 6 can be used in the calculations Furthermore, the $C_{L\max}$ of 1 62 is obtained with a jet at 45° to the chord line If in practice the thrust is maintained for this angle of depression as indicated in theory, then a larger angle can be used and $C_{L\max}$ increased

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in this way If as is more likely in practice, the thrust is simply the component of the jet thrust along the chord line, then C_J will need to be increased in the ratio of 1 4, the maximum lift being consequently increased to about 1 8 It thus appears that a C_{Lmax} of 1 62 is a conservative figure which might well be increased to 1 8 On the other hand, allowance must be made for any increase in torque coefficient required in a true assessment of the gain to be obtained

The maximum lift coefficient of the blade sections obtained on conventional blades in the hovering case depends very much on the Reynolds number and will vary along the blade and with the chord length On a large helicopter with blades of two feet chord the mean C_{Lmax} will be about 1 3 On a small helicopter C_{Lmax} is unlikely to exceed 1 0 to 1 1 Thus there is a gain in lifting capacity on using the jet flap on both categories of machine, the greater gain being on the smaller unit

If the jet unit is designed to emit a constant thrust along its whole length, then C_J will be greater inboard (since $C_J = \frac{J}{\frac{1}{2}\rho\Omega^2 r^2 c}$ where r is the radius and Ω is the angular velocity) so that more lift augmentation is obtained Since C_L varies as $C_J^{\frac{1}{2}}$ the actual lift increment will vary directly as the speed rather than the $(\text{speed})^2$ at the station in question This is a favourable feature in itself since it will mean that the disc loading of the blade will be more uniform and the downflow through the rotor more constant The induced drag obtained from the component of the lift in the direction of rotation will therefore be smaller and a more efficient system will be obtained

Let us consider now the case where the thrust J is not constant but varies as $\left(\frac{r}{R}\right)^n$ say where r/R is the distance from the hub as a fraction of the span and n is any number Since the torque Q = J r dr whereas the increment in lift due to the jet varies as $J^{\frac{1}{2}}$ r dr, we have

$$\frac{L}{Q} = \frac{\int J^{\frac{1}{2}} r\,dr}{\int J\,r\,dr} = \frac{2(n+2)}{(n+4)} \quad \text{for a full span jet unit}$$

This increases with the value of n, for example from 1 2 for n = 1 (*i e*, constant thrust) to 1 5 for n = 4 For a constant torque, the greatest overall lift (neglecting the change of efficiency due to varying induced velocities) is obtained when the thrust is greatest at the blade tip This conclusion goes against the idea of the jet flap but may be negatived by the reduced induced drag to be obtained from a more uniform loading

To sum up therefore, there appears to be an appreciable increase in lifting ability in hovering possible by the use of the jet flap but that it is impossible without a more detailed analysis to determine the optimum distribution of the jet thrust along the blade It appears probable however that the thrust at the tip should be greater than the thrust inboard, even though the downflow through the rotor is not improved in this way

Forward Flight

The maximum speed attainable in forward flight is determined partly

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by the danger of shock waves forming on the advancing blades and partly by the danger of normal stalling on the retreating ones The former can be delayed by reducing the tip speed of the blades and is not greatly affected by the use of the jet flap principle The latter limitation is however greatly affected by the method of obtaining lift and needs further study

The reduced speed of the retreating blade is compensated by an automatic increase of incidence, and if reverse flow is ignored maximum incidence occurs at the blade tip On conventional rotors the stall begins at a tip speed ratio (μ) of about 0 30 to 0 35, and spreads rapidly inboard as μ is further increased It is accompanied by a rapid rise in drag and power consumption, and by an increase in the level of vibration Obviously this is a serious limit to helicopter operation and various means of surmounting the difficulty have been used, or are projected In general the principle employed is to reduce the load carried by the blades, either by fitting stub wings and propellers or by increasing the number of blades

Jet flap offers an alternative method of delaying the onset of stall, because both the lift coefficient and the available $C_{L\max}$ are automatically increased on the retreating blade

Let $C_{L(r)}$ be the lift coefficient at radius r
$C_J(r)$ be the jet thrust coefficient at radius r
$\alpha(r)$ be the instantaneous incidence measured from zero lift
c be the blade chord
R be the tip radius
and a_0 be the slope of the lift curve without jet lift

Then $$C_{L(r)} = a_o\alpha + 4C_J(r)^{\frac{1}{2}} \sin\theta \qquad (1)$$

Now $$C_{J(r)} = \frac{J(r)}{\frac{1}{2}\rho c\Omega^2 R^2 (x + \mu \sin\psi)^2} \qquad (2)$$

where $\frac{r}{R} = x$

ψ = Azimuth angle of blade measured from downwind position

and Ω = Angular velocity of the rotor

If we assume J to be constant along the blade then

$$C_J(r) = \frac{C_{JT}}{(x + \mu \sin\psi)^2} \qquad (3)$$

where $C_{JT} = \frac{J}{\frac{1}{2}\rho c R^2 \Omega^2}$ *i e*, value of C_J at the tip

