Applications of Ducted Fans

Why a Duct?

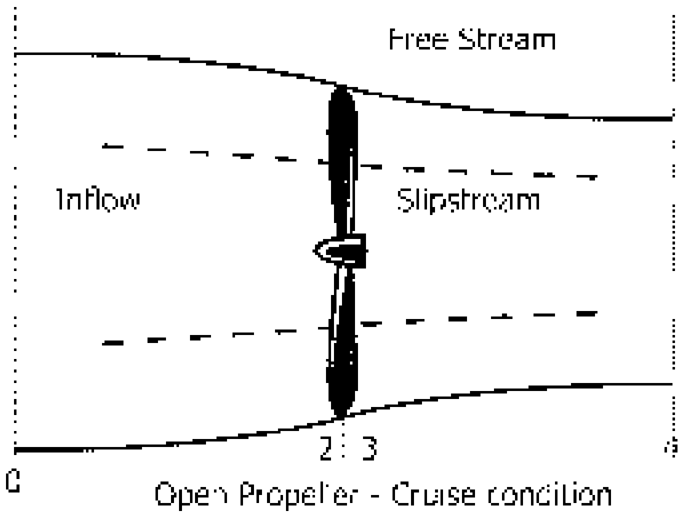
In recent years, there has been a steady increase in interest among both model and full-scale light aircraft builders in the use of ducted fans for propulsion. In the case of RC modelers, the reason for the interest is often esthetic—the builder wants to build a realistic scale model of a jet airplane, and nothing but a buried engine and ducted fan will do. This is also true of some amateur airplane builders who want a “jet-like” airplane that offers the illusion of flying a high-performance military job, but without the cost or the risk. Still others have specific design requirements, e.g. for high static and low speed thrust, or design constraints such as a ground clearance that limit propeller diameter.

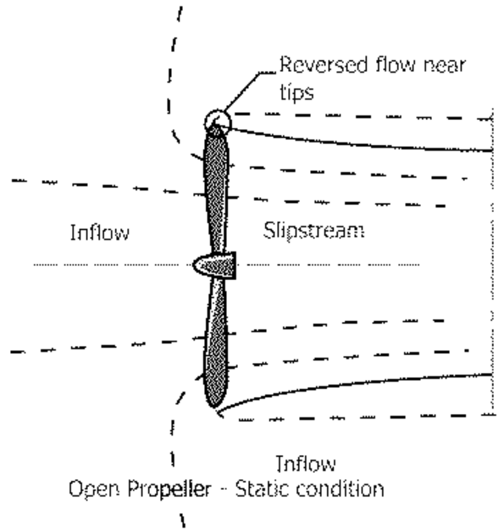
These designer/builders have read somewhere that ducted fans offer a higher static thrust/horsepower ratio for a given diameter than open propellers. Elsewhere, they read that ducted fans are useful for allowing large-diameter fans to operate at high speeds, and penalize low-speed performance to achieve this! Unfortunately, when they search for coherent written design guidance, they find that published information falls into two categories. At one end of the spectrum are the theoretical texts and technical papers written for professional engineers. The best of these texts are either admittedly out of print or are dishonestly listed by their publishers as in print, but are always “out of stock.” (Kuechemann and Weber has been “out of stock” for at least eighteen years to our certain knowledge.) At the other end of the spectrum are plans and construction manuals for specific projects, usually model-airplane related, that offer little information on scaling laws, still less on fundamental design principles. The model airplane and experimental aircraft Press sometimes publishes articles on specific ducted-fan aircraft, more rarely on ducted fans in general, but again the writers appear to have no understanding of their subject matter, as they frequently accept uncritically the claims of equally unqualified designers. The effect has been to leave the reader with a vague notion that fans can be a very good thing for someone, somehow, without clarifying to whom or how.

This chapter will summarize the advantages and limitations of ducted fans and list some of the applications in which they can do a better job than open propellers. We won’t go into the details of flow physics here, nor into the limitations of the breed. Design parameters influencing the performance of a ducted fan will also be discussed later. This is just a very brief explanation of the reasons that some engineers have for being interested in this class of propulsion machinery.

