The Trent 1000 which entered service with All Nipon Airways in October 2011 delivers the lowest fuel burn, emissions and noise for the Boeing 787 Dreamliner and formed the basis for the Environmentally Friendly Engine

PERFECTING THE JET ENGINE

Fuel costs and environmental concerns are heavily influencing developments within the civil aerospace industry. The aircraft of the future and the propulsion systems that power them might look radically different in decades to come. *Ingenia* asked Rolls-Royce, and Professor Philip Ruffles CBE, former director of engineering and technology at the company, about the work being undertaken and where that might lead.

The gas turbine engine has changed dramatically since the father of jet propulsion, Sir Frank Whittle, unveiled his first engine in 1937. Thanks to major advances in materials, design and manufacturing, engines are now much more powerful and efficient. There are however, plenty of design challenges left to address.

One of the major challenges for aero engine designers today is to find the optimum balance between fuel economy, noise and emissions. To make matters more difficult this balance is constantly changing in response to different requirements from aircraft manufacturers.

To achieve that balance, designers have to make choices. They can drive an engine's thermodynamic cycle harder, boosting its thermal efficiency and cutting fuel consumption. However, this increases engine maintenance costs and can raise combustion emissions, especially oxides of nitrogen.

Each fan blade experiences about 100 tonnes of centrifugal load, equivalent to hanging a freight train off each blade.

Alternatively, they can increase propulsive efficiency, principally by increasing fan diameter. But this has to be balanced with increases in weight and drag which in turn increase fuel consumption and consequent CO_2 emissions. Finally, designers need to design a propulsion system that minimises noise which can increase engine weight and aircraft fuel burn.

BIGGER FANS

Making the most of propulsive efficiency is crucial to reducing fuel consumption. A jet engine works by sucking in large amounts of air – see *Back to basics*. So, one way to boost efficiency is to increase the amount of air being sucked into the engine relative to that going through the engine core. To do this, the engine's fan blades need to be as large as possible while minimising the weight and drag that increase fuel consumption. There are a number of projects within Rolls-Royce working to increase propulsive efficiency.

At the moment, Rolls-Royce aero engines use super plastically formed/diffusion bonded (SPF/DB) hollow titanium fan blades to deliver the most efficient fan system created to date. With the advances in composite technology, the time is right to produce a new, lighter, composite system. Composite Technology and Applications Limited (CTAL), a joint venture

BACK TO BASICS

A jet engine works by sucking in large amounts of air, adding energy to it and pushing it out through the back of the engine. The force (thrust) that is created is used to propel the aircraft forward.

The most obvious part of any large engine is its fan, which sucks in air at the front of the engine. In modern gas turbine engines, more than 90% of this air is routed directly to the back of the engine via the bypass duct. This bypass air provides about 75% of the engine's thrust.

To develop the most efficient engine, the fan system needs to balance ever larger fan diameters to drive propulsive efficiency benefits against the consequent increase in weight and drag. Simplistically speaking, the intent is to produce the largest and lightest fan system possible.

Technologies such as Rolls-Royce's hollow super plastically formed/diffusion bonded SPF/DB titanium fan blades have been used to achieve this. But the lightness of the fan needs to be balanced with its strength. Consider that each fan blade experiences about 100 tonnes of centrifugal load, equivalent to hanging a freight train off each blade. All the while the fan blade tip travels at more than 1,000mph, is exposed to the environmental conditions and must be built to withstand impact from airborne objects, including birds, which can create massive forces.

While 90% of the air in the fan passes directly down the bypass duct, the rest passes through the engine's core, where it is used to generate the power that drives the fan. The cold air is compressed to approximately 1/50th of its original volume, by several stages of compression. Compressing the air raises its temperature to more than 700 °C; at this point, some of the air is routed away from the main gas path and taken to cool even hotter components in the combustor and turbine further back in the engine core.

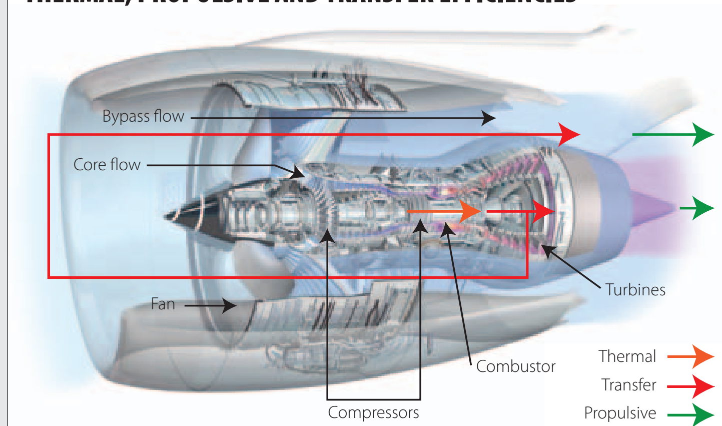
When the air leaves the compressors, it enters the engine's combustor, where fuel is injected and burned, sending hot gases downstream to the turbines. Gas temperatures within the combustor are above the melting point of its nickel alloy walls, so cooling air and a thermal barrier coating are used to protect these walls.

