1

Introduction

COPYRIGHTED MATERIAL

The modern gas turbine engine used for aircraft propulsion is a complex machine comprising many systems and subsystems that are required to operate together as a complex integrated entity. The complexity of the gas turbine propulsion engine has evolved over a period of more than 70 years. Today, these machines can be seen in a wide range of applications from small auxiliary power units (APUs) delivering shaft power to sophisticated vectored thrust engines in modern fighter aircraft.

The military imperative of air superiority was the driving force behind the development of the gas turbine for aircraft propulsion. It had to be lighter, smaller and, above all, it had to provide thrust in a form which would allow higher aircraft speed. Since aircraft propulsion is, by definition, a reaction to a flow of air or gas created by a prime mover, the idea of using a gas turbine to create a hot jet was first suggested by Sir Frank Whittle in 1929. He applied for and obtained a patent on the idea in 1930. He attracted commercial interests in the idea in 1935 and set up Power Jets Ltd. to develop a demonstrator engine which first ran in 1937. By 1939, the British Air Ministry became interested enough to support a flight demonstration. They contracted Power Jets Ltd. for the engine and the Gloucester Aircraft Co. to build an experimental aircraft. Its first flight took place on 15 May 1941. This historic event ushered in the jet age.

1.1 Gas Turbine Concepts

Operation of the gas turbine engine is illustrated by the basic concept shown schematically in Figure 1.1. This compressor-turbine ‘bootstrap’ arrangement becomes self-sustaining above a certain rotational speed. As additional fuel is added speed increases and excess ‘gas horsepower’ is generated. The gas horsepower delivered by a gas generator can be used in various engine design arrangements for the production of thrust or shaft power, as will be covered in the ensuing discussion.

In its simplest form, the high-energy gases exit through a jet pipe and nozzle as in a pure turbojet engine (the Whittle concept). This produces a very high velocity jet which, while compact, results in relatively low propulsion efficiency. Such an arrangement is suitable for high-speed military airplanes which need a small frontal area to minimize drag.

Gas Turbine Propulsion Systems, First Edition. Bernie MacIsaac and Roy Langton.
© 2011 John Wiley & Sons, Ltd. Published 2011 by John Wiley & Sons, Ltd.

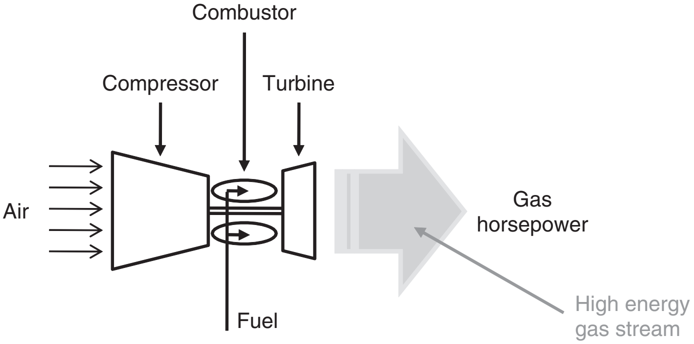

Figure 1.1 Gas turbine basics – the gas generator.

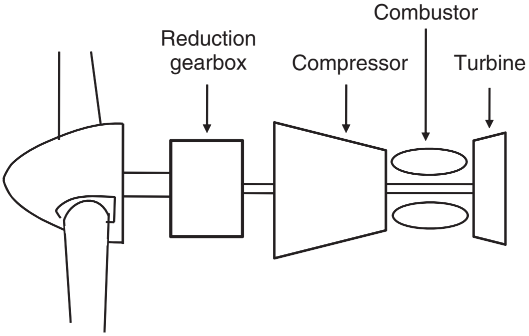

Figure 1.2 Typical single-shaft engine arrangement.

The next most obvious arrangement, especially as seen from a historical perspective, is the single-shaft turbine engine driving a propeller directly (see the schematic in Figure 1.2). As indicated by the figure the turbine converts all of the available energy into shaft power, some of which is consumed by the compressor; the remainder is used to drive the propeller. This arrangement requires a reduction gearbox in order to obtain optimum propeller speed. Furthermore, the desirability of a traction propeller favors the arrangement whereby the gearbox is attached to the engine in front of the compressor.

