Dynamic probe for the measurement of acoustic pressure in aero-engines

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ABSTRACT

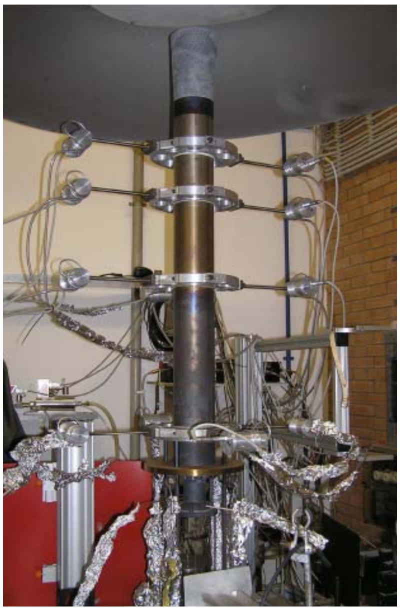
A new microphone probe for the measurement of acoustic pressure is presented which was designed for measurements within the core of an aero-engine, i.e. being able to cope with high gas temperatures and high static pressure. The new design is based on years of experience with similar sensors for ambient pressure applications. The operation principle, the calibration procedure, as well as issues of the application to laboratory experiments and full-scale aero-engines are described. The sensor has been tested successfully at a combustion facility in Romania within the framework of the EC-project TEENI (turboshaft engine exhaust noise identification). It will be applied within this project to a full-scale turboshaft engine [1] as well as for other acoustic research, e.g. the investigation of the effectiveness of liner samples in a new test facility at DLR in Berlin.

INTRODUCTION

With the increasing understanding of aero-engine noise sources from e.g. rotor/stator-interaction and high speed jet noise and the advent of respective technologies to reduce those sources, noise generation and mechanisms of propagation in the core engine become more important for future development. These internal noise sources are of even greater importance for turboshaft engines since here almost no jet noise is generated. In order to investigate unsteady phenomena in the core part of aero-engines, probes are needed which can cope with the demanding conditions in that part of the engine, i.e. high temperatures and static pressures as well as high flow velocities. Additionally to the demanding challenge due to the high mean quantities, the fluctuating components might be very strong as well, for instance the pressure fluctuations resulting from thermo-acoustic instabilities in lean combustion systems. For the investigation of combustion noise it is of utmost importance to measure the acoustic pressure fluctuations in the different engine components.
The Engine Acoustics department of the German Aerospace Center (DLR) in Berlin has developed and used microphone probes for several years. These probes are specifically designed for the application in hot environment, e.g. for the measurement of the sound field within a combustion chamber or an exhaust duct (Fig.1) where conventional microphones can not be used. The microphone itself is mounted at a remote location in order to protect it against heat and corrosive gases and requires a small amount of cooling air during operation. By combining several of these microphone probes sound generation and propagation were investigated in the small combustion chamber at DLR Berlin (Fig. 1). On the right hand side of Fig. 1 spectra of the sound pressure level in the exhaust duct of the test rig are shown (taken from [2]). Comparing the spectra of the hot and the cold (without combustion) case both having a Mach number of unity in the downstream nozzle, high amplitude low frequency fluctuations as well as broad band noise up to 3kHz - originating in the combustion process - are visible.

Although the microphone probes have been used extensively in hot regimes, no excessive pressure of the working fluid was present during these measurements. The maximum pressure encountered was less than 1bar above atmospheric pressure. In order to extend the range of application for this microphone probe to high pressure environment, a complete redesign was needed while maintaining the general principle of operation.

In the following section, the principle of operation will be described in detail as well as the improvements in design between the initial and the new pressure-proof design. Subsequently, two applications for the microphone probes of the new design will be highlighted: a full-scale turboshaft engine and a new test facility for aero-engine liner investigations.



