DEPARTMENT OF AEROSPACE ENGINEERING

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UNIT III - FUNDAMENTALS OF GAS TURBINE ENGINES

Simulations of Turboprop, Turbofan, and Turbojet Engines

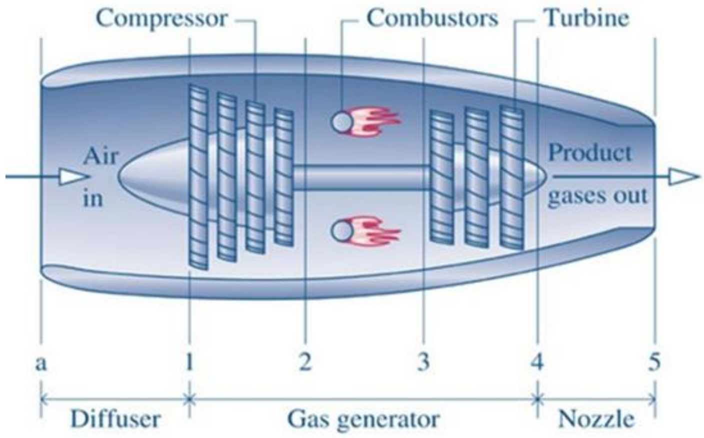
Turbojet Engine

The turbojet is an airbreathing jet engine, typically used in aircraft. It consists of a gas turbine with a propelling nozzle. The gas turbine has an air inlet, a compressor, a combustion chamber, and a turbine (that drives the compressor). The compressed air from the compressor is heated by burning fuel in the combustion chamber and then allowed to expand through the turbine. The turbine exhaust is then expanded in the propelling nozzle where it is accelerated to high speed to provide thrust. Two engineers, Frank Whittle in the United Kingdom and Hans von Ohain in Germany developed the concept independently into practical engines during the late 1930s.

While the turbojet was the first form of gas turbine powerplant for aviation, it has largely been replaced in use by other developments of the original concept. In operation, turbojets typically generate thrust by accelerating a relatively small amount of air to very high supersonic speeds, whereas turbojets accelerate a larger amount of air to lower transonic speeds. Turbojets have been replaced in slower aircraft by turboprops because they have better specific fuel consumption. At medium speeds, where the propeller is no longer efficient, turboprops have been replaced by turbofans. The turbofan is quieter and has better range-specific fuel consumption than the turbojet. Turbojets can be highly efficient for supersonic aircraft.

Turbojets have poor efficiency at low vehicle speeds, which limits their usefulness in vehicles other than aircraft. Turbojet engines have been used in isolated cases to power vehicles other than aircraft, typically for attempts on land speed records. Where vehicles are "turbine-powered", this is more commonly by the use of a turboshaft engine, a development of the gas turbine engine where an additional turbine is used to drive a rotating output shaft. These are common in helicopters and hovercraft. Turbojets were used on Concorde and the longer-range versions of the TU-144 which were required to spend a long period traveling supersonically. Turbojets are still common in medium-range cruise missiles, due to their high exhaust speed, small frontal area, and relative simplicity. They are also still used on some supersonic fighters such as the MiG-25, but most spend little time traveling supersonically, and so employ turbofans and use afterburners to raise exhaust speed for supersonic sprints.

Turbojets are the oldest kind of general-purpose jet engines. Turbojets are rotary engines that extract energy from a flow of combustion gas. They produce thrust by increasing the velocity of the air flowing through the engine and operate on Newton's third law of motion " For every action there is an equal and opposite reaction". Newton's 2nd Law on motion F= Mass * Acceleration. Here Large acceleration with a small mass of air.



Turbojet Engine a-1 Isentropic increase in pressure (diffuser)

1-2 Isentropic compression (compressor)

2-3 Isobaric heat addition (combustion chamber) 3-4 Isentropic expansion (turbine)

4-5 Isentropic decrease in pressure with an increase in fluid velocity (nozzle)

The operation of a turbojet is modeled approximately by the Brayton cycle. The efficiency of a gas turbine is increased by raising the overall pressure ratio, requiring higher-temperature compressor materials, and raising the turbine entry temperature, requiring better turbine materials and/or improved vane/blade cooling. It is also increased by reducing the losses as the flow progresses from the intake to the propelling nozzle. These losses are quantified by compressor and turbine efficiencies and ducting pressure losses. When used in a turbojet application, where the output from the gas turbine is used in a propelling nozzle, raising the turbine temperature increases the jet velocity. At normal subsonic speeds, this reduces the propulsive efficiency, giving an overall loss, as reflected by the higher fuel consumption, or SFC. However, for supersonic aircraft, this can be beneficial and is part of the reason why the Concorde employed turbojets. Turbojet systems are complex systems therefore to secure the optimal function of such systems, there is a call for the newer models being developed to advance their control systems to implement the newest knowledge from the areas of automation, so increase its safety and effectiveness.

