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A NOVEL GRAZING FLOW RIG FOR ACOUSTIC LINER INVESTIGATIONS

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Abstract

Acoustic liners can represent an effective strategy for noise reduction in aero engines. To assess the sound absorption effectiveness under representative operating conditions and to validate numerical methods, the treatments shall be characterized by using grazing flow rigs. Purpose of this survey is to describe the design solutions adopted in a brand-new test rig aimed at evaluating the performance of the liners under testing conditions representative of the turbine exhaust in an aircraft engine, i.e. high flow speed and temperature. The main components of the rig have been numerically investigated from an aerodynamic, thermo-structural and acoustic perspective. The relevant outcomes are reported in the paper. After the rig has been manufactured and assembled, a preliminary commissioning has been performed to verify the rig operability and performance, with special focus on the acoustic behavior.

KEYWORDS

Acoustic liner, grazing flow rig, noise measurement, low pressure turbine

Nomenclature

A/D	Analog to Digital
AT	Anechoic Termination
CFD	Computational Fluid Dynamics
DSA	Dynamic Signal Analyzer
FEM	Finite Element Method
inc	incident
LPT	Low Pressure Turbine
m	Mass flow
N	Rotor speed
PA	Power Amplifier
PID	Proportional Integral Derivative
PML	Perfectly Matched Layer
PR	Pressure Ratio
R	Reflection Coefficient
refl	reflected
SDOF	Single Degree of Freedom
SPL	Sound Pressure Level

INTRODUCTION

The reduction of the noise generated by the aircrafts is critical for the growth of air transports and for the quality of human life in residential areas around the airports. The fan noise is the major source of propulsion noise but other engine modules, such as the Low-Pressure Turbine (LPT), are becoming increasingly important from an acoustic perspective, especially in light of future architectures.

There are basically two approaches to limit the acoustic emissions of an aero engine: reducing the noise generation at source, and/or increasing the noise propagation losses through noise control devices, such as the acoustic liners. The installation of acoustic treatments at the wall of the flow passages (i.e. intake, bypass and exhaust) in modern turbofans represents a consolidated design strategy to keep the acoustic signature within specific requirements. Several liner configurations are normally considered to damp both broadband and tonal noise components, including locally and non-locally reacting panels. The simplest and traditionally most investigated configuration is the single layer or single degree of freedom (SDOF) treatment, consisting in a porous face-sheet joined on top of a honeycomb core that is fixed to a rigid back-plate. The acoustic performance of a liner is obviously dependent on its geometry but also the interaction of the porous surface with the air flow plays a key role. For this reason, a precise validation of the liner behavior cannot disregard the experimental assessment of its performance in representative working conditions, and the exploitation of grazing flow rigs, providing the requested aerodynamic conditions together with selected acoustic perturbations, is an attractive way to measure the liner absorption in a well-defined and controlled environment.

In recent years, some experimental activities have been carried out to evaluate the capability of grazing flow test rigs to properly assess the liners performance. Rademarker et al. (2003) [1] introduced a rig capable of testing liners under hot working conditions. This facility is able to reach a testing temperature of about 500 °C and incoming pressure level of 145 dB within the frequency band 0.5 to 5 kHz. The so-called GIT-TB and GIT-95M have been developed at NASA by Jones et al. (2004) [2]. The GIT-95M, which is an improved version of the GIT-TB, benefits 95 microphones while the previous rig version relies on 2 microphones. Both configurations are suitable for operating at ambient temperature and flow Mach number up to 0.5. The NASA CDTR, acronym for Curved Duct Test Rig, has been described by Gerhold et al. (2006) [3]. Despite other test rigs, the CDTR has a curved test-section that aims to address the effects of the duct’s curvature on the wave propagation. One of the most recent works for hot measurement purposes is done by Knobloch et al. (2011). The so called Hot-Acoustic-Test rig (HAT) can reproduce almost realistic engine condition [4]. Busse-Gerstengarbe et al. (2012, 2013) [5, 6] carried out a study to compare the results obtained with different test rigs (at NASA and DLR) to find out the effect of different test rig configurations and post-processing methods on liner characterization. They assessed the liner behavior in both rectangular (DUCT-R) and square (DUCT-S) cross-sectioned ducts.

To the authors’ knowledge, the experimental investigations targeting the turbine exhaust operating envelope are however limited, and the design guidelines usually rely on cold flow evidences through read-across approaches.

In this paper, a brand-new test rig for the acoustic characterization of flat liners is described. The document reports the main design solutions deployed to allow the evaluation of the acoustic treatments’ performance under testing conditions representative of an aircraft engine, and specifically the turbine exhaust. To achieve this goal, the rig must operate at both high flow

temperature (450 °C) and speed, and its design must be carefully addressed to meet both aero-acoustic and thermo-structural requirements.
The rig development activity is still ongoing at the Department of Industrial Engineering of the University of Florence to finalize and further improve the test bench.

TEST LOGIC AND RIG LAYOUT

The performance of a liner installed at the wall of a duct can be described by its acoustic impedance. Since the presence of an air flow inside the duct dramatically affects the liner behavior, it is essential to test the treatment under well-known and representative aerodynamic conditions.
The layout of the test rig located at the University of Florence is shown in Figure 1. The rig is substantially a long straight duct, acting as a wave guide, in the middle of which a liner is installed. An air flow at desired temperature and speed conditions is generated within the duct, and a specific acoustic perturbation is produced too, by means of a dedicated loudspeakers system. When the acoustic wave reaches the liner and interacts with it, the acoustic filed is expected to experience a reduction in its amplitude.

