The Design and the Application of Fiber-Optic Microphones for Acoustic Measurements in Hot Environments

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Introduction

A main aim of the design of modern gas turbines is the reduction of noise emission and emission of pollutants while maintaining performance objectives. One way to reduce these emissions is lean premixed combustion. However, lean combustors tend to show combustion oscillations, which increase emissions and reduce the performance of the facility. To study these phenomena and to solve subsequently arising problems of performance, appropriate measurement techniques to investigate lean combustion are necessary (see e.g. [1]-[3]).

Conventional acoustic measurement techniques, which are currently still used for this kind of application, show very limited applicability:

Condenser microphones have very strict temperature limitations ($-20°C$ to $+80°C$) and therefore they are not employable for the acoustic investigation of combustion oscillations.

Piezo-resistive and piezo-electric pressure transducers are often designed for such studies including highly complex cooling systems, but they are characterized by the limited dynamic range they cover.

Probe microphones basing on one of the former mentioned techniques delocalize the sensor position from the point of measurement using a thin tubing to guide the acoustic field that has to be detected (e.g. [4]); this design has the disadvantages that the setup is very stiff and therefore not suitable at hardly accessible test sections. Furthermore, for a proper application of these devices a complex calibration procedure is essential to correct amplitude and phase calculations of the acquired signals.

This paper presents a study where a Fiber-Optic Microphone (FOM) was designed and tested for acoustic measurements at elevated temperatures. Generally there are two different possibilities to design a fiber-optical microphone. Both are based upon the use of light scattered from a reflecting membrane, collected via a glass fiber. The first type is based upon the measurement of intensity fluctuations which are created since the membrane movement influences the coupling between the reflected light and the collecting quality of the transmitting fiber as shown in figure 1.

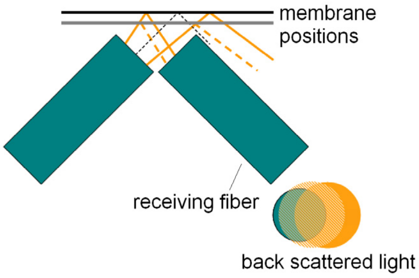

Figure 1: Possible FOM design based on intensity modulation

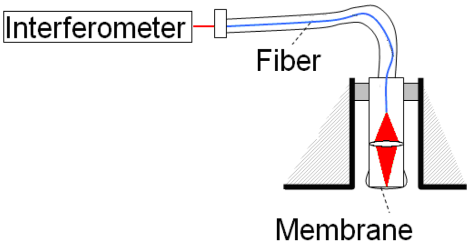

Figure 2: FOM design based on interferometry

The second type is based upon the interferometric measurement of the membrane displacement as shown in figure 2, i.e. the combination of a reflecting membrane, which is excited by the acoustic field of interest, with the chosen interferometer, whose measurement beam is guided via a glass fiber to the backside of the membrane. The presented work concentrates on this second design of a FOM on fulfilling the requirements for a hot application of the sensor. To support thermo acoustic experiments the design is based upon the use of highly temperature resistant materials, i.e. stainless steel foils, as membrane materials, fixed upon a stainless steel sensor head which contains a heat resistant optical lens for focusing the measurement beam on the membrane and collecting the back scattered light. Two different interferometers were studied for the presented experiments, a commercial heterodyne Mach-Zehnder interferometer (MZ), and a recently designed Fabry-Pérot interferometer (FP).

The FOM based upon the MZ interferometer

The MZ interferometer applies polarization maintaining single mode fibers and therefore show a very limited temperature applicability since this fiber type has an upper temperature limitation of approximately $300°C$. Nevertheless, this setup was used to perform measurements in the exhaust gas duct of an atmospheric combustion chamber. In cold experiments its performance was tested and a way to calibrate the sensor applying a one-point calibration via a pistonphone was defined. Hence, quite convincing performance data compared to a conventional condenser microphone could be obtained. Figure 3 presents the spectra of the MZ FOM and of a condenser microphone installed in parallel in an cold acoustic test rig. Both sensors were calibrated in advance and thus, the spectra show the sound pressure level $[dB]$ versus excitation frequency $[Hz]$. The excitation in the cold acoustic test rig was created via a loudspeaker controlled by a frequency generator. The excitation was done with a sweep between 200 and $2000 Hz$. The characteristic shape of the spectra results from the overall transfer function of the excitation mechanism. The spectra show that the signal of the new designed optical microphone is very well comparable to the one based on the established measurement technique of condenser microphones.

