Ducted Fan Design Issues and Errors

No discussion of ducted fans is complete without the obligatory horror story about so-and-so who tried to use a ducted fan on his design "and it simply didn’t work." The authors would be the last to claim that there are no disappointing designs out there—in fact, they are the reason for this book. But all the failures that we have seen resulted from neglect of the basic laws of physics or from a misapplication of this technology. Designing effective ducted fans is not rocket science, but it does require attention to the fundamentals. Here are the errors we found in our survey.

Copying Turbojet Inlets

The most common error is simply neglect of basic propulsion physics, which gets that topic its own chapter in this work. As shown more fully in that chapter, achieving the potential low speed benefit of a ducted fan in real life requires that the flow into the fan be accelerated. This requires a contracting inlet. What typically happens instead is that the designer copies the ducts and shrouds used in high speed turbojet-propelled aircraft, which have an entirely different purpose. Because of the high speeds at which those aircraft operate, flow into the first compressor stage of the gas turbine must be decelerated, or the first stage compressor blade tips would go supersonic, giving rise to heavy losses.

Another even more compelling reason for these expanding inlets is static pressure recovery. As the flow decelerates, some of its dynamic pressure is converted to static pressure, so the compressor “sees” inlet pressure that is higher than atmospheric. This reduces the amount of work done by the compressor, dramatically improving the overall efficiency of the turbojet. Of course none of this appies to us, and if we copy these installations we end up with mass flow reduction at cruise, that is the fan processes less air than if it were simply left out in the breeze. Small wonder there have been disappointments.

Copying Turbofan Inlets

Some designers have noted that the shrouds that carry bypass air through a turbofan engine have the same negative camber, decelerating inlet flow profile as the core engine inlets, even though the bypass air does not undergo any thermodynamic cycle. But in point of fact the first reason given above for decelerating the flow into a gas turbine—namely keeping the compressor-blade tips subsonic—goes double for the fan, which has a larger diameter. However beneficial it might be in terms of propulsive efficiency to have a positive camber, accelerating duct profile, it is not permissible on a powerplant for a Mach 0.8 aircraft.

High Pressure Ratios

This error stems from the same source as the one above, namely from designers copying turbojets. Gas turbines used in aircraft need high pressure ratios to achieve “efficiency,” so some designers struggle to achieve the highest possible pressures in their fans.

The key difference here is that the turbojet is both a fan and an engine; all the propulsive air must also go through the thermodynamic cycle of the core engine. Higher pressure ratios give the gas turbine better **thermal** efficiency, and that is why they are used.

On the other hand, the air flowing through our ducted fan is not being used to burn fuel and generate power; we are merely accelerating it to produce thrust. Higher pressure ratios in a ducted fan produce high exit velocities, and **power required goes up as the square of the exit velocity**. In order to achieve high propulsive efficiency (more thrust for a given power), we want the lowest exit velocity we can get, or in other words the highest mass flow.

Unrealistic Performance Goals

At the end of the chapter on duct applications we alluded to a disadvantage inherent in ducted fans, namely that they achieve efficiency only in a very limited speed range. Ducted fans optimized for low speed perform poorly at high speeds, while those designed to permit propellers to operate at high speeds actually hurt static and low speed performance. Yet some designers are mesmerized by the vision of a propeller-driven machine operating at high subsonic Mach numbers; at least one set his design team the goal of achieving Mach 0.8 with a piston engine driving a ducted fan. Any aircraft designed for that high a cruise speed has to have a duct and fan optimized for that speed—you simply can't allow the fan tips to go supersonic, because their aerodynamic efficiency suffers. Therefore you are stuck with decelerating flow into the fan, hence a mass flow augmentation factor less than one. This means that at low speed the fan is actually less efficient with the shroud than without. You end up with a conundrum—a machine that, if launched at cruise speed, could produce enough thrust to sustain it, but can't produce enough low speed thrust to accelerate to cruise.

If this is so, how can turbofan-powered aircraft, whose ducts are optimized for high speed, ever reach their cruise speeds? The answer is gas turbine power. The continuous combustion gas turbine has the highest power density of any internal-combustion engine, both in terms of volume and in terms of weight. Operators are willing to accept low propulsive efficiency at low speed; it simply means that they need more power to achieve a given thrust. That's not a problem for them, because the power is there. It simply isn't possible for a piston-engined airplane to carry enough installed horsepower to overcome the mass flow handicap.

Ignoring Powerplant Limitations

At least one designer has called his ducted fan, driven by a piston engine, a "cold jet." The term is not incorrect, since the device does produce a jet of air at ambient temperature. Unfortunately, it seems to imply a connection between this type of powerplant and a turbojet or turbofan engine. In fact they are different, and it's important for scale replica builders especially to understand that a jet-like appearance does not imply jet-like performance.