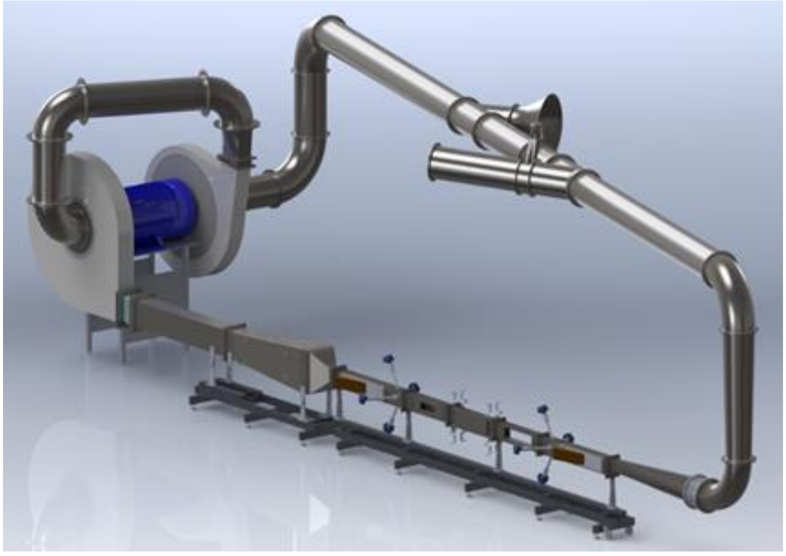

Figure 1: Grazing flow rig layout

The incoming and outgoing pressure fields are acquired by two measurement modules composed by several flush-mounted microphones, located upstream and downstream the liner according to optimized patterns. The possibility to install the microphones in front of the liner is foreseen too. Thanks to dedicated numerical techniques, the raw acoustic signals are post-processed, and the impedance and insertion loss of the investigated liner can be assessed in the frequency band of interest. Further, the implementation of anechoic terminations at the boundaries of the test section is foreseen, to avoid detrimental spurious back-reflections. The main components of the test bench are hereafter presented with a special focus on the crucial technical requirements that have been satisfied.

TEST SECTION

The test section is the first component to be designed since it not only defines the acoustic properties of the wave guide, but also strongly impacts the aero definition of the rig and the power supply requirements. A rectangular cross-section has been selected because it has the advantage of imposing different cut-on frequencies for transverse modes that relate to different directions, e.g. referring to Figure 2, n-modes and m-modes [7].

For what concerns the cross-section, two competing objectives must be fulfilled: the transverse area has to be small enough to reasonably extend the plane wave range, but not too small to prevent the propagation of higher order modes within the frequency band of interest. Moreover, a too pronounced reduction of the test section area dramatically rises the head losses inside the test duct, and the required fan power as well. This aspect is critical especially when air flows at high Mach number and high temperature. Another acoustic constraint considered during the design process is related to the separation between adjacent cut-on frequencies, to guarantee a robust and precise control on the incoming acoustic perturbations. All these considerations led to the definition of an optimal geometry for the test section as the best trade-off among the extension of the plane wave range, the separation between adjacent cut-off frequencies and the overall aerodynamic losses.

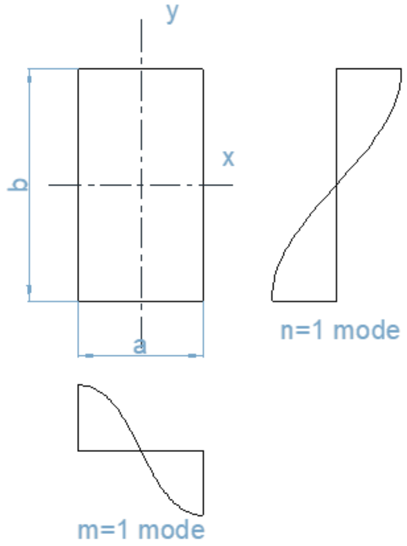

Figure 2: Test section geometry and transverse mode schematic

FAN AND INLET PLENUM

Once the test section and the overall facility envelope to be covered have been defined, the air-supply plant characteristic curves and the power requirements for the driving compressor have been easily derived. The most critical working conditions are those corresponding to the maximum temperature, hence they have been considered as the design parameters. The main difficulties to be overcome were the need to provide high prevalence at relatively low flow-rate, and the need to withstand the high temperature of the gas.

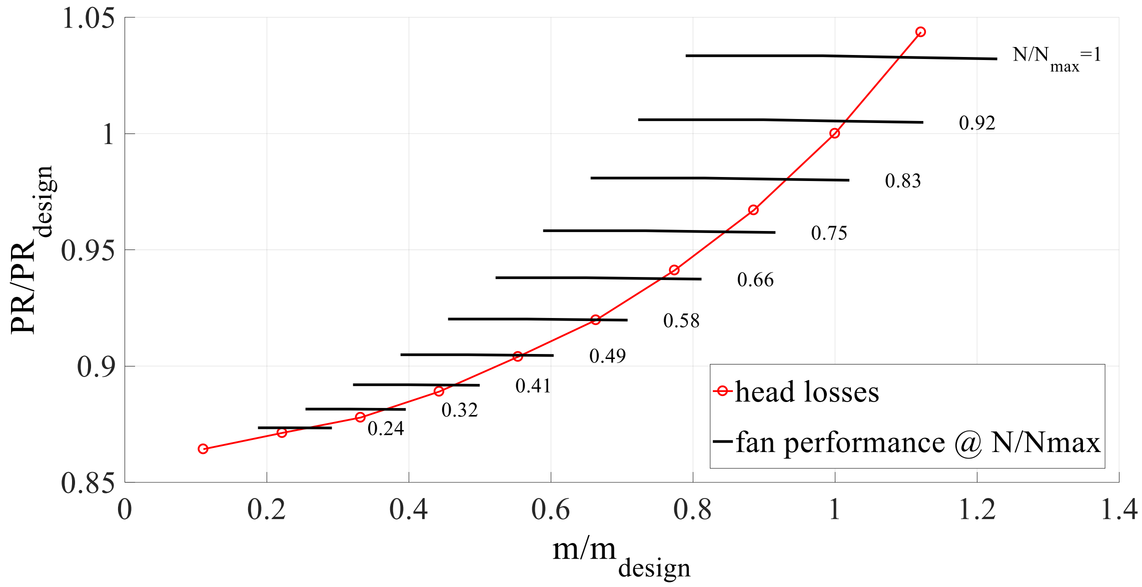

Figure 3: Fan performance map

A two-stage centrifugal fan has been selected from manufacturer's data. Figure 3 shows the non-dimensional performance curves of the fan. The parameters on the axes are:

- non-dimensional mass flow: $m = \frac{\dot{m}\sqrt{T_{01}}}{p_{01}}$
- pressure ratio: $PR = \frac{p_{02}}{p_{01}}$

The performance curves of the fan are scaled to the maximum rotation speed as fixed by the manufacturer. A thorough fan commissioning activity has been performed: both open and closed-circuit tests have been carried out to assess the performance of the fan at various inlet conditions, focusing on the capability of the fan to operate with a low inlet density representative of high temperature flows.

As it is fundamental to have a known flow regime inside the test section, a plenum has been designed and positioned at the exit of the fan to produce an air flow with a good uniformity at the desired operating conditions. Supporting CFD simulations have been performed to analyze the air flow behavior within the plenum as well as inside the test-section (Figure 4). The strong area contraction provided by the nozzle significantly improves the quality of the air flow, and this beneficial impact has been verified also imposing pronounced spatial perturbations at the exit of the fan volute. Once defined the plenum geometry, a more comprehensive CFD study has been carried out to verify the aerodynamics of the overall rig, from the fan exit station to the end of the test-section where a final diffuser has been designed to direct the air into the return circuit. The investigations confirmed the main design parameters, such as the overall pressure losses, the flow uniformity, all relevant quantities of the mean flow and the boundary layer at testing conditions representative of the LPT exhaust.

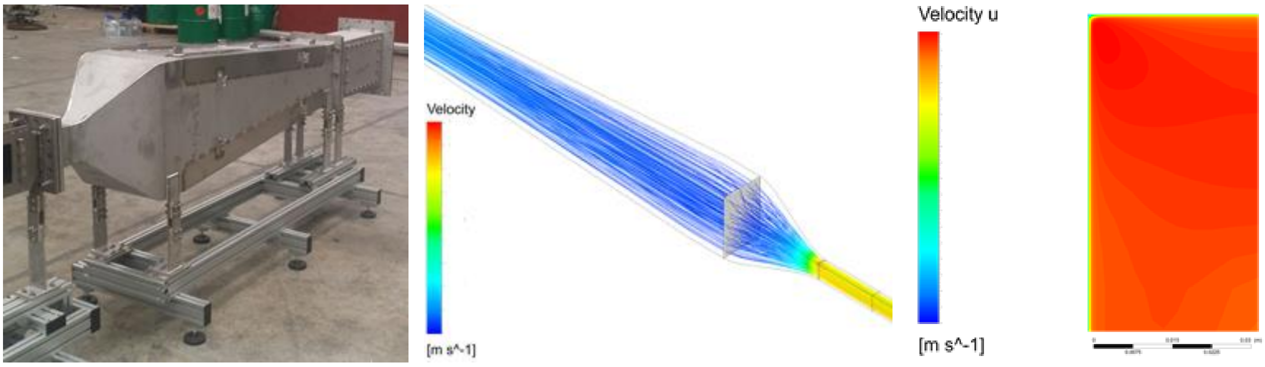

Figure 4: Inlet plenum and supporting CFD investigations

ANECHOIC TERMINATIONS

Two anechoic terminations (AT) have been placed at the boundaries of the test section to reduce the detrimental effects due to undesired spurious noise back-reflections. The acoustic design of these components has been carefully addressed to minimize the acoustic pressure reflection coefficient (p_{refl} /p_{inc}), i.e. the ratio between the reflected pressure and the incoming pressure.

Figure 5: Anechoic Termination

As shown in Figure 5, the anechoic termination is basically a cavity filled by a sound absorbing material which is separated from the flow by a perforated metal sheet (Figure 6).

Figure 6: Perforated metal sheet and absorbing material inside the anechoic termination

The design concept of the AT has already been presented by the authors [8]. However, a dedicated numerical activity has been performed to identify the best geometry, investigating different axial lengths, absorbing materials and several operating points, ranging from cold to hot conditions. For the numerical analyses, ¼ of the anechoic termination geometry has been considered. To guarantee a proper description of the wave propagation in the frequency range of interest, the mesh has been properly refined to satisfy a minimum number of cells per wavelength. Rigid walls are assumed for the duct while the sound absorbing material enclosed in the AT shell is modeled as a poro-acoustic domain. An abrupt change in the cross-section is foreseen at the exit boundary of the domain to promote the generation of significant back-reflections. To simulate a free-field radiation of the sound waves an appropriate boundary condition is considered, consisting in a two-layer sphere, with the outer layer working as a PML (Perfectly Matched Layer). Figure 7 shows the model adopted to calculate the reflection coefficient, as well as results at two frequencies in terms of sound pressure.

