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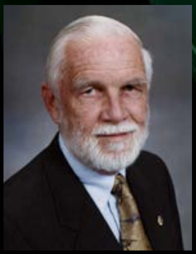
RISE Looks to Advance Open Rotor Engines



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In June of 2021, CFM International, the joint venture of jet engine companies GE Aviation (US) and Safran Aircraft Engines (France) announced their "Revolutionary Innovation for Sustainable Engines (RISE)" program. RISE is an open rotor demonstration program, targeting new generation commercial jet engines for the mid-2030s.

This CFM program is a follow-on to their successful 2008 LEAP program ("Leading Edge Aviation Propulsion" reflecting an apparent CFM passion for acronyms). LEAP currently has resulted in the successful production of 20,000 - 35,000 pound thrust (lbt) commercial turbofan engines for single-aisle airliners. Currently, CFM is the largest aircraft engine OEM, with over 30,000 jet engines delivered and several thousand CFM56 and LEAP engine deliveries per year.

Figure 1. CFM RISE concept open rotor engine.

The RISE Open Rotor Engine

The RISE concept engine is shown in Figure 1. It combines earlier GE open rotor work with Safran's current open rotor design and development efforts, to result in a simpler, single rotor (as opposed to the more complicated mechanics of two rotors, from their previous projects). Also new are variable pitch anti-swirl stators, mounted downstream of the rotor. More importantly, the new concept engine has a smaller diameter open rotor to ease aircraft integration. Figure 2 shows three possible RISE aircraft placement alternatives.

Figure 2. Possible RISE engine mounting positions on single-aisle airframes.

Open rotor engines[1] are essentially a turbojet engine driving an exterior nacelle-mounted fan (or fans), as opposed to turbofan engines where the fan is surrounded by a fan nacelle duct. The open rotor design holds the promise of the high flight speed and performance of a turbofan, while being designed to provide the fuel economy of a slower, propellor-driven turboprop engine.

Since the open rotor conception in the 1970s at United Technologies Hamilton Standard Division (in conjunction with NASA), it has had a miscellany of names: Propfan, unducted fan (UDF), advanced turboprop and more recently, contra-rotating open rotor (CROR), or open rotor for short. Based on the earlier pioneering NASA work that has been reported by Van Zante,[2] I will continue to use the "open rotor" name.

RISE Program Highlights

The RISE program goals include reducing fuel consumption and CO_2 emissions by more than 20 percent, compared to today's most efficient engines. These goals are coupled with ensuring compatibility with alternate energy sources like Sustainable Aviation Fuels (SAF) and hydrogen. (Hydrogen provides the most direct path, since its combustion completely eliminates CO_2 emissions.)

These goals are based on the single open rotor (or fan) architecture shown in Fig. 1, for current turbofan single aisle aircraft flight speeds of up to Mach 0.8.

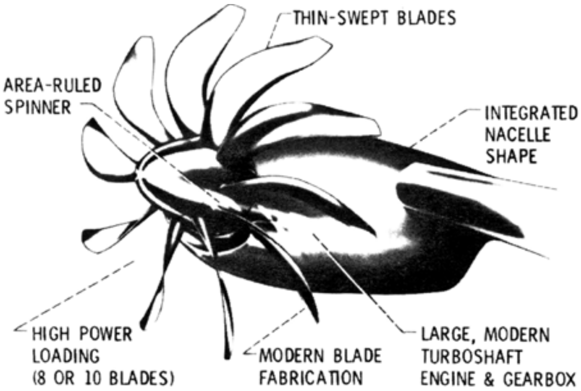

Figure 3. NASA 1980 high speed turboprop propulsion system. [4]

To see how CFM will achieve this 20 percent fuel use improvement, the resulting RISE engine must have a significant improved propulsion system overall efficiency, η_0, over existing engines. Following Mattingly[3],

$$\eta_0 = \eta_T \eta_P \quad (1)$$

where η_0 is the product of η_T, the engine thermodynamic thermal efficiency and η_P, the engine propulsive efficiency.

The standard thermo text definition of η_T in Equ. (1) is the net power developed by the engine, divided by the rate of thermal energy released by the combusted fuel. RISE video presentations indicate that η_T could be increased by achieving higher engine pressure ratios and making use of engine waste heat recovery systems.

The propulsive efficiency η_P in Equ. (1) is the ratio of aircraft power (thrust times flight velocity, V_0) to the net power developed by the engine. The RISE concept engine of Fig. 1 will maximize η_P in Equ. (1) by maximizing rotor diameter (consistent with aircraft integration restraints (see Fig. 2)), by use of anti-swirl stators, and the use of a reduction gearbox to power the open rotor. The reasoning for this η_P maximization is given in the next section.

