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Gas turbine technology

Powering the future

Trent 700 engines power these Dragonair A330 aircraft at Hong Kong airport.

The engines that power modern jet aircraft are incredibly powerful and robust, making use of the most advanced materials and design features. Phil Ruffles describes the craft of the jet-engine manufacturer and discusses some of the technical, environmental and economic issues that shape the engines of today and tomorrow.

Introduction

Air travel is the fastest growing mode of transportation in the world today. According to the International Civil Aviation Organisation (ICAO), some 1560 million passengers and 28 million tonnes of freight were transported by air in 1999 and forecasts indicate that this trend is set to continue. A 20-year market forecast conducted by Rolls-Royce last year predicts that economic growth, averaging 3% each year, will be outstripped by the growth in passenger traffic at 5% and cargo traffic at 6.5%. This picture presents exciting opportunities for the aviation industry.

But against this backdrop, a number of issues emerge. As established airlines and a rapidly escalating number of new start-up carriers vie for customers, competition in the industry is fierce. Airlines operating with reduced margins year on year demand increasingly efficient products to reduce their operating costs. Reliability is also imperative. The continual drive to maximise fleet utilisation while minimising unscheduled delays is a feature of modern civil aviation that is likely to intensify. Aircraft turnaround times, currently as tight as 20 minutes, will be further reduced, demanding robust products that excel in demanding conditions.

As an inevitable result of the explosion in civil travel, our skies – and our airports – are becoming increasingly congested. This is a reality affecting governments, town planners and global air traffic management systems, and one that requires radical reappraisal from the aviation industry on the future of civil transport. Should aircraft makers focus on bigger jets to carry more people or faster aircraft with more range, to get people to their destinations without stopping off and in less time than it takes current subsonic aircraft?

A further development resulting from the growth in air travel is the hot debate surrounding emissions. These are an unavoidable by-product of burnt fossil fuels and are the target of increasingly stringent global environmental legislation. So aircraft makers and associated suppliers must develop products that continue to mitigate their impact on our atmosphere.

For aero engine makers the challenge is to design, manufacture and bring to market products that are increasingly reliable, efficient, kind to the environment and affordable, all of which present their own unique engineering challenges. The research and development spends necessary to achieve these goals in the specialised aero engine industry are considerable. Thus Rolls-Royce has developed engine technologies which have the inherent design capability to transfer across to new engine variants and be retrofitted on existing ones.

The jet engine

The basis on which most short- to medium-term research is focused and applied builds on the established principles of the gas turbine engine, commonly known as the ‘jet’ engine. Since the advent of gas turbine technology in the 1930s, the total power output that can be achieved has increased by a factor of 50 while fuel requirements (specific fuel consumption) have been cut by 75%. These milestones have been driven by the development of advanced technology in many areas, amongst them thermodynamics, aerodynamics and materials science.

Like the motor car engine, the gas turbine is an internal combustion engine. In both, air is compressed, fuel added, the mixture ignited and the rapid expansion of the resultant hot gas produces the power. Unlike the motor car engine, however, where power is intermittent and the expanding gas produces shaft power through a mechanical piston and crank, in a jet engine combustion is continuous and its power results from expanding gas being forced out of the rear of the engine. The jet engine relies on Newton’s Third Law where every action has an equal and opposite reaction. The expanding gas flow is an action which creates a reaction of equivalent force, referred to as thrust. Thrust is transmitted through the engine to the aircraft, propelling it through the air.

The first gas turbine engines to fly in service were turbojets, used in a variety of military applications. Relying on high-velocity hot gas passing entirely through the compressor, combustor and turbines to provide thrust, this engine is designed primarily for speed, but carries the penalties of relatively high fuel consumption and noise levels.

The turbo prop, as its name suggests, uses a propeller to transmit the power it produces into thrust. The propeller is driven by a shaft from a power turbine, utilising the gas energy which would provide the thrust directly in a turbo jet. Similarly, the turbo shaft powerplant for helicopters uses a power turbine, but in this instance the power is transmitted to the rotor system of the helicopter. This type of engine is also used in industrial and marine applications, where it can drive electrical generators, pumps or a variety of marine propulsors.