The final stage of the engine core is its turbines, a series of bladed disks that spin round, gaining energy from the hot gases leaving the combustor. The hot gas expands and cools as it goes through the turbines and finally exits through the propelling nozzle. It is this expansion that provides the turbines with enough energy to drive the compressor and the fan.

The first stage of turbine blades spin at 10,000 rpm, experiencing 18 tonnes of centrifugal load, equivalent to hanging a double decker bus off each blade. What is more, the temperatures exceed 1,600 °C, beyond the melting point of the most advanced materials, so a thermal barrier coating is used and cooling air flows across the surface of the blade, which prevents it from melting.

Bypass air provides around 75% of the engine's thrust. The remaining hot gas after the final stage of the turbine is allowed to expand at high velocity through the engine's exhaust nozzle, providing the remaining 25% of thrust.

THERMAL, PROPULSIVE AND TRANSFER EFFICIENCIES



Schematic showing the thermal, propulsive and transfer efficiencies of a jet engine today

between Rolls-Royce and GKN Aerospace, is developing new ways to manufacture carbon fibre fan blades and fan cases.

Historically, composite blades have been made by hand, but the CTAL team intends to automate production, increase quality and reduce manufacturing time. CTAL is pioneering a technique known as Automated Fibre Placement in which a purpose-built robot lays strips of impregnated carbon fibre tape on to a fan-shaped mould, which is then heated and pressurised to harden the strips. Once baked, the blade's root and leading edge are machined and coated to protect the surface, edged with titanium to boost strength and, finally, painted with an environmental protective coating.

A similar process is being followed to manufacture the fan case, and the process is being further developed so it can be used to make more complex structures. The next generation of Rolls-Royce engine that uses this composite fan system could weigh between 500 and 1,000 lbs less (depending on the application) than today's equivalent – a weight saving in the range of 3-6%.

Rolls-Royce is also experimenting with mounting a bladed spinner in front of the main fan blades in order to boost mass flow. Thus additional gas flow can be captured by the fan, without increasing the load on the fan disk. In essence, more flow is squeezed through a fan of a given diameter. The downside to this would be that the additional bladed spinner will increase overall engine noise.

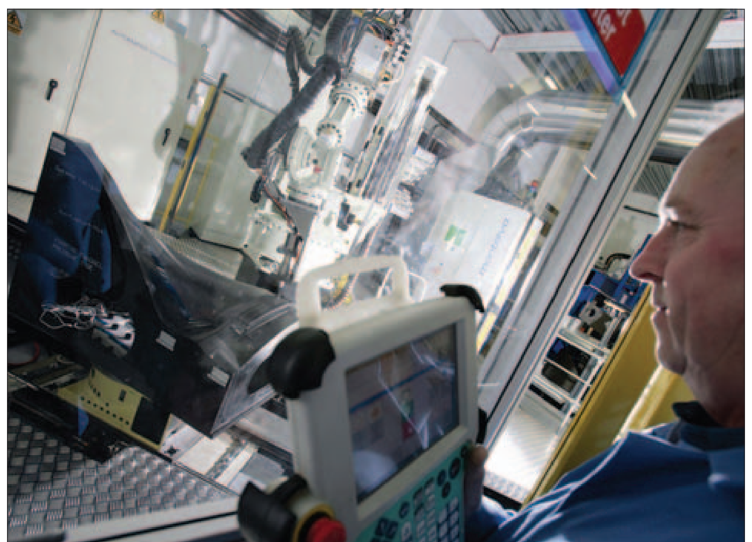
Engineers are studying ways of reducing overall engine noise, for example by using a mini-mixer which mixes some of the fan exit flow with the gases from the hot nozzle. This will reduce noise and improve the transfer efficiency of the engine by optimising the energy between the engine core gas stream and bypass stream.

More radical still, the open rotor concept has the greatest potential to increase bypass ratio and propulsive efficiency. Here, the fan case and nacelle, the outer casing of the engine, are removed from the fan system, leaving the rotors exposed without drag from the surrounding casing, enabling extremely high bypass ratios to be achieved.

