NRC Publications Archive
Archives des publications du CNRC

Folding trailable rotors for lifting VTOL aircraft

Galitzine, N.

For the publisher’s version, please access the DOI link below./ Pour consulter la version de l’éditeur, utilisez le lien DOI ci-dessous.

Publisher’s version / Version de l'éditeur:
https://doi.org/10.4224/40003969
Laboratory Memorandum (National Research Council Canada. Division of Mechanical Engineering. Engine Laboratory); no. NRC-ENG-19, 1960-05-12

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=2a33bbf8-3336-4823-a175-f19c62d2df9b
https://publications-cnrc.canada.ca/fra/voir/objet/?id=2a33bbf8-3336-4823-a175-f19c62d2df9b

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L’accès à ce site Web et l’utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D’UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n’arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

L.O. -	NATIONAL RESEARCH COUNCIL DIVISION OF MECHANICAL ENGINEERING OTTAWA, CANADA	NO. NRC-ENG-19
FILE -		PAGE 1 OF 19
PREPARED BY N. Galitzine	LABORATORY MEMORANDUM	COPY NO. 28
CHECKED BY -	SECTION Engine Laboratory	DATE 12 May, 1960

SECURITY CLASSIFICATION OPEN

SUBJECT FOLDING TRAILABLE ROTORS FOR LIFTING VTOL AIRCRAFT

PREPARED BY N. Galitzine

ISSUED TO

TABLE OF CONTENTS

FOLDING TRAILABLE ROTORS FOR LIFTING VTOL AIRCRAFT

1. INTRODUCTION

In Reference 1, a powerplant system for VTOL aircraft was proposed in which a number of dual-purpose turbo gas generators were used either to drive ducted wing-immersed fans for vertical thrust, or to supply gas for jet propulsion in horizontal flight.

The wing immersion of the lifting fans provided an elegant configuration, with minimum drag, for horizontal flight, but necessitated a high fan disc loading to match the small wing area, which was of course divorced from take-off requirements.

500 lb/ft^2 was the order of loading considered suitable for the small fans of such an aircraft. With a corresponding thrust to h.p. ratio of less than 2 (see Figure 1) there was required a large amount of installed power for take-off and hovering, resulting in an excess of power for horizontal flight.

This superabundance of power was an embarrassment rather than a benefit, because either some of the gas generators had to be shut down, or all of them run at what could be an inefficient loading, for moderate aircraft speeds in horizontal flight.

Jet propulsion also required flying fast and therefore high for efficiency, so that the proposed wing-immersed system seemed more suitable for medium to long range transports, at high subsonic or even supersonic speed, than for smaller aircraft required to fly at low or moderate speeds, on shorter range missions, near sea level.

This memorandum has been composed with the latter type of aircraft in mind, and as a contrast to the wing-immersed fan scheme.

The proposal put forward is hardly revolutionary, but a number of what might be new devices, together with a fresh statement of theory, are combined towards a possibly practical solution of an old problem.

That problem is how to minimize in horizontal flight the drag of large unducted rotors or propellers (outside the wings) whose sole purpose, like that of the wing-immersed fans, is to lift and hover the VTOL aircraft.

The disc loading considered for such rotors, of the order of about 2.5 lb/ft^2, is the same as in many helicopters, or 200 times less than in the wing-immersed fan scheme.

Such a loading gives a greatly improved thrust to h.p. ratio, about 16 to 20 or so, depending upon efficiency (see Figure 1), thus greatly reducing the power and weight of the gas generators. However, the difficulty then becomes the size of the lifting rotors, whose diameter may be from about 20 to 100 feet, depending upon their number and the size of the aircraft.

Many solutions to the problem of dealing with the large rotors in horizontal flight have been proposed and classified (Reference 2, etc.). The most recent proposal for a VTOL aircraft, advanced by one of the foremost helicopter manufacturers, had a one-bladed, counter-weighted lifting rotor, which was retractable into the fuselage (Reference 3).

The scheme examined in the present memorandum consists of tipjet-driven lifting rotors, with two or more blades, which fold like jack knives on the axis of rotation, and trail naturally downwind for minimum drag in horizontal flight (see Figures 2, 5, 6). Counter-balancing weights are not necessary because, by an automatic locking device, the blades are forced to rotate opposite each other when loaded.

Tipjet drives were considered for the immersed fan scheme, but found unsuitable, because their basic inefficiency, combined with the low thrust to h.p. ratio of the fans, required a large amount of compressed air or gas, which could not be passed through the small fan blades. The drive inefficiency moreover meant a further increase in the already basically large power and weight of the gas generators (Reference 4).

Very much less concern in this connection need exist in the case of the tipjet drives for lightly loaded rotors and tipjets are in fact used on several helicopters. The relative inefficiency is still present, because it depends on more or less the same limiting tip speed, whether of rotor, propeller, or fan, but that inefficiency influences only the small power and weight of the gas or air generators. Also, the problem of forcing the working fluid through the hollow blades is not at all severe, in contrast to the wing-immersed fan scheme.

The fresh aerodynamic statement of lifting rotor theory, particularly as regards efficiency, is presented first in this memorandum. This is combined with existing theory on tipjets to give an overall background for tipjet-driven lifting rotors.

The combined theory is then applied to an example aircraft, giving sizes, powers, and weights, for what may be considered a feasible experimental configuration.

Finally some devices for making folding trailable rotors a practical proposition are described, the testing of a model rotor is mentioned, and suggestions are made regarding full-scale proving of large rotors.

2. THEORY

Rotor Momentum Theory

Referring to Figure 2, and following the usual momentum theory of propeller performance, the lifting thrust X of the rotor = change of momentum in unit time, or

$$X = \rho A v \times \frac{\bar{v}}{g}$$

where

$\rho A v$ = mass flow through the rotor
ρ = air density
A = disc area
v = velocity through the disc
$\bar{v}$ = final velocity at some distance from the disc

The final kinetic energy generated is equal to the work done at the rotor, or

$$\rho A v \times \frac{\bar{v}^2}{2g} = X v = \rho A v \times \frac{v \bar{v}}{g}$$

from which is derived the well-known result that

$$\bar{v} = 2v$$

Substituting for $\bar{v}$ in the expression for X

$$X = \rho A v \times \frac{2v}{g} = \frac{2\rho A v^2}{g} \text{ or } v = \sqrt{\frac{gX}{2\rho A}}$$

Now if Y = power supplied to the rotor and η = rotor efficiency, then ηY = final kinetic energy (or work done at the rotor), or

$$\eta Y = X v = X\sqrt{\frac{gX}{2\rho A}}$$

from which

$$\eta^2 Y^2 = X^2 \cdot \frac{gX}{2\rho A} \quad \text{or} \quad \frac{X}{A} = \frac{2\rho\eta^2}{g(X/Y)^2}$$

This is the basic expression for unducted propellers or rotors, as used in Figure 1, and compares with the other expression also used in that figure,

$$\frac{X}{A} = \frac{4\rho\eta^2}{g(X/Y)^2} \quad \text{for ducted propellers and fans.}$$

The expressions are different because in the latter case the duct bellmouth provides additional thrust for the same power (Reference 1).