Primary Parts of Turbojet Engine

1. Air Intake/ Inlet
2. Compressor
3. Combustion Chamber
4. Turbine
5. Nozzle

Secondary Parts of Turbojet Engine

1. After Burner
2. Auxiliary Power Unit

Construction Intake

Intake refers to the capture area definition and attached ducting to an aircraft gas turbine engine. Air intake aims at bringing large amounts of surrounding air into the engine. A tube-shaped inlet, like one you would see on an airliner usually of cylindrical or conical design. Inlets come in many shapes and sizes depending on the aircraft. The intake has to supply air to the engine with an acceptably small variation in pressure (known as distortion) and having lost as little energy as possible on the way (known as pressure recovery). The ram pressure rise in the intake is the inlet's contribution to the propulsion system's overall pressure ratio and thermal efficiency.

Compressor

The compressor rotates at a very high speed, adding energy to the airflow and at the same time squeezing it into a smaller space. Compressing the air increases its pressure and temperature. The compressor is driven by the turbine. Compressors used in turbojet engines are mainly classified as: Axial Flow Compressors and Centrifugal Compressors. Turbojets supply bleed air from the compressor to the aircraft for the environmental control system, anti-icing, and fuel tank pressurization, for example. The engine itself needs air at various pressures and flow rates to keep it running. This air comes from the compressor, and without it, the turbines would overheat, the lubricating oil would leak from the bearing cavities, the rotor thrust bearings would skid or be overloaded, and ice would form on the nose cone. The air from the compressor, called secondary air, is used for turbine cooling, bearing cavity sealing, anti-icing, and ensuring that the rotor axial load on its thrust bearing will not wear it out prematurely.

Combustion Chamber

The burning process in the combustor is significantly different from that in a piston engine. In a piston engine, the burning gases are confined to a small volume, and as the fuel burns, the pressure increases. In a turbojet, the air and fuel mixture burn in the combustor and pass through to the turbine in a continuous flowing process with no pressure build-up. Instead, a small pressure loss occurs in the combustor. The fuel-air mixture can only burn in slow-moving air, so an area of reverse flow is maintained by the fuel nozzles for the approximately stoichiometric burning in the primary zone.

Further compressed air is introduced which completes the combustion process and reduces the temperature of the combustion products to a level which the turbine can accept. Less than 25% of the air is typically used for combustion, as an overall lean mixture is required to keep within the turbine temperature limits.

Turbine

Hot gases leaving the combustor are allowed to expand through the turbine. Turbines are usually made up of high-temperature alloys such as Inconel The turbine's rotational energy is used primarily to drive the compressor. And other accessories, like fuel, oil, and hydraulic pumps. In a turbojet, almost two-thirds of all the power generated by burning fuel is used by the compressor to compress the air for the engine. In the first stage, the turbine is largely an impulse turbine (similar to a Pelton wheel) and rotates because of the impact of the hot gas stream. The later stages are convergent ducts that accelerate the gas. Energy is transferred into the shaft through momentum exchange in the opposite way to energy transfer in the compressor. The power developed by the turbine drives the compressor and accessories, like fuel, oil, and hydraulic pumps that are driven by the accessory gearbox.

Nozzle

After the turbine, the gases are allowed to expand through the exhaust nozzle to atmospheric pressure, producing a high-velocity jet in the exhaust plume. In a convergent nozzle, the ducting narrows progressively to a throat. After the turbine, the gases expand through the exhaust nozzle producing a high velocity jet. In a convergent nozzle, the ducting narrows progressively to a throat. The nozzle pressure ratio on a turbojet is high enough at higher thrust settings to cause the nozzle to choke. If, however, a convergent-divergent de Laval nozzle is fitted, the divergent (increasing flow area) section allows the gases to reach supersonic velocity within the divergent section. Additional thrust is generated by the higher resulting exhaust velocity.

After Burner

An afterburner or "reheat jet-pipe" is a device added to the rear of the jet engine. It provides a means of spraying fuel directly into the hot exhaust, where it ignites and boosts available thrust significantly; a drawback is its very high fuel consumption rate. An afterburner or "reheat jetpipe" is a combustion chamber added to reheat the turbine exhaust gases. The fuel consumption is very high, typically four times that of the main engine.

