Ducted Fan

(G) The ducted fan can provide vectored thrust using exit deflectors, something much harder to implement with free propellers.

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Related terms:

Compressor, Propeller, Rotors, Turbines, Propulsion System, Unmanned Aerial Vehicle, Drone

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Fan noise

Stewart Glegg, William Devenport, in Aeroacoustics of Low Mach Number Flows, 2017

Abstract

This chapter will discuss the application of aeroacoustic theories to the prediction of ducted fan noise. The focus will be on a fan in a circular duct with a centerbody as a model of a typical aero engine, but the methods are also applicable to other geometries. The most important difference between a ducted fan and an open rotor is that the in the ducted fan the acoustic sources excite duct modes that are determined by the boundary conditions at the duct walls. This has a large impact on how the acoustic sources are coupled to the acoustic far field outside the duct and this chapter will show how these effects are modeled.

> Read full chapter

Axial-Flow Compressors and Ducted Fans

S.L. Dixon B. Eng., Ph.D., C.A. Hall Ph.D., in Fluid Mechanics and Thermodynamics of Turbomachinery (Sixth Edition), 2010

Publisher Summary

This chapter presents the basic characteristics of axial-flow compressors and ducted fans. It also covers the analysis of axial-flow compressors stage (mean-line analysis, velocity diagrams, thermodynamics, and stage loss relationships and efficiency) and axial-flow compressors rotors. Many axial compressors are multi-stage devices and repeating stages are initially assumed in which the velocity triangles for all stages are similar, the mean radius is constant, and the axial velocity through the machine is constant. The chapter covers the main preliminary design considerations such as stage loading, flow coefficient, reaction, inter-stage swirl, and blade aspect ratio. This includes a new presentation of the ways through which the measurements of cascade loss and turning can be translated into the performance of a compressor stage. Both incompressible and compressible cases are covered in the chapter and the huge importance of off-design performance is presented in detail including the ways a designer can influence compressor operating range during the very early design stages. For preliminary design and analysis purposes, a multi-stage compressor is thought of as a series of single-stage compressors, each performing as it would in isolation. However, to understand the performance of a real machine, the behavior of the overall system must be considered in more detail. This is particularly important to understand the sources of loss in a compressor and the off-design operation.

> Read full chapter

Thrust Modeling for Propellers

Snorri Gudmundsson BScAE, MScAE, Ph.D., FAA DER (ret.), in General Aviation Aircraft Design (Second Edition), 2022

15.5.2 Formulation for Shrouded Propellers and Ducted Fans

A ducted fan refers to a propeller enclosed by a cylindrical wing. The propeller is also called *rotor*. Some basic dimensions for a ducted fan are given in Figure 15-43. If the chord of the wing (*cduct*) is less than the diameter of the enclosed rotor (*DR*), it is called a *shrouded propeller*. If larger, it is called a *ducted fan*. This section attempts to provide basic information about such thrust devices.

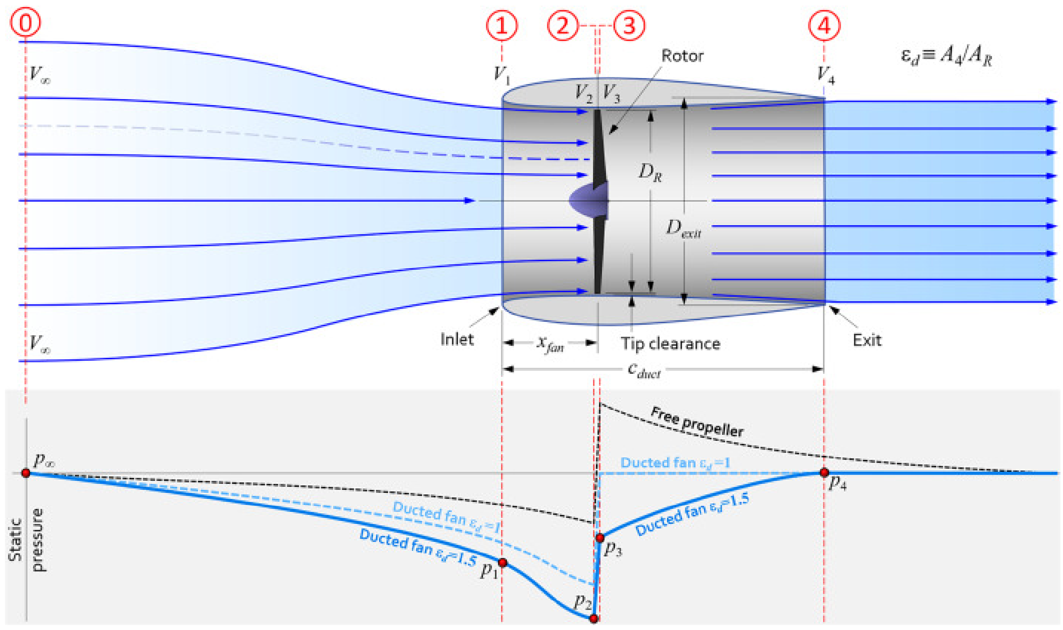

Figure 15-43. Idealized flow model for a ducted fan. Lower graph shows change in static pressure as a function of position (inspired by ref. [27]).

Aviation history reveals only a handful of fixed-wing aircraft powered by ducted fans.[14] Among those are the Airbus E-Fan, Cessna XMC, Edgley Optica, MS State University's XAZ-1 and XV-11, Rhein-Flugzeugbau RF-1, Fantrainer 400, and 600, and the Stipa-Caproni.