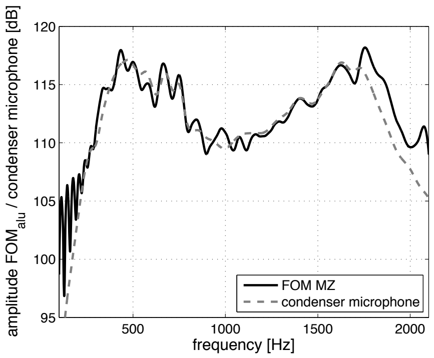

Figure 3: Spectra of the MZ FOM and a condenser microphone: cold conditions

Figure 4 shows now directly the result of the application of this MZ FOM at the exhaust duct of a atmospheric combustion setup (thermal power $7kW$). It presents the measured spectra of the MZ FOM; displayed is the displacement amplitude $[\mu m]$ versus the acoustic frequency $[Hz]$. Furthermore, the spectrum of the signal of one of two probe microphones installed in parallel is presented. Since the probe microphones were calibrated and the transfer functions of the sensors were used to correct the data, the spectrum shows the sound pressure level $[dB]$ versus the frequency $[Hz]$. The comparison of the presented spectra show a very high accordance between the data of the new designed sensor and the data of the probe microphone. See also figure 5, the amplitude of the transfer function between the two sensors, normalized on its mean value, which is close to 1 over the whole frequency range of interest.

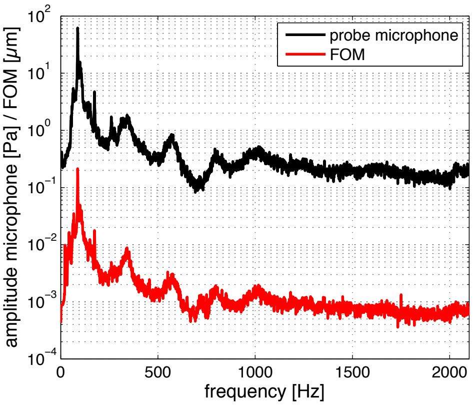

Figure 4: Spectra of FOM and probe microphone

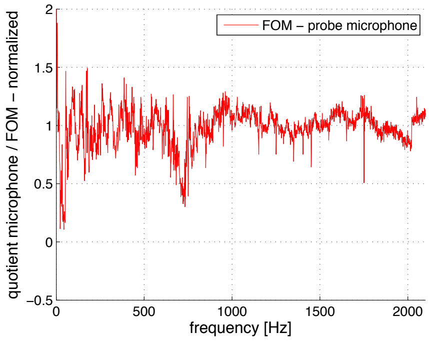

Figure 5: Quotient spectra FOM and probe microphone

Figure 6, however, shows the phase between the two installed sensor types, and thereby one further disadvantage of the used interferometer becomes evident, which was already obvious in the spectrum of the cold measurement performed in advance: since the interfering beams of the MZ setup do not both travel the optical fiber, fiber vibrations, which change the optical length of the fiber, influence the phase between the interfering beams and thus create a high noise level, particularly in the lower frequency range around $500 Hz$ (see also [5], [6]).

