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Retrofit of a Digital Engine Control Unit and Integration of an Active Stability Control System

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ABSTRACT

This paper presents the adoption of a digital engine control device to a turbofan engine and the integration of an active stability control system to suppress compressor instabilities.

For research purposes, a digital control unit offers the option to investigate engine operating conditions, which are not permissible in regular flight operation. It is well known, that an efficiency increase can be achieved by operating the engine closer to the surge line. On the other hand a significant decrease of surge margin leads inevitably to instability occurrences within the compressor system of the engine, which necessitates the application of a functional and reliable active stability control system.

At the Institute of Jet Propulsion at the University of Federal Armed Forces Munich, Germany remarkable results have been attained with a rotating stall control system adapted to a Larzac 04 twin-spool turbofan engine, which in series is equipped with an analog engine control unit.

In order to achieve the objective to integrate the rotating stall detection and avoidance system into the control system of the test engine, the Larzac first had to be provided with a digital controller. The intention was to build a digital control unit, which in a first step just copies the functionality of the series controller. After a set of tests and the validation of the new device, the stall detection algorithm was embedded into the controller and it was enabled to re-open the throttle device, used to generate the instabilities, and therefore re-stabilize the compressor after detection of an imminent stall event.

In the following, a second configuration was installed, in which the controller initiates the active stall avoidance system consisting of an air injection in front of the first rotor of the low pressure compressor. Due to the injected air at the tip region of the rotor-blade, the emerging instabilities could be suppressed successfully and the operating range of the engine could be extended significantly.

NOMENCLATURE

Symbols

F	[kN]	thrust
Π	[-]	pressure ratio
N1	[RPM]	low pressure spool-speed
N2	[RPM]	high pressure spool-speed
$n_{\theta LPC}$	[%]	relative corrected spool-speed

Abbreviations

BPR	bypass ratio
FFT	Fast Fourier Transformation
HP	high pressure
HPC	high pressure compressor
ISA	Int. Standard Atmosphere
LP	low pressure
LPC	low pressure compressor
PXI	PCI Extension for Instrumentation
TET	turbine entry temperature

INTRODUCTION

In the course of increasing environment pollution and oil resources getting scarcer, operators again more and more focus on the efficiency of gas turbines. This directly leads to new challenges for manufactures of turbo machines, like requiring greater power ranges and at the same time less fuel consumption. One opportunity to raise the power potential of jet engines is to optimize their operating performance. Thereby it is possible to adjust the software of modern digital engine control devices to the required mission profile. A second attempt is to increase the aero dynamical load especially of the compressor stages, which induces higher pressure ratios with constant number of stages or an equal pressure ratio with less number of compressor stages. Both possibilities cause a higher aerodynamic load and thus higher danger to the stream to stall. In normal operating conditions the compressor runs on or near the predefined working line, maintaining a specified distance to areas where instabilities occur and stall is developed. This limit between operation within safe condition and areas, which are characterized by massive flow separation, is called the surge line. This regime among the working line and the surge line contains a major performance-potential in terms of increasing pressure ratio, efficiency and a constant mass flow at the same time. Therefore, it is attractive to design compressors for this particular operating regime once an efficient system is available, which is able to suppress compressor stall in a reliable way and to allow for a safe operation of the entire engine. For this reason several techniques have been developed to counteract the upcoming instabilities in turbomachinery. Besides a number of passive possibilities, which often also cause several disadvantages during standard operation, active stability control systems are feasible. The big advantage of this kind of stabilization is that it can be activated if necessary and has almost no effect on the gasturbine in uncritical conditions. To simplify matters it is useful to integrate the active stability control into the digital control unit of modern aero engines. However, the test vehicle of these research activities, the Larzac 04 engine is equipped with an analog controller and a digital controller had to be provided to demonstrate the feasibility of this task.

PHYSICAL BACKGROUND

It is reasonable to integrate an active stability system onboard an aircraft engine into the digital control unit of the gasturbine. The Larzac is serially equipped with an analog engine control unit, which made it necessary to replace the analog control device by a digital one. Extensive analysis of the system behavior had been gathered and all important control parameters were recorded for the development of the digital retrofit [1].

The development of digital control systems had the focus to replace the analog control systems by more flexible tools. For a successful transfer of the control functions no changes of the sensor technology and the actuating elements were allowed in the first step. The compatibility of the individual pins was required to enable a later restore of the analog controller. Therefore the same cable harness had to be used. Additionally, the same limit values were taken into account within the digital control system, hence all parameters and limiters to be controlled have been transferred to the analog controller without any adjustments. A complete inquiry of these fundamental data for the onset procedure of the digital control system would have caused a much longer time period for the entire development process. Comprehensive literature investigation revealed additional cognitions about this topic.

First model-based multivariable engine control systems came up in the 1970s. An optimal open loop compensator combined with Riccati feedback compensator control system design was applied to the engine control of a Larzac 04 by Froriep et al. [2] in 1977. Skira et al. [3] describe the entire process including design, evaluation and testing leading to an electronic control for the F100 turbojet engine. Also some former investigations of De Hoff et al. [4] deal with the system control of the F100. Auer [5] presented a model based, digital, single parameter state control with stationary pre-control and target state generation for a twin spool turbo shaft gas turbine. For his experiments the Allison 250-C20B was used and a second parallel fuel supply was installed. Thus it is possible to switch between hydro mechanical and digital controller during engine operation. Some more background information about the operability of a surge detection and warning system for multi-stage highly loaded axial compressors can be found in Grauer [6]. Furthermore an implementation of such a system at the Larzac 04 engine is described by Leinhos et al. [7], who combined it with an active stabilization system using air injection at the rotor tip region. Similar active counter measure mechanisms were investigated by Kefalakis et al. [8] on a Larzac 1st stage compressor rig. Published results of Suder et al. [9] and Strazisar [10] et al. also demonstrate the capability, which can be achieved applying this kind of method.

