ISABE-2011-1401

COUNTERING THE ENVIRONMENTAL PENALTIES OF INCREASING AIR TRAFFIC BY MEANS OF ACTIVE CORE TECHNOLOGIES

Wolfgang Sturm
MTU Aero Engines GmbH
Dachauer Str. 665, 80995 München
Germany

Abstract

The main purpose of this paper is to give an overview of the work that was done within NEWAC subproject 4 ‘Active Core’. Based on the active core concept and its two most promising areas of application, the related activities are described with special emphasis on the findings of the conducted rig tests. Finally, the contribution to the NEWAC objectives is discussed.

Nomenclature

ACC	Active Clearance Control
ACAC	Active Cooling Air Cooling
ACARE	Advisory Council for Aeronautics Research in Europe
ASC	Active Surge Control
CO_2	Carbon Dioxide
CT	Casing Treatment
ECM	Electro Chemical Machining
EEFAE	Efficient Environmentally Friendly Aero-Engine (FP5 EU Project)
FMECA	Failure Mode Effects and Criticality Analysis
HEX	Heat Exchanger
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
LMD	Laser Metal Deposition
LTO	Landing and Take-off
NEWAC	New Aero Engine Core Concepts
NO_X	Nitrogen Oxides
OPR	Overall Pressure Ratio
SAS	Secondary Air System
SFC	Specific Fuel Consumption
SM	Surge Margin
TMF	Thermo Mechanical Fatigue

Introduction

Global air traffic is forecast to increase at an average annual rate of around 5% in the next 20 years generating the need to counter the related environmental penalties in terms of CO_2 and NO_X emissions. In order to achieve the ACARE 2020 objectives (minus 20% in CO_2 emissions and minus 80% in NO_X emissions), it is indispensable to develop new aero engine configurations and to perform complementary research in core engine technologies.

This was done within the European project NEWAC [1] whose aim was to integrate the activities of 40 European partners comprising leading engine manufacturers, the engine-industry supply chain, key research institutes as well as small and medium enterprises with specific expertise. Based on the results of the preceding European project EEFAE, their co-operation focussed on fully validated novel technologies enabling a further 6% reduction in CO_2 emissions and a further 16% reduction in NO_X emissions according to ICAO-LTO cycle by combining combustor improvements and cycle effects.

Active Core Concept

One of the new engine configurations investigated within NEWAC is based on a Geared Turbofan engine incorporating an active core and a lean burn low emission combustor as depicted in fig. 1.

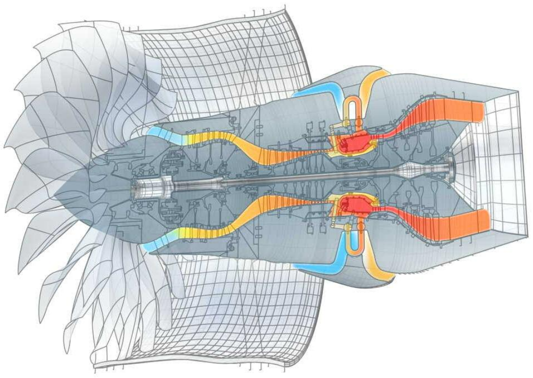

Fig. 1 Schematic of Geared Turbofan engine with active core and lean burn low emission combustor

Since an active core can be adapted to the very different operating conditions of a flight mission (e.g. climb, cruise, idle), a breakthrough is expected regarding fuel burn and operability. Furthermore, active systems open up additional degrees of freedom in the design. Finally, efficiency penalties due to deterioration can be compensated to a certain degree by adjusting the core to the actual conditions.

The high-level objective of NEWAC subproject 4 'Active Core' [2] relative to EEFAE was to develop and validate a system of interrelated core engine technologies which reduce the SFC of an aero engine by 4% due to increased core component efficiencies, core cycle improvements and related overall engine effects. Together with a lean burn low emission combustor developed by NEWAC subproject 6 'Innovative Combustor' [3], the engine configuration of fig. 1 aimed at reducing the NO_x emissions by 16%.

During the work within NEWAC two most promising areas of application for active systems were identified and investigated. The first one was an active cooling air cooling (ACAC) system, which lowers the temperature of the cooling air for the high pressure turbine and for other cooled parts. The second one was the so-called smart HPC that exhibits a big improvement potential by the adoption of both an active clearance control (ACC) and an active surge control (ASC) system.