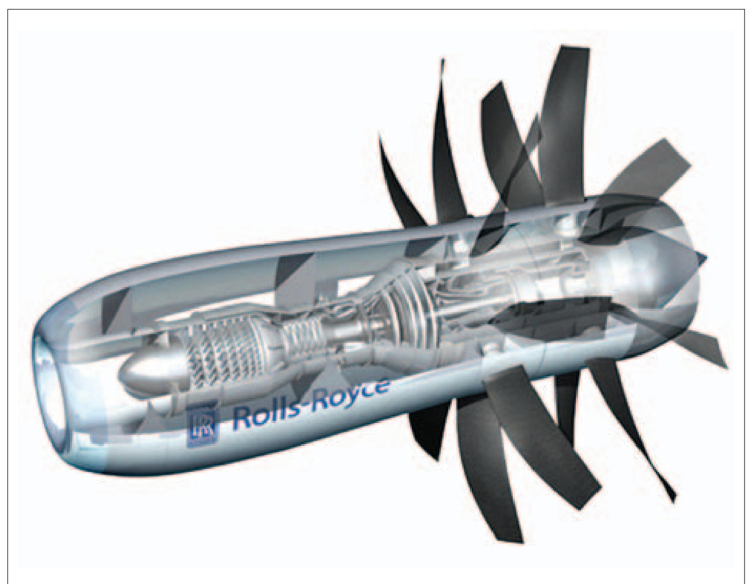
A contra-rotating system using two rows of propeller blades would be preferable thus removing the exit swirl of air that occurs in a normal single row propeller. This would eliminate wasted energy, thereby achieving the highest propulsive efficiency.

A key focus of the work Rolls-Royce engineers are undertaking on the open rotor design is around blade pitch control. With airflow on to the fan no longer controlled by a duct, the engine control system must set the blades at the correct angle to the airflow for any given operating condition or stage of the aircraft's journey. Installing such an engine to the airframe is a challenge and engine designers are working closely with airframers to ensure open rotor engines could be accommodated in new aircraft designs. Future open rotor powered aircraft will also be slightly slower than their conventional turbofan-operated counterparts. Along with noise, this is a key tradeoff that has to be weighed up against the exceptionally high efficiency benefits of this engine design.

More radical still, the open rotor concept has the greatest potential to increase bypass ratio and propulsive efficiency.



A joint initiative by GKN and Rolls-Royce, CTAL aims to leapfrog the manually-intensive production method of producing carbon composites. They have developed an automated process capable of significantly faster production rates. Here, an engineer is supervising the lamination of hundreds of layers of pre-impregnated fibres to produce considerably lighter fan blades © Rolls-Royce



Open rotor concept: open rotor technologies offer the potential for significant reductions in fuel burn and CO_2 emissions relative to turbofan engines of equivalent thrust

The Environmentally Friendly Engine demonstrator is a heavily modified Trent 1000 with the fan blades removed. Most of the engineering design and analysis on the project was carried out at Rolls-Royce's Derby site, while the assembly and test activity is taking place at Bristol where EFE has a dedicated testbed

HOTTER CORES

Thermal efficiency is essentially the efficiency at which the gas generator converts chemical energy from fuel into the available thermal energy in the gas stream.

To extract more thermal energy from the fuel and convert it into thrust, the overall pressure ratio (OPR) from the front of the fan to the rear of the compressor must be as high as possible within the constraints of available materials. However, as the OPR increases, so do the operating temperature environment of the core components and the temperature of the air used to cool the turbines.

Rolls-Royce carries out numerous technology programmes to improve engine design and performance. One such is the Environmentally Friendly Engine (EFE) demonstrator which focuses on improving the thermal efficiency of the engine. EFE utilises a three-shaft Trent 1000 engine as used on the Boeing 787 Dreamliner. This has been heavily modified to demonstrate the next generation and beyond of world class engine technologies.

Engineers working on the EFE demonstrator programme have been testing a range of materials, cooling specifications and different methods of film cooling for various blade and nozzle shapes. Additional work on lightweight intercoolers – devices that cool the air between compression stages – allows the engine to pressurise the air more efficiently and reduce the temperature of the cooling air extracted to cool other areas of the engine.

Ongoing studies continue to investigate the 'statorless' turbine. The usual set of stationary guide vanes, which direct gas flow into the next stage of rotating rotor blades, would be removed so that the gases exiting the upstream rotor impinge directly on the downstream rotor. This would lead to a large reduction in components and weights, and consequently generating fuel burn benefits.