EXPERIMANTAL SETUP

Test Facility

All engine tests described in this paper have been performed at the engine ground test facility of the University of Federal Armed Forces in Munich, which is an indoor test bed. As it can be seen from figure 1, the main air, used for the engine and also as cooling air passing the gasturbine, is supplied by the air intake tower. Through several noise absorbing cascades the fluid enters the test bench and is guided towards the test engine.

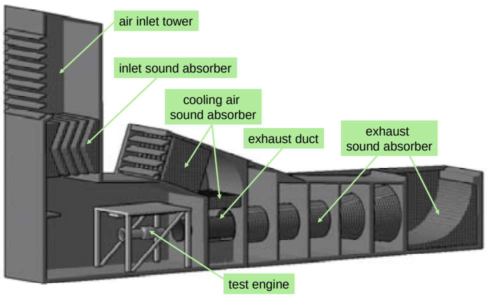

Fig. 1: Ground test facility UniBW Munich

Both, the hot exhaust gases of the engine as well as the cooling air are leaving via the exhaust duct. In a downstream mixing chamber additional air is fed in for cooling purposes of the exhaust gas. For the reduction of emitted noise, a second sound absorber is installed prior the outlet, which lowers the exhaust gas velocity by an extension of the cross-sectional area and thus effecting noise reduction. Releasing the gas vertically produces a mostly upward directed sound propagation minimizing the influence on surroundings.

Due to the fact that the facility is used for research work and educational purposes a quick change of several aircraft engines and component demonstrators is possible. This attribute is realized by a hydraulic lifting column, which attaches the engines to the test rig. All electric engine cable harness and feed lines as well as the sensor wiring are plugged to a connector panel at the engine attachment frame. Furthermore the facility features a control desk within a lecturing room. This gives the possibility for the students to participate in engine demonstration runs.

Test Engine

For the research work covered in this paper the twin-spool turbofan engine Larzac 04 C5 was used as a test vehicle. Designed during the early 70's by a Joint Venture of Turbomeca and Snecma and manufactured in license by MTU Aero Engines, the Larzac 04 was applied to the German Air Force for powering the Alpha Jet, a light attack and advanced trainer jet aircraft. The most important engine performance data at ISA conditions are listed in table 1.

The absence of an inlet guide vane, in contrast to many American turbojet engines, guarantees direct access to the LPC and is a key feature for the air injection system described later on in this paper.

Fig. 2: Larzac 04 C5 turbofan engine

The Larzac is a low bypass turbofan engine of fairly modern design. It comprises a two staged, highly transonic low pressure compressor, a four stage high pressure compressor, an annular combustion chamber and a single stage high and low pressure turbine. The core and the bypass flows expand through separate nozzles without mixture, which allows an almost independent throttling of both compressors.

F_s	13 kN
TET	1403 K
μ (BPR)	1.13
W (mass flow)	27.64 kg/s
Π_{LPC}	2.26
Π_{HPC}	4.60
n_{LPC}	17500 RPM
n_{HPC}	22561 RPM

Table 1: Engine parameters at ISA conditions

Throttling Device

The test engine uses a throttling device, forcing the engine to run at operating conditions near surge. Since the engine is equipped with two separate nozzles, originally two different throttling devices had been installed behind both nozzles. Former studies yield, that throttling the core flow forces the hydro-mechanical control unit to spike the fuel flow rapidly, leading to an excess of the TET-limit [1]. This effect reduces the life cycle time of the turbine components significantly and for this reason all measurements performed for the particular investigations presented in this paper are based on experiments applying the bypass throttling device. This throttle consists of several circular arc segments, which are driven by an electric motor via a chain and can be moved in radial direction to control the exit area of the nozzle (see Fig. 3).

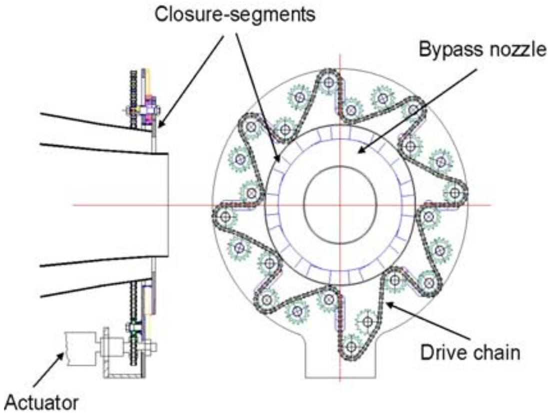

Fig. 3: Bypass throttling device

Thereby it is possible to run the LPC in an operating sector close to or beyond the surge line. At the beginning this throttling of the LPC does not significantly affect the operating point of the high pressure compressor [1]. Generated rotating stall and other flow instabilities or variations in the low pressure compressor do have influence on the entry conditions at the HPC and thus also its operating point. Further details of the controlling and operating mode of the bypass throttling device are specified in [11].