There are, as we hinted above, two major fields of application for ducted fans, at the high and low ends of the subsonic speed range respectively. The field of application that we have all experienced is the one least useful to us as light aircraft designers, namely the high speed range exemplified by the turbofan engines that propel the airliners on which we have all flown at one time or other. In these machines, low speed thrust/horsepower is sacrificed in order to make a ducted fan operate with reasonable efficiency at speeds approaching that of sound. More rare in our experience are low speed applications, typically VTOL aircraft and air-cushion vehicles. Here we will concentrate on static and low-speed thrust, because that is where the advantage of a duct is greatest and also because we won’t need any derivations to make the effects clear.

We start with the familiar diagram of an open propeller immersed in a stream of fluid; this is how cruising flight looks from the airplane’s point of view. The flow has three regions: the inflow into



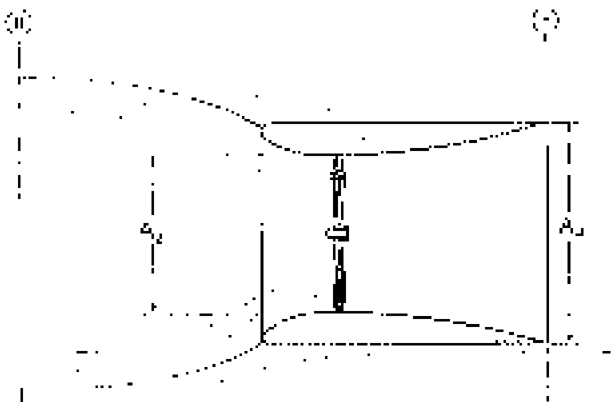


the propeller, the slipstream behind it and the free stream which doesn't go through the propeller. Propeller design calculations are all carried out in this regime. But before a 'plane can cruise it has to take off, and its takeoff performance depends on the performance of the propeller at low speed and at rest.

With the propeller immersed in a static air mass, the picture we saw earlier changes radically. Now there are two regions. The slipstream behind the propeller is familiar, but **there is no more free stream**; everything that isn't slipstream is in the inflow region. This means that the propeller is aspirating air from behind it as well as from in front. Consider now the plight of an intrepid air particle starting just outside the slipstream, behind the propeller. It has to go forward to the propeller disk, make a 180-degree turn, accelerate instantly and enter the slipstream. As real air particles have mass and therefore inertia, and as open propellers have to be lightly loaded at the tips, the result is that a region of reversed flow exists near the propeller tip. This diminishes the effective disk area of the propeller and restricts the amount of air able to flow through it, just when the highest mass flow is needed! Now take the same propeller and surround it with a close-fitting shroud having a nicely rounded leading edge, and see how the picture changes.

We still have only two flow regions, but now there is a solid boundary between them in the neighborhood of the propeller—the shroud or duct—and our air particle has a much easier time doing what is expected of it, because it need only flow around a duct lip or leading edge of finite radius. We can even provide the duct lip with a slot to help keep flow attached, as suggested and tested by Krüger. The duct also shields the propeller from the harsh realities of the outside world, and the propeller "sees" air flowing in only one direction—front to rear. In fact, from the propeller's point of view it is not at rest at all, merely cruising at some fraction of its maximum speed. What is more, the endplate effect of the duct wall allows the propeller to carry a non-zero load right out to the tip. The effects of all of this are that:

- Fewer design compromises are required; the ducted propeller operates nearer its ideal operating point throughout the aircraft's speed range
- The effective diameter of the ducted propeller is larger than its physical diameter. To understand why, look at the diagram of the open propeller at cruise and note that the slipstream contracts behind the propeller. Now look at the ducted propeller and note that the slipstream diameter is that of the duct exit. That larger diameter represents a smaller Δv and a larger mass flow—and by now we know that means higher thrust/horsepower.



Ducted Fan—Cruise Condition

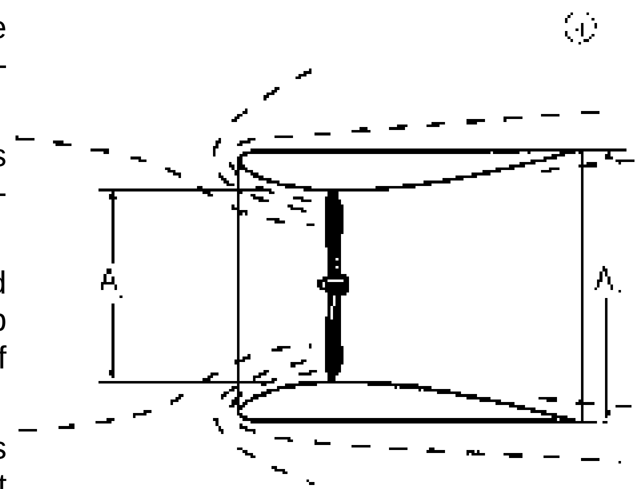
- While the propeller develops about the same thrust as before, there is now a second force acting on the duct. If the duct is shaped correctly, this force is additional thrust.