Recall from the previous chapter that power required is a function of both airspeed v_0 and mass flow $\dot{m}$. To put it another way, it takes **more** power to produce the **same** thrust at a **higher** airspeed. To get really high performance, then, we need a powerplant whose output increases with speed. That powerplant is the gas turbine.

The power output of a gas turbine depends on the performance of its compressor. The compressor benefits greatly from the ram pressure created by forward flight. As speed increases, compressor inlet pressure also increases, reducing the amount of work that the turbine must supply to the compressor, increasing output and actually improving efficiency. As speed increases, so does power, offsetting (up to a point) the additional power required. To a first approximation, then, a turbojet can be treated as a “constant thrust” powerplant.

On the other hand, piston engines get almost no benefit from forward speed, making them "constant horsepower" machines. This sets them a definite speed limit beyond which thrust declines rapidly.

The faster an airplane goes, the more propulsive power a fixed amount of thrust will produce, so the domain of the gas turbine is clean, low drag airplanes designed for high speed. A given thrust also gets you more speed at higher altitude, where lower air density reduces friction and "form" drag, so turbojets also benefit from high altitudes.

The piston engine loses engine horsepower with altitude, and that must be compensated with supercharging or oxidizer injection. That limits it to low altitudes, while the "constant horsepower" characteristic limits the piston engine/propeller combination to low speeds. So even if we build a jet replica using a ducted fan driven by a piston engine, we should not expect to mimic the original’s operating speed or altitude...only its looks.

Inlet Design; Cheater Holes, Blow-In Doors and Other Atrocities

The studies that eventually led to this book convinced us that propulsive ducted fan design is primarily duct design and only secondarily fan rotor design. We saw that, if we design for mass flow augmentation, fan loading is mild and the fan design consequently flexible and forgiving. Not so the duct. In particular the inlet is critical, and its shape is at least as important as its dimensions (much more important under static conditions, as we shall see). We can’t therefore help being discouraged when we see designers with full access to the literature concentrating on fan rotor optimization while neglecting inlet design. In particular we continue to see references to the use of auxiliary inlets like "cheater holes" and blow-in doors as remedies for supposedly inadequate inlet area—in particular to improve mass flow under static conditions. This thinking reflects, we think, an incorrect assumption concerning the form and function of the inlet, and neglects an important design point as well.

The design point should be obvious: **auxiliary inlets are inlets**! They must fulfill all the conditions imposed on the "regular" inlets, or the designer is wasting his time. Clearly, cheater holes cannot be good inlets and still be cheater holes, as they are typically cut into the side of the duct some distance downstream of the "real" inlet. The regular inlet is a nozzle, inducing air from the atmosphere and gradually accelerating it into the fan rotor, gradually converting part of its static pressure to velocity with minimal loss in total pressure. The cheater hole, on the other hand, is a sharp-edged orifice with an abrupt discontinuity in static pressure across it. Flow through such an orifice is very different from that through a convergent nozzle. Much of the pressure difference is converted to turbulence (and ultimately to heat), a loss of usable energy that will be reflected in the fan’s performance. Furthermore, the jet issuing from the orifice is fully separated from the orifice’s walls, so you have a slug of air entering at right angles to the prevailing flow inside the duct, constituting a blockage to the "regular" flow! The result is a smaller effective flow area. Blow-in doors appear to be less objectionable—after all, they only open when they’re "needed." The problem here is that, if the duct was properly designed in the first place, the static pressure inside will always be lower than outside, activating the blow-in doors at all times! With the door itself as a flow deflector and perhaps careful shaping of the downstream edge of the opening, one could at least hope for attached flow downstream of the door, but actual experience with the Jethawk suggests this is not achieved in practice—the "vacuum cleaner" noise described by builders indicates separation vortices being shed into the fan. The blockage is there still, with the extended doors serving as flow restrictors on the "regular" inlet flow.

As to the need for auxiliary inlets, consider the nature of the flow at static conditions. As we explained earlier, static flow has two regions—the inflow and the exhaust jet. There is no free stream. One consequence of this is that capture area, which is finite and calculable at cruise, is infinite in the static condition. Hence, no matter how large the inlet is made, the capture-to-inlet velocity ratio $\frac{V_0}{V_1}$ will be infinite. It is difficult under these circumstances to define an "adequate" inlet area—what percentage of infinity is enough? No matter what we do, there will be a sharp suction peak on the duct lips. It's what happens just downstream of that suction peak that determines the static performance of the duct. Our goal is to make sure that the flow stays attached to the inner wall of the duct, which means we need to provide the boundary layer, in particular, with a decreasing pressure gradient clear to the fan rotor. Let's think in terms of velocity and velocity change (since these are always finite), keeping in mind that by continuity an increase in velocity means a decrease in static pressure, and vice versa. We also need to introduce without proof some facts about camber, alluded to earlier. By camber we mean the curvature of the graph of flow area vs. streamwise coordinate called "longitudinal duct profile." We need to know that:

- Inward camber (convex down in the plot) helps induce flow into the duct and to accelerate the boundary layer, both desirable effects. Outward camber has the opposite effect.
- The local effects are the stronger, the greater the local curvature (that is, the smaller the local bend radius).