Air Injection System

In order to recover the compressor from rotating stall, the countermeasure of air injection was chosen. The Larzac test engine offers different advantages for this active stabilization system, such as the absence of an inlet guide vane, which allows a direct access to the first stage of the LPC. Also the compressor is tip-critical, meaning that an upcoming stall develops at the tip region of the compressor blade. Due to this, the air injection could be placed into the engine's inlet casing geometry.

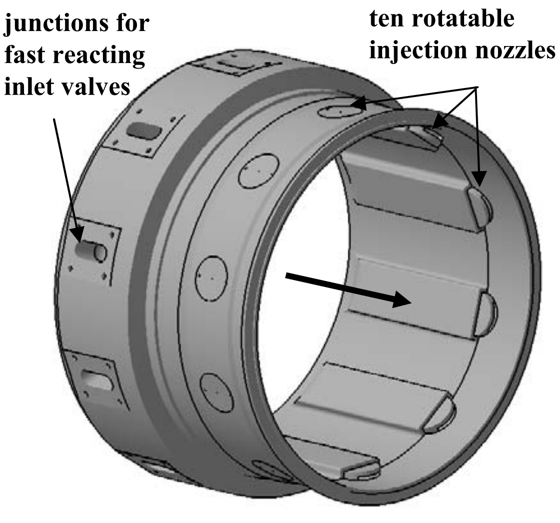

Fig. 4: Air injection housing and nozzles

A very efficient injection housing, displayed in figure 4, was developed for the Larzac engine [12]. It consists of ten separate air supply channels, with injection nozzles at the end that are arranged in circumferential position inside the inlet. All tests presented in this paper were done using the third generation of injection nozzles and a slightly improved injection housing, described in [13]. For a big variability of setups and basic research work the nozzles are ±30 degrees rotatable, which allows co-rotating as well as counter-rotating air injection. Different former investigations revealed, that an axial injection offers the best performance considering overall performance [14]. In the **Final Test Setup** section of this paper an illustration shows the assembly of the injection housing attached to the engine.

It is also possible to vary the injection mass flow, which is usually set around 2% to 5% of the main engine air-mass flow. The pressure level of the injection can be preset between 1bar and 12bar and at each of the ten air supply channels a Moog-valve is installed upstream to control the mass flow released through the nozzles. These valves have a very short response time and thus are well suited for this application.

Instrumentation and Data Acquisition

Several sensors have been installed to the test vehicle to gather information about the operation conditions of the engine and to provide input signals for the digital control unit. The instrumentation exceeds that of an in-service engine and can be subdivided into two categories, each assigned to different tasks.

In order to determine compressor maps and visualize the operation points of the Larzac 04 during the tests as well as to accomplish analysis on the performance, the low-frequency or conventional instrumentation has been attached. This instrumentation contains pressure transducers, thermocouples and other sensors to measure parameters like spool-speed or fuel-flow. While it is possible to gage the static pressure at many positions at the engine by rather simple holes at the wall, more complex probes were needed in order to measure total pressure at various locations. Several of these probes have been developed especially for the Larzac engine and are integrated in diverse sections of the test vehicle. Most of them are housing up to five either total pressure or total temperature sensors in different radial positions. Herpel [15] gives some more details on the constructional design of the mentioned probes and figure 5 presents an overview about the sensors and their positions. Also some more data channels like the throttle status are measured and recorded, which are not necessary for the gas path calculation or the controller.

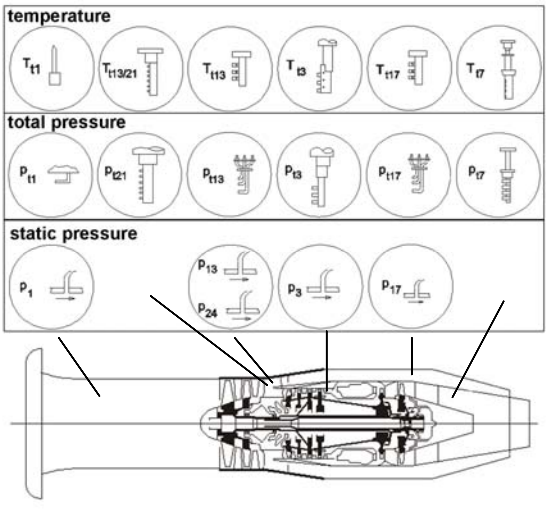

Fig. 5: Conventional instrumentation used

All these sensors are scanned with a sampling rate of 10Hz. The values are sampled for 20ms and averaged in the following 80ms leading to one value every 100ms, which is equivalent to the sampling rate of 10Hz mentioned before. Although the conventional instrumentation has a low sampling rate, it is sufficient to analyze the engine behavior in steady and transient operation points.

Conditions while throttling the engine are also well mapped as shown in the **Experimental Results** section. The data files are stored in a packed format and imported into Matlab for post-processing purposes. Some more detailed information on the used Matlab routines and their individual features can be found in [13].

Furthermore, a high frequency instrumentation was added consisting of special piezo-resistive pressure sensors so-called Kulites. Due to the very high natural oscillation of the used silicon substrate, the transducer has a short response time. This attribute enables the scanning at very high frequencies, up to 400kHz, which are necessary to detect pressure fluctuations during instability onset and to identify the different kinds of instabilities. Another advantage of piezo-resistive sensors is the impassivity against vibrations making them suitable for the implementation in aero-engines.

