Jet Propulsion of Rotor Blades

By A STEPAN, Dipl Ing

A lecture presented to the Helicopter Association of Great Britain on Saturday, 29th October, 1949, in the library of the Royal Aeronautical Society, London, W 1

Group-Captain R N Liptrot, C B E
(Member of the Council)
in the Chair

Introduction by the Chairman

From the very beginning of helicopter development the designer has had two major problems, one associated with the balancing of the torque reaction on a mechanically driven rotating system, and the other one that of mechanical difficulties associated with the transmissions Isacco for instance realized right at the beginning that what he wanted was some jet reaction device on his blade tips, but there was no jet reaction device which was efficient, and he had to have recourse to individual engines, each driving its own propeller on to his blade tips Other designers, such as Brennan, in this country, and Bleeker in America, had recourse to a single engine rotating, with the system This was only half the solution, because they still had to face all the mechanical difficulties From then onwards, many people have tried jet propulsion You will realise that because we have tip speed limitations as we go on to bigger sizes our torque reaction problem becomes worse and worse We can, of course, use multiple rotors but if we do we have mechanical complication and heavier maintenance cost Because of that, everybody is beginning to feel that jet propulsion is the ideal for development of the big helicopter, and because so little has been published so far on this problem it is of enormous value to the Association to have a paper such as we are going to hear this afternoon, in which we get a critical review of all the methods of jet propulsion and their influence on the design of the rotating system itself

One of the first—in fact, the very first—to achieve success with the jet propulsion design was Doblhoff, in Austria, during the war Our lecturer this afternoon, Mr Stepan, who is a Diplome of Dantzig, an aeronautical engineer, and of course a Member of the Association, was one of the pioneers associated with Doblhoff in that development Indeed, he personally was responsible for most of the work on the jet propulsion device which was adopted, and he was the pilot of the aircraft After the war, he was brought to this country by the Fairey Aviation Company, and for the last two or three years he has been carrying on that development Nobody therefore, anywhere, is more competent to give us an insight into all the problems associated with jet propulsion than Mr Stepan

I also want to welcome here with us this afternoon another pioneer of jet propulsion, whom I will introduce to you later, but the fact that we have two of the pioneers with us—one giving us a lecture, the other taking part in the discussion—is going to make this afternoon's proceedings of immense value to everybody I am sure I can promise that this afternoon is going to be a highlight in our current calendar Before calling on MR STEPAN, I just want to welcome any guests we may have with us here this afternoon If, after hearing and seeing what the Association can offer, they are minded to join us, then our arms are wide open They have only to go to MISS MACPHEE to get a form of application (and, of course, there is the matter of a small cheque) and we will welcome them to membership

I will now call on MR STEPAN to give us his lecture

MR STEPAN

Mr Chairman, Ladies and Gentlemen,

Before I proceed to deliver my paper, I wish to express my thanks to the Council of the Helicopter Association for the honour given me by inviting me to address you this afternoon Furthermore, I would like to express my thanks to the Fairey Aviation Co , Ltd , for the help in preparing and for permission to deliver this paper

The subject of this paper is to give a general survey of the whole field of jet propulsion of rotor blades This driving device is nearly as old as the helicopter conception itself, and its main attraction is the elimination of torque reaction on single rotor helicopters

The success of the helicopter at the end of the last war showed that the jet drive was no longer a purely theoretical speculation, but was a system which, when developed, would improve the general characteristics of the helicopter Since the war many firms have entered the field, and have carried out extensive development and testing of jet-driven rotors

The results of their investigations have produced many purely theoretical configurations and so many practical applications that it is impossible to discuss in this paper every one to its latest development stage, or to give a full account of all its parameter relations By doing so, one could give a paper for each configuration itself

This paper will confine itself to describing each jet propulsion device so far as to give a full understanding of its principal working, design and performance characteristics to enable designer, manufacturer and consumer to compare them with conventional driving devices as well as with each other

PHYSICAL AND AERODYNAMICAL CONSIDERATIONS

It is advantageous at this stage to recall a few fundamental physical laws which apply to jet propulsion, in order to give a lead for the better understanding of many relations described in later paragraphs

The impulse law

$$T = m/\text{sec} \times V_j \qquad (1)$$

shows that to obtain thrust T every second a mass of material has to be brought to a velocity V_j Except for the rocket, the convenient way is to use the air as the medium for propulsion

The air has to be brought to a velocity, which can be done mechanically (compressor, helicopter rotor), or by supplying heat energy which gives the necessary velocity Jet propulsion works on the latter principle

The second law says

$$P = T \times V \qquad (2)$$

This proves that the power which can be developed by a certain thrust is proportionate to the speed

The overall efficiency of a jet drive is

$$\eta = \eta \text{ prop} \times \eta \text{ therm} \qquad (3)$$

η prop is the propulsive efficiency and is the ratio of the resultant thrust horsepower to the power supplied to create the thrust by increasing the kinetic energy of the air

It can be shown that

$$\eta \text{ prop} = \frac{2}{1 + \frac{V_j}{V_t}} \qquad (4)$$

(V_j = velocity of the jet stream, V_t = velocity of the jet unit, in our case the tip speed)

This relation indicates that the propulsion efficiency is greater if the difference between the induced velocity V_j and the tip speed V_t is small

With equation (1) this means that large mass and low jet velocity are preferable to produce the necessary thrust

η therm is the thermal efficiency and is the ratio

$$\eta \text{ therm} = \frac{\text{Available kinetic energy in the jet stream}}{\text{Heat energy from the fuel}} \qquad (5)$$

This expression, though well-known for heat engine calculation, is unsuitable for jet calculations where the velocity of the jet stream is of greater interest than its kinetic energy

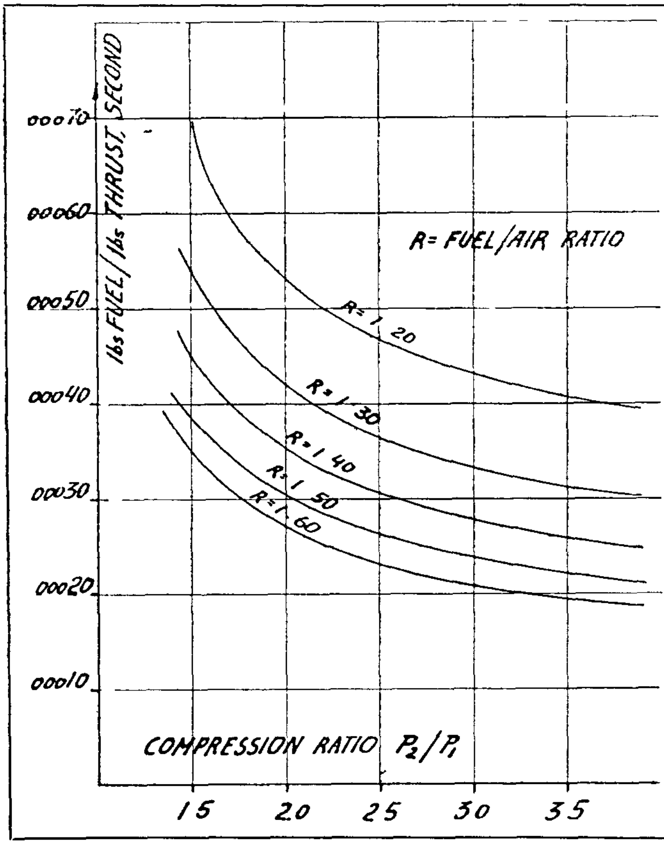


Fig 1

Specific Fuel Consumption of a Combustion Chamber with 100% Overall Efficiency

It is better to determine a relation

$$\eta_T = \frac{\text{lbs thrust}}{\text{lb fuel}} \tag{6}$$

This important figure depends mainly on two parameters

(*a*) The compression ratio at which the combustion takes place
(*b*) The temperature rise or the fuel/air ratio

Assuming 100% burning and 100% expansion efficiency, the fundamental relations (Fig 1) show that the specific fuel consumption of a jet

(*a*) Decreases rapidly with higher compression ratio
(*b*) Increases with the fuel/air ratio or temperature rise

These physical laws, though they are subject to adaptation in every configuration, give us the lead to understand the influence of the mentioned parameters on the efficiency of a jet drive

If we apply jet propulsion for helicopter rotors, we have to consider some fundamental aerodynamic differences between this rotor and a shaft-driven one A conventional rotor is designed to give best performance in hovering, climbing and forward flight Every alteration of its design parameters influences its performance or the necessary horsepower In the jet-propelled helicopter rotor the horsepower output is definitely linked with the tip speed, and every change of its design parameters changes not only its aerodynamic characteristics but also the amount of available hosrepower

For the better understanding of this important fact some aerodynamical considerations will be helpful

By calculating the conventional shaft-driven rotor a compromise has to be found to obtain good hovering as well as forward flight characteristics

Still for the hovering condition the well-known figure of merit is of some importance It is the ratio between the induced power in the slipstream under the rotor, and the power to be supplied to overcome the induced and profile drag of the rotating blades

Putting

$$T_R = C_T \frac{\rho}{2} A V_t^2 \tag{7}$$

and

$$Q_R = C_Q \frac{\rho}{2} A V_t^2 R \tag{8}$$

This efficiency is

$$\eta_{HOV} = \tfrac{1}{2} \sqrt{\frac{C_T^3}{C_Q^2}} \tag{9}$$

and

$$\frac{W}{HP_{Shaft}} = \eta_{HOV} \times \frac{\sqrt{2\rho}}{\sqrt{\frac{W}{A}}} \times 550 \tag{10}$$

