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R&D DEVELOPMENTS

Improvements in Aircraft Gas Turbine Engines for the 90s

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The gas turbine propulsion system has been playing the most significant role in the evolution and development of present-day aircraft, and has become the limiting technology for developing most new aircraft. However, the jet engine still remains the preferred propulsion choice. Aircraft gas turbines in one form or the other, viz. turbojet, turbofan, turboprop or turboshaft, have been used in commercial passenger aircraft, high performance military aircraft and in rotary wing aircraft (helicopters). The emphasis in engine development programmes world over seems to be in reducing fuel consumption, increasing thrust and in reducing weight.

Advancements in gas turbine technology over the past 30-40 years have resulted in reductions in fuel consumption and weight, with a major effort to increase power output (thrust). The thrust requirement is governed by the maximum take-off weight of the aircraft (Thumb rule is that total thrust is equal to about 30 per cent of maximum take-off gross weight). Since runway length, airfield altitude and ambient temperature, and the number of engines determine the thrust requirement; then the shorter the runway, the higher the elevation, or hotter the ambient temperature (all factors that are predominantly prevalent in India), more is the thrust required; or fewer the number of engines in an aircraft, more is the thrust required per engine.

It is not enough that the engine develops adequate thrust but must do it efficiently, i.e., fuel efficiency is identified through specific fuel consumption (SFC). For a given payload, an improvement in SFC results in increased range. SFC can be decreased through improvements in the basic thermodynamic cycle and through improvements in the efficiencies of the major engine components, such as compressors, combustion chambers, turbines, exhaust nozzle. Examples of such improvements are: higher turbine inlet temperatures, higher compressor pressure ratios and tighter clearances in rotors to reduce air/gas leakage.

Another measure of engine efficiency is the specific weight, i.e., weight per kg of thrust. As a result of advancements in materials processing and manufacturing technology, the engines of this decade operate at much higher temperatures, higher pressures and higher RPMs than the engines of earlier decades (with lighter and stronger structural components). These improvements have reduced the engine weight to half of the engine weight of 50s and 60s.

The overall efficiency of a gas turbine engine is defined as the product of its cycle efficiency and propulsive efficiency. Cycle efficiency is the ratio of thrust energy developed by the engine to the fuel energy input to the engine. Propulsive efficiency is defined as the ratio of the propulsive work done by the engine to move the aircraft to the thrust output. Thus their product is the ratio of the work done on the aircraft to the fuel energy input to the engine. The higher the overall efficiency, the lower is the SFC.

Turbojet vs Turbofan: A very simple way of differentiating these two concepts is that the turbojet moves a 'small' mass of air at high speed and a turbofan moves a 'large mass' of air at low speed. Earlier jet engines were turbojets, but they have now been replaced by turbofans, both for commercial as well as military aircraft. The reason is that the turbofan has significantly better propulsive efficiency and lower SFC which can be explained as follows. The main objective of the engine designer is to attain maximum engine efficiency for a particular aircraft application. By reducing the jet velocity, one can maximize the propulsive efficiency, but this will reduce the thrust output. So the engine mass flow has to be increased to compensate for the reduction in thrust. Engine mass

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flow can be increased by installing a large diameter compressor (fan) at the front of the engine, and then bypass some of the increased mass flow around the core of the engine. This bypass air has a lower velocity than that of the core flow, which has the effect of moving a larger mass of air at a slower speed. The effective jet velocity of the fan air added to the primary air (from the core) is less than the jet velocity from a comparable turbojet. Thus the propulsive efficiency of this turbofan is better than that of a turbojet, with a lower SFC. The ratio of fan airflow to primary air flow is referred to as the ratio of a turbofan engine. The early turbofan engines had a bypass ratio of less than one. In some military applications, this is desirable and the engine is called a 'leaky turbojet'. Today's large thrust turbofans operate at bypass ratios may be of 10:1.

While optimizing the efficiency of each of the major components of the engine (intake, compressor and fan, combustion chamber, turbine, exhaust nozzle), the inter-relationship between these components and the effect of each on the other has to be considered.

In respect of the compressor, the rotor and stator blade airfoils and planforms of the axial flow compressor are optimized to get the maximum pressure rise (pressure increase) across each stage of the axial compressor, so as to achieve the highest pressure in the least number of stages. This would keep the length and weight of the compressor to a practical minimum. In analyzing compressor performance, a compressor map is used. Figure 3 shows the compressor pressure ratio as a function of air flow. The operating line defines where the compressor operates with the engine under steady state conditions. The objective in using the compressor map is to adjust the flow areas and power input in such a manner that the compressor will operate along the lines of highest efficiency without detriment to stability (stall or surge). A one per cent increase in compressor efficiency is equal to a 0.3 to 0.5 per cent decrease in SFC.