Large rotors therefore suffer from the loss of ducting, but more than make up by the improved thrust/h.p. ratio resulting from their lower disc loading.

Rotor Aerofoil Theory

Figure 3 shows the triangles of velocity and force for an element of rotor blade dr on radius r (see also Figure 2).

The velocity v is assumed constant at all radii, and for lightly loaded rotors is very small compared to the peripheral velocity ωr, except perhaps at radii close to the hub.

Assuming for all practical purposes that the angle γ is very small at all radii, and resolving the forces parallel to the axis of rotation, gives an element of vertical thrust or lift

$$dX = b\,dr\,\rho\,\frac{(\omega r)^2}{2g}C_L$$

where b = width or chord of blade aerofoil

ρ = air density as before

ω = angular velocity

C_L = coefficient of lift

With b and C_L constant at all radii, and integrating from $r = 0$ to the tip radius $r = R$, for N number of blades, gives

$$X = \frac{N b \rho C_L R (\omega R)^2}{6g}$$

Similarly, resolving the forces in the plane of rotation, gives an element of actual power to drive the rotor

$$dY = b\,dr\,\rho\frac{(\omega r)^2}{2g}(\gamma C_L + C_D)\omega r$$

Now $\gamma = v/\omega r$

Therefore

$$dY = b\,dr\,\rho\frac{(\omega r)^3}{2g}\left(\frac{v}{\omega r}C_L + C_D\right)$$

With C_D, like C_L, constant at all radii, and integrating from hub to tip for N number of blades, gives actual power

$$Y = \frac{Nb\rho C_L R v(\omega R)^2}{6g} + \frac{Nb\rho C_D R(\omega R)^3}{8g}$$

But, as before, $v = \sqrt{gX/2\rho A}$ from the momentum theory, and also inserting the previously derived value of X in terms of the rotor blade parameters, gives

$$v = \frac{\omega r}{2}\sqrt{\frac{NbC_L}{3\pi R}}$$

Substituting for v in the expression for actual power,

$$Y = \frac{Nb\rho R(\omega R)^3}{4g}\left(\frac{C_L}{3}\sqrt{\frac{NbC_L}{3\pi R}} + \frac{C_D}{2}\right)$$

Thus, two expressions are derived, in terms of geometric and aerodynamic parameters, giving the thrust and power of a lifting rotor.

Rotor Efficiency

Rotor aerodynamic efficiency, as previously defined under momentum theory

$$\eta = \frac{\text{final kinetic energy}}{\text{actual power}}$$

Actual power Y has already been derived above, in terms of the blade parameters.

Final kinetic energy = work done at the rotor = Xv as before, and again substituting for X and v in terms of the blade parameters gives,

$$X v = \frac{N b \rho C_L R (\omega R)^2}{6g} \times \frac{\omega R}{2}\sqrt{\frac{N b C_L}{3\pi R}}$$

$$= \frac{N b \rho R (\omega R)^3}{4g} \cdot \frac{C_L}{3}\sqrt{\frac{N b C_L}{3\pi R}}$$

Hence

$$\eta = \frac{X v}{Y} = \frac{\frac{C_L}{3}\sqrt{\frac{N b C_L}{3\pi R}}}{\frac{C_L}{3}\sqrt{\frac{N b C_L}{3\pi R}} + \frac{C_D}{2}}$$

$$= \frac{L/D}{L/D + \frac{3}{2}\sqrt{\frac{3\pi R}{N b C_L}}}$$

where $L/D = C_L/C_D$ for shortness.

Returning to the expression for thrust, under Aerofoil Theory,

$$X = \frac{N b \rho C_L R (\omega R)^2}{6g}$$

and putting $U = \omega r$, rotor tip speed

$$W = \frac{X}{A} = \frac{X}{\pi R^2}$$, rotor disc loading

gives $3\pi R / N b C_L = \rho U^2 / 2gW$

Hence rotor efficiency, now specifically denoted by the subscript R,

$$\eta_R = \frac{L/D}{L/D + \frac{3}{2}\sqrt{\frac{\rho U^2}{2gW}}}$$

It is seen from this that, providing possible values of C_L are considered, the rotor efficiency η_R obviously increases with increase in lift/drag ratio L/D. It also increases with increasing disc loading and decreasing tip speed.

Disc loading is not in this case open to variation, since it is the first parameter to be settled in deciding the type of aircraft configuration. As stated previously, in the present memorandum, a value of 2.5 lb/ft^2 has been assumed.

On the other hand, tip speed is open to choice, providing it does not exceed the limits set by aerodynamic or stress considerations. However, it also affects the performance of the tipjets, whose efficiency is examined in the next section.

Tipjet Drive Efficiency

Tipjet theory has been well demonstrated in Reference 5.

The following expression for efficiency is indirectly derived from that source:

$$\eta_T = 2\left(\sqrt{1+\left(\frac{U}{V}\right)^2} - \frac{U}{V}\right)\frac{U}{V}$$

where U = rotor tip speed, and V = calculated gas or air velocity at the tipjets if the rotor were stationary.

The velocity V may therefore be derived as usual from the gas or air supply conditions:

$$V = \sqrt{2gRT_1\frac{K}{K-1}\left\{1-\left(\frac{P_0}{P_1}\right)^{\frac{K-1}{K}}\right\}}$$

where P_1 = gas or air supply pressure

P_0 = atmospheric pressure

T_1 = gas or air supply temperature

R = gas or air constant

K = ratio of specific heats

It may easily be seen that efficiency η_T increases with increase of the ratio U/V , or if V is fixed, with U , the tip speed.

This effect of tip speed is opposite to the effect on the rotor efficiency. Thus there must be an optimum tip speed U which gives a maximum efficiency for the tipjet-driven rotor combination.