The FOM based upon an advanced FP interferometer

To overcome the two main disadvantages of the MZ interferometer, namely the low temperature resistance and the high fiber sensitivity concerning setup vibrations, a new interferometer setup was designed, which bases upon a FP interferometer formed by the moving membrane and the fiber ending itself. The membrane reflection interferes with the reflection of the ending of the transmitting fiber, caused by the interface between fiber core and the free air path of the FP cavity. Two main advantages of this setup are: non-polarizing single mode fibers can be applied, whereas heat resistant types are already available (due to special metal coatings temperatures up to $700°C$ are tolerable); since both interfering beams are traveling through the fiber, fiber vibrations do not influence the quality of interference. The created interference signal could generally be processed using the fringe-counting-method; the experimental study of stainless steel membranes, however, showed that the resolution obtainable following this conventional method to process data of homodyne interferometry is not sufficient for the adequate detection of the displacement of acoustically excited membranes. Therefore, the optical setup prior to the optical fiber was advanced as shown in figure 7 to increase the sensitivity of the FP FOM.

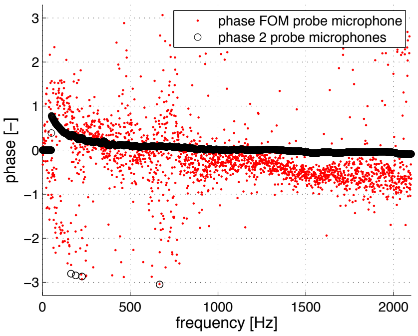

Figure 6: Phase between FOM and probe microphone

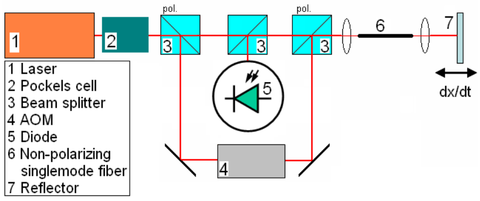

Figure 7: Advanced FP interferometer

Using a Pockels cell to feed the light of a single mode laser into two different optical paths, switched with a highly alternating square wave signal, creates two FP interference signals quasi simultaneously. By adding an acousto-optical modulator (AOM) into one of the two paths enables the possibility to shift the frequency of the passing laser beam (shift frequency $\Delta\nu$, fundamental frequency of the laser ν). Thus, two FP signals, which fulfill the quadrature condition, get detected quasi contemporaneously by the installed photodiode. This enables a signal processing similar to the one of conventional quadrature homodyne interferometers.

Therefore the distance L between fiber ending and reflector has to satisfy equation (1):

$$L = \frac{\lambda/4 \cdot \nu_0}{2 \cdot \Delta\nu} = \frac{c}{8 \cdot \Delta\nu} \qquad (1)$$

whereas c represents the speed of sound. Similar setups are presented in [5] - [6], whereas no AOM is used to create a frequency distance between the two required laser beams, but multimode lasers or two diode laser with different fundamental frequencies.

The diode signal of this presented, quasi quadrature homodyne interferometer has to be processed consequently such that, starting from the diode signal and the Pockels cell control signal, two quasi simultaneously acquired interference signals are calculated, whose phasing can be used to recalculate the original membrane movement. Figure 8 shows on the upper left the two calculated FP signals for a acoustically one-frequency excitation of a stainless steel membrane; on the right the two FP signals are plotted in the corresponding Lissajous plot; the graph on the lower left represents the recalculated time signal of the membrane movement, representing the phasing of the two FP signals. Since the phase distance between the two FP signals is constant at 90°, the corresponding Lissajous plot generates a circle. This signal processing procedure is stable not only for one-frequency excitation, but also for sweep and broadband excitation, whereas limitations are given by the maximum Pockels switching frequency and the data acquisition frequency.

Figure 9 shows the spectra of the FP FOM in comparison to the data of a conventional condenser microphone for a sweep excitation between 200 and 2000Hz at ambient temperature, whereas the sensors were installed in the former mentioned cold acoustic test rig. Figure 10 shows once again the amplitude of the transfer function between the two sensors, figure 11 the phasing between the sensors. All figures show the high accordance between the data of the presented FP FOM and the conventional condenser microphone.

