Mid-Size Marvels
The Narrowbody Engines of Tomorrow

Chris Kjelgaard reports on the far-reaching technological developments that will be introduced in the huge mid-size commercial turbofan market for the next generation of narrowbody jet airliners.

Because airframe manufacturers launch new commercial aircraft into production only rarely, engine makers have to take a long view of the market. Their job is greatly complicated by the fact that manufacturer studies of aircraft definition and the characteristics of the engines to power them change frequently, depending on market conditions and the general state of materials, systems and aerodynamics technology. Consequently, each of the big three commercial turbofan manufacturers employs a development strategy that is constantly looking a minimum of six years ahead – typically, the time it takes to develop, test and certify a new engine – and beyond to at least ten years.

This strategy results in what Robert Nuttall, Rolls-Royce Vice President of Strategic Marketing, calls a “moving conveyor belt” of new technologies. Rolls-Royce’s conveyor belt for technological development includes programmes with such esoteric acronyms as EFE (Environmentally Friendly Engine), an advanced three-shaft demonstrator; E3E, a high pressure compressor (HPC) development programme run by Rolls-Royce Deutschland that has created what “we believe is the most efficient compressor in the world, running”, according to Nuttall; and Silence(R), a programme looking at engine noise treatments of nacelles and exhaust nozzles.

Each of the major engine manufacturers is involved in many such programmes, often with development partners in...
industry and the academic world, in Europe, the United States and elsewhere. Major programmes often include sub-programmes (or “technology strands”) looking at specific single technologies, with the result that Rolls-Royce is now involved in at least 50 different development efforts, according to Nuttall. Collectively, development of different technology strands for an engine can result in an improvement of about 1% a year in specific fuel consumption, and new technologies are often incorporated into a manufacturer’s existing product lines.

But sometimes a much greater degree of improvement is needed — particularly when manufacturers get closer to defining their next-generation commercial jets, or as today when external factors such as the growing need for environmental friendliness become important. Then the engine-makers must find radical new answers to keep their customers — the airlines — happy.

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This engine would offer 15% better fuel-efficiency than today’s mid-size engines, but Nuttall said it is “an engine we’ll never do” because 15% won’t be enough of an improvement to be chosen for the next generation of Airbus and Boeing narrowbody aircraft. However, Nuttall said that by 2018 Rolls-Royce would be able to produce a three-shaft advanced turbofan (ATF) design offering a 20% improvement in fuel burn over today’s engines and which would be very quiet indeed.

Such an engine would make extensive use of integrally bladed, one-piece rotors (known as “blisks”) as high-pressure compressor stages. It would also use a carbon-fibre composite fan and casing, employ a combustion emitting very low levels of nitrogen oxides, incorporate the latest thermal-coating and cooling technology, and

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“The Open Rotor allows a turboshaft level of efficiency at turbofan levels of speed,” said Nuttall. Turboprops are 12%-efficient in terms of propulsive efficiency but don’t produce particularly fast cruise speeds. However, the geared-fan Open Rotor, with its two rows of three-dimensionally sculpted, advanced-airfoil blades made of carbon-fibre composite and gearbox driven by the last three stages of the low-pressure turbine would routinely run at thermal efficiencies no turboshaft has yet achieved.

The Open Rotor’s two rows of blades would be sized differently because this — along with optimising the distance between the rows — would allow Rolls-Royce to ensure the air pulled through the first row of blades is entrained and “doesn’t go off the top” of the blades to create vortices and increase drag, said Nuttall. (The second row of blades would be shorter “so it wouldn’t be in the first row’s blade-tip vortex.”)

Each row would have different numbers of blades and would rotate at different speeds. Optimising blade size, blade numbers, blade...
built with components currently under development. But while the challenges of designing and engineering the Open Rotor gearbox are stiff, they are by no means insurmountable, said Nuttall. For a start, the standard planetary gearbox in the Open Rotor would only require about half as much power (say 16,000shp) to produce the same amount of thrust. “We will meet Stage 4 comfortably by 2020, plus or minus one” said Nuttall. “It’s not a physics problem anymore. Now, the question is, mechanically, how are we going to do it? I’m implying it’s easy, but it’s not – you’ve got to be able to change the pitch of the blades independently and the fan is about 170 inches, about the same diameter as the fuselage of the aircraft it powers.”