Combination Efficiency

The overall efficiency of the tipjet-driven rotor combination, $\eta_o = \eta_R \eta_T$, or

$$\eta_o = \frac{L/D}{L/D + \frac{3}{2}\sqrt{\frac{\rho U^2}{2gW}}} \times 2\left(\sqrt{1+\left(\frac{U}{V}\right)^2} - \frac{U}{V}\right)\frac{U}{V}$$

The maximum value of this expression is not easily found by mathematics, since the relation between L/D and U is not a simple one. A graphical solution for a particular case is presented as an example.

The following values and conditions are assumed:

L/D = maximum values for a two-dimensional aerofoil section of 10% thickness/chord ratio.

ρ = standard atmospheric density at sea level = 0.0765 lb/ft^3.

W = rotor disc loading = 2.5 lb/ft^2.

V = tipjet air velocity = 1800 ft/sec.

Varying rotor speed U from 0 to about Mach 1.0 (1120 ft/sec.) results in the curves of Figure 4, from which it may be seen that the maximum value of the overall efficiency η_o = about 42%, at a rotor tip speed of Mach 0.7 (784 ft/sec.).

The corresponding values of rotor efficiency η_R, and tipjet efficiency η_T, are about 73% and 57.5% respectively.

Similar curves may be derived for other conditions, but the above example was worked out with the following aircraft (The DH Beaver) in mind.

3. APPLICATION TO AIRCRAFT

Unsuccessful attempts had been made on paper to fit a fan-in-wing system into a De Havilland Beaver transport aircraft. Due to the large amount of power required for lifting the aircraft, any proposed gas generators filled and strained the cabin space, and there was no room to lay out the required large-size ducting to the fans. Moreover, the fans themselves hardly fitted into the wings, requiring changes in the latter, and the heavy fuel consumption of the gas generators allowed only a few minutes operation on the tank capacity of the aircraft.

For this reason, the Beaver has been here also chosen to demonstrate the comparative advantages and disadvantages of using the proposed large rotor scheme.

Beaver Aircraft

Outlines of this aircraft (together with a proposed 50-foot diameter folding rotor) are shown to scale in Figure 5.

The outlines and details of the standard unaltered aircraft were obtained from Reference 6.

The normal sizes, weights, and performance of the landplane are about as follows:

Span	48 ft.
Length	30 ft.
Height	9 ft.
Gross wing area	250 ft^2
Cabin space	144 ft^3
Engine	P. & W. Wasp Jr.
Engine weight	682 lb.
Power	450 h.p.
Propeller	2-bladed, 8.5 ft. dia.
Internal fuel capacity	79 Imp. gallons
Empty weight	2850 lb.
Max.permissible loaded weight	5100 lb.
Maximum speed	163 m.p.h.
Cruising speed	143 m.p.h.
Cruising altitude	5000 ft.

The changes contemplated for the experimental aircraft consist only of mounting, outside the wings, the 50-foot diameter rotor, with the axle fixed at the centre of gravity of the aircraft, and the installation of a compressed air supply inside the cabin, for connection to the hollow axle, and thence to the tipjets of the hollow blades of the rotor.

The proposal of only one large rotor centered on the c.g., instead of two or more smaller rotors on, say, the wing tips or body extremities, provides an element of safety in case of rotor failure, since no violent tilting moments could occur.

The 50-foot diameter is considered reasonable relative to the 48-foot wing span of the aircraft.

Palouste Engines

The lifting performance of the proposed experimental aircraft with the 50-foot diameter rotor is limited to suit the power from two units of a commercially available gas turbine engine, the well-known Turbomeca Palouste.

The Palouste is a small compressed air supply unit, having approximately the following characteristics:

Size	19" x 20" x 49"
Weight	200 lb.
Compressed air supply	2.5 lb/sec.
Supply pressure	3.75 atm.
Supply power	250 h.p.
Fuel consumption	250 lb/hr.

The compressed air supply temperature is estimated to be about 200°C, and the velocity V in expansion to atmosphere 1800 ft/sec.

Two of these units would thus supply 5 lb/sec. of compressed air, carrying the equivalent of 500 h.p.

Their total weight with accessories = (2 x 200) + say 100 = 500 lb., and their total volume about 25 ft^3, which would easily fit into the Beaver cabin of 144 ft^3 capacity.

Rotor Thrust

Assuming that, as found previously, the optimum rotor tip speed is Mach 0.7 (784 ft/sec.), then tipjet efficiency η_T = 57.5%. Hence power Y available to drive the rotor = 500 x 0.575 = 288 h.p.

Referring to the basic expression between thrust and power, under Momentum Theory,

$$\frac{X}{A} = \frac{2\rho\eta^2}{g(X/Y)^2}$$

and assuming η or η_R, rotor efficiency = 73%, gives the lifting thrust of a 50-foot diameter rotor

$$X = \sqrt[3]{\frac{2\rho\eta^2Y^2A}{g}} = \sqrt[3]{\frac{2 \times 0.0765 \times (0.73)^2 \times (288)^2 \times (550)^2 \times \pi(50)^2}{32.2 \times 4}}$$

= very nearly 5000 lb.

The disc loading $W = \frac{X}{A} = \frac{5000 \times 4}{\pi (50)^2} = 2{\cdot}54$ lb/ft^2.

The lifting thrust of 5000 lb. hardly covers the maximum permissible loaded weight of the Beaver aircraft, but, as will be shown later, there seems to be no need to go to the limit for the experimental configuration proposed.

Blade Design

Blade design may be based on the previously derived equation (in the section on Rotor Efficiency),

$$\frac{3\pi R}{N b C_L} = \frac{\rho U^2}{2gW}$$

Rotor radius, R = 25 ft., tip speed U = 784 ft/sec., and disc loading W = 2.54 lb/ft^2. The choice is now between N, the number of blades, b, their width, and C_L the coefficient of lift.

Assuming 10% for the thickness/chord ratio of the blade aerofoil section, it is found from the literature (Reference 7, etc.) that the maximum L/D values (required for high efficiency) occur at C_L values between about 0.3 and 0.7, depending upon Mach number.

However, besides the aerodynamic criteria, there is the question of compressed air flow through the hollow blades. Too high a velocity of flow results in excessive pressure losses, too low a velocity means bulky passages and heavy sections. As in Reference 1, a Mach number of 0.3 is taken as a suitable value for design.

