Chapter 4

Compressors

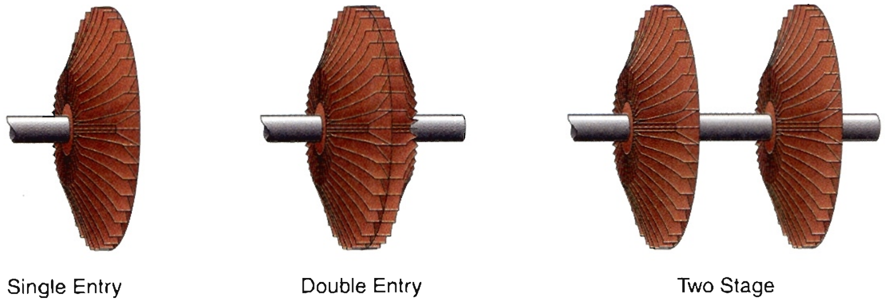

Figure 4-1 **Centrifugal impellers.**

The custom has developed in aviation for a turbine/shaft/compressor assembly that rotates as a single unit to be referred to as a "spool." From this, it is customary to refer to an engine at its higher r.p.m. as being "spooled up." Gas turbine engines (GTEs) produce the major part of their thrust in the high r.p.m. range, thus an "unspooled" engine may be at 50% of its permitted r.p.m. but only developing a small percentage of its maximum thrust. On approach for landing in heavier aircraft, safety requires engines to be "spooled up" to allow for an immediate aircraft response to throttle movements.

Two types of compressors are used in GTEs:

1. Centrifugal flow compressors
2. Axial flow compressors

Normally one or the other is used, and the axial flow is common, although sometimes air is delivered to combustors by a combination of both types. "Straight through" air passage for the length of the engine can be considered the usual with "reverse flow" permitting a reduction of engine length, making it more compact for special applications in some helicopters and turboprops.

Centrifugal flow types may feature single- or two-stage impellers, and some single units may be double sided. [Figure 4-1] An impeller accelerates air while compressing it, and a diffuser continues the pressure buildup while reducing airflow velocity.

Multistage axial compressors use alternate rows of rotating and static blades. A stage comprises one row of rotating blades plus the next downstream row of stator blades. Axial compressors of 13 stages or more are in operation. Alternate cycles of acceleration and deceleration are carried out until the required pressure rise is achieved. The following graphs show pressure and velocity variations in the operation of centrifugal and axial types. [Figure 4-2]

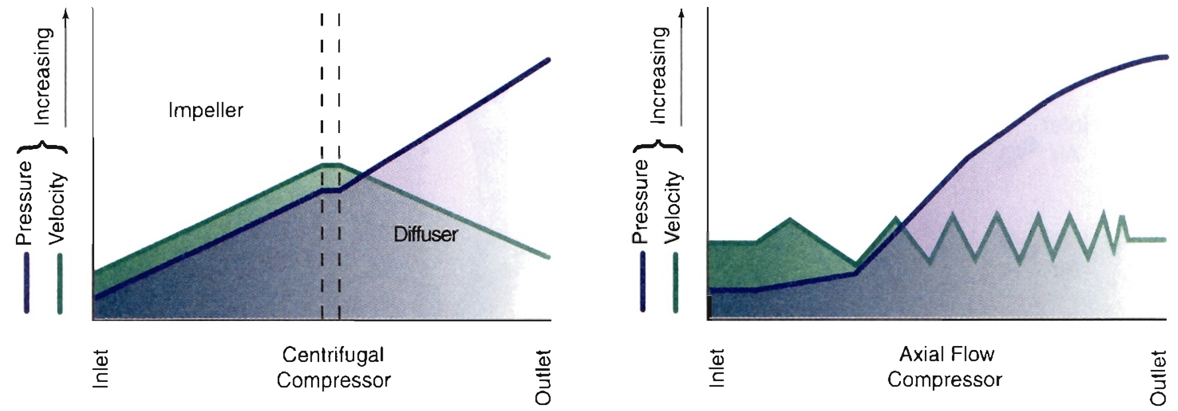

Figure 4-2. Pressure and velocity variations.