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Also, Rolls-Royce now has the results of one-sixth scale experimentation on Open Rotor fan configurations, which it began conducting in the Netherlands in early 2009 (cycling the engine through idle, taxi, takeoff, approach and landing), and completed at the Aircraft Research Association facility in Bedford in England with high-speed cruise tests in the autumn of 2009. “I can say we are very pleased with the results from the experiment,” said Nuttall.

“We are very happy that the Open Rotor has 25% to 30% better efficiency than current turbofans and 10% to 15% better than any advanced turbosfans being promoted. It’s definitely quieter than today’s aircraft and comfortably meets Stage 4,” though he concedes it would be about 10 EPNdB louder than R-R’s putative 2018 Advanced Turbopfan. “Also, it would have 20% lower NOx compared with any advanced turbosfan, for any given combustor, because of the way a turboprop gets its power, particularly round the airport,” said Nuttall.

The NG34

Given that General Electric’s CF34 engines (power business jets [notably Bombardier’s entire Challenger family] as well as regional jets, the CF34 has proved an enormously successful, strong-performing engine line for the company. So successful in fact that GE is determined to develop an equivalent, all-new engine family — currently labelled the NG34, though the name may change — within the next few years.

“We have a clear intent to take a new engine to market in the next decade,” said Andre Robert, Head of Marketing for GE Aviation. GE is aiming to make an NG34 engine available from 2015, the exact date depending on the engine being chosen for an airframe application and the service-entry date the airframer requires.

For the purpose of maximising fuel-burn and maintenance cost improvements, GE is looking at the NG34 as an entire propulsion system “from the pylon down”, including the nacelle, the quick engine change (QEC) kit and the engine itself. “We will integrate that entire system as one,” said Robert. “We’re aiming for 10 to 15% improved economics compared with the versions in service today. But what is critical is that the reliability of the current CF34 is unparalleled. ‘High-cycle is critical.’ Operators have made this very clear to GE,” he said.

“Our belief is that a simple, robust architecture is the way to go,” using a two-spool, direct-drive architecture rather than [say] a concept such as PW’s geared turbosfan or Rolls-Royce’s Open Rotor. However, the NG34 will employ some or all of the new technologies that GE is testing in its eCore programme. These are aimed to verify new engine-core technologies that will earn their way into GE and CFM engines through...
the entire thrust range that the company offers, from low-thrust business jet engines to very high-thrust versions of the new GE90s that would power Boeing's eventual replacement for the 777-300ER.

For more detail, Robert, “There is a plan to incorporate CMCs (silicon carbide ceramic matrix composite) in the engine; eCore as a suite of technologies has CMCs factored into its configuration, so we’ll use that as the architecture, then we make a determination that the technology earns its way on to the engine.” Additionally, while today’s CFM6 is a feature a keeler upgrade on the fan case, the N34’s entire fan case will be made of carbon-fibre composite. Also being tested in GE’s eCore programme is GE’s latest TAPS II combuster, which has two concentric fuel nozzles and pre-swirls air directed to the bypass flow from the air behind the fan and splitter lip (which splits the large fan for the size of the engine). The PW1000G has been chosen to power the new Bombardier Cliey family of 110-130 namemobiles from 2013 on which will have a bypass ratio “in the 12 to 13 range.”

The PW1000G has also been chosen to power the 61in (1.55m) of the CFM56-7B family of 110-320 seat aircraft, Russia’s next generation of marnoe mobile jets. While Pratt & Whitney hasn’t yet discussed in detail the specific bypass ratio of the PW1000G version that will power the Irkut MC-21 family, it is known that the larger versions of the MC-21 family will require an engine with a thrust level of some 20,000lb (133.7kN). As a result, the PW1000G version provided to the Irkut MC-21 will be even more powerful than the PW1000G version that powered Airbus’ LEAP-X demonstrator engine.

“Very high bypass ratios are not a new technology,” said Robert. “There is a huge learning curve in terms of being able to produce two-dimensional (2D) composite blades, which need to be thinly layered to produce the required impact resistance, in Snecma’s wovem-RTM technology, composite filars are stitched together in a 3D configuration.” This gives it the additional strength needed for the smallerr diameter fan,” while keeping the blades thin enough to ensure aerodynamic efficiency.

