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GAS TURBINE ENGINE

15

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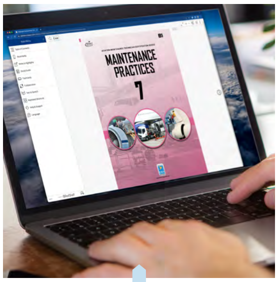

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REVISION LOG

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VERSION	EFFECTIVE DATE	DESCRIPTION OF REVISION(S)
001	2016.01	Module creation and release.
001.1	2022.06	Inclusion of Measurement Standards for clarification, page iv. Minor appearance and format updates.
002	2024.11	Regulatory update for EASA 2023-989 compliance.

Module was reorganized based upon the EASA 2023-989 subject criteria. Enhancements included in this version 005 are:

15.1 *Geared turbofan engines* - topic added.
15.3 *Turboprop and Turboshaft Engine Inlets* - topic added.
15.4 *Multispool designs* - topic added.
15.4 *Axial compressor blades, vanes, tips, and roots* - topic added.
15.4 *Compressor Rotor; drum, disk, and blisk types* - topic added.
15.4 *Combination compressors* - topic added.
15.4 *Compressor anti–stall bleed system* - topic added.
15.6 *Counter rotating turbines* - topic added.
15.8 *Labyrinth Seals* - topic added.
15.9 *Alternative and drop–in fuel* - topic added.
15.11 *Electronic power augmentation* - topic added.
15.13 *Large engine starter generators* - topic added.
15.13 *FADEC ignition system on GE CFM 56* - topic added.
15.15 *Power Augmentation* - replaced with alternative turbine construction.
All Submodule questions/answers updated.
Additional author and format enhancements.

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15.3 INLETS

COMPRESSOR INLET DUCTS

The inlet duct of a turbine engine must furnish a uniform supply of air to the compressor for the engine to enjoy stall free compressor performance. The inlet duct must also create as little drag as possible. Even a small discontinuity of airflow can cause significant efficiency loss, as well as many other engine performance problems. To ensure that the flight inlet duct delivers air with minimum turbulence, it must be maintained in as close to new condition as possible. If repairs to this component are necessary, expertly installed flush patches are mandatory to prevent drag. Moreover, the use of an inlet cover should be used to promote cleanliness and to prevent corrosion and abrasion. A typical turbofan inlet can be seen in **Figure 3-1**.

Proper inlet design contributes materially to aircraft performance by increasing the ratio of compressor discharge pressure to duct inlet pressure. This is also referred to as the compressor pressure ratio. This ratio is the outlet pressure divided by the inlet pressure. The amount of air passing through the engine is dependent upon three factors:

1. The compressor speed (rpm).
2. The forward speed of the aircraft.
3. The density of the ambient (surrounding) air.

INLET CONFIGURATIONS

SUBSONIC FLIGHT INLETS

Subsonic flight inlet ducts, such as those found on business and commercial jet aircraft, are of fixed geometry and have a divergent shape. A diverging duct progressively increases in diameter from front to back, as shown in **Figure 3-2**. This duct is sometimes referred to as an inlet diffuser because of its effect on pressure. Air enters the aerodynamically contoured inlet at ambient pressure and starts to diffuse, arriving at the compressor at a slightly increased static pressure. Usually, the air is permitted to diffuse (increase in static pressure) in the front portion of the duct and to progress at a fairly constant pressure past the engine inlet fairing to the compressor. In this manner, the engine receives its air with minimal turbulence and at a more uniform pressure.

As the aircraft approaches its desired cruising speed, the increased inlet pressure adds significantly to the mass airflow. At cruising speed, the compressor reaches its aerodynamic design point and produces its optimum compression and best fuel economy. At this point, the flight inlet, compressor, combustor, turbine, and tailpipe are designed to work in concert with each other. If any

Figure 3-1. Typical turbofan inlet.