Active Cooling Air Cooling

For state-of-the-art core engines about 20 to 30% of the air delivered by the HPC is used for cooling the HPT. The current trend to increasing OPRs leads to higher HPC exit temperatures resulting in a further demand for cooling air and expensive rear cone materials (e.g. powder metal).

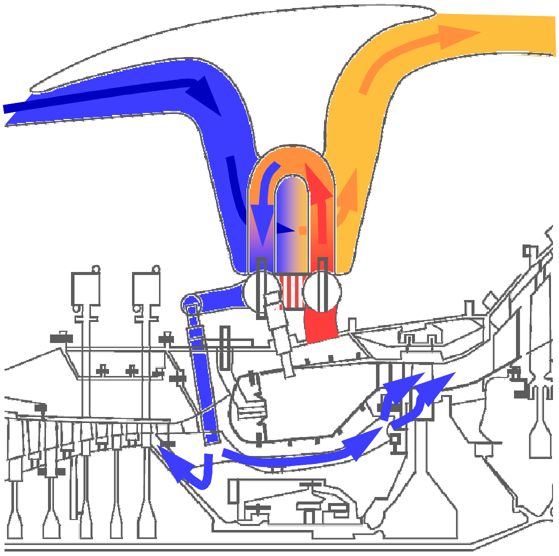

Fig. 2 Operating principle of an ACAC system

An ACAC system as depicted in fig. 2 lowers the temperature of the cooling air, modulates cooling air temperature and allows for new design approaches (thickness, material and manufacturing). Furthermore, the use of cooled air for cooling the HPC rear cone, which is a critical part concerning temperature level and related temperature stresses, opens up new manufacturing options for this component.

General ACAC Concept Study

A general concept study was done by an engine system evaluation of the benefits of an engine with ACAC in comparison to a conventional engine design. It comprised a design study as well as a weight, reliability and performance analysis using a modern civil jet engine dataset. Main objectives were the identification and evaluation of potential showstoppers and the assessment of system benefits in terms of SFC.

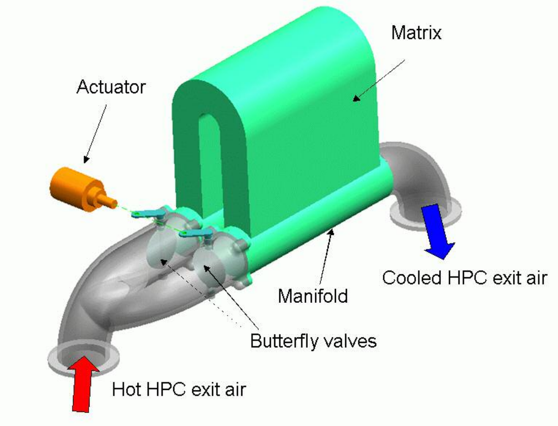

Fig. 3 Set-up of MTU heat exchanger and related valve system

In a first step, a general arrangement configuration was worked out as a starting point for all further investigations. Based on this, a secondary air system (SAS) was developed, which was used as input for investigations concerning heat pick-up and combustor case and diffuser concepts. Furthermore, the MTU heat exchanger technology developed in earlier programs (e.g. EEFAE CLEAN [4]) was investigated with respect to the feasibility of the design for this application (see fig. 3).

The results of this study demonstrate that the basic concept is able to meet the requirements in terms of design space, weight, shock resistance and life aspects. Since the increased complexity is critical, the ACAC system was assessed by a FMECA and no general showstopper was identified. But the study revealed the need for special attention on reliability aspects during the design phase. In order to reduce the risk, HEX arrangement, actuator system and sensors should be designed with some redundancies.

In addition to that, the potential of HPC rear cone cooling was investigated in terms of weight and cost reduction. Although it proved that the rear cone weight could not be reduced significantly, the lower temperatures will allow the use of materials less expensive than powder metal and, thus, help to reduce the material costs. In this context, also the application of sophisticated production technologies like ultrasonic shot peening and advanced electron beam welding was investigated.

Finally, an exemplary HPT vane was investigated with reduced cooling air temperature. The cooling system was modified in a way, that a significant reduction of the cooling air mass flow could be realized without compromising backflow margin and TMF life aspects.

ACAC Combustor Case Design

Apart from the heat exchanger, the combustor case is another key element within an ACAC system because it has to ensure that the cooled cooling air is routed properly from the HEX exit to the HPC rear cone and the HPT. In order to do this without an additional air pump, the pressure losses should not exceed a value of 6%. Another requirement was that the heat pick-up should not be more than 30K.