Using composite blades also potentially means CFM potentially can reduce the size of the fan hub, allowing a bigger fan-blade radius for a given fan diameter. “We’re looking at that,” confirmed Klapkoff. Snecma completed major bird- strike and endurance tests on its new wovem-RTM fan design this year and it’s looking very encouraging.”

“Towards the jet’s no doubt that composites are the future,” said Klapkoff. “We’re using Snecma’s weft fibre up the front or PW1000G engine, because the LEAP engine is smaller in size and thrust.

While Ron Klapkoff, Director of CFM International’s LEAP Programme, says CFM hasn’t yet decided whether to choose a single HPT (high pressure turbine) stage or a two-stage design, GE’s eCore is testing the former configuration and eCore 2 the latter. CFM’s trials believe the partnership already has effectively decided on a two-stage HPT for LEAP-X. In any event, CFM promises that the engine, which is scheduled to run as a demonstrator in 2012 and could be certified by 2016, will be 16% more fuel-efficient than today’s CFM56a.

Whatever architecture CFM does choose, the LEAP-X HPT will be “the most highly loaded HPT ever designed for a commercial application,” said Klapkoff. Also, since eCore’s design “has raised the conventional manufacturer wisdom is that composite fans don’t make sense on mid-size engines because to be adequately bird-strike resistant the fan blades need to be too thick to be aerodynamically efficient. However, Klapkoff said that the world’s transformational subtracting (RTM) technology developed by Snecma over many years has changed the equation.”

“Please we’re not lying on today’s composite technology – you need next-generation technology to do composite mid-size blades,” said Klapkoff. Where others’ composite blades can produce two-dimensional composite laminates, which need to be thinly layered to produce the required impact resistance, in Snecma’s wovem-RTM technology, composite filars are stitched together in a 3D configuration.” This gives it the additional strength needed for the smaller-diameter fan,” while keeping the blades thin enough to ensure aerodynamic efficiency.

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In conventional turbofan engines, the bypass ratio effectively is set by the fan tip speed and the low-pressure turbine speed and the lag-turbine laytigger on the fan, the faster the tip speed becomes, the faster the bypass ratio. This blade tip ends end at supersonic speeds when the engine is producing more than about 80% of maximum thrust, creating shock waves that decrease the engine’s efficiency and make it much noisier. It can be useful to the conventional turbofan, turning the fan to faster a higher bypass ratio also in the case that the fan is directly linked to the bypass ratio and the LPT has to become much bigger and heavier to run faster. Weight and drag go up, which means that you have to overtake the specif fuel consumption efficiency, Adams explained. However, in the PW1000G the fan blade rotation speed is subsonic and there is no adverse shock wave effect. At the same time, the LPT and the LPC (boosted), which it drives runs faster than the LPT and the LPC for conventional turbofans because they are not directly linked to the fan. “The LPT and booster in the PW1000G run at speeds much closer to a turbojet-type engine,” he said. “The fan and the turbine are much more naturally matched.”

That faster rotating speed makes the PW1000G’s LPT and booster so efficient that, compared with a conventional turbofan engine producing the same thrust, Pratt & Whitney would be able to do away with five to six stages on the LPT and the LPT.

The architecture of the PW1000G uses three booster stages, where a conventional turbofan would classically use few, and just
three in the LPT, where (depending on a manufacturer’s decision to trade between fuel efficiency and maintenance cost) a conventional engine would have six or seven stages, according to Adams.

Elsewhere, the PW1000G’s architecture and materials technology is less conventional. Every one of the eight HPC stages in the engine is a blisk. The PW1000G has a two-stage LPT and Adams said both stages of the HPT and the stages at the rear of the HPC (where the core air starts becoming very hot) employ powder-metal materials. “We’ve used a fair bit of powder metal,” he said.

Additionally, the annular combustor in the PW1000G uses Pratt & Whitney’s latest TALON-X (Technology for Advanced Low NOx) design, which not only employs “floatwall” inner-lining panels that can expand and contract independently of each other as the engine heats up and cools, reducing wear and thus the amount of maintenance required, but also a “rich-lean-queue” combustor. This design “runs the primary zone [of combustion temperature] rich and then quenches it very quickly,” cooling the combustion air off below the temperature-resonance levels at which nitrogen oxides form, said Adams. “We burn quick and we burn rich, but we quench very quickly.” The PW1000G will produce NOx levels “minus 50%” and beyond compared with CAEP 6, ICAO’s latest emissions standard, according to Adams. “It’s very simple, very durable, low-maintenance cost and extremely safe,” while also offering “world-class” emissions performance. “We also have a very, very strong track record of the combustor not blowing out,” he said.