The number of blades N must be even, since each one must be balanced by another, when the rotor is unfolded. Trying N = 2 gives the compressed air flow through each blade = 2.5 lb/sec., and with the assumed Mach number of 0.3 for the flow velocity, 10% thickness/chord ratio, results in the requirement that the blade chord or width b should be equal to about 0.75 ft. or 9".

Substituting these values in $3\pi R/N b C_L = \rho U^2/2gW$, gives C_L = 0.55, which is a good figure for maximum L/D values, and therefore for maximum rotor efficiency.

Such slim (9") long (25-foot) blades must be treated in the same manner as helicopter blades when questions of stiffness and strength arise.

In motion, the centrifugal force must be utilized to counteract the bending moment caused by the lifting forces, so that impossibly high stresses do not occur, and at rest, the sag due to the weight must not be excessive.

In the first case, the solution is to raise the blades from the horizontal at an angle δ (see Figure 2) so that the upward moment at the axis caused by the lifting forces of the aerofoil are exactly balanced by the downward moment of the centrifugal forces, thus giving pure tension in the blade.

Starting from basic principles, the following relation may be derived for a blade of constant metal cross-sectional area (same metal thickness, same aerofoil section perimeter, at all radii):

$$\sin\delta = \frac{3 C_L \rho R}{16 t w}$$

where, as before, R = blade tip radius, C_L = coefficient of lift, ρ = atmospheric density, and now, t = metal thickness, w = metal density.

Substituting R = 25 ft., C_L = 0.55 for the proposed blade, ρ = 0.0765 lb/ft^3, and assuming high-strength aluminum alloy as the material with, say, t = 1/8", w = 0.1 lb/in^3, gives δ = about 6°, which seems a reasonably small rise angle from the horizontal of the blades.

The resulting pure tensile stress in the blade root near the axle = about 12,000 lb/in^2 at the full speed of 300 r.p.m. corresponding to the tip Mach number of 0.7.

This compares with the yield stress of 26,000 lb/in^2 (at 200°C) of the chosen high-strength wrought aluminum alloy (24 ST).

In the case of the static sag of the blades, there are several means of limiting this, including tapering the metal thickness or the chord or in other ways increasing the relative modulus of the aerofoil section at the root.

It is assumed here for simplicity that the blade is made from a tube 6" diameter, 1/8" thick, and pressed into a 10% aerofoil section towards the tip. This does not quite correspond to the previous assumptions of constant C_L and C_D along the blade, but is sufficient to illustrate the order of sag to be expected. The weight of each blade is estimated at about 70 lb.

With the above design, the sag at the tip, due to the weight of the blade, is equal to about 2 feet, which is considered reasonable when compared to the rise of about 3 feet corresponding to the angle of 6° in the rotating case.

Summarizing the proposed rotor details:

Rotor diameter	50 ft.
No. of blades	2
Width or chord	9"
Aerofoil thickness/chord ratio	10%
Blade material	24 ST
Material thickness	1/8"
Compressed air flow per blade	2.5 lb/sec.
Temperature	200°C
Flow Mach number	0.3
Weight per blade	70 lb.
Coefficient of lift,	0.55
Tip Mach number	0.7
Tip speed	784 ft/sec.
Rotational speed	300 r.p.m.
Vertical thrust	5000 lb.
Disc loading	2.54 lb/ft^2
Drive power	288 h.p.
Maximum blade stress	12,000 lb/in^2
Material yield stress (at 200°C)	26,000 lb/in^2
Blade rise angle, δ	6°
Blade rise at tip	3 ft.
Static blade sag at tip	2 ft.

Weights

The weights of the main items of the experimental installation have already been estimated (2 Palouste engines and accessories = 500 lb., 2 rotor blades = 140 lb.).

There remain to be estimated the axle, bearing and control weights for the rotor, and the fuel for the engines.

Unlike in a conventional rotor or propeller, the centrifugal force of the folding blades is directly carried by the bearings. Moreover, these bearings are to operate at about 200°C, since the compressed air is to flow in their vicinity. Allowing 2 bearings per blade (4 in all) and following the usual design procedure set out in manufacturers' handbooks with regard to load, life, speed, temperature, etc., gives the size of each bearing a rather bulky 9" o.d., and the weight 20 lb.

The hollow axle post (4 1/2" o.d.) and the blade hubs are assumed of steel. The weights of the rotor may then be summarized as follows:

Rotor Weights

Two 9" x 25' hollow aluminum blades	140 lb.
Steel hubs	90
4 Bearings (SKF 7321)	80
4 1/2" dia. hollow steel axle post	75
Tipjets, etc., say	10
Control valves, etc., say	5
	400 lb.

The fuel weight is calculated by assuming that the whole internal capacity of the aircraft (79 Imp. gallons) is filled. This is equivalent to about 550 lb., which would provide at least one hour's experimental running on the two Palouste engines.

The experimental aircraft weights may then be summarized as follows:

Aircraft Weights

Beaver empty weight	2850 lb.
Fuel, 79 Imp. gallons	550
2 Palouste engines and accessories	500
Lifting rotor, 2-bladed, 50 ft. dia.	400
Pilot	200
	4500 lb.
Rotor lifting thrust	5000 lb.

It should be noted that the aircraft empty weight includes the 682 lb. of the Wasp Junior engine and the weight of the propeller, both of which could be removed if it were chosen to divert part of the Palouste compressed air from the lifting rotor for horizontal propulsion, instead of using the Wasp engine and propeller in the conventional manner.

4. BLADE DEVICES

In order to operate properly the proposed folding trailable rotor of the experimental aircraft requires a number of special mechanical and other devices to meet the problems of the peculiar configuration.

Unfolding

If the tipjets of the two blades were of equal size and power, the admission of compressed air would start the two blades rotating together from the rearwards trailing position, with little chance of angular separation for attaining the desired opposing position. This would cause an unbalanced centrifugal force, shaking the aircraft.

The solution proposed for this problem, is to have one tipjet somewhat larger and more powerful than the other one, say, sufficiently to achieve opposition of the blades in one or two revolutions.

Locking in Opposition

As specified previously, it is necessary for the blades to rotate opposite each other when loaded, but to be free to fold for downwind trailing in horizontal flight.

The proposed device to achieve locking might consist of a latch between the two blade hubs, which would be automatically operated by the compressed air pressure.

Thus under load the latch would be partly forced out of one hub into the other, whilst with the compressed air switched off, gravity or a spring could ensure return.

Trailing

The two blades would be expected to swing downwind towards the rear of the aircraft in horizontal flight.