At cruise, the advantages are less pronounced and limitations more obvious, but we can still note that the effective area of the propulsor is approximately that of the duct inlet, which may be considerably larger than the swept area of the propeller itself.

We can note here a subsidiary advantage of the ducted propulsor, namely that it offers the possibilty of thrust vectoring and even thrust reversal.

Another area in which ducts offer advantages is noise suppression. Ducts allow noise to be reduced three different ways:

- Running the propeller under optimum flow and loading conditions eliminates the propeller-tip "buzz," a substantial component of the noise of a propeller-driven airplane.
- Enclosing the propeller in a duct allows various acoustic treatments to absorb noise before it can impinge on the ears of bystanders.



Ducted Fan—Static Condition

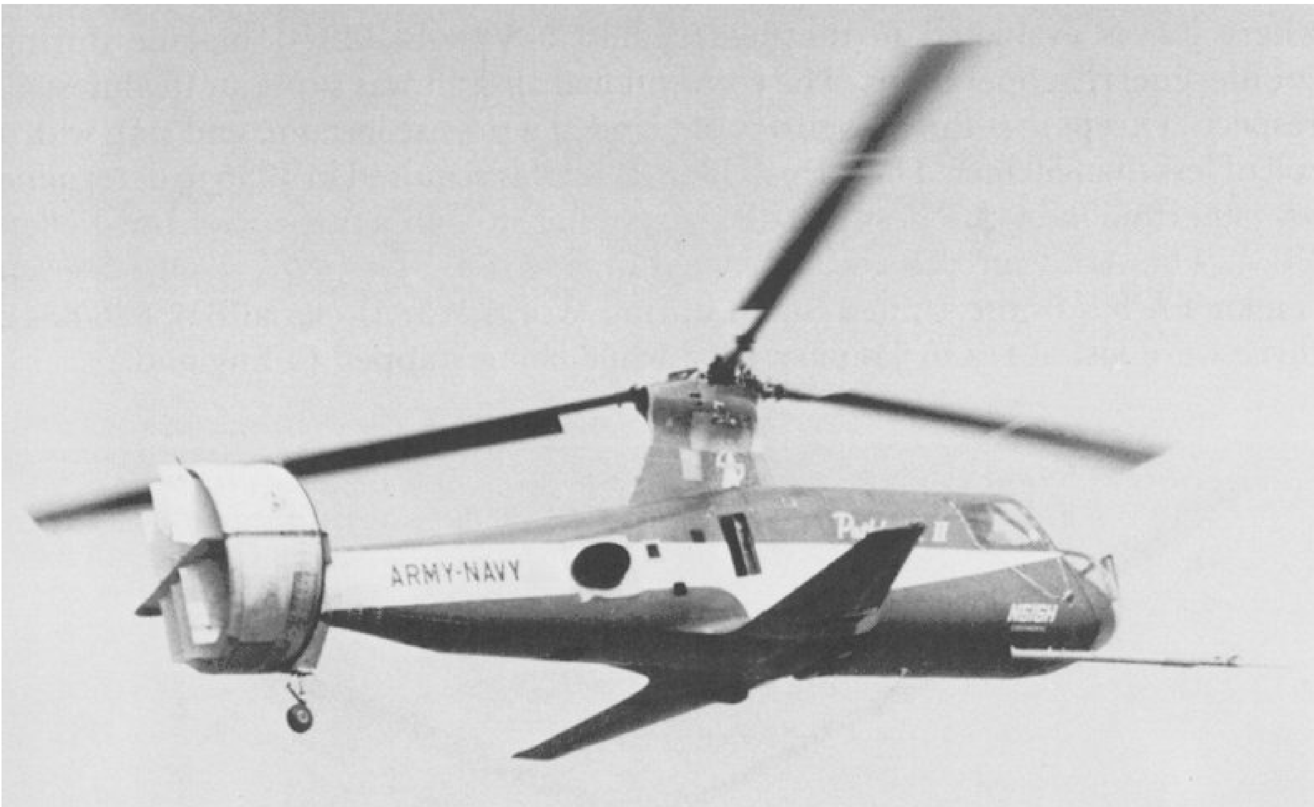
- By offering improved static and low-speed thrust, ducted fans make possible steeper climb-out, which in turn reduces perceived noise at the airport boundary, an important public-relations advantage.

