AVRO AIRCRAFT LIMITED

MALTON • ONTARIO

TECHNICAL DEPARTMENT (Aircraft)

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REPORT NO: 72/Systems 22/137

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TITLE:

PROPOSED MASS FLOW CONTROLLER

PREPARED BY J. Dubbury JD DATE March 26/58

CHECKED BY G Shaw DATE Mar 26/58

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AVRO AIRCRAFT LIMITED
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TECHNICAL DEPARTMENT

REPORT No. 72/System 22/137
SHEET No. 1

AIRCRAFT:

PREPARED BY	DATE
J. Dubbury	March 26/58
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INTRODUCTION

For many pruposes it is necessary to know or control the mass flow of fluid (liquid or gas) down a duct.

The cooling capacity of air in aircraft air conditioning systems depends on the mass flow and it is therefore necessary to control this quantity.

In connection with the development of the CF 105 air conditioning it has been found that no known purveyor of air conditioning equipment has a satisfactory mass flow controller available.

All available systems have fundamental errors which (over the relatively large range of pressures required) cause unacceptable tolerances.

The present proposal is for a simple robust mass flow controller which should provide more than adequate accuracy for the 105 application beside possessing possibilities of development for many other applications.

FORM 1319A

Principle

Consider a rotor consisting of blades having their zero lift chord lines parallel to the direction of ~~undistributed~~ undisturbed flow.

Then the torque exerted by a blade element is given by (See Figure 1)

$$\delta Q = C_N \frac{\rho}{2}\left(V^2 + \omega^2 r^2\right) c r \, \delta r \qquad \text{--------(1)}$$

Where C_N is the blade normal force coefficient

ρ is the air density

V is the axial velocity of flow

ω is the angular velocity of the rotor

r is the radius of the element

c is the chord of the element

Now if $\omega r \ll V$ then $\omega^2 r^2 \ll V^2$

therefore equation (1) becomes

$$\delta Q = C_N \frac{\rho}{2} V^2 c r \, \delta r \qquad \text{-----------(2)}$$

Now the incidence of the blade is given by,

$$\alpha = \tan^{-1}\frac{\omega r}{V} \doteqdot \frac{\omega r}{V} \quad \text{if} \quad \omega r \ll V$$

Assuming that $C_N = a_1 \alpha = a_1 \frac{\omega r}{V}$ then (2) becomes,

$$\delta Q = a_1 \frac{\rho}{2} V \omega r^2 c \, \delta r \qquad \text{---------(3)}$$

Now the mass flow down the duct is given by

$$m = \rho V A$$

Where A is the annules (annulus) in which the rotor acts.

Thus $\rho V = m/A$ which substituted in (3) gives,

$$\delta Q = \frac{a_1 m}{2A} \omega r^2 c \, \delta r \qquad \text{--------(4)}$$

Integrating (4) gives,

$$Q = \frac{N a_1 m \omega c}{2A} \int_{r_1}^{r_2} r^2 dr \quad \text{(for a constant chord blade)}$$

$$= \frac{N a_1 m \omega c}{6A} \left(r_2^3 - r_1^3\right) \qquad \text{--------(5)}$$

Where N is the number of blades on the rotor

In (5) $\frac{N a_1 c}{6A}\left(r_2^3 - r_1^3\right)$ is a constant for any given rotor equals K say.

Thus (5) becomes

$$Q = K m \omega$$

$$\text{or } m = Q/K\omega \qquad \text{-------(6)}$$

Then if the angular velocity is kept constant, the mass flow is directly proportional to the torque (Q) applied to the rotor.

It should be noted that the above analysis neglects the effect of ~~rational~~ rotational inflow. This has been included in more detailed analyses and does not affect in any way the linear relationship between m and Q above, though it does effect the value of the constant K.

Sources of error

The torque will be proportional to mass flow if the following conditions are satisfied.

(1) The motor speed is constant. This can easily be achieved with a sychronous hysteresis motor where a constant frequency supply is available (as on the 105)

(2) The rotor blades must always be operating within the range for which $dC_N/d\alpha$ is constant.

This implies small incidence and thus low rotational speed. Since blade drag coefficient is of little, significance it may well be that the use of blunt trailing edge aerofoil sections will be beneficial. However, there must always be some volume flow below which the linearity between torque and mass flow fails.