Propulsive Efficiency Details

Using a control volume around the RISE concept engine of Fig. 1, it can be shown for subsonic flight[3], that η_P is directly dependent on the engine velocity ratio, V_e/V_0. The variable V_e is the mass-averaged flight-direction velocity of the downstream flow exiting the engine which includes that through the open rotor (fan) and the engine exhaust nozzle flow. This results[3] in

$$\eta_P = \frac{2}{V_e/V_0 + 1} \quad (2)$$

Equation (2) elegantly shows that to maximize propulsive efficiency (and increase η_0) an engine in flight must produce thrust by moving flow through it with as little change in average velocity as possible. The limiting case of $\eta_P = 1$ is practically unattainable, since the engine must produce a 2nd law momentum rate increase to produce thrust. Thus in Equ. (2), $V_e/V_0 > 1.0$.

The engine bypass ratio, BPR, which is the mass of rotor or fan air for every unit mass of air through the engine core, determines the value of V_e/V_0. High values of BPR yield values of V_e/V_0, closer to 1.0, to maximize η_P in Equ. 2.

The popular turbofan LEAP engine mentioned earlier has BPR values between 9-11, while Pratt & Whitney's competing geared fan engine BPR values are between 9-12.5. Highest are turboprops with BPR values in the 50-60 range. Open rotor design BPR values fall in between turbofan and turboprops, so the goal for RISE engine designers will be to provide the largest diameter open rotor (highest BPR) that can be accommodated on the aircraft.

Lastly, the contribution to engine performance of the variable pitch anti-swirl stators shown on the Fig. 1 RISE concept engine, can be ascertained from early tests run by NASA. Figure 3 is taken from a 1980 paper by Dugan, et al[4], reporting on a NASA high speed turboprop program. (The reader may note the striking similarity shown in Fig. 3 to the RISE concept engine in Fig. 1).

A subsequent NASA study, reported on in 1992[5], tested the NASA high speed turboprop configuration with fixed downstream swirl recovery vanes, and measured a performance gain. NASA expert Dale Van Zante (see [2]) explained to me that the vanes provided about a 2% gain in additional thrust, produced for the same power input to the propeller. He commented that the NASA test pointed to possible greater benefit for a clean sheet design, like the RISE concept engine, with its variable pitch stator vanes and higher power loadings.

RISE Risks

All new engine programs bring about risks. For open rotor engine programs these risks include protecting passengers in the event of a fan blade failure (e.g. a bird strike) and noise[1,2]. Time will tell if RISE can rise above the risks, while rising to its full potential.

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Development of Hypersonic Pre-Cooled Turbojet Engine

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The Japan Aerospace Exploration Agency (JAXA) has been researching next-generation supersonic and hypersonic aircraft[1]. Hypersonic aircraft (Figure 1) with Mach 5 capability is suitable for carrying passengers and for use as a first stage in reusable space transportation. This paper reports on JAXA's research into a hypersonic pre-cooled turbojet engine (PCTJ) that can be operated continuously from takeoff to Mach 5 for application to hypersonic flight. The engine uses cryogenic liquid hydrogen fuel as a coolant to reduce the air temperature at hypersonic flight. A small demonstration engine has been fabricated to prove its feasibility in an actual flight environment. Demonstration experiments for sea level static, Mach 2, and Mach 4 conditions have already been carried out.

When flying at Mach 5, temperatures at the intake outlet reach as high as 1000°C. Precooler was applied to the hypersonic turbojet engine making use of cryogenic liquid hydrogen. The high-temperature air is chilled down to 300°C, which is an acceptable temperature for the core engine, by the precooler. The air density is increased by precooling and this feature contributes to increase the thrust. The hypersonic pre-cooled turbojet comprises a variable-geometry air intake, precooler, core engine, afterburner, and variable-geometry nozzle. The variable-geometry air intake is a mixed compressive intake with an external compression part and internal compression part. Supersonic and hypersonic wind tunnel tests validated the air intake performance from Mach 1.5 to Mach 5.0. The precooler is a shell-and-tube heat exchanger. Supercritical hydrogen is supplied to the heat exchange tube to cool the hot air during hypersonic flight. The core engine is a single-spool turbojet with a mixed-flow compressor, hydrogen fuel combustor, and axial-flow turbine. The performance of the hydrogen fuel combustor was determined by a combustion test rig simulating flight conditions from takeoff to Mach 5. The afterburner was designed to attain a combustion temperature of 2000 K with fuel-rich combustion. Fuel-rich combustion with the equivalence ratio of 2 was selected to enhance the precooling effect. The exhaust speed is increased by selecting the fuel rich combustion because the sound velocity of hydrogen fuel is very high and the hydrogen fuel acts as propellant. This feature contributes to enhance the thrust to weight ratio of high speed propulsion system. The fuel consumption of fuel rich combustion with hydrogen fuel is not greatly increased comparing to that with fuel lean combustion. The fuel rich combustion is normally selected for rocket engines using hydrogen fuel with the same reason. The afterburner injector was designed based on experiments with model injectors, and the formation of NOx with the afterburner was evaluated by experiment. The variable-geometry exhaust nozzle was designed with internal expansion part and external expansion part. The excess fuel reacts with the ambient air and the reaction raises the surface pressure of the external expansion part. The airflow rate can be adjusted according to flight conditions from takeoff to Mach 5.

