Bernie MacIsaac and Roy Langton

Gas Turbine Propulsion Systems

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GAS TURBINE PROPULSION SYSTEMS

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GAS TURBINE PROPULSION SYSTEMS

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About the Authors

BD (Bernie) MacIsaac

Dr MacIsaac received an Honors B. Eng. (Mechanical) from the Technical University of Nova Scotia in 1970. He was awarded a Science ’67 graduate scholarship which took him to Ottawa to study Jet Engine Dynamics and Controls at Carleton University. He was awarded an M.Eng. in 1972 and a Ph.D. in 1974.

Following completion of his studies, Dr MacIsaac spent four years at the National Research Council of Canada where he helped to develop the first 8-bit microprocessor control for general aviation gas turbines. He was awarded a patent for a control design to prevent in-flight engine stalls on helicopter engines.

Dr MacIsaac formed GasTOPS Ltd. (Gas Turbines and Other Propulsion Systems) in 1979, an Ottawa-based company which specializes in the application of intelligent systems to machinery protection and machinery maintenance systems. Much of this company’s work has focused on aerospace and industrial power plants. About 1991, GasTOPS began the development of an on-line oil debris detector for damage recognition of the oil-wetted components of power plants. This device is now fitted to many modern fighter aircraft, many land-based CoGen and pipeline engines and is selling well in the new emerging wind turbine market. This development has led to the establishment of a manufacturing facility and to worldwide sales of this product.

Dr MacIsaac served as GasTOPS Ltd. President until 2007, at which point he turned management of the company over to his longtime colleague Mr David Muir. Since then, Dr MacIsaac has devoted his efforts to the establishment of an R&D group at GasTOPS, which is responsible for the definition and subsequent demonstration of new technologies that will form the basis of the next product line for GasTOPS.

Dr MacIsaac participates as a lecturer in professional practice courses at both Ottawa and Carleton Universities as well as Carleton University-sponsored short courses on gas turbines.

He is a past president of the Canadian Aeronautics and Space Institute and is a past Chairman of PRECARN, a network of companies engaged in collaborative applied research. He currently serves as Chairman of the Senior Awards Committee of the Canadian Aeronautics and Space Institute.

Dr MacIsaac was born in 1945. He is married (1969) and has twin daughters who were born on Christmas Day in 1973 and three granddaughters and one grandson. He has lived in Ottawa, Canada with his wife Ann since 1970.

Roy Langton

Roy Langton began his career as a Student Apprentice in 1956 with English Electric Aviation (now BAE Systems) at Warton in Lancashire, UK. After graduating in Mechanical and Aeronautical Engineering, he worked on powered flight control actuation systems for several military aircraft, including the English Electric Lightning, the Anglo-French Jaguar, and Panavia Tornado.

In 1968 he emigrated to the USA working for Chandler Evans Corporation in West Hartford Connecticut (now part of the Goodrich Corporation) and later with Hamilton Standard (now Hamilton Sundstrand) on engine fuel controls as the technology transitioned from hydromechanics to digital electronics. During this period he was exposed to a wide variety of projects from small gas turbines such as the Tomahawk Missile cruise-engine to large, high-bypass gas turbines used on today's commercial transports. A major milestone during this period was the introduction of the first FADEC into commercial service on the Pratt & Whitney PW2037 engine, which powers many of the Boeing 757 aircraft.

In 1984, he began a career in aircraft fuel controls with Parker Hannifin Corporation as Chief Engineer for the Fuel Products Division of the Corporation's Aerospace Group in Irvine California. In the 20-year period prior to his retirement in 2004 as Group Vice-President of Engineering, he played a major role in establishing Parker Aerospace as a leading supplier of complete fuel systems to aircraft manufacturers around the world. This began in 1993 with the Bombardier Global Express business jet and culminated in 2000 with the Fuel Measurement and Management system for the A380 superjumbo commercial transport.

Roy Langton was born in 1939, married his wife June in 1960 and has two daughters and five grandchildren. Roy and June currently reside in Boise Idaho USA.

Roy continues to work as a part-time technical consultant for Parker Aerospace and has been an Aerospace Series Editor for John Wiley & Sons since 2005.

Preface

The gas turbine industry began in the 1940s and, for many decades, it remained an object of research by universities and government laboratories as well as the many commercial establishments which sprang to life in an effort to exploit the technology. During this period, much basic research was conducted and information exchange was encouraged. It is noteworthy that the British Government, which had sponsored much of the development of the Whittle engine, shared the entire technical package with the US Government as a war measure. This resulted in the US Government supporting its continued development at the General Electric facilities at Lynn, Massachusetts.