Today, modern, large civil transport aircraft are powered by turbo fan engines. In these ‘bypass’ gas turbines a large mass of air is pressurised by a big fan at the front of the engine – at take off a Trent 800 powering a Boeing 777 would empty all the air in a squash court in a third of a second. Some of this air then passes through the engine core, where it is further pressurised before the combustion and expansion processes. The remaining fan air flows through the bypass duct, re-mixes with the hotter core gas and leaves through the nozzles as the jet which provides the engine’s thrust.

The bypass ratio – the mass of air going down the bypass stream divided by the mass going through the core – is the principal difference between modern civil and military aero engines. For example, the EJ200 engine built for the Eurofighter has a bypass ratio of

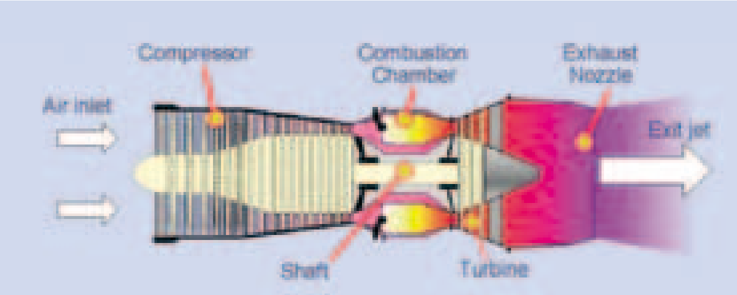

Figure 1: The jet engine.

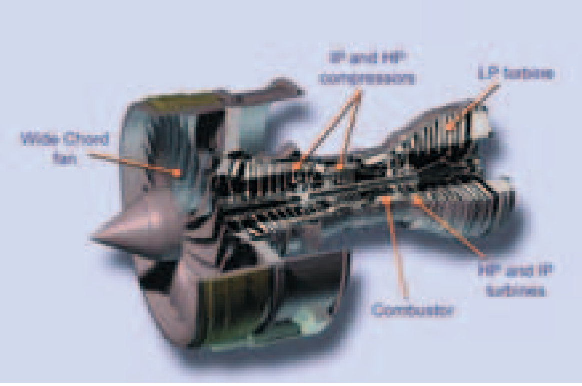

Figure 2: The Rolls-Royce Trent 800.

0.4 whereas on large modern civil engines it can be as high as 9, with the fan air producing more than 80% of the total thrust. Higher bypass ratios are used on civil transports for their improved fuel consumption and lower noise levels, whereas lower bypass ratios are used on military applications for their higher thrust-to-weight ratio.

The new generation

With an eye on the forecast market growth in large civil transport aircraft carrying upwards of 300 passengers, Rolls-Royce embarked on a new engine strategy in the early 1990s to design and manufacture a high-bypass turbo fan engine which could be optimised for a range of large wide-body civil aircraft. Consuming over a billion pounds in research and development costs and 12,000 man years of engineering effort, the unique Trent three-shaft engine architecture is derived from the earlier Rolls-Royce RB211 engine series and features a number of innovations.

Low, intermediate and high pressure systems, each consisting of a number of compressor and turbine stages, are mounted on independent shafts which run at their optimum aerodynamic speeds. As a guide, for a Trent 800 engine, the low pressure system will operate at 3000 revolutions per minute (rpm), the intermediate pressure system at 7500 rpm and the high pressure system at 10,000 rpm. The fan needs to rotate relatively slowly, being limited by the stress and aerodynamic tip speed of the blade. Optimum engine efficiency, governed by the maximum pressure and temperature achieved in its core, is enhanced by the three-shaft design. The pressure of the air as it enters the combustion and turbine components in a Trent engine is at around 40 atmospheres, with turbine entry temperatures above 1600°C providing an environment significantly in excess of the components' melting temperatures. This necessitates advanced materials, including ceramic coatings, and cooling technologies.

