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# ACOUSTIC PRESSURE MEASURMENTS IN HIGH-TEMPERATURE ENVIRONMENT

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## ABSTRACT

In order to measure acoustic pressure in flow ducts at temperature above 100°C or in combustion chambers, the use of high-accuracy condenser microphones is no longer possible due to the heat load damaging the delicate components. A possible mitigation is the remote placement of the microphone, with the sensor connected via a small diameter waveguide to the desired measurement location. Such a device (called ”microphone probe”) has been build and used by DLR Berlin for several years for the investigation of in-duct sound fields at elevated pressure and temperature. However, there are certain calibration procedures and corrections required to account for the probe design. An experimental test series has been made to assess the probe characteristics. Special focus was set on the influence of the extension of the waveguide, which shall reduce the detrimental effect of reflections on the measured signal. Tests included a comparative calibration and high temperature and high pressure testing. The results are compared to a one-dimensional model of the probe design.

## 1. INTRODUCTION AND MICROPHONE PROBE DESIGN

Accurate acoustic measurements in high temperature and/or high-pressure environments are very challenging. While some commercial products are available, their maximum tolerable temperature is typically around 620 K (in a very few cases the specifications go as high as 920 K). These are usually piezoelectric pressure sensors, whose sensitivity and dynamic range is much lower than that of standard condenser microphones. In order to overcome the temperature and sensitivity limitations, a microphone probe has been developed at DLR. The initial design has been used successfully for several years, e.g. for acoustic measurements at a laboratory combustion chamber operating at nearly ambient pressure conditions. Due to increased requirements – mainly in terms of operating pressure a modest re-design has been made thereby enabling acoustic measurements in high pressure environments of up to 2000 kPa (20 bar). The microphone probes have been successfully applied in a combustion facility with respect to their safety and data reproducibility at conditions up to 1350 kPa and 1500 K and used since then in different applications.

The design of the microphone probes is illustrated in Figure 1. The probes are mounted to the test rig via a flange. The tube below the flange is inserted into a guiding duct and ends at the wall of the test duct without protruding. The lower end of the tube is the measurement location where the acoustic pressure shall be captured. The tube (sometimes also called waveguide) extends outwards with a constant diameter. After a certain length, a microphone is mounted perpendicular to the tube inside a pressure-proof housing. The housing contains a standard ¼ inch condenser microphone (e.g. GRAS 40BP or 40BH for high dynamic ranges) and its preamplifier (e.g. GRAS 26AC). The acoustic pressure is transmitted from the tube to the microphone membrane via a small opening. For the electrical connection of microphone and pre-amplifier (both are located in the designated high-pressure environment), a specific pressure-proof LEMO connector is used.

In order to minimize reflections of sound (and thereby minimize also standing wave patterns inside the wave guide), the tube is extended beyond the location of the microphone, following the principle of a semi-infinite tube [1].