Merits

1. Very high power-to-weight ratio.
2. Compact than most reciprocating engines of the same power rating.
3. High operation speeds.
4. Low lubricating oil cost and consumption.

Demerits

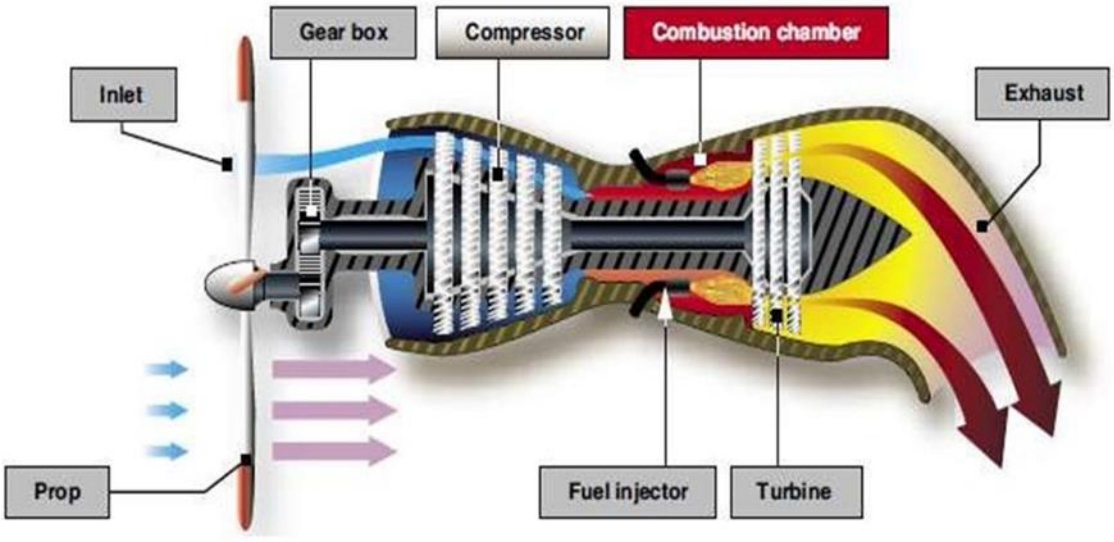
1. Cost and Longer startup than reciprocating engines
2. Less responsive to changes in power demand

Application

Supersonic aircraft and Military aircraft.

Turbo-Prop Engine

Turboprop engines generate substantial shaft power in addition to nozzle thrust. Turboshaft engines generate only shaft power. These engines are used in helicopters. The shaft power is used to drive the main rotor blade. Both turboprops and turboshafts have applications at relatively lower speeds. Turboprops and turboshafts usually have a free turbine or power turbine to drive the propeller or the main rotor blade (turboshafts). Stress limitations require that the large-diameter propeller rotates at a much lower rate and hence a speed reducer is required. Turboprops may also have a thrust component due to the jet exhaust in addition to the propeller thrust.



Turboprop Engine

Advantages

1. In dense air, i.e. lower levels, a propeller has a higher efficiency than jet exhaust;
2. Generally, turboprop aircraft can operate on shorter runways than turbofan; mechanical Reliability due to relatively few moving parts
3. Lightweight and simplicity of operation
4. High power per unit of weight

Disadvantages

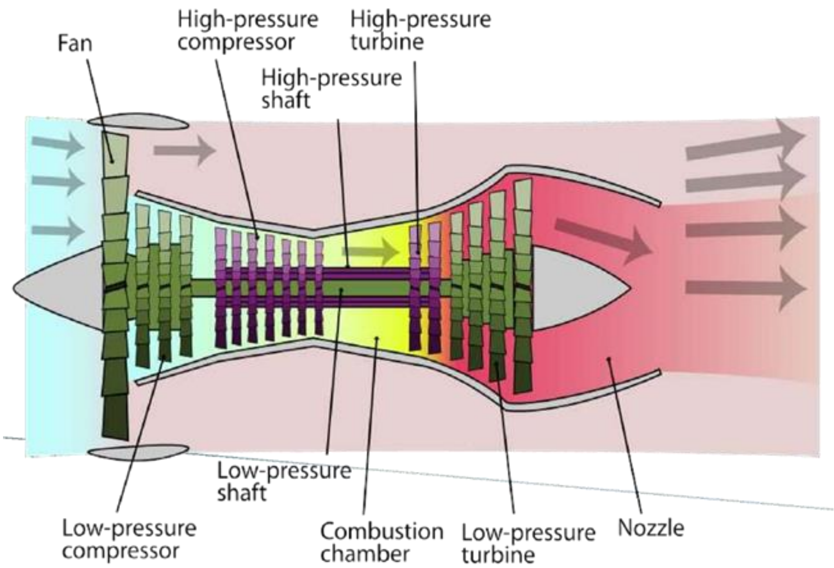
1. Propellers lose efficiency at high altitudes;
2. Vibration levels can cause slight passenger discomfort;
3. En-route weather (icing/turbulence) can cause problems and additional passenger discomfort due to operating altitudes