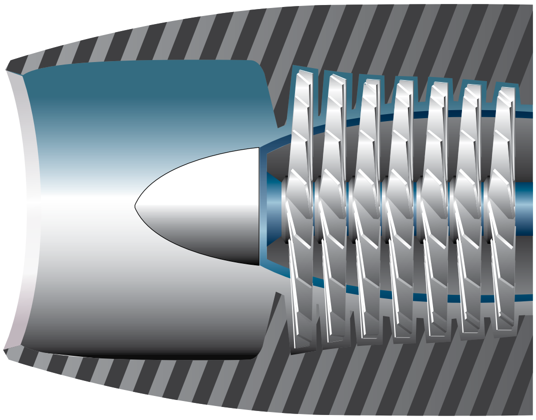

Figure 3-2. An inlet duct acts as a diffuser to decrease the airflow velocity and to increase the static pressure of air.

section does not match the others, for example because of damage, contamination, or ambient conditions, engine performance will be affected.

Figure 3-3 shows two common airflow arrangements. **Figure 3-3A** is a full duct design utilized on low and medium bypass engines, and **Figure 3-3B**, is the short duct design of a high bypass turbofan. The long ducting configuration reduces surface drag of the fan discharge air and enhances thrust. Many older engines did not take advantage of this drag reduction because of the excessive weight of the wider diameter and longer duct. However with new lightweight materials the newer generation engines can take advantage of this concept.

In *Submodule 2*, the concept of ram pressure recovery was mentioned. Ram compression occurs when the velocity of the air (kinetic energy) is converted to pressure (potential energy) due to the shape of the duct the air is flowing through. Because the subsonic inlet ducts for a turbojet or turbofan airplanes is diverging in shape, Bernoulli's principle teaches us that as the air spreads out the velocity will decrease and the static pressure will increase. A typical commercial airliner cruises at approximately Mach 0.85. That means the velocity of the air entering the inlet duct is Mach 0.85, which is much too fast to enter the engine's compressor. Because the ideal velocity to enter the compressor is Mach 0.5, the diverging shape of the inlet must slow the air down and as a result increases static pressure (ram compression).

Figure 3-4 shows the diverging shaped inlet duct for a high bypass turbofan engine, typical of what would be used in today's subsonic airliners. Noted in the figure is the fan duct flow area, with the arrow pointing at the fan exit guide vanes. The core inlet flow area is also shown, with the arrow pointing at the core inlet guide vanes. The fan exit guide vanes straighten the air before it goes out the fan duct, and the core inlet guide vanes direct the air into the compressor at the proper angle.

TURBOFAN ENGINE INLET SECTIONS

High bypass turbofan engines are usually constructed with the fan at the forward end of the compressor. A typical turbofan intake section is shown in **Figure 3-5**. Sometimes, the inlet cowl is bolted to the front of the engine and provides the airflow path into the engine. In dual compressor (dual spool) engines, the fan is integral with the relatively slow turning, low pressure compressor which allows the fan blades to rotate at low tip speeds for best fan efficiency. The fan permits the use of a conventional air inlet duct, resulting in low inlet duct loss. The fan reduces engine damage from ingested material because much of any material that is ingested is thrown radially outward and passes through the fan discharge rather than through the core of the engine. Warm bleed air is drawn from the engine and circulated on the inside of the inlet lip for anti-icing. The fan hub or spinner is either heated by warm air or is conical as mentioned earlier. Inside the inlet by the fan blade tips is an abraidable rub strip that allows the fan blades to rub for short times due to flight path changes. [**Figure 3-6**] Also, inside the inlet are sound reducing materials to lower the noise generated by the fan.

The fan on high bypass engines consists of one stage of rotating blades and stationary vanes that can range in diameter from less than 84 inches (2.1 meters) to more than 112 inches (2.8 meters). [**Figure 3-7**] The fan blades are either hollow titanium or composite materials. The air accelerated by the outer part of the fan blades

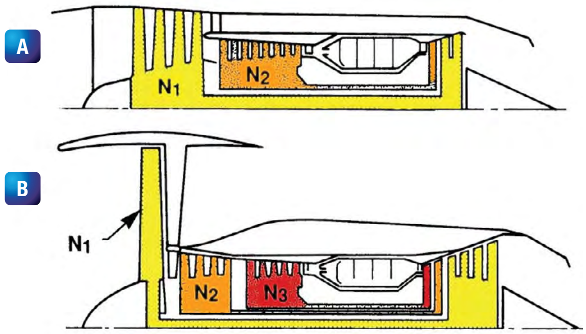

Figure 3-3. (A) Turbofan low- and medium-bypass ratio. (B) Turbofan high-bypass ratio.