A pilot-operated latch in the fin could be used to secure the blades in a fixed position, until they were ready again for lifting duty.

Stagger

Because the proposed blades are independent of each other, one blade has to be staggered relative to the other on the axle, as shown in Figure 2.

An attempt should be made to reduce this stagger to a minimum, but nevertheless there would remain a rocking moment on the aircraft due to the centrifugal forces of each blade.

The proposed solution to this problem is to increase the lift of one blade relative to the other, so that a rocking moment would result equal and opposite to the centrifugally-caused moment.

The higher lifting blade could conveniently have the more powerful tipjet, which was found necessary for unfolding.

5. ROTOR TESTING

Model

Figure 6 shows an 18-inch diameter model rotor, which was crudely made and run, merely to demonstrate the operation of two of the mechanical devices mentioned previously. There was no attempt made to obtain lift or in any way to test aerodynamic characteristics.

The rotor was started and driven by compressed air tipjets, in a wind of about 100 m.p.h. velocity.

In rotation, the blades were locked at the opposing position by a small steel ball, which was automatically forced exactly half way between the two blade hubs by the compressed air pressure. When the compressed air was shut off, the ball returned to the lower hub by gravity, allowing the two blades to fold and trail downwind in the 100 m.p.h. velocity.

One of the tipjet holes was made slightly larger than the other, thus allowing the blade with the larger hole to race ahead of the other upon starting, before locking in the opposing position.

Full-scale

Before considering trying on any aircraft, a full-scale rotor, 50-foot diameter, could perhaps quite well be tested on the ground outdoors, in the blast from a jet engine.

If the rotor were mounted a sufficiently long distance from the jet nozzle, the blast there probably will have entrained enough outside air to cover the rotor with a flow of reasonably low velocity and temperature.

The vertical thrust of the rotor, both in and out of wind, the compressed air power, and therefore the efficiency, could possibly be measured without too much difficulty.

However, of special interest would be the measurement of the drag of the folded blades in the trailing position, since this would probably be the main penalty of the scheme when compared to others.

6. CONCLUSIONS

The test of a model tipjet-driven two-bladed rotor demonstrated that some of the mechanical problems of folding and trailing may not be too difficult of solution.

Theoretical treatment of a full-scale rotor for an example aircraft shows that the weight and power of the scheme need not be excessive.

Testing of such a rotor outdoors in and out of the diluted blast of a jet engine may be a crude but inexpensive way of proving the performance and showing up the penalties.

In any case, the idea would seem to offer an amusing source of practical and theoretical interest in thermodynamics, aerodynamics and mechanics.

7. REFERENCES

1. N.R.C. Aeronautical Report LR-265, "Powerplants for VTOL Aircraft: A Proposed Dual-Operation System Using Wing-Immersed Fans for Vertical Thrust." By E.P. Cockshutt and N. Galitzine.

2. Convertible Aircraft Congress Proceedings, 1949, 1952 and 1953. Sponsored by the American Helicopter Society and the Institute of the Aeronautical Sciences.

3. Aviation Week, March 28, 1960. "Sikorsky S57 Jet VTOL Stores Rotor in Fuselage."

4. N.A.E. Laboratory Memorandum ENG-56, "Dual-Operation Powerplants for Vertical Take-off Transport Aircraft: A Comparison of Several Drives for Wing-Immersed Fans." By E.P. Cockshutt and N. Galitzine.

5. NACA TN 1155, "A Preliminary Study of a Propeller Powered by Gas Jets Issuing from the Blade Tips." By J.C. Sanders and N.D. Sanders.

6. De Havilland Beaver DHC-2 Flight and Maintenance Manual, 1954 Edition.

7. NACA TN 2670, "High-Speed Subsonic Characteristics of 16 NACA 6-Series Airfoil Sections." By Milton D. Van Dyke, 1952.