(1) **Pros of Ducted Fans**

(A) The exit area of ducted fans may be larger than the prop's disc area. This reduces the exit velocity and increases mass flow required to produce given thrust. Thus, its thrust generation uses less power compared to a free propeller (see Section 15.5.1(3)). Alternatively, it is possible to develop a given thrust using a smaller diameter rotor. (B) Smaller piston engines (intended for LSA or kitplanes) often run at much higher RPMs (e.g., Rotax 912 runs at about 5800 RPM), requiring a gear reduction unit to keep tip speed subsonic. It may be possible for a ducted fan to do away with the gear reduction unit by allowing a smaller diameter rotor. (C) Improved protection from FOD and for people walking around the aircraft with the rotor spinning. (D) A tight tolerance duct works like an endplate for a lifting surface (prop blade). This reduces blade-tip lift losses, increasing thrust for a given prop disc area. Thus, given the same disc area, the rotor blades of the ducted fan develop greater thrust than free propellers (assuming the same blade geometry and number for both). (E) The duct can serve as an effective noise suppressor. (F) If properly shaped, the duct develops supplemental thrust. (G) The ducted fan can provide vectored thrust using exit deflectors, something much harder to implement with free propellers. (H) Some people find the device attractive.

(2) **Cons of Ducted Fans**

(A) The wetted area and geometric interferences of the duct adds drag to the airplane. (B) The duct adds weight (although this may be offset by the removal of a gear reduction unit). (C) It is an additional component to be manufactured, adding acquisition and maintenance cost for the customer. (D) Duct must be designed for a specific cruise condition for improved system efficiency. (E) Duct requires tight tolerances between the blade tip and internal surface, which increases cost of manufacturing. (F) The duct contributes to stability of the aircraft. If flow is separated on one side, the consequence is undesirable asymmetric lift and moments (e.g., see [28, 29]). (G) Ducted fans are better suited for lower speeds than free propellers. Note that the fan of a turbofan engine is (a) most effective at high M, whereas at low speeds, the thrust is largely generated by the hot section and (b) a turbofan is a fan + engine that requires the thermal cycle to be considered in addition to the movement of mass of air. Of course, the efficiency can be improved at higher airspeed, but only with reduced low-speed performance (unless variable pitch is employed). See ref. [30] for more drawbacks.

(3) **Thrust, Power, and Propulsive Efficiency**

Investigation of the ducted fan dates to 1944 to work by Krueger [31]. This was followed by contributions by Kucheman and Weber [32]. Experimental work is presented by Mort in refs. [33, 34]. Additional information on ducted fan design is provided by Sheehy [35] and Yılmaz *et al.* [36], to name a few, with the latter reflecting a recent renewed interest by researchers. Ducted fans are analyzed using the momentum theorem, just like free propellers. The presence of the duct introduces important changes to the flow-field. For instance, the static pressure behind the fan increases to ambient static pressure at the exit of the duct. This prevents *vena contracta* from forming in the propwash and, thus, realigns streamlines to eliminate momentum flux through the sides of the control volume. Using the geometry of Figure 15-43, thrust is written using Equation (15-85). Assume that (1) static pressure at the inlet and exit are equal and (2) an absence of *vena contracta* behind the exit. This gives:

Airspeed through rotor:

(15-87)

(15-88)

(15-89)

(15-90)

(15-91)

where *AR* is the rotor disc area and □*d* □ A_4/*AR* is the *diffuser expansion ratio* (see Figure 15-41). An □*d* = 1 means the exit diameter (A_4) equals the rotor diameter (*AR*). An □*d* > 1 means the exit diameter is larger. The expansion ratio is the most effective design variable for the ducted fan [37].

Of course, the designer is interested in what engine power this calls for. In real applications, the duct and fan may be located on the airframe and be subject to flow contamination. To improve fidelity, it is necessary to incorporate an empirical constant, call it *fan effectiveness*, *Kfan*. Thus, we write

(15-92)

where □*p* is the propeller efficiency of the fan (rotor). For an ideal fan installation *Kfan* = 1. For typical aviation applications, expect the following range 1 < *Kfan* < 1.15 (or even higher for poor installations).

(4) **Determination of Static Thrust**

Consider the special case when $V_\infty = 0$. In this case, the induced velocity per Equation (15-91) reduces to:

(15-93)

Similarly, per Equation (15-90), since the rotor is at rest, only the induced power applies:

(15-94)

This yields the following expression for static thrust, *TSTATIC*:

(15-95)

Equation (15-95) overestimates *TSTATIC* for various reasons, such as absence of blockage effects, the presence of the hub, which reduces the disc area, reduction of lift distribution near the hub, and so on. Therefore, for design purposes, estimate *TSTATIC* by the following empirical correction:

(15-96)

where K_P is a correction factor that depends on propeller geometry. Suitable values based on real airplanes are listed in Table 15-6.

(5) **Reflections on Power Required**

Note an interesting insight is gleaned by comparing the static power relations of the free propeller and ducted fan, Equations (15-79) and (15-94), respectively:

(15-97)

Considering $d = 1 and $A_R = A_P$, the expression shows that to generate equal static thrust, the ducted fan requires only 71% of the power of the free propeller. Alternatively, given the same power, the ducted fan will develop 26% greater static thrust.