The Kulites have been distributed at various positions throughout the low and high pressure compression system of the Larzac 04. Similar to the conventional instrumentation, some sensors are designed as static wall pressure sensors and others as free-stream pressure probes. The locations and kinds are shown in figure 6. More details about probe development and integration of the sensors are described in [16].

The major difference to the probes used for low-frequency measurements is, that the Kulite sensors are small enough to fit them directly inside the probe. Due to the fact, that the membrane of the sensor is proximate to the measurement position, no time lag emerges by oscillating fluid volume.

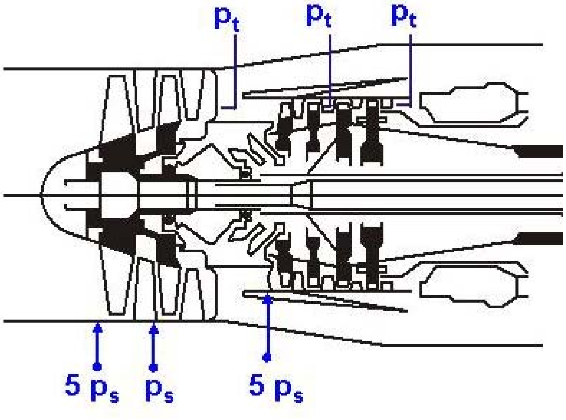

Fig. 6: Positions of Kulite sensors

Overall 14 Kulites are installed in the LPC and HPC, which have been the basis of other investigations performed with this test vehicle. However, the stall detection algorithm presented in this paper uses only two of the five sensors installed 7mm upstream the leading edge of the first low pressure compressor rotor. Prior research done by the institute of jet propulsion at the University of Federal Armed Forces and other research institutes revealed this to be the ideal position to obtain utilizable signals of the rotating stall precursors. Sensor 1 (332°) and sensor 3 (116°) of the equidistantly distributed XCE-093 Series Kulites have been chosen as input signals, because of their nearly opposite arrangement.

Additional to the processing by the stall detection system, the signals are monitored with a National Instruments PXI system, containing three PXI-6254 high frequency measurement cards, which allow a sampling rate above 1MS/s for both sensors. A sampling rate of 50kHz for this experiment gives the opportunity to analyze instability precursors and on the other hand generates data files small enough to handle them properly. All visualization and data storage is done with LabView®, which offers very good software – hardware – interoperability, since both are National Instruments products. Also a pre-analysis by means of a FFT is done online to observe the development of secondary frequencies during instability onset. Besides the two Kulite signals other parameters like the spool speeds and the throttle position are recorded with this data acquisition system to generate references within the data files.

Digital Control Unit

In order to be able to conduct the surge avoidance investigations, the engine was equipped with a digital controller. The main reason for this step was the ability to implement the stall detection and control system with the electronic part of the control system. By this, all data necessary for the compressor stall detection algorithm can be accessed via the engine control system where they are available anyway. Furthermore, the use of a digital control module gives additional flexibility for later investigations on engine performance in general. In a first step, the functionality of the digital controller was adapted to the behavior of the original, analog controller in order to directly compare both systems.

The control system of the LARZAC 04 engine consists of a hydro-mechanic control and fuel metering unit, and an electronic controller box, that together operate the engine by use of the two main actuation systems. These are the combustor fuel flow and the HPC bleed valve setting. The fuel flow necessary for engine rating is generated by a centrifugal governor in the hydro-mechanic controller that utilizes the high pressure spool speed N2. The hydro-mechanic controller also provides functionality for handling engine startup as well as transient operation.

The electronic controller of the engine features several interfaces with the hydro-mechanic part of the control system and provides limiting control input to the fuel metering unit. Limitation of the combustor fuel flow is triggered in case of excessive turbine temperature as well as low pressure spool overspeed. As well, the controller hosts the N2 acceleration limiter schedules. Furthermore, several switches are provided for discrete signals, such as the bleed valves, engine starter engage and the start fuel nozzles.

The digital adaptation of the electronic controller is fit to provide the same functionality as the original analog controller box, but offers flexibility to vary the engine operability over a wide range, as could be required for future investigations on engine steady state and transient behavior.

The controller software is designed by the use of a Matlab/Simulink® model. Subsequently, the software code is generated by the Mathworks code generation tool Realtime Workshop®. After compilation and linking, the controller code is downloaded to a dSpace® rapid prototyping system that communicates with the engine instrumentation via a custom built interface box.

Besides the basic engine control functions, the digital controller hosts the surge detection algorithm and the compressor stabilization functionality. For detection of a compressor rotating stall event, the system utilizes the input from the fast pressure sensors, as well as the LP spool speed input from the control system. By a correlation of pressure variations in combination with the actual spool speed, rotating stall cells can be anticipated, depending on the strength of the pressure variations and the relative speed compared with the spool speed. According to these inputs, a surge indicator value is calculated that triggers the stabilization system, once a pre-defined threshold value is exceeded. The trigger is used to either open the bypass throttling device, or activate the compressor air injection system.

Final Test Setup

Being able to compare the test runs performed with the digital control unit to previously conducted engine tests using the analog controller [1], an almost identical test setup has to be provided. In this test arrangement the Larzac 04 engine was operated in standard configuration consisting of a bellmouth inlet and the two separate nozzles. Only the bypass throttling device was installed but deactivated to take no effect on the test vehicle. For the testing of the digital control device only the controller boxes attached to the engine have been changed and some additional wiring has been applied to support the dSpace System described before.