Concerning the pressure losses, a study was performed on different ways of routing the cooled cooling air from the HEX exit. Due to the restriction of not affecting the axial balance of the rotor shaft, a tube solution was selected (see fig. 4). As a consequence, the combustor case had to accommodate the tubing via an increased number of holes and bosses. Although stress analyses showed a significant increase in local stresses, no general showstoppers were identified.

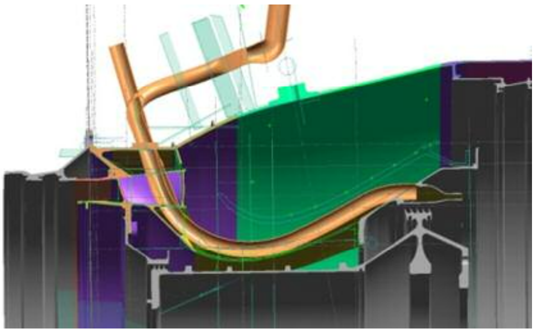

Fig. 4 Combustor case with cooled cooling air tubes

In order to assess the related heat pick-up correctly, heat transfer tests were performed at Lund University to verify the analytical heat transfer results. As a consequence, a heat shield or thermal barrier coating had to be added to stay below 30K of heat pick-up.

Manufacturing Methods

Fig. 5 Boss added by LMD to a used combustor case

As mentioned above, an ACAC combustor case will incorporate a large number of bosses to accommodate the required tubing, not to mention fuel nozzles, igniters, boroscope ports, etc. Since large complicated castings would result in low flexibility during the design phase and a monopoly situation for very few possible casters, Volvo Aero developed a technique to add bosses by laser metal deposition (LMD) as shown in fig. 5.

SONATS developed an ultrasonic (US) shot peening apparatus for outside and inside peening of an HPC rear cone that was demonstrated with a realistic rear cone geometry. Steigerwald Strahltechnik developed a high-speed beam deflection system with online joint tracking for a quality improvement of electron beam welds. A key element of this system is the analysis of backscattered electrons as a means for identifying sink holes, pores and material inclusions close to the surface as well as not properly prepared joint areas.

As mentioned above, HEX arrangement, actuator system and sensors of an ACAC system should be designed with some redundancies. Since this can result in a weight penalty, it was investigated whether some of that weight could be compensated by the use of advanced light weight alloys.

1) ECM of airfoil **2) Root grinding**

3) Side frame cut-off **4) Final shaping**

Fig. 6 Manufacturing trials for TiAl demo blade

This was done by WSK with special focus on material and manufacturing issues of TiAl bladings. The producibility via different manufacturing techniques (see fig. 6) and the strength characteristics were demonstrated. In addition to that, the applicability of protective coatings and laser machining methods was investigated.

In order to develop a cost effective process, the semi-products have to be optimized near net shape and the machining parameters have to be further optimized. In the context of a future high volume production, ECM proved to be a promising alternative to rough milling.

Smart High Pressure Compressor

As far as the smart HPC is concerned, the persistent goal of a higher pressure ratio at unchanged stage count and higher efficiency was directly leading to two key elements (see fig. 7): Active surge control for the compressor front stages, resulting in higher part speed surge margin, and active clearance control for the compressor rear stages, resulting in higher efficiency and higher full speed surge margin.

An increased stability margin offers the potential for

- a higher operating line translating into an efficiency benefit,
- a reduced number of stages translating into a length and weight benefit and
- a reduced blade count translating into an efficiency and weight benefit.

In addition to that, an ACC system allows for

- small tip clearances over the whole mission even during transients as depicted in fig. 8 and
- compensation of casing deflections due to manoeuvre loads.