The Rolls-Royce Dart is an early and very successful example of this configuration. This engine comprises a two-stage centrifugal compressor with a modest pressure ratio of about 6:1 and a two-stage turbine. The propeller drive is through the front of the engine via an in-line epicyclic reduction gearbox. The Dart entered service in 1953 delivering 1800 shaft horsepower (SHP). Later versions of the engine were capable of up to 3000 SHP and the engine remained in production until 1986.

Today, single-shaft gas turbines are mostly confined to low power (less than 1000 SHP) propulsion engines and APUs where simplicity and low cost are major design drivers. There are some notable exceptions, however, one of which is the Garrett (previously Allied Signal and now Honeywell) TPE331 Turboprop which has been up-rated to more

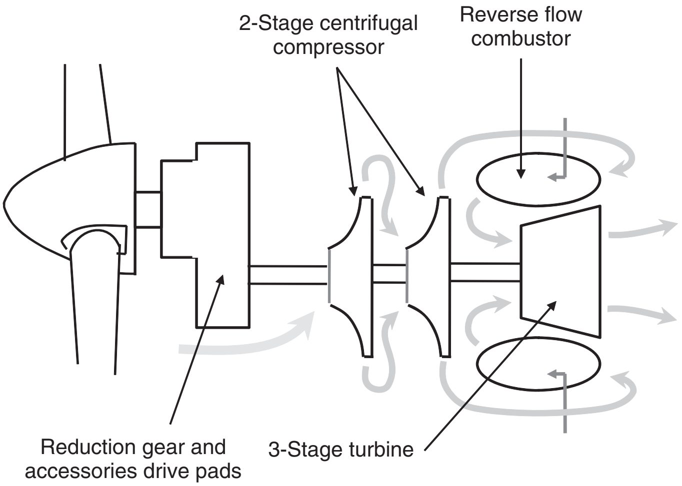

Figure 1.3 TPE331 turboprop schematic.

than 1600 SHP and continues to win important new programs, particularly in the growing unmanned air vehicle (UAV) market.

This engine is similar in concept to the Dart engine mentioned above, as illustrated by the schematic of Figure 1.3. The significant differences are the reverse-flow combustor which reduces the length of the engine and the reduction gear configuration which uses a spur-gear and lay-shaft arrangement that moves the propeller centerline above that of the turbine machinery, thus supporting a low air inlet.

A more common alternative to the direct-drive or single-shaft arrangement described above uses a separate power turbine to absorb the available gas horsepower from the gas generator.

Since the power turbine is now mechanically decoupled from the gas generator shaft, it is often referred to as a ‘free turbine’.

For the purposes of driving a propeller, this configuration (as shown in Figure 1.4) indicates a requirement for a long slender shaft driving through a hollow gas turbine shaft to the front-mounted gearbox. Such a configuration carries with it the problems of shaft stability, both lateral and torsional, together with more complex bearing arrangements.

In their turboprop concept, Pratt & Whitney Canada chose to ‘fly the engine backwards’ by arranging for sophisticated ducting for the inlet and exhaust while benefitting from the stiffness and robustness of a very short drive shaft through a reduction gearbox. Their engine, the PT-6 in its many configurations, is one of the most reliable aircraft gas turbines ever built. It has an exceedingly low in-flight incident rate and has sold over 40 000 copies. It was first introduced in 1964 and is still very much in production. A conceptual drawing of the PT-6 engine is shown in Figure 1.5.

The pure turbojet produces a high-velocity jet, which offers poor propulsion efficiency with the singular advantage of higher aircraft speed, and the turboprop produces good propulsive efficiency but only at a relatively low top aircraft speed. The two configurations can however be combined to produce the turbofan engine, depicted in Figure 1.6. As is

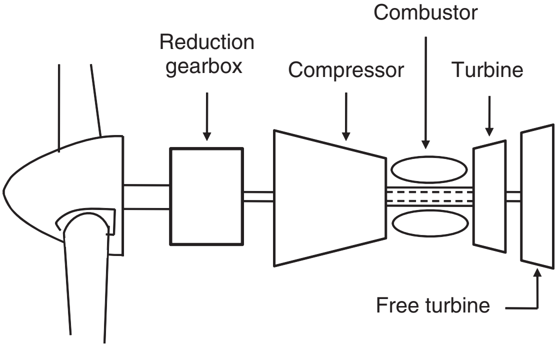

Figure 1.4 The free turbine turboprop engine.