Application

1. Passenger Aircraft of the least range
2. Military Cargo Aircraft
3. Trainer Aircraft

Turbo-Fan Engine

Propulsion efficiency is a function of the exhaust velocity to flight speed ratio. This can be increased by reducing the effective exhaust velocity. In a turbofan engine, a fan of a larger diameter than the compressor is used to generate a mass flow higher than the core mass flow. This ratio is called the bypass ratio. Turbofan engines have a higher propulsion efficiency as compared with turbojet engines operating in the same speed range. A turbofan engine is the most modern variation of the basic gas turbine engine. As with other gas turbines, there is a core engine, whose parts and operation are discussed on a separate page. In the turbofan engine, the core engine is surrounded by a fan in the front and an additional turbine at the rear.



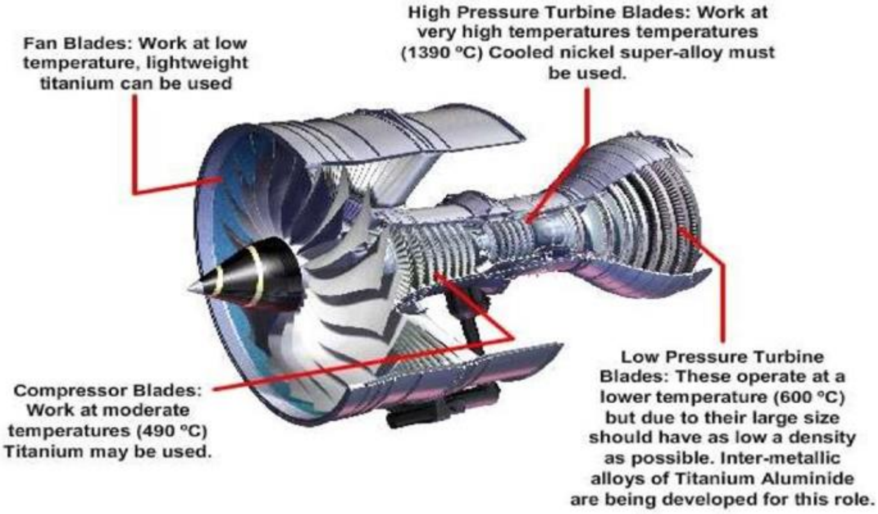
Turbo Fan Engine

Fan

The fan is responsible for producing the majority of the thrust generated by a turbofan engine and is easily visible when looking at the front of the engine. The fan is directly connected to the low-pressure compressor (LPC) and the low-pressure turbine (LPT) by way of a shaft known as the low-pressure shaft. Turbofans were invented to circumvent the undesirable characteristic of turbojets being inefficient for subsonic flight. To raise the efficiency of a turbojet, the obvious approach would be to increase the burner temperature, to give better Carnot efficiency and fit larger compressors and nozzles. However, while that does increase thrust somewhat, the exhaust jet leaves the engine with even higher velocity, which at subsonic flight speeds, takes most of the extra energy with it, wasting fuel. Instead, a turbofan can be thought of as a turbojet being used to drive a ducted fan, with both of those contributing to the thrust. Whereas all the air taken in by a turbojet passes through the turbine (through the combustion chamber), in a turbofan some of that air bypasses the turbine. Because the turbine has to additionally drive the fan, the turbine is larger and has larger pressure and temperature drops, so the nozzles are smaller. This means that the exhaust velocity of the core is reduced. The fan also has lower exhaust velocity, giving much more thrust per unit of energy (lower specific thrust). The overall effective exhaust velocity of the two exhaust jets can be made closer to a normal subsonic aircraft's flight speed. In effect, a turbofan emits a large amount of air more slowly, whereas a turbojet emits a smaller amount of air quickly, which is a far less efficient way to generate the same thrust. The ratio of the mass flow of air bypassing the engine core compared to the mass flow of air passing through the core is referred to as the bypass ratio. The engine produces thrust through a combination of these two portions working together; engines that use more jet thrust relative to fan thrust are known as low-bypass turbofans, conversely, those that have considerably more fan thrust than jet thrust are known as high-bypass. Most commercial aviation jet engines in use today are of the high-bypass type and most modern military fighter engines are low-bypass. Afterburners are not used on high-bypass turbofan engines but may be used on either low-bypass turbofan or turbojet engines.

