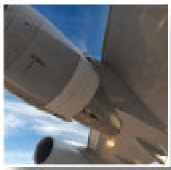
SBAC

Open Rotor Engines

SBAC Aviation and Environment Briefing Papers

3: Open Rotor Engines

Summary of Facts

- Open rotors are one of several new technologies offering potential solutions for the next generation aircraft
- Open rotors are engines in which the fan/propeller is not enclosed within the nacelle (engine casing)
- Open rotors proposed for new single aisle aircraft (Boeing 737/Airbus A320 replacement) will not be conventional turboprops / propfans: they will incorporate new, advanced technologies
- Open rotors are predicted to provide a 25–30% reduction in specific fuel consumption & CO_2 emissions relative to current, equivalent turbofan engines
- Challenges associated with open rotors include noise, aircraft integration, certification requirements (blade off), accessibility & maintenance – however all can be overcome
- Increase in journey time for open-rotor powered aircraft will be small (<10 mins for 2 hr flight)
- Research & development programmes on open rotor technology include DREAM & CLEAN SKY Joint Technology Initiative (EU)

Introduction

This paper is one of a series of briefing papers being produced by the SBAC to explain the work being undertaken by the UK aerospace industry to address the environmental challenges associated with aviation. The papers aim to present new advances in technology so that the reader can better appreciate what the industry is doing and why developing solutions can be challenging.

This paper discusses open rotor engines, a technology that may be used on the next generation of single aisle aircraft and has the potential to significantly reduce carbon dioxide (CO_2) emissions.

The turbofan engine

Since the invention of the jet engine by Frank Whittle in 1930, the greatest advance in aviation has arguably been the development of the turbofan engine, the engine most commonly in use in civil aviation today. The turbofan engine is essentially a jet engine with a large ducted fan at the front. This fan allows the engine to suck in a massive volume of air, some of which goes through the engine core (jet engine), the rest of which travels relatively slowly through the engine's bypass duct.

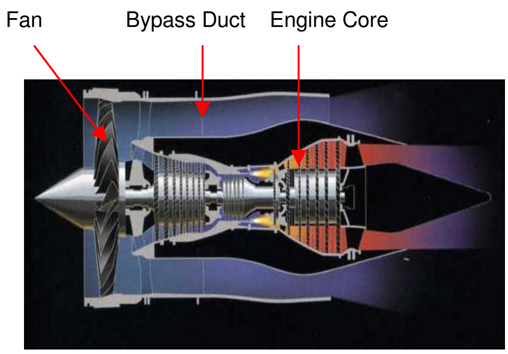


Figure 1: Turbofan engine[1]

[1] Rolls-Royce, The Jet Engine, 2005, p.16

Turbofan engines that have a high bypass ratio (ratio of air entering the bypass to air entering the engine core) can produce large amounts of thrust for significantly less fuel than traditional jet engines. As the CO_2 emissions produced by the engine are directly proportional to the amount of fuel burnt, these engines also have much lower emissions than pure jet engines, where most or all of the air passes through the core. These two desirable characteristics, low fuel burn and CO_2 emissions, make turbofan engines the current universal choice for high speed civil aircraft.

How do turbofan engines produce low emissions?

To reduce CO_2 emissions, the amount of fuel that must be burnt to produce the required engine thrust must be reduced.

Engine thrust F_N is given by the following equation:

$$F_N = \dot{m} \times \left(V_{jet} - V_{aircraft}\right)$$

Where $\dot{m}$ is the air mass flow rate through the engine

V_{jet} is the velocity of the engine jet

$V_{aircraft}$ is the velocity of the aircraft

It is clear from the equation above that an increase in thrust can be achieved by either an increase in $\dot{m}$ or an increase in $\left(V_{jet} - V_{aircraft}\right)$. However, fuel burn varies with V_{jet}^2 so a small increase in V_{jet} will lead to a much larger increase in fuel burn and hence CO_2 emissions. Therefore, it is better to increase thrust by increasing the mass flow rate through the engine. This can be achieved by using a turbofan engine with a high bypass ratio as this passes a large amount of air with a low mean jet velocity.