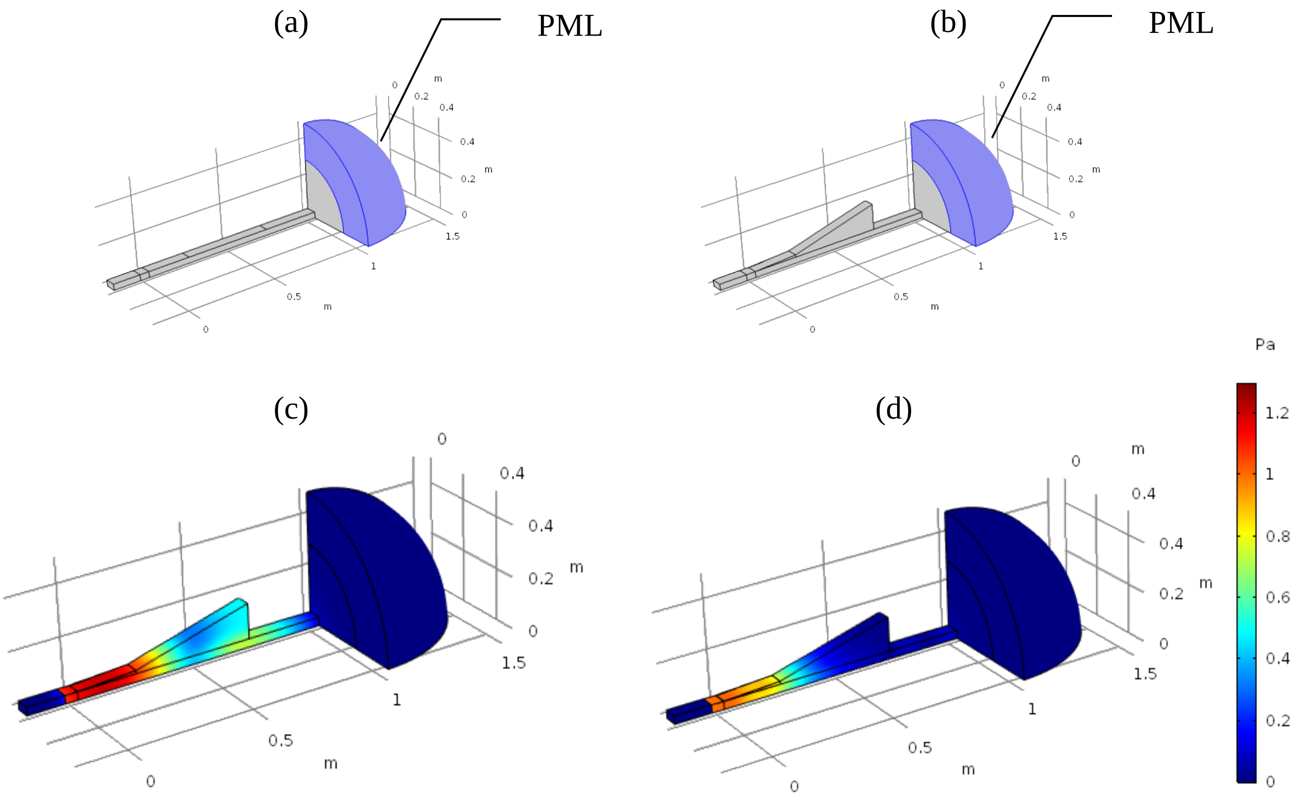

Figure 7: Standalone duct with PML (a), Duct with poro-acoustic domain (b), FEM results for acoustic pressure @ 200 Hz (c), FEM results for acoustic pressure @ 1000 Hz (d)

Figure 8 reports the numerical predictions of the reflection coefficient for anechoic terminations of different sizes. It should be mentioned that the numerical analysis has been limited to 1 kHz to reduce the computational effort. However, it is expected that the reflection coefficient at higher frequencies is lower.

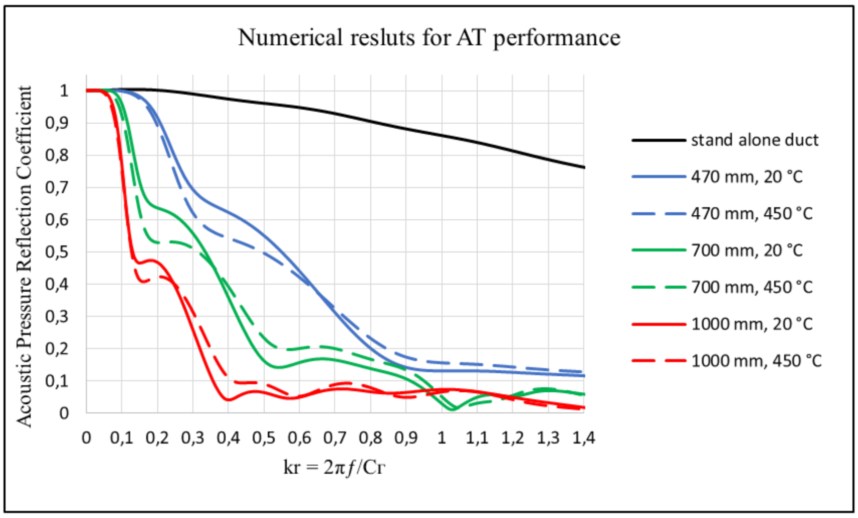

Figure 8: Numerical results gained for reflection coefficient of AT

The 700 mm length has been selected as it guarantees an excellent performance in the frequency band of interest, in spite of the limited axial extension. Once realized and installed on the test rig, the AT has been preliminarily tested to validate its acoustic behavior. As shown in Figure 9, the measured reflection coefficient is sufficiently low within the analyzed frequency range (500 Hz to 2500 Hz) and it also provides a qualitative good matching with the numerical predictions. The discrepancies in terms of absolute values are probably related to the uncertainty in the definition of the absorbing material's properties. Furthermore, as suggested by the experimental curve, the value of reflection coefficient is expected to be small enough also in the high frequency range. Further, it was observed that the reflection coefficient curve does not change significantly in the presence of a high-speed grazing flow within the duct.