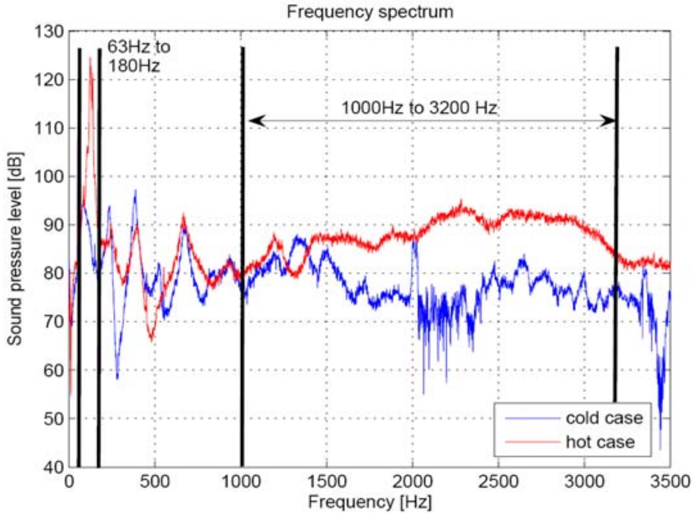


Fig 1. Left: Model combustor and exhaust duct at DLR lab with microphone probes (initial design) mounted at the exhaust duct. Right: Narrow and broad band combustion noise during operation compared to cold reference measurement (nozzle Mach number Ma=1, from [2])

OPERATING PRINCIPLE AND PROBE DESIGN

The new microphone probe - alike the probe in its initial design – uses some standard G.R.A.S. ¼" condenser microphone and pre-amplifier (type 40BH and 26AC), which are placed at a remote location for protection against heat and corrosive gases. The sound enters the probe from within the test facility through a tube which is mounted on the casing of the test facility. The microphone itself is placed perpendicular to the connection tube with its membrane flush to the tube wall (Fig.2). It is important to prevent reflections in this connection tube by extending it well beyond the location of the microphone membrane - following the principle of a semi-infinite duct. The overall length of this tube is about one meter which is mostly wind up in spirals to save space. Also, a small amount of cooling air is send during operation through this tube preventing hot gases getting into contact with the microphone membrane.

With the microphone probes of the initial design, an investigation was made into the effect of cooling flow on the measurement results. It could be shown that under atmospheric conditions as little as 0.054 kg/h cooling air (which corresponds to a cooling flow velocity of 4 m/s) is enough to protect the delicate G.R.A.S. microphone. Detrimental noise components were found only for cooling flow velocities above 30 m/s.

The required value for the cooling flow velocity holds also for applications with elevated pressure. However, the mass flow has to be adjusted according to the change in density of the cooling air.

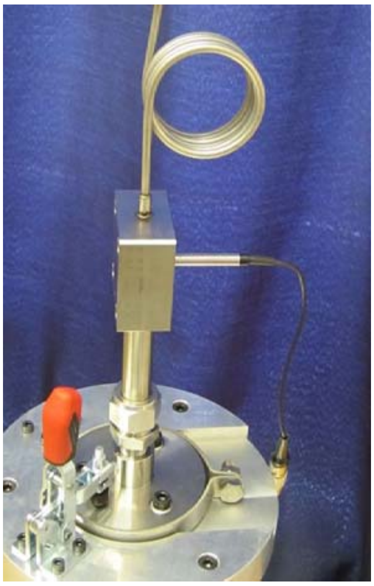


Fig. 2: Microphone and pre-amplifier are mounted perpendicular to the connection tube.

In Figure 3, a sketch of the new design and a pre-assembled prototype of the new design microphone probe are shown. As design criterion, a maximum allowable pressure of 20 bar was chosen in order to fulfill the requirements for the full-scale engine test within the TEENI project and for other future applications. The microphone probe will be mounted to a test rig via the large flange (12 in Fig. 3) and sealed with a metal C-Ring. For thermal insulation, a fiber disc can be placed between upper and lower flange. The electrical connector (Lemo, 11 in Fig. 3) and the quick connector for the cooling air (Parker, 8,9 in Fig.3) are rated beyond 20 bar. In case of a heavily vibrating test rig, a support beam (13 in Fig. 3) can be mounted yielding additional stiffness. Sealing of the microphone protection tube (2) to the end pieces (1 and 3) is accomplished by means of two graphite sealings.