A further benefit of the three-shaft concept is the ease with which it can be optimised for specific aircraft applications. The Trent family provides a thrust range from 53,000 lb to more than 100,000 lb by scaling its modularised components: the fan, compressor, combustor and turbine systems. In addition to the applications shown in the figure, a Trent 8104 engine has run to 104,000 lb and demonstrated technology for future projects.

The 'family' concept is attractive on a number of counts, particularly in engine development, which is cost effective and ensures that customers obtain the benefit associated with a completely new and different product without Rolls-Royce incurring excessive risk. Maintenance costs, including training and tooling, are also reduced due to the high level of commonality between different versions of the Trent. Finally, new technologies, proven in service, can be retrofitted to existing variants. For instance, Trent technology has been incorporated in the RB211-524G/H-T engine, providing increasing competitiveness on the Boeing 747 and 767.

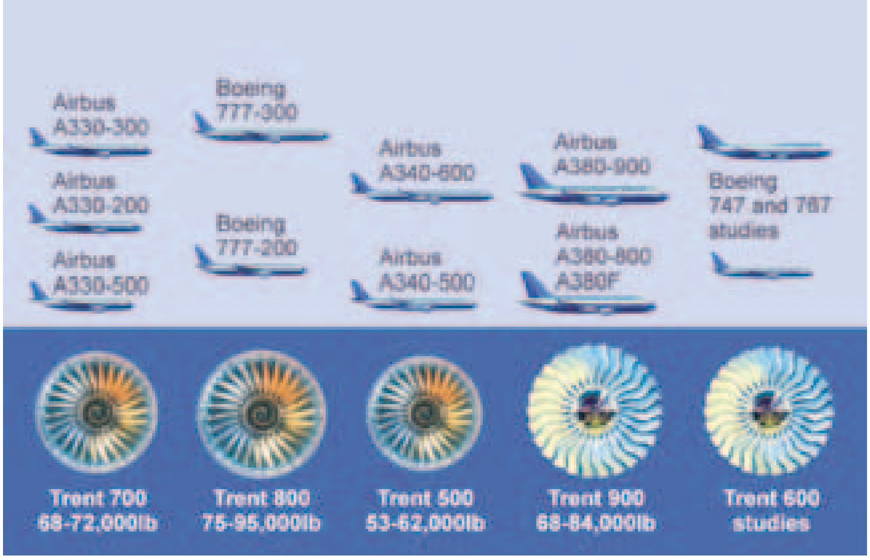

Figure 3: The Rolls-Royce Trent family.

Trent technology: the wide-chord fan blade

The wide-chord fan blade (WCFB), pioneered by Rolls-Royce in the 1980s on the RB211-535 engine for the Boeing B757, is an example of successfully applied technology. Designed specifically for high-bypass turbo fans, the latest standard of WCFB is made from three layers of titanium which are first formed, then bonded together using the diffusion-bonded superplastically formed (DB-SPF) process, and then inflated to produce an exceptionally strong, hollow and lightweight structure. While each fan blade exerts a centrifugal force of around 70 tonnes, equivalent to the weight of a modern locomotive, the resulting fan set is far lighter than those in competing powerplants, contributing significantly to the Trent's overall weight advantage.

Figure 4: The wide-chord fan blade.

This innovation was first introduced on the Trent 700 for the Airbus Industrie A330 in 1995. It has since been optimised for all derivative Rolls-Royce Trent engines either in service (with the Trent 800 on Boeing's current 777) or in development. The Trent 500 for Airbus Industrie's A340-500/600, scheduled to enter service next year, features the WCFB; an advanced 'swept' version is being designed for the Trent 900 under development for the European manufacturer's super-large A380 aircraft programme.

