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THRUST SYSTEMS FOR LIGHT AIR CUSHION VEHICLES

BY H.S. FOWLER

A discussion of the qualities, merits, and drawbacks of various propulsion systems, to aid the designer in the choice of the most appropriate system for any specified application.

> "Then Sinbad took from the Djinn the bag of Fair Winds and opened it, thus driving his enchanted ship at great speed over land and sea to his destination."

THRUST SYSTEMS FOR LIGHT ACVs

1. Introduction

This note is intended as an introduction to the subject, to put the characteristics of the various systems in perspective for the designer of light ACVs, in order to help him make the best choice of a system for any particular vehicle.

Inevitably, aerodynamics and efficiency are only some of the considerations affecting the designer's choice, but only by having as critical an awareness of these as of other factors can the designer choose a thrust system harmonizing with the rest of his design.

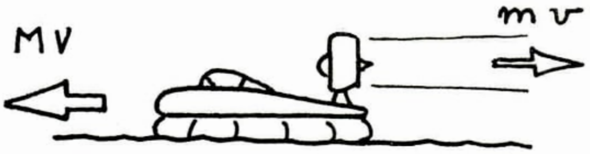
While this note is not in any sense a design handbook, it does attempt to point out the why's and wherefore's, and the advantages and disadvantages of each system at the present state of the art.

2. Basis of Aerodynamic Propulsion

The designer decides at an early stage that he needs x lbs. of thrust, and can allow y lbs. of engine and fan, costing z dollars. Where he can stow this package, and how many cubic feet it will occupy have yet to be found out, but this affects greatly the balance, appearance and noise of his machine.

The basis of the whole process is that aerodynamic propulsion is described by Newton's Laws of Motion, and operates in exactly the same way as a rifle and its bullet.

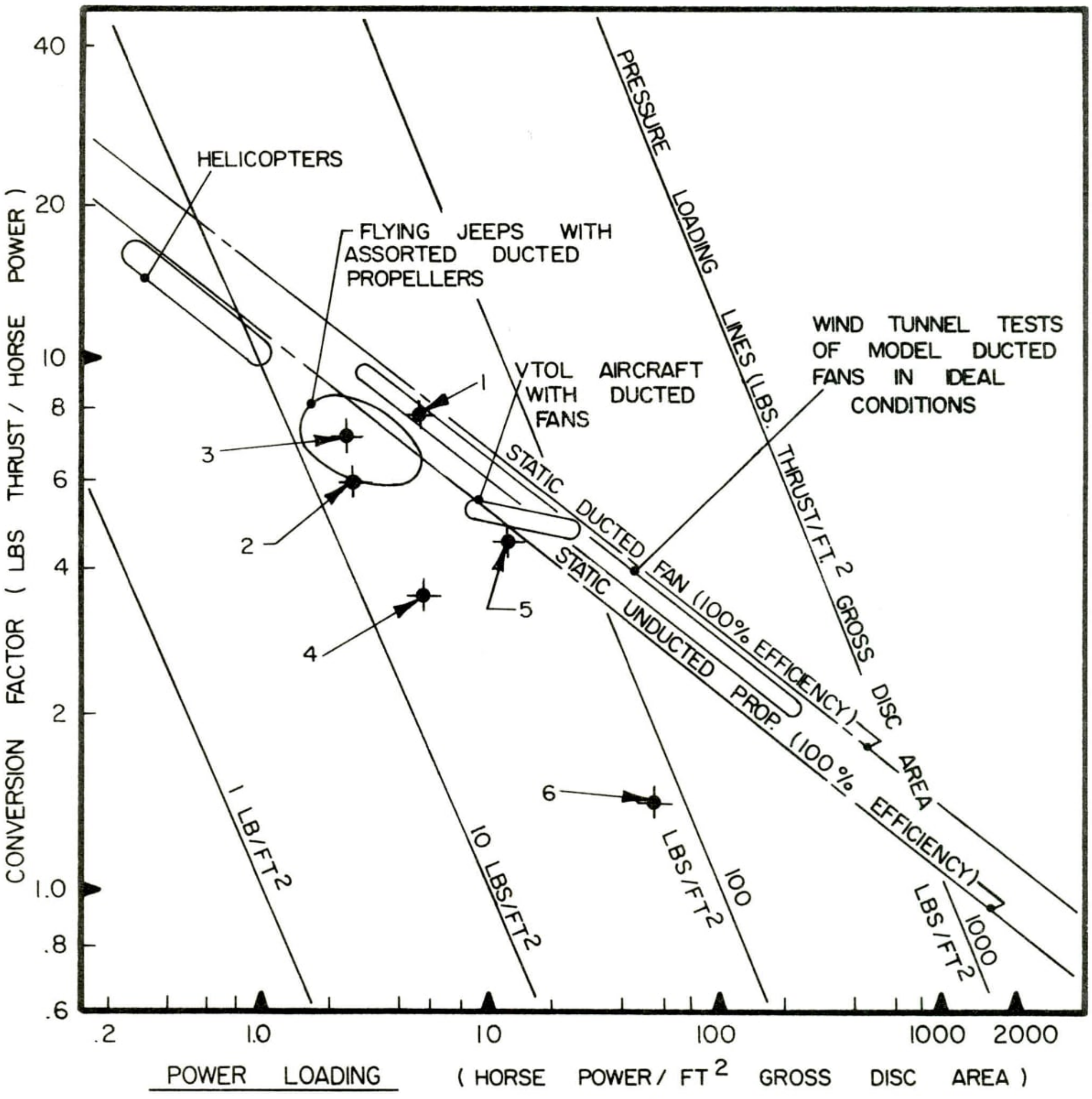
When the bullet is fired in one direction, the rifle is kicked back in the other. Similarly, when the fan blows a jet of air one way, the ACV is thrust along in the opposite direction. The momentum of the air being blown backwards is equal to the force exerted on the ACV moving forwards, and the momentum produced per second by the fan is equal to the thrust in lbs.



However, the energy to generate this jet of air, or the horsepower of the thrust engine, is proportional to the Kinetic Energy in the airstream. The equations describing this process are laid out in Appendix 1, where all of this information is brought into focus very clearly in a single graph, which applies to any sort of aerodynamic thrust device - jet, propeller, ducted fan or whatever. Without bringing any engine or fan efficiency into the question, this graph (Main Graph 1) shows the static thrust obtainable per unit horsepower from an air jet of any particular area.

At the extremes (at the right-hand end of the graph) the 1 ft^2 nozzle of a small 2000 HP jet engine would give something like 0.7 lbs. of thrust per horsepower, while at the other end of the scale (left-hand end) the 40 ft. diam.

A.C.V. THRUST SYSTEM OPERATING MAP.



ACV THRUST SYSTEMS — ✦ 1 TO 6

1. GOOD 4-BLADED DUCTED FAN.
2. POOR 2-BLADED PROP. AT HIGH TIP-SPEED IN CRUDE DUCT.
3. STANDARD SMALL U.K. MULTIBLADED FAN IN GOOD DUCT.
4. GOOD DUCTED FAN WITH POOR INLET AIR CONDITIONS.
5. LARGE A.C.V. WITH SINGLE UNDUCTED 4-BLADED PROP. AT 40 KNOTS.
6. (ESTIMATED) OPERATING POINT OF ACTUAL MEDIUM – SIZED ACV WITH CENTRIFUGAL FAN THRUST (AFTER SUBTRACTION OF INTEGRATED LIFT POWER.)

MAIN GRAPH - I.

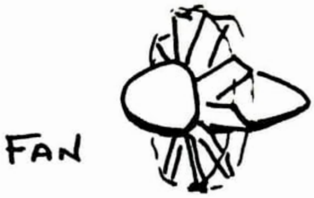
rotor of a helicopter with a 450 HP engine would produce 15 lbs. of thrust (lift) for each 1 horsepower. However, common sense suggests that one cannot put a 40' dia. helicopter rotor up on edge as an ACV propeller, and common sense also dictates that the 200 gallons an hour fuel consumption of a jet engine would not be welcome on an ACV.

Let us therefore explore the various thrust devices, and see where they fit on this graph, and how they fit onto an ACV.

3. How is the Jet Generated?

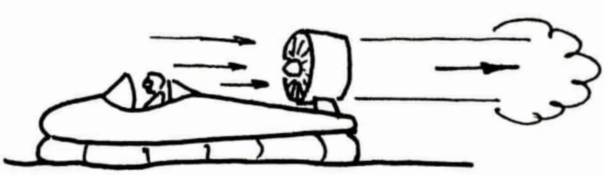
Basically, any of these systems depend on either an axial fan or a centrifugal fan, but these can be applied in various ways, and in different disguises. We will therefore look over the whole range, and set down their characteristics. (It may be noted at this point that the crossflow fan, also called the tangential flow fan, does not appear at present to be suited to ACV propulsion. Apart from its airflow characteristics, it is inherently bulky and heavy for the flow it can generate.) The propulsion system of an ACV ranges all the way from a complex integrated lift/thrust system in which the hull forms the major part of the air ducting, to a very simple system consisting of a propeller and engine bolted onto the outside of the hull.

At the complex end of the spectrum, either type of fan is used to blow air into a large box formed by the vehicle hull, from a hole in the rear of which a jet of air blows



Firstly we consider these devices (usually fans) in a still smaller "box" - the "ducted" fans.

Here the axial fan runs in a streamlined duct, which in effect gives an effective jet diameter equal to the fan diameter, instead of considerably smaller as in the case of a fan without a duct. However, the weight and cost of the duct cannot be neglected. (Pessimists also point out that the duct is a safety device which collects the pieces when the fan explodes, instead of peppering the onlookers.)



Finally, the cheapest and simplest device is the plain unducted propeller. However, as one might expect it is a lot less efficient than a ducted propeller, and if we try to get the same thrust out of it as we can get from a multibladed fan we have to drive it at very high tip speeds, at which the noise increases violently, the efficiency falls off drastically, and the danger of flying apart becomes very real.

out and propels the vehicle. This is the so-called "Ducted Jet" system. The lift air may also be "stolen" from this box, although this integrated lift/thrust system has more surprises and disadvantages than show on the surface.

The next stage along the series is to shrink the "box" or "plenum chamber" somewhat, until it becomes the volute round the fan, which in this case must be a centrifugal blower. This arrangement will be discussed in detail later, as it has some outstanding advantages, and as one might expect, some compensating drawbacks. However, it can be the most suitable compromise if vehicle controllability is more important than speed or economy.

Next we come to the axial fans, which we will quite arbitrarily call "fans" if they have more than 4 blades, and "propellers" when they consist of 4 blades or less.

4. Detailed Discussion of Various Systems

We shall now consider each of the systems sketched above, and see how it fits into a vehicle, what it has to offer, what demands it makes on weight and space, and what its limitations are.

4(a) The Ducted Jet

Aside from the possibilities of using the one fan for an integrated lift/thrust system, (a subject which will not be discussed here, but see page 40/41), the main reason for using a ducted-jet system is that it allows the fan to be placed conveniently relative to engine and centre of gravity, and the air to be ducted to a well-placed jet nozzle, giving a low thrust line and the possibility of neat jet-deflectors for side and reverse thrust for control of the vehicle.

A centrifugal blower can be used, giving relatively high-pressure air, and a wide operating range. This latter means that thrust reversers or other controls can be applied quite powerfully without stalling the fan, as is likely to happen if an axial fan is used. (This most important point is looked at in more detail at the end of this section.)