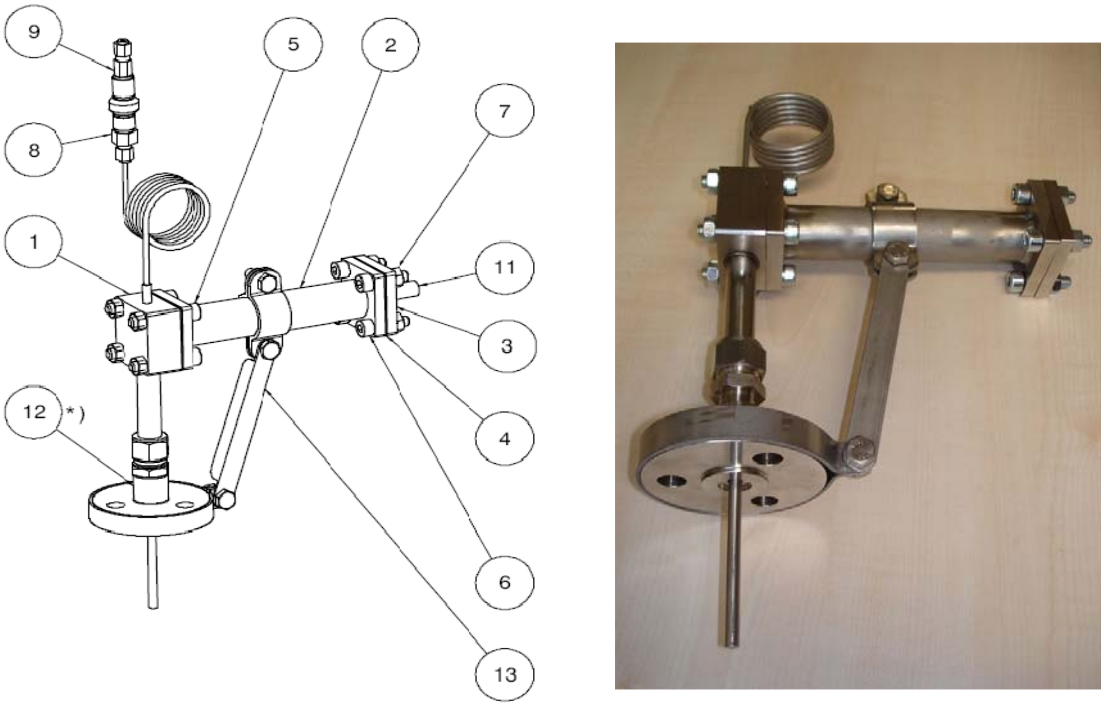


Fig. 3: Left: sketch of the new design of the probe microphone. Right: picture of first prototype (electrical connector (11) and quick connector for cooling air (8/9) missing).

During test rig installation, the 6 mm tube protruding below the flange (12) is inserted in the respective counter flange that the tip of the tube is flush with the test rig casing wall. This ensures negligible disturbance for the flow field while exposing only the tip of the probe to the highest temperatures.

CALIBRATION

Due to the remote location of the microphone membrane compared to the sound field inside the test facility, a transfer function has to be determined via a calibration over the frequency range of interest (usually between 50 Hz and 4 kHz). Generally speaking, this transfer function is determined by the geometry of the probe, i.e. the thickness of the tube, the distance between the tip of the probe and the microphone membrane, and other dimensions of the microphone installation. It was aimed to keep volumina in front of the microphone as small as possible in order to avoid strong resonance at certain frequencies. Since this mechanical setup does not change once the probe is assembled, the transfer function does not change significantly over the period of time the probe is used. However, small variations in manufacturing and assembly require the determination of individual transfer functions for each probe.