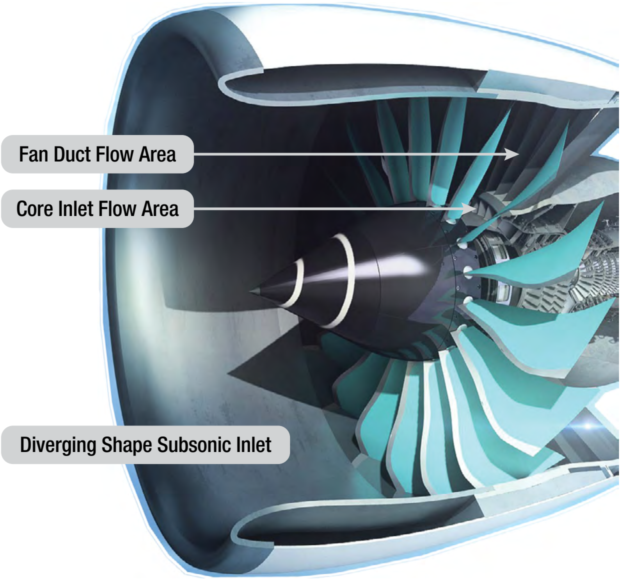

Figure 3-4. Diverging inlet for ultra-high-bypass turbofan.

Figure 3-5. A typical turbofan intake section.

forms a secondary airstream, which is ducted overboard without passing through the main engine. This secondary air (fan flow) produces 80 percent of the thrust in high bypass engines. The air that passes through the inner part of the fan blades becomes the primary airstream (core flow) through the engine itself. The air from the fan exhaust, which is ducted overboard, may be discharged in either of two ways:

- To the outside air through short ducts (dual exhaust nozzles) directly behind the fan. [**Figure 3-8**]
- All the way to the rear of the engine via closed ducts where it is exhausted to the outside air through a mixed exhaust nozzle. This type engine is called a ducted fan and the core airflow and fan airflow mix in a common exhaust nozzle.

TURBOPROP INLETS

Although a few turboprop airplanes have the propeller in the back and the engine inlet in the front, like the Piaggio Avanti seen in **Figure 3-9**, most have the propeller in the front and the engine inlet directly behind it. The engine inlet duct will have a diverging shape to it, and it will be able to convert velocity into pressure, but it will not be nearly as effective as the turbofan inlet duct in creating ram compression. However, because turboprop airplanes do not typically fly in the high subsonic velocity range (Mach 0.8 to 0.9), ram compression is not a primary consideration.

Some turboprop powered airplanes take off and land at non-improved grass, gravel and dirt airstrips. With this type of application, it is very important to have an inlet duct that separates debris from the air and does not allow it to enter the engine's compressor.

The Piaggio Avanti and the Turbo Ag-Cat airplanes are both powered by the Pratt & Whitney PT6 turboprop engine, but as **Figures 3-9 and 3-10** clearly show, their inlet ducts are completely different. On most airplanes the PT6 engine sits backward in the airframe, with the inlet in the rear and the exhaust in the front. For the inlet air to enter the engine's compressor, it must make a 90 degree turn to pass through the inlet screen and then another 90 degree turn to enter the rotating blades. Because the PT6 is a low mass airflow engine, the air is able to make these turns without too much loss of energy. The layout of the PT6 turboprop is shown in **Figure 3-11**.

The configuration for the inlet duct on the Turbo Ag-Cat would be like that shown in **Figure 3-12**. The air enters the inlet from the bottom after passing through the propeller, and then passes by a movable deflector vane that forces the air downward. Any debris in the air is forced downward and dumps out the back. Thus, only clean air is able to make the turn and flow up to the engine's screened inlet. The figure shows debris laden air in orange flowing out the back and clean air in blue making the turn toward the engine.