Many companies were formed in Europe and in North America during the 1950s, each of which offered designs tailored to specific applications. In addition to the rapidly expanding aeronautical and defense industries, other applications began to emerge for non-aeronautical engines. These included gas pipelines, electrical power generation and naval propulsion. In short, the industry was booming and employment for engineers was readily obtained. More importantly, there were many opportunities to learn about this fascinating machine.

Today, the industry is reduced to a handful of very large companies. The investment required to develop an engine is enormous and the competition can only be described as fierce. Engineers are much more specialized and commercial secrecy is a fundamental element of corporate survival. For the true engineering specialist, the work remains a fascinating push into the unknown. For the systems engineer who must develop strategies and equipment which supports and manages the operation of the engine, the work has however become more complex and information has become more difficult to obtain in a form that allows synthesis of system behavior.

There are many books available that describe gas turbine engines, focusing primarily on the ‘turn and burn’ machinery from an aerothermodynamic perspective. Typically, the coverage given to the peripheral systems that support the complete gas turbine propulsion system is either not described at all or is often superficial. As the industry continues to demand improvements in performance and reductions in weight, the engine continues to be refined and, in some instances, made more complex. The system engineer can therefore expect to be working on not only more refined control systems but also information management systems designed to keep ownership costs as low as possible.

This book is organized to provide the reader with a basic understanding of how a gas turbine works, with emphasis on those aspects of its operation which most affect the task of the system designer. We have attempted to cover the propulsion package as a combination of functional components that must operate properly in unison to produce power. The famous remark by Sir Frank Whittle–that the gas turbine has only one moving part–happily neglects the many subsystems that must operate in unison with the prime mover to create a viable propulsion system package. In Whittle's day, it was sufficient for the engine to run smoothly. Today, the complete engine design must take into account cost of ownership, maintainability, safety, and prognostics and health monitoring.

The book describes the basic gas turbine in terms of its major components at a level sufficient to understand its operation and to appreciate the hard limits of its operating envelope. In particular, the issues associated with the handling of the gas generator or 'core' of the turbine engine in aircraft propulsion applications in preventing the onset of compressor surge or flame-out during transient throttle changes is addressed in some depth, including the need for stable speed governing in steady-state operation.

The importance of understanding and managing the engine inlet and exhaust systems together with the issues associated with power extraction and bearing lubrication are also given extensive coverage.

The gas turbine has found application in a number of important non-aeronautical industries. These include pipeline compressor drives, electrical power generation and naval propulsion systems. From a systems design perspective, the naval application is arguably the most demanding. In keeping with the propulsion focus of this book, the naval application has been chosen as an example of the challenges of introducing the gas turbine engine–developed for airborne applications–into such a hostile environment. The subsystems required to support and protect the engine in a navy ship are described in some detail.

Finally, prognostics and health monitoring must be recognized as a key aspect of the need to develop reliable algorithms that can effectively forecast the operational life remaining. This is increasingly important as both the commercial and military operators move into the realm of condition-based maintenance as a means of controlling and minimizing cost of ownership. Some of these systems will be fitted to future engines; as their underlying advantages are recognized, it is of equal importance that they interact with ground-based logistics systems.

Notwithstanding the book's focus on the system aspects of gas turbine propulsion systems, the fundamentals of gas turbine engine design are covered to a level that is considered more than adequate for the practicing systems engineer and/or business program manager. In addition to the devotion of one complete chapter to gas turbine basics, there are several appendices that provide a substantial grounding in the fundamentals of gas turbine design, modeling and operation.

Series Preface

The propulsion system of an aircraft performs a number of key functions. Firstly it provides the propulsive energy to propel the aircraft throughput its route or mission with the appropriate achievement of performance, efficiency, safety and availability. Secondly it provides the prime source of energy for the on-board systems by enabling the generation of electrical, hydraulic and pneumatic power for their effectors. Finally it provides the air to create a habitable environment for crew, passengers and avionic equipment. It is also a major capital item in any modern commercial and military aircraft and its incorporation into the aircraft affects both airframe and systems, not only in technical interface terms, but also in terms of safety, reliability and cost of ownership.

Unsurprisingly then, a knowledge of the propulsion system is key to understanding how to integrate it with the airframe and the aircraft systems. Other books in the *Aerospace Series* cover the topics of aircraft performance, avionic and aircraft systems – all of which depend on the propulsion system to complete their tasks. A number of these systems have an intimate link with the propulsion system such as aerodynamics, structural design, fuel types, onboard fuel storage and system design, cabin environment and cooling, hydraulic and electrical generation, flight control, flight management, flight deck displays and controls, prognostic and health management, and finally systems modelling. The degree of integration of these systems varies with aircraft role and type, but in all cases the design of the systems cannot be complete without an understanding of the system that provides their energy.