Applications

The alert reader will already have chosen one or more applications based on the characteristics mentioned above. They include:

Autogyros

Although it can be argued that autogyros (rotorcraft whose lifting rotors are not powered) are not inherently high-induced-drag machines, nearly all the machines currently on the market or built from plans are designed for low takeoff and landing speeds rather than high cruise performance. As a result, they need a great deal of static and low-speed thrust from their powerplants. This already makes them good candidates for ducted fan propulsion, but another factor is now intruding, namely noise regulations. Autogyros are noisy! Ducted fans allow lower installed power, lower source noise and faster climb—all tending to reduced perceived noise.



Piasecki "Pathfinder"—a Compound Helicopter

Compound Helicopters

Compound helicopters are so called because they are hybrids of helicopters and fixed wing aircraft. In addition to having supplementary fixed wings to supplement rotor lift at high speeds, they are also provided with means of forward propulsion independent of the lifting rotor. Not all compounds use ducted fans, but their small diameter for a given thrust/power ratio makes them attractive in this application, as does the fairly modest top speed of application (compound helicotpers, though faster than conventional helos, are still limited by rotor tip speed and stability).

Seaplanes, Flying Boats and Amphibians

These require a great deal of thrust at low speeds in order to overcome wave drag and viscous drag while on the water. Once the hull (or the pontoon) is "up on step" and planing, drag drops considerably and the airplane can accelerate to takeoff speed.

The limited static thrust of open propellers has two unfortunate effects on the design of seaplanes and amphibians. Typically, engine horsepower is dictated by the "hump drag," the drag that must be overcome to begin planing (to "get up on step," in seaplane parlance), rather than by cruise requirements, so the airplane ends up carrying a lot of extra engine weight that is used only at the very beginning of each flight. This extra engine weight in turn cuts into payload.

Unable to exert much control over water drag, designers often try to keep total thrust required at low speed as low as possible by minimizing induced aerodynamic drag; this is accomplished through some combination of increased wing area and/or span and by eschewing the use of flaps for takeoff. Of course, the designs thus arrived at end up carrying a lot of extra wing at cruise speed, which imposes both a weight and a drag penalty.

MSU/US Army "Marvel" High Performance STOL Airplane
[SETP]

The only way to get better thrust per horsepower out of an open propeller is to increase propeller diameter. This of course creates clearance problems, requiring truly heroic solutions—very high wing positions or pylon-mounted engines or deep fuselages. One recent design mounts the engine on the top of the vertical tail! It is probably not necessary to point out the weight penalties these configurations impose, although in recent years materials with very high strength/weight and stiffness/weight ratios have become available and have made some wild designs at least feasible, though not necessarily practical. Another consequence of larger propellers is the necessity of geared engines to control tip speed—more weight!