(3) Since the blade incidences are very small under some circumstances (i.e. high flow at low pressure and high temperature) the flow ahead of the rotor must be very free of swirl

This is easily and conveniently accomplished by the insertion of a short length of honey comb a short ~~distrubance~~ distance upstream of the rotor.

(4) The rotor blades must be set with their zero lift chord lines exactly parallel to the undisturbed flow direction.

This could in all probability be most conveniently achieved in practice by mounting the rotor in the duct so that it is free to turn and if necessary adjusting the blades until no rotation occurs. Making diametrically apposed pairs of blades of the solid piece of material should help since a small positive error on one side automatically becomes a small negative error on the other and thus largely cancels out.

(5) The Mach number of the blades must be sufficiently low for $dC_N/d\alpha$ to be unaffected by compressibility.

(6) The torque required by the motor must be within the capacity of the motor to maintain synchronous speed.

Numerial investigations carried out to date suggest that this is easily arranged for motors available "off the shelf".

Fundamental advantages

Within the limitations mentioned above, the torque is dependent only on the mass flow - it being independent of pressure, temperature and chemical composition. (i.e. independent of density).

This characteristic is not (to the authors knowledge and belief) ~~extributed~~ exhibihited by any commercially available flow meter or controller.

The torque available to operate a control or indicating system can be increased to any valve required by reducing the stiffness of ~~the~~ restraining spring and increasing the reduction gearing between motor case rotation and output (See Figure 2). Thus no delicate signal amplification is necessary.

The flow to which the device controls can easily be changed by increasing or decreasing the spring torque. Since the torque is a linear function of mass flow changing the flow setting would not effect the sensitivity (This is not so on venturis for example) The sensitivity can be changed to any required degree by varying the spring stiffness. The device can be made robust so that the passage of small foreign bodies through it (e.g. ice) would not cause damage. In this respect steel rotor blades would seem desirable.

Typical applications

It is designed to control the flow in a duct to 27.5 lb/min. The total pressure at the controller varies between 6 and 16 psia at a total temperature of 520°R.

The above conditions corresponds to the 105 cockpit inlet conditions. Note that the density at the controller is varying by 2.67:1.

Assume a rotor having two blades and of 1" chord.

The root and tip radii are 1" and 1.75" respectively

The rotor is driven at 600 RPM

The blade elements were assumed to have a lift curve slope of 2π/radian up to an incidence of 4°. This is probably a somewhat pessemistic assumption.

The torque or mass flow characteristics are shown in Figure 3.

These calculations included the effect of rotational inflow.

The effect of varying the number and chord of rotor blades at the design point was next investigated, the results being shown in Figure 4.

It was assumed that 27.5 lb/min was passing through the rotor at a total pressure of 16 psia and a total temperature of 520°R. The rotor root and tip radii were 1 inch and 1.75 inches respectively.

The blade incidence of the tip (where it is a maximum) was assumed to be 3.5°.

The effects of rotational inflow are shown by the increasing RPM with solidity to maintain constant tip incidence.

Both the above sets of calculations make no allowance for tip losses so that the torque actually achieved is likely to be somewhat less than calculated.