T_J = Jet thrust
T_R = Rotor thrust
Q_R = Rotor torque
C_T = Thrust coefficient
C_Q = Torque coefficient
ρ = Density of air
A = Rotor disc area
R = Rotor radius
V_t = Tip speed
W = Weight of helicopter
HP_{Shaft} = Shaft horsepower
ηHov = Hovering efficiency
$\frac{W}{A}$ = Disc load
σ = Rotor solidity = $\frac{\Sigma \text{Blade area}}{\text{disc area}}$

The efficiency of a shaft-driven rotor depends on the design parameters $\frac{W}{A}$ σ and V_t and on the aerodynamic characteristics of the aerofoil

By calculation or by means of full scale wind tunnel tests, these relations can be composed as shown in Fig 2, where ηHov is shown as a function of C_t and the blade loading factor $\frac{C_t}{\sigma}$ (Ref 1) There is a definite optimum ηHov at values of $\frac{C_t}{\sigma}$ = 0 20, while σ and C_t are still variables

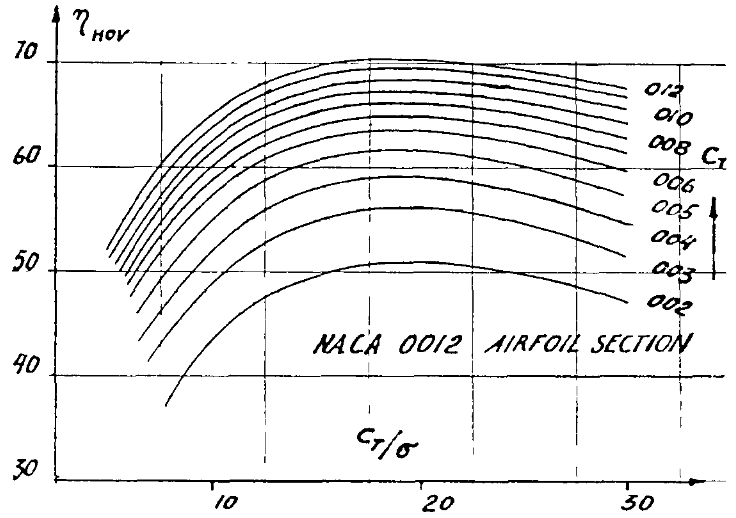


Fig 2 Hovering Efficiency Chart of Shaft Driven Rotor

In a jet-propelled rotor the corresponding expression for ηHov is the figure (Ref 2)

$$\frac{T_R}{T_j} \quad \text{or} \quad \frac{\text{lbs rotor thrust}}{\text{lb jet thrust}} \qquad (11)$$

Considering that

$$T_j = \frac{QR}{R} \qquad (12)$$

we obtain by substituting (7) and (8) in (11)

$$\frac{T_R}{T_j} = \frac{C_T}{C_Q} \qquad (13)$$

For the same rotor the corresponding chart to Fig 2 is Fig 3 showing $\frac{T_R}{T_j}$ as a function of $\frac{C_T}{\sigma}$ with σ as parameter

The optimum values of $\frac{T_R}{T_j}$ are obtained at a lower blade loading figure $\frac{C_T}{\sigma}$ than for the shaft-driven rotor

For both rotors the typical design characteristics are shown in Fig 4 and Fig 5.

They show that the shaft-driven rotor needs for best hovering performance high solidity and low tip speed which is contrary to the requirements of forward flight, while the jet-driven rotor needs the lowest possible solidity, and high tip speed It is obvious that in this case the requirements for hovering and forward flight are the same

Fig 5 shows further that a certain value of $\frac{\text{T rotor}}{\text{T jet}}$ can either be achieved by low solidity σ and low tip speed by working at the optimum $\frac{C_T}{\sigma} = 0\ 2$ (see Fig 2) or at high σ and high tip speed at the optimum $\frac{C_T}{\sigma} = 0\ 11$ (see Fig 3) This means that the curve $\frac{C_T}{\sigma} = 0\ 11$ shows the highest obtainable $\frac{\text{T rotor}}{\text{T jet}}$ for a certain σ, while the curve $\frac{C_T}{\sigma} = 0\ 2$ shows the highest obtainable $\frac{\text{T rotor}}{\text{T jet}}$ for a certain tip speed

This chart can be used to derive from it the design parameter chart for every sort of jet drive

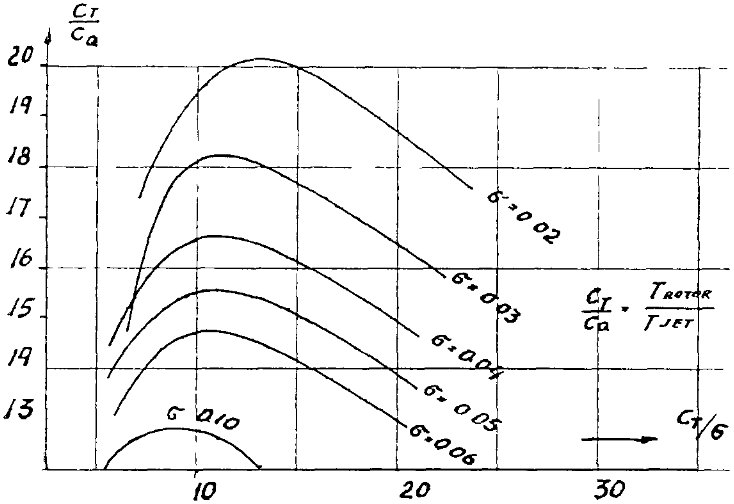


Fig 3 $\left(\frac{\text{T Rotor}}{\text{T Jet}}\right)$ Hov — Chart of a Jet Propelled Rotor

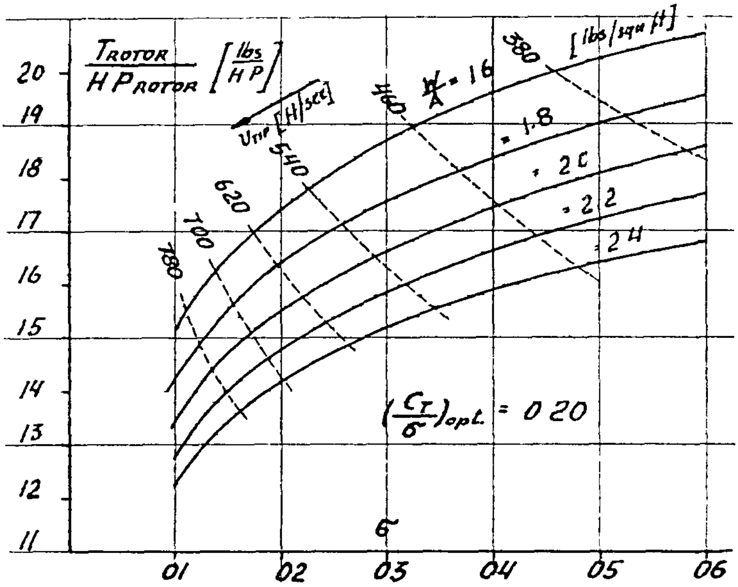


Fig 4 Design Chart of Shaft Driven Rotor

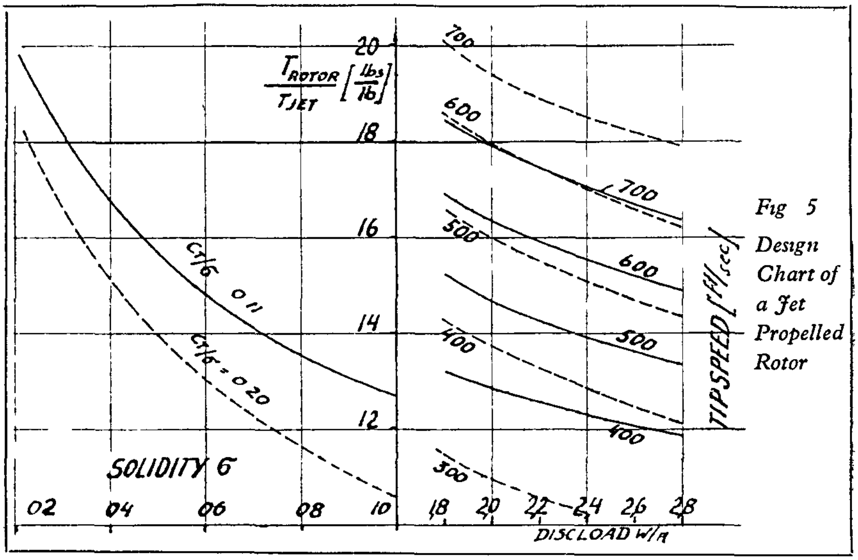


Fig 5 Design Chart of a Jet Propelled Rotor

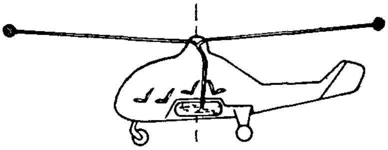
Present-day practical configurations of rotor-jet drives may be listed in order of their application as follows —