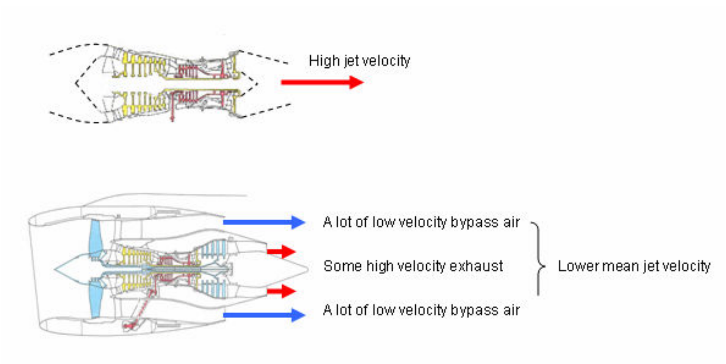


Figure 2: A turbojet and a high bypass ratio turbofan engine and their jet velocities[2]

Engine manufacturers have exploited this characteristic by progressively increasing the bypass ratios of modern turbofan engines. However there is a limit to how much the bypass ratio of an engine can be increased, as eventually the fuel burn benefit associated with the high bypass engine will be offset by the weight and drag and hence fuel burn penalties associated with the large nacelle (engine casing). At this point, a better approach may be to utilise an open rotor engine, an engine where the propeller/fan is not contained within the nacelle, offering a significant further increase in bypass ratio.

An Opportunity for Open Rotors

Ageing fleets requiring replacement coupled with high growth in low cost carriers in both traditional markets (US, Europe, etc.) and emerging markets (China, India, Latin America, Africa, etc.) mean that the forecast demand for new single aisle aircraft up to 2025 is in excess of 15,000. This represents a market opportunity of around US$1 trillion.[3]

[2] Adapted from Wickerson, J. Rolls-Royce Holistic Gas Turbine Basic Course Presentation, 2007.
[3] Airbus, Global Market Forecast: the future of flying 2006-2025, 2006.

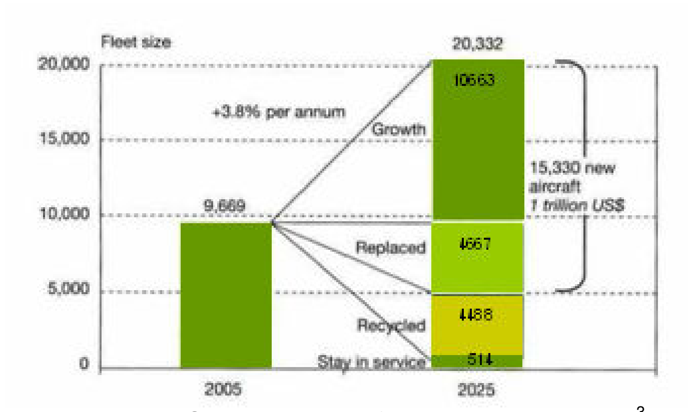


Figure 3: Single aisle aircraft market 2005 and 2025[3]

However, this significant demand for new single aisle aircraft offers more than just economic benefit. It provides the perfect opportunity for new engine and aircraft designs with radically improved environmental performance to be implemented on a grand scale.

Open rotor engines are one technology that has the potential to deliver significant environmental improvements for new single aisle aircraft. The increase in propeller diameter and removal of the heavy, drag-inducing, nacelle means that the fuel burn and hence CO_2 emissions of an open rotor engine could be significantly less than that of an equivalent high bypass ratio turbofan engine. Rolls-Royce predicts that open rotor engines could offer a reduction in specific fuel consumption (amount of fuel consumed to produce each pound of engine thrust) of 25-30% relative to current single aisle turbofans.

What will open rotors look like?

Two common open rotor configurations exist – a puller and a pusher. In a puller configuration, the propellers are mounted at the front of the engine. In a pusher configuration, the propellers are mounted directly behind the turbine stage.