(6) **Basic Sizing Procedure**

Refer to the basic sizing procedure in Section 15.5.1 for additional information. To improve fidelity, the drag should incorporate changes associated with the size of the duct. The larger the duct, the more drag it develops. This requires drag to be written as $D = D_{basic} + D_{duct}$, where D_{basic} is the drag of the airplane minus the duct and D_{duct} is the drag of the duct. D_{basic} can be assumed that which was determined in Section 15.5.1(4).[15] D_{duct} can be estimated as $D_{duct} = qS_{wetduct}C_f$, where q is the dynamic pressure at cruise, $S_{wetduct}$ is the wetted area of the duct, and C_f is the skin friction coefficient (see Table 16-4). The $S_{wetduct}$ can be approximated as the total surface area of a cylinder of diameter $d_4 = (4A_4/\pi)^{1/2}$ and depth of c_{duct}.

STEP 1: Specify a target cruising speed (V_∞) for the vehicle and expected drag (D) at that airspeed. This drag must account for the presence of the duct. The designer should expect the drag for the ducted fan aircraft to be larger than that for an identical un-ducted aircraft.

STEP 2: Specify a desired rotor diameter (D_R) and calculate corresponding actuator disc area (A_R).

STEP 3: Calculate required induced velocity (w) per Equation (15-91).

STEP 4: Calculate the required power for flight (P_{req}) using Equation (15-90). It will be in units of J/s (or watts) in the SI-system or ft·lb_f/s in the UK-system.

STEP 5: Calculate the required engine power (P_{ENG}) per Equation (15-92) with an appropriate K_{fan} and $p appropriate for the fan. It may be helpful to convert the power to kW or horsepower (see Table 7-1).

Derivation

Refer to Figure 15-43 for geometric definitions and stations. Define *expansion ratio* as $d = A_4/A_R, airspeed through fan as $V_3 = V_\infty + w$, and exit airspeed as $V_4 = V_\infty + \Delta V = V_3/$d. Thus, we can write the mass flow through the device as(i)(ii)(iii)

Solving for the airspeed through the fan, V_3, leads to the following quadratic equation and solution:(iv)

Thus, the induced speed at the fan is(v)(vi)

Substitute Eqs (i), (ii), followed by Equation (iii) to get(vii)

Then, substitute Equation (iv) for V_3 into (vii) and after algebraic manipulations, we get(viii)

> Read full chapter

Jet and Gas Turbine Engines

Kenneth W. Bushell, in Encyclopedia of Physical Science and Technology (Third Edition), 2003

III.B The Bypass Engine and Turbofan

As indicated previously, one way of increasing the engine efficiency is to extract more energy from the exhaust system by using additional turbine stages to drive a ducted fan or propeller. In the bypass engine, this is done by adding additional stages of compression after the intake but directing only a portion of the total air through the core and combustor section. This produces a reduced energy hot exhaust and a cool bypass stream exhaust. The bypass ratio (BPR) is defined as the ratio of the flow that bypasses the core to that passing through the core. The two exhaust streams can be allowed to exit separately through coannular nozzles or can be mixed to exit through a single nozzle. A lobed mixer is often used to mix the two streams more fully to improve efficiency and reduce noise.

Usually the bypass stream compressor (or fan) is driven by a separate shaft and turbine system, which allows the two systems to operate at their optimum rotating speeds. This is the two-shaft engine. A typical twin spool bypass engine layout is shown in Fig. 4.

FIGURE 4. Twin-spool bypass engine. (With permission from Rolls-Royce plc.)

A design and patent for a bypass engine were first produced in 1940, but the first production bypass engine, the Rolls-Royce Conway, which powered the VC-10, DC-8, and B707 aircraft, was not introduced until the 1960s. This engine had an extremely small BPR (of around 0.2), which was considered optimum at that time. The operating efficiency continued to improve with increasing BPR such that, by the 1970s, BPRs of 4 were common and one engine design with a BPR of 8 was in service. This trend has continued so values of 6–8 are commonly used, and higher values have been tested for future aircraft. Many factors affected the gradual move to these more efficient cycles, not least of which was the availability of improved design methods for compressors, fans, and turbines as well as new materials and new manufacturing methods.

In the 1970s, improvements in design and manufacturing capability for compressors and fans allowed a single-stage fan to be used for the bypass flow. Pressure ratios of 1.6–1.8 became possible and the use of high-strength forged titanium for the blades allowed operation at very high blade tip speeds (around 1500 ft/sec). Engines with a single-stage fan became known as turbofan engines. The general configuration of a modern turbofan engine is illustrated in Fig. 5. Some turbofan designs use two shafts for the core, giving rise to the three-shaft engine configuration.

FIGURE 5. Typical high-bypass turbofan engine. (With permission from Rolls-Royce plc.)

The choice of bypass ratio for a given aircraft engine is influenced by the mission of the aircraft and its speed, the noise level required, and the type of installation. The higher the BPR, the larger the diameter of the engine and the higher the drag. Thus, high-BPR (HBPR) engines are chosen for slower moving aircraft and low-bypass ratios for high-speed aircraft. The lower exhaust velocity of the bypass engine provides a much quieter engine because the reduced shearing of the jet with the ambient air reduces the jet noise generated. The public pressure that began in the 1960s to reduce aircraft noise together with the improved fuel consumption accelerated the adoption of high-bypass engines for almost all commercial transport aircraft.

> Read full chapter

Polymer Matrix Composites: Applications

Ram Upadhyay, Shatil Sinha, in Comprehensive Composite Materials II, 2018

3.6.1.1 History of PMC Fan Blade Development

In June 1967, Rolls-Royce was the first to offer a fan stage built of a new carbon fiber material called “Hyfil” developed at the Royal Aircraft Establishment (RAE) at Farnborough as part of RB211 engine. In May 1970, after having passed every other test, the fan stage could not pass the bird strike test which shattered the blade into pieces.[3] This failure, although a setback for composites, emphasized the need for a tougher matrix material, and eventually led to development of HexPly 8551–7, an amine-cured toughened epoxy resin system.[4] A preferred reinforcement for this resin is continuous IM7 graphite fibers, and consequently all current GE PMC fan blades in service have been made from IM7/8551–7 prepreg (pre-impregnated unidirectional ply).