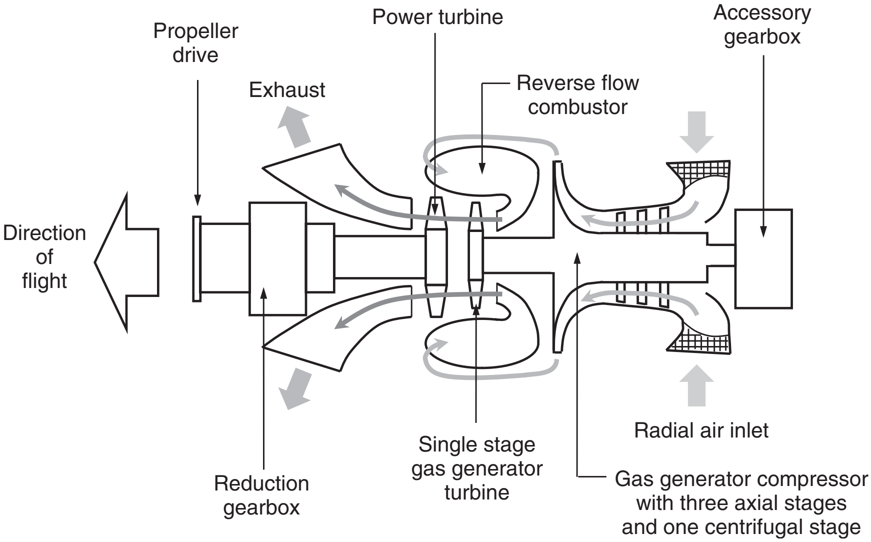

Figure 1.5 A sectional drawing of the PWA PT-6 turboprop engine.

indicated in this figure, the front-mounted fan is driven by a shaft connected through the core of the engine to the second or low-pressure turbine which can be likened to the free turbine of the turboprop application. Some of the fan flow pressurizes the compressor while the remainder is expelled through a so-called ‘cold nozzle’ delivering thrust directly. Such an arrangement can produce high thrust and good propulsive efficiency, and this engine concept is one of the most common types in commercial service today.

Another important configuration used in aircraft propulsion is the twin-spool turbojet engine which is essentially a twin-spool gas generator with a jet pipe and exhaust nozzle. If a second turbine can drive a large fan, it can also drive a multistage compressor with an output which is entirely swallowed by the downstream compressor. This configuration is shown in Figure 1.7.

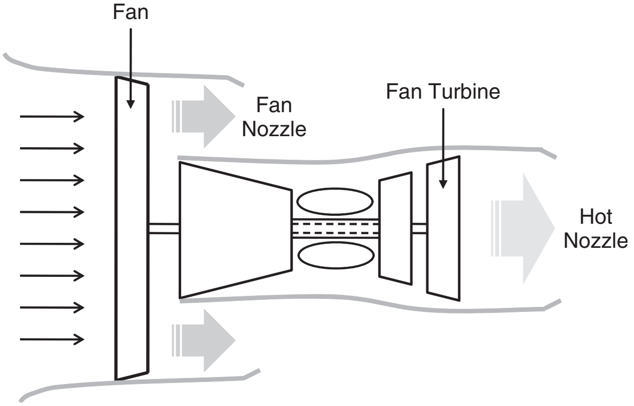

Figure 1.6 The turbofan engine configuration.

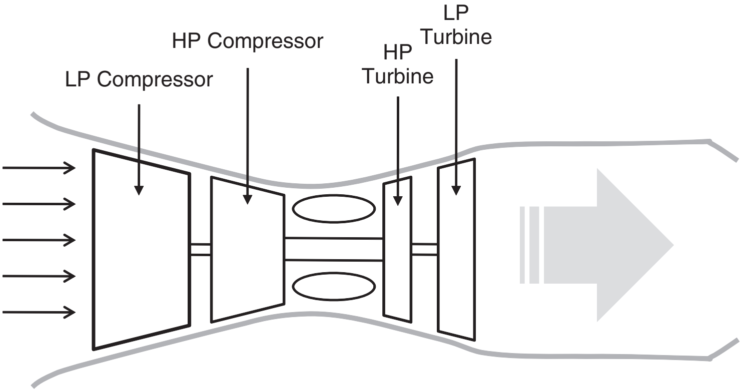

Figure 1.7 The twin-spool turbojet engine configuration.

So far in this discussion, we have assumed that the thermodynamic processes of compression and expansion are ideal and that there is no apparent limit to the magnitude of the pressure that can be obtained. In addition, we have not considered how the heat is going to be delivered to the gas to raise its temperature.