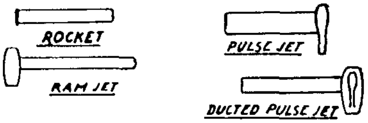
(*a*) *Pure Jet Rotors*

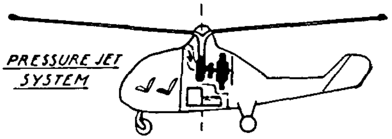
- (1) Rotor with tip-located power plants
  - (*a*) Rockets
  - (*b*) Ram jets
  - (*c*) Pulse jets
  - (*d*) Ducted pulse jets
  - (*e*) Turbojets
- (2) Rotor jet systems which require ducted blades and ducted hub, and where part of the jet equipment is enclosed in the fuselage
  - (*a*) Pressure jet systems
  - (*b*) Fuselage enclosed gas-stream generators

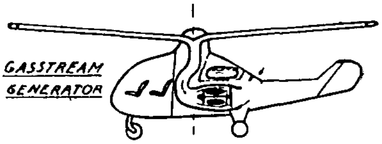
(*b*) *Gyroplane Rotors* with jet assistance for starting and landing

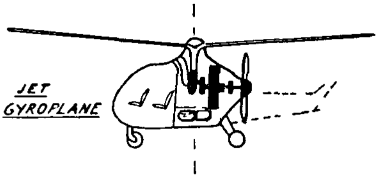
- (*a*) Rockets
- (*b*) Pressure jets











Rockets

The rocket drive is a constant thrust unit which may be used only for a short time as starting and landing assistance for a gyroplane or as a continuous drive for helicopters In the latter case the handling technique of the fuel fed to the burners (mostly liquid fuel) under high pressure, and the short life of the engine may represent the most difficult problems

From the economic point of view, the weight and cost of the fuel combined with the necessity of much supplementary equipment like fuel pumps or high pressure bottles makes the rocket drive a less promising configuration

The Ram Jet

The ram jet unit represents the simplest configuration Except for its size, which endangers the autorotation of the rotor in the case of power failure, its application for the helicopter would be an extremely attractive possibility

Principally the ram jet consists only of a cylindrical shell S with an entry and outlet orifice A_0 and A_1, built in flame holders or baffles B, and the fuel sprayer Sp

No moving parts whatever are necessary and one could not imagine a simpler engine

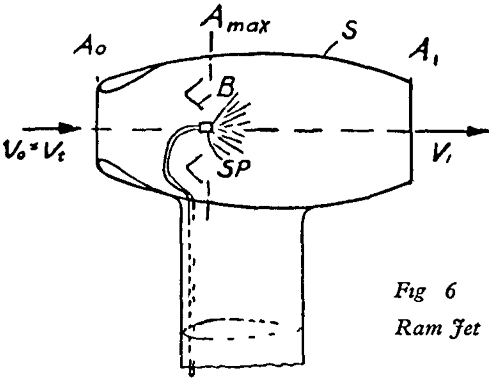


Fig 6
Ram Jet

Its function is explained as follows

(1) Air is taken in at A_0 with the tip speed V_t

(2) This air is slowed down to a much lower velocity in section A max and its pressure increases The maximum theoretically obtainable pressure could be the full ram pressure when the air comes to an actual standstill

(3) Heat is supplied in form of fuel

(4) The exhaust gas expands with highly increased speed V_1 through the outlet A_1 The resulting impulse is the gross thrust of the ram jet
The net thrust usable as motive power for the rotor is obtained by deducting the amount which is necessary to overcome the inside ram pressure and the drag of the body
From this description we gather that

(1) The ram jet gives no static thrust at all and has to be moved before it works

(2) The thrust depends primarily on its speed and secondarily on the fuel/air ratio

(3) As the tip speed of the helicopter blade is limited by aerodynamic considerations, say to 750 ft /sec , one can see that the obtainable pressure rise from the ram effect is very low $\left(\frac{P_2}{P_1} = 1\ 32 \text{ at } 750 \text{ ft /sec}\right)$ and, remembering Fig 1, the fuel consumption will be extremely high

Though the practical calculation of a ram jet is mostly based on the assumption of a thermal cycle process of compression, burning and expansion, this method of calculation is incorrect as it neglects the influence of the airstream outside the ram jet This effect improves the actual working to a certain extent and makes it more an aerodynamical problem The assumption of rather optimistic efficiencies for the thermal cycle calculations covers these gains from the aerodynamical side

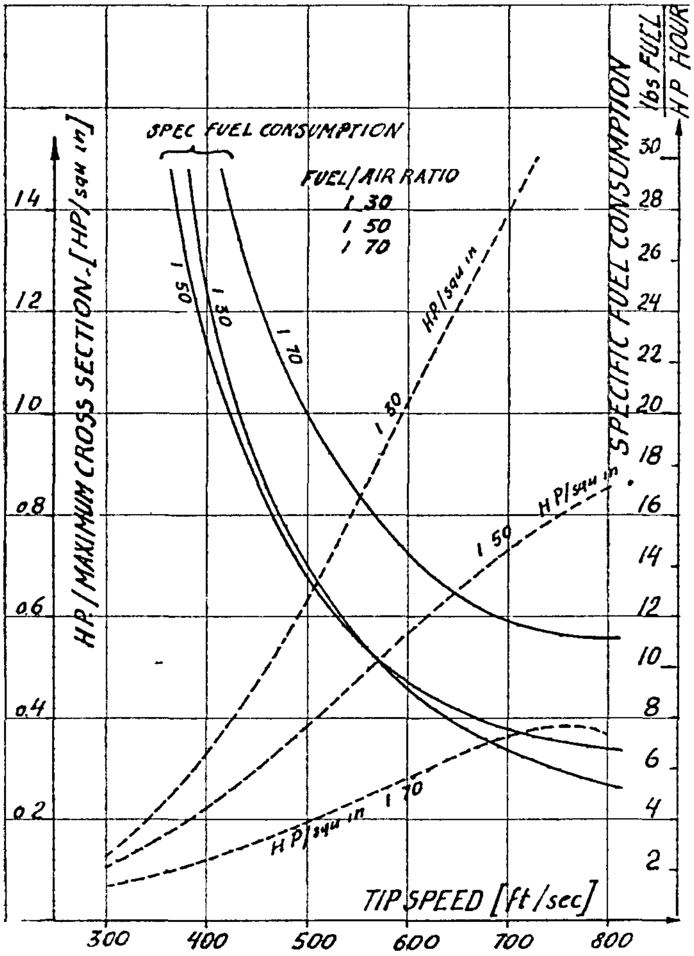


Fig 7 Ram Jet Performance Chart

Fig 7 shows a performance characteristic of a ram jet based on the following realistic assumptions for ram jet sizes usable on helicopter blades

η comp = 90% (compression efficiency in the cone)
η burning = 90% (burning efficiency)
η expansion = 90% (expansion efficiency in outlet orifice)
Δp baffles = 2x dynamic head at A max (pressure loss in baffles)
$V_{A\,max}$ = 130 ft /sec (velocity of the slowed-down air at baffles)
C_D = 0 11 (drag coefficient of body related to its front area)

This chart shows the tremendous importance of the tip speed and gives some realistic impressions about the necessary ram jet size

The size can be decreased by applying higher fuel/air ratios The temperature rise by this method is limited by structural considerations and at high fuel/air ratios by increasing specific fuel consumption For the chosen example the specific fuel consumption decreases with higher fuel/air ratios up to 1 30, which can be explained by the compression efficiency of 0 9 and the pressure loss in the baffles

From the constructional point of view the design of efficient flame holders with the lowest possible pressure loss represents the most delicate feature Besides keeping the flame front stationary in the high velocity airstream they are responsible for good mixing and burning so that the jet unit may be kept as short as possible

For the aerodynamic design of a ram jet rotor the leading requirements are the smallest possible solidity and high tip speed, combined with low disc load These parameters are limited by the design forward speed and by structural considerations

For forward flight the tip speed has to be reduced because of the compressibility effect, and the solidity is limited by the stalling effect on the retreating blade Assuming a maximum permissible mean profile lift coefficient, the lowest possible solidity of a rotor is a function of the forward speed and disc load

Higher design forward speed means higher solidity, lower tip speed, bigger ram jets and higher fuel consumption On the other hand, there is a power surplus in hovering flight when the pilot increases the tip speed by appropriate pitch reduction

In a highly efficient ram jet it may occur that the horsepower output increases so tremendously with the tip speed that the power control is critical

The horsepower-tip speed characteristic for a ram jet should be so that it governs itself to a certain optimum tip speed at each fuel flow ratio so that the throttle control is satisfactory

The Pulse Jet

The next simple tip-located power generator for rotor blades is the pulse jet

Its principal feature is an intermittent combustion together with a pulsating gas column

Though the pulse jet may seem from its appearance a unit almost as simple as the ram jet, a closer introduction into its working cycle will prove that it represents a very ingenious engine in which the balance of the components needs very careful study and much experimental effort

It works as follows (Fig 8)

(*a*) A petrol/air mixture occupying only a short section of the duct is ignited and the excess pressure of the explosion moves the air cushion in front of it in the direction of the open outlet, and at the same time it reacts on the closed inlet valve, producing the propulsive force

(*b*) The expanding gas moves with high velocity through the duct The point of atmospheric pressure is over-run and the inertia of the gas column creates even a suction pressure