Compressor

The purpose of compression is to prepare the air for combustion by adding energy in the form of pressure and heat. The compressor is divided into two portions: the low pressure compressor, mentioned above, and the high pressure compressor however, they interact with different parts of the turbofan engine.



High Pressure and Low-Pressure Blades

Combustion Chamber

Combustion occurs within the combustor, a stationary chamber within the core of the engine The combustor is directly downstream of the HPC and directly upstream of the high pressure. The purpose of the combustor is to add even more energy to the airflow by way of heat addition. Within the combustor, fuel is injected and mixed with the air. This fuel-air mixture is then ignited, creating a dramatic increase in temperature and energizing the flow, propelling it rearward toward the high-pressure turbine.

Turbine

Expansion occurs within the high-pressure and low-pressure turbines. Similar in appearance to the compressors, the turbines have rows of blades that spin. The purpose of the turbines is to extract energy from the flow which is then used to spin the compressors and the fan. The spinning fan draws more air through the core of the engine which continues the entire process, and it pulls more bypass air around the engine, generating continuous thrust.

Nozzle

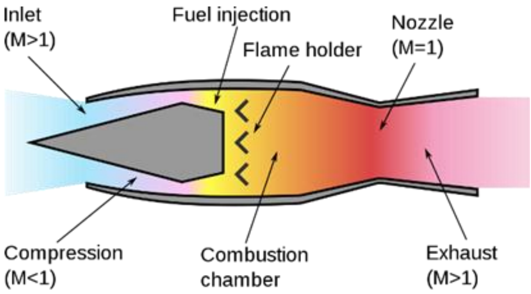
The exhaust nozzle is located directly downstream of the LPT and it is the last component that the airflow touches before exiting the engine. The purpose of the exhaust nozzle is to propel the core flow out of the engine, providing additional thrust. This is accomplished by way of its geometry or shape. The nozzle also helps regulate pressures within the engine to keep the other components functioning properly and efficiently.

RAMJET

A ramjet is simply a duct of a special shape, which faces the airflow caused by the forward motion and relies on the ram effect to collect the air, add heat to it by combusting suitable fuel, and then exit through a nozzle at higher velocity and mass to create ever-increasing thrust. There are no moving parts, no need for lubrication, and no energy losses in trying to run something. To put it simply, it is an 'Aerodynamic engine' or to make it sound more complicated we can call it Athodyd short for 'Aero- thermo-dynamic duct'. In which the injectors spray the mist of fuel into the ram compressed air stream and a spark ignites the mixture. The grill-type flame holder provides a type of barrier to the burning mixture while allowing, expanding hot gases to escape through the exhaust nozzle. The high-pressure air coming into the combustion chamber keeps the burning mixture from effectively reacting toward the intake end of the engine. It is important to note that ramjets will not function until enough air is coming through the intake to create a high-pressure flow. Otherwise, the expanding gases of the burning fuel-air mixture would be expelled from both ends of the engine.

Ram Effect

By a suitable design of intake, the additional compression and therefore pressure rise can be achieved at the air intake which is called as ram effect. The ram effect increases with the increase in forward speed. At 1.0M the external compression caused by the ram effect in the engine intake is approximately equal to that of the engine. At higher Mach No the contribution of the ram effect increases markedly as compared to the turbojet engine. Thus, now we can dispense off the compressor and achieve the necessary compression by pure ram effect. The above three components viz. Ram effect, compressing the air, the Engine, converting the chemical energy into heat and pressure energy, and finally the jet converting heat and pressure energy into forward push making what is called ram jets. Now comparing the thrust obtained by the reaction engines, against the speed of the aircraft (TAS), it can be seen that the trust without intake ram effect would be a straight line and will show a steady drop as the TAS increases and tends to equal the exhaust jet velocity. The ram effect however starts to increase as speed goes past 300 kts (500 kmph) and continues to increase the thrust till about 3.0M for the Turbojets. The subsequent drop in Turbojet thrust in this graph is again due to TAS approaching jet exhaust velocities (V) and the difference Ve-Vo reduces drastically (V being the TAS). This can be increased slightly by using Reheat augmentation engines, however, 0 the turbojets have to now make way for ramjets to take over from here onwards.



Ramjet Engine