This book, *Gas Turbine Propulsion Systems*, provides the key to that understanding by describing the propulsion system in terms of its major sub-systems with a suitable and readily understandable treatment of the underlying mathematics. An important point is that the book completes the picture of the aircraft systems by taking a systems engineering approach to propulsion. It deals, not only with the gas turbine engine and its aero-thermodynamics, but with the propulsion system as an integrated set of sub-systems that control the engine throughout the flight envelope and provide suitable controlled off-takes. The treatment of fuel control, thrust control, installation aspects and prognostics clearly link into integration of the propulsion system with the aircraft and its systems for pure gas turbines and shaft power turbines.

For good measure there is a chapter devoted to marine propulsion systems, and appendices complete the treatment of the underlying theory and provide guidance on thermodynamic modelling. There is also a discussion of the future direction of propulsion systems that addresses some aspects of reducing engine off-takes and contributes to the more-electric aircraft concept.

This is a book for all practising aircraft systems engineers who want to understand the interactions between their systems and the provider of their power source.

Allan Seabridge, Roy Langton, Jonathan Cooper and Peter Belobaba

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- Herb Saravanamuttoo of Carlton University;
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- Jean-Pierre Beauregard of Pratt & Whitney Canada (retired).

In particular, the authors would like to acknowledge the support received on three specific topics:

1. the Pratt & Whitney Canada PW150A engine control system;
2. the Concorde air inlet control system; and
3. the Meggitt Engine Monitoring Unit installed on all of the A380 engine options.

The first subject, addressed in Chapter 5, describes a modern turboprop application embodying a state-of-the art FADEC-based control system. In support of this topic, the authors would like to thank Pratt & Whitney Canada and particularly Jim Jarvo for his consultant services and active participation in the generation and review of the material. Jim is currently a Control Systems Fellow in the Engineering department of Pratt Whitney Canada based in Longueil, Quebec, Canada.

Regarding the second topic, the authors would like to thank the British Aircraft Corporation (now BAE Systems) for access to historical technical documents describing the Concorde air inlet system. We would also like to thank Roger Taplin who was the Lead Engineer on the Concorde AICS project during the design, development, and operational launch phases of the program. Roger, who is currently employed by Airbus at their Filton (UK) facility in the position of Aircraft Architect-Wing, provided valuable consultant and editorial support throughout the generation of the material presented in Chapter 6.

Thirdly, the authors are grateful for the information and support provided by Mervyn Floyd of Meggitt Plc in the UK concerning one of their most recent Engine Monitoring Unit programs. This topic is covered in Chapter 10 in support of the prognostics and health monitoring discussion.

In addition, the authors would like to acknowledge the following organizations that provided an important source of information through published material in support of the preparation of this book:

- Boeing;
- CFM International;
- General Electric Honeywell;
- Parker Aerospace;
- Pratt & Whitney; and
- Rolls-Royce.

List of Acronyms

ACARS	Aircraft Communication And Reporting System
ADC	Air Data Computer
AFDX	Avionics Full Duplex Switched Ethernet
AICS	Air Inlet Control System
AICU	Air Inlet Control Unit
AMAD	Aircraft Mounted Accessory Drive
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio Incorporated
ASM	Air Separation Module
C-D	Convergent-Divergent
CDP	Compressor Delivery Pressure
CDU	Cockpit Display Unit
CFD	Computer Fluid Dynamics
CLA	Condition Lever Angle
CMC	Ceramic-Metal Composite
CPP	Controllable Pitch Propeller
CRP	Controllable Reversible Pitch
CSD	Constant Speed Drive
CSU	Constant Speed Unit
DEEC	Digital Electronic Engine Control
EBHA	Electric Back-up Hydraulic Actuator
ECIU	Engine-Cockpit Interface Unit
ECAM	Electronic Centralized Aircraft Monitor
ECS	Environmental Control System
EDP	Engine Driven Pump
EDU	Engine Display Unit
EEC	Electronic Engine Control
EFMPS	Electric Fuel Pumping & Metering System
EHA	Electro Hydrostatic Actuator
EHD	Elasto-Hydro-Dynamic
EHSV	Electro-Hydraulic Servo Valve
EICAS	Engine Indication and Caution Advisory System
EMI	Electro-Magnetic Interference
EPR	Engine Pressure Ratio