COMPOSITE MATERIALS

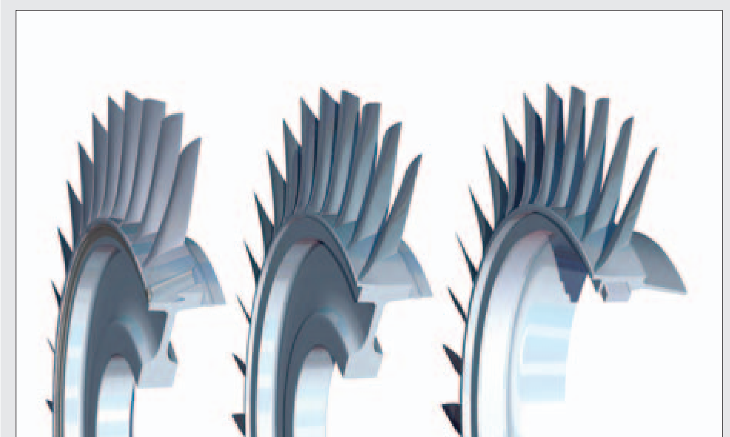
Minimising the weight of an engine can reduce its fuel consumption and carbon dioxide emissions, so engine designers have spent recent decades incorporating more and more lightweight alloys and composite components. Polymer matrix composites (PMCs) account for almost all of the composite materials used in the engine today, despite their relatively low temperature capability of less than 150 °C. But this is changing. Indeed, the gas turbine in 20 years' time could see PMCs constituting much of the nacelle, fan system, shaft support structures casings and stators with Metal Matrix Composites (MMCs) being used in intermediate and high pressure compressor rotors.

Meanwhile, MMCs offer possibilities at intermediate temperatures, particularly in the engine's compressor section. While this section currently comprises alternate stages of titanium alloy bladed rotating disks (separately bladed disks) and/or blisks (integrally bladed disks) with static vanes, engineers are now looking to remove the inner disk, leaving an integrally bladed reinforced ring – or 'bling' – to carry all the centrifugal loads.

The ring at the heart of the bling will be made from a very strong silicon carbon fibres and very stiff titanium metal matrix composite, in which silicon fibres have been embedded into the titanium alloy. This composite is twice as stiff and 50% stronger than the parent material, while the bling will be 70% lighter than a conventional disk and blade arrangement and 40% lighter than a blisk.

Importantly, the move from a disk to a blisk configuration will boost the aerodynamic efficiency of the compressor in the engine to enable further reduction in core size, while the change to a bling will create space within the centre of the engine to enable further reductions in core size and space for embedded systems such as electrical generators, all improving on basic engine performance.

Ceramic matrix composites (CMCs) suit high temperature applications as long as loads are modest. In future engines, a large proportion of the combustor and turbine systems, nozzles and some of the rear structure will be fabricated with CMCs.



A bladed disk, a blisk and a bling

Lastly, advances in computing power have led to engineers on the project developing new algorithms for electronically monitoring and controlling the engine. Active tip clearance control is a key example. Here, control software has been developed to monitor and alter the gap between the tip of a turbine blade and its casing. The turbine tip seal gap is in the magnitude of the width of a human hair. It minimises airflow losses and keep the blades and casing cool. However, the gap width normally varies throughout flight, as the casing and blade heat up and cool down and as the blade is subjected to centrifugal forces.

With active clearance control, sensors in the EFE continuously monitor the width of this gap and feed data back to the engine's electronic control unit. Crucially, the control system can use this data to alter the width of the gap, according to engine condition, on a second-by-second basis. Systems such as active tip clearance control are paving the way to an intelligent engine that will 'morph' to its operating conditions.

AIRCRAFT OF THE FUTURE

Ultimately, tomorrow's engines will largely be defined by future aircraft designs. New concepts in development include Boeing's blended wing body, Lockheed Martin's box-wing and Northrop Grumman's flying wing designs. All of the proposed aircraft are designed to halve landing and take-off emissions of nitrogen oxides by reducing the take-off thrust requirements. They also aim to cut fuel consumption by nearly 50%, compared with aircraft flying today, with a large proportion of this benefit being delivered by the engines. These future aircraft concepts are not only radically different, but all point towards a need for closer integration between the airframe and the engine, even designing the aircraft and the engine as a single, fully integrated entity.