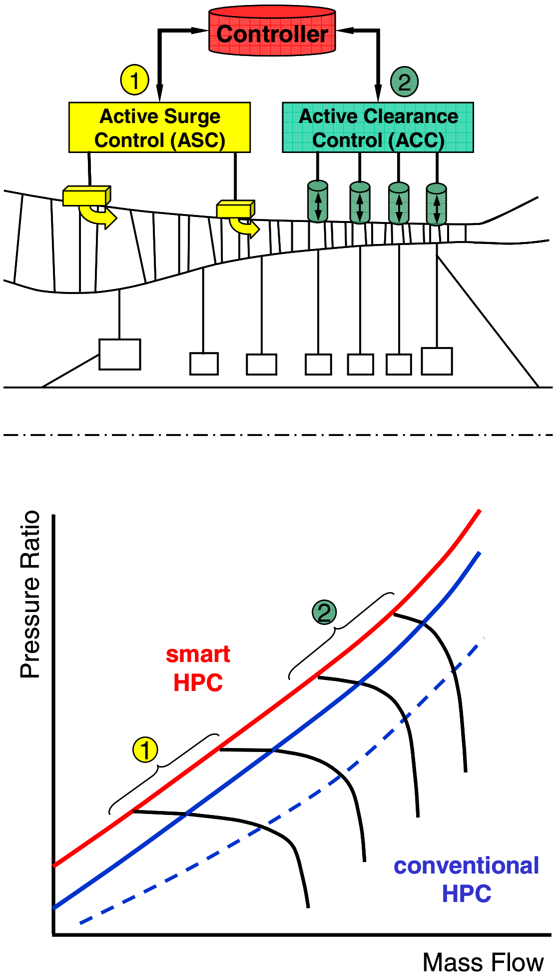

Fig. 7 Effect of smart HPC technologies on HPC performance

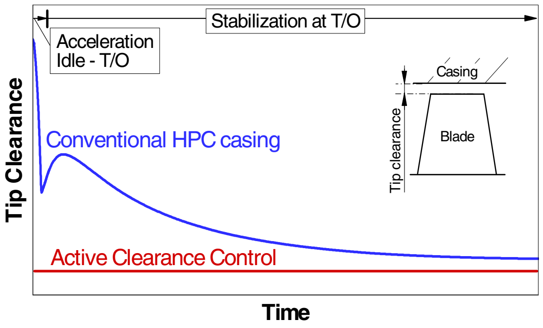

Fig. 8 Small tip clearances even during transients

Active Surge Control

Usually, a highly-loaded HPC that is optimized for high efficiency at cruise condition would suffer from a relatively low surge line at part load caused by the tip critical front stage rotor. In order to avoid increasing the part load stability by trading it against full speed efficiency in a modified design, the tip leakage flow in the front stage can be influenced either by casing treatment (CT) or tip injection. The latter consists of a few small nozzles around the circumference generating jets in the tip region ahead of the leading edge of the rotor using air taken from inter-stage bleed or compressor exit. A proper control system allows to activate the tip injection only temporarily.

Fig. 9 Project team and compressor rig of ASC test campaign

Within the scope of NEWAC MTU developed a tip injection system for an existing state-of-the-art 8-stage high-speed HPC rig (see fig. 9). During a previous test campaign, the part speed stability of this compressor had proven to be limited by the front stage because the rotor of that stage is tip critical, i.e. the compressor surge is initiated by the rotor tip flow there.

Various injection liners as shown in fig. 10 were designed and manufactured as a drop-in replacement for the existing smooth wall liners above the front stage rotor. The compressor casing above the front stage was modified to allow for the injection air to be routed to the injection liners and to create an optical access for PIV measurements.

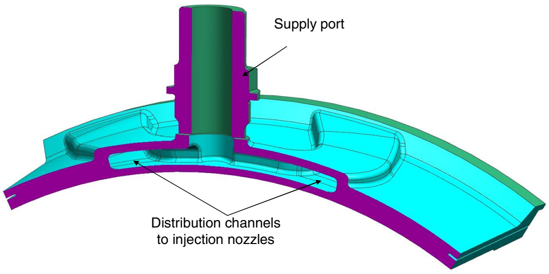

Fig. 10 Cut-open view of an injection liner segment

Testing of ASC by tip injection was done in two separate test campaigns. The first one was performed in September 2008 accumulating 13 test days and 75 test hours. It comprised the variation of mass flow and temperature of the injected air and was focussed on overall and stage characteristics. The second one was performed between December 2009 and June 2010 accumulating 44 test days and 215 test hours. In addition to the variation of mass flow and temperature of the injected air it also included the variation of injection liners and the number of active injection nozzles. In addition to the measurement of overall and stage characteristics, the interaction between injection jet and main flow was investigated by means of probe traverses (5-hole pneumatic, FRAP and temperature probes) and PIV measurements. Finally, in addition to steady state injection also tests with a controller modulated injection were performed.

As shown in fig. 11, the part load operating range of the overall compressor could be significantly extended by means of tip injection [5]. However, it has to be noted that this extension is specific for the compressor used in the ASC test campaign because the radial distribution of loading without injection and unsteady effects due to injection are closely related to the design of the compressor under investigation.