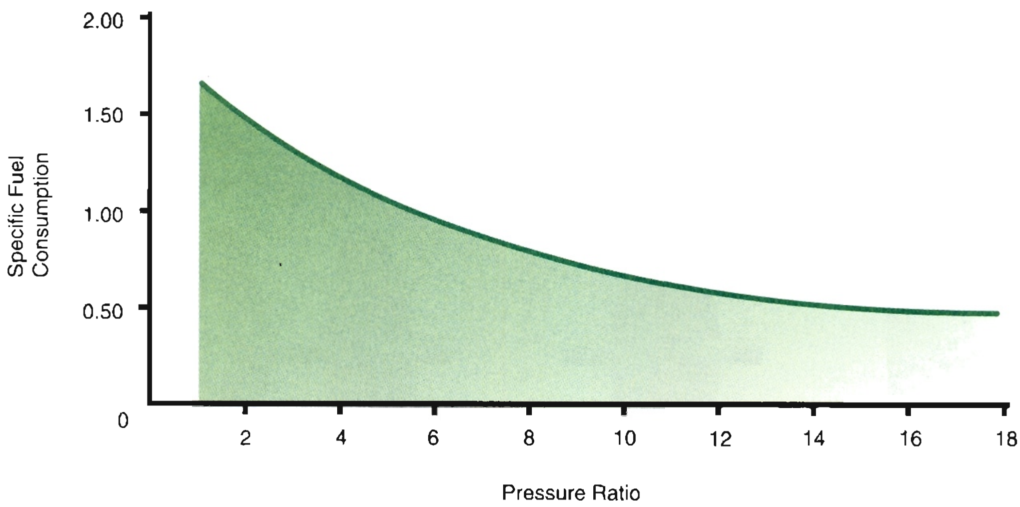

Figure 4-3. Decreasing fuel consumption.

A common feature of both types of compressors is that specific fuel consumption of the engine decreases as the compression ratio rises. Higher compression ratios are obtainable by the axial compressor, hence its greater appeal. [Figure 4-3]

Most early jet engines used centrifugal compressors that were easily derived from existing supercharger compressors from big piston engines. In addition to being robust, centrifugal units have the advantage of being relatively simple to manufacture. They are often used in smaller engines to combine simplicity with ruggedness that is needed to cope with diverse field conditions.

Rotation of the centrifugal impeller induces airflow into its center. The air is given radial motion by centrifugal action, and the air pressure rises. Accelerated compressed air from the impeller passes into a ring of diverging diffuser blades, which give direction to the air while decelerating it to produce a further pressure rise. Processed air is collected in the compressor manifold for onward passage to the burner cans. [Figure 4-4]

Rapid rotation gives impeller tip speeds up to about 1,600 ft/sec. This produces the high air velocity necessary for the efficient conversion of velocity to pressure with smooth airflow.

As shown in the left-hand graph of figure 4-2, about half of the total pressure rise of a centrifugal compressor is produced in the impeller and half in the diffuser. Very small clearances are maintained between the rotating impeller and its stationary case to reduce air leakage. Clearances for the impeller/diffuser assemblies must be precise in order to prevent vibration.

Diffusers may be incorporated as integral parts of the compressor manifold or may be separately attached assemblies. In all types, diffusion is achieved by curved vanes tangential to the impeller.