Fig. 2 shows the history of composite fan blades at GE starting with the un-ducted fan blade in 1980. The un-ducted fan concept never went in production, but it provided a good knowledge base for development of the GE-90 fan blade that went into commercial production in 1995. Since then there have been significant improvements in the aerodynamic design and a reduction in number of blades, and we are poised for further advances into the fourth generation. Composite fan blades have set a benchmark for future developments and further improvements in propulsive efficiency.

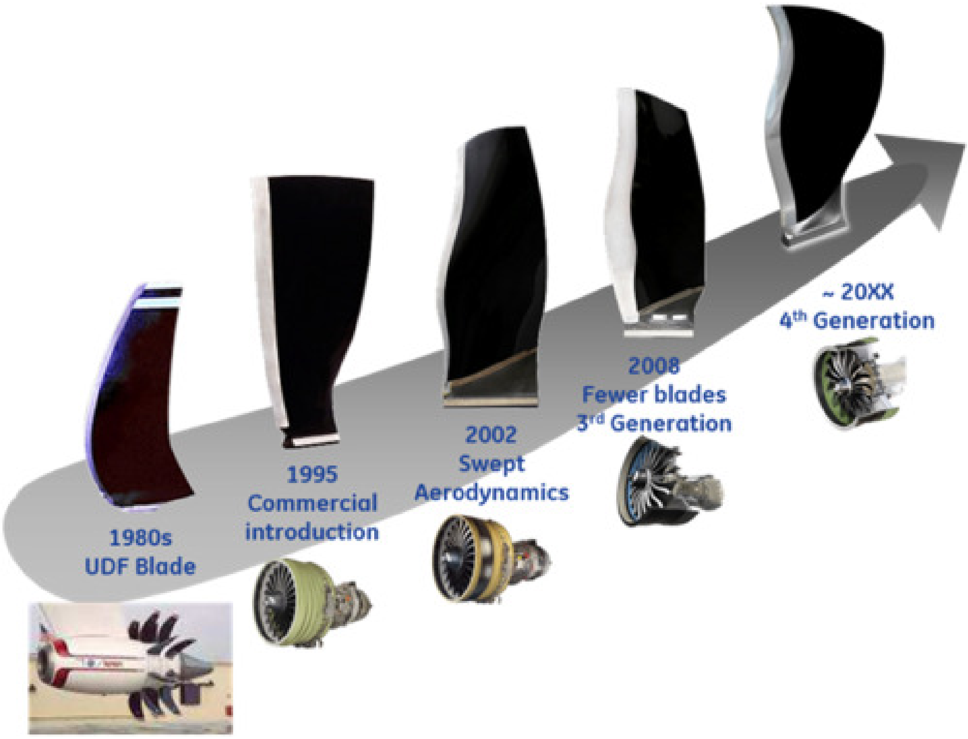

Fig. 2. Historic perspective of composite fan blade development at GE.

Fig. 3 shows the typical steps of the blade manufacturing process. We start with a solid model of the blade driven by aerodynamic requirements. Blade volume is then divided into 3-D layers, each having the thickness of the prepreg sheet, using a process commonly referred as "peeling the onion." Each layer, referred to as a ply, is then flattened into a 2-D shape and cut from a roll of prepreg with fiber direction being determined by the blade structural requirements. Plies are then laid up in a tool to build the intended volume of the part which is then cured under temperature and pressure.

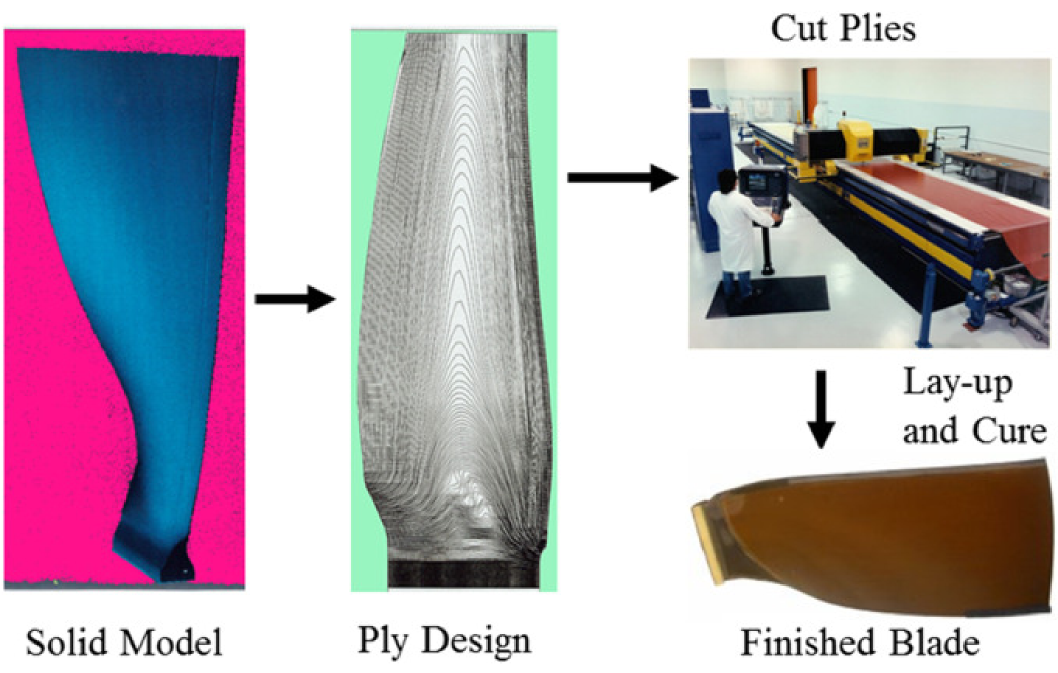

Fig. 3. Typical steps in a blade manufacturing process starting from a solid model to finished part.