FAA	Federal Airworthiness Authority
FADEC	Full Authority Digital Electronic Control
FMU	Fuel Metering Unit
FRTT	Fuel Return To Tank
IEPR	Integrated Engine Pressure Ratio
HBV	Handling Bleed Valve
ICAO	International Civil Aviation Organization
IBV	Interstage Bleed Valve
IDG	Integrated Drive Generator
IGV	Inlet Guide Vanes
IP	Intermediate Pressure
HIRF	High Intensity Radiated Frequencies
HP	High Pressure
LP	Low Pressure
LVDT	Linear Variable Differential Transformer
MCL	Maximum Climb
MCR	Maximum CRuise
MEA	More Electric Aircraft
MEE	More Electric Engine
MR	Maximum Reverse
MTO	Maximum Take-Off
NGS	Nitrogen Generation System
NTSB	National Transportation Safety Board
OLTF	Open Loop Transfer Function
O&M	Overhaul & Maintenance
PCU	Propeller Control Unit
PEC	Propeller Electronic Control
PEM	Power Electronic Module
PHM	Prognostics and Health Monitoring
PLA	Power Lever Angle
PLF	Pressure Loss Factor
PMA	Permanent Magnet Alternator
PTIT	Power Turbine Inlet Temperature
R&O	Repair & Overhaul
RAT	Ram Air Turbine
RTD	Resistance Temperature Device
SD	Shut-Down
SFAR	Special Federal Airworthiness Regulation
SHP	Shaft Horsepower
SLS	Sea Level Static
SOV	Shut-Off Valve
STOVL	Short Take-Off and Vertical Landing
teos	Technology for Energy Optimized Aircraft Equipment & Systems
TGT	Turbine Gas Temperature
TIT	Turbine Inlet Temperature
TM	Torque Motor

TRU	Transformer Rectifier Unit
VIF	Vectoring In Flight
VLSI	Very Large Scale Integration
VSCF	Variable Speed Constant Frequency
VSTOL	Vertical or Short Take-Off and Landing
VSV	Variable Stator Vane
UAV	Unmanned Air Vehicle

1

Introduction

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.

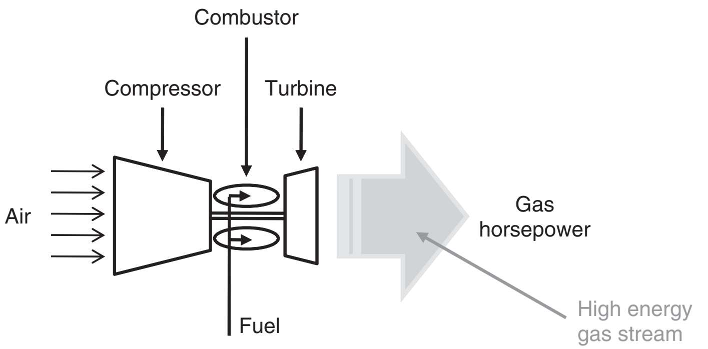

Figure 1.1 Gas turbine basics – the gas generator.

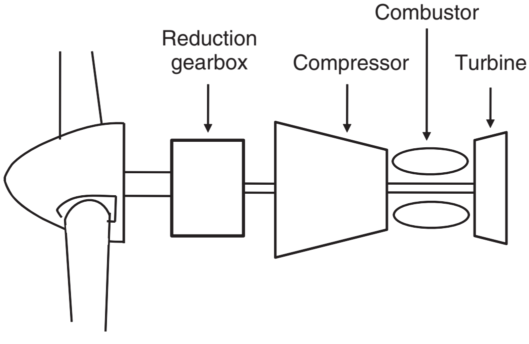

Figure 1.2 Typical single-shaft engine arrangement.

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

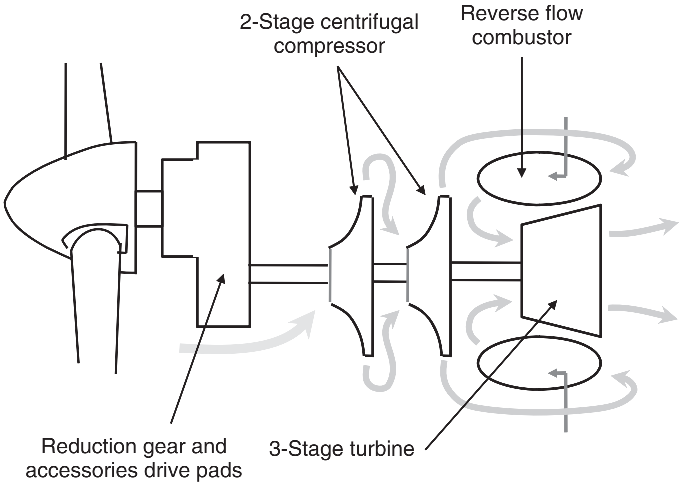

Figure 1.3 TPE331 turboprop schematic.