The practical implementation of the gas turbine involves turbomachinery of finite efficiency and an internal combustion process that adds heat through the burning of a hydrocarbon fuel in a combustion chamber which must be small and compact.

Throughout its development, there have been enduring themes which place specific technologies in the vanguard of engine development. The first of these themes is engine performance: the capacity of the engine to produce thrust with sufficient thermal efficiency to provide an airplane with an acceptable range while carrying a useful payload. The response to this requirement is found in the techniques of internal aerodynamics and combustion.

Saravanamuttoo *et al.* [1] provide a comprehensive treatment of gas turbine performance. Simple cycle calculations highlight the need for high overall engine pressure ratios and high turbine temperatures for good efficiency to be achieved. Similarly, high specific thrust demands high isentropic efficiency of each major component. Finally, size matters. In order to achieve high levels of thrust, high air flow rates must be obtained. This argues powerfully for large axial flow turbomachinery. This is very much a pacing item, since the design of such machines is very complex and the investments in equipment and facilities required to complete the development are very large indeed.

A similar argument can be made for combustion technologies. The compressor must deliver a uniform flow of air at high pressure to a combustion chamber. Fuel must be introduced into the combustor in sufficient quantities to raise the average temperature by at least 1200 °F. Assuming that the combustion process takes place at nearly stoichiometric conditions, localized temperatures in excess of 3500 °F can be expected. Excess air is essential in the gas turbine combustor to cool the flame to acceptable levels while, at the same time, mixing the hot gas to deliver a uniform, high-temperature gas to the throat of the turbine. Finally, in the interests of weight and overall engine stiffness and robustness, the combustor must be kept as short as possible. Again, this is a technology which relies heavily on experiment which, in turn, involves large investments in equipment and facilities.

The second major theme that runs throughout the development of the jet engine is that of longer life and improved reliability. This requirement has driven a relentless quest for improved materials and design methodologies. The basic need is for turbine components capable of operating continuously at elevated temperatures. (Turbine inlet temperatures for uncooled blades can run as high as 2500 °F.) Both blades and disks must be capable of withstanding the enormous stresses imposed by rotational speeds which push the materials past the elastic limit, thereby encountering low cyclic fatigue. This must be understood well enough to ensure reasonable life as well as removal before safety concerns overtake them.

The twin themes of continuous improvements in aerothermodynamics and in materials would suggest that the gas turbine engine, while sophisticated, is actually a very simple machine. In fact, the quest for improved performance has led designers to a remarkable number of variations in engine configuration. Each configuration, when matched to the airframe for which it was designed, offers a different balance between fuel efficiency, specific thrust and overall propulsive efficiency. Single-, twin- and triple-spool engine configurations have been developed with attendant increases in the complexity of bearing and lubrication systems. The turbofan engine has become the workhorse of the civil aviation industry with sophisticated thrust management, including thrust reversal and power extraction to drive a variety of accessories. The gas turbine engine has therefore emerged as a sophisticated and complex machine requiring a systems approach to its design and development.

1.2 Gas Turbine Systems Overview

In order to provide the reader with a basic knowledge, the gas turbine engine aerothermodynamic principles described in Chapter 2 of this book provide insight into some of the challenges associated with the fundamentals of gas turbine design, operation and control. A more detailed treatment of axial compressor design concepts, including compressor performance analysis and the principles of compressor performance map estimation, are included as Appendices A and B, respectively. For completeness, thermodynamic modeling of the gas turbine engine is described in Appendix C.

While there are many systems and subsystems that make up the gas turbine-based propulsion power plant, perhaps the most critical function is performed by the fuel control system.

This system must provide high-pressure fuel to the combustor of the gas generator or 'core' section of the engine over the complete operational envelope, while protecting the machine from temperature, pressure and speed exceedances for any combination of dynamic and steady-state operation.

In addition, the fuel control system may be required to manage airflow though the compressor by modulating compressor stator vanes and bleed valves.

The gas generator produces high-energy gases as its output, sometimes referred to as gas horsepower or gas torque, which can be converted into direct thrust or shaft power.

In military aircraft with thrust augmentation (afterburning), the fuel control system is also required to control afterburner fuel delivery together with the control of exhaust nozzle exit area in order to maintain stable gas generator operation.