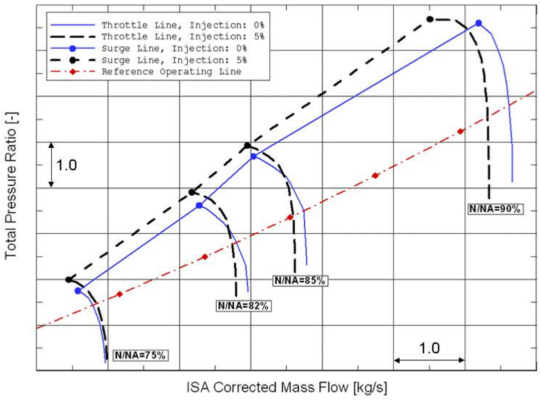

Fig. 11 Influence of tip injection on part load operating range of overall compressor

In order to achieve a more general assessment, effects found within the NEWAC test campaign were modelled by means of a streamline curvature tool. This tool was enhanced to account for unsteady effects that are crucial for the total temperature rise in blade sections inside the injection jets which in turn influence the radial distribution of the streamlines. Using this method it will be possible to transfer the governing effects of tip injection to other compressors and create a proper design which incorporates tip injection.

As a conclusion, tip injection in the front stage proved to be a proper means to extend the operating range. This offers new opportunities for the future design of compressors incorporating tip injection, e.g. lower axial velocity at compressor entry, reduced blade count, more aggressive profiles and altered VGV schedules. By all these means, design point or part speed efficiency can be improved while their negative influence on part speed stability can be compensated by tip injection.

Active Clearance Control

During a typical flight mission the mean equivalent tip clearance of a conventional HPC varies significantly as a result of transient effects. In addition to that, manoeuver loads or deterioration lead to further tip clearance changes. Due to the small blade heights especially in the rear part of the HPC, these tip clearance changes have a significant negative influence on compressor efficiency and stability.

Therefore, the integration of ACC in the rear part of the HPC promises substantial performance improvements in modern aircraft engines resulting in a reduction of mission fuel consumption and combustor exit temperature. In this context, an improved compressor aerodynamic design is achieved by taking into account the benefits of the ACC system with respect to compressor efficiency and stability.

Fig. 12 ACC proof-of-concept rig

Within the scope of NEWAC MTU developed a mechanical ACC system that was integrated in a proof-of-concept rig (see fig. 12) and tested extensively. The main purpose of that rig was to validate the basic working principle demonstrating its overall kinematics, speed, accuracy and failure tolerance. In addition to that, it allowed to develop the necessary control system including tip measurement sensors and software. In order to reduce the complexity of the system and to minimize the risk in case of any soft- and/or hardware failure, the rig was laid out without any rotating parts. It was a full scale set-up representing a rear stage of a mid-sized civil turbofan engine.

The test campaign with the ACC proof-of-concept rig was performed between February and May 2010 accumulating 31 test days, 134 test hours and 24.000 load cycles. It comprised the adjustment of various centric, eccentric and oval tip clearance distributions under steady state conditions. In addition to that, the compensation of transient tip clearance changes during a typical square cycle and the compensation of external loads as well as of rotating clearances was tested.

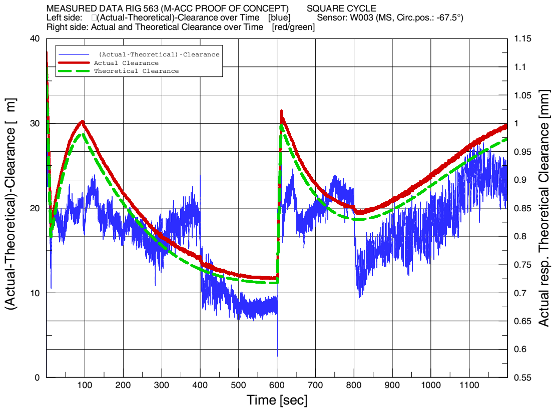

Fig. 13 Simulation of tip clearance changes during a typical square cycle

During this test campaign the developed mechanical ACC system proved to be able to adjust steady state centric tip clearance distributions, steady state eccentric tip clearance distributions and transient centric tip clearance distributions according to a typical square cycle (see fig. 13) within the required accuracy. However, it was found to be necessary to modify the system in order to improve its ability to compensate casing ovalizations, the effects of external loads and rotating tip clearance distributions.