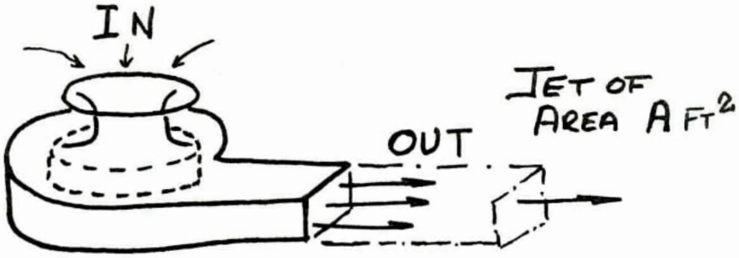
However, we had better face another difference between centrifugal and axial blowers at this point.

An axial fan, or blower, has the largest airflow capacity possible, relative to its size. It is simply a disc, through which air flows freely, with no bulky external parts.

Furthermore, in passing through it the air suffers hardly any change in direction, with only a small loss of pressure resulting.

A centrifugal blower, on the other hand, has a much greater bulk of casing to cope with the same flow capacity, and also inflicts at least a 90° change of direction on the air, which may or may not suit the installation, but which in any case causes a loss of pressure which has to be paid for.

Therefore, if we wish to generate the same size jet of air, at the same speed, to produce thrust at the same point on the graph we showed in Section 2, either we have to use a very large centrifugal blower running at low speed, or a much smaller, axial fan, whose whole disc is only the same size as the exit duct of the centrifugal blower.

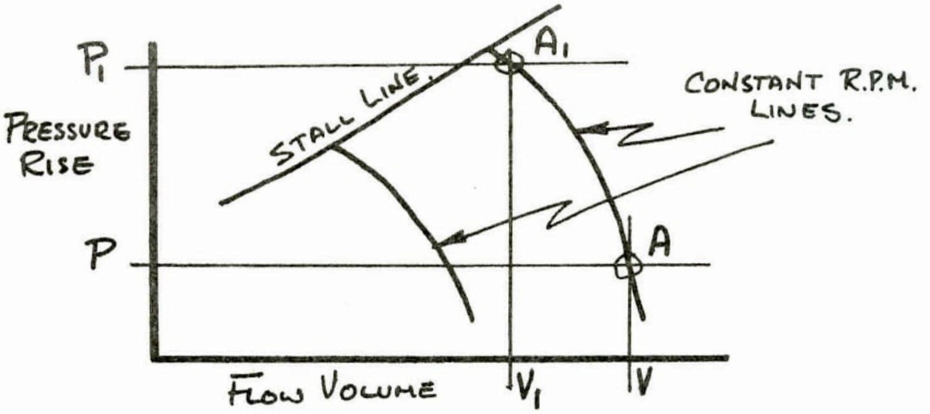


There is of course a way round this absurd state of affairs. We can use a centrifugal blower running at higher speed, generating a high-pressure and high speed exit flow through its small volute, and then slow this jet down to fill a large final jet. However a "diffuser", the expanding duct required to do this, is a bulky and sensitive device. The process has to be done gradually in a long gentle expansion, or else the flow "breaks away" from the duct walls and becomes unstable. This unstable flow in a too-abrupt diffuser can batter the walls badly enough to cause metal fatigue in a few hours, and in any case causes such loss of pressure as to make the system useless. This means that in practise the designer who uses a centrifugal blower either puts up with severe internal pressure losses which cut down the available thrust, or else uses a small high speed jet to get his thrust. And as the graph in Section 2 showed, this means a lower thrust per installed horsepower. So the centrifugal blower is a poor bargain for efficiency, from any point of view.

However, the centrifugal does allow more latitude in the layout of the vehicle, and the ducting of the air from either a centrifugal or an axial blower to the propulsion jets allows these to be placed in the most advantageous positions. By splitting the flow to two nozzles, one each side of the stern, and using "dampers", differential thrust will contribute a lot to the steering control of the vehicle. Indeed, the "dampers" can be elaborated to modulate from ahead to astern thrust, which gives the ultimate in steering and even braking control. This can be achieved from the same pair of stern outlets, or the main "air-box" duct can have separate "astern" jets located near the front of the vehicle, and even side-force outlets ("puff-ports") on the beam faces. The possibility of keeping the main propulsion jets low down also minimizes the nose-down moment at full thrust.

Before summarizing the ducted jet layout, we will return to the difference of characteristic between axial and centrifugal blowers to which we referred briefly at the beginning of this Section.

The output of a blower is represented typically by the graph seen here. From this we see that if the blower is run at a fixed speed (RPM) it generates an airflow of some volume/sec. and pressure corresponding to a point on the fixed speed line (for example A in line AA_1).



Now if in an ACV the thrust blower is running at set speed and the controls are centered for straight track, the flow is a maximum, at say V ft^3/sec, which is forced through the propulsion nozzle by pressure P.

But if we put the deflector vane in the nozzle hard over, or use a thrust reverser, this will impose a higher pressure loss on the flow. This means that the blower must now generate a higher pressure P_1, and the flow will fall to V_1, which in turn means that the thrust (due to the lower flow) may fall off.

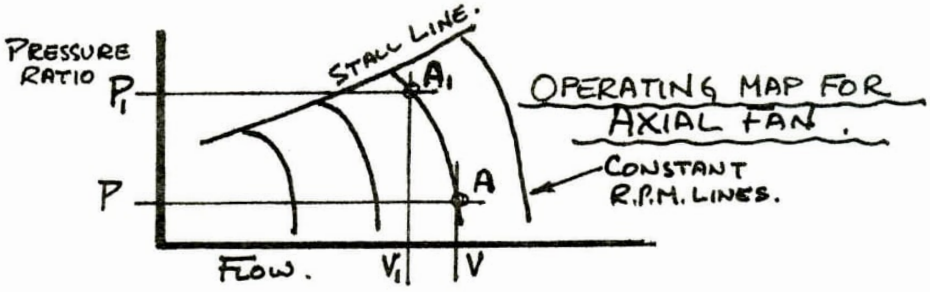
Even worse, ultimately the operating point will be forced back past A_1 to the Stall Line. This is the point beyond which the blower can no longer generate the required pressure, or the flow below which it cannot operate. Beyond this point the flow becomes unstable and pulsates, and may shake the fan and ducting badly enough to damage it. And since the blower is no longer absorbing power properly it may overspeed and blow up.

One may remark at this point that the fan characteristic is fixed and unalterable, except by altering the geometry of the fan itself. Changes in duct resistance may impose additional limitations on the characteristic, or blow-off valves etc. may help a vehicle to live with an unsuitable characteristic at the price of wasted power, but these things do not alter the characteristic itself.

The above general remarks are true of any blower, but the curves for axial and centrifugal blowers are in general very different.

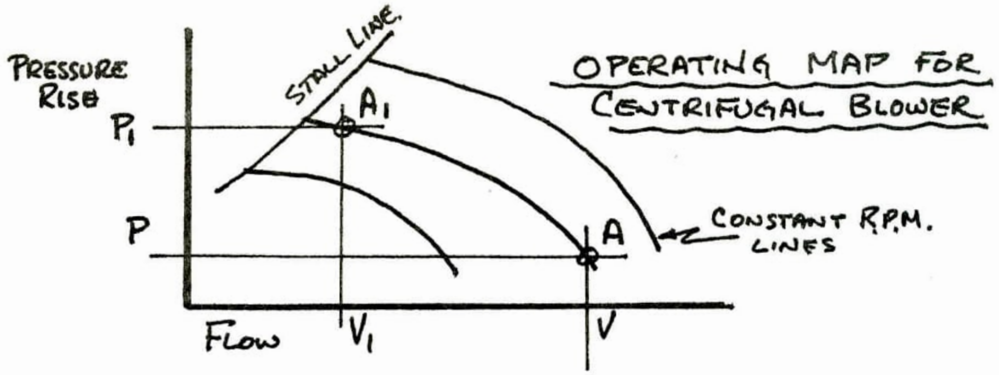
The axial fan usually has a somewhat "steep" constant speed line, with a relatively small range of flow quantity at any fixed speed.

This shows that the flow range V to V_1 is not great, and that much throttling of the exit area will easily cause the fan blades to stall.



OPERATING MAP FOR AXIAL FAN.

A centrifugal blower, on the other hand, usually has a much "flatter" operating line, with a much greater range between maximum and minimum flow at any speed.



It is of course possible to alter the RPM and so move over a much greater range of flows, but it is obviously undesirable to have to juggle the RPM in order to be able to use the rudder - and if the machine is already at maximum thrust it may not be possible to compensate.

One way out of this difficulty is to fit a blow-off valve in the duct downstream of an axial blower. This means that as back pressure rises or flow is decreased to near the stall point, the valve opens and allows extra flow to bypass the normal exit duct, thus averting stall. The valve is controlled by delivery pressure, and its setting represents a compromise over the fan speed range. It is a bulky and expensive item, and should not be needed with a properly matched system, but it is sometimes fitted as a way out of trouble.

Summary

We may therefore summarize the arguments for and against Ducted Jet thrust systems, and also for the use of Axial or Centrifugal blowers in these systems.

Ducted Jet Systems

Advantages

Flexibility of placing engine, blower, jets

Possibilities of steering and reverse thrust by deflected or multiple jets

Absence of large external fan units, which can be unsightly, create drag, and are exposed to damage

Disadvantages

Poor thrust/horsepower ratio

Large ducting, the vehicle is likely to become one vast duct

Centrifugal vs. Axial Blowers in Ducted Jet Systems

Centrifugal

Advantages

Freedom of intake position, top or sides of hull

Flat characteristic allows powerful controls without stalling blower

Rugged, relatively immune to foreign object damage

Disadvantages

Poor thrust/horsepower ratio due to small high speed jet unless an impossibly bulky diffusing duct is used

Axial

Advantages

Good thrust/horsepower ratio is possible, if suitable intake position for straight-through flow is possible

Disadvantages

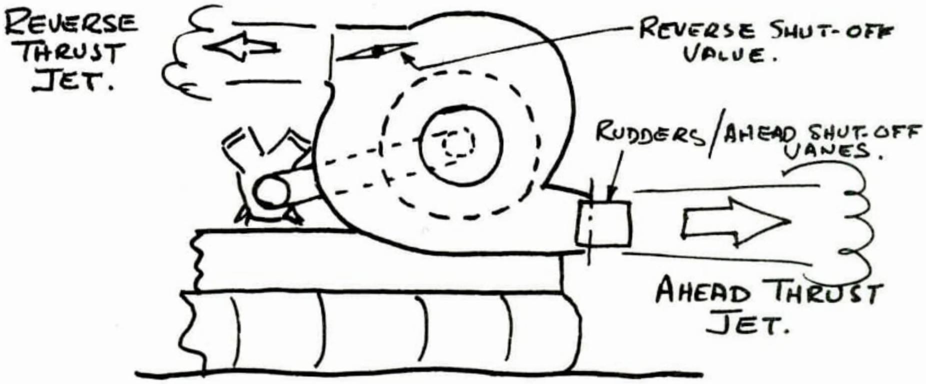
Less flexible vehicle layout. Very sensitive to use of controls, which are likely to stall fan if they are at all powerful

Relatively liable to damage or disintegration on ingesting foreign objects

4(b) The Centrifugal Blower/Volute Thrust System

This system is a development of the "box/ducted jet", in which the size of the "box" duct is reduced to the minimum, becoming the simple blower volute itself. Usually two blowers are used, on the same shaft. The two outlets then give the possibility of differential thrust, and a smaller overall bulk than a single blower of the same airflow capacity.

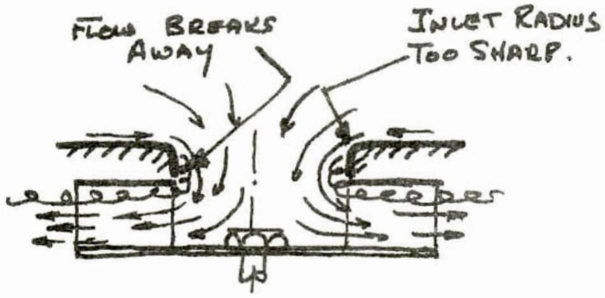
By careful design of the volutes it is possible to arrange reverse thrust jets, with simple control vanes for lateral deflection (steering) or changeover to the reverse jets for braking (both volutes) or steering (one volute only).