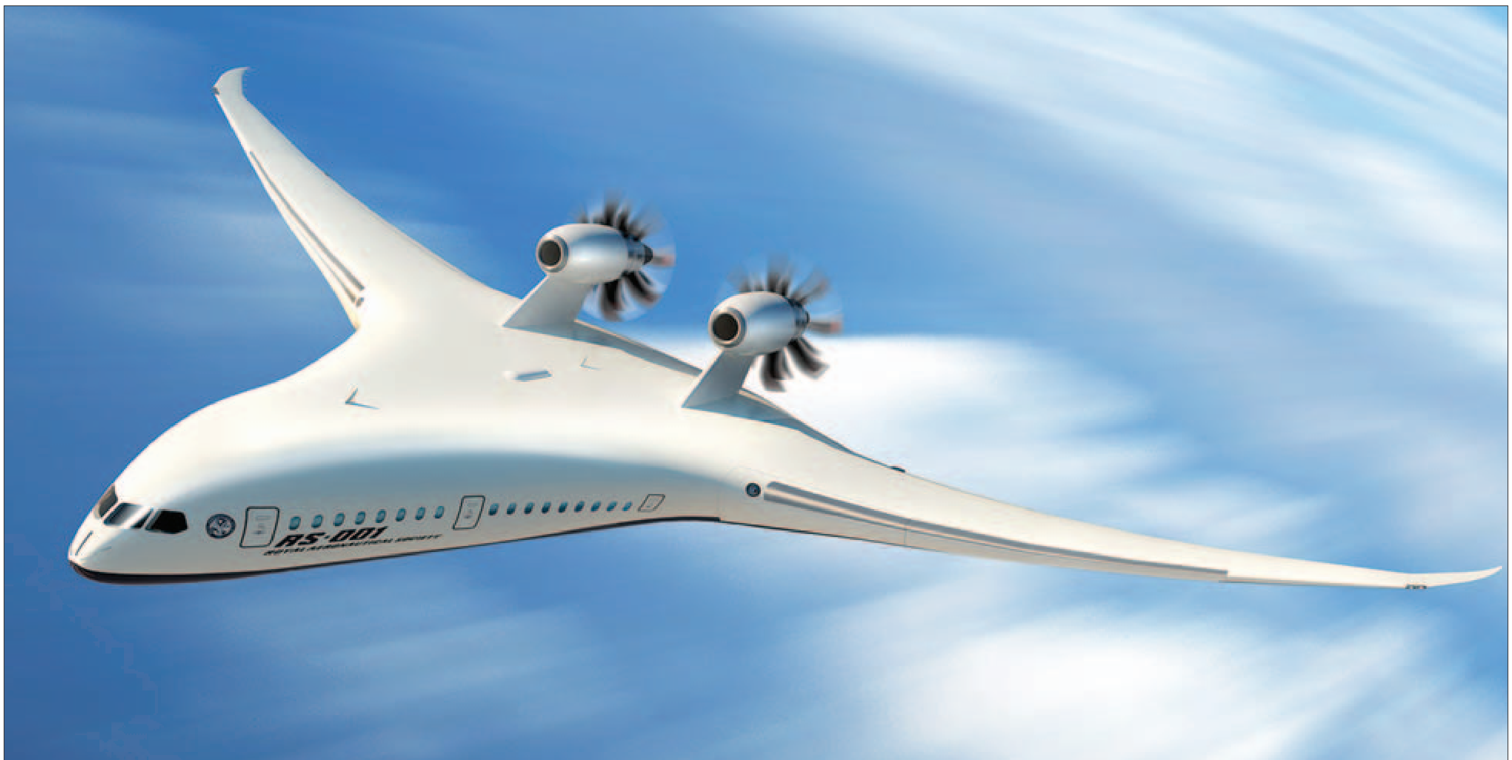
Danish physicist Niels Bohr reportedly said that "prediction is very difficult, especially about the future". We cannot foresee what the aeroplanes of tomorrow will look like, but all the signs are that they will burn less fuel and emit less carbon dioxide and oxides of nitrogen.

See Professor Philip Ruffles' talk: *Past, present and future – sustaining the traditions of Sir Henry Royce* at **http://tv.theiet.org/technology/transport/13479.cfm**

BIOGRAPHY

Professor Philip Ruffles CBE FREng FRS enjoyed a distinguished career in engineering at Rolls-Royce, becoming director of engineering and technology from 1997 to 2001. He led on the development of the Trent aero engine, which won the MacRobert Award. Professor Ruffles was also awarded and the Prince Philip Medal from the Royal Academy of Engineering and became a Commander of the Order of the British Empire in 2001.

Ingenia *would like to thank Dr Rebecca Pool, science and technology writer, Ian Doherty, Strategic Marketing Manager at Rolls-Royce, and John Whurr, Chief Project Engineer – Future Programmes, Rolls-Royce, for their help in producing this article*



Airframers are looking to the future with designs that can accommodate open rotor (above) or geared turbofans © concept by Royal Aeronautical Society with rendering by Kaktus Digital