THE OPTICAL MICROPHONE – PRINCIPLE AND APPLICATIONS

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1 INTRODUCTION

This paper describes an optical excursion measurement principle suitable for high quality and robust opto-acoustical microphone transducers. These transducers allow microphones to be placed in application fields where other microphone transducer principles (e.g. dynamic or electrostatic) are not suitable or result in recording a mostly disturbed audio signal. The optical microphones can be used as measurement microphones in harsh environmental conditions.

2 CONSTRUCTION PRINCIPLE

At Sennheiser research laboratories several optical construction principles have been conceived and investigated [1]. Optical microphone principles based on intensity modulation are known from literature [2]. The set-up using MEMS manufactured optical lenses on fibre-optic cables in a MEMS manufactured high precision carrier frame has proven to be the most robust solution with the highest audio quality achievable and will be described here in detail. (see also [3] and [4])

Optical transducer principles offer some specialties compared to other principles. The conversion of the acoustical signal is done in two steps. First the sound is picked up by a membrane which transforms a constant source of light into an intensity-modulated light signal. The intensity modulation is proportional to the excursion of the membrane. In a photo detector (PIN diode) the light signal is then transformed into an electrical signal. Figure 1 shows the schematic set-up of the optical principle with lenses on the optical fibres. A transmitting fibre brings low noise high intensity IR light from a LED to a diaphragm. This light is focused and emitted onto the moving membrane (diaphragm) and reflected to the receiving fibre. The focus of the lens is adjusted in the way, that the focal point is positioned exactly on the edge of the receiving fibre when the membrane shows no excursion. The focal point covers the opening of the receiving fibre exactly by half. When diaphragm excursion takes place, the focal point moves either onto the opening of the fibre (higher light transmission coefficient) or away from it (lower light transmission coefficient). This results in intensity modulation of the IR-light in the receiving fibre and at the Photo PIN diode.

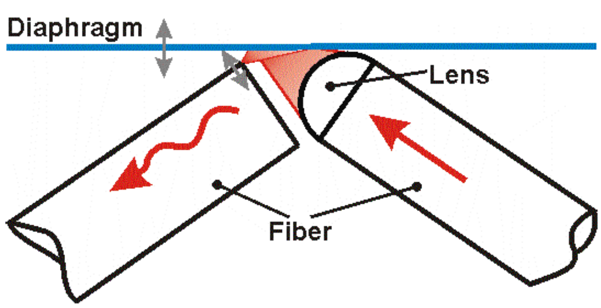


Fig. 1 Schematic construction principle of the optical microphone with lenses on the fibres. A constant intensity low noise light source emits light to the back of the microphone diaphragm via the transmitting fibre (right). The excursion of the microphone diaphragm then yields to a modulation of the light intensity in the receiving fibre (left).

3 TRANSDUCER Q-FACTOR

3.1 Theory of Operation

To understand the calculation of the quality of the excursion detector we have to consider the coupling curve in Figure 2 that relates the excursion *d* of the membrane to the reflection coefficient *K* of the optical transmission system. The reflection coefficient *K(d)* is determined by

$$K(d) = \frac{P_E(d)}{P_S} \tag{1}$$

were P_E is the light intensity in the receiving fibre and P_S is the light intensity in the transmitting fibre. K_0 corresponds to the coupling at zero excursion d_0. The coupling curve at d_0 is also characterized by its slope *S* in K_0 assuming the curve is linear in the region around it which can be found in practical situations. The slope is defined by

$$S = \frac{\Delta K}{\Delta d} \tag{2}$$

The noise current of the optical excursion detector is very much determined by the shot noise of the receiving photo diode. The noise in the light intensity of the emitting diode can be neglected. The shot noise is determind by

$$I_{noise} = \sqrt{2eBI_{Ph0}} = \sqrt{2eB\eta P_S K_0} \tag{3}$$

Here *e* denotes the electron charge, *B* denotes the bandwidth in (Hz) of the system, I_{Ph0} denotes the current caused by the light in the receiving photo diode in neutral position which can be expressed by $\eta \cdot P_S \cdot K_0$ (η: sensitivity of the photo diode)