In the following sections we will look back at the development and commercialization of wide chord fan bladess which included the utilization of a tougher matrix material, process modeling techniques, process design methods, and systems for manufacturing producibility. Each of these will be discussed in detail, followed by a summary with lessons learned and prospects for future developments.

> Read full chapter

Aircraft Performance and Design

Francis Joseph Hale, in Encyclopedia of Physical Science and Technology (Third Edition), 2003

VII.C Propulsive Efficiency

Although the piston–prop has the lowest specific fuel consumption of all the air breathers, it is also the heaviest and has the largest drag, and its best-range airspeed is 24% lower than that of a comparable turbojet. Furthermore, the propeller efficiency drops off sharply at relatively low Mach numbers as the propeller tip speeds approach the sonic velocity. The turbojet produces its thrust by expanding all of the turbine exhaust gases through a nozzle, and it has the highest specific fuel consumption but is the lightest. It also has the fewest moving parts and the lowest drag, and its propulsive efficiency improves with airspeed. The turbofan and the turboprop are basically turbojets in which part of the exhaust gases is used to drive an ungeared multibladed ducted fan (the turbofan) or a propeller connected to the turbine drive shaft through a gearbox (the turboprop). The ratio of the mass of the cold air passing through the fan (or the propeller) to the mass of the hot air passing through the burners and turbines is called the bypass ratio. If the bypass ratio is zero, the turbofan becomes a pure turbojet; current operational bypass ratios are of the order of 5–6. As the bypass ratio increases, specific fuel consumption decreases and the turbofan begins to take on the characteristics of a turboprop with the exception that the ducted fan efficiency is essentially independent of the airspeed. Although it is not customary to refer to the bypass ratio of turboprops, it is of the order of 50.

Although turboprops have a specific fuel consumption that approaches that of the piston–prop and are four times lighter, their cruise speed has been limited by the degradation in the propeller efficiency at higher airspeeds. The fuel shortage in the mid-1970s and the subsequent increase in prices sparked the development of two ultrahigh bypass (UHB) engines, one known as a propfan and the other as an unducted fan (UDF), which in appearance resemble each other. They each have 2 rows of counter-rotating blades (6 or more in each row) that are approximately 12 ft in diameter; the blades do not resemble conventional propeller blades, being highly swept and having variable camber. The propfan is essentially a turboprop with a gearbox that reduces the high rpm of the turbine to that of conventional propellers; the rpm and the pitch of the blades can be varied. The unducted fan, on the other hand, is essentially a turbofan with a bypass ratio of the order of 28; it has no gearbox and operates at a constant rpm (that of the turbine), although the pitch of the blades can be varied through feathering and into reverse. With the duct removed, it is necessary to give greater consideration to the fan efficiency.

Although the propeller efficiency has been extended, it still drops off at the higher subsonic Mach numbers. Furthermore, the best-range airspeed of aircraft using both of these UHB engines is still lower than that of the pure turbojet and turbofan so that at competitive airspeeds the UHB lift-to-drag ratio will also be lower. In spite of these off-design point degradations at the high subsonic Mach numbers of current airliners, the specific range of UHB-equipped aircraft is sufficiently higher to make such an aircraft commercially attractive at Mach 0.8.

Although both types of engines were flown on demonstrator aircraft and design studies for commercial aircraft with UHB engines were started, current efforts seem to have ceased.

The thermal efficiency of gas turbine engines is strongly dependent on the turbine inlet temperature, which is primarily limited by the physical properties of the turbine blades. There are ongoing investigations into new materials and alloys, into techniques for forming turbine blades and fastening them to the hub, and for controlling the clearance between the blade tips and the hubs. As the turbine inlet temperature increases, so does the exhaust temperature, with a subsequent increase in acoustic noise, which must be considered in light of the drive for quieter engines.

In concluding this section, mention should be made of the increasing use of derated turboprops to replace piston (reciprocating) engines; derating means that the propeller selected cannot absorb all of the sea-level power developed by the engine. As the engine shaft power decreases with altitude, the propeller thrust power will remain constant until the maximum engine power available decreases to that value. The altitude at which the engine power and propeller thrust power are equal is analogous to the critical altitude of a turbocharged piston–prop and can be as high as 20,000 ft; the derated turboprop behaves like a turbocharged piston–prop but with a much lighter weight and less complexity.

> Read full chapter

Duct acoustics

Stewart Glegg, William Devenport, in Aeroacoustics of Low Mach Number Flows, 2017

17.1 Introduction

In the early days of commercial air transportation the noise from aircraft was dominated by jet noise, which scales with the sixth or eighth power of the jet velocity depending on the temperature of the jet. However, in the 1970s high bypass-ratio turbofan engines were introduced, and this enabled the same thrust to be obtained with a lower jet exit velocity relative to the surrounding flow and a corresponding reduction in jet noise. Aircraft noise levels were significantly reduced as a consequence, and the fan noise sources became comparable in level to the noise from the jet. To further reduce aircraft noise, the fan noise sources had to be minimized as well as the jet noise, and consequently ducted fan noise has become an important consideration in low noise aircraft engine design.