Trent technology: the high-pressure turbine blade

Gas turbine aero engines are assembled from components made to specifications matched by few other industries in their exacting requirements. Advanced materials research plays a key role in the design process, in particular for high-performance parts which require resilience to extreme environments. An end product of this discipline is the High-Pressure Turbine (HPT) blade. The function of HPT blades (92 of which are employed in a Trent 800 engine) is to extract power from the hot gas stream exiting the engine's combustion chamber, in order to drive the six stage High-Pressure Compressor (HPC).

First, the blades must be immensely strong and robust. Each HPT blade operates at a speed of 10,000 rpm and extracts around 750 horse power – about the same as a Formula 1 racing car. The blades will average a minimum of 15,000 hours in service between engine overhauls. An aircraft will have flown approximately eight million miles during this period. As HPT blades do their work in the hottest part of the engine core, they must also be able to function at peak performance in gas temperatures of up to 1600°C.

Comprising an advanced nickel alloy base with additions of cobalt, chromium, tantalum, tungsten, aluminium, rhenium and other trace elements, additional strength is derived by the specially controlled casting process which removes the normal formation of solidifying grains in the metal. These grains, with boundaries between them, are potential sites for impurities and weakness. Control of the solidification process allows the blade to be cast as one single crystal of nickel alloy with no grain boundaries. The resulting blade has a temperature melting point of between 1200°C and 1300°C and operates at an average metal temperature of 1000°C. Its hollow design allows air to flow through internal passages to cool the component, before passing through holes to form a protective film over the blade surface. 'Cool' air temperatures are, in the case of a large civil turbo fan engine, in the region of 650°C.

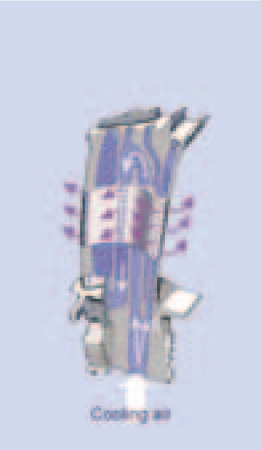

Figure 5: Cutaway of an HPT blade.

Reducing environmental impact

The continual reduction of emissions and noise continues to be at the forefront of advanced aero engine design. But designing an engine which achieves both optimum performance and low emissions presents a conundrum at the epicentre of advanced aero engineering. Increased temperatures improve the thermodynamic cycle and the engine fuel efficiency; indeed, since the 1960s the fuel burnt per passenger seat has more than halved due to improved engine technology and lighter aircraft designs. This has a direct benefit in reducing the amount of CO_2 produced. However, nitrogen and oxygen – both present in the atmosphere – react at very high temperatures and this chemical reaction produces nitrogen oxides, NOx, a contributor to acid rain. The higher the air temperature and exposure time to these high temperatures, the greater the production of NOx.

Advanced combustion technology has come a long way in addressing these issues. Today by-products such as soot, smoke, hydrocarbons and carbon monoxides have all but disappeared. Emissions of nitrogen oxides have been reduced by making improvements to combustor mixing processes by lowering peak gas temperatures and reducing burning exposure time in the 'hot spots' of the combustion chamber.

Great strides have been made by the aviation industry during the last 30 years in reducing noise pollution. About 20 decibels (a fourfold reduction) has been cut from aircraft noise in this time through the use of improved technology. However, as numbers of aircraft multiply, increasing regulatory attention is being focused on the issue of noise emissions both on take-off and landing.

An example of how technology is being used to reduce noise is the swept fan, which has potential to further reduce an aircraft's total noise emissions. Progress in a number of other areas is being made. Working closely with engine nacelle manufacturers, Rolls-Royce is conducting research to extend an engine's lower-lip intake, referred to as 'negative scarfing', to re-direct engine noise normally affecting airport communities 'into the skies'. Treatments to muffle noise generated by engine core components, including advanced acoustic liners, are also being evaluated.