TURBOSHAFT INLETS

Turboshaft engines in helicopters are subjected to some of the most adverse conditions any turbine engine could experience. Helicopters are able to take off and land from virtually any location, and during this operation they are directing a huge amount of air straight down against the ground. This air being


Figure 3-6. Rubber stripping inside a turbofan engine inlet allows for friction for short periods of time during changes in the flightpath.

Figure 3-7. The air that passes through the inner part of the fan blades becomes the primary airstream.


Figure 3-8. Air from the fan exhaust can be discharged overboard through short ducts directly behind the fan.

directed against the ground causes a lot of debris to be kicked up and eventually ingested by the engine. For this reason, a helicopter turboshaft engine must have a sand and ice separator as part of its inlet configuration, or some other type of air filtration system. **Figure 3-13** shows a sand and ice separator for a turboshaft engine that relies on the same concept shown for the turboprop in **Figure 3-12**. The air enters the inlet from the side, and on its way to the engine has to make a sharp turn. Any heavy debris in the air is forced to the outside and so only clean air makes the turn to enter the engine. Air laden with debris gets separated and the debris then drops into a sediment trap.

SUPERSONIC FLIGHT INLET DUCTS

All supersonic aircraft require a convergent-divergent inlet duct, either fixed or variable. Supersonic aircraft are configured with an inlet that slows the airflow to subsonic speed at the face of the engine, regardless of aircraft speed. Subsonic airflow into the compressor is required if the rotating airfoils are to remain free of shock waves. Even if the air is entering the inlet duct at Mach 2.0, by the time the air reaches the engine's compressor it is slowed down to approximately Mach 0.5.

Figure 3-14 depicts a nonadjustable convergent-divergent duct in which supersonic airflow is slowed by compression in its throat area (where the converging shape changes to diverging). After its velocity is reduced to slightly below Mach 1.0, the airflow enters the subsonic diffuser section where velocity is further reduced and its pressure increased before entering the engine compressor.

VARIABLE GEOMETRY DUCTS

In practice, inlet ducts for supersonic aircraft follows the general design of **Figure 3-14** only as much as practical. For very high speed aircraft, the shape of the duct can be changed by a movable restrictor such as a ramp or wedge inside the duct to form a convergent-divergent configuration of variable proportion. A duct of this type is known as a variable geometry inlet duct.

BELLMOUTH COMPRESSOR INLETS

A bellmouth inlet is usually installed on an engine undergoing testing in a test cell. [**Figure 3-15**] It is generally equipped with probes that can measure intake temperature and pressure.

During testing, it is important that the outside static air is allowed to flow into the engine with as little resistance as possible. The bellmouth is attached to the movable part of the test stand and moves with the engine. The thrust stand is made up of two components, one nonmoving and one moving. This is so the moving component can push against a load cell and measure thrust during the testing of the engine. The bellmouth is designed with the single objective of obtaining very high aerodynamic efficiency. Essentially, the inlet is a bell shaped funnel having carefully rounded shoulders which offer practically no air resistance. Duct loss is so slight that it is considered zero. The engine can therefore be operated without the complications resulting from losses common to an installed aircraft inlet duct. Engine performance data, such as rated thrust and thrust specific fuel consumption,

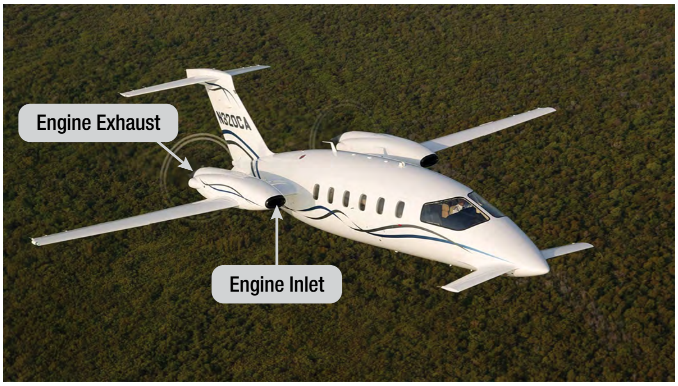

Figure 3-9. Piaggio Avanti engine inlet configuration.