Figure 4: Puller configuration[4]

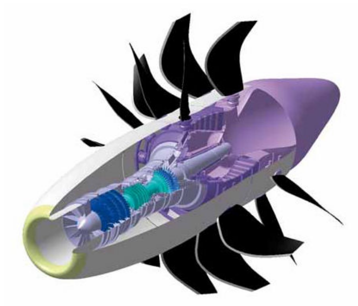


Figure 5: Pusher configuration[5]

Both engine configurations can either have a single propeller or a pair of contra-rotating propellers, however historically, puller configurations have generally had only one propeller and pusher configurations have usually had two contra-rotating propellers. The advantage of using the second propeller is that the rotational component of velocity (swirl) of the air leaving the first set of propeller blades will be corrected by the second set of blades and so will increase the engine's effective thrust. This means that to achieve a given thrust, an open rotor engine with contra-rotating blades can have a reduced propeller diameter and/or speed compared to a single propeller engine. Reduced propeller diameter offers the benefit of easier integration with the aircraft design. As the noise generated by the propeller increases with the rotational speed of the blades, reduced propeller speed offers the benefit of a quieter propeller; however, the interaction between the blade rows of a contra-rotating propeller creates additional noise. Using a pair of contra-rotating propellers also enables the aircraft to fly at significantly higher speeds, almost as fast as today's turbofan powered aircraft. The drawbacks associated with a pair of contra-rotating propellers are increased weight, cost and complexity.

There are two ways to drive the large, slow moving propeller(s):

- Using a reduction gearbox driven by a high speed, low stage count, low pressure turbine.
- Directly using a low speed, multi-stage, low pressure turbine.

[4] http://en.wikipedia.org/wiki/Propfan, sighted 15/01/08
[5] http://www.flightglobal.com/assets/getAsset.aspx?ItemID=18032, sighted 23/01/08

Both geared and direct drive options have advantages and disadvantages. Reduction gearboxes can be heavy and complex which can lead to unreliability and increased maintenance effort. On the other hand, direct drive engines will endure a performance penalty. A low pressure turbine operates most efficiently at high speeds whilst the propeller's optimal efficiency occurs at low speeds. In direct drive engines as the propeller is driven directly by the low pressure turbine, the speed at which the propeller/turbine system rotates will be a trade-off between the optimal speeds of the two.

Are open rotors actually anything new?

Open rotor concepts have been around for some time. The turboprop engine, a basic jet engine that drives a single propeller through a gear box, has been around since 1939 and is still widely used to power small, low speed aircraft. In the 1980's when fuel prices rose considerably, a turboprop engine that used a pair of contra-rotating propellers was developed. However, these engines, termed propfans or UnDucted Fans (UDFs) were never produced commercially due to the unresolved technical issues (complexity, noisiness, etc.) and because fuel prices decreased, reducing their commercial advantage.

However, the open rotor engine designs being considered for the new single aisle aircraft will not simply replicate past turboprop or propfan configurations. Designs will incorporate new and novel technologies currently under development in research and validation programmes. Although it is not yet known exactly which technologies will be incorporated into open rotor engines, it is likely that at least some of the following advances will feature:

- Advanced turbine and compressor systems – new materials and coatings, improved aerodynamics and reduced use of cooling air will lead to improved component efficiency and/or fuel burn.
- Low emissions combustors – novel lean burn combustor designs will enable NO_x to be reduced.
- Improved control systems – more advanced electronics, sensors, actuators and software will help to optimise engine performance and thus emissions throughout the flight envelope.
- Light weight structures – new materials, innovative design and manufacturing techniques will be used to produce light weight structures and hence reduce fuel burn.
- Advanced propeller blades – improved aerodynamics and pitch control systems will allow optimised propeller performance in all flight conditions.

What are the challenges associated with open rotors?

There are some substantial challenges associated with the use of open rotors. These include noise (cabin and community), blade containment and other certification issues, integration with the airframe, accessibility and maintenance issues. In addition, if the full environmental benefits are to be realised, aircraft powered by open rotor engines will need to fly slightly slower than aircraft powered by turbofan engines, resulting in increased journey times.

Noise

Open rotor engines are likely to be noisier than turbofan engines as there is no nacelle to absorb and attenuate the noise generated by the engine. As a result, it is very unlikely that new open rotor engines will be able to achieve noise levels comparable to or less than future equivalent turbofan engines. However, with the latest technology they will be quieter than today's turbofan engines. Some have suggested that stringent noise requirements should be relaxed so that the significant fuel burn reductions offered by open rotors can be realised. However, it is questionable whether this proposal would be accepted by governments and community groups.

