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The ACONIT project: an innovative design approach of active flow control for surge prevention in gas turbines

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Abstract. The objective of the ACONIT project is to design, manufacture and test actuators for flow control for an implantation in an aircraft engine. The actuators will fulfil aeronautics requirement in order to increase the Technology Readiness Level (TRL) in this domain. In particular, for the present proposal, one plans to focus on the extension of the stable operating range of axial compressor, allowing thus a reduction of the surge margin through postponing the stall onset. To do so, the first objective of the work is to improve the knowledge of the flow physics of an efficient flow control system by joint numerical and experimental analyses performed in a low speed, single stage axial compressor. The results of this analysis will be used to derive the fluidic specifications for high-TRL actuators and control systems. These specifications will be the base for the design and manufacturing of amplified piezo-electric actuator prototypes whose fluidic performance and operational performance in an environment with vibration and controlled level of temperature will be precisely evaluated before manufacturing final actuators that will be integrated in a full-scale engine test facility. Their performance will be evaluated in terms of Surge Margin Improvement (SMI) as well as in terms of energy balance between the induced consumption and the machine performance improvements. The consortium grouped for carrying out this project is composed of a SME (CTEC), two academic institutions (Bundeswehr University Munich and ENSAM) and a Research Centre (ONERA). It groups skills ranging from internal flow analysis in turbomachinery, to flow control or actuators design, manufacturing and characterisations.

1. Introduction

Surge and rotating stall are unstable flow phenomena which can occur in aeronautical compressors operating at low flow rate [1]. They represent serious concerns for flight safety as their arising can lead to some dramatic accidents. Consequently, the engine manufacturers and users introduce safety margin to avoid that surge and rotating stall set in the compression stages of the engines. They consequently deprive the machine of its higher pressure ratios and higher efficiencies. An improvement of the so-called 'surge margin' can directly allow to have a beneficial impact on the engine weight by reducing the number of the compressor stages and thus on its Specific Fuel Consumption [2].

The present European financed project focus on the extension of the stable operating range of axial compressors by controlling the flow at compressor blade tip thanks to fluidic jets blowing at the machine casing. The final goals consist of reducing the surge margin by postponing the stall onset. More specifically, the objective of the ACONIT project is to design, manufacture, and test actuators for flow control to integrate them in an aircraft engine. The actuators must, therefore, fulfil aeronautics requirement in order to increase the Technology Readiness Level (TRL) for aeronautical active flow control applications.

To this end, the first objective of the work is to carry out an in-depth characterization of the flow physics of an efficient flow control system by joint numerical and experimental analyses performed in a low-speed, single stage axial compressor. Thereafter, the fluidic specifications for a high TRL actuator and control system will be derived. Such specifications will be the basis for designing and manufacturing of amplified piezo-electric actuator prototypes whose fluidics and operational performances will be precisely evaluated before manufacturing final actuators to be integrated in a full-scale jet engine test vehicle. The performance evaluation will be carried out in an environment with vibrations and controlled level of temperature.

2. Motivation and state of the art

Figure 1 depicts a generic performance curve of an axial compressor. In axial compressors commonly employed in aircraft engines, the pressure ratio increases as the flow rate decreases. As tempting it is to use machines at these operating points, they are also close to a certain limit where unsteady phenomena can occur. These phenomena, known as stall and surge, can have destructive effects on the engine, and so severe up to catastrophic consequences for the aircraft. Hence, engine manufacturers use a security margin known as Stall Margin (SM), who prevents the machine to be used in such regime. This safety margin has two detrimental effects: on the one hand, it deprives the machine from its higher pressure ratio (and so it imposes more stages and / or larger compressor), on the other hand, it brings the machine far from its optimal efficiency line. Both effects have a detrimental influence on the aircraft consumption and its pollutant emission. Improving the stability would thus improve aircraft performance, as well as the flight safety owing to a decrease of surge risk.