Figure 1. Hypersonic aircraft.

Figure 2. Sea Level Static Experiment of PCTJ.

A sea-level static experiment was conducted on the PCTJ (Figure 2) in 2008 to establish a starting sequence for the engine. Liquid hydrogen was used for cooling in the precooler and for combustion in the afterburner. It was supplied under supercritical pressure to prevent flow vibration caused by vaporization. The precooler was designed with a gap between the tubes to avoid blockades caused by frost, which forms as a powder on the tubes due to the liquid-hydrogen cooling and can be blown about by the airspeed during engine operation. The experiment attained stable combustion in the afterburner with a fuel-rich mixture. The structure of the afterburner and the exhaust nozzle was cooled with regenerative cooling channels using liquid hydrogen supplied from the precooler. The noise pattern around the exhaust nozzle was measured to evaluate its effect on the areas surrounding the airport[2]. The precooling effect increases the airflow rate of the engine because the air density is increased by cooling.

The Mach 2 flight experiment of the PCTJ was conducted in 2010. A flight model with a hypersonic pre-cooled turbojet was dropped from a stratospheric balloon and reached Mach 2. The ignition capability under high altitude conditions was obtained at the low pressure of the hydrogen combustor and the core engine before the flight experiment.

The Mach 4 direct connect experiment[3] of the PCTJ was conducted in 2013 at a high-temperature air supply facility. The performance of the precooler, core engine, and afterburner was verified in the experiment. The cooling performance and pressure drop at the precooler was obtained. The thermal stress in the precooler casing structure between hot air and cryogenic hydrogen was evaluated by FEM analysis, and the temperature distribution was measured using an infrared camera. The acceleration of the core engine from engine start to the design speed was improved with the experimental results. The speed had to be reached within one minute to conduct the propulsion wind tunnel test.

The Mach 4 environmental experiment of the PCTJ (Figure 3) was initiated in 2014 at the ramjet engine test facility at JAXA's Kakuda Space Center. The initial experiments used liquid nitrogen as a coolant instead of liquid hydrogen to ensure safety. The initial experiment determined the starting capability of the mixed-flow air intake. A Mach 4 propulsion wind tunnel experiment using liquid hydrogen was conducted in 2017 and provided the cooling characteristics of the precooler with liquid hydrogen and the combustion characteristics of the afterburner. Subsequently, the liquid hydrogen fuel supply system was improved for more precise fuel flow control. A bypass door was installed on the engine to increase the airflow and initiate air intake during the core engine starting sequence. The temperature field around the exhaust nozzle was measured using the two-color method with near-infrared luminescence. The combustion instability at the fuel-rich combustion was investigated using an afterburner model.[4]

Figure 3. Mach 4 Flight Environmental Experiment of PCTJ

The measurement system for the engine is now improved to analyze the engine performance in greater detail. A Mach 5 propulsion wind tunnel test and Mach 5 flight experiment using a sounding rocket is planned, and it is hoped that PCTJ technologies will find application to subsonic turbo-fan engines for hydrogen-fueled aircraft. Japan also plans to develop the hydrogen fuel supply system and the hydrogen combustor for subsonic hydrogen-fueled aircraft.

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Micro Gas Turbines — Trends and Opportunities

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Trying to find the best possible answer to the energy problem for a sustainable future is not an easy task. It gets even harder with the changes in the energy landscape, the planet's climate, dispatchability issues of existing solutions, the emission requirements and the public's demand for comfort at home and work. Within this complex puzzle, gas turbines, which have long been hailed for their efficiency and performance, have become a devil due to the increased emissions associated with the use of fossil fuels, particularly in air transport. As a result, research into alternative fuels is increasing, for all engine sizes, with power generation applications being particularly promising as they are not limited by power-to-weight performance. With a power output from a few kW to a few hundred kW, micro gas turbines (microGTs) are used for a wide range of applications, including unmanned aerial vehicles (UAVs) and for water desalination in remote locations. This is reflected in the market, which has risen steadily over the past years to nearly $180 Mn in 2018 and is projected to exceed $360 Mn by 2026[1].