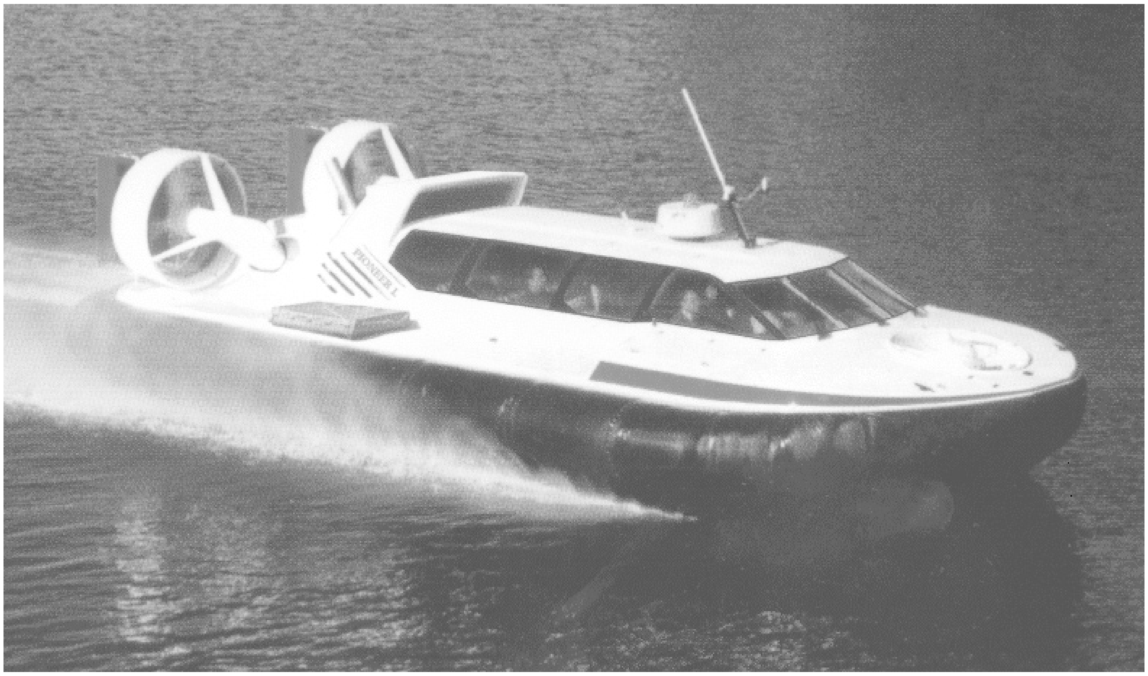
Ducted fans can help. First of all, they can achieve a higher thrust per horsepower for a given diameter, mitigating clearance problems and allowing the use of direct-drive engines turning high rpm. By making high thrust available at low speeds, they allow the use of higher wing and span loadings and the use of high-lift devices for takeoff. Finally, thrust vectoring and thrust reversal make mooring and taxiing much easier, but at a lower cost (and sometimes at a lower weight) than a controllable-pitch propeller.

Short Takeoff Aircraft

STOL airplanes need high static and low speed thrust, both for overcoming inertia to accelerate to takeoff speed and to counter the high induced drag at takeoff of wings operating at very high lift coefficients. In addition, aft-mounted ducted fans can provide additional static longitudinal and yaw stability at low speeds.

Vertical Takeoff Aircraft

Several VTOL aircraft have employed ducted fans in various configurations and capacities. The Ryan “Hummingbird,” for example, used fixed vertical-axis fans—one in each wing panel—to provide lift during VTOL and STOL operation. “Barn door” covers closed over the fan intakes and exhausts when they were not in use. More familiar shrouded lift/cruise fans were developed for other VTOL configurations. One Piasecki design used fixed fans with more or less horizontal axes, vectoring thrust with airfoil cascades in the exits. Another design (designation unknown to the authors) had swiveling ducted fans mounted at the tips of tandem wings. In every case,



Airlift 1060P Commercial Hovercraft [Airlift]

the high mass flow (hence high thrust/horsepower) per unit frontal area was the main reason for choosing ducts despite additional cost, complexity and manufacturing problems. The alternative, exemplified by the likes of the "Convertiplane" and the recently abandoned Osprey, is a very large-diameter open rotor reminiscent of helicopters but used for both lift and propulsion.

Airboats and Air-Cushion Vehicles

The arguments for seaplanes apply even more strongly to these vehicles. They have, by aircraft standards, a very narrow speed range, but need substantial thrust for overcoming surface drag and (in the case of the air-cushion vehicles) for driving uphill (e.g. up a boat ramp). Thrust vectoring is essential to air-cushion vehicles that must occasionally travel crosswind or traverse a slope, and can be achieved either by swiveling the duct or by employing a cascade of airfoils in the duct exit. A very special kind of ducted fan is that used to provide air-cushion vehicles with lift, although it is outside the scope of this book because it is not a propulsor.[1]