With these facts, we know that the physical inlet area must be greater than the fan area, or we can't maintain flow acceleration from inlet to fan. We also know that the duct lip must be highly cambered (convex inward) and have a generous radius to accomodate the high static-flow suction peak without separation. Camber can (and generally should) gradually decrease to zero at the fan plane. There doesn't seem to be any problem with plain conical exit nozzles.

Assorted Ducted Fan Design Questions
Fan Placement, Boundary Layer Aspiration

Fan Placement: Inlet, Throat or Exit?

One question that we have successfully dodged so far is the question of the best placement of the fan plane. Is it better to place it in the entrance to the duct, à la Stipa? Is the duct exit plane a better location? Finally, is the intermediate position assumed so far the best?

Well, what are our design goals? We would like to achieve:

- good fan efficiency over the aircraft's entire speed range
- the lowest fabrication cost we can manage
- an installation that is easy (and therefore cheap) to maintain.

With that in mind, let's first consider a forward fan. One obvious advantage is ease of access to the fan for maintenance and inspection, and the obvious disadvantage is that the inlet must be circular and unique—multiple inlets imply multiple fans. What about efficiency, though? One of our key arguments for ducted propulsors in general is that a properly-designed duct "shields the propeller from the harsh realities of the outside world..." But that is not strictly true of an inlet-mounted propeller. Although the duct's influence, even at cruise, extends some distance forward of its physical inlet, the entrance-mounted propeller must "see" more of the raw inlet flow's character than one mounted inside; both average velocity and inflow-velocity profile will vary more than for a "buried" fan. Figure 6-5 in Küchemann and Weber shows the strong radial variation of inflow velocity for an entry-mounted propeller compared to a very even distribution for a centrally-mounted one. What is remarkable is that these figures apply to what we call a shrouded propeller, with shroud chord equal to only half of the propeller diameter. This points to our primary reason for restricting our current discussion to a buried fan—it is compatible with our design method, in that it allows us to assume a radially uniform inflow velocity at the fan plane.

This still leaves the exit-mounted fan to be considered. A priori, it seems to have some advantages. In a duct designed for moderate to high cruise speeds the exit area will typically be the smallest duct cross-section, allowing the use of a small-diameter fan. The obvious disadvantage is that the exit area is constrained to be unique and circular. This might be a very troublesome constraint, because it eliminates any opportunity we might otherwise have to incorporate variable exit area and/or thrust vectoring.

Boundary Layer Ingestion vs Boundary Layer Bleed or Diversion

Modern turbojet engine installations, especially on high performance aircraft, are often provided with ways to prevent the turbojet from ingesting the fuselage boundary layer. Typically, these are either spacers—like those on the chin scoop of the F-16—designed to allow boundary layer air to slide by between the inlet and the fuselage, or suction slots designed to remove the boundary layer from the incoming air. Küchemann and Weber, in their discussion of inlets, devote much space to what they call "approach loss," namely the loss of total pressure of the incoming air due to boundary layer development ahead of the inlets. This is potentially a serious problem in turbojet installations.

First, the most common ducted propulsors in use today are turbojet and turbofan engines. In these engines, inlet conditions are the same for the core engine and for the propulsor. In other words, the air that participates in combustion and the air that is merely accelerated for propulsive effect come from the same source. Gas turbine efficiency is very sensitive to the efficiency of the compressor, which needs to get "clean" intake air to work well; even a very small increase in compressor work causes a drastic decline in output and efficiency. This gives rise to the use of boundary layer diverters, internal boundary layer bleed and other measures used in modern jet aircraft to ensure that, to the extent possible, the buried jet engine gets air initially at free stream conditions. The point here is that this is a core **engine** problem, not a propulsor problem.

In a piston-engine driven ducted fan, this core engine problem does not exist. In the first place, air/fuel mixtures in piston engines are nearly stoichiometric, so mass flow per unit power through the core engine is much lower than for a gas turbine. Second, positive displacement machinery is much less sensitive to inlet head loss (which can in any case be compensated by turbosupercharging). Third, it is easy to provide a separate inlet for engine air.

Conclusion: once we get away from gas turbines, core engine efficiency and propulsor efficiency become separate issues.

Second, because the inlet of a turbojet installation is a diffuser—that is a widening channel designed to reduce speed and convert dynamic pressure into increased static pressure—the pressure gradient in the inlet is unfavorable and the flow shows a greater tendency than in accelerating inlets to separate from the wall of the duct, restricting effective flow area and degrading static pressure recovery. Admitting already-depleted air from the fuselage boundary layer is asking for trouble. Worse still, the air ahead of the inlet is already being decelerated, so the boundary layer has grown considerably before even reaching the inlet.