CHARACTERISTICS OF DUCTED FANS & UNDUCTED ROTORS

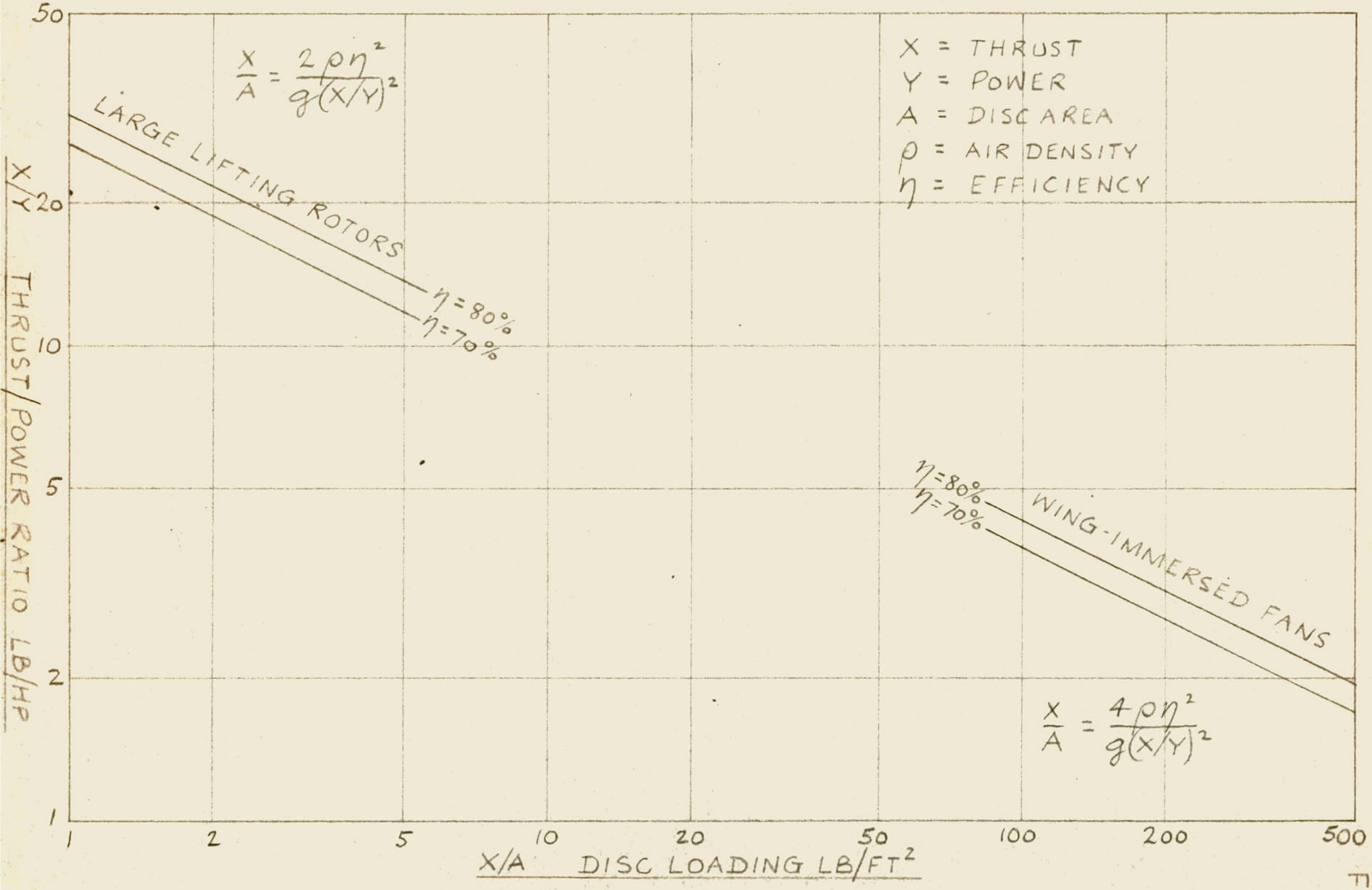


FIG. 1

TIPJET-DRIVEN LIFTING ROTOR

FIG. 2

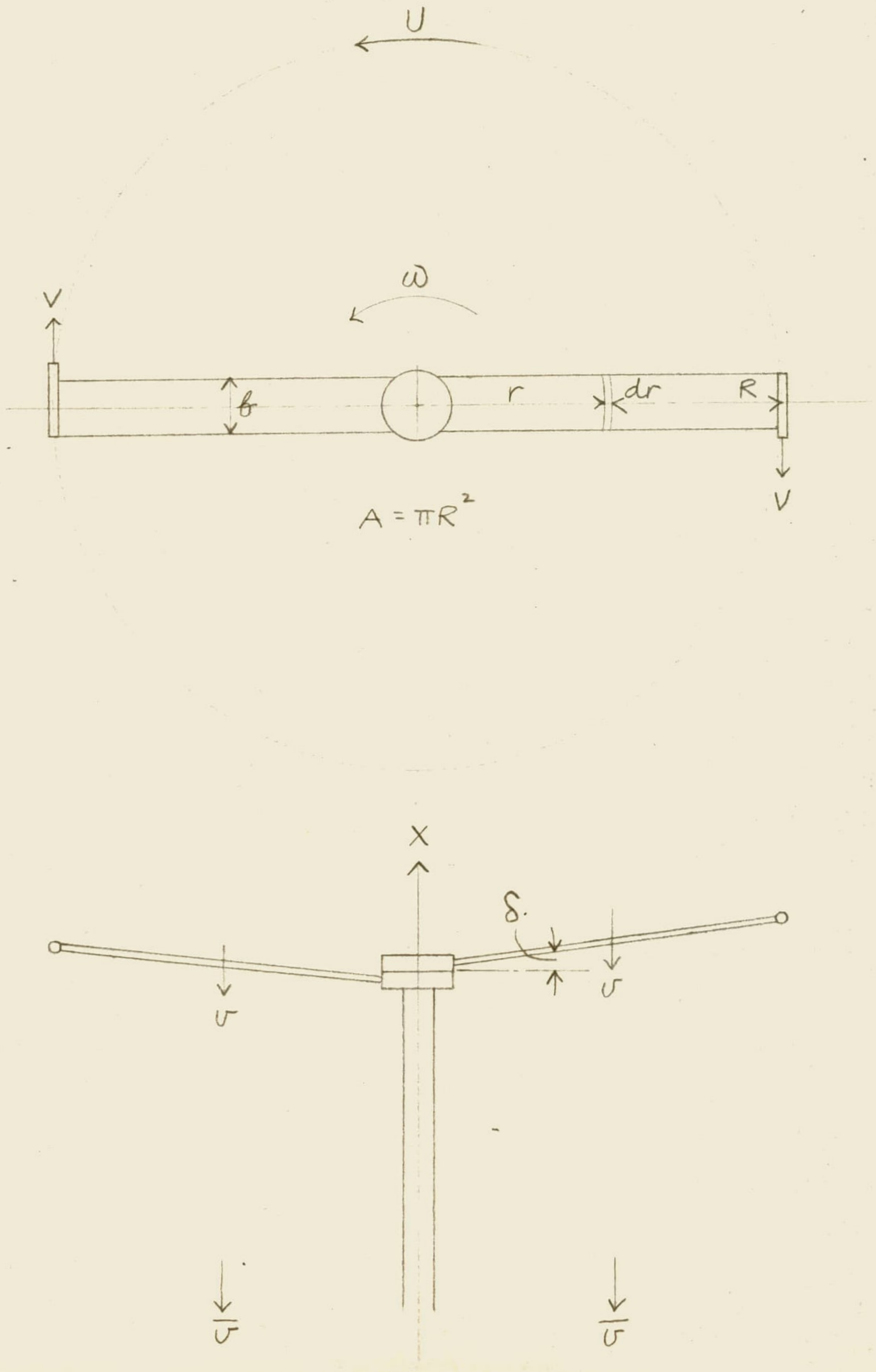


FIG. 3.