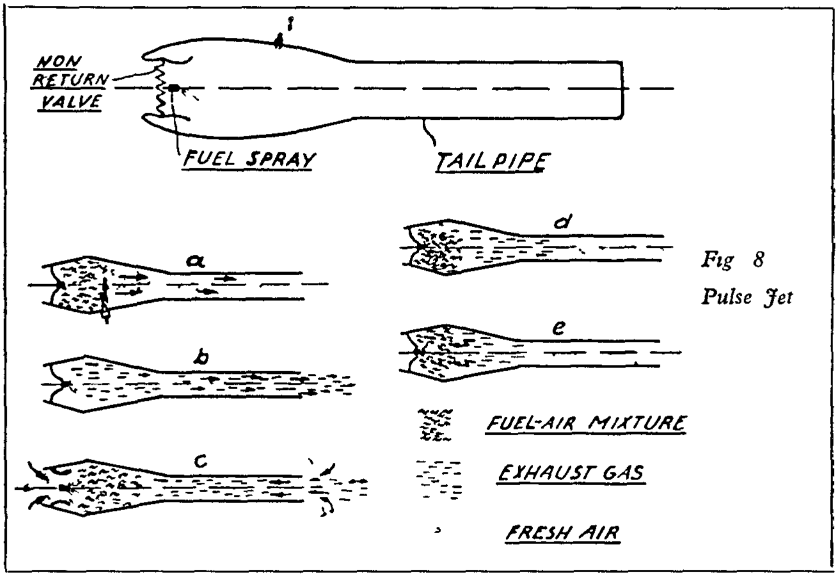


Fig 8

Pulse Jet

(*c*) This is the moment when the valve opens and fresh air comes in and mixes with the petrol spray At the same time some remaining exhaust gas mixed with fresh air flows back from the exit nozzle

(*d*) When atmospheric pressure is reached the valve closes and the back-flowing gas column gives by its inertia some compression to the combustible mixture which ignites itself on the remaining gas from the previous explosion

(*e*) The next cycle starts

The number of cycles per second can be calculated like the frequency of an open organ pipe or for special configurations with the formulae of the Hertz resonator The frequency is approximately proportional to the length of the unit

To give an idea of its value it may be noted that

A 2 ft unit works with 270 cycles per second
A 3 ft unit works with 180 cycles per second

We gather from this description that the proper function depends on

(1) Right frequency, opening ratio and duration of the inlet valve

(2) Absolutely balanced parameters as inlet area, combustion room size, length of tail-pipe and outlet area

The efficiency of the pulse jet depends mainly on the design of the inlet valve

Most of the valves used in present pulse jets are Schmidt valves or mouth-organ valves composed of very thin steel plates working on a supporting grid

The advantages of the pulse jet compared with its simpler brother the ram jet are

(1) Static thrust is obtainable

(2) It has a much lower specific fuel consumption and higher thrust output per square inch frontal area

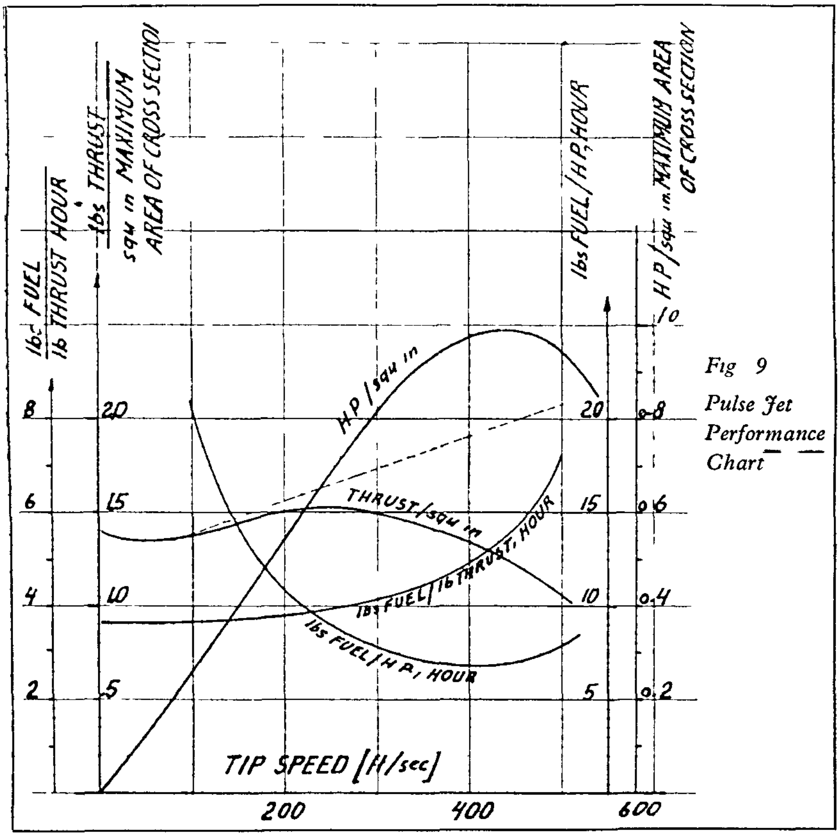


Fig 9 Pulse Jet Performance Chart

The disadvantages are

(1) Frequent replacement of the non-return valve is necessary (At the present time with reed valves, reliable operation of only one or two hours is expected

(2) High noise level

(3) Compressed air for starting is necessary to excite resonance

Furthermore, the pulse jet requires for efficient working a certain overall length of about ten times its outlet diameter, which is very undesirable from the structural as well as from the control point of view Fatigue failures of the pulsating tail-pipe are a great problem on present pulse jet rotors

Multiple units at each blade tip can be used to reduce the length and increase at the same time the reliability It is possible by this arrangement to bring the cycles of the units in phase, *i e*, the combustion of each of the ducts follows at equal time intervals, and the mean change of thrust is much more favourable

To illustrate the possibilities and limits for the application of pulse jets on helicopter rotors, a few relations about its fundamental performance characteristics are given as follows

The available thrust per square inch tail-pipe area is

3 5 to 5 0 lbs /sq in for big units from 3 5 inch tail-pipe diameter upwards
2 5 to 3 5 lbs /sq in for smaller units

These values depend entirely on the design of the valve and the balance of the other previously mentioned dimensions Theoretically much higher values should be obtained and the pulse jet is still open to a wide field of investigation

The maximum diameter of the jet depends mainly on the fuel mixing device and can be assumed as 1 6 to twice the outlet diameter

Fig 9 shows the performance characteristics as functions of the tip speed

The most significant point is a rather defined optimum performance at a limited tip speed of about 450 ft /sec The physical explanation of this limit is the fact that, from a certain speed upwards, the increase of drag of the intermittent valve rises more than the increase of impulse by the ram pressure At the same time the fast moving outside air near the outlet has an inferior effect on the flow-back cycle which decreases the thrust till the jet blows out The limited tip speed calls for higher solidities than the ram jet and gives, therefore, better autorotation aspects

Using Fig 5 and Fig 9, the design and performance characteristics of the pulse jet rotor can be calculated

The Ducted Pulse Jet

This configuration is an interesting combination of the two previously described power plants

In the principal it consists of a pulse jet unit enclosed in a ram jet duct so that the pulse jet works under higher pressure and its heat output is used for supplementary impulse Though no data about practical results is available, performance characteristics lie between those of the pulse jet and ram jet Contrary to the pure ram jet, there is static thrust available and, furthermore, there should be no sudden drop in horse-power, as in the pure pulse jet, but a continuous rise with tip speed In the specific fuel consumption the ducted pulse jet is superior to ram and pulse jets, which makes its development very attractive

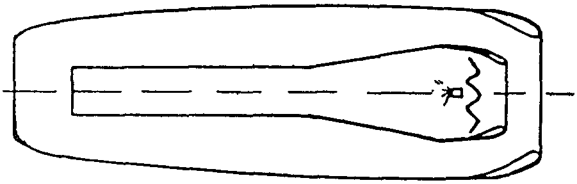


Fig 10

Ducted Pulse Jet

Turbojets on the Rotor Blade Tips

This possibility is also still a theoretical one and depends mainly on the development of small units with much lower weight per thrust ratios than is usual for present turbojets

High bending loads on the stationary blade and high centrifugal loads on the rotating blade and turbine with remarkable gyroscopic effects on the latter represent the most difficult problems

From the economical point of view the turbojet would have the lowest fuel consumption of all jet drives with 1 4 to 1 6 lbs fuel/h p hour

THE PRESSURE JET SYSTEM

An outstanding example of this type was the first actual flying jet helicopter, the WNF 342 or Doblhoff helicopter, built during the war in Germany

A motor-driven compressor enclosed in the fuselage delivers air through a ducted hub and ducted blades to tip-located burners Here fuel is injected and the combustion takes place

The impulse of the exhaust gas provides the thrust which is rather independent of the tip speed

The principal characteristics of this drive compared with tip-located power plants are higher empty weight, higher production costs, but much lower fuel consumption due to the higher combustion pressure