Hence $$C_{L(r)} = \left\{a_o\alpha(r) + \frac{4C_{JT}^{\frac{1}{2}} \sin\theta}{(x + \mu \sin\psi)}\right\} \qquad (4)$$

i e, C_L varies automatically as the blade rotates, independent of the variation of $\alpha(r)$

Also if we assume

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$$C_{L\,max} = 0\ 6 + 4C_J^{\frac{1}{2}}\ \sin\theta \tag{5}$$

Then
$$C_{L\,max} = 0\ 6 + \frac{4C_{JT}^{\frac{1}{2}}\ \sin\theta}{(x + \mu\sin\psi)} \tag{6}$$

On the retreating blade $180° < \psi < 360°$ and $C_{L\,max}$ will be a maximum when $\psi = 270°$

The value of C_{JT} will depend upon the total drag, inflow distribution, etc , but at the maximum forward speed will be about the same as in hovering Hence if we assume

$$\mu = 0\ 35, \quad C_{JT} = 0\ 13, \quad \psi = 270° \text{ and } \theta = 45°$$

then at the tip $C_{L\,max} = 2\ 17$, *i e* , about twice the usual value

If μ is increased to 0 5, assuming C_J to remain constant, the new value of $C_{L\,max}$ at the tip is 2 64 , hence as μ increases $C_{L\,max}$ increases Also the increase of $C_{L\,max}$ is greater for the inboard stations ($x < 1\ 0$) than for the tip, and the tendency for a stall to spread is reduced

It has been shown that—equation (4)—cyclic variations of C_L are produced automatically for a constant C_{JT} It is possible that this could be utilised to replace, or at least to reduce, the cyclic pitch variation necessary for a given manoeuvre, but this would be a matter of design Certainly some forced variation of pitch would be necessary (either by varying C_J or α) to initiate forward flight in a given direction

At this stage we cannot arrive at any definite conclusions about the effect of jet flap on the blade motion, but it follows from (4) that the blades will be in some form of forced oscillation Since jet lift would constitute an appreciable part of the total, smaller pitch angles would be used and possibly the inflow could be reduced Thus the amplitude of the vibrations might not differ much from that of a conventional rotor

To conclude therefore, a considerable gain in the stalling qualities of the retreating blade can be achieved by the use of the jet flap principle In fact it seems probable that the stalling limitations on helicopter blades can be eliminated over the range of tip-speed ratio $0 < \mu < 0\ 70$ At higher μ the flow over a considerable portion of the retreating blade will be reversed and the preceding theory will be invalidated

Optimum Design

Very much greater gains would be obtained if a higher value of C_J could be used Since this can only be justified if the mean radius of operation is reduced, it may well be that the best way of utilizing the system is by reducing the rotor diameter, keeping the tip speed as it is, and increasing the disc loading Since this is a matter for a very detailed and comprehensive design, it is impossible to comment on it here It is also impossible to comment on any difficulties arising from centre of pressure changes without a detailed analysis being made

Conclusions

The above analysis is extremely tentative, being kept as general as possible, and is made by the authors who do not profess to be experts in

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helicopter design They must be accepted therefore in this spirit and are only put forward as a basis for discussion Within these limitations the following conclusions are relevant however —

(1) The very striking noise reductions on tip jets obtainable by the use of long thin slots make the " two-dimensional pressure jet " a unit worth developing

(2) Since these will occupy some considerable proportion of the blade radius, they should be integrated into the blade design to give both optimum noise reduction and performance gain

(3) The principle of the jet flap (or some boundary layer blowing device) can with advantage be applied to the design of the blades, both to improve the hovering and forward flight efficiency

(4) In hovering it should be possible to increase the maximum lift coefficient by at least 0 4 Tests need to be carried out to give more information on this point

(5) In forward flight, stalling problems of the retreating blades are eased while at the same time the average working lift coefficient of the blades can be increased by 50% or more This result can be used equally to increase the maximum feasible forward speed of the helicopter

(6) At this stage, the scheme does not offer the elimination of collective and cyclic pitch The difficulties are not insurmountable however, and a further detailed design study should be made of such a project

RECOMMENDATIONS

It is recommended that

(1) A two-dimensional pressure jet should be developed and tested for noise reduction

(2) A simple rotating jet flap rotor should be made for performance on a rotating ground rig

(3) In view of the apparent possible advantages, a detailed design study should be carried out at a firm to establish the feasibility of a fundamental change in rotor design

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