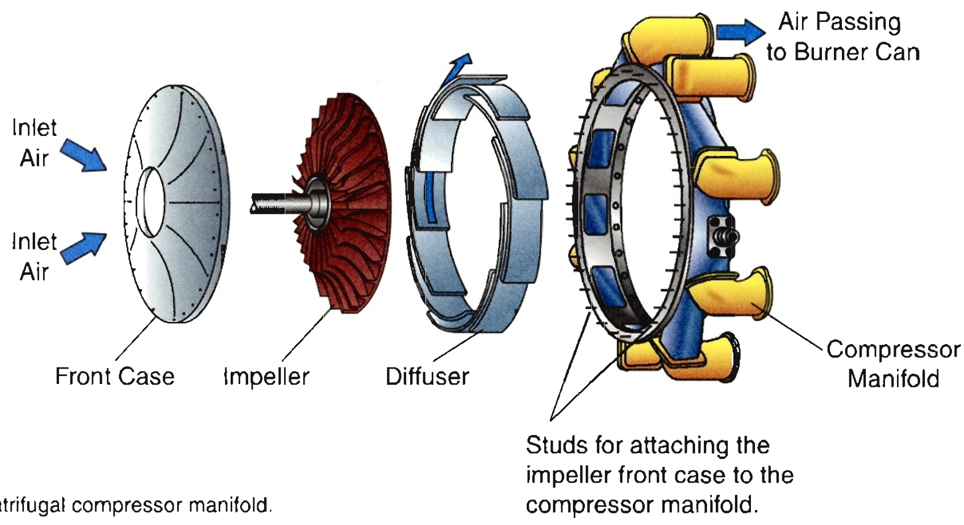

Figure 4-4. Centrifugal compressor manifold.

Fixed swirl vanes are often provided to direct intake air onto the eye of the impeller at the best angle for efficiency. Some impeller vanes have the central parts of their leading edges curved forward in the direction of rotation. Acting in unison with swirl vanes, these curved parts smooth the airflow into the impeller. Curved leading edge parts may be integral to impeller vanes or may be separate pieces; the latter allow more accurate machining.

Impeller disks are forgings with integral radial vanes on one or both sides. These radial vanes, which may be straight for ease of manufacture, form divergent passages when mated with the compressor cases.

When in operation, axial compressors induce an inflow of air and pass it down their length with alternate accelerations and decelerations. Rotating blades impart velocity to the air in each stage and the following stator blades convert velocity to pressure energy as shown in the right-hand graph of figure 4-2. The final stator blades direct air to the combustors in a straight axial flow. As pressure increases along the length of the axial compressor, temperature also rises, as illustrated in Chapter 2, figure 2-3.

Although sensitive to foreign object damage (FOD), axial flow compressors are preferred because of their ability to provide the necessary high compression ratios. As mass airflow is a major factor in producing thrust, an axial flow engine will provide more thrust than the centrifugal counterpart of a similar frontal area. Additionally, the manufacturer may add extra blades to an axial compressor in subsequent development to increase thrust by increasing pressure ratio. Because aircraft have become so expensive, this option is very attractive to operators.

As compression ratios increase, the difficulty of efficient operation over the entire engine r.p.m. range also increases. To achieve the best results at high r.p.m., the ratio of compressor intake area to its discharge area needs to be large. Consequently, as r.p.m. decreases when the throttle is retarded, the high intake/discharge areas ratio becomes too great. To meet the reduced requirement for intake mass airflow, the velocity of entering air is reduced until it is too slow to match the blade r.p.m. As angles of attack of the blades increase, flow over the airfoil-shaped blades breaks down, resulting in the stalling of the front stage blades. [Figure 4-5]

When high pressure ratios are required in a single spool compressor, the possibility of stalling is reduced by the use of spill valves, which automatically remove and dump some air from the compressor mid-section. This

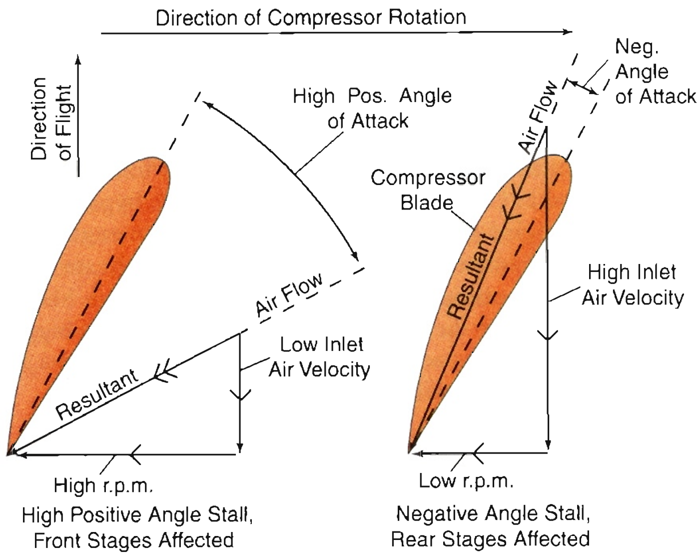

Figure 4-5. Compressor blade stalls.