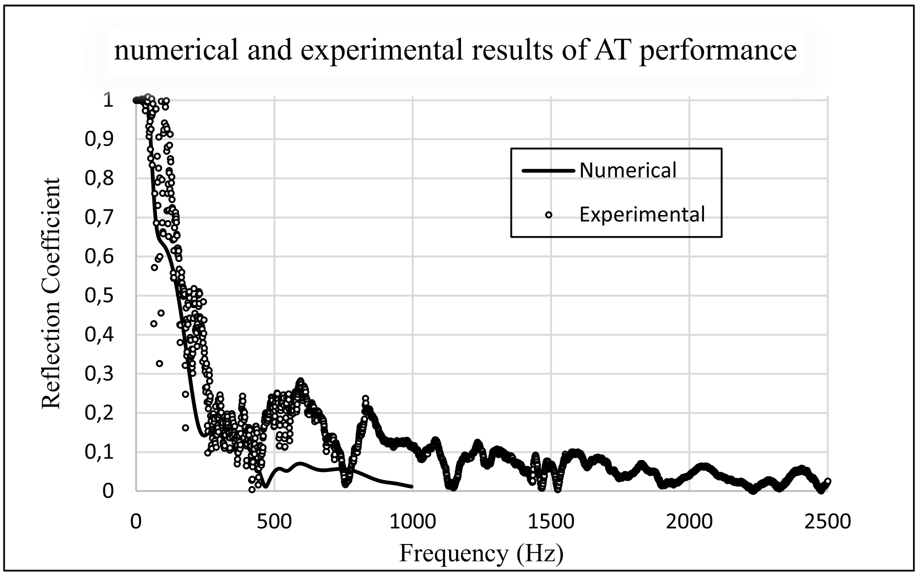

Figure 9: Numerical and experimental results comparison for 700 mm AT @ 20 °C

MEASUREMENT SECTIONS

The most important part of the rig, from the measurement point of view, is of course the test-section, even if a wide set of sensors has been deployed in different parts of the rig to guarantee the correct functionality and stability of the facility during operations. The test section is provided with removable side plates that can be used for the installation of acoustic and aerodynamic instrumentations (Figure 10).

Figure 10: Test-section and instrumented sections

Aerodynamic Instrumentation

Since a precise measurement of the background flow field is crucial for the acoustic characterization of the treatments, a set of aero sensors is foreseen at different positions to describe the flow inside the rig. A Kiel probe with thermocouple is placed in the inlet plenum to acquire the total flow quantities. This is particularly important for the setting of the operating conditions. A 3-dimensional probe can be installed on a traversing system in the measurement sections, upstream and downstream the liner port, to get the flow map inside the duct. One Pitot tube is mounted at the end of the duct to monitor the flow speed and exit conditions. All the selected sensors and probes are appropriate for working in a high temperature environment. A multi-transducer pressure scanner equipped with a multi-channel A/D is deployed for the acquisition of the mean flow parameters during the tests. Finally, some non-intrusive static pressure taps and thermocouples are foreseen along the test-section to monitor the flow evolution within the duct also during the acoustic characterization, when intrusive probes are not installed.

Acoustic Instrumentation

The acoustic instrumentation setup is composed of a wave generator and a measurement system. The acoustic excitation within the duct is provided through a set of speakers, acting as acoustic sources. These speakers are mounted at the upstream and downstream sides of the test-section to generate both downstream and upstream traveling sound waves, and are connected to the internal duct by means of stainless tubes following angled patterns to avoid severe aerodynamic interactions in the junction points. To generate the desired acoustic field within the duct, a signal is produced through an arbitrary waveform generator, then it is amplified to gain a well-defined sound pressure level and sent to the speakers.

For what concerns the acoustic measurement system, it is composed of a 24 Bit resolution Dynamic Signal Analyzer and Acquisition System (DSA), providing up to 80 channels for the high-speed synchronous sampling of the acoustic signals with maximum allowed sample rate per channel of 204.5 kHz. The system allows also to use high sampling speed boards for bridge-type channels with a passband up to 40 kHz for the conditioning and the acquisition of pressure signals provided by piezo-resistive dynamic sensors. The acoustic signals are measured at a given number of measurement positions through an on-purpose designed array. The rig can provide up to 30 measurement points in both the upstream and downstream sections, allowing the modal decomposition of the acoustic field up to a non-dimensional frequency $k_0' * b = 10$. Figure 11 shows the results for the conditioning number obtained with the chosen measurement array.

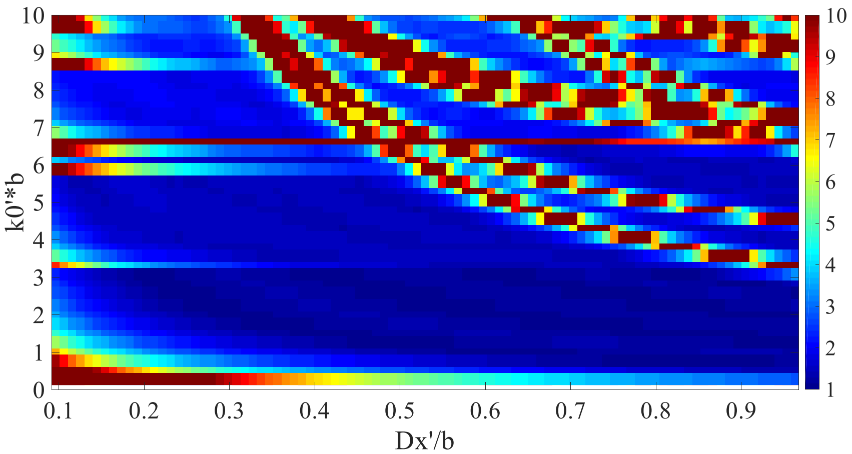

Figure 11: Conditioning number analysis for microphones' arrangement

Another linear array of sensors can be deployed in front of the liner to evaluate the impedance. High dynamic range ¼" pressure-microphones can be used for sound pressure measurements in the flow duct, while miniaturized piezo-resistive pressure sensors can be exploited for in-situ impedance measurements. A dedicated mounting system providing the required thermal insulation has been developed for the microphones, to allow their installation and use also at high temperature testing conditions [9].