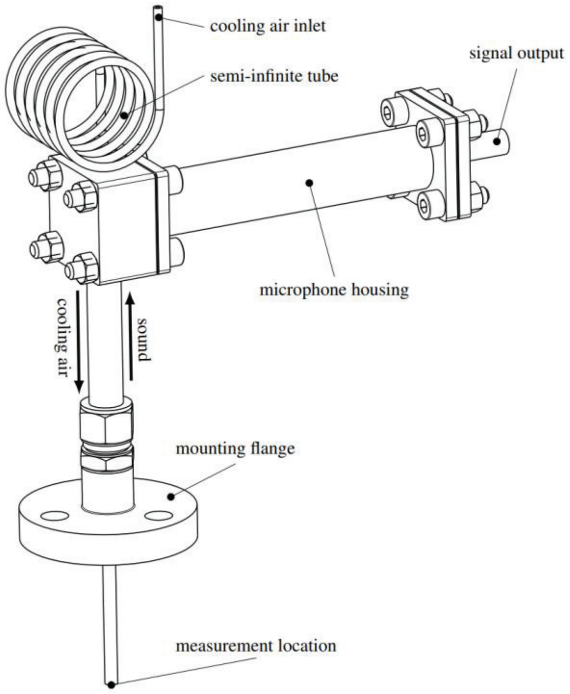

**Figure 1:** Design of the microphone probes for acoustic measurements in high-temperature/high-pressure environment.

The overall length of this tube extension is about one meter (standard probe design – also called ‘short coil’ hereafter), which is mostly wound-up in a spiral to save space. The large ratio between diameter and length of the tube provides sufficient viscous damping, so that the frequency range of interest is almost free from resonances. The latter statement holds at least for operation in ambient pressure environment. For high-pressure environment (frequently, applications reach 1000kPa operating pressure), the viscous damping is reduced considerably and it becomes mandatory to account for the acoustic reflections in terms of a specific transfer function. On the other side, the semi-infinite tube can be extended to further increase the viscous damping and reduce acoustic reflections. Both aspects are discussed in detail in this paper.

In order to allow operation in hot-temperature environment or with corrosive gases, a small amount of cooling air is fed through the tube, preventing hot gases from the test rig to enter the tube and get into contact with the microphone membrane. The cooling air supply can be easily attached via a quick connector (not shown in Figure 1, but visible in Figure 9). A study concerning the influence of the cooling flow on the acoustic measurement was done with the initial design of the microphone probes. At atmospheric pressure conditions it could be shown that a velocity of 4 m/s in the tube is sufficient to ensure the safe operation of the microphones. This corresponds to a mass flow rate of only 0.054 kg/h at atmospheric conditions. At elevated operating pressure, the cooling flow velocity should remain constant. Therefore, the mass flow rate has to be adjusted according to the change in density. Usually, the total mass flow of cooling air through the microphone probes is lower than 0.5% of the total test rig mass flow. A disturbance of the microphone signal by the cooling air could be observed only for velocities beyond 30 m/s, i.e. much higher than the 4 m/s applied here.

## 2. TRANSFER FUNCTION

Each microphone probe has a characteristic transfer function, which is determined by the geometric dimensions of the probe. Major influence has the distance between the measurement location and the microphone membrane. Furthermore, the diameter of the tube, the length of the semi-infinite tube part and other dimensions determine the transfer of the acoustic pressure signal to a minor degree. The transfer function has to be considered in the analysis, correcting the signals from the influence of the probe. While the specified geometry is identical for all probes, so should be their transfer functions. However, small variation in manufacturing and assembly require the determination of an individual transfer function for each probe.

A probe together with a microphone is forming one unit, which is only separated if a component is damaged. Instead of determining the transfer function of each item (microphone, pre-amplifier, microphone probe) separately, a calibration curve for the whole unit is recorded. Consequently, the calibration curve includes the transfer function of the probe as well as the characteristic sensitivity of the microphone itself.

Three different ways of calibration have been established:

(1) Absolute calibration: Calibration with a pistonphone, regarding the established magnitude at one frequency.
(2) Quasi-absolute calibration: Calibration regarding magnitude and phase over the complete frequency range with respect to a reference condenser microphone, usually at atmospheric conditions.
(3) Relative calibration: Calibration regarding magnitude and phase over the complete frequency range with respect to a reference microphone probe. This calibration can be performed at every combination of temperature and operating pressure.

The absolute calibration (1) defines the deviation of the measured signal to a reference signal supplied by a pistonphone, i.e. 124 dB at 250 Hz. The magnitude correction value, expressed as sensitivity in V/Pa, can be saved in the data acquisition system and is usually directly applied to the recorded data.

The two other options (2) and (3) rely on an in-duct calibration method. This method is based on the fact that the wave motion of plane waves is one-dimensional. Therefore, microphones installed in a duct at the same axial position should experience the same values for amplitude and phase.

As discussed already, the behavior of each microphone probe is slightly different. A pair of magnitude and phase values corrects and equalizes the behavior of the combination of microphone and probe, respectively. The correction values can be determined for the whole frequency range, reproducing any frequency dependent behavior.

The in-duct plane-wave principle sets also the upper frequency limit for the respective calibration by the cut-on of higher modes in the respective duct.