In a second test series the stall detection and avoidance system had to be tested. Due to this the air injection housing was integrated into the inlet duct of the engine. It is placed straight in front of the first stage of the low pressure compressor. Also some tubes were installed and connected to the air system of the test facility to ensure the supply with external air. This system provides air for a constant injection up to 30s at highest flow rates (approximately 5% of entire mass flow) fed by a screw compressor and a storage volume of 7500 liters. In figure 7 the fully equipped test vehicle is shown and the mentioned attachment parts are named.

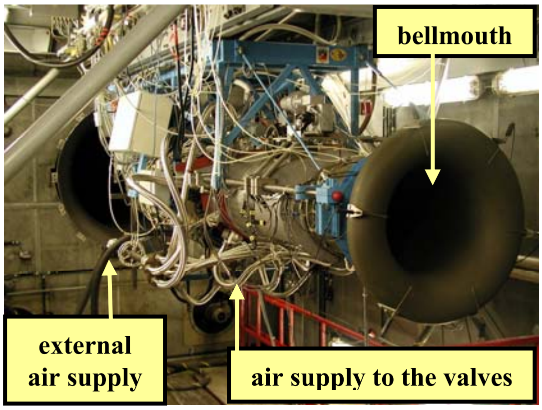

Fig. 7: Larzac 04 setup up for test run

In order to trigger active countermeasures by the stall detection algorithm embedded in the digital control unit of the engine it was necessary to enable the controller to reopen the throttling device if instabilities are detected. The throttle control is operated by a separate control mechanism, which is only used for closure of the throttle in this experiment. Besides, an emergency button of higher priority was installed, to override the signals of the digital controller in case of a malfunction.

In a second set of tests the detection system was given the opportunity to initiate the air injection by controlling the fast acting valves attached to the injection housing instead of reopening the throttle device, which requires some additional wiring.

EXPERIMANTAL RESULTS

Adjustment of the digital controller

In a first step the new digital controller was attached to the engine and programmed to fulfill the same function as the analog did before. A series of tests at different stationary points have been performed to adjust the output parameters and also the engine performance. After proofing the reliable function of the control device throughout the whole operating range the engine behavior during highly transient conditions was checked in a second set of tests. For this purpose a combination of accelerations and decelerations has been performed. The tests are similar to those with the analog engine control unit, described and analyzed in [1].

During one cycle, the test engine was accelerated from idle to maximum power setting followed by a stabilization period of 30 seconds and a deceleration to idle speed again. The duration of power lever adjustment was reduced stepwise from 25s to 5s and additionally a rapid speed-up and rundown, in which the power lever was changed within only 2 seconds, have been accomplished. By a very fast alteration of the power lever, controller inputs become less important and mechanical and physical basic conditions of the gas turbine become dominant. In order to guarantee the repeatability of the power lever adjustment a separate computer was given authority to operate it in a preset way.

The acceleration of the first cycle lasting 25s from idle to maximum power setting is displayed in a prepared LPC map, to compare the two control units in terms of engine performance during transient load change (see Fig. 8).

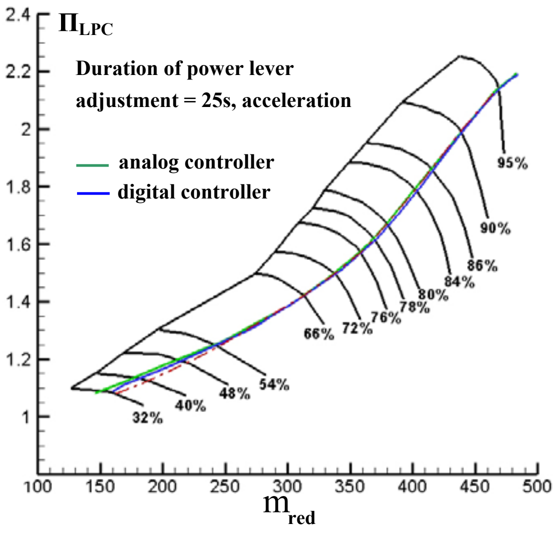

Fig. 8: Comparison of acceleration lines (25s)

As it can be seen both acceleration lines are almost congruent. Due to the very slow acceleration of the test engine the acceleration lines match the steady operating line, which reconfirms that the digital control unit induces similar quasi-stationary operating behavior throughout the whole operating area. Minor deviations emerge only in areas of lower speed ranges. For this reason the rapid speed-ups for both control units are shown in figure 9 to analyze if the controller is responsible for this deflection. As explained above, a very fast alteration of the power lever avoids controller influences on engine performance. It can be recognized, that the offset between the operating lines occur in the same way like they do during a slow acceleration.

This indicates that the observed deflection is not in consequence of a difference between the control devices. One possible explanation for the observed phenomenon could be the less significance of minor spool-speeds for this kind of investigations and consequently that the entire measurement chain is optimized for the relevant middle and higher speed ranges, which leads to marginal tolerance discrepancies near idle power setting.