Figure 3-10. Turbo Ag-Cat engine inlet configuration.

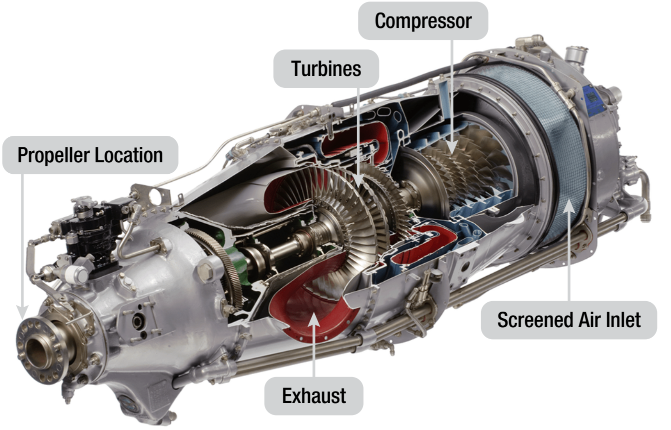

Figure 3-11. Pratt & Whitney PT6 layout of components.

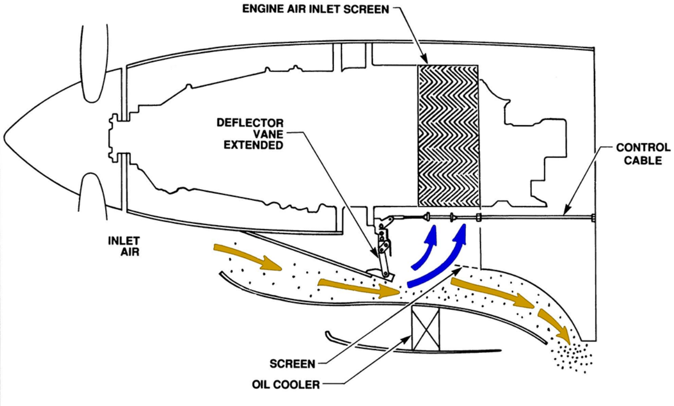

Figure 3-12. Turboprop sand and ice separator (inertial).

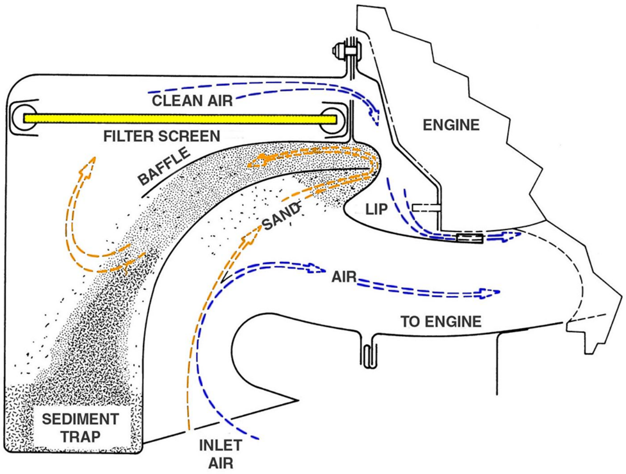

Figure 3-13. Turboshaft sand and ice separator (inertial).

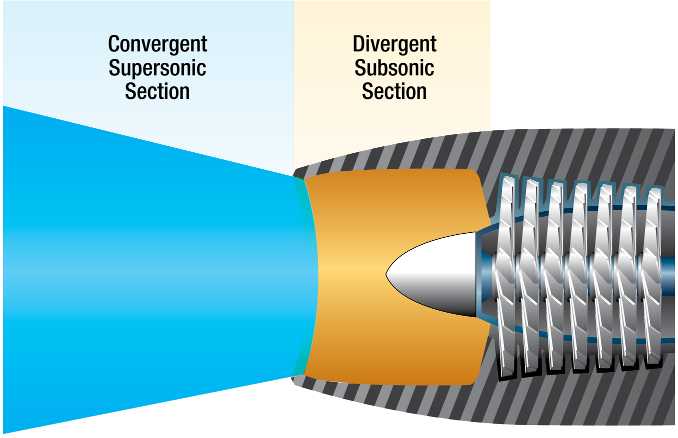

Figure 3-14. The aft section of an inlet duct acting as a subsonic diffuser.