Micro Gas Turbines to Close the Energy Gap

The energy puzzle, with the unpredictability of wind and solar energy and the time lag between supply and demand requires both energy storage and new approaches to power generation. Pumped hydro storage represents the majority of energy stored around the world[2] but is limited to mountainous regions. Battery energy storage is still limited by the cost of large-scale production and can provide a solution in the longer term. In the meanwhile, the energy production can be supported by combined heat and power (CHP) units based on microGTs. Compact and lightweight, and with few moving parts compared to the alternatives, microGTs are increasingly used for small scale power generation as they can offer stable and reliable power, fast startup times and good efficiency for CHP. They can complement large scale heat and power plants in urban areas without district heating networks, and sub-urban areas where district heating networks investments are not a realistic option, but a natural gas and electricity grid is well developed, such as in Germany, the Netherlands and the UK. MicroGTs can fill the gap in energy production, offering dispatchable electricity with reduced carbon emissions, that can support the increasing integration of intermittent renewable energy sources.

Operation with Alternative Fuels

A key element for the widespread use of microGTs is fuel flexibility. This often requires the redesign of the combustor for the use of lower grade fuels, with some manufacturers choosing an externally fired configuration. Commercially available gas turbines already operate with alternative fuels: some examples are Ansaldo Energia and Capstone engines which operate with biogas and other fuels, the Aurelia Turbines A400 engine which can operate with hydrogen and other fuels, and the MTT 3kW engine which has been tested with fuel blends including hydrogen and methane, shown in Figure 1. As hydrogen can already be used in existing pipelines mixed with natural gas[3], fuel blends can be a quick way to reduce emissions, until there are solutions for transport and storage.

The use of renewable synthetic fuels (e-fuels), generated with renewable sources, can overcome some of the limitations, as they have higher energy density and are easier to store. These are typically produced by combining hydrogen generated by electrolysis and carbon captured from different sources to form a hydrocarbon with zero net greenhouse emissions. Ammonia is another fuel option, which can be produced through the same pathways but

Figure 1. The 400kW Aurelia Turbines A400 (left) and the 3kW MTT EnerTwin which uses automotive turbocharger components (right).

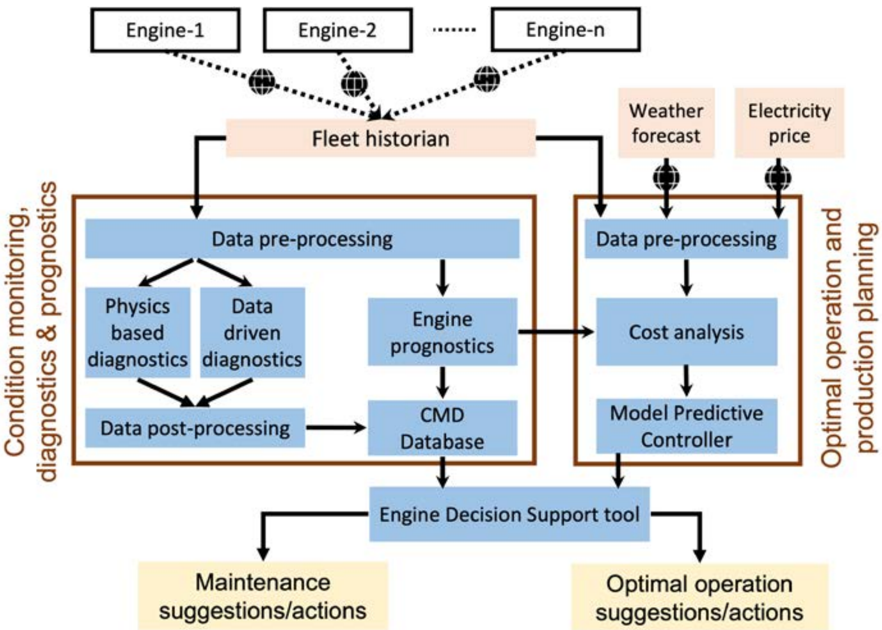

Figure 2. Framework for micro gas turbine fleet monitoring, diagnostics, and production planning.[4]

offers more challenges in its use. However, research in that direction is also increasing, and Mitsubishi Power is targeting to commercialize an ammonia-fuelled 40MW engine by 2025. Since the generation of such fuels is still a relatively inefficient and expensive process, a near-term solution is the production of alternative fuels from non-renewable sources. In order to achieve net zero emissions, all different alternatives that offer cleaner energy generation need to be researched and employed.