For both calibration procedures (2) and (3), the microphone probes are installed around the circumference of a duct at the same axial position. The test signal used can be identical to the one for the measurements, or can be a frequency sweep containing all frequencies of interest. Finally, this procedure provides corrective values for each frequency excited during the measurement. The quasi-absolute calibration (2) employs a wall-flush mounted condenser microphone as reference, while the relative calibration procedure (3) uses one of the microphone probes as reference.

### 2.1 Quasi-absolute calibration

A quasi-absolute calibration was performed in a 50mm diameter duct segment using a sweep excitation in the frequency range from 200 Hz to 4 kHz with the microphone probes all mounted at the same axial position. A GRAS 40BP condenser microphone was flush mounted to the duct serving as reference.

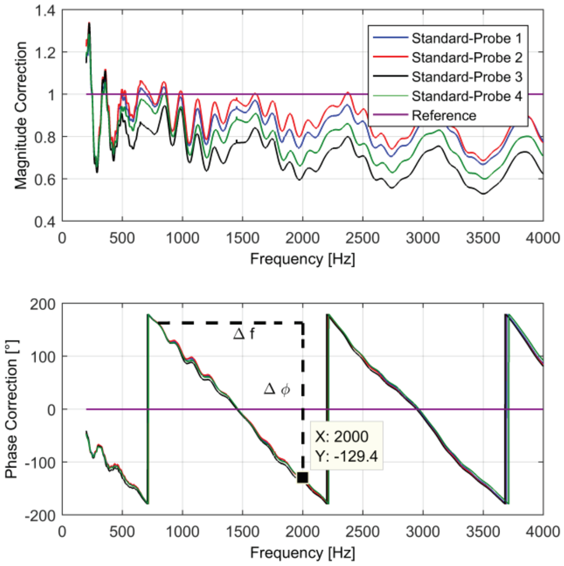

**Figure 2**: Quasi-absolute calibration for four microphone probes with a flush-mounted condenser microphone as reference.

The condenser microphone and the microphone probes are first calibrated with a pistonphone at 250Hz, so that the results can be considered to be quasi-absolute. Plots of the magnitude and phase correction values for four exemplary microphone probes are given in Figure 2. The reference magnitude and phase have a constant value of unity and zero, respectively. Due to the pistonphone calibration at 250 Hz, all four microphone probes exhibit magnitude correction values at 250 Hz that are equal to unity. The plot shows the frequency dependency of magnitude and phase. The continuous slope of the phase reveals that there is almost no resonance within the frequency range. The slope itself defines the time delay of the acoustic wave traveling from the measurement location to the microphone: $\Delta t = \Delta\varphi/360°/\Delta f$. Picking two random points from the phase curve of probe 16, say (794 Hz, 162.2°) and (2000 Hz, -129.4°), yields a time delay of $\Delta t = -6.716 \cdot 10^{-4}$ s (the negative sign indicates the delay). Assuming $c = 343$ m/s gives a distance of 230.3 mm between measurement location and microphone. This agrees very well with the actual distance of 220 mm.

The physical process exhibits a monotonic increase of the phase shift with increasing frequency, which is wrapped into the -π…. π-range for better visualization in Figure 2 and subsequent figures.

### 2.2 Relative Calibration

The third calibration method is the relative calibration with respect to a chosen reference microphone probe. Again, the procedure is based on the in-duct calibration method explained above.