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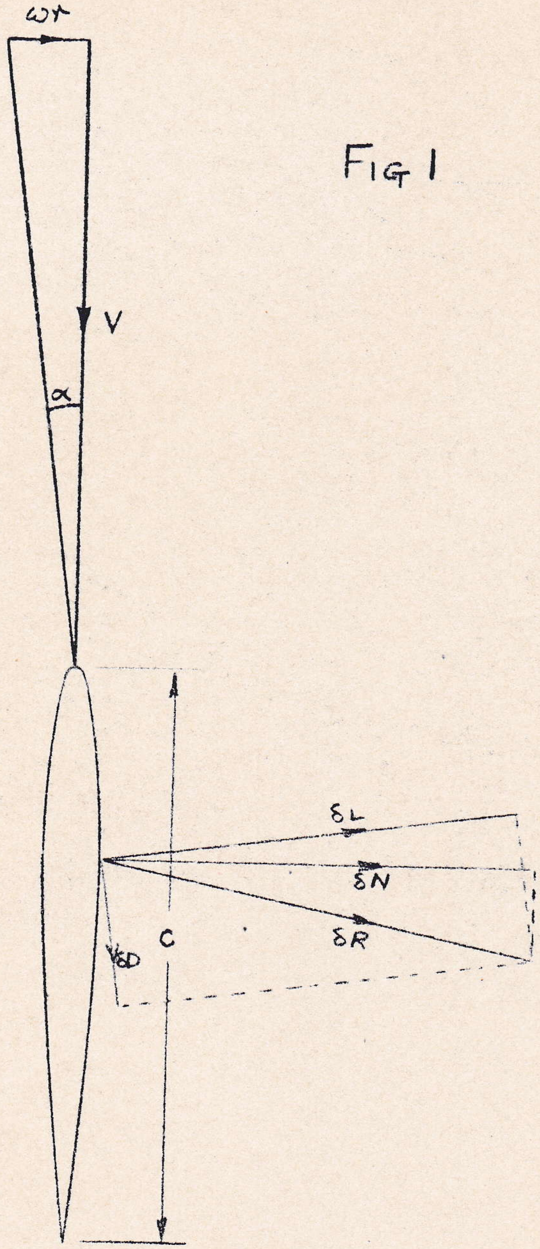