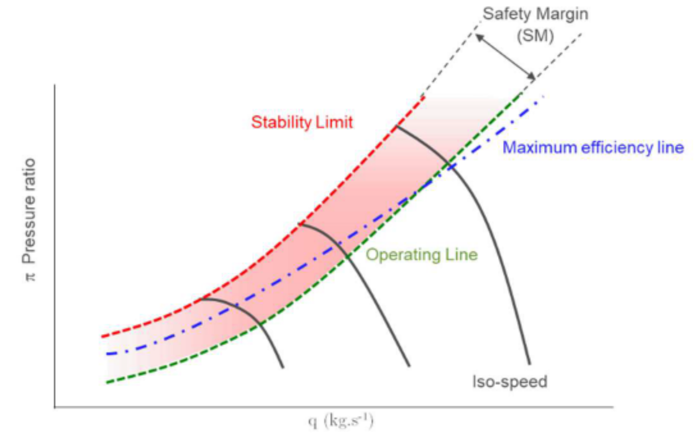

Figure 1. A typical performance curve depicting stability limit and surge margin.

In the literature, two types of stalls are reported, namely "mode" and "spike" type [1]. According to Ref. [1], the latter happens to be the most common in aero-engines, and it is consequently target of great attention paid by the scientific community, even more during the last few decades owing to an increasing attention to the reduction of CO_2 emissions. Even if the associated flow physic is not yet fully understood, the scientific community agrees on the interpretation of a few crucial aspects of the spike stall. The blade tip region appears to be the location where the instability sets in, with some unsteady phenomena occurring under high-flow incidence. Several scenarios can be found in literature (see Figure 2), depending, in particular, on the tip gap size [3,4]. However, the understanding of the physical mechanisms leading to stall need more investigation to support the development of efficient control strategies.

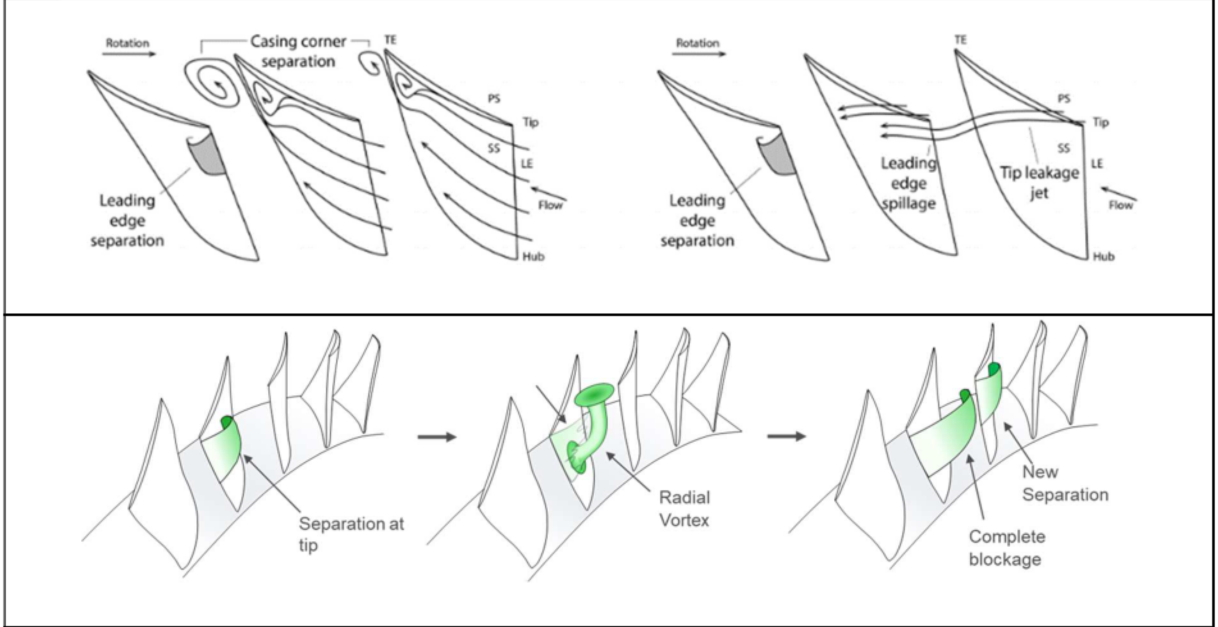

Figure 2. Different stall onset scenarios for the spike case (from [4] - top and [3] - bottom).