Prior to the determination of the transfer function and before each use, a quick one-point calibration with a pistonphone (250 Hz, 124 dB) is made. This provides an easy way for health checking of the microphone/pre-amplifier combination and by comparison with earlier readings spurious behaviour can be easily identified. In Fig. 4, the one point calibration (using an appropriate support for probe and pistonphone) and the device for the frequency calibration are shown.

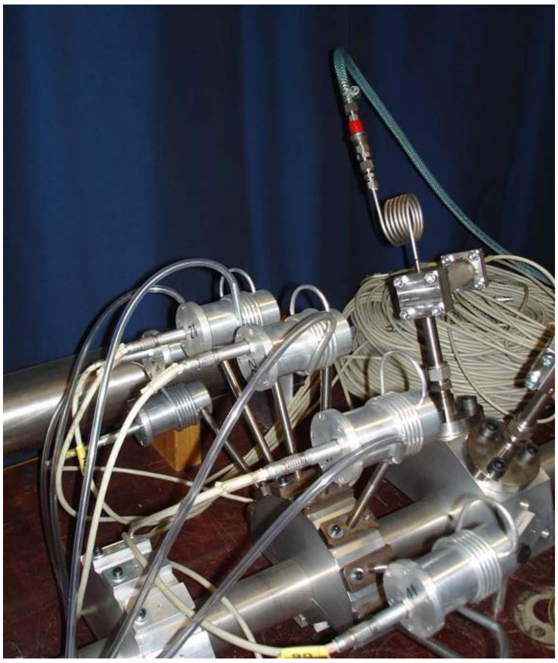


Fig. 4: Left: support device for one point pistonphone calibration. Right: Calibration device for frequency calibration supporting numerous probes of initial and new design.

The frequency calibration is made using a 50 mm-diameter tube to which probes of initial and new design can be mounted at different rings. The tip of the probe is flush with the tube inner wall. A reference microphone G.R.A.S. 40BP (with pre-amplifier 26AC) is mounted at the same axial position of such a ring of microphone probes. At the one end of the calibration unit, a sound field is excited by driving a Monacor KU-516 speaker with sine signals of certain frequencies. Below the cut-on frequency of the duct (which is about 4 kHz), only the plane wave mode can propagate yielding the same sound pressure at each circumferential position.