Fig 1

Conditions at a rotor blade element

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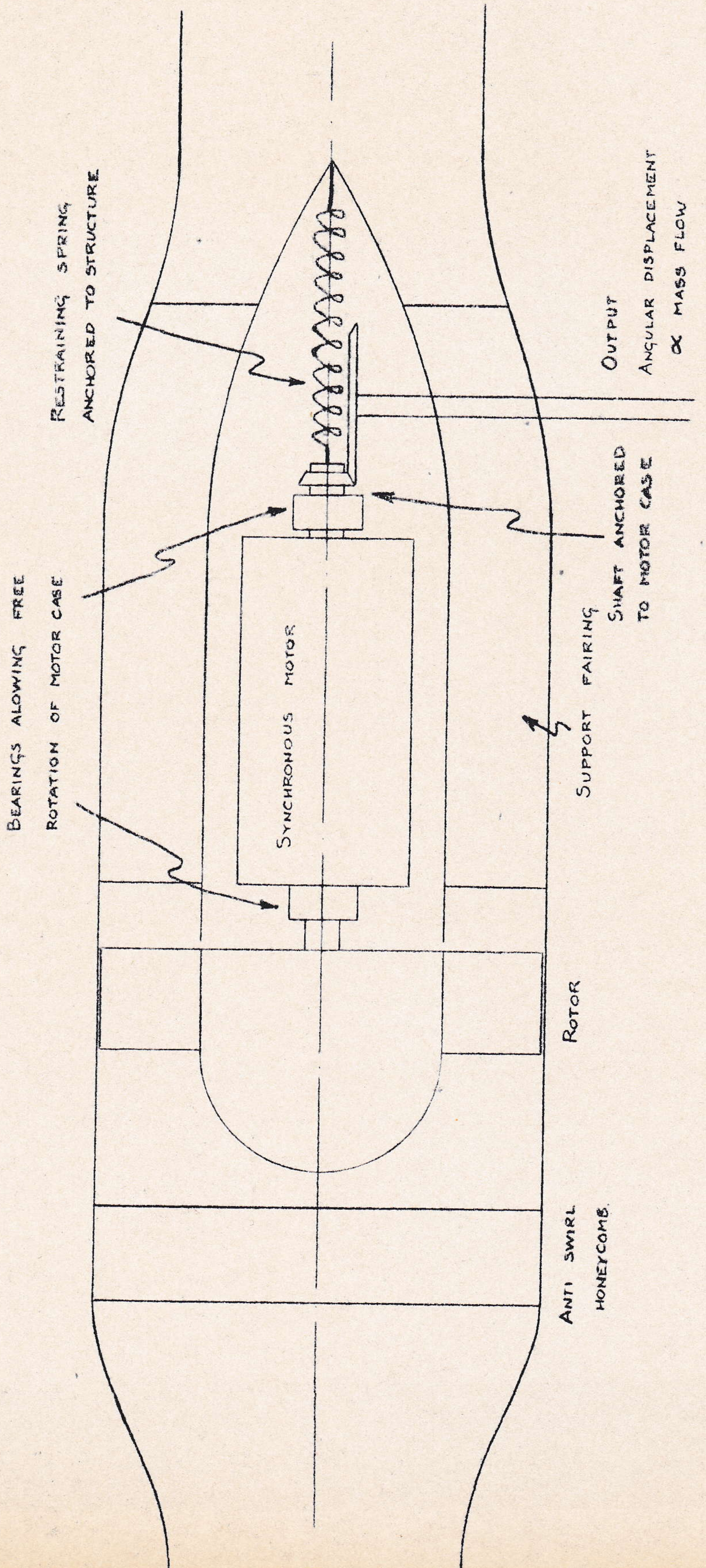
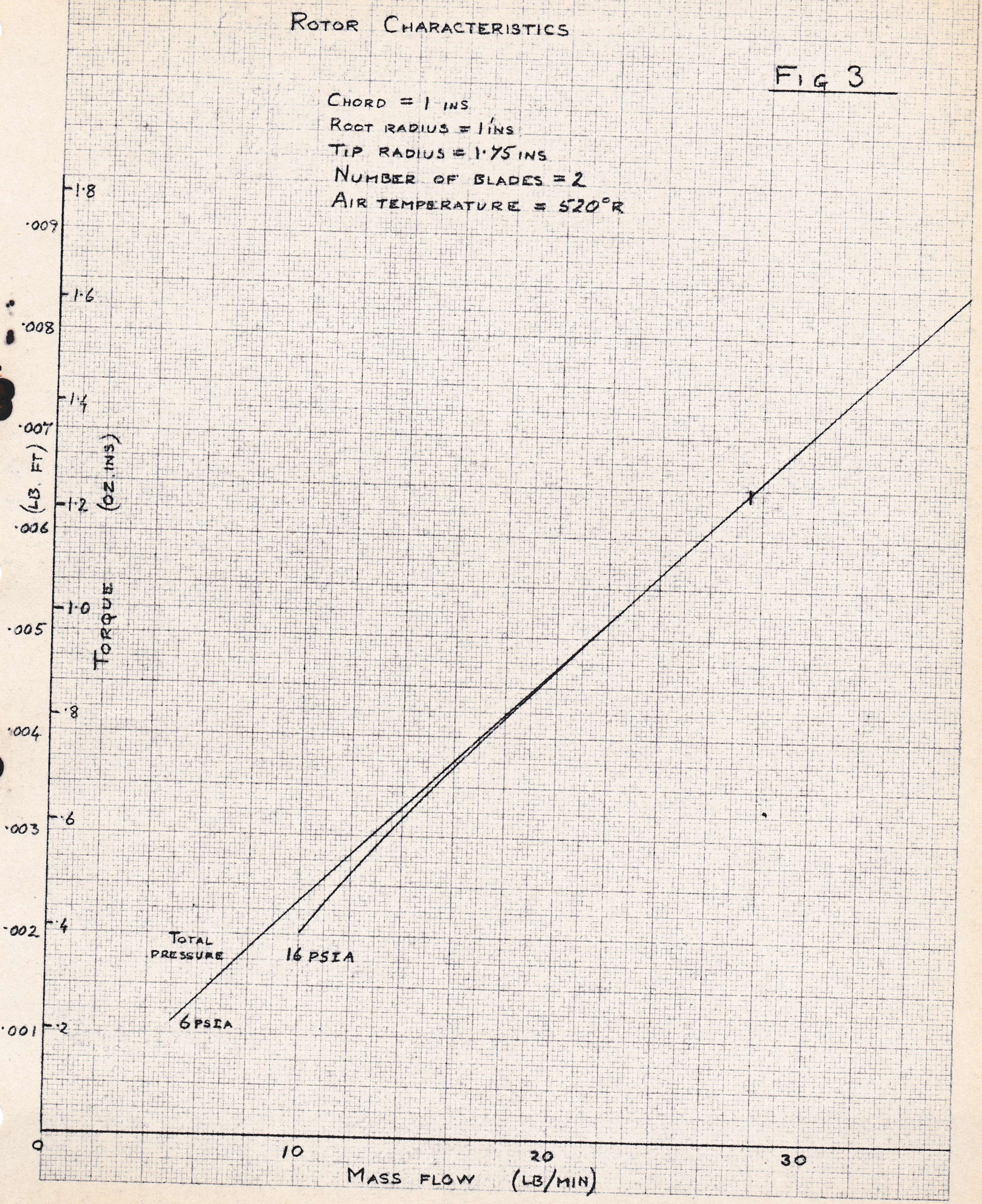
SCHEMATIC OF MASS FLOW CONTROLER