Acting on the tip region is thus a common method to control the set-in of instabilities, and so to stabilize the compressor. Several strategies can be found in literature, including passive flow controls known as casing treatment [5]. Involving the machining of several particular shapes on the casing above the blade tip, these methods are effective, but they are hardly adaptive to different flow configurations encountered during both, flight and engine life. On the contrary, active flow control solutions can be activated and deactivated as needed, and adjusted to use the minimum energy input for producing the desired results [6].

Tip blowing using various source of flow (recirculation from downstream high - pressure compressor, additional air source…) have been experimented with success, and the influence of several parameters has been documented (mass flow, momentum, injection location…) while some others still require an in-depth investigation [7].

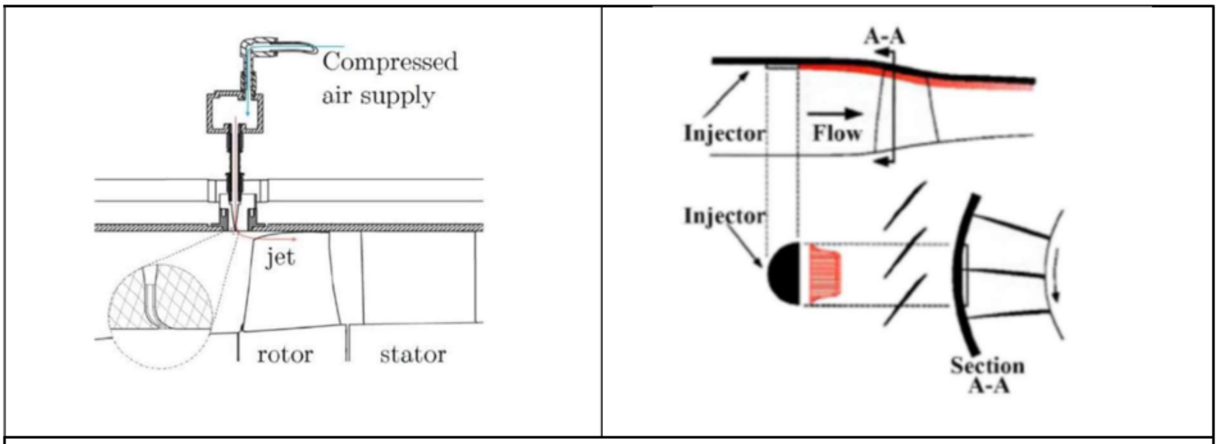

Figure 3. Two examples of tip blowing experiments in axial compressor, from [3] (left) and [8] (right).

Most of the times, these research works have been performed on simplified geometries, like isolated stage and/or at low Mach number. A few exceptions are reported in literature, such as the study of Freeman et al. on a Rolls-Royce Viper Turbojet [9], or, more recently, the works carried out by Stößel et al. on a Snecma-Turbomeca Larzac [10]. Some details about this experimental apparatus and associated results are given on Figure 4.