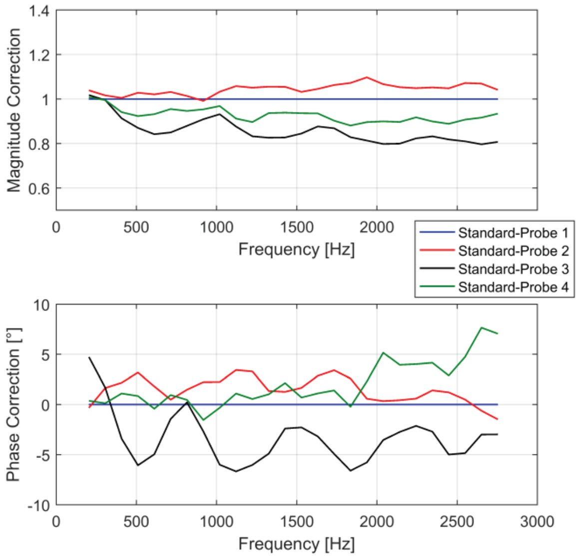

**Figure 3**: Relative calibration curves at ambient temperature and pressure.

Figure 3 shows the resulting calibration curves for the same microphone probes from the previous plot. The curves look very different to Figure 2, but they basically contain the same information. The advantage of the third method is that it only employs microphone probes, so that the calibration can be done at the actual operating condition of the measurements. Doing so reveals the dependency of the microphone probes on temperature and pressure.

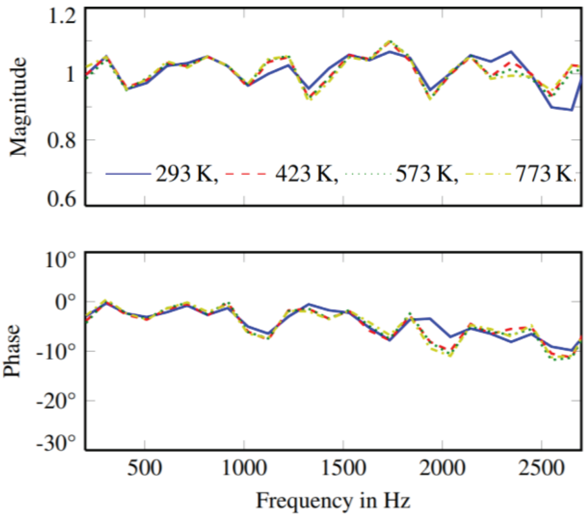

**Figure 4**: Relative calibration curves of single microphone probe for various duct temperatures (operating pressure p=300 kPa).

The influence of temperature and pressure on the transfer function of a microphone probe is shown in Figure 4 and Figure 5, respectively. The calibration curves show only a weak dependency on the temperature in the duct. This is expected, as the microphone probes are designed to maintain a low internal temperature while the duct temperature increases. Actually, the temperature within the probes does not change that much, since the constant cooling flow keeps the wave guides temperature at a nearly constant level. The static pressure, on the other hand, is the same within the probe and the duct.

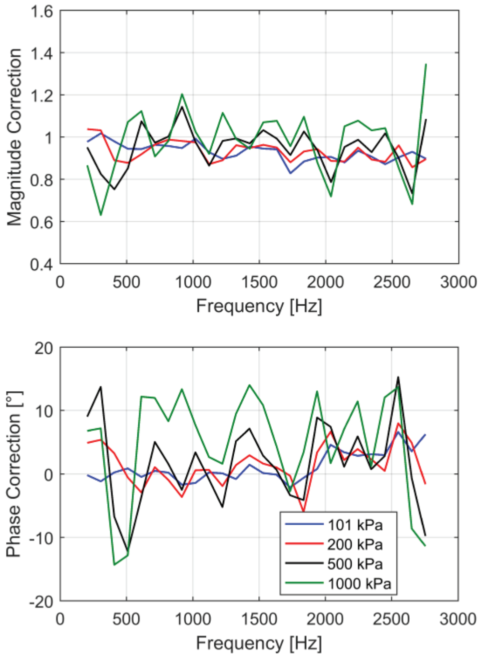

**Figure 5**: Relative calibration curves of Standard-Probe 4 (reference Standard-Probe 1) for varying operating pressure at ambient temperature.

A strong influence of the static pressure on both magnitude and phase can be observed in Figure 5. This effect is caused by the decrease of viscous damping with increasing pressure, which emphasizes the small variation in microphone probes geometries and microphone sensitivities. However, due to the ability to provide magnitude and phase correction values for each operating condition, the pressure dependency can be handled very well.

Each of the three methods is important to characterize the behavior of the microphone probes. The quasi-absolute calibration served as a one-time check for the general design (no resonances). The absolute calibration with the pistonphone equalizes the levels of all microphone probes. Furthermore, it serves as an easy way of health checking between two measurements. The relative calibration at operating condition is crucial for the analysis of the data. Therefore, a relative calibration is performed in regular intervals, at least at the beginning of every measurement campaign.