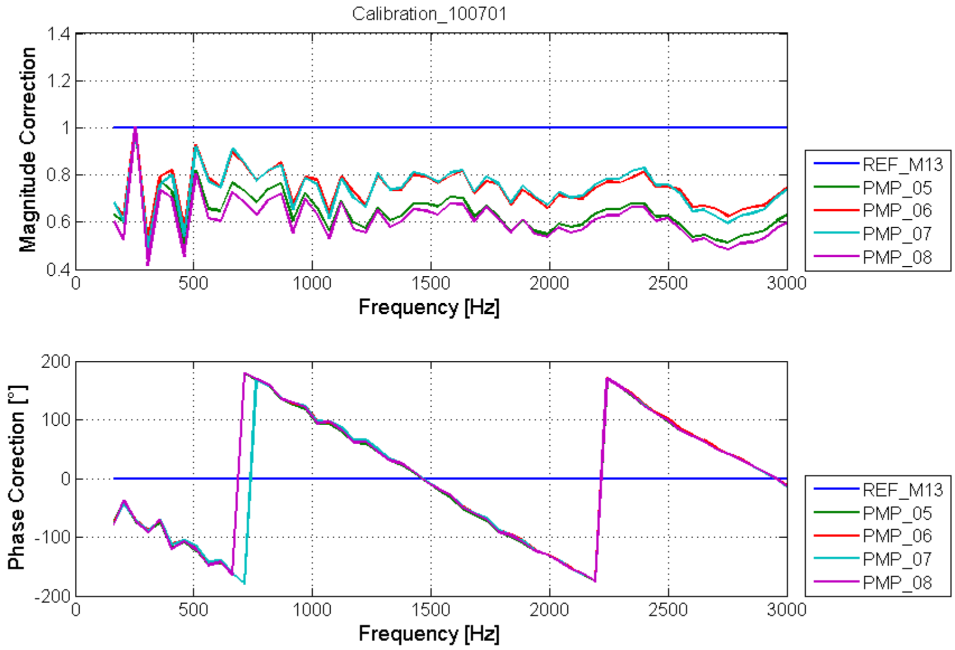


Fig. 5: Result of a frequency calibration (transfer function) for 4 new microphone probes.

Depending on the application, the calibration is made in steps of 1 Hz or at larger steps (e.g. 51 Hz for liner investigation) with the intermediate values being interpolated linearly. The lower frequency limit of the calibration is determined through the speaker. Since the Monacor KU-516 must not be used below 160Hz, a sub-woofer may be used instead to obtain the transfer function at lower frequencies. The microphone voltage is acquired using an OROS36 system with 24 Bit resolution at a sampling frequency of usually 8192 Hz.

In Fig. 5, the result of a frequency calibration is shown. The magnitude of the pressure fluctuations at the excited frequency is divided by the magnitude measured by the reference microphone. A factor below unity indicates an attenuation of the signal through the remote location of the membrane in the microphone probe. For the phase correction, the difference between the phase of the probe microphone signal and the reference microphone signal is used. The increasing phase difference with increasing frequency resembles the decrease in wavelength while keeping the travel length (from tip to microphone membrane) constant. Therefore the phase jump at about 700Hz and 2200Hz is just an artefact from the ambiguity of the inverse trigonometric function which can be corrected by physical reasoning.

The four probes shown in Fig. 5 show in general the same qualitative behaviour as could be expected due to their same dimensions. However, small deviations due to manufacturing tolerances cause the difference between the probes while the pairs (probe number 5 and 8, repectively 6 and 7) must be very similar.

The transfer funtion can be applied to acoustic measurements where the sound field is not known a-priori by correcting magnitude and phase of the spectral data in a postprocessing operation.

COMBUSTION NOISE APPLICATIONS

One of the design requirements for the new probes was the application to different engine zones of a turboshaft aero engine within the EC-project TEENI. The aim is to identify the different noise sources and to investigate the propagation through the other components of the core engine. Therefore, the expected engine parameters have been taken into account during the design phase with the combustion chamber imposing the strongest requirements with respect to temperature and pressure.

In order to prove the function of the probes well before the expensive main test, dedicated test facilities were chosen which resemble the expected engine conditions as close as possible. This will decrease the risk of sensor failure during the main test significantly and yield time for modifications and improvements after these test.

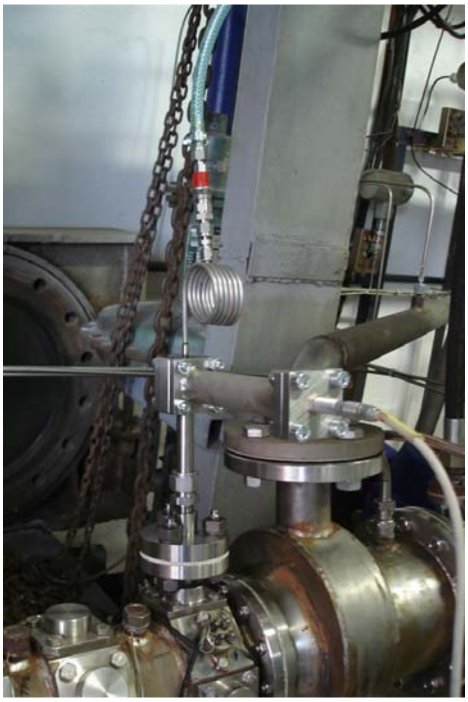


Fig. 6: New-design microphone probe during the high pressure test at COMOTI, Romania