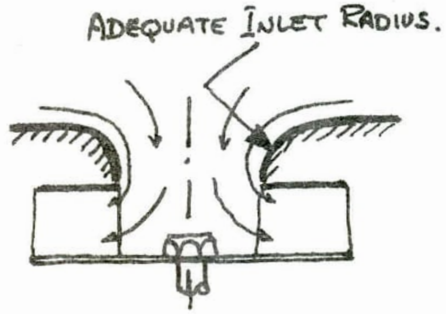


The difficulty of this system lies mainly in the fact that the design of volutes is not well understood, and is in any case a compromise between many conflicting factors. Unfortunately the volute design usually adopted for ventilating blowers is not suitable for a thrust system unit, and the design which would be most suited to a thrust system cannot take advantage of the relative compactness usually built into ventilating blowers. In the design of any such volute an intensive experimental development programme is absolutely essential.

We will discuss the design of inlets and volutes for centrifugal thrust units in some detail. These "snailshells" can make or kill the performance of a vehicle.

Firstly, the air must be led into the "eye" of the impeller in a uniform parallel stream. The speed in the eye is likely to be about 100 ft/sec, much above the forward speed of the vehicle, or any crosswind speed. The inlet has therefore to take low-speed air from all directions and guide it smoothly into the eye. If the lip radius of the inlet is too sharp, the flow will break away from it and enter only the centre of the eye.

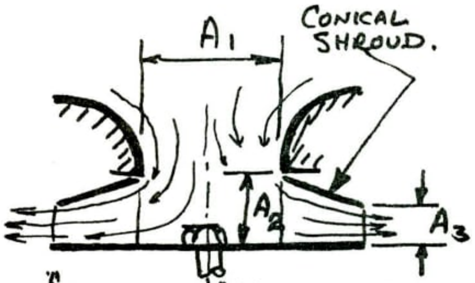




At this point it is worth remarking on the necessity of a good seal between inlet bellmouth and impeller shroud. At this region the airstream has accelerated to high speed without having energy yet added to it in the impeller. Its static pressure is therefore well below atmospheric, and if there is a gap between impeller shroud and inlet duct then a jet of external air will enter here, probably blowing the main stream off the wall despite care in giving a generous inlet radius as described above.

Next, it is important that the impeller leads smoothly from the inlet radius. The "flat" impeller commonly seen is an extremely poor device, and emits a powerful jet of air from the disc side of its exit, with the shroud side running empty except for a mass of eddies.

"FLAT" IMPELLER.

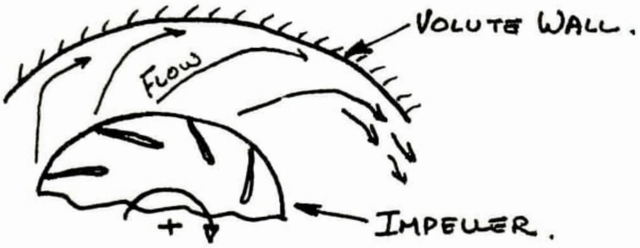


"CONICAL" IMPELLER.

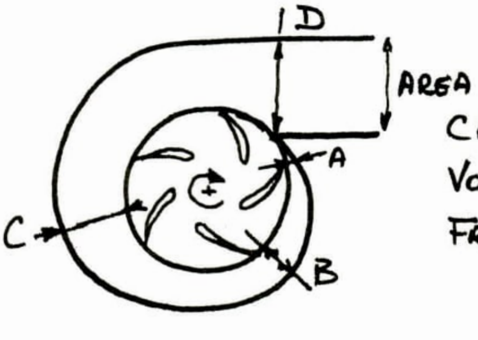
We noted in the previous section the difficulty of stabilizing a decelerating "diffusing" flow, and there is virtually no hope of diffusing the flow as it passes through the spinning impeller. The area available for flow should therefore be roughly constant through the "Eye" (A_1), the blade inlet "cylinder" (A_2) and the blade exit cylinder (A_3). In the "flat" impeller, where the thickness remains constant from blade inlet at small circumference to blade outlet at a larger circumference, A_3 is obviously going to be much greater than A_2. The flow simply will not fill the exit of a flat impeller, and will leave a mass of eddies under the shroud as shown above.

It is therefore essential that the inlet should be a generous "bellmouth", and the impeller should have a conical (or even better curved) shroud, to maintain reasonably constant area. If this is done, at least a chaotic mess is not inflicted on the exit volute, whose problems are severe enough without this.

The general idea of the "snailshell" volute is to collect the air spiralling off the impeller, and bring it at constant speed to a straight tangential duct, in which it can be diffused down to a required larger jet at lower speed. Diffusion in the actual unbladed volute is in fact simply impossible, the centrifugal force on the spiralling flow off the impeller will sling it to the outer wall of the volute and hold it there, leaving an empty space within.



The design of volutes is normally based on the idea of keeping constant speed in them so that as the impeller makes its revolution, feeding more air into the volute, the sectional area of the volute increases uniformly through the revolution.

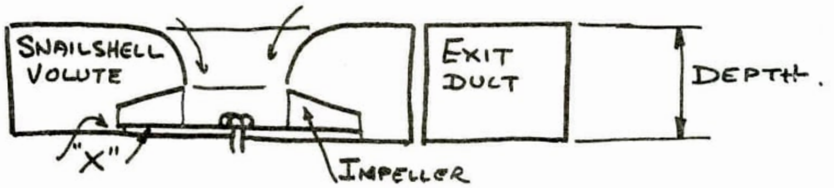


CROSS-SECTIONAL AREA OF THE VOLUTE INCREASES UNIFORMLY FROM "A" TO "D".

Two points of argument arise here, which are not of great importance in the design of ventilating blowers, but which are vital in the case of a thrust fan. In a ventilating system there are so many bends and elbows which cause turbulence and pressure losses that the added loss due to the fan volute is hardly noticed. But in a thrust system which has this one volute as its main source of loss of pressure, and which should present a uniform flow to the propelling nozzle a very short distance downstream, these losses and maldistribution are catastrophic.

A few moments on the drawing board will show that if the volute is kept at the same "depth" as the impeller tip, it will spread out in a snailshell of very large "diameter". In ventilating practise this outside dimension is usually kept down by deepening the volute, and for simplicity the impeller is often run in one side of a deep box, which includes the inlet bellmouth within its depth.

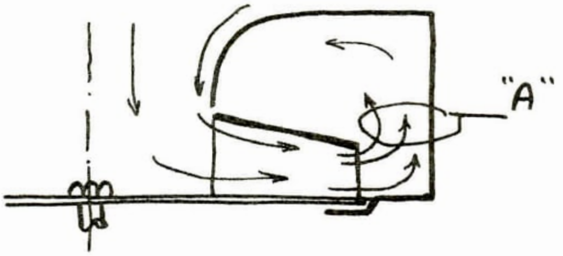
A word of warning may be given here on the necessity of allowing pressure relief in the space between the impeller disc and the casing. If this is not done, this space "X" fills with air at impeller tip high pressure, while the opposite face of the disc, opposite the open "eye" is exposed to low pressure, down to inlet pressure at the centre. The resulting imbalance across the disc generates a considerable axial thrust on the impeller, which loads the bearings and can shorten their life seriously. Small holes in the impeller disc are sometimes used to relieve this pressure, or rudimentary vanes on the back of the disc generate an opposing pressure gradient behind the disc.



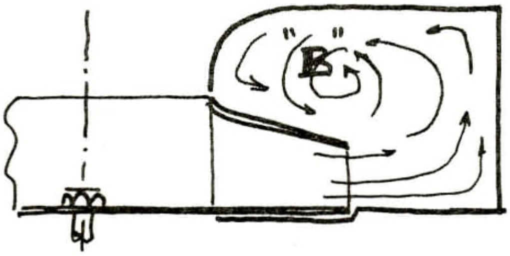
To return to the volute described above, this design is certainly compact and simple, but aerodynamically it is less than admirable. And the primary purpose of a fan volute seems to be aerodynamic.

A detailed look at the flow in such a volute may help us to design one more suited to a thrust fan.

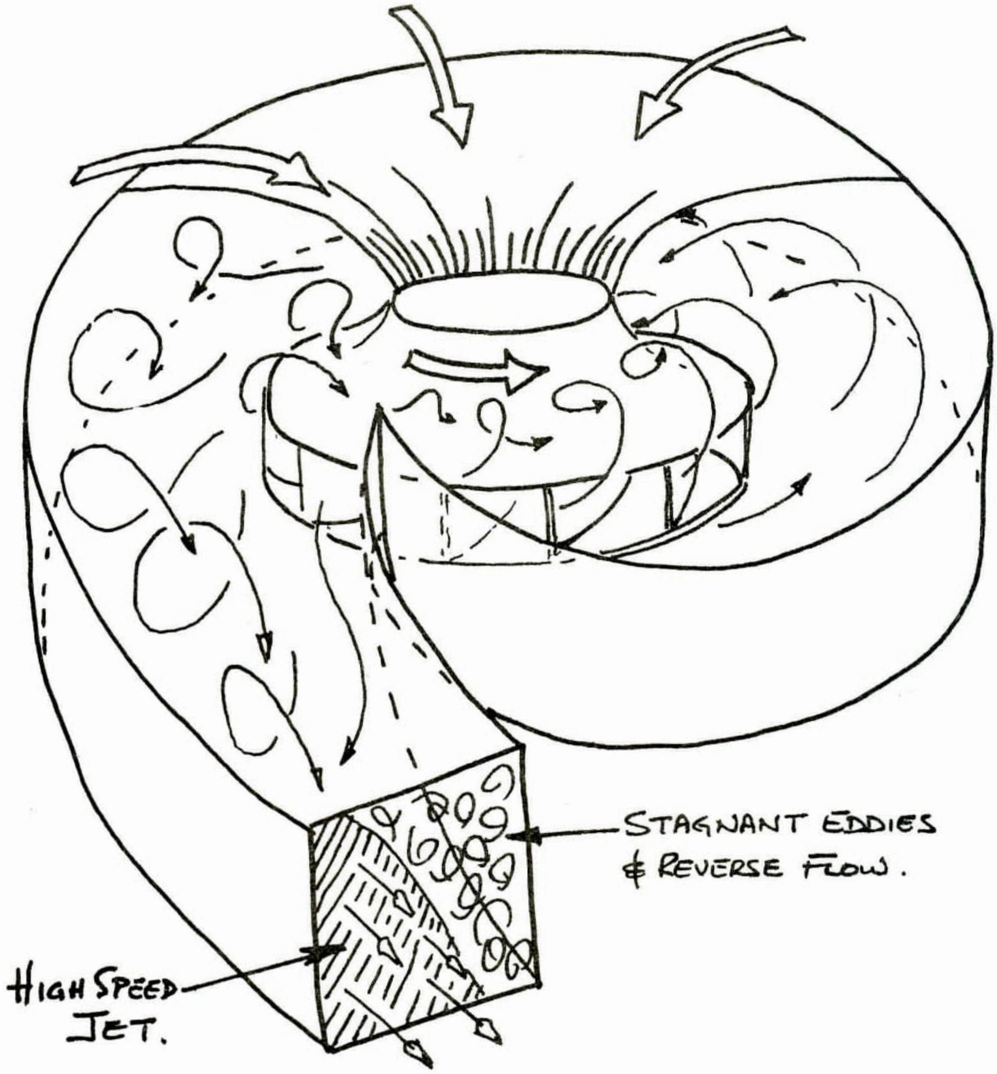
The trouble starts as soon as the flow leaves the impeller, heads outwards on a spiral path, and hits the volute outer wall.