## 3. MODELING OF THE PROBE CHARACTERISTICS

A transfer matrix model for simple tube networks has been implemented as a Matlab function. Basic elements which can be used to simulate a given setup are straight ducts, sudden area changes, and side branch resonators. [2-8]. The impedances on both ends can be prescribed. For a specified sensor location, the transfer function, the attenuation and related quantities can be obtained.
This tool was used in order to simulate the behavior of the microphone probes. Given the limited complexity of the model elements, some reasonable compromises had to be made to model the actual probe geometry. The sound attenuation in the tube caused by visco-thermal losses is accounted for using Kirchhoffs formulation [9].

In Figure 6, the simulation results are shown for the standard design probe. Since the operating pressure has the largest influence on the transfer function, this parameter was varied. As could be anticipated from the experimental values (see previous section), there are pronounced maxima and minima for the transfer function which increase considerably when the pressure is increased. The phase relation is influenced only to a minor degree.

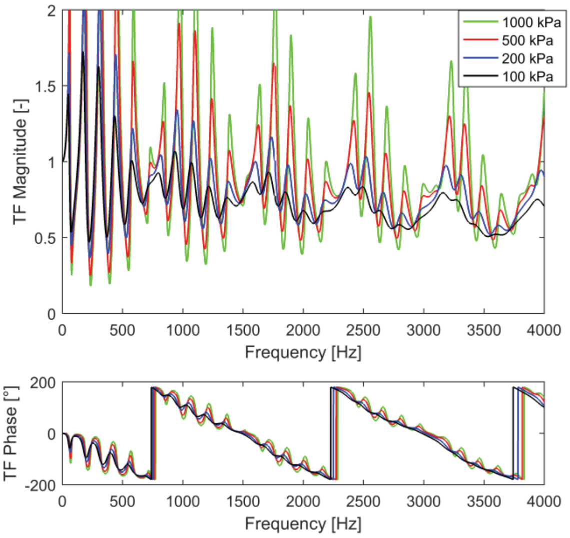

**Figure 6**: Simulation of Standard probe (short coil of approximately 1 m) for various operating pressure.

In order to improve the acoustic characteristics of the microphone probe and reduce reflections at the end of the tube (connector for air supply), an extension of the semi-infinite tube is considered.
Figure 7 shows the simulation for a 10 m (i.e. 9 m extension beyond the coiled tube of the standard probe) semi-infinite tube. The maxima and minima of the transfer function are reduced to very low values even for the highest pressure considered (1000kPa = 10bar). The dashed green line shows the ideal behavior with the microphone attached to the waveguide without any gaps or cavities. Thereby it becomes clear, that the remaining “waviness” of the transfer function can be hardly

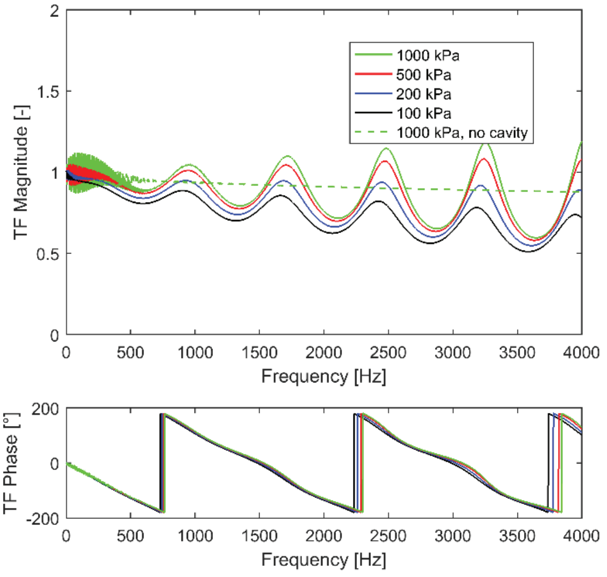

**Figure 7**: Simulation of improved probe (long coil of approximately 10 m) for various operating pressures.

removed with the necessity to physically join the microphone diaphragm to the circular waveguide.