The pressure jet helicopter is, therefore, suitable for longer ranges

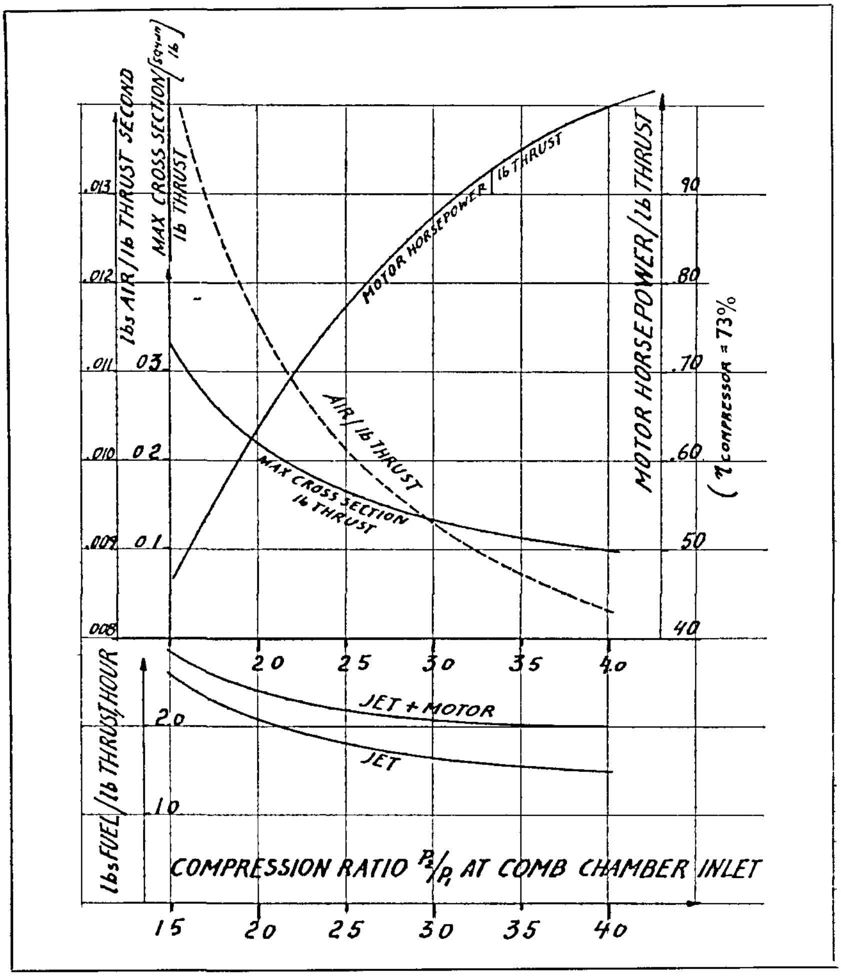


Fig 11 Pressure Jet Performance Chart

For the general layout the mass flow and the compression ratio are the variables There are two ways of development

High mass flow and low compression ratio results in

1. High ratio of rotor horsepower to compressor horsepower
2. High specific fuel consumption
3. High solidity and poor aerodynamic qualities of the rotor
4. Big combustion chambers

Small mass flow and high compression ratio results in the contrary characteristics

Power plant weight calculations indicate that for short endurance of about one hour a compression ratio of 2 1 and for longer endurance of about three hours a compression ratio of 4 1 are optimum values

In the pressure jet helicopter the design problems of the rotor with its ducted blades are so intimately related to the power plant that they are much more difficult than in all other configurations

A short introduction into design calculation is presented to show the influence of the numerous parameters

Starting from the assumption of a certain disc load and maximum tip speed, the necessary thrust horsepower is determined Then we fix the compression ratio of the compressor Assuming that the pressure would be maintained to the tip burners, the necessary jet thrust and air mass flow can be determined using a calculated or measured jet characteristic (Fig 11)

The actual pressure (P_{res}) in the combustion chamber inlet is composed in the following way

$$P_{res} = P_{compr} + \Delta P_{pump} - \Delta P_{loss} \qquad (14)$$

The pressure rise Δ Ppump is due to the pumping effect of the rotating blade It is roughly

$$\Delta P_{pump} \sim \frac{1}{2} \rho mean \times Vt \qquad (15)$$

Pmean = assumed mean air density in the duct
V_t = tip speed

The gain in rotor h p by this pressure rise is nearly the same as the horsepower necessary to produce this rise Actually it improves the burning efficiency and decreases, on the other hand, the propulsive efficiency due to the higher outlet velocity

The pressure drop due to the friction losses in the blades is a very critical parameter as it influences the aerodynamical and structural qualities of the blade

It is

$$\Delta P_{loss} = K \frac{\rho}{2} V_D^2 \frac{1}{D} L \qquad (16)$$

K = Constant depending from Reynold No in duct
ρ = Density in duct
D = Hydraulic radius of duct
L = Length of duct
V_D = Air velocity in duct

A limit for the amount of area within the blade contour that may be used as duct is the chordwise position of the centre of gravity, which for normal airfoils should be kept approximately at 25% Keeping the duct area in a constant ratio to the entire cross-sectional area, the pressure drop rises approximately inversely proportional with the fifth power of the blade chord (see Equation 16)

Assuming a rotor solidity and the approximate tip speed (Fig 5), the pressure drop has to be calculated

Together with ΔP_p (Equation 15) the resultant pressure is established (Equation 14) With the assumed mass flow the available jet horsepower is derived By repeating this procedure we obtain a typical design characteristic as given in Fig 12 It shows a definite optimum value for σ with the appropriate tip speed

With lower solidity the benefit of the tip speed is lost due to the inferior effect of the pressure drop

The low pressure plant with high air mass flow is much more sensitive to the pressure loss in the blades than the high pressure plant, and requires thicker and heavier blades

At high pressure ratios, we have to consider the effect of pressure and temperature in the hub and duct construction

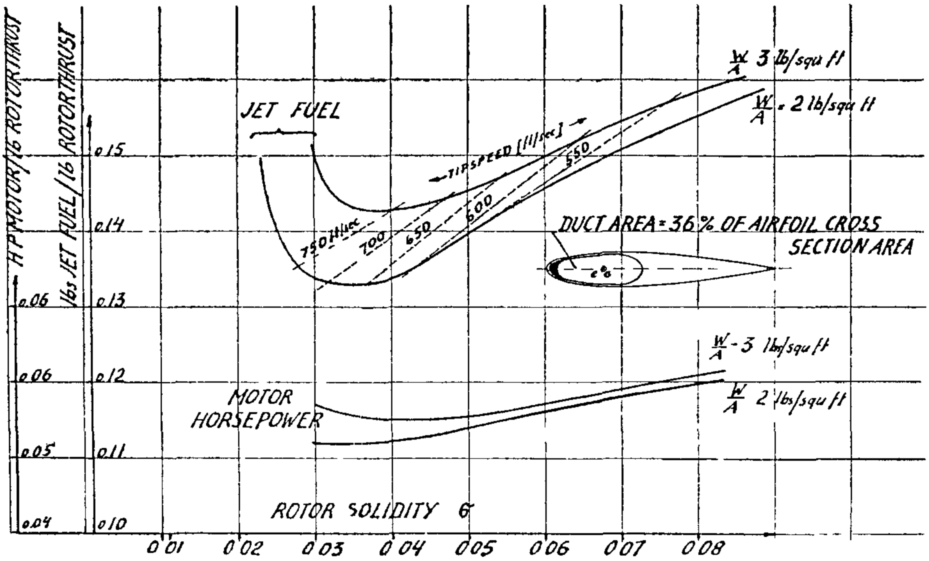


Fig 12 Design Chart of a Pressure Jet Rotor Compression ratio = 2 5 (Compressor)

The combustion chamber of the pressure jet system has two principal layouts In one case the burner is parallel to the blade and the high velocity exhaust is turned 90° There are inevitable friction losses in the bend In the other case the cold air is bent and the burner is located normal to the duct, and the main problem is to avoid excessive pressure drop across the burner

The fuel/air ratio is mostly very high and temperatures up to 1600°C may be obtained This high temperature, together with the necessity for keeping the drag of the burner as low as possible, is the reason that the combustion intensity $\frac{\text{C H U}}{\text{cb ft,} \times \text{atm} \times \text{hour}}$ is much higher than on turbojet combustion chambers Higher losses in the flame holders and higher friction losses are to be expected

In Fig 10 a typical characteristic is given with the following assumptions

Fuel/air ratio = 1 20

$\Delta\ P_{\text{baffles}} = 5 \times$ dynamic head at baffles cross-section

$$\text{Combustion intensity} = 5 \times 10^6 \ \frac{\text{C H U}}{\text{cb ft} \times \text{atm} \times \text{hour}}$$

η burning = 93% η expansion = 95% η compressor = 73%

For the hub design special attention has to be paid to the sealing problems

Two-bladed rotors present the easier solution from this point of view, and are better regarding the pressure drop in the duct

THE JET GYROPLANE

It is principally a gyroplane with an engine driving a propeller for forward flight when no power is transmitted to the rotor in autorotation

For starting and landing the propeller is declutched or put in zero pitch, and the power plant drives a compressor During this state of operation, the rotorcraft is a pressure jet helicopter with tip burners as described in the previous paragraph The principal idea of this combination, which was employed for the first time in the last two types of the Doblhoff machines, is the saving of fuel

Except for a few applications where the helicopter is expected to hover most of its flying time, it is still mainly a means of transport where forward flight will occupy 95% of its total life

In this flight condition, the gyroplane was a very pleasant aircraft While it could start and land on very restricted areas it just could not hover For this short but very important manoeuvre the pressure jet equipment enables it to behave like a helicopter, while in forward flight it regains all the advantages of the gyroplane, which are mainly much smoother operation at high forward speed It may be mentioned at this point that the chief problem of helicopter forward flight is vibration mainly created by the periodic blade tip stall

The blade tip stall of the autorotative rotor is relatively innocuous because it occurs on the inside part of the blade due to the adverse flow through the rotor disc

The general layout of a jet gyroplane is somewhat different from the pressure jet helicopter

The propeller-driving engine is chosen according to the power necessary for maximum forward speed