In general it moves on round the volute, but an appreciable part of the flow is deflected upwards (at A). This process keeps on, all round the volute, with the highest energy just leaving the impeller always pushing outwards, displacing the existing stream upwards and inwards (B).

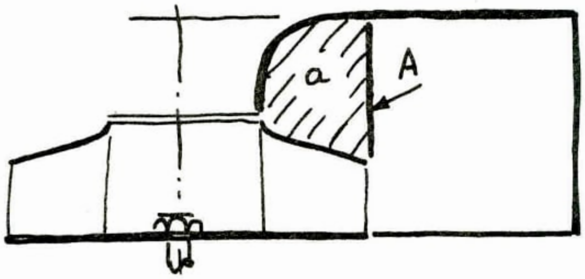


Ultimately this leads to a stable flow state which has very little resemblance to the designer's original intentions, with a high speed jet of swirling air shooting out of perhaps one third of the snailshell exit, and the rest of the duct full of a mass of stagnant eddies, vortices, or even reverse flow. Naturally any thrust calculated on a basis of the duct flowing full at mean velocity will not be realized.

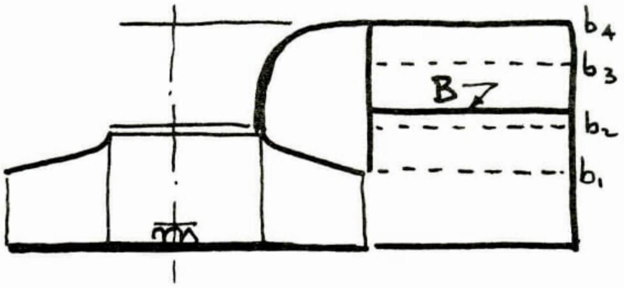


This exact state of affairs has been clearly seen and measured with wool tufts, smoke, and pressure probes on numerous occasions. How then can it be avoided?

In the first place, while retaining the structural simplicity of the large box volute, the parts filled with useless eddies can be blanked off. The first part for this treatment is the volume within the impeller tip radius.

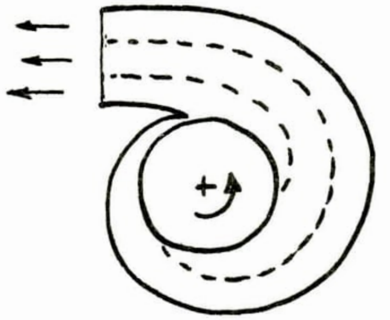


A cylindrical baffle A will eliminate this volume (a), which the designer may have included in his calculations, but which the air never used.

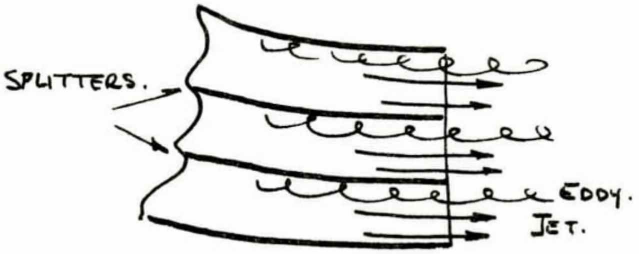


Next, a false roof "B" can be put into the box, climbing from b_1 at the start of the snailshell to b_4 at the exit. These two devices between them should reduce the eddying greatly. The flow will still tend to fling to the outside of the volute, but even this tendency should be minimized in this design.

One device may be mentioned as a thing to be avoided. A very obvious "fix" for the outward flow seems to be to install one or more spiral baffles in the volute, as shown by dotted lines.



In practise this has two results. It produces a very heavy frictional loss due to scrubbing on the outer walls of three passages instead of one, and it produces three badly distributed flows, with heavy wakes between them instead of one badly distributed flow.



Few designers try this twice, but far too many try it once.

Enough has been said to indicate that centrifugal blower exit volute design is a very difficult problem, and that model experiments on this component before finalizing a design will prove worth their weight in dollar bills. It is also obvious that a volute cannot easily be squeezed into a small volume and hidden, to improve the sleek outline of the vehicle.

The final argument that a centrifugal fan vehicle is quieter than one with axial fans is not necessarily true. The noise of axial fans will be spoken of in Section 4(c)2. One may say even at this point that modern fan technology has now produced some very quiet axial fans. However, if a particular design requirement rates manoeuverability and quietness much more important than efficiency and high thrust, then this form of centrifugal thrust system may be the most suitable.

Summary

The arguments for and against the Centrifugal Blower/ Volute Thrust System may be summarized as follows:

Advantages	Disadvantages
Quiet	Bulky
Possible to integrate powerful steering and reverse thrust jets to give good control	Poor Thrust/Horsepower efficiency
Centrifugal Blower characteristic permits powerful control operation without danger of fan stall	Volute design is difficult and involves much cut-and-try testing

4(c) The Ducted Axial Fan Thrust System

We now consider the third type of thrust system, the

Ducted Axial Fan. This system may use a "fan" of more than four blades, or a "propeller" of four or less blades. We will discuss the choice of the number of blades later in this Section, but at this stage it makes no essential difference.

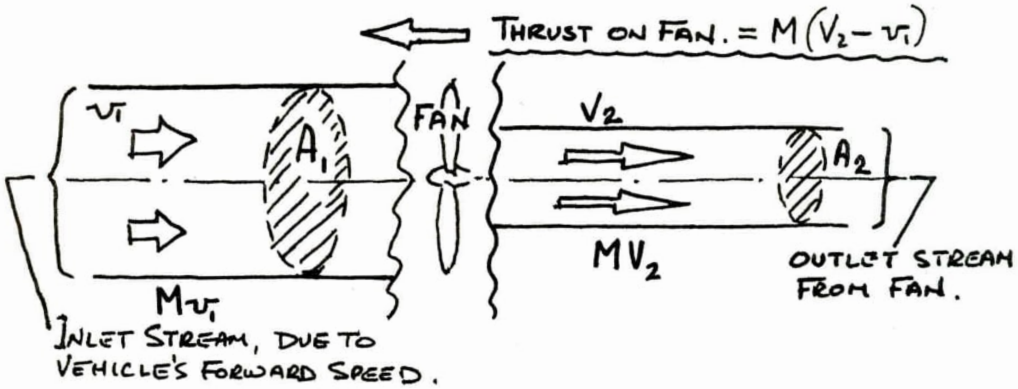
4(c)1. The Duct Inlet

The presence of the duct in which the fan runs, however, is a very important factor, which we will look at immediately. As we explained at the start of this Note, in Section 2, the thrust is generated by increasing the speed of the stream of air blown through the fan.

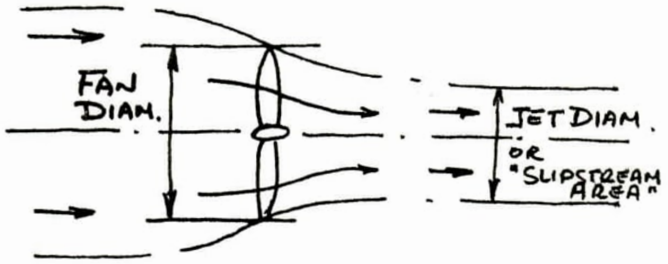
To make this quite clear, the inlet speed v_1 which is the speed at which the air approaches the fan, is in fact the forward speed of the vehicle approaching the stationary air in front of it. The outlet speed V_2 is the speed at which the stream is blown out of the fan.

Since the vehicle speed in ACVs is usually so much lower than the fan exhaust speed, we usually consider the vehicle to be stationary, making $v_1 = 0$. Thus the following statements describe the "Static Thrust" which would be measured on a stationary vehicle. This is not greatly reduced at the relatively low forward speeds of most ACVs.

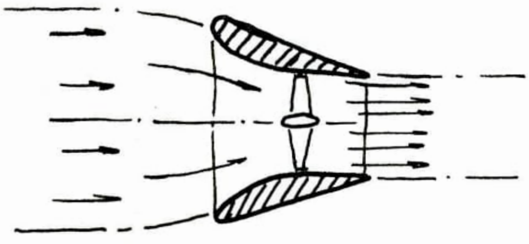
Since the density of the air does not change much as it passes through a fan of this sort, the cross-sectional area of the airstream will change as it goes through this acceleration in the fan, inversely as its speed.



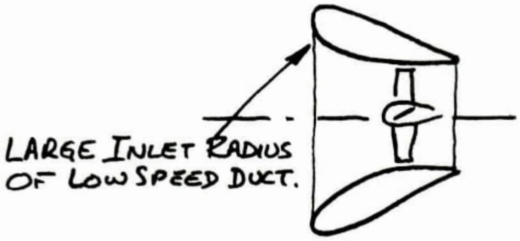
If we do not have a duct round the fan, to organize the flow the way we want it, a lot of this contraction of the jet takes place <u>after</u> the fan, which means that the exit airstream, whose diameter at any given jet speed governs the "M" and hence the amount of thrust, is considerably smaller than the fan diameter.



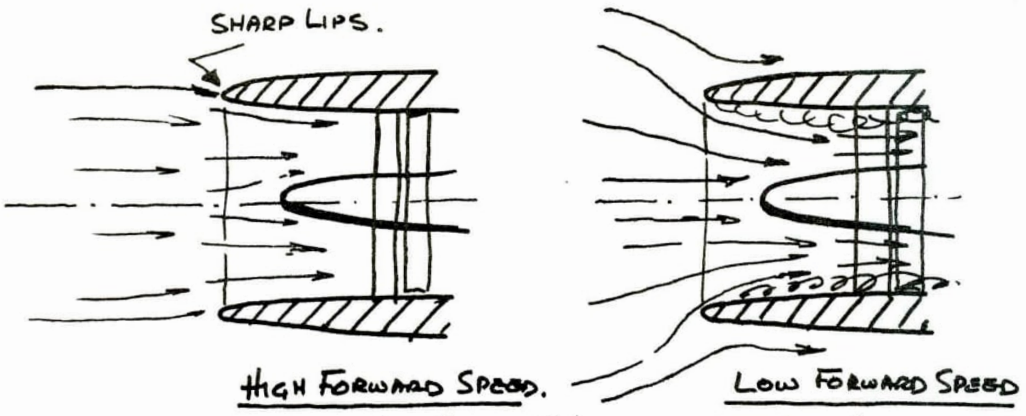
However, if we use a duct with a proper inlet section, the fan can, so to speak, be moved back into the small exit stream, and thus a smaller ducted fan will do the job of a large unducted propeller.



This effect is most pronounced at low forward speeds relative to the exit jet speed, which as we explained above is the characteristic case of an ACV, propelled at perhaps 40 ft/sec by a jet leaving the fan at perhaps 180 ft/sec. Here the inlet air is inhaled from a very wide zone, and the duct must become almost a bellmouth with a very widely flared inlet lip, to avoid flow breakaway.



This is quite different from the sharp inlet of a high speed aircraft jet engine, which will probably choke at low forward speed, owing to flow-breakaway from the sharp lip at an unsuitable incidence angle.



AN INLET DESIGNED FOR HIGH SPEED.

There are further effects which exaggerate this effect of the ducted fan, which will be noted in the section on unducted propellers. But we can already see that the duct has more functions than just catching the bits of exploding fans.

4(c)2. The Aerodynamics of the Fan

We must now look in detail at the way in which the unducted axial fan or propeller generates its thrust. A propeller acts as a wing, and its performance is based on aerofoil performance. The total thrust of the propeller is the sum of the thrust (which is in effect the "lift") of all the aerofoil elements which make up the blade (blades).