A properly designed ducted fan will have accelerating flow into the inlet, giving a favorable (negative) pressure gradient. This in turn keeps the boundary layer thin and encourages it to stay attached. The small amount of boundary layer air that does get in can actually **increase** propulsive efficiency. How?

Effect of Boundary Layer Ingestion

For our purposes boundary layer diversion is not only unnecessary—it is undesirable. Ingesting boundary layer air can improve overall propulsive efficiency. For a complete derivation, see the paper "Wake Ingestion Propulsion Benefit," cited in the Bibliography. Briefly, the reason relates to the basic physical relations governing propulsive efficiency. Recall that:

$$P = 0.5T(2v_0 + \Delta v) \qquad \text{(power)}$$

Note that power required to achieve a given thrust increases with increasing inlet velocity. The notation in the above equation assumes that the inlet velocity of the propulsor is the free-stream velocity. With this assumption, power required to produce a given thrust increases with increasing airspeed. But now suppose that we ingest air from the boundary layer, at some average velocity v_{BL} less than v_0, instead of free air at velocity v_0. **The result is a decrease in power required**, all other things being equal. In theory, the ideal propulsion system would ingest only boundary layer air, accelerating it back to free stream speed. In theory, such a system has a propulsive efficiency (based on free stream velocity, remember) greater than 100%. In fact, tests at realistic Reynolds numbers of wake-immersed propellers (torpedoes and airship models with stern propulsion) have demonstrated η_p of up to 120%. Why then do jet aircraft incorporate boundary layer diversion? Simply because the **thermodynamic** efficiency of the gas turbines powering them requires that the compressor be fed with air having the highest possible total pressure—meaning free-stream air—irrespective of propulsive efficiency concerns, and because as already mentioned there must be static pressure recovery in the inlet.

What interests us here is the effect on the efficiency of the propeller of ingesting boundary layer air, that is air that is moving at less than free stream velocity. Interestingly, the efficiency of the propeller **increases**. The propeller produces its share of thrust by imparting a fixed increment of velocity to the air mass flowing through it. For thrust-producing purposes, it doesn’t matter if the air came in at free stream velocity or at a much lower one--only the velocity **change** produces the force. On the other hand, the power required to accelerate slow-moving air is less than that required if the air started off at a higher speed. This is of course the secret of the wake-adapted propeller, and in a sense a long duct ingesting boundary layer air is a wake propeller turned inside-out.

This insight leads us to some interesting--and unconventional-- design precepts:

1. In a long duct, viscous effects favor placement of the propeller farther to the rear than the optimum for ideal, inviscid flow. This is because the propeller can actually recover some of the energy otherwise lost in duct wall friction upstream of it.

2. Far from avoiding ingestion of boundary-layer air, designers of ducted fans should try to ingest as much as possible of the external body boundary layer to recover the propulsive work that it represents.

This offers a fascinating design problem, since a typical buried duct will have its inlet well forward. One solution is to place the fan at the extreme rear of the duct, just at the exit. In an augmenting (accelerating) duct designed for moderate to high speeds, the flow area will be contracting, and the static pressure inside the duct will everywhere be lower than that of the free stream, and steadily decreasing aft of the fan. This means that, in a fan-in-fuselage design, we can provide an auxiliary inlet near the tail which will aspirate the fuselage boundary layer before it is shed into the wake. The low internal static pressure guarantees aspiration, while the favorable internal pressure gradient and the small boundary-layer mass flow makes separation of flow inside the duct unlikely, provided of course that the auxiliary inlet is correctly shaped.

Fan design will not be straightforward, because the fan will see a ring of slow air surrounding a core of faster-moving air. With the auxiliary inlet far aft, there is little opportunity for the two flows to mix--not that we want them to, as mixing creates a shear layer, much of whose energetic vorticity is not recovered by the fan.

Obviously, there are costs and losses associated with this scheme, in addition to the problems mentioned earlier in connection with fan placement. Only an analysis of the aircraft as a whole can determine whether there is a net improvement in efficiency. As you might expect, the biggest benefit of wake ingestion is found when it is applied to "dirty" bodies—that is bodies with thick boundary layers. It makes sense to build the cleanest airplane you can in most cases, so there may simply not be enough energy there to be worth recovering. Another point is that the energy recovered is that of skin-friction drag. If your machine operates in a regime where induced drag is the dominant component (as in an optimized Wing-In-Ground effect vehicle), there too wake ingestion has little benefit.

Fan design for such an hypothetical propulsor would be complicated; the simplified method of fan design that we offer here would not be adequate, as it assumes uniform inflow velocity to the fan plane.