FIG 2





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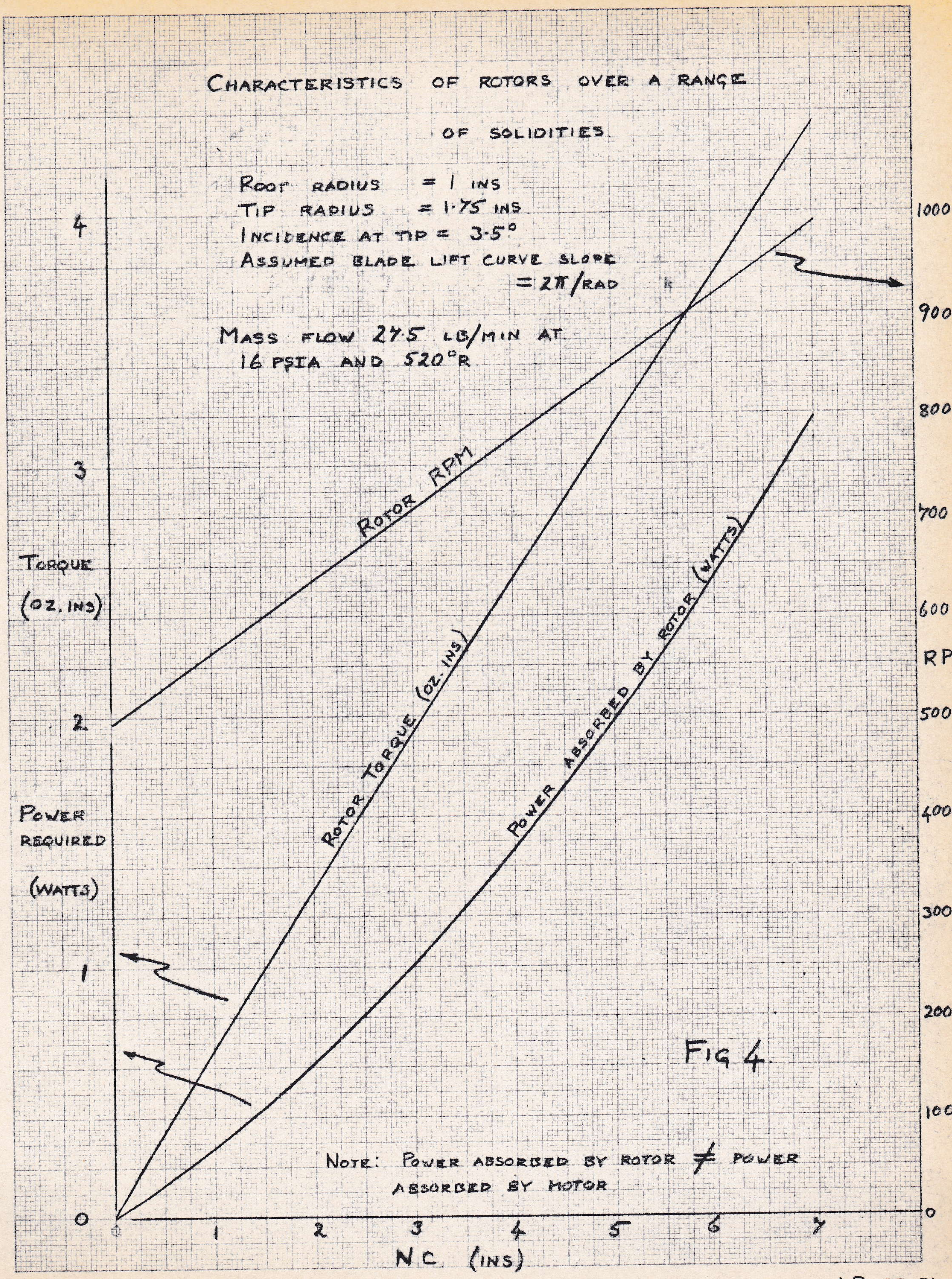

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