In the PW1000G’s combustor, Pratt & Whitney has stuck with a single-nozzle design rather than the dual-nozzle, concentric-ring design favoured by GE for its TAPS and TAPS II combustors. “We like this architecture and we think we can be extremely competitive in providing world-class emissions and do it with very low maintenance cost,” said Adams.

Additionally, the PW1000G’s turbine casing will employ active clearance control (ACC), a technology originally developed by Pratt & Whitney and over which it won a patent lawsuit with GE, to minimise any gaps between the casing and the turbine blades while the engine is running.

Adams said Pratt & Whitney has also developed “what we believe is next-generation cooling technology” for the PW1000G’s turbine blades in terms of the geometry of the specific cooling-air passages within the blades, and a combination of the materials from which the blades are made and the thermal barrier coatings with which they are treated, to help keep cooling-air requirements down.

At the back end, the PW1000G will have a cut-off nacelle design rather than a full-duct nacelle, with Pratt & Whitney using scalloped chevrons at the rear of the nacelle, as well as acoustic treatments within the engine to reduce exhaust-air noise.

But it is the PW1000G’s fan that could prove to be its most exotic innovation. Counter-rotating to the low-pressure spool (which rotates in the same direction as the engine’s high-pressure spool), Adams said that in this case “we think we end up being more efficient” in terms of core-airflow aerodynamic, the fan will have 18 highly three-dimensionally sculpted blades. However, for now Pratt & Whitney won’t say what they are made of, believing it has come up with an exciting new materials concept.

At this point in time it’s a lightweight hybrid,” said Adams, noting that because of technology sharing with its United Technologies sibling Hamilton Sundstrand – the world’s largest manufacturer of propellers for turboprop and piston-powered aircraft – Pratt & Whitney believes “we have some unique technology” for the PW1000G fan.

“We think we have an extremely good concept,” he said. “We’re probably not ready to go out to full market on that” in terms of public discussion of the technology, but he believes the company “will be ready for prime time by the summer” and can then say more about exactly what the PW1000G’s fan will be made of.

The slow rotation speed and large size of the PW1000G’s fan – particularly on the Bombardier CSeries – will create tremendous advantages in two areas quite apart from the impressive 12% fuel efficiency boost Pratt & Whitney promises the first-generation PW1000G will deliver compared with comparable current-generation turbfans.

One area is noise reduction. Because the PW1000G’s bypass ratio will be so high, the large amount of cold bypass air produced as the engine’s main thrust component will mix extensively with the hot exhaust air exiting the core and largely mask the noise produced by the exhaust air. Also, because the fan-blade tips are rotating at subsonic rather than supersonic speeds even at maximum thrust, the shock-wave noise associated with supersonic blade rotation speeds will be absent.

The PW1000G’s slow fan-blade rotation speeds will also help make the engine much more resistant to foreign object debris – including bird-strikes – than today’s engines, Adams believes. “Most damage from bird-strikes comes from fan speed, not blade speed,” he said. In current engines, typically, fan blades rotate “five to seven times faster than the blade is flying” – but the PW1000G’s blades will be turning more slowly and the forces associated with impact won’t be as high. Additionally, the large size of the fan will create more centrifugal force, tending to push FOD out to the edge of the fan and away from the engine before it has a chance to enter the booster and engine core.

In the United Technologies group of companies, another sibling of Pratt & Whitney is Sikorsky, which has decades of experience designing and running huge geardrives in its helicopters. This, along with the fact that PW itself is the world’s largest supplier of turboshaft engines (with 400 million hours of in-service experience) and also that PW has already run the PW1000G planetary gearbox at maximum power for over 1,000 hours in rig tests, “helps build our confidence that this should be a flawless entry into service,” said Adams.

After completing its entire demonstrator testing for the PW1000G using a PW6000 core, Pratt & Whitney started running the full PW1000G engine core in mid-December 2009. The development plan called for the full PW1000G test programme to begin in the first quarter of 2010 and for PW to begin running the fully configured PW1000G for the CSeries by mid-summer, allowing an entry into service on the new Bombardier mainline jet at the end of 2013.