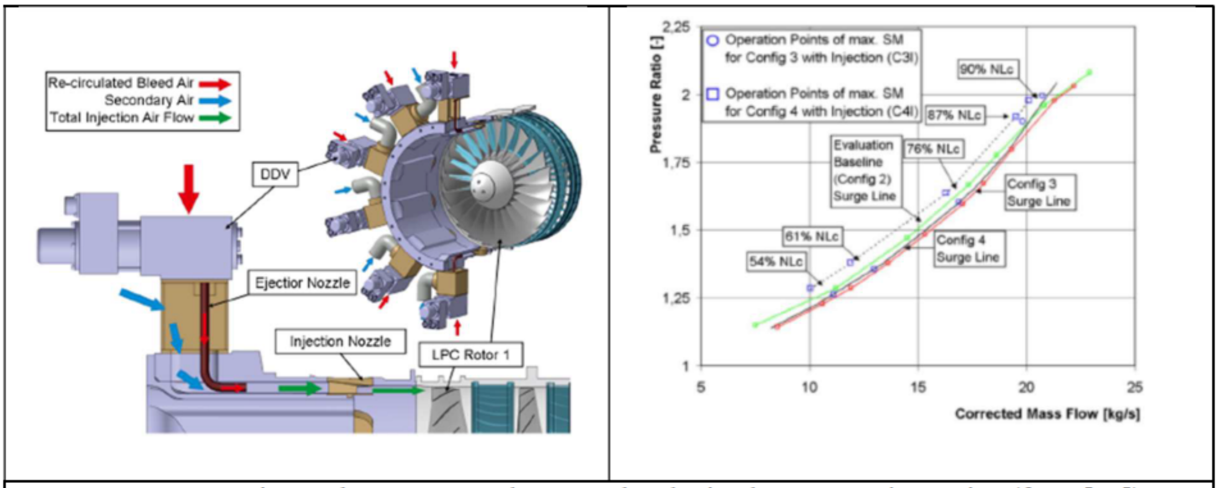

Figure 4. Experimental apparatus and test results obtained on Larzac jet engine (from [10]).

Meanwhile, to the authors' knowledge, most of these studies involves "research grade" actuators, as they usually do not fulfil many of the industrial requirements (compactness, cost, and efficiency to cite a few, without mention to redundancy and certification aspects). Even if some demonstrations are based on real engine tests, actuators, on their side, are still at rather low Technological Readiness Level (TRL).

This statement represents the main motivation of the ACONIT project that aims to set a demonstration of active flow control in a real aircraft engine using high-end actuators, which actuators could potentially fulfil industrial needs and so contribute to a widespread use of active flow control.

3. Project organisation

The project workflow is structured in four work packages (see Figure 5). Starting from tests on simplified configurations, we aim at improving the physical understanding of the problem. Building on the acquired knowledge, our flow control solutions will be tested infull-scale engines. Within this framework, the actuators will be designed and tested in various conditions, and CFD simulations will be supporting the design and complementing the experiments at every step of the project.

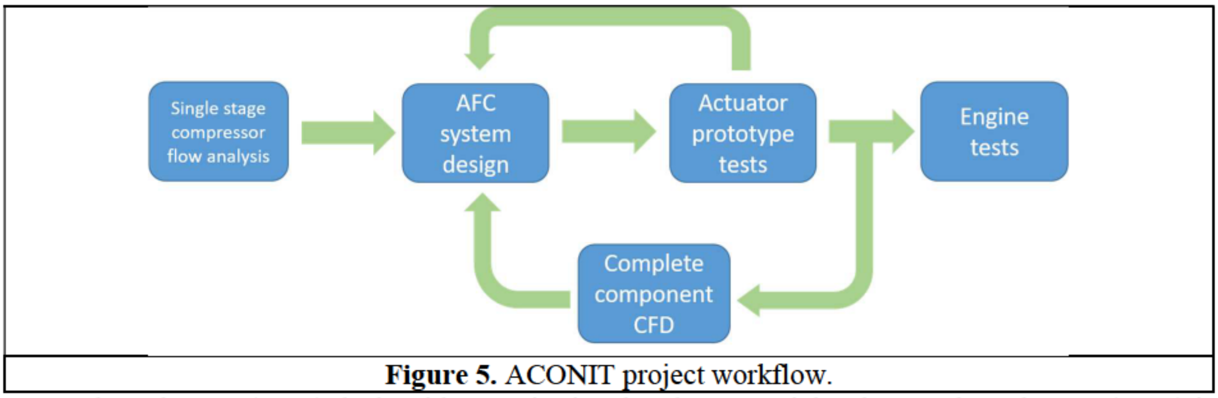

Figure 5. ACONIT project workflow.