For the microphone probes, a test rig of the Romanian Insitute for gas turbine research, COMOTI, in Bucharest had been chosen and prepared by designing respective flange connection (Fig. 6). Furthermore, the systems for air and gas supply where upgraded and standard instrumentation for pressure and temperature measurements was installed. Using natural gas and a huge air compressor station (with 2000 m³ pressure tanks) a continous operation at different pressure and temperature regimes was possible. These tests took place in February 2010 using two microphone probes of the new design. The cooling air was supplied from a bottle of compressed air (50 l, 200 bar). The cooling air mass flow for the two probes was adjusted by a Bronkrost ElFlow F-201AC (range 0.1-5 kg/h) depending on the pressure within the test facility. Data acquistion was made using the same OROS system as for the calibration.
The tests conditions were gradually increased from low pressure to high pressure with no problems in probe operation occuring during the full test. Temperatures up to 1200°C and and absolute pressure of 13.5 bar (limits of the test facility) have been reached. A typical test point – exhibiting also some unsteady low frequency

oscillations are shown in time (upper right graph) as well as in frequency domain in Fig 7. During the test it became clear, that the very high pressure amplitudes (beyond 50kPa) encountered during thermoacoustic resonance conditions may even reach the limit of the microphone capsules which is 100kPa (194dB) for the high pressure type 40BH. The ``normal version'' G.R.A.S. 40BP with its limit at 172dB can not be used at these combustor locations but may be used in other engine sections with lower pressure fluctuation amplitudes.