ROTOR BLADE AEROFOIL

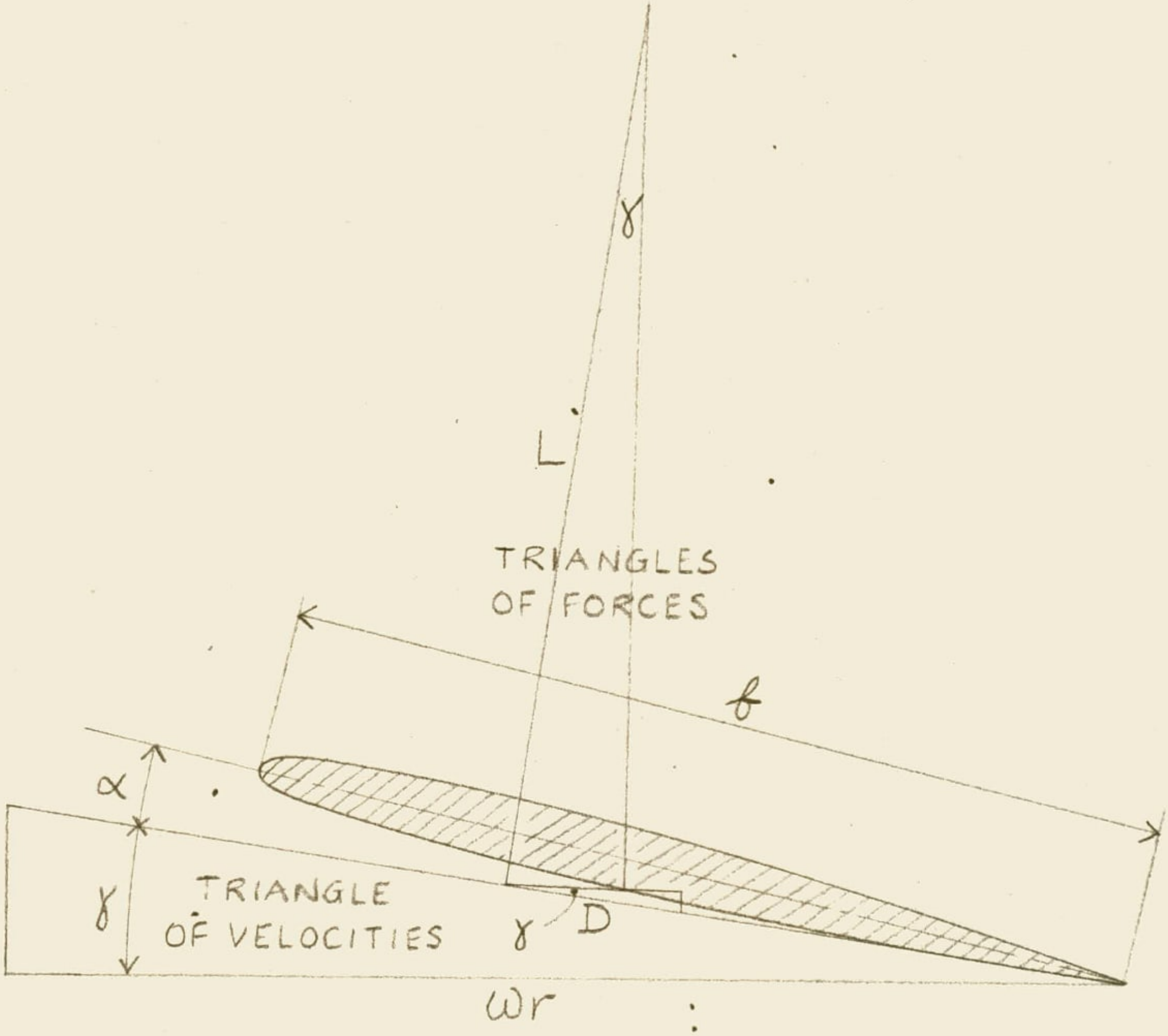


FIG. 4.