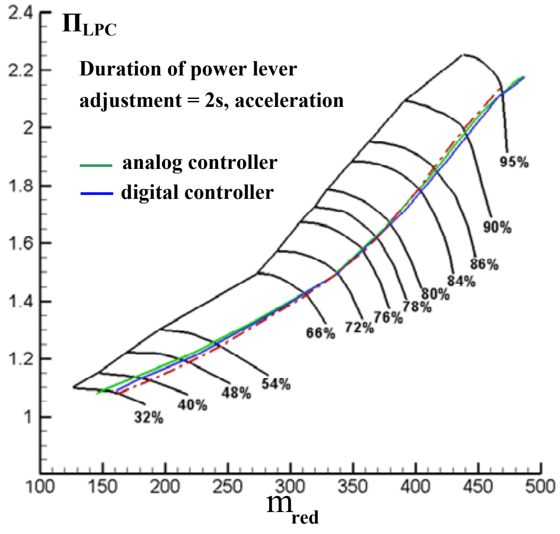

Fig. 9: Comparison of acceleration lines (2s)

Furthermore it is shown in figure 9, that for spool-speeds above $n_{\theta LPC}=80\%$ both running lines are located below the steady operating line. This is caused by the effect, that in twin- or three-spool engines the LPC is influenced by the HPC with the consequence, that the HPC performs a typical excursion in direction to the surge line, when accelerated, while the LPC is unloaded by this fact. Such an oppositional behavior reflects also in some other physical aerodynamic effects, which affect the performance of both the components of the compressor and the turbine systems. The reason for this interaction of the LPC and HPC can be found in the corresponding bypass ratio and the ratio of the polar moments of inertia.

While in the lower speed regime, at which the bleed valves are open (in between idle and about $n_{\theta LPC}=66\%$), the acceleration lines are above the steady operating line, the discussed distinction appears in the upper speed band up to maximum power setting. Initiating the closure of the HPC bleed valves provokes, that the LPC shows a de-throttled behavior during its acceleration run, because no bleed-air is added to the bypass behind the low pressure compressor anymore [1].

Analyzing the test run in total, the spool-speeds give information about the acceleration and deceleration processes in relation to each other. Figure 10 shows this context and reveals a very good data match of the spool-speeds during the dynamic cycles carried out, which is another evidence for a similar engine performance, while using the analog or digital controller. Due to the different ambient temperature a slight offset between N1 spool-speeds is visible, which is less distinctive in the HPC spool-speed. This confirms the assumption that the HPC is less influenced by this parameter and thus it shows no discrepancy.

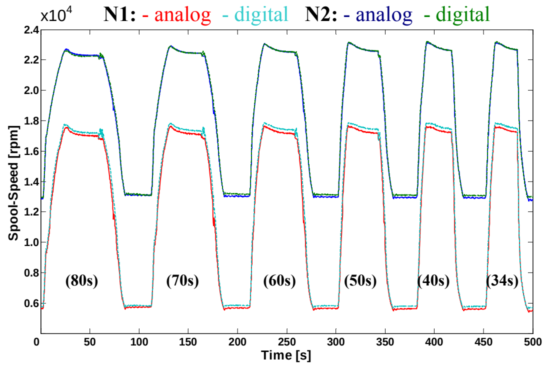

Fig. 10: Spool-speeds during test run

It also points out, that a power lever adjustment faster than 5s is put into effect by the engine similarly. In this interval, an increase of spool-speed depends not on the power lever movement but on the engine dynamics. The plot shows that the gradient of acceleration and deceleration is equal for the 40s and 34s cycle and a further reduction of cycle time is not possible by control input, which offers the opportunity to investigate engine performance independent of controller inputs.

Besides the retrofit of the control device the standard fuel metering unit remained in service unchanged. In figure 11 the actual fuel flow during the acceleration and deceleration phases is illustrated to analyze the interaction of both units. A good match of graphs in operation areas with moderate spool-speeds is obvious as well. Only at the stabilization phases at maximum power setting a gap of the fuel mass flow is recognizable, which can be explained by the different ambient temperature conditions and the T_{t7} limiter.

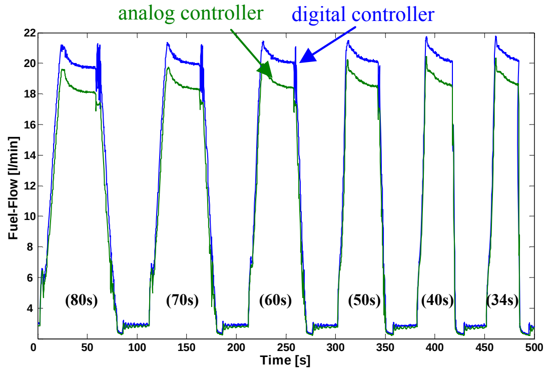

Fig. 11: Fuel-flow during test run

In order to avoid over temperature of the exhaust gas this parameter is by default measured with a set of thermocouples behind the low pressure turbine. A fixed, preset maximum is set in both control devices, which retract fuel-flow if the temperature limit is reached. Low ambient temperature effects that more fuel is necessary to obtain the limit. During slow power lever adjustment (more than 10s) in both curves, of figure 11, a significant overshoot is followed by stabilization. Runs performed with the analog controller feature a short decline with a subsequent stabilization before the deceleration, while the data of the digital control device shows an oscillation just before the deceleration. This phenomenon is caused by the integral element of the digital control unit and offers the possibility for a further optimization like an alignment of the input signal for the fuel metering unit.