method reduces the axial velocity through the preceding stages but wastes energy. A preferred, more economic method uses automatic, variably angled stator blades in the compressor front stages. Those automatically variable stator blades adjust their angular settings relative to the longitudinal axis as the pressure ratios and r.p.m. vary; good directional feed of air to the following rotor blades is assured.

The tendency for blade stalling due to an increase in pressure ratio between stages is reduced by having only a small increase across each stage. Normally, inlet to outlet pressure ratios are between 1 : 1 and 1 : 2. It should be noted that, although the ratio increase across each stage is small, the final pressure can be quite high because of the number of stages. Carefully controlled air velocities and straight-through flow contribute to high efficiency with minimum energy losses. Because of varying stage airflow requirements, designing efficient compressors calls for carefully matching every stage with the characteristics of its neighbors. The matching process is not too difficult for one set of conditions, but it does become very complex when considering the whole range of operating circumstances to which an aircraft might be exposed.

A single-spool axial compressor has one rotating assembly with as many stages as required for pressure rise. Although an engine with a twin-spool compressor can put all its air through the turbine as a pure jet, the configuration generally leads to a bypass arrangement like the single spool engine.

Further development of the bypass principle led to the introduction of fan engines in which inner sections of fans form the first row of low-pressure (LP) compressor blades, while outer sections of fan blades accelerate the bypass air. The fan is part of the LP compressor with which it rotates, and the whole is driven by the LP turbine. The front fan bypass principle is illustrated in Chapter 2, figure 2-11. A variation of the front fan, the three-spool engine with the fan being driven at optimum aerodynamic speed by its own turbine, is illustrated in Chapter 2, figure 2-13. The high bypass turbo fan engine is a development of earlier fan engines. A large-diameter fan is driven by its own dedicated turbine at optimum speed. Inner sections of fan blades pass air into the LP compressor, while the much bigger outer sections accelerate large quantities of bypass air in a manner similar to a conventional propeller.

For best performance, bypass flow pressure needs to be approximately 1.6 times the ambient air pressure. This is achieved by having fan tip speeds as high as 1,500 ft/sec. However, by using a dedicated turbine for the fan alone, it can operate closer to its aerodynamic best; variable angle-of-attack blades provide further improvement. Although use of reduction gearing in the fan drive is a complication, it is considered acceptable. Engine weight and overall mechanical complexity are reduced by the combination of fan and compressor. Improvements result without the use of inlet guide vanes. Bypass and fan engines provide high sub-sonic speeds for airline operations. Accelerations for large masses of air are, in principle, similar for both turboprops and fans. While turboprops are sometimes referred to as being extensions of large fan engines, chronologically, the turboprop preceded the fan.

The words "surge" and "stall" of an axial compressor mean different things to different people. To some, a surge is blade stalling over a few stages, while stalling amounts to total breakdown of airflow through the whole compressor. To other people, the word meanings are reversed. It probably matters little which is used, provided there is no breakdown in communication. Pilots seem to lean to the first definition, which is the one used here.

A disruption of airflow over the blades due to a change in angle of attack, i.e. blade stall, can be brought on in one of two ways. The first concerns the high angle of attack or positive angle stall, which is much like the aerodynamic stall of the airplane itself. This may occur in a compressor having a low inlet velocity combined with high engine r.p.m., and it affects the front stages of the compressor.

The second is the low angle of attack or negative angle stall. This is comparable to inverting an airplane, then pushing its nose above the horizon to stall the wings while still inverted. Such a stalling of compressor blades may occur when high inlet air velocity is combined with low engine r.p.m.; rear compressor blades will be affected (see Figure 4-5).