At less than near-shock speeds, the choice of aerofoil section is not very critical, so a "typical" one can be considered, and the maximum lift coefficient will not alter much from this.

Lift of an aerofoil is:

$$L = C_L \, A \, 1/2 \, \rho V^2$$

where L = Lift (total)

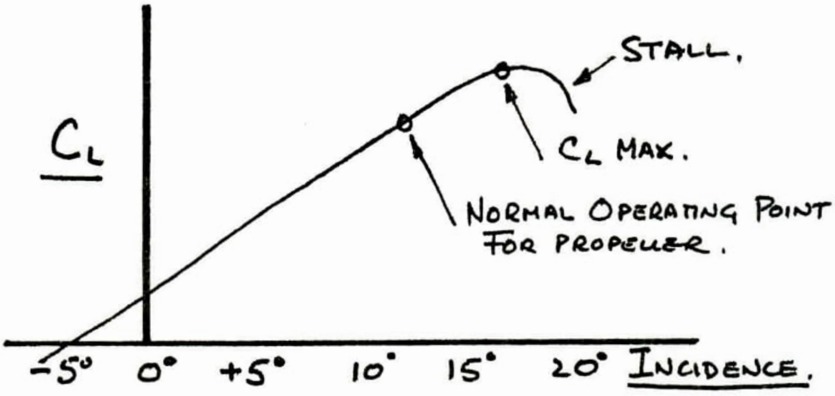
C_L = lift coefficient

A = plan area of blade

ρ = air density

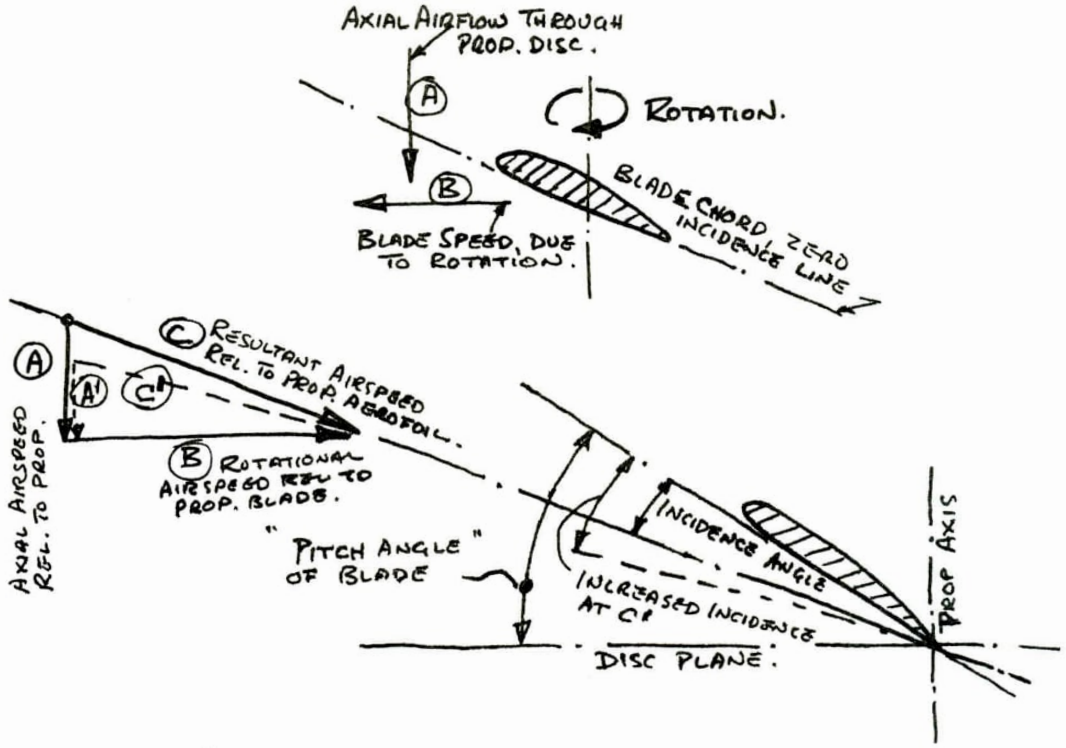
V = air speed relative to blade.

For typical aerofoils, C_L is shown by the following curve.

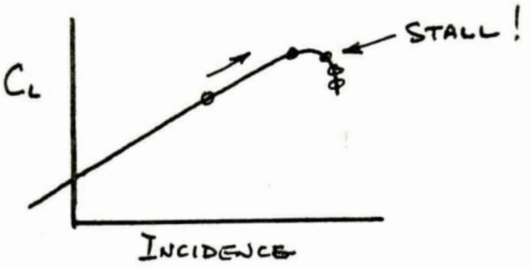


In a propeller, the incidence angle is the difference between the Resultant Air Angle at inlet C and the blade pitch angle (see figure below). Therefore, for a given blade rotation speed and axial airflow, we choose a blade pitch angle to give an incidence angle a little below the stalling angle on the C_L/Incidence curve (above).

When set up as a propeller, the blade operates like this:



Now, if a blockage (e.g. thrust reversers etc.) slows down the airflow then the throughflow (A) will reduce (A^1), the resultant (C) will come down to a flatter angle (C^1), the blade incidence will increase, and we move up the C_L/ incidence curve towards stall, at which point the propeller abruptly loses thrust.



So we begin to see how the factors affect propeller performance.

Lift L(proportional to thrust = $C_L A\ 1/2\ \rho V^2$. To increase L, we could increase C_L. But we can only do this by running in coarser pitch, nearer stall. We normally design as close to stall as we dare, leaving only a safe margin for rudder action, take-off (acceleration at low speeds) etc. So we can't do much there. We could increase A, the <u>blade</u> area. Total thrust of the propeller is directly proportional to blade area. We can get more by increasing diameter, which adds a few inches more to the blade tips. (<u>Not</u> the increase of <u>annulus</u> area, but of <u>actual blade area</u>.)

We can add to blade chord, and get wide paddle-wheel blades. Or we can use more blades, which is by far the most productive way of getting extra area. In addition, if we use more blades to achieve a given thrust, the blade-loading reduces, and this reduces the noise output by a substantial amount.

If we add too many, they begin to interfere with each other aerodynamically, and we have to consider multiblade fan theory, but this would not happen until there were more than 6 blades in most cases.

The air density, ρ, we can't alter. Finally, we can get more L by increasing the V, that is the propeller RPM. (Strictly, the (B) arrow, the blade speed due to rotation - the tip speed.) But this leads to NOISE!

Propeller noise comes from several sources, the main ones being:

(a) "Pure tones" - due to blade wakes passing a fixed strut - a siren effect.

(b) "Wide band noise" - due to vortices shed off the blades, probably proportional to blade loading or C_L, and

(c) "Shock waves" - due to sonic flow at high speeds. To avoid this, the tips MUST be kept well below 700 ft/sec or so. At that sort of speed, the local acceleration over the tips pushes the local flow to Mach 1, and the crackling screech of the common small high-speed propellers starts.

So it becomes pretty clear that the road to maximum thrust without excess noise is to keep the tip speed as low as possible, and to increase area as much as possible, by using four blades or more, as broad as may be.

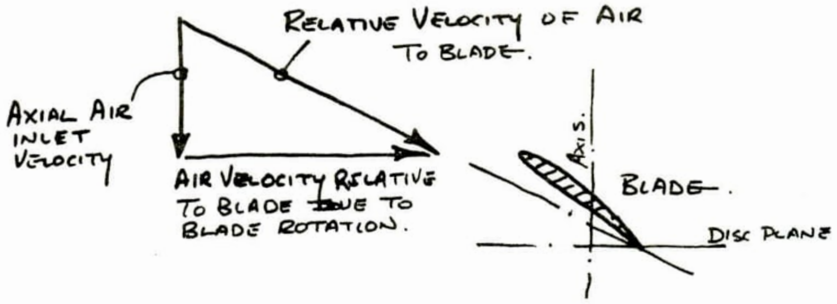
There is also a further thing to think of. As we explained at the outset, in Section 2, the Thrust from a jet of air is proportional to its MOMENTUM (M × V, or Mass Flow × Speed) whereas the Power to accelerate the air jet to that speed is proportional to its Kinetic Energy ($1/2\ \rho \underline{\underline{V}}^2$).

From this it follows that a large propeller blowing a low speed jet gives a better thrust per horsepower than a small fan blowing a high speed jet, although both are sized to give the same actual thrust.

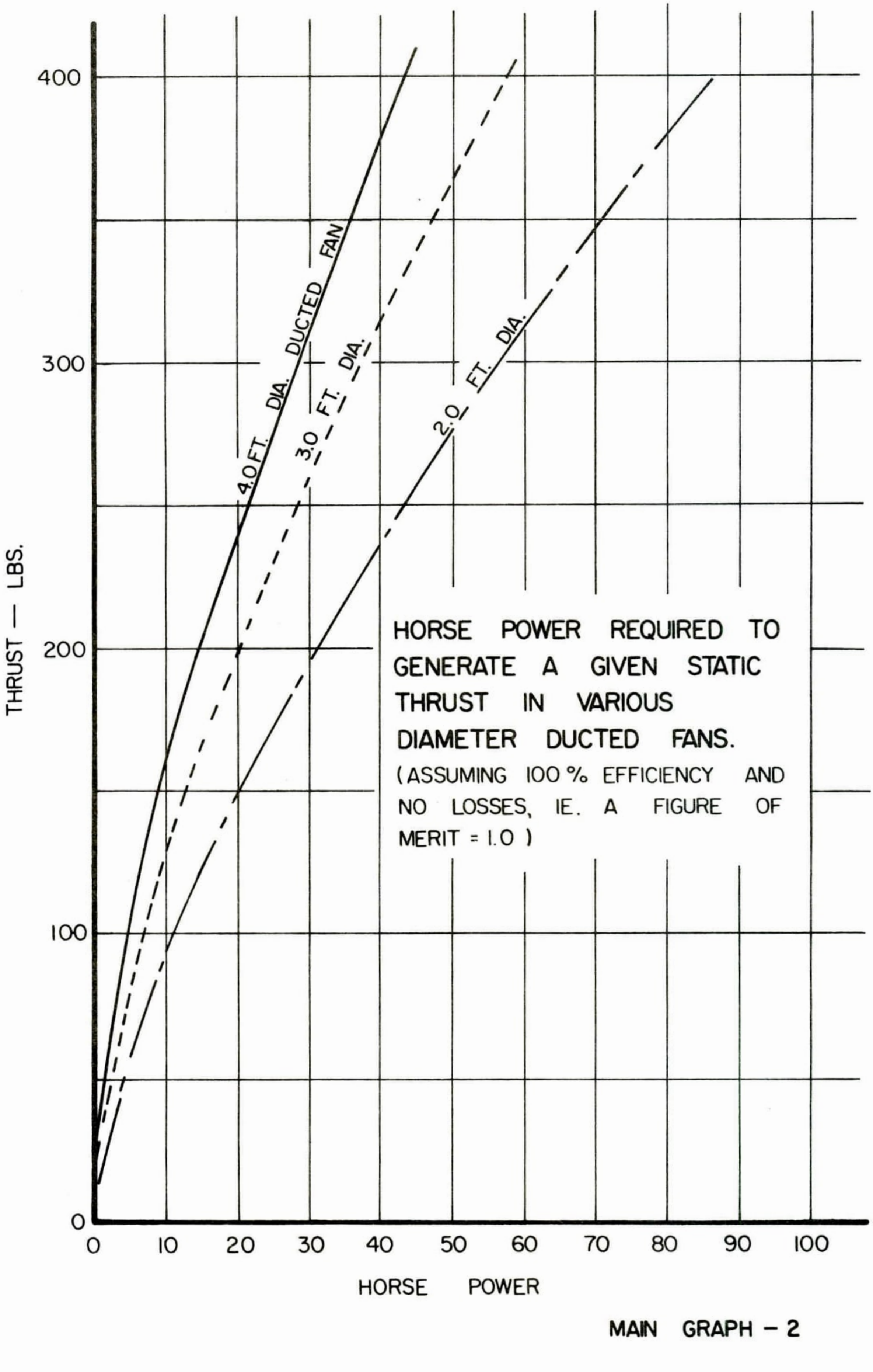
The following graph (Main Graph 2), derived from the Fan Performance Map, (Main Graph 3) gives this in numbers, and this thrust/horsepower obviously reflects vitally on the engine weight - although a larger ducted fan is heavier than a smaller one. But we must remember that this shows the efficiency in thrust/HP within the working range. It does not show the limit of the working range, or how to extend it. This is controlled simply by the C_L/Incidence curve of the aerofoil.