Sensor Development

The application of smart HPC technologies in future production engines will require reliable controller input signals on surge detection/precursor for ASC and tip clearance distributions for ACC. The systems currently in use for development testing have significant constraints in terms of robustness against temperature and vibrations, size (sensor and signal conditioning unit) and lifetime.

Therefore, MEGGITT developed and delivered a fast pressure sensor for the front stage and two different types of tip clearance sensors based on eddy current and microwave (see fig. 14) for the rear part of an HPC. These sensors were installed in the HPC rig also used for the ASC tests mentioned above and showed promising results for a future engine application.

Fig. 14 Microwave tip clearance sensor and rig adapter

Overall Achievements

The assessment of the overall achievements of NEWAC subproject 4 ‘Active Core’ was done considering the impact on whole aircraft system and mission level. This particular work was performed within the NEWAC subproject 1 ‘Whole Engine Integration’ [7] selecting a typical S/R application that features a 30klb thrust class engine.

The general concept study for active cooling air cooling indicated a significant reduction of the cooling air mass flow, a remarkable increase of HPT efficiency (due to the significant reduction of coolant mixing losses) and a slight weight reduction.

The ACC test campaign showed the potential to remarkably increase the HPC efficiency. As a result of the ASC test campaign, the part speed surge margin could be significantly increased which offers the potential of a reduced blade count translating into a further efficiency benefit. Therefore, the best benefit in terms of HPC efficiency can be achieved in combination of ACC and ASC. However, both technologies proved to require some additional weight vs. the reference design.

For the engine configuration depicted in fig. 1, these results translated into a significant reduction of CO_2 emissions close to the 4% objective. In terms of reduction of NO_X emissions, the Active Core engine was capable to fully meet the objectives by using the lean burn combustor developments from NEWAC subproject 6 ‘Innovative Combustor’.

Conclusion

The work that was done within subproject 4 ‘Active Core’ of the European research project NEWAC provided a multitude of concepts, studies, designs and tests to verify predicted improvements towards overall goals. The rig tests on Smart HPC Technologies showed encouraging results. The manufacturing and sensor technology development contributed vital input for the use of active elements in future engine programs. Finally, the cooperation of partners from engine industry, suppliers and university has proven to be an effective way forward.

Acknowledgement

The author would like to thank MTU Aero Engines GmbH and the other NEWAC partners for permission to publish this paper. The author also wishes to thank the E.U. for supporting this project - the work was part funded under E.U. contract number FP6-030876.

Fig. 4 and 5 are reproduced courtesy of Volvo Aero Corporation, fig. 6 is reproduced courtesy of WSK "PZL-Rzeszow" SA, fig. 14 is reproduced courtesy of MEGGITT.

Last but not least, the author appreciates the support of the colleagues of NEWAC subproject 1 for the assessment of the overall achievements and the contribution of NEWAC subproject 6 in terms of lean burn combustor development.

References

[1] Wilfert, G. et al., New Environmental Friendly Aero Engine Core Concepts, ISABE 2007, Beijing, China, Paper No ISABE-2007-1120.

[2] Bock, S. et al., Active core – a key technology for more environmentally friendly aero engines being investigated under the NEWAC Programme, ICAS 2008, Anchorage, Alaska, USA, Paper No ICAS-2008-686.

[3] Colantuoni, S et al., Low emissions combustors development for new aero-engines core applications,

5th European Congress on Computational Methods in Applied Sciences and Engineering, ECCOMAS 2008, Venice, Italy.

[4] Wilfert, G. et al., CLEAN - Validation of a GTF High Speed Turbine and Integration of Heat Exchanger Technology in an Environmental Friendly Engine Concept, ISABE 2005, Munich, Germany, Paper No ISABE-2005-1156.

[5] Kern, M. et al., Effects of Tip Injection on the Performance of a Multi-Stage High-Pressure Compressor, Paper to be presented at the German Aerospace Congress, 27 - 29 September 2011, Bremen, Germany, Paper No DLRK2011-241213

[6] Kern, M. et al., Proof of Concept of a Mechanical Active Clearance Control System, ISABE 2011, Gothenburg, Sweden, Paper No ISABE-2011-1221

[7] Rolt, A.M. and Kyprianidis, K.G., Assessment of New Aeroengine Core Concepts and Technologies in the EU Framework 6 NEWAC Programme, ICAS 2010, Nice, France, Paper No ICAS-2010-408