The design of a typical high bypass-ratio aircraft engine is shown in Fig. 17.1. The outer duct extends from the engine inlet to the bypass duct exit and is supported by the stator vanes and struts that are downstream of the fan. Just aft of the fan is the compressor inlet, which leads to the combustion chamber and the turbine, and the high speed flow generated by combustion exhausts through the turbine exit to form the jet core. The fan generates thrust, and the turbulent flow that results from the loaded fan blades impinges on the downstream stator vanes. The wake flow is highly turbulent and has a swirling motion, and the stator vanes are designed to reduce the swirl, recovering the energy lost to angular momentum downstream of the fan. The primary source of noise in the engine has been found to be the impingement of the wake from the fan onto the stator vanes.

Fig. 17.1. Schematic of a high bypass-ratio turbofan engine.

In general, the outer duct of the engine is circular, but in some applications the inlet is modified so that it interferes less with the aerodynamic performance of the aircraft or enables additional ground clearance when the engine is mounted below the wing. The duct shape also has a varying cross section, and this can impact the propagation of acoustic waves along the duct. However, a great deal can be learned from studying the acoustic propagation in circular ducts and treating the variations in the duct cross section as a second-order effect. However, there are instances when the variation in duct cross section is vital to the understanding of sound propagation, and we will discuss these effects in more detail later.

In the analysis given in this chapter we will assume that sound propagation along the duct is linear, which implies the use of Goldstein's equation given in Chapter 6, and excludes the nonlinear propagation of sound associated with buzz-saw noise (noise caused by the rotating shock structure produced when the rotor is operated supersonically). We will limit consideration to circular ducts with a steady mean flow, which may be a function of radius and may include a swirling flow. We will also evaluate the effect of liners on the duct walls and radiation from the duct exits upstream or downstream of the fan. In general, we will consider these effects as idealized with simple boundary conditions so that we can identify the physical effects that are taking place. For an accurate calculation for aeroacoustic sources in a duct, numerical methods must be used. However, these are beyond the scope of the current treatment, and so references will be provided when appropriate.

> Read full chapter

Vacuum and Low Pressure

Antony Barber C.Eng., M.Sc., F.I.Mech.E., M.R.Ae.S., in Pneumatic Handbook-(Eighth Edition), 1997

Ducted fans

The performance of a simple propeller type fan can be considerably improved by enclosing it within a close-fitting open-ended cylindrical casing, Figure 5. The design is critical. It may be parallel sided or convergent–divergent with the fan at the throat. Diffuser vanes may be added. Much depends on the individual installation as to how efficient the fan is, although quite high pressures can be realised with suitably proportioned ducted fans.

FIGURE 5.

With peripheral velocities of the order of 100 m/s a pressure rise of 0.07 bar is possible, but it is more common, with industrial fans, to limit the peripheral speed to 50 m/s and a pressure of 0.007 bar so as to limit the noise generation. Multi-stage units are also possible.

Advantages of propeller type fans are simple construction, low cost and an ability to handle contaminated air. Their short axial length, even including the motor, makes them suitable for installation directly in walls or ceilings or for compact installation elsewhere. They are widely used for ventilation, forced draught and cooling purposes and are normally quiet running at low or moderate speeds, being directly coupled to an electric motor, with a maximum speed of the order of 2700 r/min.

They may generate noise and vibration if run at higher speeds, although if care is taken with the installation, these can be reduced by incorporating duct attenuators and anti-vibration mountings (see Figure 6).

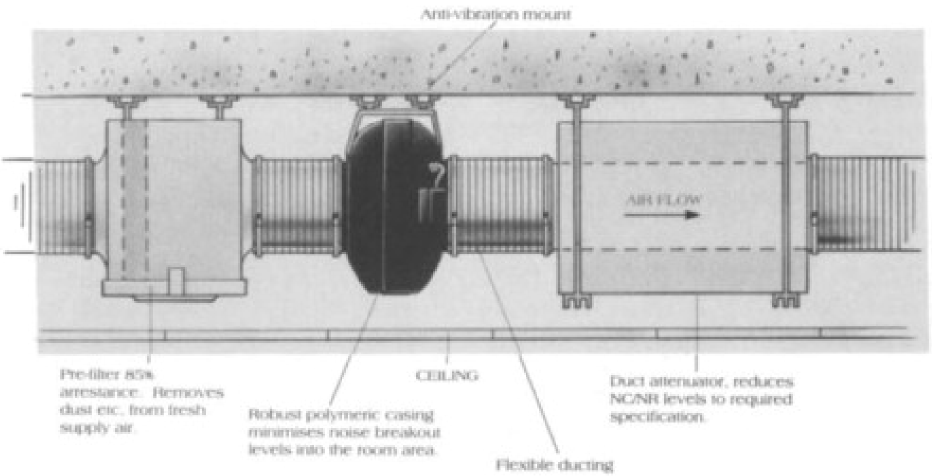

FIGURE 6. – Ducted fan installation. *(Ventaxia)*

Axial flow fans are a development of the simple propeller type. They are ducted with a small clearance between fan blades and casing (consistent with safety and noise). The smaller the clearance, the more effective the casing is in preventing recirculation at the blade tips and consequent loss of efficiency. The sides of the casing are normally parallel, although entry may be convergent and long enough completely to enclose both fan and motor. An axial fan can generate a higher pressure than a simple propeller type fan (up to two and a half times) with a high efficiency.