Hereafter, all the mentioned instruments are shown in Table 1.

Table 1: Possible rig instrumentations

Instrument	**Description**
Amplifier; Multi-channel PA amplifier	Channels: 8 Frequency range: 12 – 60,000 Hz
Speakers; high SPL compression driver	Max Power Rating: 50 w Impedance: 16 Ω Frequency range: 160 – 6,500 Hz Sensitivity: 113 dB/W/m
Microphone; ¼" Pressure-field Microphone	Nominal sensitivity: 1.6 mV/Pa @ 250 Hz Frequency range (±1 dB): 10 to 25 kHz Frequency range (±2 dB): 4 to 70 kHz

LINER SECTION

The test article, i.e. the liner sample, is placed in the middle of the test-section and, at both sides, measurement modules, speakers and anechoic terminations are installed (Figure 12).

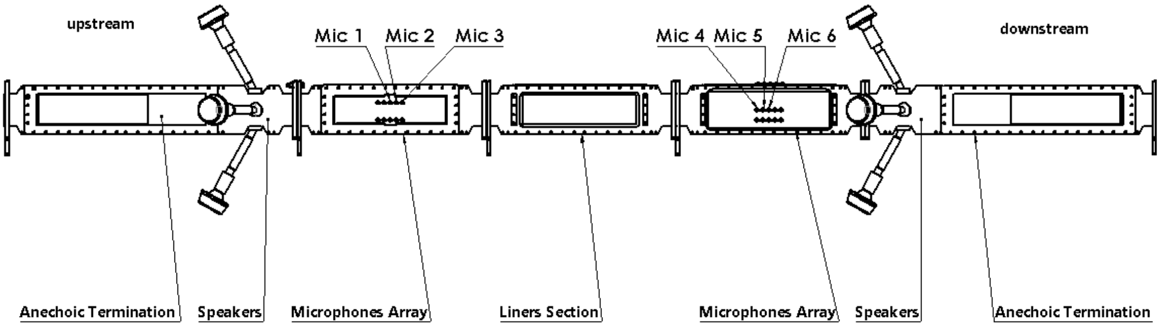

Figure 12: Schematic of the test-section with indication of main components

The liner is mounted in a dedicated port and properly sealed by a ceramic gasket (Figure 13). Different axial lengths and cavity depths can be investigated since the holding system can easily manage liner's geometry variations. Currently, just one side of the duct is equipped with an acoustic treatment but the installation of two liners is possible too.

Figure 13: Liner and liner port

RIG THERMAL CONTROL

The test rig has been designed to work at both cold and hot conditions. The maximum feeding temperature is 450 °C and the maximum flow Mach number at high temperature is around 0.5.

Following analytical simulations, the target temperature is expected to be reached through the air recirculation inside the test rig, i.e. heating can be provided by the friction itself. This aerodynamic heating of the air is due to the small cross section area of the test section and the high speed of flow inside the circuit, which is achieved through the full-power fan operating condition. Resulted temperature is expected to rise because the test rig is a closed circuit and is thermally insulated by an external glass wool shell. In case of need, an electrical heater is foreseen to provide additional heating. In order to compensate the thermal expansion stresses, two expansion joints are installed at the boundaries of the test-section and the entire bench can move on rotating supports (Figure 14).

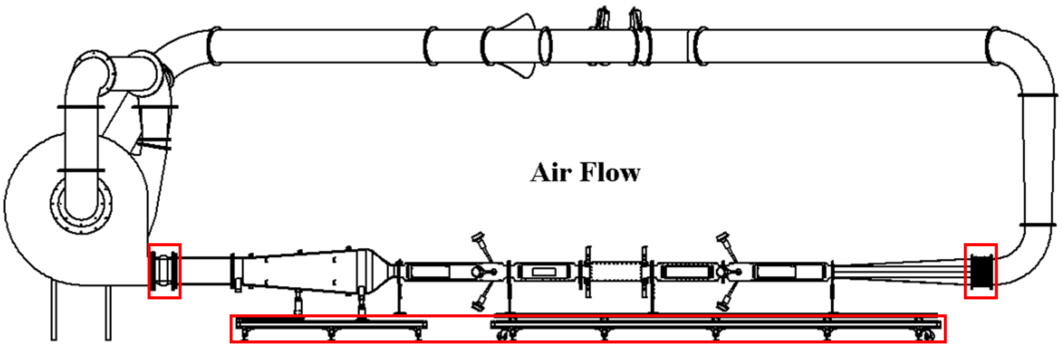

Figure 14: Thermal expansion control devices (in red)

The thermal control and stabilization of the testing condition at high temperature is achieved through the returning circuit, which allows the mixing between cold external air and hot internal air thanks to the activation of two dedicated valves (Figure 15):

- a discharge valve at the outlet port, which vents part of the hot air into the external environment
- a recharge valve at the inlet port, which sucks the required cold external air

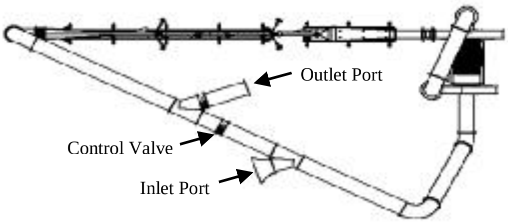

Figure 15: Return circuit and mixing valves

To investigate the capability of the proposed temperature control system to provide stable operating conditions, a simulation has been performed (Figure 16) through a dynamic simulation software. The test bench is simply modelled by means of different pipe sections, having appropriate lengths and areas in order to reproduce the aero losses expected within the circuit. The mass flow rate is inserted through the model by means of the fan and is gradually increased until reaching the desired target value. Then it is controlled to keep it constant and guarantee its stability throughout the entire test duration. The outlet is modeled by the aforementioned discharge valve, whose working condition is described by a percentage of the fully open position. A PID controller is dedicated to change the position of this valve and keep the temperature in the desired range. The outlet port is followed by a control valve, which is located between the outlet and inlet ports to control the pressure difference between these two axial stations. The inlet port is also modeled by a recharge valve, whose position is imposed at the beginning of the simulation process and is considered, for the moment, as a fixed parameter to limit the complexity of the control logic.