The available power for hovering flight is, therefore, high enough to allow some losses in the jet drive circle To maintain optimum aerodynamic quality of the rotor during its forward flight condition, higher duct and combustion chamber losses can be admitted, than would be advisable for a pure pressure jet helicopter The burners are of minimum size, being only visible as a small ejector orifice at the blade tips and working with the highest possible fuel/air ratios up to 1 15 and with very high combustion intensities Their overall thrust efficiency is of course much lower than for the pure pressure jet helicopter This may result in lower hover or vertical climb reserve as one could expect with optimum burners, but this loss is inevitable to keep the cold drag of the windmilling rotor tips as low as possible in the other 95% of the entire flying time

The principal characteristics of the jet gyroplane are

(1) Compared with the conventional helicopter there is elimination of the reduction gear, transmission, rotor clutch, free-wheel mechanism and torque reaction equipment, but on the other hand it requires a declutchable compressor, variable pitch propeller, ducted blades and tip burners On very small machines there is practically no saving in weight, but as the size increases say to 5,000 lbs and over, there is a considerable saving in weight and initial cost

(2) The fuel consumption is very low, increasing that of the conventional gyroplane only by the amount used for the burners during starting and landing

(3) It is free from vibration in forward flight

(4) No blade pitch reduction is necessary when power failure occurs in forward flight

Summary

After the detailed description of the various configurations, a summary of their principal advantages and disadvantages as well as their structural and economic aspects will now be based on a practical design study

A 5,000 lb helicopter is investigated with ram jet, pulse jet, pressure jet and conventional shaft-driven rotor (Fig 13)

It should be emphasized that the design parameters of this example represent a compromise in order to obtain not only optimum conditions for the jet drive, but to fulfil at the same time aerodynamical, structural and operational requirements

To reduce the number of variables, a constant disc load for all four configurations is assumed The principal advantages of the jet drive are as follows

(1) There is no reaction torque transmitted to the fuselage and no torque balancing equipment is necessary This advantage, which was the most attractive one in the early days, cannot be fully realized, as it has been found necessary to introduce some means to regain controllability about the yawing axis of the aircraft

It should be mentioned at this point that rudders or fins working in the slipstream under the rotor, mostly hinged about a horizontal or inclined axis, are unreliable while hovering near the ground, because of the turbulence of the ground cushion which prevents the development of a regular air flow A supplementary small tail-rotor driven by the main rotor is one of various solutions where precise controllability near the ground is required

(2) A further advantage is the elimination of the conventional gearbox, transmission shafts, rotor clutch and free-wheel mechanism This shows to advantage when we visualize very large helicopters with their very high torque loads or multiple rotor arrangements where these components present considerable design difficulties

(3) Much lower initial costs and higher useful loads for short periods of operation are, therefore, the most characteristic advantages of jet helicopters

From the design and structural point of view there is the following summary

The ram jet and pulse jet represent the simplest and lightest engines

In the case of the ram jet, lowest possible solidity and highest tip speed are required Both parameters are limited by forward speed considerations, structural requirements and by the necessity of reliable autorotation Fig 14 shows that the high ratio of ram jet drag to profile drag may endanger the autorotation in case of power failure Attention has to be paid to the high bending and centrifugal stresses of the rotor blades

	GROSS WEIGHT	WEIGHT / FUSELAGE	WEIGHT / MOTOR TRANSMISSION	EMPTY WEIGHT P O	DISPOSAL LOAD	ROTOR DIAMETER D	DISC LOAD $\frac{W}{A}$	TIP SPEED v_t	NUMBER / BLADES n_B	SOLIDITY σ	η_{tot}	$\frac{T_R}{T_{JET}}$	MAX CROSS SECTION JET	SPECIFIC FUEL CONSUMPTION
	lbs	lbs	lbs	lbs	lbs	ft	$\frac{lbs}{sq\ ft}$	ft/sec				$\frac{lbs}{lbs}$	squ in	lbs FUEL/HO / lb ROTORTHRUS
RAM JET R 50	5000	2050	110	2330	2670	50 5	2 5	650	3	0 045		16 2	190	0 615
PULSE JET	5000	2100	90	2360	2640	50 5	2 5	450	3	0 055		13 6	101	0 415
PRESSUREJET P/p 25 R 1 20	5000	2300	750	3220	1780	50 5	2 5	650	3	0 045		16 2	206	0 170 (JET MOTOR
SHAFTDRIVEN ROTOR	5000	2200	1350	3720	1280	50 5	2 5	620	3	0 038	0 61			0 035

Fig 13 Comparison of the Weights and Fuel Consumption of a 5,000 lb Helicopt with various Rotor Drives

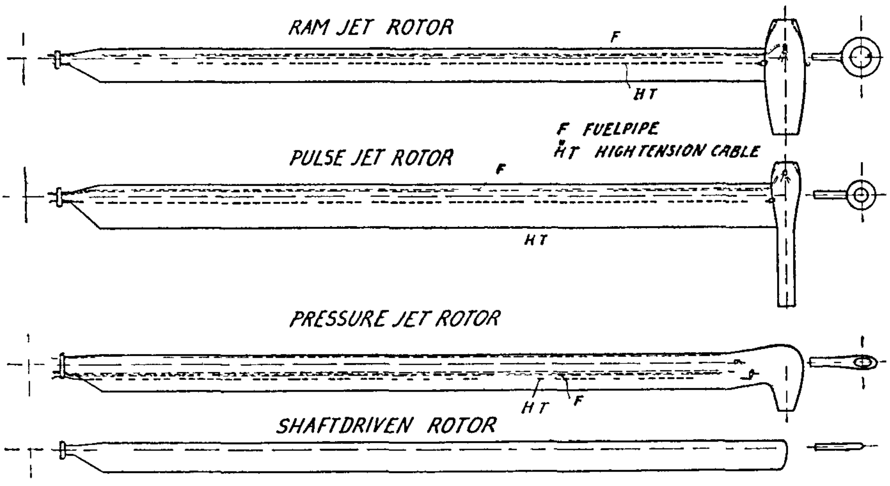


Fig 14 Rotor Blades of the 5,000 lb Helicopter drawn to scale

The most remarkable aspect of present pulse jets is their limited and comparatively low tip speed This results in high solidity and bad propulsion efficiency The endurance of present non-return valves is about one to two hours After this time they must be replaced Fig 14 shows that better autorotation characteristics than in the case of the ram jet are to be expected, though the cold drag per square inch frontal area of the unit is higher than that of the ram jet For this power plant a large field of development is still open Better valves, high working velocities and better specific size and fuel consumption, especially for small units, should be the aim of further improvement This makes the pulse jet and ducted pulse jet seem the most promising power plants for aircraft with low forward speed A drawback of the pure pulse jet is its high noise level

For starting, the ram jet needs initial spinning of the rotor , the pulse jet requires compressed air

The pressure jet requires very special attention to the construction of the ducted blades which must be a compromise between duct area, c g position and the stresses imposed by centrifugal loads Careful ducting of the rotor head for lowest possible pressure losses and good sealing of the compressed air on its way through the various hinges makes the rotor head more complicated than for conventional helicopters

Although the pressure jet system is more complicated than either the ram jet or the pulse jet, in cases where it is essential for the aircraft to operate in forward flight with the rotor in autorotation (jet gyroplane), it is the only system which enables us to produce blades to fulfil this condition

Re-ignition is reliable in all three configurations In all the three cases the fuel is usually supplied by a low pressure pump up to the hub from where the centrifugal force transmits it to the tip burners and provides at the same time the necessary pressure for injection

Through the lack of direct driving connections with the fuselage, jet rotors are expected to be very smooth and controllable

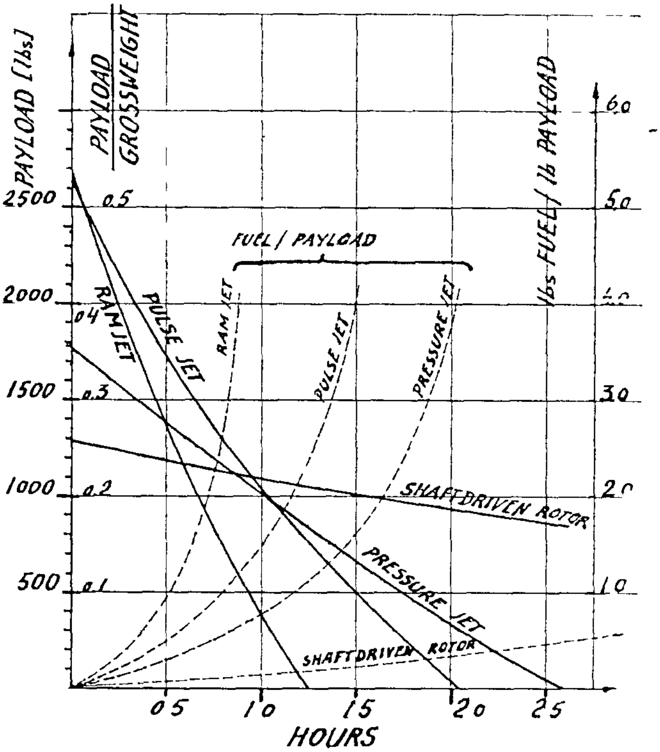


Fig 15
Maximum Endurance for the Example of a 5,000 lb Helicopter

Economic Aspects

All enthusiasm about an attractive and ingenious solution is wasted if it does not survive on the field of economic competition

Though it is outside the scope of this paper, a short consideration about initial costs, maintenance costs and operating costs will be given as follows

The low empty weight in the case of tip-located power plants indicates much lower initial costs (See Fig 13) The pressure jet system is competitive in respect of initial cost only for very large helicopters where the saving in transmission costs represents the decisive factor

