Miniaturized all-optical Sound Pressure Sensor

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ABSTRACT

The membrane-free optical microphone, an alternative concept to measure sound pressure, will be presented. A laser beam, locked to a millimeter-sized Fabry-Pérot interferometer experiences a change in wavelength, if the pressure of the medium and hence the refractive index inside the interferometer is altered by a sound wave. The resulting change in back reflection of the laser is measured by a photo diode, thus providing a direct measurement of the sound pressure. It is important to mention, that the system operates without any moving parts. Hence, the measured signal is not a result of a mechanically moving or deformable mirror, but a consequence of the change in the density's medium itself. Therefore, this sensor principle is free from mechanical resonances and allows for a linear frequency response expanding over 1MHz in air and over 25MHz in liquids.

The talk compares operation in gaseous and liquid media and addresses potential contributions of internal structure-borne movements of the mirrors. It is shown that, even if Eigenmodes of the mechanical sensor structure are excited by sound pressure, their contribution is on the order of 3 decades below the contribution of the refractive index change, and may therefore be neglected. Several applications are presented.

Keywords: 71.1 Transducers; 72.1 Sound pressure level; 11.6.6 Power transmission

1. INTRODUCTION

Microphones representing the current state of the art use membranes or piezoelectric materials as intermediaries between the incoming acoustic and the resulting electrical quantity for the detection of sound waves. In other words: the core of a conventional transducer is a mechanical movable or deformable part. This mechanical component will, to some extent, determine the properties and the performance of the transducer. While conventional acoustic transducer technology produces good to excellent results in many situations, there are significant shortcomings that have not been solved to date.

From a fundamental perspective: membrane-based non-linearity in the frequency domain make microphones based on moving parts an imperfect sound detection device. In fact, a mechanical spring-mass oscillator (such as a membrane) inherently has a self-resonance introducing bumpiness in the frequency response of the device. This unwanted behavior can be compensated for by damping, but only at the undesirable expense of the sensor's sensitivity, phase linearity or frequency range. Furthermore, structure-borne sound susceptibility and wind noise are significant issues today. In acoustical metrology applications such as non-destructive testing or process control, the detection of a broader ultrasound spectrum is strongly desired. In medical ultrasound, more specifically in Photoacoustic Imaging, higher transducer sensitivity results in images with higher contrast in a shorter scanning time. Finally, there are several applications where a high directivity is desired, which is difficult to provide with current microphone technologies.

An overview on the operational principle of the novel acousto-optic sensor is given in section 2.

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The subsequent section 3 deals with the question, if structure-borne vibrations of the mirrors may have a contribution on the output signal. The paper closes by presenting application examples in section 4.

2. THE MEMBRANE-FREE OPTICAL MICROPHONE'S FUNCTIONAL PRINCIPLE

An acoustic pressure wave is a change of the local density of the medium. As a result, the optical refractive index of the sound-propagating medium is altered. If one looks at two points in space in this very medium, the following is observed: Whilst the geometric path between the two points remains constant, the optical path length between them is altered. This means that sound influences the speed of light; light propagates slower if the medium's density is increased. An optical interferometer may be used to quantify this change in the speed of light thereby revealing the momentary sound pressure. This describes the basic principle of the present transducer, illustrated in Fig 1.

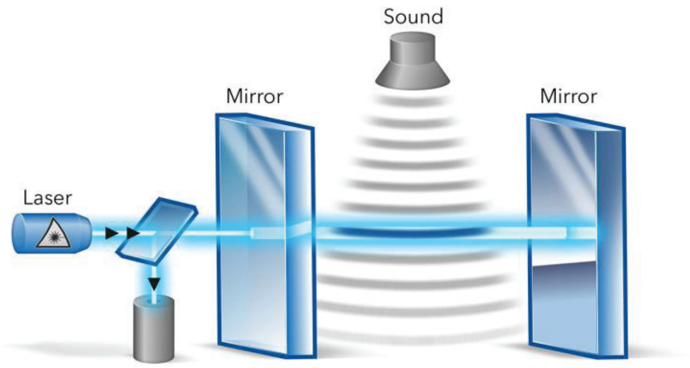

Figure 1 – Illustration of the functional principle of the membrane-free optical microphone. Sound pressure changes the density inside an air-spaced Fabry-Pérot etalon, inducing a change of light intensity.