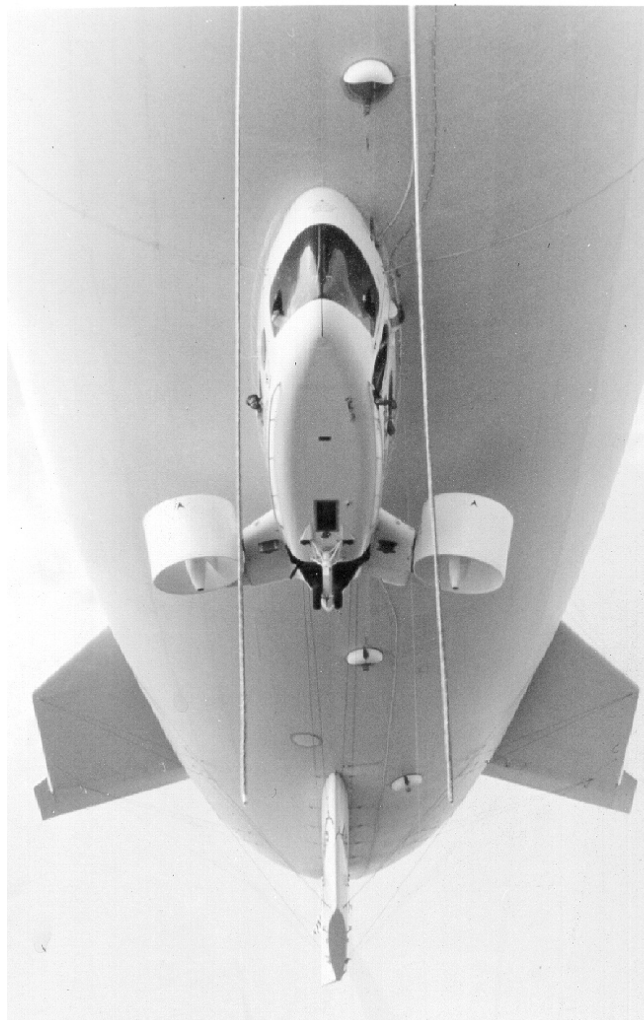
Wing-In-Ground Effect (WIG) Craft

Wing-in-Ground effect machines minimize induced aerodynamic drag by flying near the ground (or rather near the water, since they are less likely to encounter obstacles there). They are inherently low-speed craft, since induced drag loses its importance as speed increases and parasite drag becomes the dominant component. Their application—if they ever have one—will be carrying cargo and perhaps passengers over open water at speeds higher than those of surface craft but lower than those of conventional aircraft. WIG machines are ideal for ducted fans, because their cruise power requirements are even lower than those of conventional seaplanes, but their takeoff thrust requirements are as great or higher. Their narrow speed range

1 **Unless, as in some small air-cushion vehicles, a portion of the skirt flow is diverted to provide thrust. A fascinating design problem, not tackled in this book!**

completes the profile of an ideal fan application. Here considerable engine weight savings should be possible over WIG machines with open propellers.[2] The arguments concerning propeller clearance, taxiing, etc., used in the seaplane discussion, are equally applicable here. There is an additional reason for using ducts in WIG machines, and that is thrust vectoring in a vertical plane. Certain WIG schemes (e.g. Bardini) require that the jets from canard-mounted ducted fans be directed under the wing for liftoff, then redirected straight aft for cruise.

Airships



Airship Industries Skyship 600 Nonrigid Airship (Blimp)
seen from below. The twin Porsche-driven ducted fans are set for climb [AI]

Vectored thrust is the key to improving the economics of operating an airship, whether it's the monstrous rigid airships of old or the modern nonrigids (blimps). The ability to vector thust in the vertical plane allows an airship to take off statically heavy and to land light. As much as 25% can be added to the airship's useful load, which can be devoted to payload, extra fuel or both. Navy blimps routinely used rolling takeoffs to achieve the same thing, but vectored thrust allows vertical takeoffs and landing approaches, eliminating the need for a runway. Ducted fans, though not essential, offer the advantages of reducing the weight and size of the swiveling propulsor. Ducted fans can also be very quiet, as mentioned above; this is a big advantage to ships operating near the ground in populated areas, which they must do in order to be effective advertising media! The Skyship 500 and 600 non-rigids currently in service use dual car-mounted swiveling ducted fans driven by Porsche aircraft engines. They are very quiet, and watching one rise vertically in a level attitude from its mooring circle is a very different experience from the violent and noisy "up ship" maneuvers of conventional blimps.

...and Why Not

This discussion would not be complete without some mention of the drawbacks and disadvantages of ducted fans for aircraft. We have talked about their potential for high static and low-speed thrust, but we haven't talked about the cost.

2 **In practice the savings may not be fully realized, because of the necessity of providing reserve thrust for getting over obstacles that force the aircraft out of ground effect.**

As we will see later, a ducted fan with fixed exit area is optimized for one speed. So long as the speed range of the vehicle is low, there is no problem, but as the speed range increases it becomes increasingly difficult to get a satisfactory design. As speed range widens, first the exit, then the inlet must be provided with variable area. The mechanisms needed to do this add weight and cost to the design.

In this book, we will assume a speed range of 0-200 knots roughly. This allows us to design for cruise—which we must do in order to avoid a stiff drag penalty—while still ending up with a fixed duct geometry that can achieve decent static thrust.