Industry and academic groups have embraced the challenge of understanding and reducing the noise signature of open rotor engines, with projects such as DREAM and the OMEGA Integrated Study of Advanced Open Rotor Powered Aircraft (described on pages 6-7) currently underway.

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3. Open Rotor Engines

Blade Containment & Other Certification Requirements

For a turbofan engine to achieve certification, it must be demonstrated that one released fan blade can be safely contained within the engine's fan case. In the case of an open rotor where the fan case and nacelle are absent, designers must return to the philosophy employed with conventional propellers and demonstrate that the probability of a blade being released is "extremely remote" (in the order of one failure per 1 x 10^8 flying hours). The propeller blades being designed for new open rotors will be highly aerodynamic, lighter and less bulky than conventional propeller blades making this an extremely challenging task. However, engine manufacturers who already fulfil this requirement for other critical engine parts (e.g. compressor discs) are confident that this will not prevent the development of open rotor engines.

There is also a requirement for aircraft manufacturers to ensure that aircraft systems (e.g. hydraulics systems) and passengers are sufficiently protected in the case of blade release. Fulfilling this requirement may involve repositioning of certain aircraft systems or the use of shielding.

Integration with Airframe

The large propeller diameters (~ 4m) prohibit the use of open rotor engines on most existing aircraft; they simply will not fit within the dimensional limits of the wing and landing gear. Therefore the new open rotor engines will need to be integrated into advanced airframe designs. The engines could be wing, fuselage or rear mounted according to the airframe size and design. Whichever mounting configuration is selected, the significant weight and interference drag associated with large engine size will create installation challenges.

However, close coordination between aircraft and engine manufacturers from design conception to product delivery, which has already started, will help to ensure designs effectively address such issues.

Accessibility & Maintenance Issues

The most popular mounting configuration for current aircraft engines is under the wing. This offers easy access for on-wing checks and maintenance. However, under wing mounting is unlikely to be suitable for the new open rotor engines. New engine mounting positions could have a significant impact on maintenance times and cost. In addition, reliability concerns and the potential maintenance burden of certain open rotor engine components such as the gearbox and propeller pitch control systems may make open rotor engines a less desirable choice for operators.

Increased Flight Times

The flight speed of an open rotor powered aircraft is limited by the propeller speed – propellers experience a dramatic loss in efficiency at high speeds, reducing the fuel burn benefit associated with the design. While open rotors could operate at today's cruise speeds, (Mach Number of about 0.8 for short-haul flights) for optimum fuel efficiency they should fly at a Mach Number of about 0.75. Although this means that open rotor powered aircraft will fly slightly more slowly than aircraft powered by equivalent turbofan engines, the impact on flight time on a short-haul journey is likely to be minimal (under 5 minutes on a one-hour journey and 5-10 minutes on a two-hour journey). Different flight profiles, which are currently being considered for open rotor powered aircraft, may help to reduce this time difference.

However given that a high proportion of the total journey time for a short-haul flight is spent travelling to the airport, checking in, going through security, collecting baggage, etc it is anticipated that any small increase in flight time will be acceptable to passengers once they are aware of the environmental benefit offered by open rotors.

What work is being done on open rotors?

Preliminary work on open rotors has begun. Concept designs such as the easyJet ecoJet have been produced and academic studies such as the OMEGA 'Integrated study of advanced open rotor powered aircraft' are underway. The detailed research and development work into open rotor engines will be undertaken by engine manufacturers, through research and technology validation programmes such as DREAM and the CLEAN SKY Joint Technology Initiative, both commencing in 2008. Some of these initiatives are described below.

easyJet ecoJet

In 2007, easyJet released a concept design for the ecoJet, which it asserts could be an environmentally friendly single aisle aircraft replacement. easyJet predicts that the ecoJet, which is to be powered by open rotor engines, could be in operation by 2015 and has the potential to deliver CO_2 and NO_x emission reductions of 50% and 75% respectively, and a 25% reduction in noise, compared to current Boeing 737 and Airbus A320 variants.