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

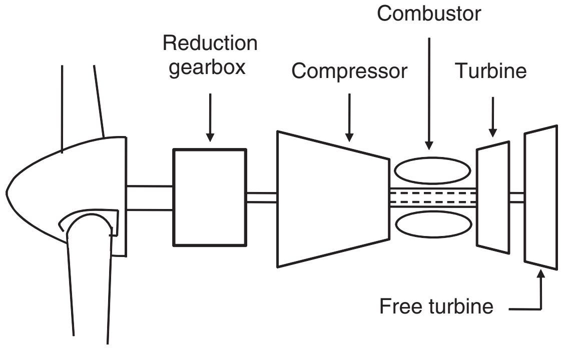

Figure 1.4 The free turbine turboprop engine.

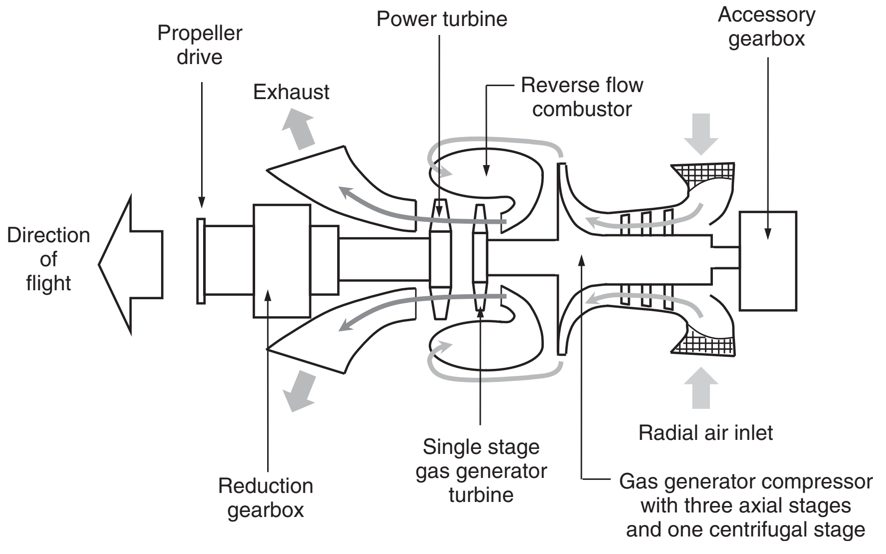

Figure 1.5 A sectional drawing of the PWA PT-6 turboprop engine.

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.

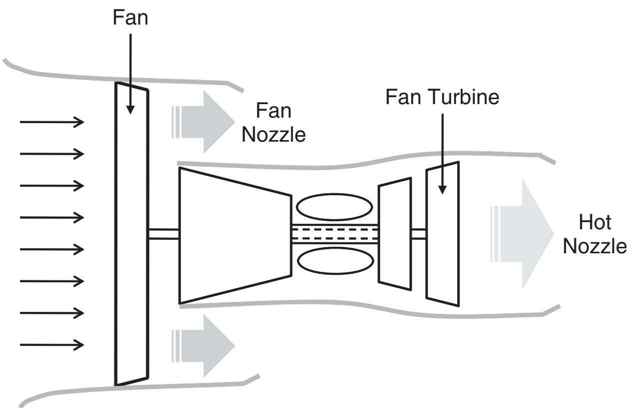

Figure 1.6 The turbofan engine configuration.

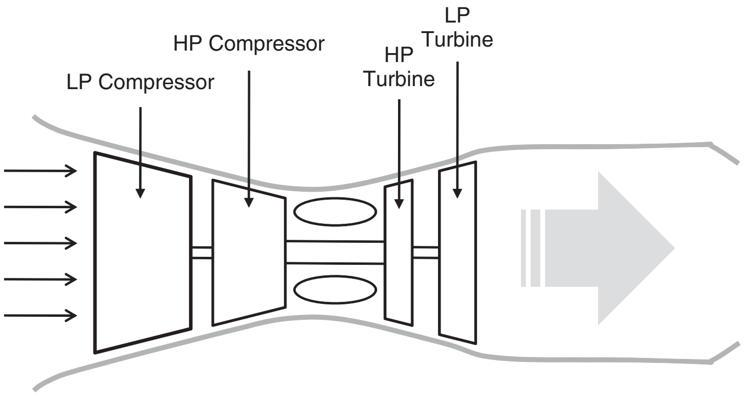

Figure 1.7 The twin-spool turbojet engine configuration.

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.