The combustion chamber must heat a large volume of air in the smallest space, while using minimum amount of fuel. A chemically pure mixture of fuel and air (stoichiometric fuel/air ratio) would give maximum combustion efficiency, but the internal metal components of the combustion chamber would not be able to withstand the extremely high temperatures required to achieve that level of efficiency. Thus, a large part of the air that enters the combustion chamber is used for cooling the liner wall. Therefore, a highly efficient combustion system is desirable to reduce the quantity of fuel burnt, to reduce emissions and to provide as high a temperature as possible to the turbine. Research on combustors includes: (i) combustion chamber aerodynamics, which is associated with the design and analysis of the combustor geometry and its effect on air flow distribution, pressure losses, exit temperature profile; (ii) liner cooling—development of analytical liner temperature prediction programmes and improved film cooling techniques, such as transpiration cooling; and (iii) better methods of fuel injection, such as the air blast atomizer and air-assist nozzle.

The purpose of the turbine is to provide the shaft horse- power to drive the fan, the compressors and the accessories, such as fuel pumps, oil pumps, gear train, etc. The aim, to obtain optimum energy from the gas stream, is to attain the maximum shaft power with as low a number of turbine stages as possible. The shaft power to the compressors (transmitted through the HP and LP shafts) is determined by the pressure drop across the turbine and the flow area. The flow area and the power across the turbine and the compressor are to be matched to ensure that each component operates at peak efficiency within the constraints of the total system, such as maximum diameter, length, weight. One way of reducing engine weight is to reduce the number of stages. In another method, counter-rotating rotor blade rows eliminate the number of stator rows, since one rotor stage is aerodynamically coupled to the next, instead of mechanically via the next stator stage. By decreasing the number of turbine stages, more work has to be extracted per stage, which in turn means a higher turbine rotor speed. Thus current research is focusing on blade sweep, blade aspect ratio, blade taper, counter swirl and/or unsteady flow as a means of increasing turbine work output per stage.

Though optimum cycle efficiencies occur at higher pressure ratios and higher turbine inlet temperatures, the materials used in present-day turbines cannot accommodate these high temperatures, unless they are cooled adequately. Cooling schemes for turbine blades and vanes involve very complicated serpentine passages internally, through which air bled from the compressors is passed. This results in reduction of gas flow to the turbine, thereby decreasing its efficiency. It has been shown that a one per cent increase in turbine efficiency can reduce SFC by 0.6-0.8 per cent.

In the exhaust nozzle, where the gases are discharged from the engine, the discharge area and the pressure ratio across the nozzle determine the discharge velocity. Since, the discharge velocity affects the thrust and propulsive efficiency of the engine, considerable design effort has been done in optimizing the nozzle configuration. In military aircraft, where the engine is provided with an afterburner, a variable exhaust nozzle with a converging/diverging configuration influences the aft-end design of the aircraft and thereby its base drag. The objective is to develop such a design where the jet velocity approaches the velocity of the aircraft. With the emphasis on stealth, low infrared signature and thrust vectoring during combat, the two-dimensional nozzle instead of the conventional axisymmetric nozzle, becomes more attractive. In-depth R&D is being pursued on these nozzles to resolve the complicated mechanical, fabrication and materials (composites) problems.

In commercial aircraft, because of regulations on noise levels, noise abatement/noise suppression has become a major factor in designing aeroengines. Discharge velocity is lowered by minimising noise, since jet wake noise is a function of discharge velocity. In the turbofan engine, an exhaust mixer is employed which mixes the lower velocity fan exhaust with the higher velocity primary jet to effectively reduce the discharge velocity.

Some of the advanced technologies that have a significant influence on aircraft engine design and development have been discussed in the following paragraphs.

Internal computational fluid mechanics is contributing to a more efficient engine design process wherein accurate quantitative trade-offs can be made between performance, structural design and weight. Also, internal computational fluid mechanics can predict heat transfer in the hot section more accurately, resulting in more uniform metal temperatures, lower cooling flow rates and longer component life. With these tools, the designer should be able to predict average temperatures of around 1500 °C within ±5 per cent. The aspect of fluid dynamics, which deals with analysing the thermal environment of an engine including local heat distribution, is the concern of the heat transfer analyst. The available and continuing sophisticated analytical techniques in heat transfer would result in (a) increase in temperature capability equivalent to a 6-8 per cent increase in thrust performance, and (b) temperature predictions of specific engine parts to such an accuracy that the calculated stresses of these parts would predict their life realistically.

The capability of materials has been another limitation in the component design of the engine. For example, the allowable compressor outlet temperatures cannot be increased much further because of limitations in the capability of materials used for compressor blades and compressor casings. Limitations of disc materials impose restrictions on rotor speed. However, with present-day materials research, it is foreseen that many lightweight materials having a high temperature resistance will be soon available; anisotropic alloys, non-metallic structures and ceramics are examples of such materials. Composites, particularly metal-matrix composites (MMCs), are finding their utility in engine casings, frames, stators and bypass ducts. Presently, composites are used in engine parts operating up to 300 °C. The development of titanium MMCs is a breakthrough. It replaces the nickel base alloy, now used in the last stages of the high pressure compressor and reduces weight enormously. There are possibilities of integrating the turbine blade and disc into a single structural component (called Blisk) because of the strength and stiffness of these MMCs. Solid ceramics will also be used in this application, when problems of their manufacturing process are solved and the capability to withstand thermal shock is enhanced in these ceramics. In future, gas turbine engines will make extensive use of thermal barrier coatings on hot end parts to reduce the losses due to cooling requirements of the existing uncoated parts.