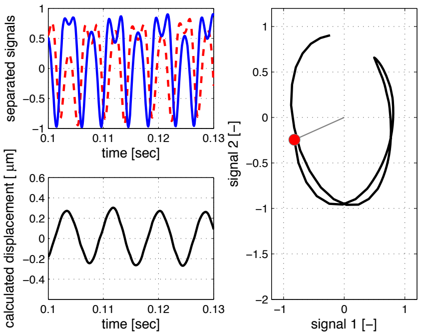

Figure 8: FP FOM signal and processing

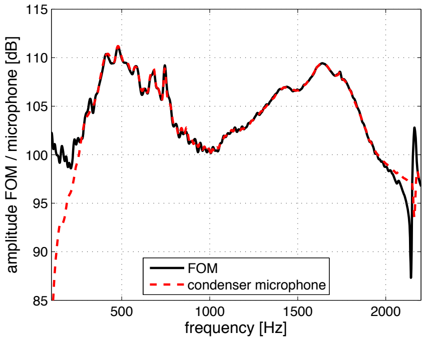

Figure 9: Spectra of the FP FOM and a condenser microphone for a cold experiment

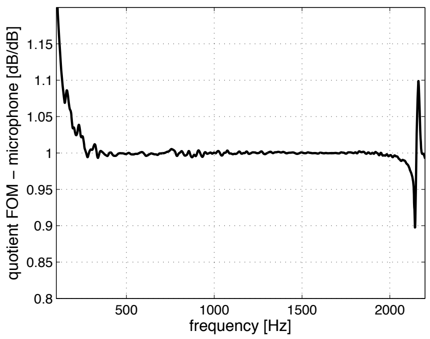

Figure 10: Quotient of the presented spectra

A more relevant acoustic test case for thermo acoustic experiments is shown in figure 12. Four discrete frequencies in the range between 60 and 200Hz were

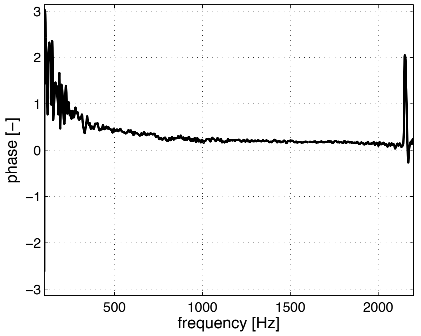

Figure 11: Phasing between the FP FOM and the parallel installed condenser microphone

excited simultaneously (indicated by vertical lines) and the corresponding figure shows the spectra of the FP FOM and the applied condenser microphone. This result demonstrates the good applicability of the FP FOM for acoustic experiments, where similar acoustic signals can be expected.

Up to now the FP setup has a limited applicability for high frequency detection, since high frequencies and high membrane displacements require high switching frequencies for the used Pockels cell and consequently high data acquisition rates. Given that thermo acoustic oscillations generally concentrate on the lower frequency range around $100 Hz$, the presented result clarifies that the FP setup will cover the region of interest for the planned hot application of the new designed sensor.

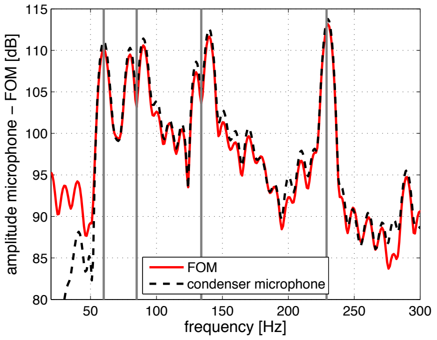

Figure 12: Spectra low frequency excitation

Conclusion

A way to design a FOM for the application for acoustic measurements in hot environments is presented. A first prototype based upon a commercial MZ interferometer was successfully applied for cold measurements and for acoustic measurements in the exhaust duct of an atmospheric combustion test rig. However, its vibration sensitivity and its very limited temperature resistance required a new interferometer design to tolerate both higher temperatures and setup vibrations. Therefore, an optical setup based on a FP interferometer was designed and tested under relevant acoustic conditions. The high performance data at ambient temperatures encourage its direct application in the combustion chamber of an atmospheric combustion test rig. These experiments are currently under preparation.

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