Reliability, Monitoring and Diagnostics

The development of microGT technology leading to engines that are more energy efficient and can be operated with renewable fuels paves the way for the use of smaller and smaller engines for distributed generation of heat and power with cleaner fuels, something which is not too far into the future. The key element will then become the reliability of the engine in order to be able to compete with conventional systems. This, in addition to a fleet monitoring system, made possible by the advances in monitoring for maintenance and diagnostics, can support their widespread use and allow optimal operation and production planning, as outlined in Figure 2[4]. Micro gas turbines can be as high tech as other appliances and as robust and reliable as large gas turbines. The possibility to monitor them in the same way as other smart devices that are used every day can allow the user to optimize their operation and provide more advanced functionality, such as trading in the energy market.

With electricity demand growing faster than renewables, leading to an increase in the share of fossil fuels and corresponding CO_2 emissions from the power sector[5], there is a need for more and cleaner energy. In order to secure electricity supply and deal with spikes in demands and electricity prices, the use of dispatchable units can offer multiple opportunities for micro gas turbines. Monitoring and diagnostics are key for distributed generation. The same holds true for aircraft applications, but it is the day-to-day customer that needs to be persuaded, and a key requirement is low unit cost. Competitive technologies in the energy market include diesel generators, which however do not typically offer heat recovery for domestic heating, and traditional natural gas boilers. For a commercial consumer to invest in a microGT unit, the cost also needs to be competitive. This requires that the development costs for advanced combustors, materials and sensors are recuperated through increased sales and mass manufacturing.

Another important parameter is the electrical efficiency of such engines. Some of the smallest engines today are based on automotive turbocharger components rather than purpose-designed turbomachinery. The smaller the engine the greater the small-scale effects that limit its efficiency (eg. low Reynolds numbers, low temperature and pressure ratio, and high tip clearances due to manufacturing tolerances). Design optimization and especially technology developments such as 3D printing are expected to further increase the efficiency of microGTs and revolutionize their applications.

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ASME Turbo Expo 2022 Conference Theme

June 13 – 17, 2022 · Rotterdam Ahoy, Rotterdam, The Netherlands

The need for zero-emissions is molding the future energy panorama. This year's ASME Turbo Expo Conference in Rotterdam, The Netherlands June 13-17, 2022 aims to accelerate the transition of the energy and propulsion sector to meet a carbon-neutral future by 2050.

Top experts and decision-makers will gather in-person to exchange ideas and experiences to develop and discuss the implementation of safe, reliable carbon neutral solutions while shaping the future of the turbomachinery industry. Turbo Expo will serve as a synergetic platform for government, academic, research, and industry professionals to discuss multidisciplinary approaches for decarbonization.

The 5-day conference will include hundreds of live presenting authors as well as recorded video presentations on-demand. The conference will feature a spotlighted Hydrogen and Energy Storage Day, a 3-day engaging exhibition, various networking opportunities and dedicated student events.

Plenary Sessions

KEYNOTE

Road-Mapping the Future of Propulsion and Power

Industrializing Terabytes for Propulsion and Power

Hydrogen & Energy Storage for Propulsion & Power

Conference Events

Hydrogen and Energy Storage Day

WEDNESDAY, JUNE 15

All tutorials, technical papers and plenary speakers will focus on the future of turbomachinery and its role in decarbonization.

Celebrating Women in Turbomachinery

TUESDAY EVENING, JUNE 14

Attendees will have the opportunity to network and learn about the career paths of successful women in the industry.

Student Poster Competition

EXHIBIT HALL

The competition is organized by students for students contributing to the advancements in turbomachinery.

Welcome Reception

MONDAY EVENING, JUNE 13

Network in a casual atmosphere and meet thinkers from around the world who are shaping the future of turbomachinery. All Conference registrants are invited to complimentary drink reception.

Student/Early Career Engineer Mixer

WEDNESDAY EVENING, JUNE 15

Meet with students and early career engineers. If you are a student or early-career engineer, be sure to plan to attend.

3-Day Exhibition

TUESDAY - THURSDAY

Featuring professionals ready to share their products and services with the turbomachinery industry.

Visit the Turbo Expo 2022 Website at www.turboexpo.org and register today!