The rms signal current of the excursion detector is determined by the transmitting diode's light intensity P_S the slope *S* the amplitude of the excursion Δd and the sensitivity of the photo diode η according to:

$$I_{signal} = \frac{\eta \cdot P_S \cdot S \cdot \Delta d}{\sqrt{2}} \tag{4}$$

This yields to the signal-to-noise ratio (SNR) according to:

$$SNR = 20 \log\left[\frac{I_{signal}}{I_{noise}}\right] = 20 \log\left[\frac{1}{2}\sqrt{\frac{\eta P_S}{eB}} \cdot \frac{S}{\sqrt{K_0}} \cdot \Delta d\right] \tag{5}$$

From this formula we see, that the achievable *SNR* is determined by the Q-factor $S/\sqrt{K_0}$ when excursion and emitting light intensity are constant.

3.2 Example

As an example we can calculate the SNR for practical values of $\Delta d = 1,0\mu m$, $S/\sqrt{K_0}$ = 0.02/μm, $P_S = 1,1 \cdot 10^{-3} W$ and $B = 10^4 Hz$:

$$SNR = 20\log\left[\frac{1}{2}\sqrt{\frac{0,6 \cdot 2.667 \cdot 10^{-3}}{1,6 \cdot 10^{-19} \cdot 10^4}} \cdot 0,02 \cdot 1,0\right] = 80\text{dB}$$

This SNR is the pure excursion detector SNR. To get the acoustical SNR, compliance and mass of the membrane, its resonance frequency, have to be considered. The membrane operates below its resonance frequency as an omni-directional receiver where excursion is proportional to the sound pressure in air.

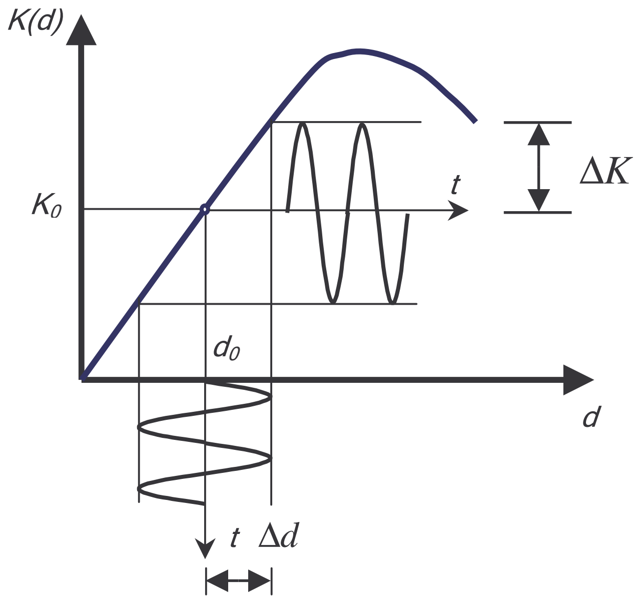
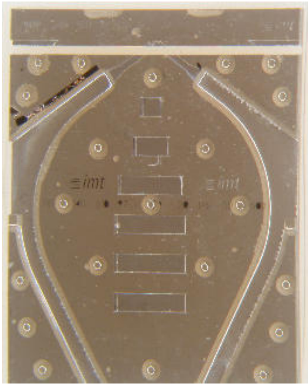


Fig. 2 Schematic for explanation coupling curve and Q-factor of the excursion detector

4 PRACTICAL ASPECTS

The practical realization of the optical microphone system yet shows several difficulties: For good audio quality the position and the tilt of the transmitting fibre and the receiving fibre relative to each other and to the membrane may not show tolerances larger than 1-5µm and about 0.5-3° from the optimum positions. The fibre itself has a diameter of 200/230µm and the distance between the diaphragm to the lens is approx. 50µm. The lens radius curvature may not tolerate larger than 5µm.

To yield these tolerances in a series production process the lenses are MEMS manufactured and the fibres are placed in a micro machined carrier frame which itself sits in a plastic housing holding the membrane and the strain-relief. Fig. 3 shows the MEMS manufactured carrier frame and the fibres first snapped and then glued to the carrier system. By doing this, the tight tolerances can be achieved. The prepared optical carrier is then positioned in a housing and the membrane is adjusted to the housing and the slit between membrane ring and housing is filled with UV hardening glue. Fig 4 shows a drawing of the whole system. For better visibility the membrane is opened and bend away. It can be recognized by a little golden spot in the center of the membrane that is used to yield better reflection.