A further set of simulation with a variation of the length of the semi-infinite tube was made in order to investigate the requirements for high-pressure operation (Figure 8).

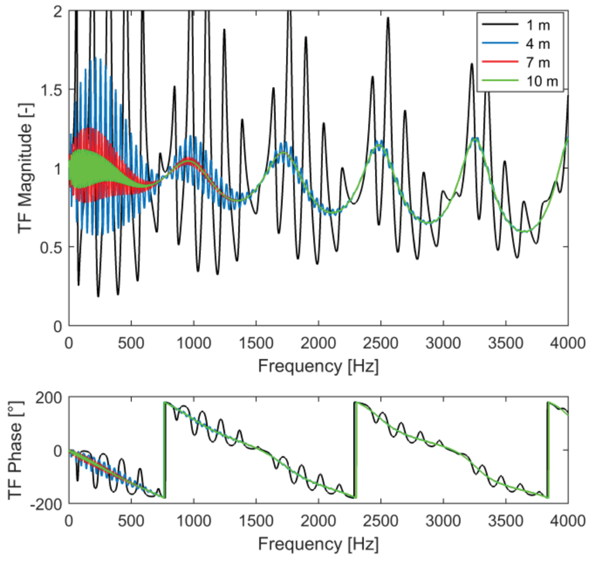

**Figure 8**: Simulation of varied coil length (1-10 m) for operating pressure of 1000 kPa.

While for 1 m - which corresponds to the length of the coil of the standard microphone probe – and the 4 m significant oscillations of the magnitude of the transfer function can be observed below approximately 1500 Hz, these oscillations are much less pronounced for 7 m and 10 m coils, respectively. For the latter, the magnitude factor wiggles between 0.9 and 1.1 only below 500 Hz. The remaining waviness (with peaks roughly every 700Hz) is caused by the connection of the microphone as pointed out before. Therefore, for high pressure applications, the microphone probe with a 10 m semi-infinite tube seems to be most appropriate.

## 4. EXPERIMENTAL VALIDATION OF THE IMPROVED DESIGN

According to above findings, a 9 m extension has been built with the same diameter as the original tube diameter and a specific joint was manufactured to connect both without an additional gap (change of diameter).
Two microphone probes were equipped with these extensions and have been calibrated as described in the first section (Figure 9).

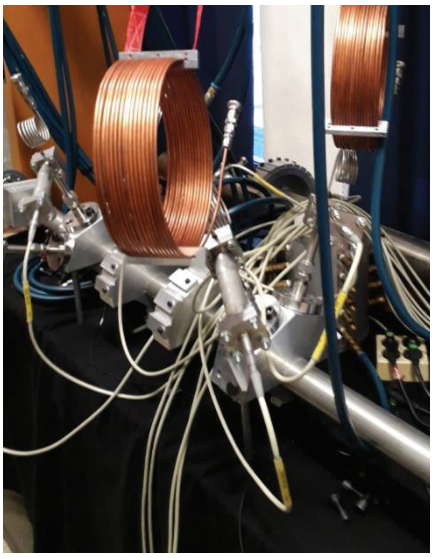

**Figure 9**: Microphone probe with extension of semi-infinite tube in the calibration duct for quasi-absolute calibration

The quasi-absolute calibration is shown in Figure 10. The experimentally determined transfer function is in reasonable agreement with the simulation (compare Figure 7).

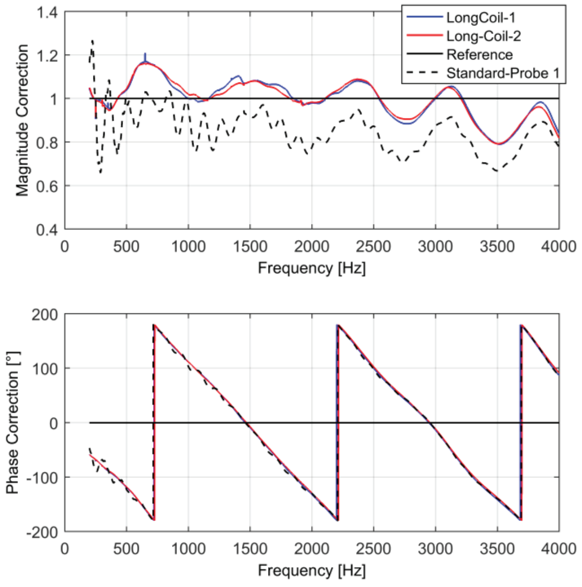

**Figure 10**: Quasi-absolute calibration for two microphone probes with long coil and standard-probe-1 (short coil) Reference: flush-mounted condenser microphone