A surge involving a few compressor stages will be accompanied by a low rumble, discernable in the cockpit. A complete compressor stall produces a violent explosion noise that leaves no one in doubt. This happens when the stalling of all stages reduces the compressor pressure below combustor pressure. A long tongue of flame shoots forward from the air intake accompanied by a loud bang and loss of thrust. Explosive compressor stalls are startling for all on board; however, engine damage is not common.

A compressor stall reduces airflow through the engine and the fuel control unit reduces the fuel flow. This decreases back pressure on the compressor and allows an increase in airflow, which clears the stall condition. The fuel control unit then restores the fuel flow, and the compressor back pressure rises again. If this back pressure becomes too great, the stall will occur again, and the cycle repeats. Most compressor stalls take place during engine acceleration or at high altitude. A strong crosswind on takeoff adds to the possibility of a stall. However, design improvements have almost eliminated the phenomenon. Variable inlet guide vanes, variable stator blades, and two-spool compressors rotating at different speeds help alleviate the problem. In addition, improved automatic fuel control units compensate for rapidly changing conditions.

To clear the most common compressor stalls, engine r.p.m. and fuel flow should be reduced, if at all practicable, by retarding throttles.

The importance of throttle closing in flight may not be evident. In normal flight of piston-engined aircraft, the only time a throttle will be fully closed is just before touchdown. "Balanced power" restrictions on the combination of manifold pressure and engine r.p.m. of large piston-engined aircraft mean that the throttle is partly open throughout flight. The situation is very different in a turbine-powered aircraft.

Newer aircraft, which feature computers and a coupled autopilot, do the whole job with maximum efficiency. Older turbine aircraft still require a "hands on" descent. Although variations will be required by some operators and traffic control authorities, or by particular engine and airframe combinations, turbine engine aircraft easily carry out the entire descent with throttles fully retarded. Engines idle smoothly, there is little risk of the "light going out," and residual thrust is reduced to something between zero and 1,000 lb. (However, some

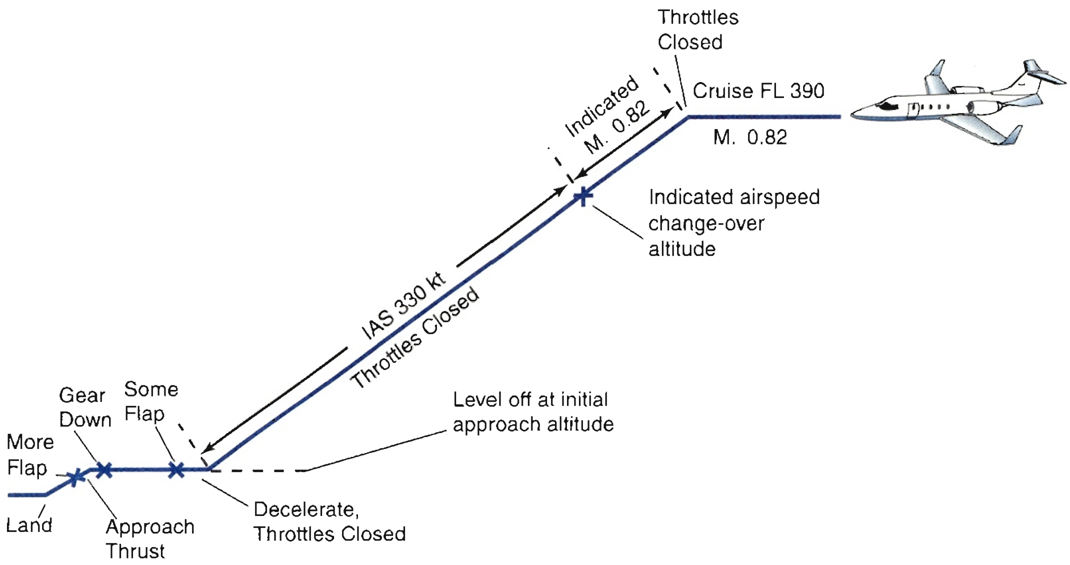

Figure 4-6. Possible descent profile.