4(c)3. The Effects of Poor Inlet Flow

After seeing something of the way in which a fan generates thrust, we can look back at a particular aspect of the inlet flow, that is the effect of disturbances in it. Remembering the flow velocity triangle at the fan blade inlet,



It is clear that if the air inlet velocity alters, by altering its speed or its direction, and the fan blade continues to move at the same velocity (constant RPM), then the shape of this triangle will alter, the air incidence angle relative to the blade will alter, and therefore the operating point will move up and down the aerofoil curve,



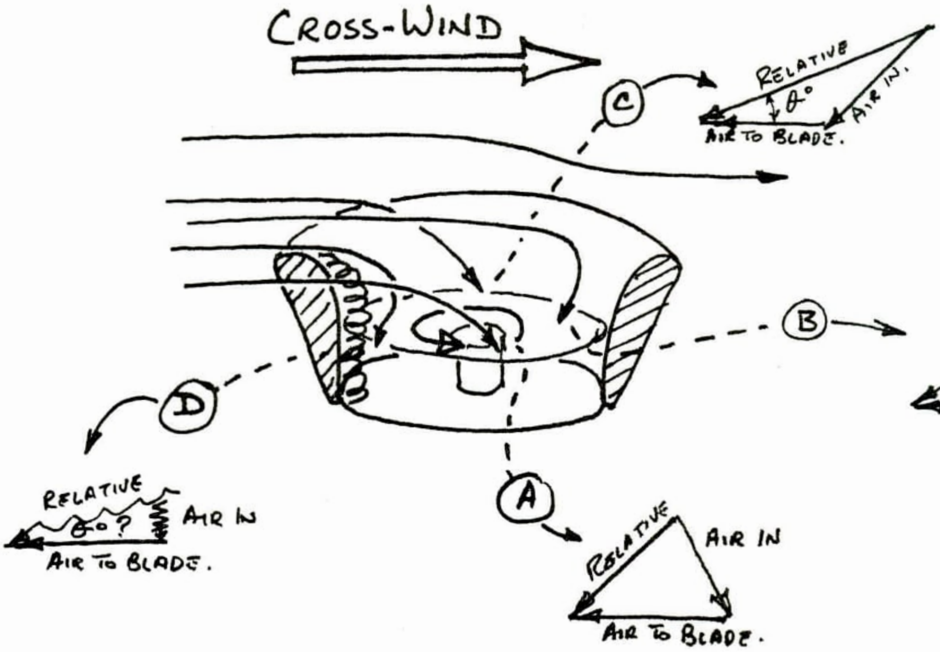
HORSE POWER REQUIRED TO GENERATE A GIVEN STATIC THRUST IN VARIOUS DIAMETER DUCTED FANS.
(ASSUMING 100 % EFFICIENCY AND NO LOSSES, IE. A FIGURE OF MERIT = 1.0)

MAIN GRAPH – 2

either losing lift (at lower incidence) or approaching stall (and maybe actually stalling) if the incidence rises.

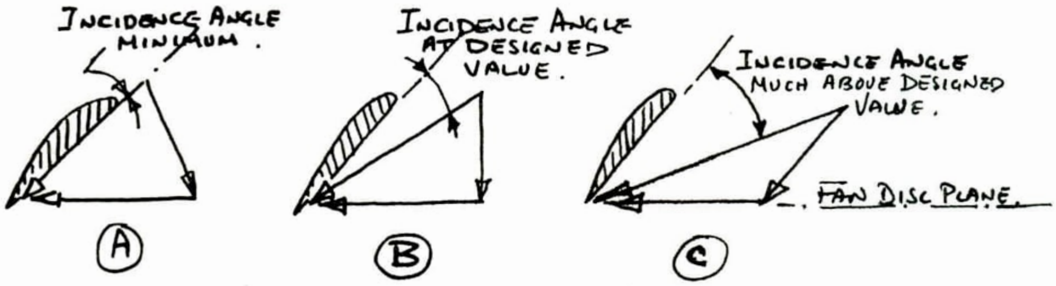
Several things can cause this, such as a side wind across the fan inlet, which can give odd inlet flow direction and can break away from the duct lip, and also the wake of an engine cowling or cockpit cover close in front of the fan. We must remember that ACVs may often operate in crosswinds with speeds comparable to the vehicle's speed, and that when running yawed along a side slope or in a turn an apparent crosswind is produced.

Looking for a moment at the effect of a crosswind on the inlet, we can see that its effects will be very much as shown here.



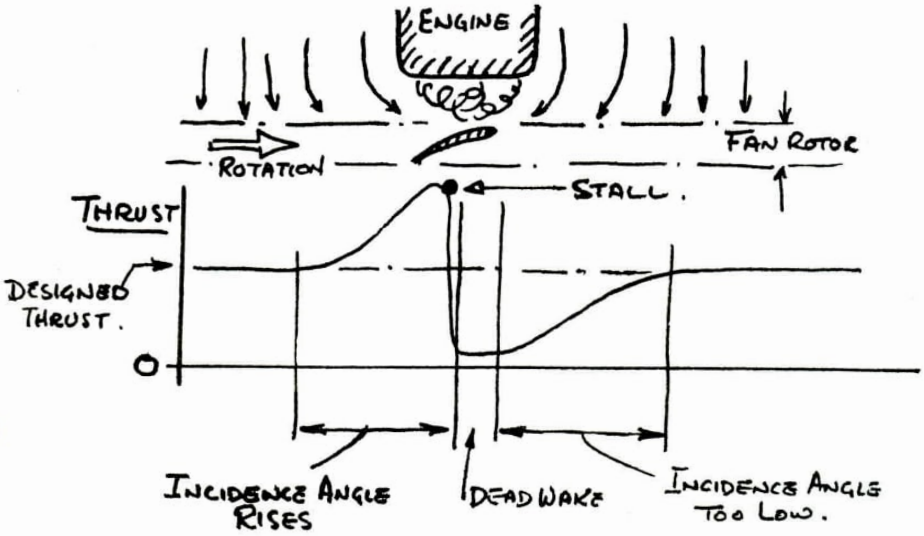
It is obvious that the air inlet angle relative to the fan disc plane, $\theta°$, varies as the blade makes a revolution, from a maximum at (A) through the design angle at (B), to a minimum at (C), and a somewhat indeterminate value in the broken-away eddies at (D). This means for one thing that the blade incidence angle, and therefore the thrust, will be varying rapidly through the revolution, possibly with stalled values at (C), at which point the incidence angle may have increased above the stall value, and at (D), where the flow may be dead.

The air velocity triangles at (A), (B), and (C) are repeated below, with the blade aerofoil added, showing this variation of the air incidence angle onto the blade.



As well as possibly reducing the average thrust value below the expected design value, this in turn imposes a cyclic variation of loading on the blade, which could lead to material fatigue.

A much more potent cause of fatigue is the presence of an engine or a thick blunt strut close in front of the fan. The wake from such an obstruction has two effects, in addition to being a powerful noise source. Firstly it produces a wake of low speed air or eddies which hits the fan blade once per revolution, and drops the axial air inlet velocity, with corresponding fall-off or fluctuation of load, and therefore thrust. Secondly, on each side of the obstacle as the airflow curves in to fill the wake behind it, the inlet angles to the fan blade change abruptly.



The suddenness of the load-change on the blades, as they pass through such a wake, leads to severe fatigue. Many cases of ACV fan and propeller failure can be traced directly to the presence of an engine directly in front of one part of the fan annulus.

Visualization of the flow, with wool tufts or smoke streamers, on a mock-up of the installation will give clear warning of such a state of affairs without waiting for the fan to fly to fragments.

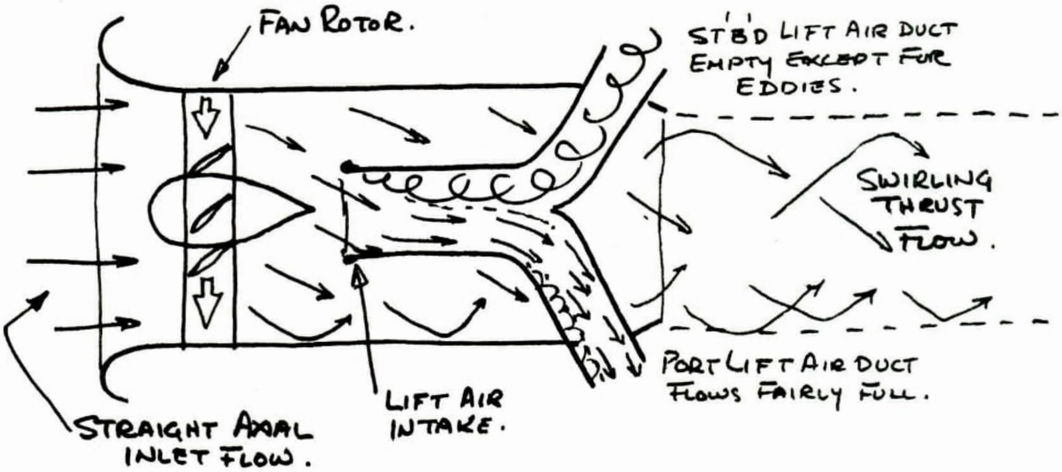
4(c)4. The Effects of Fan Swirl

Finally, we should think about the effects of swirl in the fan duct.

A fan does its blowing by adding energy to the airstream, and this is done by deflecting the air as it passes between the blades. This adds a swirl to the flow, and the amount of swirl is proportional to the thrust. If we wish, we can remove the swirl by a second set of blades which are really a second fan running at zero speed. These "stators" or "deswirl vanes" will remove the swirl, at the expense of a very small pressure loss. Swirl is apparently not much of a nuisance, so to save the small pressure loss, the weight, and the cost, the stators are usually not fitted to ACVs.

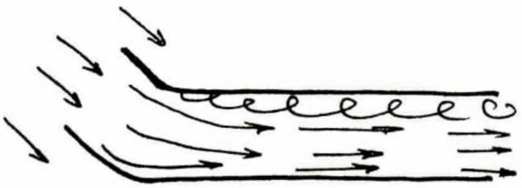
However, the swirl can have very serious side effects in some cases, so we had better examine the question carefully.

An example of the first kind of problem arises when a designer decides to use a single-fan integrated lift/thrust layout, "stealing" the lift air from the thrust duct. If the duct contains swirling flow, and the lift air intakes in it assume straight flow, the state of affairs can be as shown below.



Clearly, the swirl across the lift intake gives very poor distribution in this duct, breaking away from one wall and blocking half the duct with a mass of eddies. This loss of flow area leads to heavy losses and low flow in the lift system, and if a bifurcation to port and starboard ducts were introduced as shown, the starboard duct would be almost completely starved of air.