The critical parameters of a fan design are the aerofoil blade form, the number of blades, angle and area, diameter, hub ratio and tip clearance. For low pressure working, the hub ratio is small (small diameter with long blades). For high pressure working, hub ratio is large and the aerofoil section chosen differently. Guide or diffuser vanes may be fitted downstream to straighten the flow and improve pressure development.

Noise generation limits the practical maximum speed of a fan, the critical factor being the entry velocity which should be limited to 50 m/s, above which the noise can be intolerable. The presence of guide vanes can also cause noise problems by setting up local oscillatory flow, which can generate high pitched noise.

The pressure available from an axial flow fan can be increased by two-staging. The two stages may be driven off the same shaft (by a motor with a shaft at each end) or may be contra-rotating with two motors. In the former case, straightening vanes are necessary between the two impellers to ensure efficient working of the second stage. With contra-rotating fans, no straightening vanes are necessary, but the drive system is more complicated. In practice the two fans are driven by separate motors.

A further development is the bifurcated co-axial fan where the motor is isolated from the downstream flow by taking it through separate ducts as in Figure 7. This can be useful where the air is contaminated or hot, with the possibility of damage being caused to the motor. It also improves access to the motor for maintenance purposes. The drive motor can also be placed outside the duct and the fan driven by a V-belt or the fan can be placed at a bend in the ducting allowing the drive shaft to be taken through the wall to an external motor.

FIGURE 7.

> Read full chapter

Fan noise

WTW (Bill) Cory, in Fans and Ventilation, 2005

14.5 Acoustic impedance effects

An alternative and/or parallel explanation for some of the differences in sound level which have been noted, is the acoustic impedance of the ductwork configuration. Until recently, there were severe practical difficulties in making impedance measurements but these have been reduced with recent advances in digital frequency analysis and correlation techniques.

Whereas it was previously necessary to investigate the standing wave patterns by a microphone traverse along the duct for each discrete frequency of interest, it is now possible to use phase-matched condenser microphones for simultaneous measurement of sound pressure levels at a known separation. The signals may then be processed through a Fast Fourier Transform (FFT) twin channel frequency analyzer to derive impedances from the cross-spectral density function (see Bibliography, Section 14.15) or by a transfer function method.

The specific acoustic impedance i may be defined as the ratio of acoustic pressure p to acoustic particle velocity u and in air is equal to pC.

In a duct, however, this is not a particularly helpful concept and the acoustic impedance I is used, defined as the ratio of acoustic pressure p to the acoustic volume velocity q.

With plane wave propagation along a duct of cross-sectional area A and with no reflected waves, then

Equ 14.24

Where reflected waves are present, the pressure and volume velocities are the sum of incident and reflected pressures and the difference between forward and reflected velocities respectively so that the ratio of is generally complex. Knowing the impedance at a point together with either the acoustic pressure or volume velocity, it is possible to calculate the unknown parameters.

Whilst the main applications of these acoustic impedance concepts have been in reactive silencer design, an impedance model of a ducted fan as been given by Baade where it is considered as a dipole source of noise with internal impedance I_F.

Acoustic loads of impedance IL_i and IL_o are coupled to the end of straight inlet and outlet ducting respectively. Acoustic impedances seen by the fan impeller are I_i and I_o. The volume velocities q_i and q_o are equal in magnitude but of opposite sign and are related to the dipole source strength by equation:

Equ 14.25

By manipulation of these terms and noting that the acoustic power flow $W_o = q_o{}^2 R|I_o|$

Baade deduced that:

Equ 14.26

It will be noted that the sound power in the discharge duct is a function not only of the outlet duct length and outlet terminating load, but also of the inlet duct length and inlet terminating load.

Bolton and Margetts have also looked at the influence of changing duct configurations on the noise generated and concluded that, there was no way of estimating the inlet or outlet sound power for one particular installation category from tests carried out on another. Tests are, therefore, necessary in all four categories from which it may be possible to identify those fan designs that are installation sensitive.

It will also be noted that it should be possible in a fully ducted situation (Installation category D) to position the fan for the minimum noise at a desired observer location. Figure 14.20 shows the differences for a bifurcated for the same aerodynamic duty but with vary distribution of the resistance on the fan inlet and outlet.

Figure 14.20. Variations in sound power levels for 610 mm bifurcated axial flow fan

For any meaningful comparisons to be made between noise tests and fans in a homologous range, and also to compare sound power levels of fans of different types, it must be accurate and repeatable. They must provide information that can be used by a system designer for noise management and, where necessary, attenuation. To do this, it is necessary that they are conducted under a similar ducting configuration and if at all possible, under a similar distribution of inlet to outlet ducting resistance.

To repeat, the ducting acts as an acoustical impedance. The noise output at inlet and outlet not only varies according to the point on the fan characteristic. It also varies according to how it is ducted and the distribution of this ducting. We thus have at least eight different noise levels (four installation categories to be measured for inlet and outlet noise). If we add to these the “breakout” noise levels, then a further four levels can be expected.

Some representative differences for different fan types are shown in Table 14.5. And still our misery is not ended! The actual type of microphone head used can affect the results (unless correction factors are included in the measurement code) see Figure 14.21.