Work Package 1 (WP1) deals with organisational and managerial tasks. Work Package 2 (WP2) is dedicated to increasing the physical knowledge of such complex flow control configurations, involving pulsating jets interacting with a boundary layer and then with a rotating wheel. Moreover, WP2 is also devoted to providing fluidic and geometric parameters to improve the design process of the high-end actuators. To do so, a dual approach with experimental and numerical studies will be used. Experiments will rely on the CME2 test bench (see Figure 6 and reference [11]), a single stage, low speed, axial compressor, located at Arts et Métiers Institute of Technology (Lille). Numerical simulations will be performed using the elsA code from ONERA and advanced methods (hybrid RANS/LES and Chimera technique with overset grids).

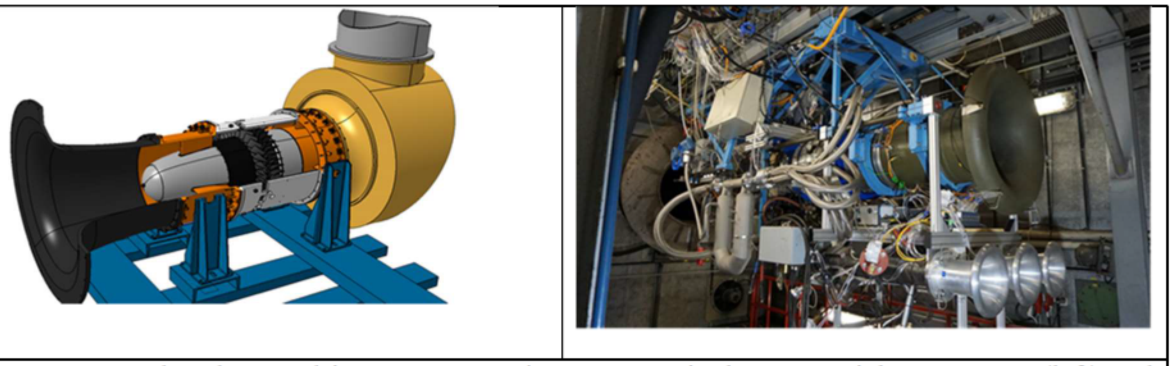

Figure 6. Test benches used in ACONIT project: CME2 single stage axial compressor (left) and Larzac turbojet engine (right).

The actuators' design and test are realised in the framework of Work Package 3 (WP3), thanks to the experience and knowledge acquired by one of the project partner (CTEC) during previous projects in aerospace domain, using various kinds of devices relying on amplified piezo - actuators [12–14]. Several design phases are planned, interleaved with validation of their fluidic performance on a specialised test bench operating at ONERA Lille. Also a validation of their resistance will be performed, taking into account the harsh environmental conditions due to strong thermal and vibratory constraints like those encountered in aircraft engines.

Completion of WP3 will offer to the project a set of high - end actuators, to be installed on the Larzac test engine located in the Institute of Jet Propulsion (Munich, see Figure 6, right, and reference [15] for more details). Airflow blowing will be realised near the casing wall in front of the Low Pressure Compressor (LPC) blades, with the aim to apply the control strategy developed in WP1. As for the whole project, these experiments will be completed and corroborated with advanced CFD simulations.

4. Preliminary results

The project schedule has been slightly delayed due to the Covid-19 pandemic, which lead to a temporary shut-down of the experimental facilities. First results of the project are then mainly numerical, but are very promising when compared to available experimental data.