The disruptive acousto-optic sensor technology does not rely on the detection of movement or displacement of an optical element such as a deformable mirror or a vibrating reflective membrane. By contrast, it is based on a rigid and non-deformable miniaturized interferometer consisting of an arrangement of two parallel mirrors. This allows direct assessment of the acoustic pressure without mechanical parts. Hence, sensor properties or distortion resulting from a mechanical nature can be eliminated. Most prominent of these properties are the sensor's susceptibility to mechanical disturbances as well as its non-linearity and its inherently limited frequency bandwidth. This optical microphone technology platform uses a rigid, so-called Fabry-Pérot etalon consisting of two parallel optical mirrors. A laser beam with a diameter on the order of 0.1 mm is directed onto the first mirror. Since the mirror is only partially reflective, a portion of the light is transmitted and hence coupled into the space between the two mirrors. The light is then bounced back and forth between the two mirrors, each time interfering with the previous beam. Depending on the local pressure of the medium in-between the mirrors, the phase of the light is altered and the interference may occur in a constructive or destructive way, according to the momentary refractive index or the acoustic pressure. A simple photodiode is used to detect the out coming light intensity, which is directly proportional to the sound signal. The optical microphone is — to the best of our knowledge — the world's first microphone without any moving parts. The optical microphone technology is currently being commercialized by the start-up company XARION Laser Acoustics GmbH and led to two product lines. They include a fiber-coupled optical (ultra)sound sensor (1,2) and a hydrophone (3). Also refer to figure 2 for a photo of the sensor.

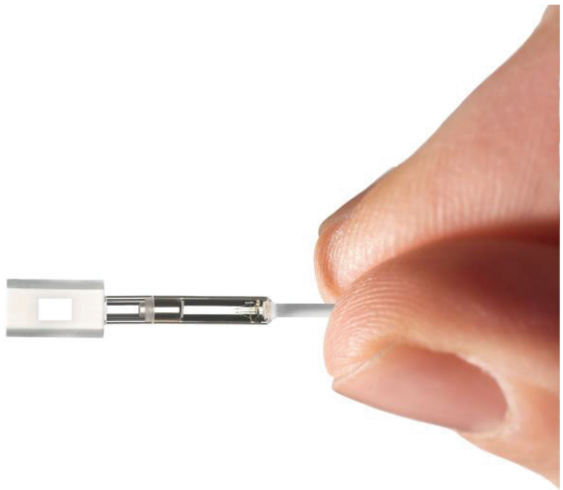

Figure 2 – Photo of the all-optical sensor head

3. INFLUENCE FROM MECHANICAL MIRROR VIBRATIONS

3.1 Motivation and simulation method

Of particular importance for the membrane-free optical microphone is the question, whether the mirrors may contribute to the output signal via (unintentional) vibration. To investigate this question, a comprehensive FEM study has been performed for microphone operation in both air and liquid. First, the Eigenmodes of the geometrical structure have been calculated. It is found that, due to the small geometrical dimensions of the sensor head (mm-size), the Eigenmodes lie mostly in the higher ultrasound range. The first Eigenfrequencies in air are 25.6kHz, 44.3kHz and 93.3kHz.

Then, a sound source was placed at a distance of 100mm from the etalon (i.e. the microphone head). The etalon has been placed at different angles, also refer to fig.3. The sound source with a diameter of 10mm is modelled by a point source superposition method (4). The excitation of the Eigenmodes is investigated, by calculating the excursion of the relative mirror movement induced by sound pressure. Finally, the sound pressure required for a given mirror excursion is compared to the equivalent microphone output signal, as induced by refractive index change.