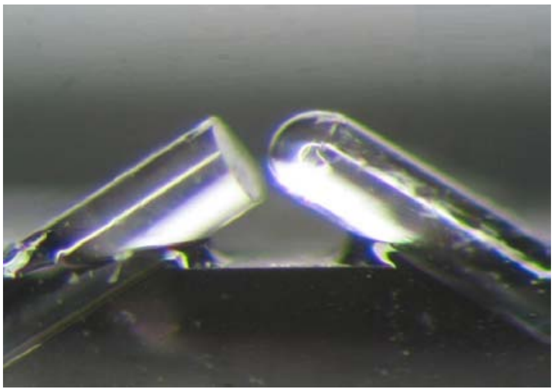


Fig 3 shows on the left the MEMS carrier with a protection and adjusting piece on the upper end that is removed after inserting and gluing the fibres. On the right we see the actual fibres glued onto the carrier frame. For better visibility the diaphragm was not mounted yet. It sits very close above the two fibres.

When the membrane is mounted the transmission coefficient *K* changes with diaphragm excursion (distance to the fibres). The coupling curve shows *K* over diaphragm excursion *d*. It is depicted in Fig. 2. The microphone can operate either on the increasing (membrane is closer to the lens) or on the decreasing slope (membrane is further way from the lens) of the curve. The practical excursion of the membrane is only in the range of 500-1000nm thus yielding a good linear audio performance when the favourable working point is on the middle of the steepest slope.

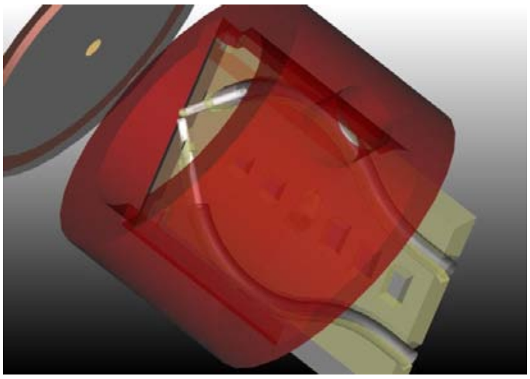


Fig 4 Shows the set-up of the optical microphone in a drawing with the membrane bent away for better visibility of the optical fibres

Figure 5 shows different samples for different applications. The optical microphone comes in ½ inch diameter to be compliant with most measurement setups (left part of Fig 5). When the orange coating of the glass fibres is omitted a microphone stand for th eoptical microphone is absolut translucent. A design sample of such an arrangement is shown in Fig 5 on the right.

Figure 6 shows the acoustical frequency response of the optical microphone. Its equivalent noise floor is in the range of 30dB(A) and peak sound pressure level at 1% distortion is in the range of 120dB.

For IR-light generation and conversion of the reflected light to current the optical microphone uses a driver and amplification unit. This unit is in a separate housing and contains a standard dual optical fibre connector, the IR diode and the photo diode and adjustable electrical amplification. The signal is fed out via standard XLR connectors. The unit needs a power supply.

Fig 5 Shows samples of the optical microphone in translucent housings (left: with standard optical fibres with strain relief, right: with fibre coating eliminated in a design housing)

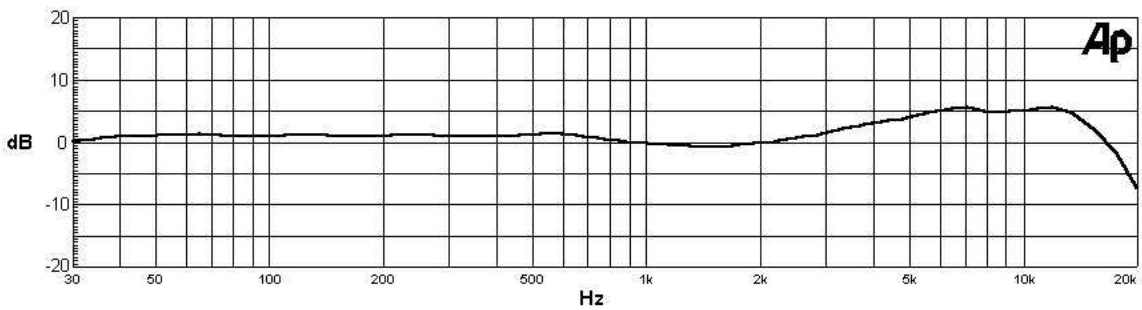


Fig 6 Relative frequency response of the optical microphone

5 ADVANTAGES AND APPLICATION FIELDS

Optical transducer principles offer some specialties compared to other principles:

- The optical microphone is completely insensitive to electrical and magnetic stray pick-up and thus gives the guarantee to measure only the acoustical signal at the position of the microphone head even in the presence of very strong electrical or magnetic disturbance (RF or static fields).
- The optical microphone system does not generate any electric or magnetic field. Thus it does not disturb any RF fields and has zero RF field emittance.
- The microphone head can be placed distant to the light source and the photo detector. More than 100 meter of fibre-optical cable can be placed between those components without degrading the quality of the audio signal
- The optical microphone does not need electrical wiring to the microphone head. This eliminates possible interference with EMC regulations and allows the use of the microphone in hazardous locations (UL / HazLoc) where explosive gases or dust are present.
- The optical microphone cannot be detected by metal detectors or electric/magnetic field detectors since it contains no metal or flowing current.
- Operation under strong magnetic or electric or RF fields. The optical microphone guaranties, that the audio signal is absolutely free from any disturbances that might be caused by those fields.
- Operation in hazardous locations. The optical microphone cannot generate ignition of explosive atmospheres or dust since it uses no electrical wires.
- Operation in high humidity.

As an example, Figure 6 shows an application of the optical microphone in a MRI scanner for patient communication microphone and for inputsignal to an ANR system. The optical microphone does not disturb the imaging process since it contains no significant metal parts. The audio signal of the microphone is completely free from stray pick-up of the rapidly changing strong magnetic field components in the core zone of the MRI. Other applications are shown in Fig 7 and 8.

Figure 6 shows the optical microphone placed in a MRI system. Using the microphone as an input to a patient communication and ANR system requires its placement in the high magnetic field. Plastic tubes for acoustic wave guide cannot be use in an ANR application.

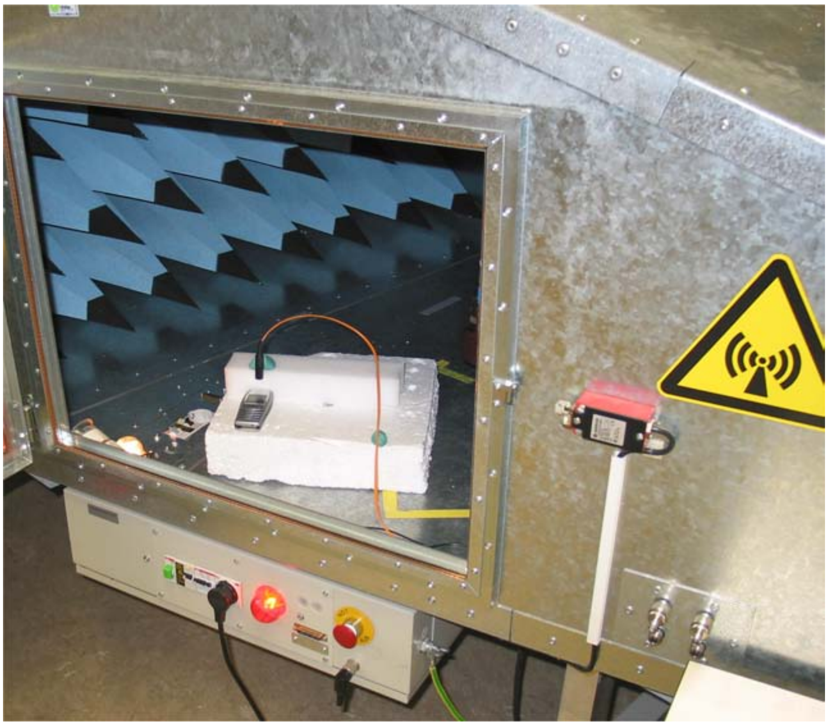


Fig 7 shows the optical microphone in a EMC measurement chamber.

Fig 8 shows the optical microphone in a hazardous explosive gas atmosphere region picking up acoustical signals for automatic leak detection and surveillance at a gas production plant

6 REFERENCES

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