The maintenance costs for the power plant are in the case of the ram jet practically nil For the pulse jet they are determined by the frequent changing of the inlet valve and occasional changing of the jet tail-pipe, both of which are comparatively cheap elements

Except for very large configurations, the maintenance costs of the pressure jet power plant are not much lower than those of the conventional one

To determine the operating costs it has to be admitted that the most definite drawback of the jet helicopter is its very high specific fuel consumption which cuts its endurance time or range to a fraction of that of the conventional helicopter This disadvantage in certain cases is outweighed by the low initial cost

Fig 15 shows the relation between endurance, payload and fuel consumption per lb payload, based on an all up weight of 5,000 lbs The specific fuel consumption figures are based on the characteristics given in previous paragraphs, and are not too optimistic , on the contrary, especially for the pulse jet, a much better fuel consumption and endurance is to be expected if the specific values of small units should be improved

It will be noted from this chart that the chief advantage of the jet helicopter is its ability to carry high payloads for short flying times

Conclusions

The most promising aspects for the further development of rotor jet drives are tip-located power plants The most attractive characteristics of the jet helicopter are its low initial costs and high payload to gross weight ratio for very short flying times It is, therefore, specially suitable for all applications where short endurance and high loads are required, as for instance in agriculture and observation, or as a flying crane for hauling supplies and material in restricted areas or mountains

In the case of very large helicopters the direct drive of the rotor eliminates the problems arising in the conventional machine due to torque and transmission difficulties Very large helicopters for short distances and comparatively low forward speed seem to be an especially promising field for jet application

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DISCUSSION

Group-Captain Liptrot introducing **Monsieur Paul Morain** said

I would now like to introduce a very old friend of mine, and a pioneer in jet propulsion, MONSIEUR PAUL MORAIN, who has come over specially from France to take part in our meeting and to join in our discussion, and to give us the benefit of his experience He worked on jet propulsion before the war, and since then has been steadily working on jet propulsion schemes He was the first man to produce a two-seater operational helicopter, jet-propelled

Monsieur Paul Morain replied I am very honoured by your reception, but my English is very bad, and I ask GROUP-CAPTAIN LIPTROT to read for me my remarks on MR STEPAN'S lecture

Monsieur Paul Morain's contribution to the Discussion was then read by GROUP-CAPTAIN LIPTROT as follows

First of all I should like to thank the Council of the Helicopter Association of Great Britain for having given me the great honour of inviting me, through my old and dear friend, Group-Captain Liptrot, to take part in this discussion

The ideas I am going to expose are based on the research and development work we have done at the SNCASO since 1945 with a small team working together very closely, and including Messrs Laville, Maillard, Laufer This work resulted in flying the various models of the SO 1100 Ariel during the years of 1947 to 1949 At present the SO 1110 Ariel Mark II, the result of our previous experience is ready for her maiden flight

Let me congratulate Mr Stepan on having given us such a precise idea of the various difficult problems in his very clear and condensed lecture, problems involved by the application of jet propulsion to the helicopter I agree fully with him on the general principles My remarks will mainly deal with some details and a different point of view has only been adopted where the basic data differs somewhat, and where our experience of our flying models interferes

In general Mr Stepan compared the different types of helicopters in hovering flight only Then no diagram or table takes account of the forward speed, tip speed ratio or the flying range The number of variables in the technical definition of a helicopter being considerable, the introduction of a new parameter would have considerably complicated the report Nevertheless we are told that the forward flight comprises 95 per cent of the flying time of a helicopter So it seems to me that the comparison should not deal exclusively with the hovering flight As we shall see later, the condition of forward flight will change somewhat the classification given by the lecturer

Furthermore, in order to facilitate the comparison between shaft and jet driven rotors, Mr Stepan has chosen for all of them the same airfoil, NACA 0012 This, though correct for ram-jet and pulse-jet rotors, will not be convenient for the pressure system, where the chosen airfoil will be too thin to get sufficient duct area into the blades As a matter of fact, we had to choose an airfoil of about 18 per cent thickness like the NACA 23018 Consequently the diagram of Fig 3 will look somewhat different and the maximum of σ = CT curves will be found at greater values of CT/σ specially for small values of σ Therefore, the curves $CT/\sigma = 0{,}11$ and $CT/\sigma = 0{,}2$ in Fig 5 are to be replaced by others, the maximum value of TR/T_j being nearer to $CT/\sigma = 1{,}2$ than to $CT/\sigma = 0{,}11$ Besides that, to avoid stalling in forward flight, we take care to choose a smaller value of CT/σ than that corresponding to the maximum TR/T_j

I have no comment to make about pulse-jets, of which we have no experience yet

As for ram-jets, for which we have undertaken serious research work and for which we hope to have soon a flying machine, I think that the lecturer under estimated considerably the pressure losses in the baffles Practically we never obtained a loss smaller than twice that given by Mr Stepan, which means four times the dynamic pressure in the maximum section Constructively, let me indicate the difficulties to overcome the centrifugal forces, acting on the ram jet itself, which works at high temperatures, and to build a reliable fastening of the jet to the blade, without excessive weight, size and cost On the contrary, the power control does not seem difficult, if the quantity of fuel is controlled, and not the fuel/air ratio only In this case, if the rotor speed increases, the fuel/air ratio decreases automatically, and the power output will equally decrease, or in the utmost, will increase less than the drag The latter influence will be specially remarkable at high Mach numbers, where the compressibility effects must be taken into account

Coming back to the pressure jet helicopter, the given pressure ratios, of 2/1 for one hour endurance, and of 4/1 for three hours endurance, are indeed optima for stationary flight and stochiometric mixtures Nevertheless, these values will be used at the moment of maximum power output only and not for any practical flight of endurance In this case it is better to use a leaner mixture, which makes preferable the use of a lower pressure ratio Thus it is possible to get an appreciable saving in the total weight of the power plant and fuel and supplementary power becomes available for special cases of emergency, vertical climb, and so on

Regarding the forward flight for a given range, we obtain small fuel/air ratios and greater power plants for long range missions and *vice-versa* The optimum pressure ratio will then be between 2/1 and 3/1, varying little On the other hand, the increased power output is only acceptable, if we have light engines having small fuel consumption For big machines, the gas turbines seem to be an interesting solution

Speaking of the jets, we used in the beginning radial combustion chambers, but we have now definitely adopted the tangential solution Let me mention the principal advantages The pressure losses in the 90° become smaller, the gas being still cold and the velocity being smaller for the same duct area , the cross section in the jet may be greater, the gas speed will be lower, which allows to fix the flame front with a smaller pressure drop , finally the external drag of the tangential chamber is smaller, its interaction with the blade is not appreciable, and the autorotation qualities of the rotor are practically unaltered

As for the jet propelled gyroplanes, we started with this type of machine at the SNCASO, which we had patented in France during the war while DOBLHOFF was developing it in Austria We have abandoned this solution which leads to an excessive empty weight, and to a more complicated mechanical construction than the pure pressure jet system For medium and long range missions, and for a weight of about 4 to 5,000 lbs , this type is handicapped by the fact that in Autogiro flight, the global efficiency of an autorotative rotor, plus a propulsive airscrew, will always be lower than that of a pure helicopter

Considering now the final comparison of the different jet propelled helicopters, resumed in Fig 13 and diagram 15, we are led to the following remarks

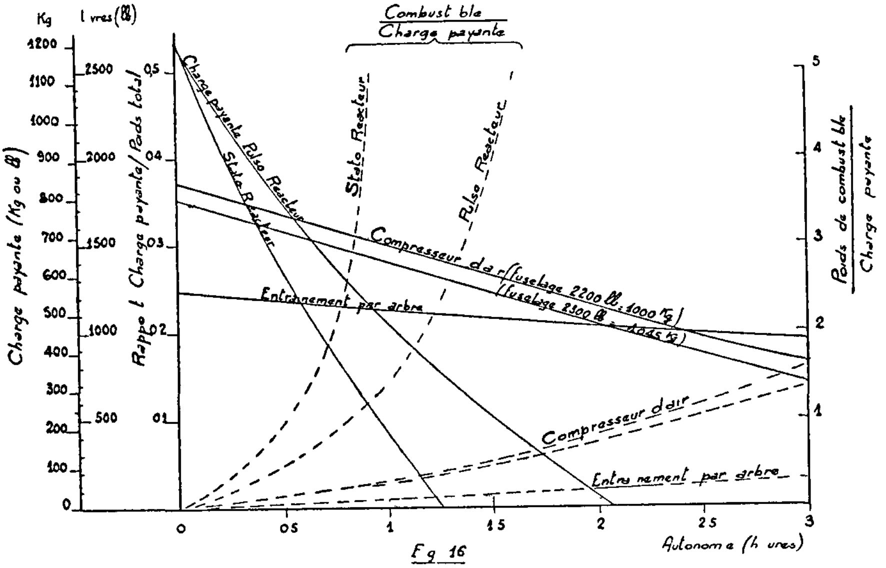

Fig 16

Autonomie maximum pour L'helicoptere—Type de 5000 Livres (2270 Kg) en vol en avant

This comparison is based exclusively on the stationary flight As I said above it would be more logical to base it on the forward flight and cruising speed Starting nevertheless from the data of MR STEPAN we have drawn a new diagram given by Fig 16 As we know the consumption of the ram jet and of the pulse jet will decrease very little in forward flight, the cyclically varying relative tip speed influencing in a bad manner the efficiency of these jets, if not confugated with cyclic variation of the fuel flow as I have shown in a patent On the contrary, the consumption of the shaft driven helicopter may be decreased by about 40 per cent in forward flight at cruising speed