The direct comparison with the standard probe (coil only 1m) shows the large benefit of the increased coil length with much less local maxima/minima in the transfer function. As could be derived from the simulations, the remaining “waviness” can only be reduced further by a redesign of the physical coupling of the microphone to the wave guide.

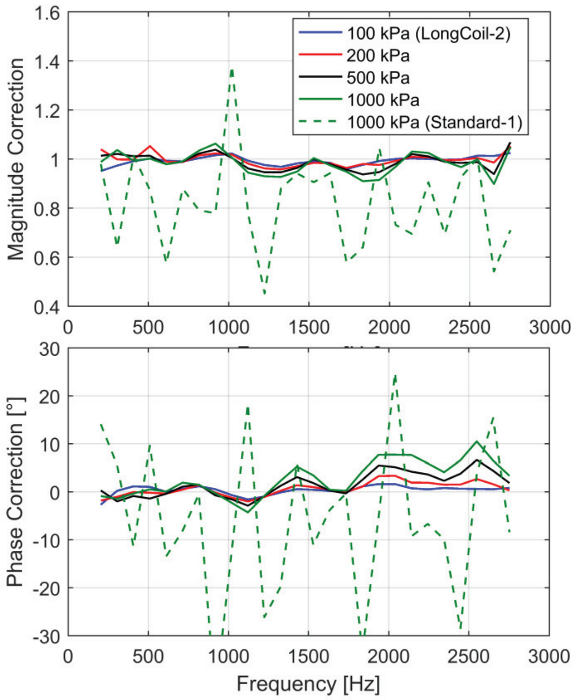

**Figure 11**: Relative calibration curves of LongCoil-2 and Standard-Probe 1 (Short Coil) for varying operating pressure and ambient temperature. Reference Long-Coil-1.

Finally, a relative calibration was performed for different operating pressure values.
A microphone probe with an extension of the semi-infinite tube (LongCoil-1) was taken as reference (Figure 11). The data presented is mainly for the other microphone probe with the longer coil (LongCoil-2). The differences with varying pressure are much smaller than what was observed for the standard probe (compare Figure 5). For direct comparison, one data set is also included here (standard probe-1).

It becomes clear, that the microphone probes with extended coils exhibit significantly less variations of the transfer function.

## 5. APPLICATION OF MICROPHONE PROBES

Microphone probes have been applied for several investigations involving heated and/or pressurized environment. Permanently, they are used at the Hot-Acoustic-Testrig (HAT, Figure 12), a facility jointly built and operated by DLR, Dept. Engine Acoustics, Berlin and the Chair of Aeroengines of TU Berlin [10].

The facility was initially set up for the investigation of perforated liners, as found in combustion chambers of gas turbines. While the microphone probes frequently serve for the acoustic characterization of the test objects, e.g. the acoustic dissipation or transmission loss, other measurement techniques can be applied as well.
Beside the initial test purpose, plane liner samples for cold and hot regions of aero-engines have been investigated in the past. Also, experiments with respect to noise generation through the acceleration and deceleration of entropy spots (indirect combustion noise) have been performed, with the microphone probes measuring the incoming and outgoing acoustic signals.
For the tests at the HAT, usually the absolute and the relative calibration are applied. For the investigations of indirect combustion noise, the quasi-absolute calibration - yielding knowledge about the transfer function and phase lag - are of highest relevance.