Titanium aluminides in both reinforced monolithic and reinforced composite form were first used in the demonstrator engine of the integrated high performance engine technology, USA. Alpha 2 and Gamma titanium aluminides have the advantage of high elastic modulus, low density, elevated temperature strength and creep resistance. But titanium aluminides have substantially lower temperature ductility and lower room temperature fracture, toughness than conventional alloys. Silicon carbide reinforced Ti_3Al MMCs have been used in engine components. Components fabricated from the Alpha 2 alloy Ti_4Al-21Nb are used in the F404 primary exhaust seal, formerly produced by super plastic forming and diffusion bonding.

For the IHPTET programme, the new materials being explored for hot section components have high specific strength (material strength divided by material density) and can withstand high temperatures. Materials in this class include intermetallics, nickel-based alloys, fibre reinforced titanium, ceramic-matrix composites and carbon-carbon composites. Because carbon-carbon composite is exceptionally light and very strong at high temperatures, its mechanical properties are not affected by temperatures up to 1650 °C and its use for turbine blades may significantly reduce the weight of the entire rotor system through resulting lighter discs, shafts and bearings. Also, temperature-resistant carbon-carbon composite blades can be solid avoiding cooling air tapping, thus giving increased thrust and turbine efficiency. Some typical axamples of the above innovations/improvements incorporated in military engines are now described:

The Pratt & Whitney PW 2037 engine of 170 kN thrust, uses controlled diffusion airfoils in its compressor for better aerodynamic efficiency. These airfoils are generated by computerised 3=D modelling and flow analysis techniques that analyse surfaces for optimum airflow characteristics. This aerodynamic shape reduces considerably the separation region at the airfoil trailing edge suction surface, i.e. reduces airfoil stall.

The Pratt & Whitney F 119 PW-100 engine is chosen for the USAF Advanced Tactical Fighter Aircraft and is installed in the Lockheed/General Dynamics F 22 ATF. The F 119 has a simple configuration and is equipped with FADEC. It incorporates two-dimensional thrust vectoring, which is designed to provide significant increase in combat performance. It is an axial flow fan engine of 156 kN thrust.

In The General Electric (GE) unducted fan demonstrator engine, an innovative feature has been the counter-rotating fan blades constructed from high-strength composite materials. The counter rotation feature of the propulsor allows the fan and power turbine to run efficiently at the same rpm, thus eliminating the complexity associated with a reduction gearbox.

The General Electric F 404 RM 12 engine used in the Swedish JAS 39 Grippen aircraft has been supplied as a variant, designated F 404 F2J3, for India's LCA as its interim power plant. The engine has three fan stages and seven HP compressor stages to achieve a pressure ratio of 26:1, with a specific fuel consumption at maximum power of 1.81. With a maximum thrust of 81.3 kN, the engine has a thrust to weight ratio of 7.83:1. A variant, the F 404-GE-402 rated at 78.7 kN having a thrust to weight ratio of 7.75:1, is now (from 1992) the standard production engine of the McDonnel Douglas F/A-18 aircraft of the US Navy. A non-afterburning version, the F 404-100D engine powers the Super Hawk A-4S of Singapore Air Force, whereas the F 404-400D engine, also non-afterburning engine, powers the Grumman A-6 aircraft. On the other hand, the General Electric F 110-GE-129 increased performance engine, which has a pressure ratio of 30.7 from three fan stages and nine HP compressor stages delivers 129 kN thrust and has a thrust to weight ratio of 7.3:1. This engine will power the F16C/D aircraft of the USAF. In its T 700 turboshaft engine, GE has introduced many aspects of latest technology. These are as follows: (a) For the first time, the serpentine cooling channel used in the turbine of large engines has been miniaturised for small engine application, i.e. more than 75 mm of cooling passages were cast in each turbine blade of height less than 25 mm and thickness 3 mm, (b) directionally solidified solid turbine blades (uncooled), (c) turbine discs made by powder metallurgy forging technique, improving low cycle fatigue and fracture mechanics life of the discs, and (d) ceramic coating sprayed on the shroud rings of the first stage HP turbine improves thermal insulation of these rings, resulting in tighter turbine tip clearances and enabling the turbine entry temperature to be higher without increasing the temperature of the shroud rings.

The Rolls-Royce Trent engine of 290 kN thrust has a fan diameter of 250 cm. Its wide chord blades were super plastically-formed using a diffusion bonding fabrication process. The V2500 turbofan engine used in the Airbus 320 has the unique feature of hollow titanium wide chord fan blades, which may give protection from foreign object damage, the ingested material being centrifuged outward by the wide blade without failing itself.

With advances in materials, computational and manufacturing techniques being used in aerogas turbine engine development today, engines that are more efficient, more powerful, more reliable, quieter and having less emissions will be seen by the end of the century.