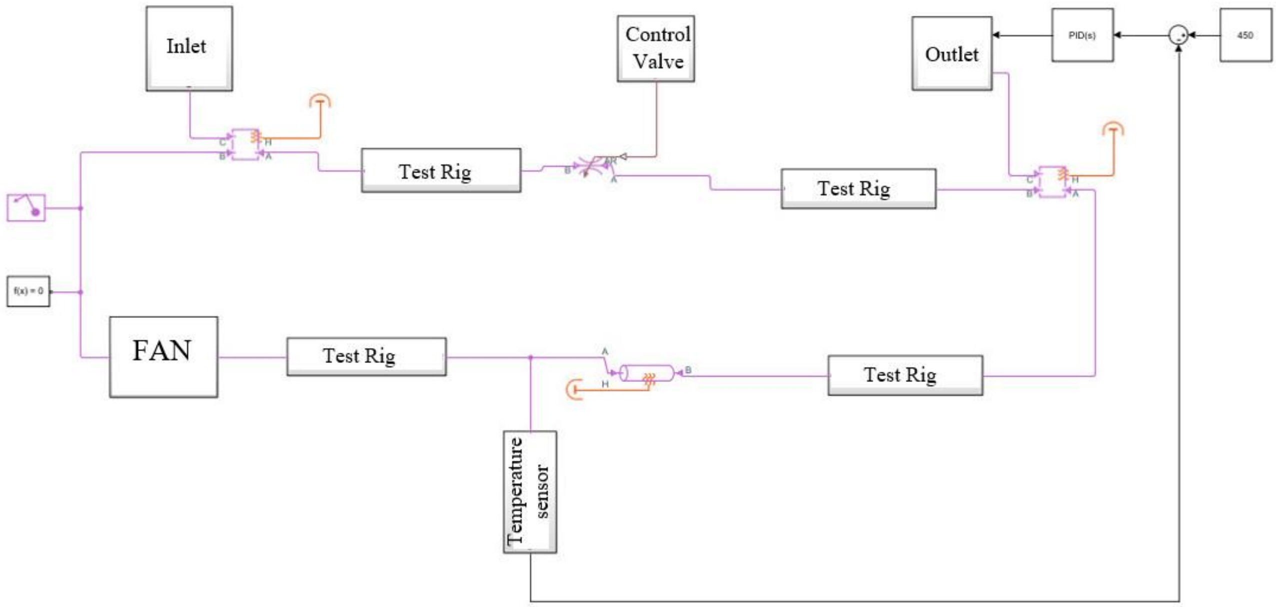

Figure 16: Simplified schematic of the simulation

An example of simulation's results is reported hereafter. In the current simulation, the mass flow rate of the fan is linearly increased from 0 to the target value in the first 50 seconds and then, for the entire simulation, it is kept constant. The target temperature is set to 450 °C while the control valve and the recharge valve are set to the 50% and 70% of their opening positions respectively throughout the entire simulation. It is worth to consider that, at the beginning of the simulation, the discharge valve is completely closed. It can be seen from Figure 17 and Figure 18 that meanwhile the temperature is below 450 °C, the PID controller keeps the discharge valve closed until the temperature exceeds the target temperature. At this point the PID controller partially opens the discharge valve to keep the temperature close to the desired value. When the discharge valve is close to the 6% of its opening position, the operating condition is guaranteed. From Figure 18, it can be noticed that, according to the control system logic, the transient phase is of short duration and the stabilization is achieved without temperature oscillations or severe unsteady spikes which could represent a concern for the structural integrity of the test bench. Therefore, according to this preliminary investigation, the system seems able to control the working temperature in a rather quick and stable manner.