Figure 3-15. Bellmouth inlet mounted on test cell engine.

are obtained while using a bellmouth inlet. Usually, the inlets are fitted with protective screening. In this case, the efficiency lost as the air passes through the screen must be taken into account when very accurate engine data are necessary.

COMPRESSOR INLET SCREENS

To prevent the engine from readily ingesting any items that can be drawn in the intake, a compressor inlet screen is sometimes placed across the engine air inlet at some location along the turboprops [**Figure 3-16**] and APUs [**Figure 3-17**] are not as vulnerable to FOD.

The advantages and disadvantages of a screen vary. If the engine is readily subjected to internal damage, as would be the case for an engine having an axial compressor fitted with aluminum compressor blades, an inlet screen is almost a necessity.

Screens, however, add appreciably to inlet duct pressure loss and are very susceptible to icing. Failure due to fatigue is also a problem. A failed screen can sometimes cause more damage than no screen at all. In some instances, inlet screens are made retractable and may be withdrawn from the airstream after takeoff or whenever

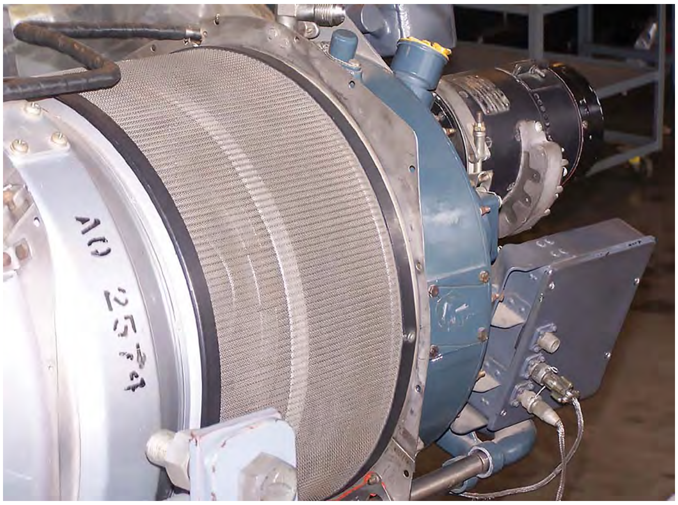

Figure 3-16. Example of a turboprop engine that incorporates inlet screens.

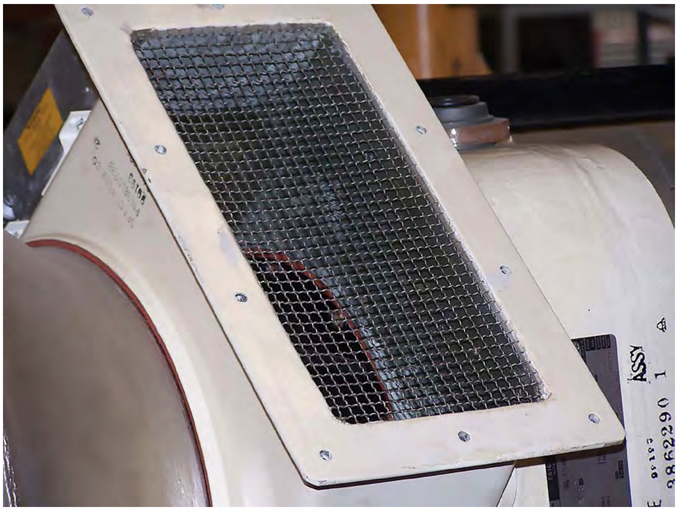

Figure 3-17. An example of an inlet screen on an APU.