EFFICIENCIES

η_R ROTOR EFFICIENCY
η_T TIPJET EFFICIENCY
η_0 OVERALL EFFICIENCY

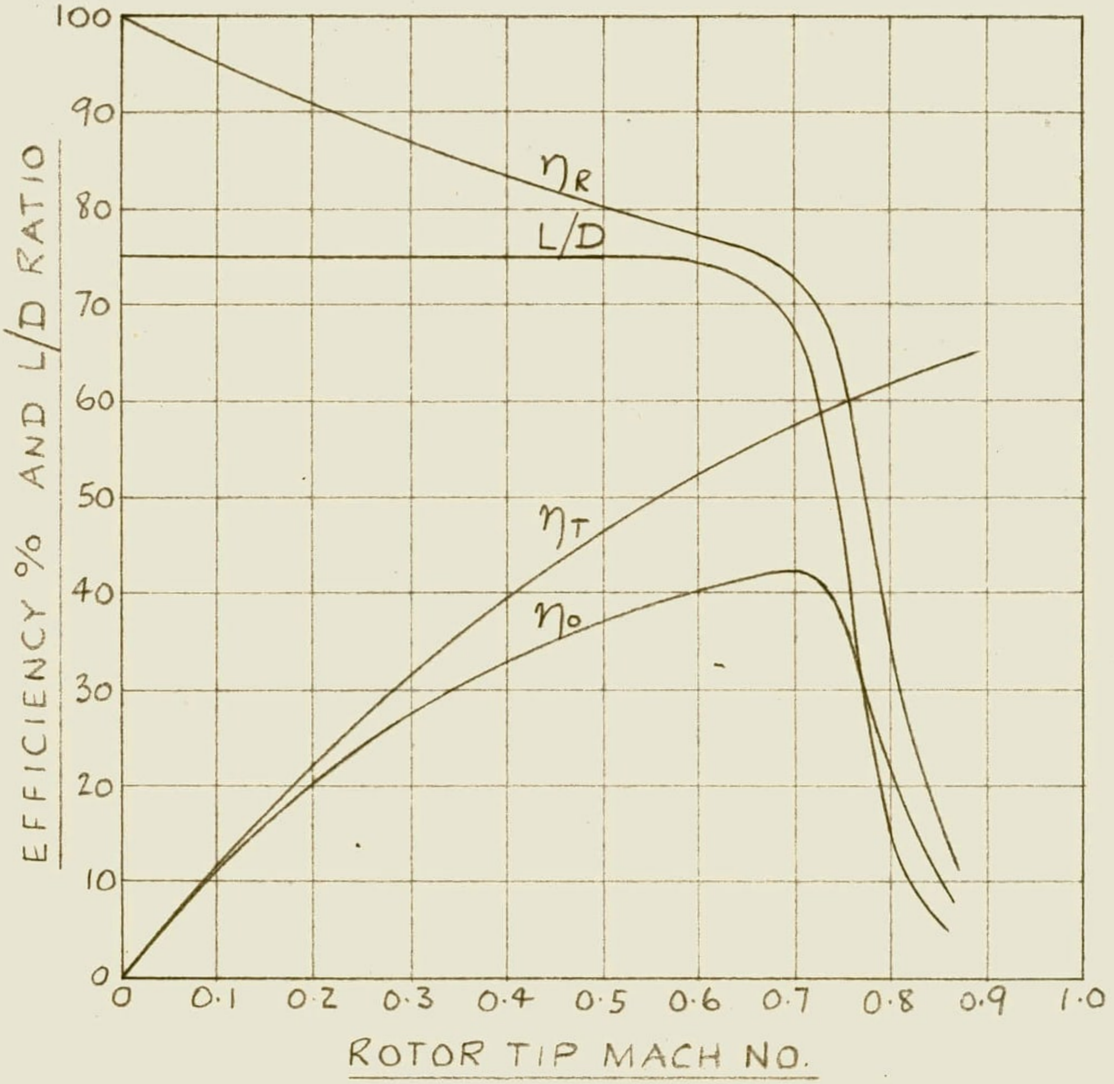
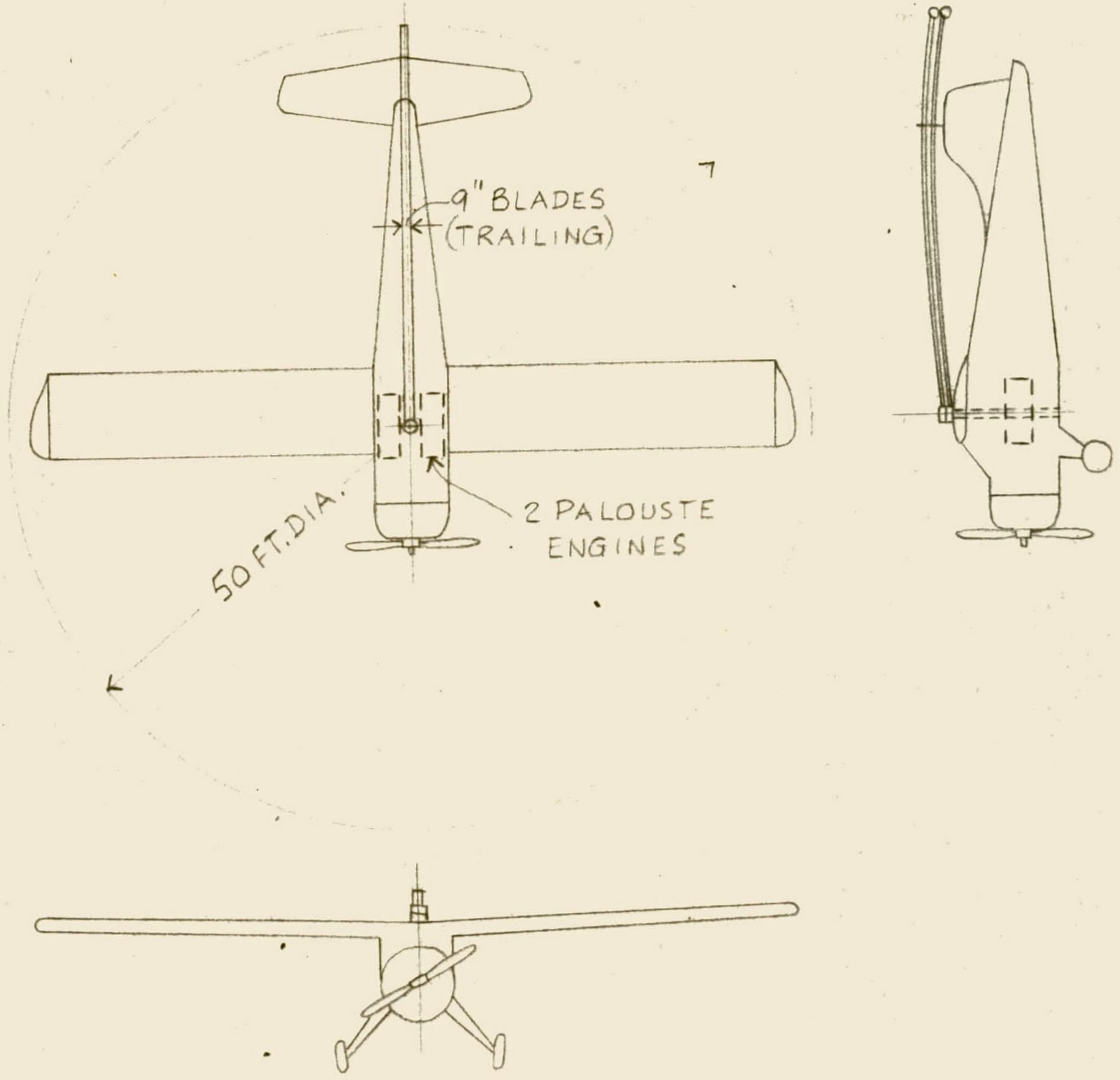


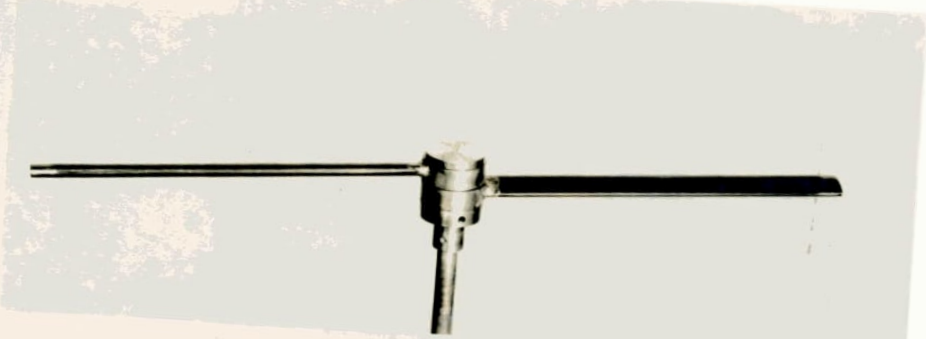
FIG.5.



VTOL BEAVER

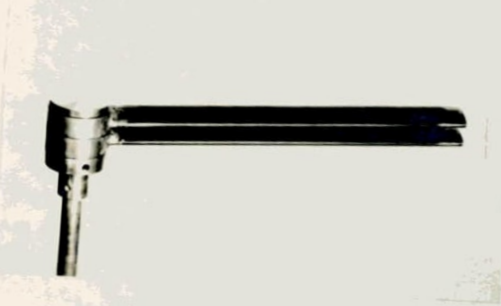
WITH FOLDING TRAILABLE ROTOR

FIG.



BLADES AUTOMATICALLY LOCKED IN OPPOSING POSITION FOR VERTICAL LIFT

EXPLODED VIEW
SHOWING LOCKING DEVICE



BLADES FOLDED
FOR DOWNWIND TRAILING
IN HORIZONTAL FLIGHT

18" DIAMETER
DEMONSTRATION
MODEL ROTOR