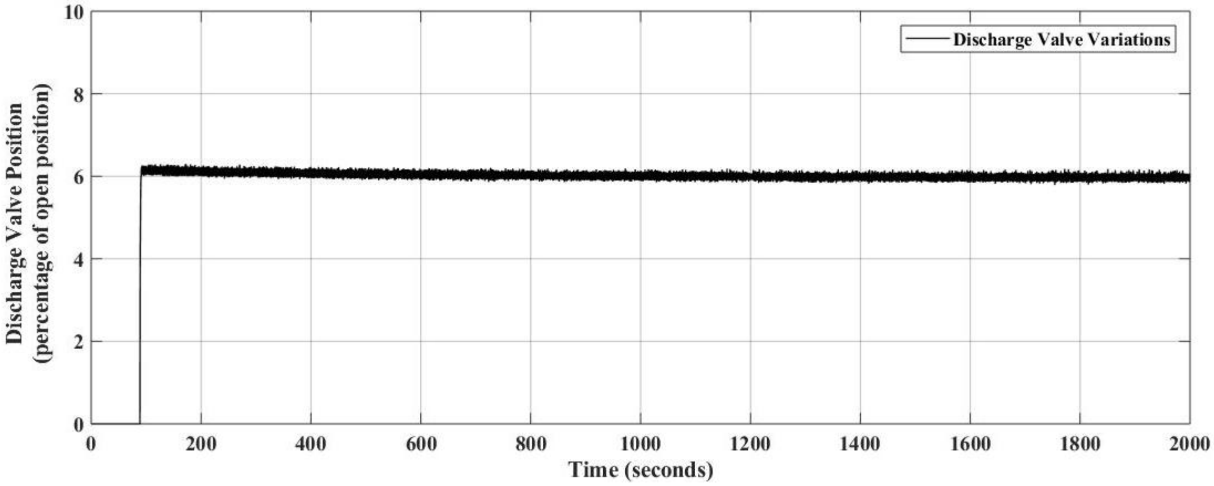

Figure 17: Discharge valve position through the simulation

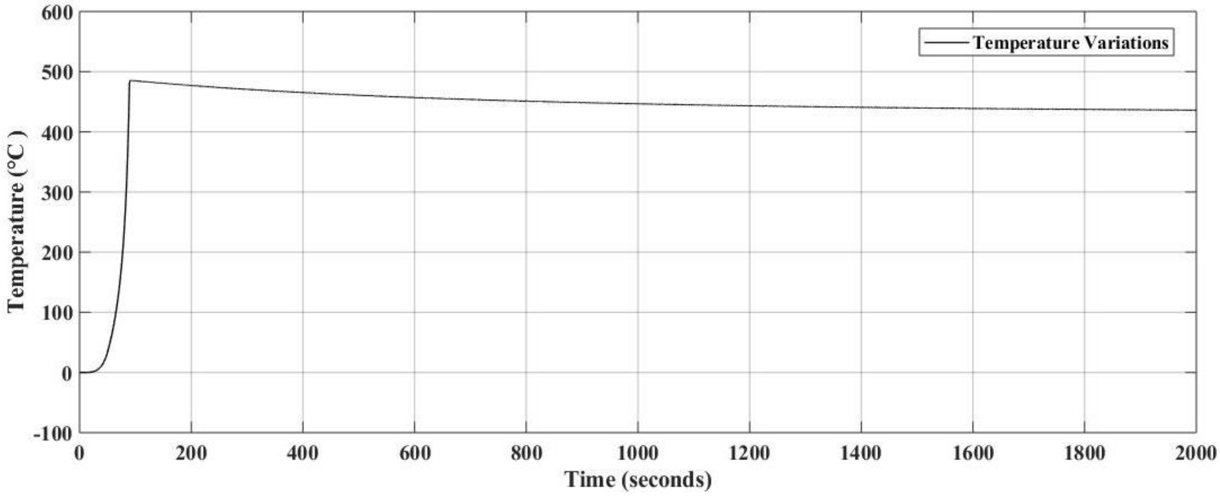

Figure 18: Temperature variation through the simulation

CONCLUSION

A test rig for hot acoustic measurements has been designed and manufactured at the Acoustic Lab of the University of Florence. The test rig aims to assess the effectiveness of acoustic liners which are supposed to be installed on turbofan engines, and specifically the turbine exhaust, for noise reduction purposes. The main design solutions adopted to meet the demanding test requirements (mainly high flow temperature and speed) are illustrated in the present work. The design has been supported by dedicated numerical analyses including aero, thermo-structural and acoustic modelling. The acoustic measurement set-up has been designed by using a condition number approach and the proposed methodology and results have been mentioned as well. A comprehensive study has been dedicated to the design of the anechoic terminations, representing a crucial component for the effectiveness and reliability of the rig. Furthermore, a description of the thermal control system is reported, and the outcomes of dynamic control simulations confirm the feasibility of the proposed approach to keep stable temperature and flow conditions.

All the rig components have been produced and assembled together and the rig is operating. A preliminary commissioning of the rig has been carried out and the performance of the anechoic terminations has been verified. The results demonstrate the effectiveness of this component as it provides a reflection coefficient lower than 0.2 in the frequency range of interest. In future publications, the complete aerodynamic, thermal and acoustic commissioning of the rig and the experimental characterization of conventional SDOF liners will be reported.

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REFERENCES

1. Rademaker, E.R., Idzenga, S.T., Huisman, H.N., Nijboer, R.J. and Sarin, S.L., (2003). *A new facility for hot stream acoustic liner testing*
2. Jones, M., Watson, W., Parrott, T. and Smith, C., (2004), May. *Design and evaluation of modifications to the NASA Langley flow impedance tube*. In 10th AIAA/CEAS Aeroacoustics Conference (p. 28-37).
3. Gerhold, C., Cabell, R. and Brown, M., (2006), May. *Development of an experimental rig for investigation of higher order modes in ducts*. In 12th AIAA/CEAS Aeroacoustics Conference (p. 26-37).
4. Knobloch, K., Lahiri, C., Enghardt, L., Bake, F. and Peitsch, D., (2011), January. Hot-Acoustic-Testrig (HAT): *A unique facility for thermoacoustic research.* In ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition (pp. 1023-1032). American Society of Mechanical Engineers.
5. Busse-Gerstengarbe, S., Richter, C., Thiele, F.H., Lahiri, C., Enghardt, L., Roehle, I., Ferrante, P. and Scofano, A., (2012). *Impedance eduction based on microphone measurements of liners under grazing flow conditions*. AIAA journal, 50(4), (pp.867-879).
6. Busse-Gerstengarbe, S., Bake, F., Enghardt, L. and Jones, M.G., (2013). *Comparative study of impedance eduction methods, Part 1: DLR tests and methodology*. In 19th AIAA/CEAS Aeroacoustics Conference (p. 21-24).
7. Munjal, M. L. (1987). Acoustics of ducts and mufflers with application to exhaust and ventilation system design. New York, Wiley
8. Taddei, F., De Lucia, M., Bartolozzi, L., Salvestroni, M. and Torzo D., (2016). *Setup of a test rig for the characterization of devices for acoustic measurements in hot flow*. In 23rd International congress on sound and vibration.
9. Taddei, F., De Lucia, M., Pourreza, A., Rashidi, H., Pierucci, G., Messeri, M., Fagioli, F., Salvestroni, M., Torzo, D., (2018) *Development of a measurement system for hot flow acoustic tests.* In 15th ISUAAAT International Symposium on Unsteady Aerodynamics, Aeroacoustics & Aeroelasticity of Turbomachines, Oxford, UK.