A further application is the investigation of noise generation and transmission in the core region of gas turbines. Here, the combustion chamber is a region, where high pressure and high temperatures are encountered at the same time. Further downstream, in the different stages of the turbine, the noise transmission through the stages can be investigated with the help of microphone probes (Figure 13)

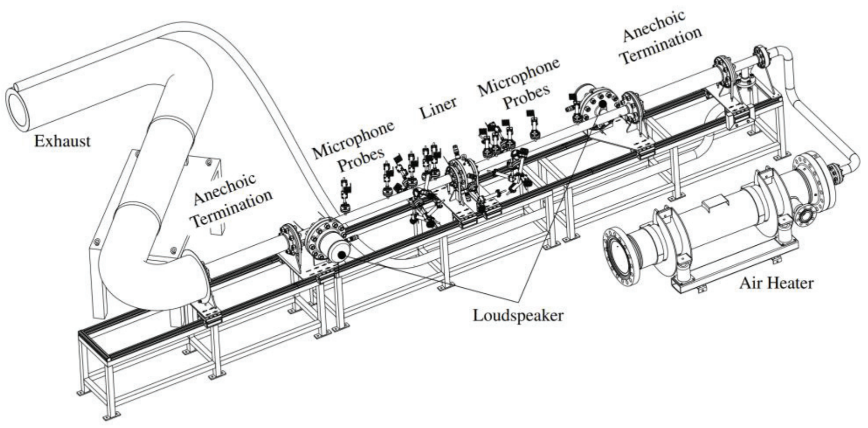

Figure 12: Overview of the Hot Acoustic Testrig (HAT)

While a detailed relative calibration at relevant pressure and temperature regimes is difficult to accomplish, the measurements must rely on absolute and quasi-absolute calibration procedures. If the absolute level of noise is required, a transfer function, which can be easily predicted over the full frequency range, might be needed in order to post-process the acquired data successfully.

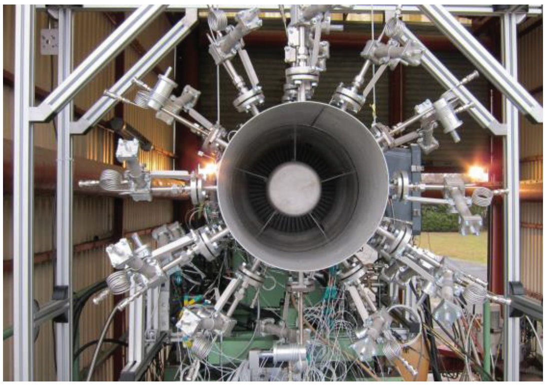

Figure 13: Microphone probes at the exhaust section of a turboshaft engine for noise path investigations.

This means, that microphone probes with long coils might be required for high pressure environment measurements.

## 6. CONCLUSIONS AND OUTLOOK

A microphone probe for the accurate measurement of acoustic pressure in high-pressure and high-temperature environment has been presented. Three different calibration procedures have been described and examples of calibration results have been provided. All three methods yield important information for the application of microphone probes and the correction of acquired data. With a simple transfer matrix method simulations of the acoustic characteristics of the microphone probe were made. While the principle of the semi-infinite tube is supposed to reduce efficiently the acoustic reflections at the end of the wave-guide, this holds only for measurements at nearly atmospheric pressure for the standard design. For elevated pressure, a significant extension of the semi-infinite tube is required in order to obtain a “smooth” transfer function. Specific care should be taken to reduce cavities and gaps to a minimum inside the microphone probe. Further, it could be shown that the operation at elevated temperatures does not significantly change the acoustic transfer function of the probes – mainly due to the application of a small amount of cooling flow.

However, a relative calibration of the microphone probes at relevant operating conditions (mainly operating pressure) and the subsequent application of these specific transfer functions can yield high accuracy measurements also for microphone probes with the standard length of the wave guide. This is for instance the case if a wave decomposition is performed using only the ratio of wave amplitudes and no absolute values. Most of the acoustic measurements in the HAT test rig are based on this principle. A convincing accuracy of these measurements has been demonstrated in the past [10].

In a next step, it will be investigated if the measurement accuracy within the HAT facility can be even further improved if the wave decomposition is entirely based on microphone probe signals from “long-coil” probes.

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