The open rotor engines proposed for the ecoJet design have a geared drive system and are rear-mounted for improved efficiency and reduced noise. The proposed airframe is light-weight, with a significant proportion of the structure likely to be made from composite materials. The proposed design has wings that are slightly swept forward for reduced drag at cruise. The ecoJet is designed to have a lower cruise speed and a shorter design range than a traditional single aisle aircraft, to reduce drag and weight respectively.[6]

Figure 6: Model of easyJet's ecoJet design[7]

Producing the ecoJet design concept demonstrates the eagerness of airlines like easyJet to adopt new technology offering improved environmental performance. However it is important to remember that the ecoJet is a concept design only, significant work is required by manufacturers to develop and validate the technologies proposed by the design.

DREAM - Validation of Radical Engine Architecture Systems

DREAM is a research and development programme that aims to demonstrate new open rotor engine concepts. Led by Rolls-Royce and involving 47 partners from 13 EU countries, the €40 million, three-year programme is due to commence in 2008 and will involve both component (e.g. gearbox, low pressure turbine) and rig testing in an effort to improve understanding of noise and other performance characteristics of open rotor technology. Both geared and direct drive contra-rotating open rotor engines will be considered in DREAM. It is hoped that engines developed and validated in the project will achieve a 27% reduction in CO_2 emissions and a 3-decibel reduction in noise per operating point relative to year 2000 engines. The project will also assess, test and develop specifications for alternative fuels.

CLEAN SKY Joint Technology Initiative

CLEAN SKY JTI is a large scale, EU-wide research programme that aims to accelerate the delivery of technologies and operating practices that will drastically minimise the environmental impact of air transport.[8] The €1.6 billion, seven-year project was formally launched in Brussels in February 2008. The six Integration Technology Demonstrators that make up the CLEAN SKY JTI are shown below.

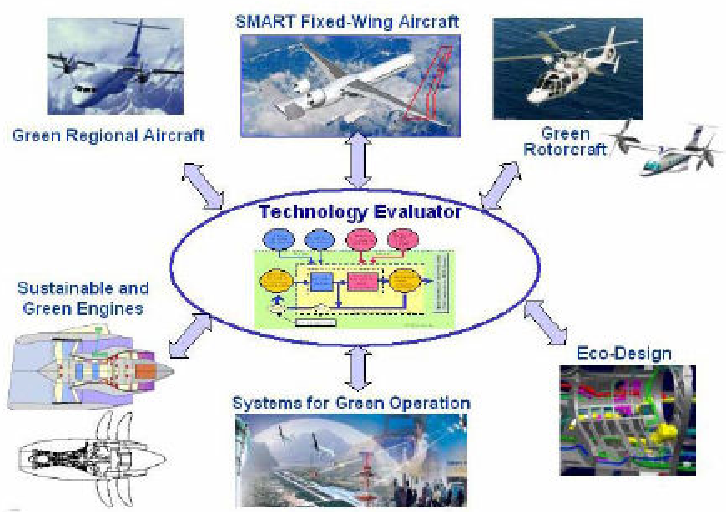

Figure 7: The six Integration Technology Demonstrators of the CLEAN SKY JTI[9]

The results from the DREAM project will feed into the €425 million 'Sustainable and Green Engine' Integration Technology Demonstrator, with the aim of running an open rotor engine ground demonstrator around 2011-12. This engine will be a pusher design.

[6] http://www.easyjet.com/EN/News/easyjet_ecojet.html, sighted 01/11/07.
[7] http://www.ecofriend.org/entry/ecojet-emits-50-less-co2-than-the-existing-aircrafts/, sighted 01/11/07
[8] http://www.cleansky.eu/index.php?arbo_id=35, sighted 18/01/08
[9] http://www.asd-europe.org/Content/Default.asp?PageID=32, sighted 08/10/07

Funded by the Higher Education Funding Council for England (HEFCE), OMEGA is a multidisciplinary partnership of leading academics from nine UK universities established to study the environmental, business and operational impacts of aviation and develop strategies to reduce environmental impacts and business risk.[10] One of the projects being undertaken within OMEGA is the integrated study of advanced open rotor powered aircraft. Led by the University of Southampton, in partnership with the University of Cambridge, this two-year parametric study will compare traditional single aisle airframes and engines with modern open rotor engine designs mounted on advanced airframes (e.g. blended/composite wing). The study will focus on noise in an attempt to understand how design decisions (e.g. engine/airframe configurations, mounting positions, etc) and operational parameters (e.g. manoeuvres such as Continuous Descent Approach and new steeper ascent/descent profiles) influence the noise signature of the aircraft. The study will also consider the effectiveness of noise reduction techniques such as shielding, increasing the frequencies of the noise sources (as the atmosphere absorbs high frequencies better than low frequencies) and active noise control technologies.