As an example, Figure 7 (left panel) presents the first performance curves computed with various turbulence models and based on one single blade passage and mixing plane approach with a 3.1 million mesh. One can observe that the four RANS turbulent models provide similar results, and that the static pressure at a 4 kg/s flow rate is correctly predicted compared with experiments. More specifically, all four models predict very similar flow fields. Results obtained with Spalart - Allmaras (SA) model are presented, for example, in Figure 7 (right panel), and show that mean flow exhibits separation at various locations when approaching stability limit on the performance curve.

A first experimental test campaign has been completed, and results are currently being post - processed. Attention has been paid to the yaw angle of the injection ports, as it seems to dramatically increase the effect of the active flow control.

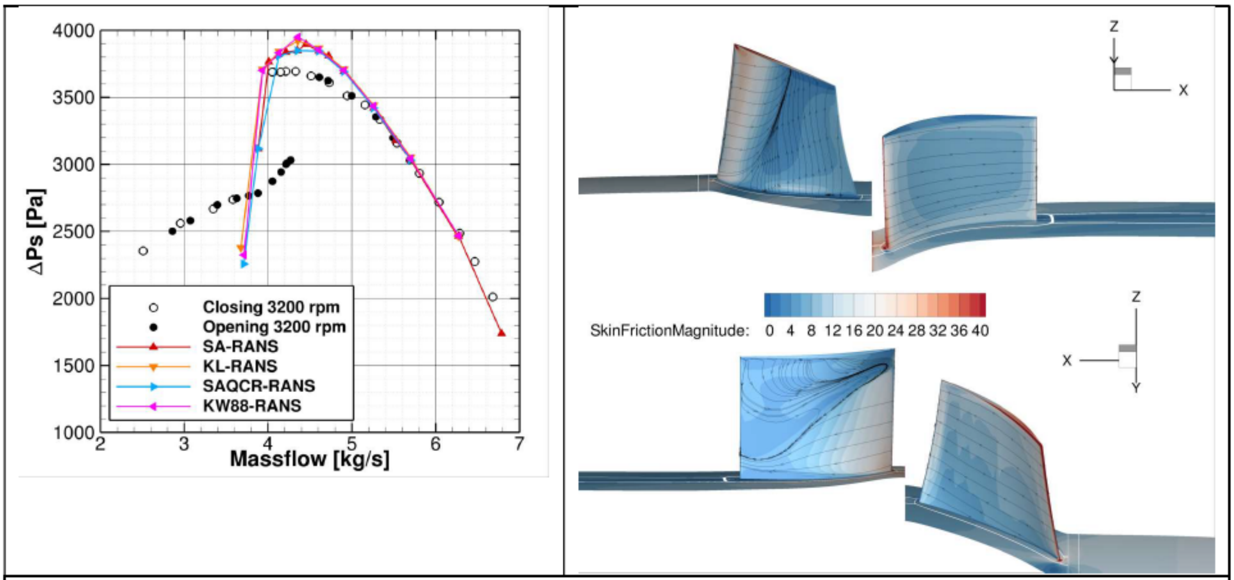

Figure 7. First numerical results of axial compressor (CME2) simulation: performance curves obtained with various turbulence model (left), and mean flow field computed with SA model (right).

5. Conclusion

The ACONIT project aims at contributing to several high - level goals of the European initiative Clean Sky 2. In fact, for industrial-grade actuators it is mandatory to consider a large-scale deployment of active flow control techniques on aircraft engines (and on any industrial domains from a wider point of view). An application of such flow manipulation techniques is to safely reach higher pressure ratios on axial compressor stages by extending their stable operating range. Such improvement will naturally lead to more efficient and / or smaller engines, thus reducing both CO_2 and NO_X. As energy efficiency performance will be a crucial factor in the international global competition, the development of more efficient aircraft engines will directly drive the expansion capability of air transport and then the competitiveness of the European Industry thanks to such new generation engines. Making aero engines more efficient is opens a promising avenue to make the mobility of passengers and freight more sustainable, which, in turn, marks a positive impact on the European integration policy and economic development.

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