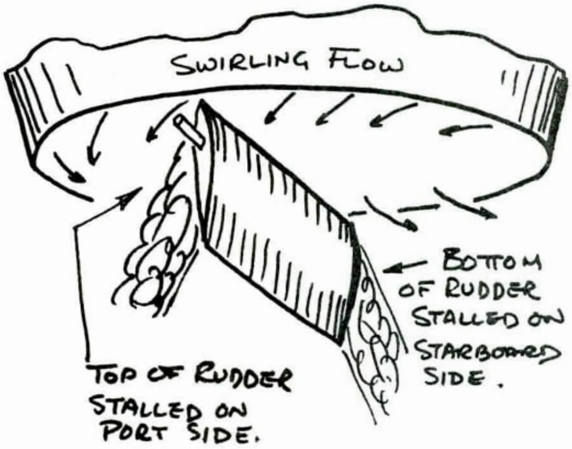
There are three ways of tackling this problem. A complete set of stator blades would eliminate the swirl, and prevent it ever arising, but is the heaviest and most expensive answer. A bent inlet to the lift duct, so that it is aligned to the swirl direction, is a partial remedy. The flow in the duct will probably detach further downstream, where the duct straightens out, and still cause trouble.



Probably the simplest solution is to put a cascade of turning vanes (in effect a small local element of the stator ring) in the inlet to the duct.

The second problem posed by swirling flow in the thrust duct is its effect on controls, such as rudders or thrust reversers.

RUDDER IN THRUST-DUCT EXIT.



The 20° or so of swirl often generated by a fan may well be enough to stall the top and bottom of a rudder, on opposite sides, as the figure shows. One could argue that the effects are equal and opposite and may be neglected. However, this means that two large areas of the rudder are useless, and the rudder may therefore be much less effective than the designer expected. Thrust reversers too may be put at a considerable disadvantage by the odd incidence angles imposed by swirling flow. In these cases a set of deswirl vanes, designed as an integral part of the fan aerodynamics, is the only satisfactory solution.

This problem arises even more acutely when the lower part of the thrust fan is obscured by the wake of a closely spaced engine, as is often the case in small ACVs. As the diagram above shows, with an anticlockwise fan rotation a left turn will align the top of the rudder with the flow and actually increase thrust, while the bottom of the rudder being in the engine wake is dead anyhow. On the other hand, a right turn completely stalls the top of the rudder while the bottom is still dead in the engine wake. Thrust therefore falls off badly, and the right-hand turning ability of the vehicle is marginal.

The writer recently spent some hours on two vehicles with this unhappy state of affairs, and found that the only way to get a sharp 90° right turn was to spin 270° left, which was not always convenient. Moreover, the increase of thrust from poor with right rudder, through moderate at neutral rudder to maximum at full left gave an accelerating left turn which was nothing short of vicious.

The same problem arises with unducted propellers, but since stators cannot be fitted in this case a cure is much more difficult to achieve. Oversize control surfaces, sometimes biased to accept the odd flow, have been used.

The remaining problem due to swirl in the thrust duct is concerned with diffusion. If a long duct is used, and there is much swirl in it, the flow will migrate to the outer part of the annulus under the centrifugal force generated by its rotation. The empty centre core left by the rotor hub will certainly never fill in with good flow while swirl is present, it will remain a dead core full of eddies. Calculations of exit velocity, flow velocity, flow quantity, and thrust, on which thrust and pressure loss figures are based, will therefore go sadly astray if the optimistic designer imagines that the flow is occupying the whole duct area, in a uniform manner.

A few minutes' flow-visualization, using a wool-tuft on the end of a wire rod to explore, will speedily cure this naive attitude.

Summary

The arguments for and against Ducted Fan (Propeller) Thrust Systems can be summarized thus:

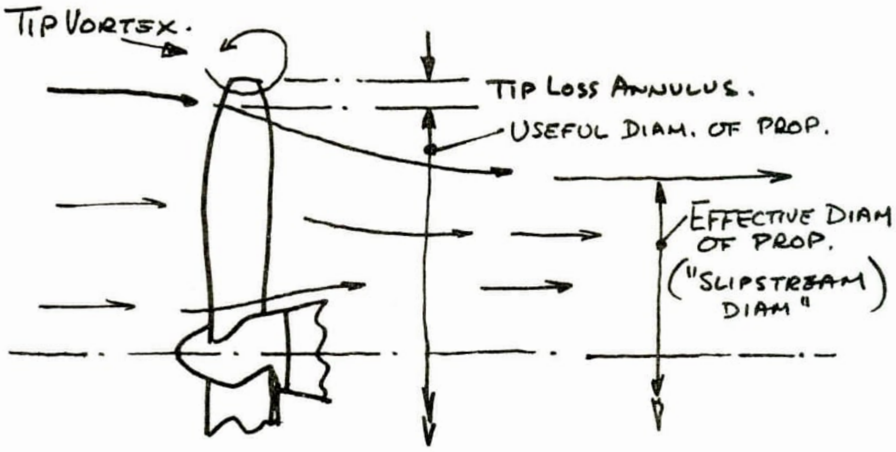
Advantages	Disadvantages
Best Thrust/H.P. ratio obtainable	Very sensitive to accurate selection of correct design point
Best Thrust/device volume obtainable	Very sensitive to control inputs
Can be made reasonably quiet	Max thrust/HP ratio implies large area, hence large diameter and high thrust line, with attendant nosedown moment at full power
Can be made light	
Can be relatively cheap.	Needs "clean" intake to avoid fatigue.

4(d) The Simple Propeller

Finally we consider the simple unducted propeller, usually a two bladed device.

As we saw in Section 4(c)1 above, the stream flowing through any fan contracts as it passes the fan, and the greater the acceleration of the stream by the fan, the greater the contraction. Therefore the ACV with its low forward speed (flow speed before the fan) and quite high jet speed to get enough thrust, will have a much larger contraction than a vehicle moving at higher speed, such as an aircraft. We also saw that a ducted fan forces this contraction to happen in the bellmouth duct inlet <u>before</u> the fan, thus using a fan rotor of diameter equal to the propulsive jet.

However, the simple propeller has no duct, and half the contraction takes place in the jet after the blades. The propeller disc is therefore considerably larger than the propulsive jet issuing from it. This effect is made even worse by the "wing-tip" vortices coming off the propeller tips. Because of the pressure difference between the front and back of the blades, a vortex rolls up and recirculates round the tips, if there is no duct to prevent it.



Owing to these factors, at static conditions the unducted propeller could be 40% greater in diameter than a corresponding ducted fan of equal thrust, although as the vehicle's forward speed increases the difference of diameter becomes less.

Even so, it becomes clear that at low vehicle speeds (say below 60 ft/sec, or 40 mph), the simple unducted propeller is at a decided disadvantage. It may be argued that the absence of the weight and cost of a duct may compensate for the bigger (and heavier) propeller, but a plain propeller requires some sort of a guard on an ACV to keep people out of it anyhow.

From the point of view of quietness the simple propeller is also a poor choice. Unless it has many blades, which is most unusual in an unducted propeller, it increases its thrust either by using very wide blades, or by running at high tip speed. Since most of the propellers used are ex-aircraft propellers, by reason of their ready availability, they have light narrow blades, and run at high tip speeds. The noise generated is abominable, but in an aircraft which is usually some distance from people this is tolerated. On an ACV which is right down level with people, it is not acceptable.

Special broad bladed propellers which develop more thrust than noise have been developed for some large commercial ACVs, at enormous expense, but for small vehicles the simple propellers available are usually inefficient and noisy.

APPENDIX

A SIMPLE ANALYSIS OF AIRFLOW THROUGH A ROTOR, WITH OR WITHOUT A DUCT

1. Unducted Rotor (Propeller or Fan)

The rotor raises both total and static pressure as the air flows through it, and since the axial velocity does not increase across the rotor disc, the dynamic pressure remains contant. Therefore total and static pressures rise equally. To return the static to atmospheric in the slip-stream, the velocity must therefore rise (no loss in jet, therefore total pressure stays constant) to increase the dynamic and drop the static to atmospheric as required. This must involve contracting the jet, to obey continuity.

It can be shown that (neglecting swirl, turbulence, preswirl, losses at jet boundary, and one or two other minor snags) the process is as below:

Summary

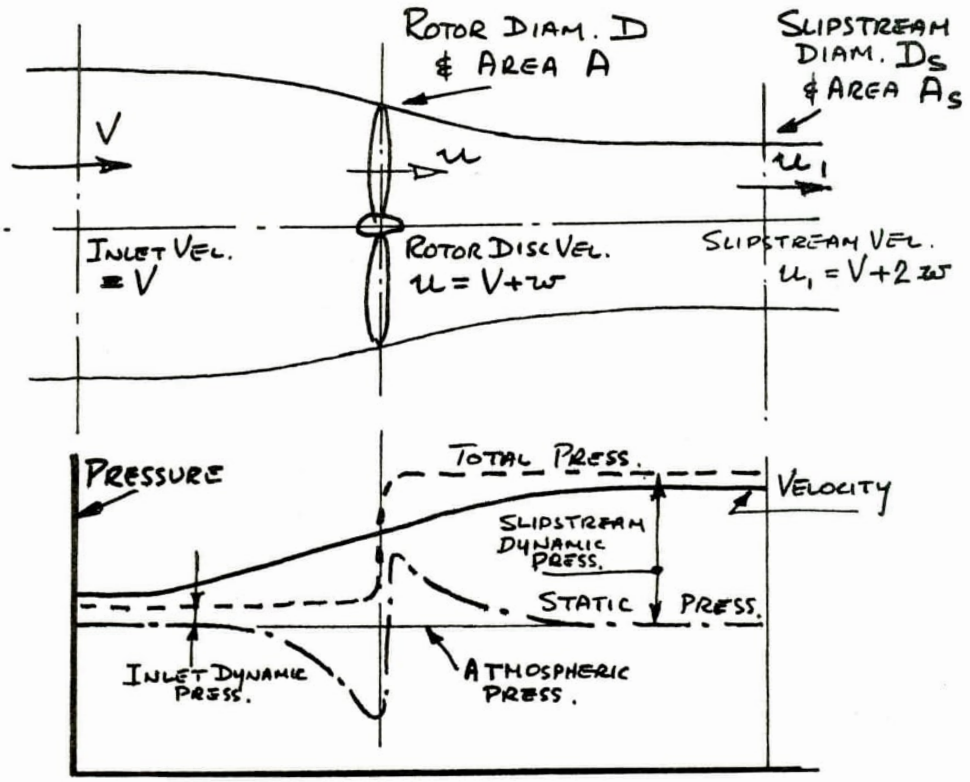
The arguments on the Simple Propeller can be set out as follows:

Advantages	Disadvantages
Cheap	Large compared with a ducted fan of the same thrust
Perhaps lighter than smaller ducted fan and duct.	Low thrust/horsepower ratio
	Noisy unless specially designed with broad "paddle blades" for low rpm
	Requires a guard ring, which offsets the absence of a duct.

5. Acknowledgement

It is hoped that these notes will be of some assistance in deciding on the most suitable propulsion system for a particular vehicle, and also in pointing out some of the traps the designer must avoid once his choice is made.

My sincere thanks are due to all my friends, both academic and industrial, in the A.C.V. community. Their occasional disasters may appear here as my "horrible examples", but their brilliant remedies also appear, as the ways of dealing with the problems. Tact forbids me to thank them all by name, but perhaps they will accept my gratitude for sharing their troubles and triumphs. I have learned much from them.