Test of the Stall Detection Algorithm

After proving the functionality of the new controller, the stall detection algorithm was embedded and activated. At first a verification of the reliability of the algorithm has been accomplished by authorizing the controller to de-throttle the engine by an emergency opening of the bypass throttling device. For this purpose the Larzac 04 was throttled at $n_{\theta LPC}$=68%, which is within an operation area where the Larzac does not develop surge as a direct consequence of rotating stall, but rather can be kept in stall condition for a period of time. Moreover a possible surge event at moderate pressure ratios would not cause major damage to the engine.

The throttling, done by the bypass throttling device, effects a displacement of the operating point towards the surge line, which is represented by the first part of the blue graph displayed in figure 12.

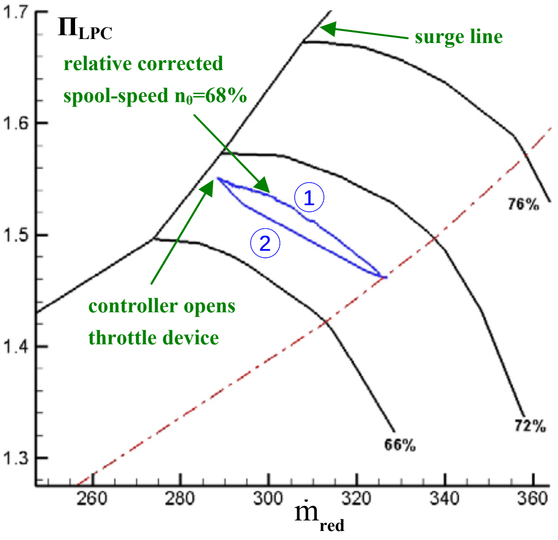

Fig. 12: De-throttling of LPC after stall detection

Just before reaching the surge line and generating compressor stall the controller identified the upcoming stall precursors and opened the throttle device forcing the operating point to return to the steady state operating line, which is illustrated by the second part of the blue graph. The very small remaining surge margin is distinctive in this case. Hence it is possible to make use of a wider operating range of the compressor without danger to suffer unstable conditions. This emphasizes the benefit and efficiency of this particular stall detection algorithm.

A set of tests in different operation areas of the Larzac engine confirmed these results. Thus the reliable detection of stall well in advance of flow separation on the compressor airfoils was proved.

Instead of de-throttling the LPC, which is not practicable at all aircraft engines, because of their fixed nozzle geometry, the controller was enabled to trigger another active stabilization system.

For this reason some further test runs have been performed to investigate the interaction between the stall detection system and the compressor stabilization via air injection in front of the low pressure compressor. As it is illustrated in figure 13 the engine is exemplary throttled at a spool-speed of $n_{\theta LPC}=56\%$ and the operating point approaches the surge line. Close to this stability limit the stall precursors are detected and the fast acting valves have been opened starting the axial air injection for an interval of 10 seconds. Within the described tests always all of the ten valves have been opened simultaneously.

By suppressing stall in the compressor the air injection allows running the engine continuously stable under typically insecure conditions.

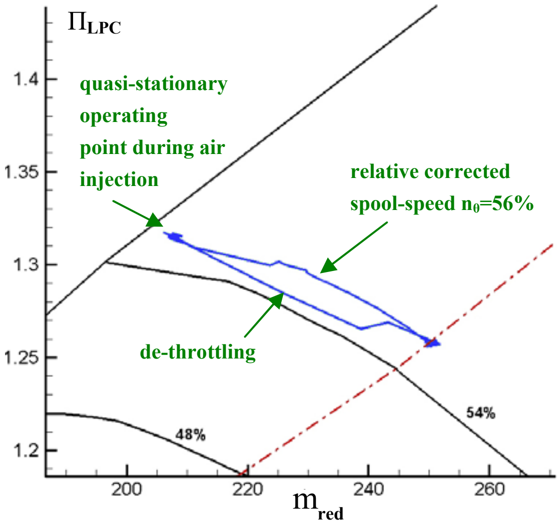

Fig. 13: Four cycles of air injection

If the LPC is not de-throttled during the air injection phase the compressor stalls immediately after the injection stops. The upcoming stall cells are detected by the controller and the counteractive measures are started again. In the illustrated test run the throttle was reopened during the fourth injection phase and the engine recovers at the steady running line.

Within these experiments the operation point was not shifted towards the surge line, since it was emphasized on stall detection and not on air injection as a method to increase the operating range. That this is also possible was proved by Leinhos et al. [7].

SUMMARY AND CONCLUSION

This paper presents the implementation and validation of a digital replica of the Larzac 04 C5 control device and an implemented active stability control system in order to operate aircraft engines at points of high efficiency close to the surge line. For this purpose, a twin-spool turbofan engine was equipped with extensive instrumentation, containing pressure transducers, thermocouples and other sensors to observe engine performance. The task to integrate a stall detection system into the control unit necessitates a retrofit of the standard analog controller by a digital control device. All tests performed and results discussed herein have been accomplished with both the original analog controller and the digital one. Dedicated parameters have been investigated to analyze the engine performance obtained with the two controllers within the whole operation area. This data does not reveal any inconsistency or anomaly. In order to investigate the interaction of the new digital control device and the series fuel controller, which remained at the test vehicle, additionally some selected parameters like the fuel-flow were examined during dynamic processes. For this reason the Larzac engine was accelerated and decelerated within different time intervals to cover as many transient operation conditions as possible.

After proving the full function of the new control unit, the stall detection algorithm associated with the active stability control system was tested. As an input parameter the signals of two Kulite pressure sensors installed upstream of the 1st LPC rotor were used. Summarizing the test results of the performed test runs using this system, a reliable and flawless service can be ascertained and it can be proved, that no compressor surge or other critical situations emerged with activated stall control.