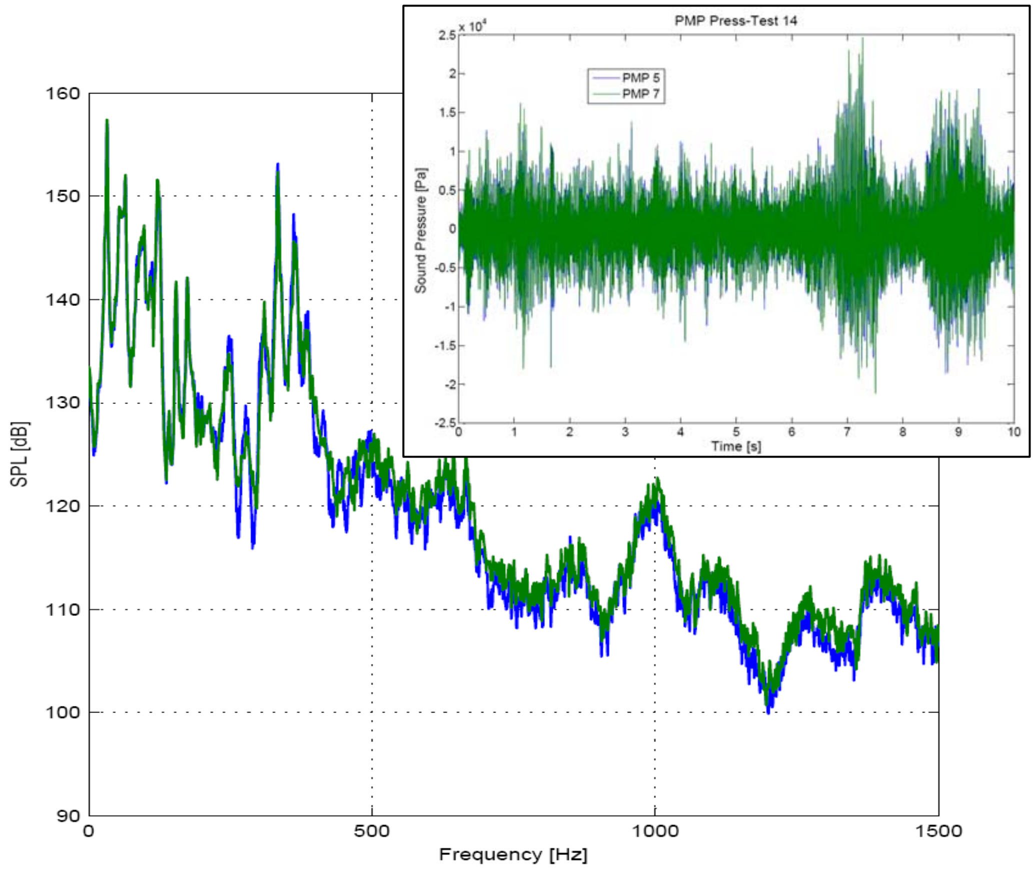


Fig. 7: Frequency spectra and time records of microphone probe signals at a typical working point of a combustor exhibiting some thermoacoustic instabilities.

While the safe operation of the new probes could be shown during the tests, the preparation of the full-scale engine test (scheduled for early 2011) involves serious considerations with respect to the integration due to limited space at the turboshaft engine. Therefore, modifications will be likely, e.g. skipping the large connection flange providing the sealing via the Swagelok connector which is screwed to the upper flange in regular assembly. The reduction of the overal length of the connection tube would be another option. However, this would invoke a large risk of sensor failure due to increased heat load for the electronic parts in the microphone capsule and the pre-amplifier. Furthermore, different access ports for the calibration device would be needed for each individual probe. The discussion on integration issues for the full-scale test is still on-going.

APPLICATION FOR LINER INVESTIGATIONS

A second field of application for the new microphone probes is the investigation of the acoustical behaviour of liner samples within high pressure and high temperature environment. The Department of Engine Acoustics in cooperation with the Technische Universität Berlin has recently constituted a unique test facility – the hot acoustic test rig (HAT) - for the investigation of perforated liners – also called bias flow liners - under conditions relevant for aero-engine applications. This facility can deliver a total mass flow of nearly 0.8 kg/s at temperatures reaching 800 K. The pressure within the facility can be adjusted between atmospheric conditions and 10bar. The bias flow liners to be investigated are used for instance in combustors to reduce thermoacoustic instabilities and to provide cooling of the structure at the same time. A comparable facility for investigation at atmospheric conditions (no additional heating, no elevated pressure) has been used successfully during recent years at DLR-Berlin [3]. A schematic view – representing the working principle of both (hot and cold) test rigs – is shown in Fig. 8. The loudspeaker on either the left or the right generates a sound field (plane wave below the cut-on frequeny) which propagates through the duct. In the liner sample module a part of the acoustic energy is dissipated due to the interaction of the bias flow with the sound field. When a mean flow is present in the duct, there is a difference between downstream and upstream propagation of the sound field requiring two measurements with subsequent acoustic excitation on either side. Actually, the details of the mechanism of dissipation of acoustic energy are not yet fully understood and subject to current research.