Table 14.5. Difference between outlet and inlet sound power levels for various fan types each at their design flowrate expressed as (outlet – inlet) in sound power level re 10^{-12} watts

Frequency Hz	**Mixed flow**	**Mixed flow**	**In-line radial**	**Bifurcated axial**	**Axial**	**Backward curved centrifugal**
Duct configuration						
Type D	**Type B – Type C**	**Type B – Type C**	**Type B – Type C**	**Type B – Type C**	**Type B – Type C**	
dBW	**dBW**	**dBW**	**dBW**	**dBW**	**dBW**	
50	5.0	17.0	–1.9	7.1	–0.4	–4.0
63	8.5	9.9	–2.1	1.9	1.8	0.8
80	6.0	12.3	–2.9	–5.3	–1.1	2.1
100	8.0	5.2	–7.8	–5.2	–1.7	4.4
125	9.5	8.0	–10.7	–9.3	–11.3	4.7
160	9.0	16.3	–1.6	–16.2	–10.7	4.1
200	5.5	5.3	–4.8	–4.0	–3.4	–2.7
250	4.0	4.8	–4.2	0.7	–2.0	0.5
315	6.5	6.6	–4.2	–6.1	–0.5	3.9
400	7.0	9.6	0.1	–5.0	–0.2	3.0
500	7.0	8.4	3.5	–3.3	0	5.1
630	5.5	3.1	4.8	–2.6	–2.1	5.0
800	5.0	1.5	1.5	–1.8	–2.2	4.9
1000	2.5	–0.7	–0.7	–3.2	–1.8	5.3
1250	–2.5	–3.7	–0.6	–4.3	–2.3	3.6
1600	1.0	2.4	–0.8	–3.3	–2.5	3.3
2000	2.0	4.7	–1.7	–3.7	–2.7	3.0
2500	0	3.0	–2.6	–3.7	–3.0	1.8
3150	–4.5	1.2	–3.3	–4.7	–3.7	2.2
4000	–2.5	3.2	–3.6	–5.7	–3.4	2.5
Total	4.6	6.8	–2.1	–2.9	–3.7	–0.9

Figure 14.21. Variations in measured sound power levels for a mixed flow fan according to microphone shield used

ISO 5136 gives these correction factors, for the different types of shield identified, according to the flow velocity and modal effects. The turbulence screen is recommended for the highest velocities, but a foam ball is adequate for the velocities experienced in normal HVAC applications.

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The Ffowcs Williams and Hawkings equation

Stewart Glegg, William Devenport, in Aeroacoustics of Low Mach Number Flows, 2017

5.4 Sources in a free stream

In many applications we are interested in the sound radiation from a uniform flow over a stationary object. Examples include model testing in wind tunnels, the flow in ducts, flow over large surfaces such as aircraft fuselages, and perhaps most importantly CFD calculations in body fixed coordinates. In each case there is a uniform steady flow at large distances from the region of turbulence that causes the sound and this contradicts the assumption, made in both Lighthill's acoustic analogy and the Ffowcs Williams and Hawkings equation that the medium is at rest at infinity. We showed in Section 4.2 that, in a uniform flow, the Lighthill stress tensor needed to be modified to only include the unsteady perturbations relative to the uniform flow, and that the acoustic propagation was determined by the convected wave equation. In principle, we can solve this modified equation using the techniques described earlier in this chapter using solutions to the convected wave equation. However, a simpler approach is often possible if we work in a frame of reference moving with the uniform flow, in which the medium appears stationary and the source and the observer are seen to be moving upstream at the flow speed. This approach is accommodated by modifying the results of this chapter to include a moving source and observer and by referencing flow velocity perturbations to the free stream.

An important application of this theory is to ducted fan noise where the sources are stationary or rotating next to stationary surfaces. The acoustic propagation is most readily addressed in this case by using the convected wave equation. It is possible to model this propagation by using a Green's function that satisfies the boundary conditions on the wall of the duct. We therefore need a formulation that will correctly allow for moving sources in a uniform flow that is bounded by stationary surfaces.

First consider the solution to Lighthill's wave equation in a frame of reference moving with the uniform flow velocity $\mathbf{U}_{(\infty)} = (U_\infty,0,0)$. The velocity perturbations relative to the moving frame of reference are given by $\mathbf{w}$, so the velocity in the fixed frame is $\mathbf{v} = \mathbf{U}_{(\infty)} + \mathbf{w}$. Lighthill's stress tensor is defined in the moving frame as

Also the velocity of the surface relative to the fixed frame is . Eq. (5.2.8) can then be written, for the positions **x**□ and **y**□ in the moving frame as

(5.4.1)

We wish to change this result to give a solution at the points **x** and **y**, which are the observer and source locations in the fixed frame of reference. As part of this we need to replace the Green's function. In the moving frame where no free stream is observed, the Green's function is a solution to the inhomogeneous wave equation,

(3.9.2)

The Green's function in the fixed frame, $G_e(\mathbf{x},t|\mathbf{y},$□$)$, will be related to G by straight-forward translation of the coordinates,

and thus

where D_∞/D□ is the free stream convective derivative, introduced in Eq. (4.2.9). Applying these conversions to Eq. (3.9.2) we see that the fixed frame Green's function must be a solution to the equation,

(5.4.2)

and so we obtain

(5.4.3)

An important application of Eq. (5.4.3) is in CFD calculations or surface flows in which the surfaces are stationary and the medium is in uniform motion at infinity. In this case **V** = 0 and the nonpenetration boundary condition on the surfaces require that $(\mathbf{U}_{(\infty)} + \mathbf{w}) \cdot \mathbf{n} = 0$ on all the surfaces. The integrand of the last integral in Eq. (5.4.3) then reduces to which does not vary with time and so makes no contribution to the acoustic field. A similar reduction can be made to the second integral in Eq. (5.4.3) and, neglecting viscous stresses as we did in Section 4.5, gives

(5.4.4)

where $p' = p - p_\infty$. This result is identical to Eq. (4.5.1), which was the result for a stationary medium, the differences being that the Green's function must satisfy the convected wave equation (5.4.2), and that the Lighthill stress tensor depends on $\rho w_i w_j$.

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