Air injection at the tip region of the first rotor of the low pressure compressor represents an effective method to suppress rotating stall and increase the operating range of the engine. For the integration onboard an aircraft the injected air has to be provided by the engine itself or a second one. Therefore future research will focus on the assembly of recirculation for demonstration of the stall avoidance system in an environment compatible with airborne applications.

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REFERENCES

[1] Scheidler, S.G., Bindl S., Mundt C., 2006, "*Mapping the Control Parameters of an Analog Fuel Control to Prepare fort he Retrofit of a Digital Control Unit*", ASME GT-2006-90126, Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air, May 8-11, 2006, Barcelona, Spain.

[2] Froriep, R., Joos, D., Kreisselmeier, G., 1977, "*Optimal Open Loop Compensator combined with Riccati Feedback Compensator Control System Design applied to the Turbofan Engine Control*", Proceedings of the 1977 International Forum on Alternatives for Multivariable Control, Chicago, Illinois, USA.

[3] Skira, C.A., De Hoff, R.L., Hall, W.E., 1979, "*Design, Evaluation and Test of an Electronic, Multivariable Control for the F100 Turbofan Engine*", AGARD Conference Proceedings No. 274, Advanced Control Systems for Aircraft Powerplants.

[4] De Hoff, R.L., Hall, W.E., 1977, "*System Identification Principles Applied to the Control and Fault Diagnosis of the F100 Turbofan Engine*", Proceedings of the 1977 Joint Automatic Control Conference, San Francisco, California, USA.

[5] Auer, E.J., 1995, "*Modellbildung, Simulation und Entwicklung eines digitalen Reglers für eine Hubschraubergasturbine*", Dissertation (Ph.D. Thesis), Technische Universitaet Muenchen, VDI-Fortschrittsberichte, Reihe 8, Nr. 581.

[6] Grauer, F., 1999, "*Entwicklung einer Pumpgrenzwarnung für mehrstufige, hochbelastete Axialverdichter*", Dissertation (Ph.D. Thesis), Ruhr-Universität Bochum, VDI-Fortschrittsberichte, Reihe 7, Nr. 355.

[7] Leinhos, D.C., Scheidler, S.G., Fottner, L., Grauer, F., Hermann, J., Mettenleiter, M., Orthmann, A., 2002, "*Experiments in Active Control of a Twin-Spool Turbofan Engine*", ASME GT-2002-30002, Proceedings of ASME Turbo Expo 2002: Power for Land, Sea and Air, June 3-6, 2002, Amsterdam, Netherlands.

[8] Kefalakis, M., Papailiou, K.D., 2006, "*Active Flow Control for Increasing Surge Margin of an Axial Flow Compressor*", ASME GT-2006-90126, Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air, May 8-11, 2006, Barcelona, Spain.

[9] Suder, K.L., Hathaway, M.D., Thorp, S.A., Strazisar, A.J., Bright, M.B., 2001, "*Compressor Stability Enhancement Using Discrete Tip Injection*", ASME Journal of Turbomachinery, 123, pp. 14-23.

[10] Strazisar, A.J., Bright, M.M., Thorp, S., Culley, D.E., Suder, K.L., 2004, "*Compressor Stall Control Through Endwall Recirculation*", ASME GT-2004-54295, Proceedings of ASME Turbo Expo 2004: Power for Land, Sea and Air, June 14-17, 2004, Vienna, Austria.

[11] Hoess, B., Leinhos, D.C., Fottner, L., 2000, "*Stall Inception in the Compressor System of a Turbofan Engine*", ASME Journal of Turbomachinery, 122, pp. 32-44.

[12] Leinhos, D.C., 2003, "*Aktive Stabilisierung der Verdichterstroemung in einem Zweikreis-Turbostrahltriebwerk*", Dissertation (Ph.D. Thesis), Universitaet der Bundeswehr Muenchen, VDI-Fortschrittsberichte, Reihe 7, Nr. 448.

[13] Bindl, S., 2005, "*Neuaufruestung eines Larzac 04 Triebwerkes an der Triebwerksversuchsanlage und Durchfuehrung erster Messungen*", Diplomarbeit (Diploma Thesis), Technische Universitaet Muenchen & Universitaet der Bundeswehr Muenchen.

[14] Scheidler, S.G., Fottner, L., 2003, "*Active Stabilization of the Compression System of a Twin-spool Turbofan Engine at Inlet Distortions*", ISABE-2003-1083, Proceedings of the XVI. International Symposium on Air Breathing Engines (ISABE), Cleveland, Ohio, USA.

[15] Herpel, T., 1995, "*Untersuchungen zum dynamischen Leistungsverhalten von Turbostrahltriebwerken unter Beruecksichtigung instationaerer Verdichterstroemungen nahe der Stabilitaetsgrenze*", Dissertation (Ph.D. Thesis), Universitaet der Bundeswehr Muenchen, VDI-Fortschrittsberichte, Reihe 7, Nr. 286.

[16] Hoess, B., 1998, "*Zum Einfluß von Eintrittsstoerungen auf das dynamische Leistungsverhalten von Turbostrahltriebwerken unter besonderer Beruecksichtigung instabiler Verdichterstroemung*", Dissertation (Ph.D. Thesis), Universitaet der Bundeswehr Muenchen.