This study is well underway, with work currently focused on the implementation of an open rotor noise prediction model.

When can we expect to see open rotors?

Engine manufacturers such as Rolls-Royce have begun work on open rotor engine designs for the next generation single aisle aircraft. It predicts that by 2013 the open-rotor concept will be sufficiently mature for the anticipated performance benefits to be confirmed and that engines will be available between 2015 and 2020.[11]

Are there any alternatives?

Open rotor engines are not the only technology being developed for the next generation of single aisle aircraft. Some engine manufacturers believe that the installation impact and extra weight of open rotor engines will offset their fuel burn benefit[11] and so are taking a different route, developing a new geared turbofan (GTF) engine. A GTF is a very high bypass ratio turbofan engine whose fan is driven through a reduction gearbox rather than being directly connected to the engine. This allows the fan and the compressor-turbine system that drives the fan to both run at their optimal speeds resulting in an engine that is quieter and more fuel efficient than a conventional two-shaft aero-engine.

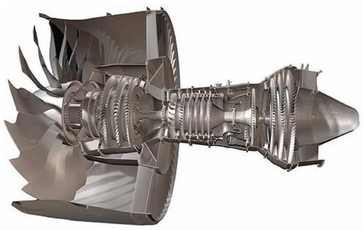

Figure 8: A GTF design[12]

Pratt & Whitney claim their GTF engine offers a 12% reduction in fuel burn over current engines with a further potential improvement of 5-7% available by 2020.[13] Although this fuel burn reduction is less than that predicted for an open rotor engine, GTF technology offers the benefit of enhanced maturity and hence reduced time for entry into service, is likely to be slightly quieter than an open rotor engine and is exempt from some of the challenges associated with open rotor technology (e.g. fan blade off and some integration issues).

A third option for powering the new single aisle aircraft is a turbofan engine with novel three-shaft architecture. The three-shaft architecture has some inherent benefits over the two-shaft architecture of the GTF; it is shorter and lighter and has fewer stages of compression. Furthermore, as there is no compressor (booster) running on the fan shaft, the fan can be allowed to run at its optimum slow speed, producing less noise, without the added complexity of the gearbox. Rolls-Royce predicts that novel three shaft engines will have a specific fuel consumption comparable to the GTF, around 15% less than current two- and three-shaft engines. The three-shaft engines also have enhanced maturity and are exempt from many of the challenges facing open rotors.

[10] http://www.omega.mmu.ac.uk/, sighted 06/11/07
[11] Barrie, D. et al, Open Rotor Poses Maturity Dilemma for Next-gen Narrow Body, Aviation Week, Oct 21 2007.
[12] www.flug-revue.rotor.com/.../FRH0702/FR0702c.htm, sighted 15/01/08
[13] Norris, G. Pratt & Whitney's Geared Turbofan Moves Closer to Launch with Mitsubishi RJ Selection, Aviation Week, Oct 15 2007

UK and European research programmes such as EFE (Environmentally Friendly Engine) and VITAL (enVIronmenTALly friendly aero engine)[14] are working to develop the technology for these significantly more efficient three-shaft engines. Rolls-Royce is leading the EFE programme and will utilise this technology if open rotors are not the chosen architectural style for future single aisle aircraft.

The Future…

Whether open rotor, GTF or novel three-shaft engines are selected for the new single aisle aircraft, it is clear that the opportunity to implement radical environmental improvements on a grand scale must not be missed. The next generation single aisle aircraft market represents a rare and exciting opportunity that the aviation industry is determined to seize to make a significant difference to the future of the environment.

Carrie Lambert
If you have any questions about this paper please email briefingpapers@sbac.co.uk

[14] See SBAC Aviation and Environment Briefing Paper titled 'Engine Technology and Emissions' for more information on these programmes.