Secondary functions of the fuel control system include cooling of the engine lubricating oil and, in some applications, providing a source of high-pressure fuel to the airframe to act as motive flow to the aircraft fuel system ejector pumps [2].

In view of the complexity and extent of the fuel control system issues, this important topic is covered in three separate chapters as follows.

1. The fuel control of the gas generator section, including acceleration and deceleration limiting, speed governing and exceedance protection, is covered in Chapter 3.
2. Thrust engine fuel control issues, including thrust management and augmentation, are described in Chapter 4.
3. Fuel control and management of shaft power engines, including turboprop and turboshaft applications, are presented in Chapter 5.

Since major performance issues associated with fuel control systems design involve dynamic response and stability analyses, Appendix D is provided as a primer on classical feedback control.

In commercial aircraft it is standard practice to install many of the engine subsystems and associated major components as part of an engine, nacelle and strut assembly. This integrated nacelle/engine package is then delivered to the airframe final assembly line for installation into the aircraft.

For reasons of aerodynamic performance or stealth, military aircraft are more likely to integrate the propulsion system assembly more closely with the fuselage.

While the primary function of the engine installation arrangement is to provide efficient and effective air inlet and exhaust for the gas turbine engine, provisions for minimizing engine compressor noise propagation as well as ventilation and cooling of the installation must also be considered. The thrust reversing mechanism, including actuators and nozzle flow diversion devices, is also typically installed at the nacelle or propulsion system assembly stage.

Supersonic applications present a special case to the propulsion system designer. Here the task of recovering free stream energy efficiently to the engine inlet face requires the management of shock-wave position within the inlet through the control of inlet geometry. While supersonic inlet control is often included as an airframe responsibility, it is nevertheless a major factor is providing efficient propulsion in supersonic flight and is therefore addressed in this book.

Installation-related systems issues, focusing primarily on inlet and exhaust systems, are presented in Chapter 6.

As with any high-power rotating machine, bearing lubrication and cooling is a critical function and the task is further complicated by the operational environment provided by an aircraft in flight. Chapter 7 addresses the primary issues associated with lubrication systems of aircraft propulsion gas turbines engines.

In addition to providing propulsion power in aircraft applications, the gas turbine engine must also provide a source of power for all of the energy-consuming systems on the aircraft. This power is removed from the engine in two forms, as described below.

- Mechanical power is taken from the shaft connecting the turbine and compressor. This power source, which involves a tower shaft and reduction gearbox, shares the engine lubrication system. A number of drive pads are typically provided for electrical generators and hydraulic pumps. Engine starting is effected through this same gearbox
- Bleed air is also used by the airframe for cockpit/cabin pressurization and air conditioning. This source of hot high-pressure air is also used for anti-icing of both the wing and engine nacelle air inlet.

The systems, subsystems and major components associated with mechanical and bleed air power extraction and starting systems are covered in Chapter 8.

So far we have considered gas turbines in aircraft applications only. In the defense industry, however, the benefits of the gas turbine in terms of power per unit weight have not gone unnoticed. Many of today’s high-speed naval surface vessels use the gas turbine as the main propulsion device. For completeness, marine gas turbine propulsion systems focusing on naval applications are therefore included in Chapter 9.

The issue of prognostics and health monitoring (PHM) has become a critical issue associated with in-service logistics over the past several years; both the commercial airlines and military maintenance organizations are moving away from scheduled maintenance to on-condition maintenance as a major opportunity to improve efficiency and reduce the cost of ownership.

Chapter 10 describes PHM, covering the basic concepts of engine maintenance and overhaul strategies and the economic benefits resulting from their application. Also addressed are the techniques used in the measurement, management and optimization of repair and overhaul (R&O) practices for application at the fleet level.

Finally, some of the new system technologies that are being considered for future gas turbine propulsion systems are discussed in Chapter 11. Of particular interest by many engine technology specialists is the ‘more-electric engine’ (MEE) initiative which is an offshoot from what began as the ‘all-electric aircraft’ (now the ‘more-electric aircraft’) launched by the Wright Patterson Air Force Laboratory some 40 years ago.

References

1. Saravanamuttoo, H.I.H., Rogers, G.F.C, and Cohen, H. (1951–2001) *Gas Turbine Theory*, 5th edn, Pearson Education Ltd.
2. Langton, R., Clark, C., Hewitt, M., and Richards, L. (2009) *Aircraft Fuel Systems*, John Wiley & Sons, Ltd, UK.