older engines require monitoring to maintain tailpipe temperature above a certain minimum level.) [Figure 4-6]

The technique calls for maintaining Mach number, about M 0.82, when entering descent by slowly closing the throttles fully and holding the Mach number by varying the rate of descent. At "change over" altitude, aircraft forward speed is controlled by IAS rather than Mach number, and is held constant thereafter, as in figure 4-6. When traffic or established control restrictions do not apply, the high IAS can be held until 1,500 ft. above the destination runway. Then, while maintaining a constant altitude, airspeed is allowed to bleed off until flap and gear extension speeds are reached. With their extension, throttles are opened as required for final approach. Nothing is proved by all of this, but it gives some satisfaction to close the throttles above 30,000 ft. and not need to touch them, or to use speed brakes, until on long final. A rough rule of thumb for commencing descent is 3 x FL, i.e. at FL 330, commence descent at 99 DME.

Modifications to the basic technique may be brought on by head or tail winds, cabin pressurization needs, en route weather, traffic, and descent clearances; they are of no further interest at this time.

The message is that full closing of GTE throttles in the air can be quite routine and the engines remain running smoothly.

Because of high centrifugal loads, axial compressor rotor blades must be securely attached to central drum disks, which are themselves bolted or welded together. Two methods are shown in figure 4-7. Rotor blades are machined to airfoil shapes with a high degree of accuracy. They are given a "twist" to provide a pressure gradient along the span of each blade, thereby producing a uniform velocity of axial airflow. Twisting the blades produces equal angles of attack over the blade span in the same way as twisting does in normal propeller blades.

Axial compressor stator vanes are also of airfoil design; they may be attached to the outer case directly as single units, or they may be assembled in vane retaining rings, which are then attached to the case in segments. Longer stator vanes may tend to vibrate, which is overcome by fitting shrouds to the vane ends.

Materials used in aviation engine manufacture are those having the best combination of heat resistance, high strength, and low weight. Aluminum is used at the front of the compressor casing. Further aft, steel alloys are used because working temperatures increase.

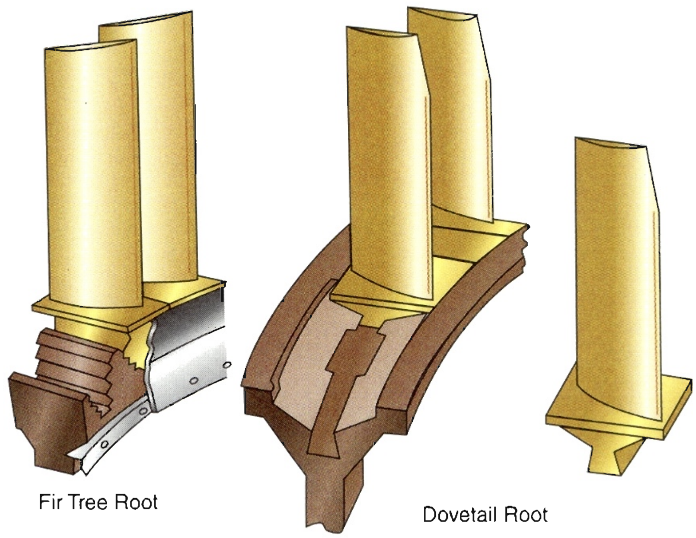

Figure 4-7. Blade attachment.

Nickel-based alloys suit compressor areas having the highest temperatures, however, titanium is becoming more favored for construction in critical areas. This case, which carries rows of stator vanes, may be assembled around the rotor by joining two halves. Alternatively, it may be made up of a number of short cylinders bolted together.

Steel or nickel alloys are materials most used for stator vanes, but titanium is used for compressor rotor blades, disks, and drums that carry high centrifugal loads when working. Large-diameter fan blades are also made of titanium to combine low weight with high strength.

Rotating assemblies are carried on self-aligning shafts mounted in bearings that are located in compressor casings. In all rotating parts of a GTE, balance is of utmost importance. Special machines are used to ensure that the correct degree of balance is achieved.