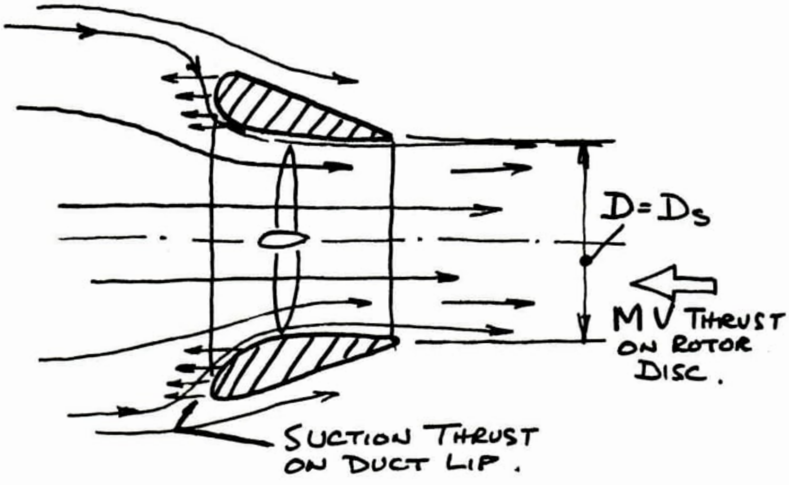


This curve shows the slow adjustment of jet static to atmospheric pressure after the fan, which causes the slow contraction of the jet.

It can further be shown, on the simple theory and assumptions stated above, that $A/A_S = 2$, for the static case. In practise, the ratio is somewhat less than 2, and decreases further towards 1 if forward speed is introduced.

2. Ducted Rotor

In the case of a ducted rotor a stationary annular aerofoil has been added round the rotor tip, and may be represented by a toroidal (ring) vortex. This alters the inlet flow to the rotor disc, and in effect causes the contraction of the jet to take place entirely ahead of the rotor disc, instead of half upstream and half downstream as in the unducted case.



This has two important effects. Firstly, the A/A_S ratio becomes 1, and secondly, the reduced static pressure on the leading edge of the duct due to the acceleration of the flow entering it produces a forward suction force on the duct. This can be shown to be of a magnitude equal to the thrust on the rotor disc, so that half the thrust on the whole rotor/duct assembly is that produced by the momentum change in the jet acting on the disc, and half is due to the suction on the duct in the static case.

Further, if the duct is given a divergent downstream duct profile, the jet can be diffused after the fan disc so that the area ratio A/A_S becomes less than 1, therefore increasing the effective rotor area.

However, in practise the full advantages of the duct are hardly ever attained, and in any case this added thrust would be at least partly paid for in increasing duct-drag, and in added horsepower required to generate the flow distribution round the duct which does produce this added thrust.

For one thing, if the full effect of the leading edge suction is to be gained, the duct has to have a large inlet radius which carries too high a drag penalty at forward speed to be tolerated. Again, although some ducts have a diffusing downstream profile, the fans very rarely have a stator row of blading, so that the swirl generated by the rotor is left in the slipstream. It is firmly established that diffusing flow in the presence of swirl is next to impossible as the flow is centrifuged onto the outer walls of the diffuser and leaves an eddying core of dead air in the centre. Also, the tip clearance between fan and duct is frequently excessive, for mechanical reasons, so that the duct flow suffers badly from this.

Poor inlet flow due to near upstream obstructions or crosswinds, and the presence of rudders etc. in the exit flow, both conspire further in the practical case to degrade the performance of both ducted and unducted fans below the theoretical propeller performance.

However, it appears clear that in practise a ducted fan will give far higher thrust per horsepower and per diameter than an unducted propeller.

3. Conclusions

From the foregoing discussion of the ducted and unducted cases, the following simple expressions for the thrust and power of both types of fan may be derived.

For a static fan:

Thrust = Mass Flow × Change in Velocity of air

$= \rho V A V_S$ (where flow is accelerated from zero velocity to slipstream velocity V_S)

$$\therefore\ T = \rho V A V_S \qquad (1)$$

Power = Rate of Increase of Kinetic Energy in jet (from zero at inlet)

= Mass Flow × Kinetic Energy of exit air

$$\therefore\ P = \frac{1}{2}\rho V A V_S^2 \qquad (2)$$

Hence by substitution, we obtain the key expression:

$$T = \sqrt[3]{\frac{2^2 \rho A P^2}{(A/A_S)}} \qquad (3)$$

<u>For an unducted propeller</u>, in which we showed that $A/A_S = 2$, this reduces to:

$$T = \sqrt[3]{2\rho A P^2} \qquad (3A)$$

<u>For a ducted propeller or fan,</u> in which we saw that $A/A_S = 1$ this becomes

$$T = \sqrt[3]{4\rho A P^2} \tag{3B}$$

A term from helicopter design is useful here. "Figure of Merit" is a form of fan efficiency, and is defined as:

$$\text{Figure of Merit} \equiv \frac{\text{Ideal Power Input}}{\text{Actual Power Input}} \text{ (for a given static thrust)}$$

The Ideal Power Input "P" is that needed to accelerate the jet mass flow (to produce the required thrust) neglecting the unproductive slipstream rotation, turbulence, and other losses. The Actual Power Input P_A is that measured on test to produce this thrust under these conditions.

It can also be shown that the total static thrust (shown in the graph) of a ducted fan is split into two equal portions; 50% is generated by the disc load on the fan blades, and 50% by the suction on the leading edge of the bellmouth inlet of the duct. This latter is of course inextricably bound up with the flow distribution which forces the jet contraction <u>before</u> the fan, and leads to a slipstream area equal to the fan disc area.

4. <u>A Ducted Fan Performance Map</u>

It is from the above expressions that we are able to construct the ducted fan performance map. (Main Graph 3, on page 56.)

This map is presented for ducted fans, and relates three useful parameters:

Disc Loading (lbs. of thrust per ft^2 of fan disc area).

Power Loading (Horsepower/ft^2 of fan disc area) and

Conversion Efficiency (lbs. of thrust obtained/horsepower).

In fact the "Disc Area" referred to is strictly the Slipstream Area A_S, but in the ducted fan (static case) we have shown this to equal fan disc area A. So for simplicity the Fan Disc Area is used.

The performance of a simple Unducted Propeller can be estimated for the same graph by using an area equal to HALF the propeller disc area, that is equal to the contracted slipstream area.

The Thrust referred to is the actual thrust required (or measured on test) in lbs.

The horsepower can be stated in either of two ways. Lines of Figure of Merit have been plotted.

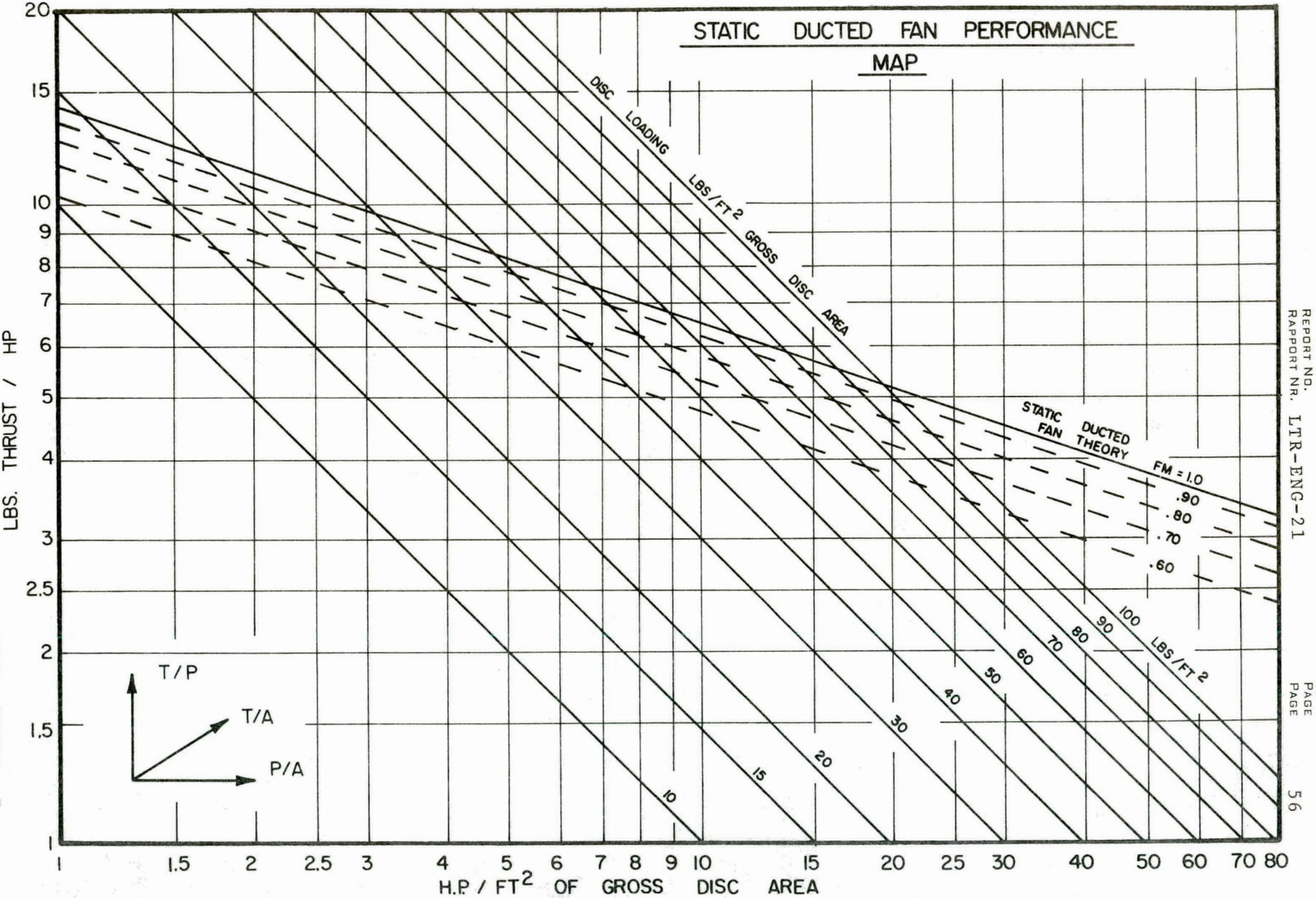
(a) If a Thrust and Horsepower are stated, then a horizontal line will intercept the line of Ducted Fan Theory FM = 1.0, vertically above the appropriate value of HP/ft^2, which will define the required disc area and hence fan diameter. However, in an actual case, the appropriate Figure of Merit line should be used instead of the "Ducted Fan Theory" line, which will result in finding a larger fan area, to compensate for the less-than-100% efficiency mentioned above in the definition of Figure of Merit.

(b) If a given thrust is required from a chosen fan diameter, then the intersection of this Disc Loading line and the appropriate Fan Theory × Figure of Merit line will show the Horsepower required.

At present data on Ducted Fan Figures of Merit is not readily available, but NRC experiments on an excellent but bulky design have given values of .92, while more practical designs have given values as low as .80, with some regrettable designs falling to .7.

Figures of Merit for Unducted Propellers are expected to fall in the range .7 to .8 under good conditions, but may fall somewhat lower, particularly if a propeller designed for fair forward speed in an aircraft is used at low speed in an ACV. Crosswind, or other unsuitable operation or installation conditions can further play complete havoc with these figures.

Finally, it is worth noting that in both ducted and unducted cases, it is not necessary to account for the loss of area due to the fan hub. The loss of area due to this blockage results in higher-than-calculated speeds in the jet, which are among the multitude of sins covered by the use of the Figure of Merit.


STATIC DUCTED FAN PERFORMANCE MAP
DISC LOADING LBS/FT 2 GROSS DISC AREA
STATIC DUCTED FAN THEORY
FM = 1.0
.90
.80
.70
.60
10
15
20
30
40
50
60
70
80
90
100 LBS/FT 2
T/P
T/A
P/A
LBS. THRUST / HP
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
H.P / FT2 OF GROSS DISC AREA
1
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25
30
40
50
60
70
80

MAIN GRAPH — 3