But the consumption of the pressure jet system may be reduced even more Indeed a decrease of 40 per cent of the jet impulse may be got by reducing the temperature of the burning gas of the jet and by keeping the power input of the compressor at an H P only slightly decreased Thus it is possible to have the reduced jet impulse with gas temperature of say, 900° C instead of say, 1,800° C which may be obtained with a jet consumption of about 40% and a motor consumption of 80% On the whole the consumption is reduced to about 50 per cent Therefore, as you see from Fig 16 the pressure jet system gives the biggest payload at cruising speed, for time ranges from 40 minutes to 2 hours, which cover most of the helicopter uses This scope is, of course, still increased, if a fuselage weight of 2,200 lbs is taken, as for the mechanical solution, instead of the 2,300 lb indicated by the lecturer As a matter of fact I think that the fuselage will be even lighter than that of a shaft driven one

As for the yawing control of jet propelled helicopters, of small and medium weight, I think, having in view our Ariel, that rudders inclined to 45° placed in the vertical airflow of the rotor, give a sufficient control even in hovering in the ground cushion

For bigger machines, having a greater momentum of inertia, the question has to be examined very carefully For my part, I believe that for very large helicopters, at least two rotors will be necessary, which will give a solution as well of the control as of the trimming problems It will be necessary to conjugate them mechanically, but this transmission will have to take care only of the differences of the couples introduced by the manoeuvres, and will be essentially smaller and lighter than if it had to transmit the whole driving couple to the rotors

Finally, I should like to emphasize that we found the stability of jet propelled helicopters considerably superior to that of a shaft driven one We attribute it to the increased moment of inertia due to the weight of the jets This latter particularity makes easier the transition from helicopter state to Autogiro state and gives the possibility of landing in Autogiro flight, almost vertically using the kinetic energy of the blades

W Stewart (*Member*) In his " Jet Propulsion of Rotor Blades " Mr Stepan has presented the first lecture before the Helicopter Association and, I think, the first in this country, on the application of jet propulsion to the helicopter It is therefore quite natural that the lecturer should devote a large part of his paper to a description of the various systems in detail and in this respect the lecture forms an excellent survey Unfortunately this has resulted in a severe condensation of the work involved in estimating the performance of the various engines, together with the appropriate optimum rotor parameters, and it is this problem which is the most controversial In view of the lack of detail given, I propose to reserve comment on the methods used and pass on to the final results evolved

Some time ago I made similar calculations and took as a basis for the estimates helicopters of 2,500 lb and 10,000 lb all up weight Interpolating to the 5,000 lb helicopter considered by Mr Stepan, we may compare the results with those obtained in the present paper (given in graph) The general agreement of the results for the various helicopter configurations is good The discrepancies can be summed up briefly in that Mr Stepan's results show more optimistic results in basic percentage payload available together with a higher fuel consumption

One of the great disadvantages of considering the application to only one size of helicopter is that it eliminates the important influence of this parameter As size increases, so also do the percentage payload (to a small extent) and the duration of flight (considerably) Thus, the time of flight during which the jet-driven helicopter can carry a greater load than the conventional helicopter increases with size As most of the uses envisaged for the helicopter do not consist of flights of long duration, the gain in payload due to the use of tip-jets increases considerably with size for large helicopters

A vital problem, which the lecturer does not mention and on which I would like to hear his views, is the type of rotor to which he would apply the jet power at the blade tips The use of articulated rotors controlled by cyclic pitch becomes extremely difficult due to the magnitude of the inertia forces Possible differences in the thrust of the tip units can lead to considerable trouble with the in-plane motion of blades There would seem to be very good reason to introduce the rigid rotor simultaneously with the application of jet propulsion This would also allow us to reach the higher forward speeds we are looking for, if the blade stressing cases can be met without too great a weight penalty

Finally, there are two problems which may in themselves debar the use of ram jet or pulse jet units and I put these as direct questions

(1) How is autorotation to be achieved, without resorting to an absurdly low disc loading? The C_D of 0 11 mentioned is only applicable to the jet working case, in autorotation the value would be of the order of 0 4

(2) What are the possibilities of reducing the noise level from its present unacceptably high intensity?

THE AUTHOR'S REPLIES TO THE DISCUSSION

In reply to Monsieur Morain

I would like first of all to express my thanks to M MORAIN for visiting this country to open the discussion, for his interesting comments on the subject, and for his introduction of the forward speed case into the discussion

I agree with M MORAIN that the consideration of the forward flight conditions is very important but, as he pointed out, this was left out of my paper in order to avoid further complication I agree that in forward flight the consumption of the pressure jet is reduced compared with the consumption in hovering flight I would suggest, however, that a saving of 40% of the hovering horsepower can only be achieved at comparatively very low forward speed Fig 16 shows that with this optimum forward speed, a considerable endurance is possible by working the jets with very low fuel/air ratios This saving of fuel is only possible if we are satisfied with a low forward speed

Regarding the combustion chamber, I agree that the tangential type has many advantages compared with the radial one, especially in the case of pure pressure jet helicopters with continuously working jets, but I would like to mention that results of a large number of tests which I made with both types of combustion chambers indicate that, especially in small units with very high combustion intensities, the turbulence and friction of the burning jet in the 90° bend improves the burning to such an extent that the flame holders and mixing devices could be kept even smaller than in the straightforward combustion chamber with the same velocity in the baffle cross section

I agree that the jet gyroplane is more complicated and heavier than the pure pressure jet helicopter, especially for small machines, but I still believe that for high forward speed where the previously mentioned fuel saving on the jet side could never be achieved, the jet gyroplane will have the lowest fuel consumption in this field

Regarding the pressure loss in the baffles of the ram jet, I agree that the assumption of 2 × the dynamic head seems to be low, but on the other hand it depends very much on the speed of the slowed down air in this section, which is on our example only 130 ft /sec Furthermore, I mentioned in connection with the chosen assumptions that they are somewhat optimistic compared with measured values on the static test stand, but that performance data of spinning tests with ram jets show better results than one would expect from the static tests because of aerodynamical gains

In reply to Mr Stewart

I agree entirely with MR STEWART that for estimating the optimum rotor parameters for a jet-propelled rotor, a large field of combinations presents the most controversial problems The size of the helicopter, constructional and control considerations are intimately linked with these problems and could not possibly be dealt with in the limited scope of an introduction lecture Though the inertia forces of tip-located power plants in the case of ram jet, pulse jet and ducted pulse jet are considerable, a relief of the cyclic pitch forces is obtained by the centrifugal pitching moment This problem can be eliminated by using rigid rotors, rotors with aileron-controlled blades, or by rotor blade arrangements where the tip-located power plant is connected separately to the root and remains, therefore, in the tip path plane, while the blades are cyclic pitch controlled

Regarding the question about autorotation, it is to be admitted that the application of tip-located power plants necessitates a very careful investigation of the autorotational aspects of the rotor While the pressure jet burner interferes only very little, the ram jet, pulse jet and ducted pulse jet deteriorate the autorotation to a very high extent To my knowledge, no autorotational tests in free flight with cold ram or pulse jet units have so far been carried out

The application of the ram jet in the range of efficient tip speeds calls for very small solidities and in this case the autorotation is critical, if not impossible

The pulse jet presents much better aspects from this point of view, as its smaller frontal area with the much lower design tip speed and therefore higher solidity are in favour of the autorotational qualities

For the ram and pulse jets a considerable cut of their cold drag could be achieved by blocking the internal flow in case of autorotation, as this internal flow increases the drag of the cold unit to a very high extent

While in the case of the present ram jets the autorotation calculation shows very pessimistic results, the pulse jet rotor should enable us to perform safe autorotational landings with moderate rates of descent

The second question about the noise level is also a very critical one, and is the drawback of every jet drive Still, my experience with pressure jets indicates that the noise level, especially when the jets are rotating, is not alarming and is lower than the noise of the engine and compressor

The same applies to the ram jet, the noise of which, as recorded from tests with the " Little Henry " machine in America, is very low The high noise level of the pulse jet can only be reduced by applying the pulse jet in form of the ducted pulse jet as described in the paper

Mr Stewart's (Final Remarks)

Mr Stewart in his final remarks said First of all, I should like to thank Mr Stepan for his very interesting lecture There does not seem to be very much of a discussion, however—this is either a case of the lecturer having completely over-awed the audience, or that there are too many questions I myself could have gone on asking questions for another hour

In today's lecture, and also in the contribution which we have had from France, we have had a very excellent introduction to the application of jet propulsion to rotors We have seen some of the problems involved, and undoubtedly there are many others, some of which the lecturer knows but has not had time to put forward, and others which will only come to light as we get there things into operation Undoubtedly when we start operating we will find many problems which we did not anticipate, which will also have to be solved I think the general interest and adaptability of ram jets and other types to the helicopter shows great promise, particularly in the large machines, and there seems to be very little doubt that the work that is going on in this country, in France and America, and in other countries, is of great interest in helicopter operation We shall see very large advances in this particular respect within the next year or two

Group-Captain Liptrot (Closing Remarks)

I promised you an interesting afternoon, and I am sure you have had it Mr Stepan has presented a remarkably concise comparative statement of the various jet propulsion devices He has indicated how they reacted on the design of the helicopter, and I am sure everyone is going away with a lot of food for thought It just remains for me now to pass a hearty vote of thanks to Mr Stepan for his excellent lecture