Future concepts

Incremental changes to gas turbine technology have yielded improvements in performance and reliability since the advent of the gas turbine. Alongside improvements in traditional areas, the search for continuous reductions in cost and environmental emissions may require a departure from the boundaries of existing gas turbine architecture. Amongst the concepts being studied by the industry which may make their way on to the world's runways in a few years time, Rolls-Royce engineers are investigating the concept of the 'More Electric Engine'.

This engine is based on a revised Trent engine architecture with fewer compressor and turbine stages; benefits are largely derived from the elimination of the aircraft pneumatic system, together with significant simplifications in the aircraft–engine interface. Power will be produced by generators embedded in the engine and, ultimately, it may be possible to remove the engine oil system completely. Many studies have shown that the integration of the More Electric Engine into the More Electric Aircraft would result in worthwhile cost and efficiency savings. While the concept is still in its infancy, some aspects of this technology could enter service within the next ten years.

Some passengers are prepared to pay premium fares and this group is likely to welcome the contribution to reduced journey times of flying faster. The need for large aeroplanes with significantly increased speed seems unlikely in the near to medium term. However, the engine maker must now give consideration to the availability within current horizons of a small-to-medium aircraft operating at near sonic speeds.

Gas turbine technology, such as that which has made the Trent family so successful, is directly applicable to a powerplant for a 250 to 300 seat aircraft flying at around sonic speeds. Studies suggest that the engine cycle selected for such an application would differ from that which would be chosen for a similarly sized conventional subsonic aircraft. A greater proportion of the energy would have to be provided by the core in order to satisfy climb and cruise considerations. This emphasises the need for lightweight materials and high-temperature capability in the compressor and turbine, and provides demanding requirements in terms of noise and emissions.

In years to come, whether airframe makers and customers demand step changes in gas turbine technology or leaps into new directions, it is likely that developments will be driven by a combination of economic and environmental conditions and technical feasibility. Whatever the future brings, the drive to provide value through innovative engineering solutions remains as strong as ever. ■

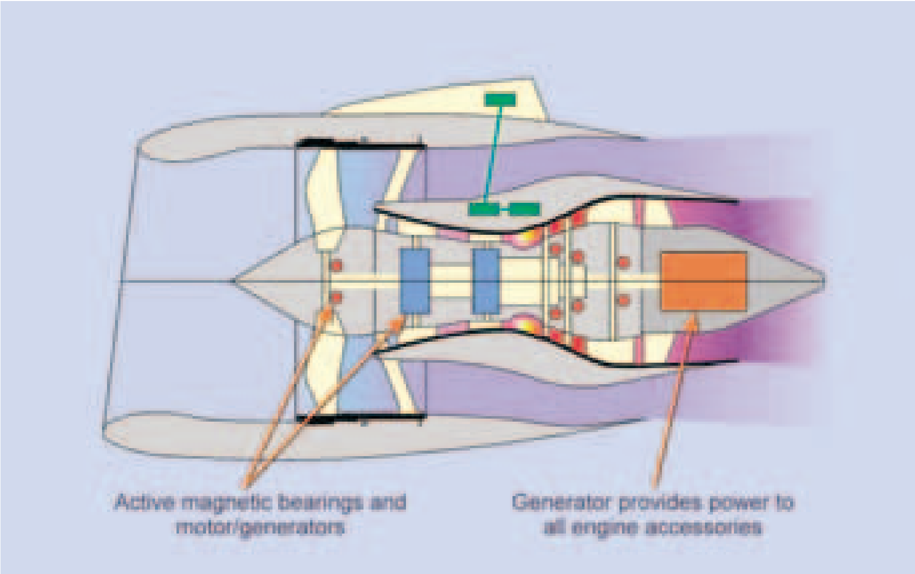

Figure 6: The more electric engine.

Philip Ruffles joined Rolls-Royce in 1961 and has held a variety of senior engineering positions. He was appointed to the Main Board as Director, Engineering and Technology, in January 1997. He has received many awards and distinctions including the Royal Academy of Engineering MacRobert Award for his work on the Trent engine and the Institute of Mechanical Engineers James Clayton Prize for his contribution to aero engine technology.

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