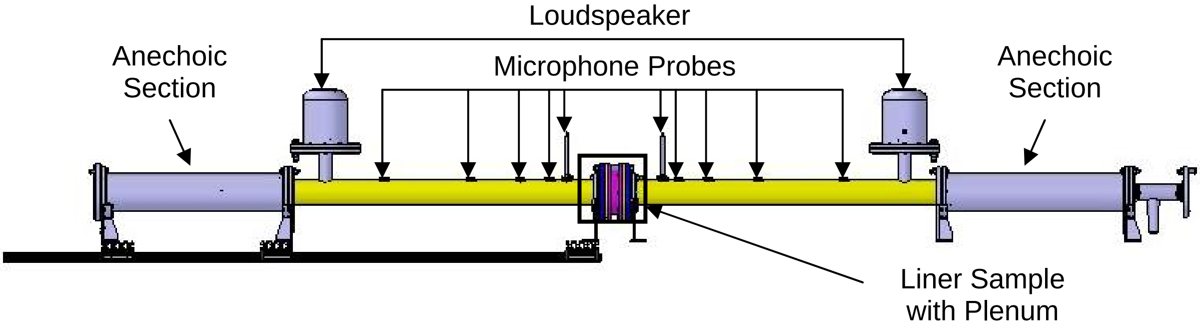


Figure 8: Principle of operation of liner test rig

While conventional microphones (G.R.A.S. 40BP/26AC) can be applied in the atmospheric test facility operating at ambient temperature, the new hot acoustic test rig requires the microphone probes described above. They are installed at certain locations as sketched in Fig. 8. The measurement of the acoustic pressure upstream and downstream of the liner allows determining the acoustic reflection, transmission and dissipation coefficients of the sample.
A calibration of the microphone probes can be performed similar to the calibration method described above (see section Calibration). Here, the microphone probes are mounted at the same axial position around the circumference of the duct. In this case the reference microphone is omitted and one microphone probe serves as reference. The resulting calibration data is relative to this chosen reference probe. Therefore it is possible to achieve calibration data at various temperatures and pressures for the frequency range of interest.

A first test demonstrates the accuracy of the new setup including the microphone probes. A zero-sample with a rigid surface without perforation (exhibiting virtually no dissipation) was used to determine the dissipation error. The resulting error of the dissipation coefficient below 3% over most of the frequency confirms the high accuracy provided by the new new mcirophone probes.

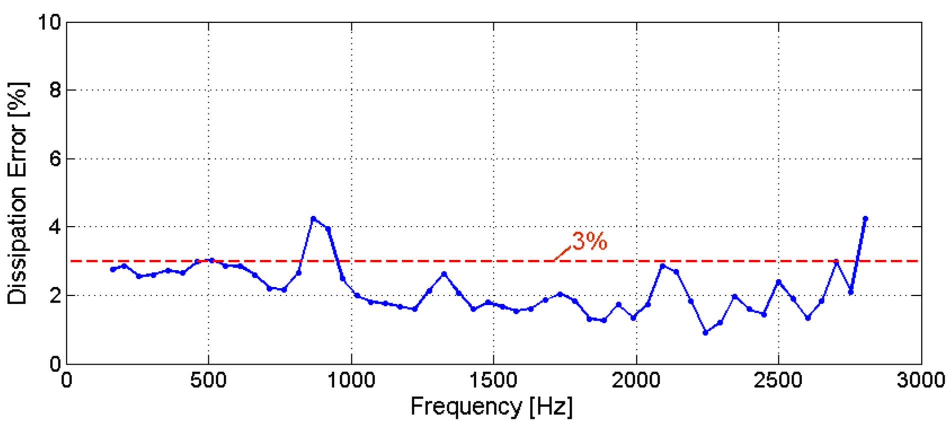


Fig. 9: Error for the determination of the dissipation measured with new-design microphone probes in the HAT (hot acoustic testrig).

In future tests series, bias flow liners as well as other liner typers (e.g. Helmholtz liners) can be investigated in a wide range of Mach numbers, temperature and pressure levels. This type of test under realistic conditions closes the gap between the generic tests in a normal laboratory test facility and the application in the aero-engine and helps to improve the effectivess of these noise damping devices and the methods for their design.

It is also planned to use another test section with optical access to the HAT facility which allows optical measurements and acoustical measurments with the new microphone probes at the same time increasing the understanding of different thermoacoustic phenomena.

CONCLUSION

A microphone probe for application in high pressure and high temperature environment has been developed and tested thorougly for save operation and accuracy. It is easy to implement in large industrial rigs as well as in laboratory environment and requires only a small amount of cooling air for operation in high temperature environment. Using the methods described for calibration and data processing, the microphone probe enables the accurate measurement of sound pressure in amplitude and phase. It will be used in EC projects (e.g. TEENI) as well as for thermoacoustic investigations in the new hot acoustic test rig (HAT) and various other future projects.

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