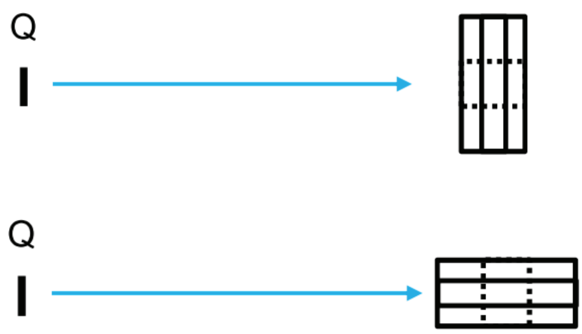

Figure 3 – Sound source (Q) is placed at a distance of 100mm from etalon. With respect to the opening towards the medium, angles of 0° (upper image) and 90° (lower image) have been investigated.

3.2 Microphone in gaseous media (airborne microphone)

The sound pressure level at the location of the etalon was calculating assuming an oscillating piston at the location of the sound source. Whilst some Eigenmodes do not have an impact on the microphone performance, since they do not move the mirrors apart from each other – seen from the perspective of the crossing laser beam – some others do. This is illustrated in Fig 4: while in the upper image, the path length of the laser, traversing etalon from the left to the right will remain unchanged, the path length in the lower image will be altered. Vibrations not affecting the path length of the laser beam between the two mirrors will not have any effect on the sensor output signal.

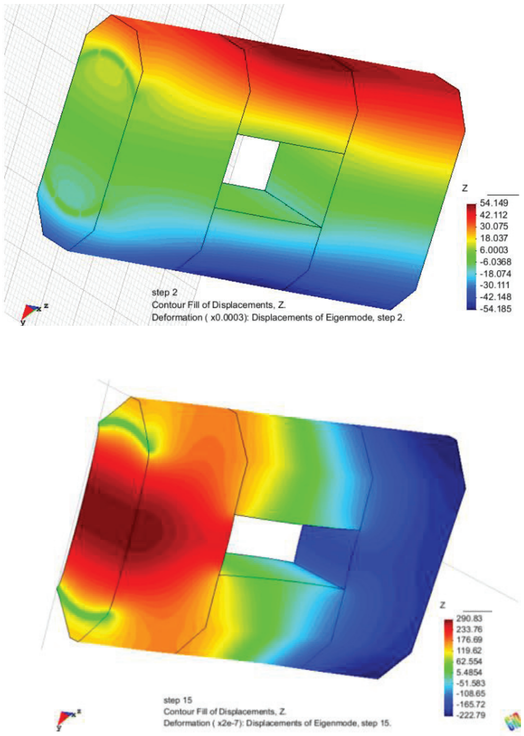

Figure 4 – Two Eigenmodes of the microphone head in air, 44.3kHz (upper image) and 615kHz (lower image). The color code stands for the level of excursion; yellow means zero excursion while blue and red signify positive and negative excursion, respectively.

The first Eigenmode with significant influence on the laser path length in air occurs at a frequency of 158kHz. The computer simulation yields: in order to physically move the mirrors by the distance of 1fm (10^{-15}m), sound pressure needs to amount to $100dB_{rel.\ 20\mu Pa}$ (equivalent to 2Pa) at the location of the etalon (90° orientation). How does this compare to an optical path length difference, induced by the change of refractive index? As mentioned above, for the intended operation of the microphone, the mirrors do not move at all. However, the refractive index change of the medium inside the cavity can be expressed as an equivalent change of length, the so-called change of optical distance. For a light propagating in any type of medium, the relationship $L_{optical} = n_{medium} \cdot L_{geometrical}$ holds. Thereby, L are the optical and geometrical lengths, respectively, and n is the refractive index of the medium. The optical cavity has a length of 2mm, and the pressure dependent change of refractive index of air is on the order of $2.7 \cdot 10^{-9}$/Pa (5). According to the equation above, the optical path length change induced by 1Pa pressure change is therefore $L_{optical} \approx 2.7 \cdot 10^{-9} \cdot 2 \cdot 10^{9}$ m $\approx$ 5pm. Therefore, the contribution from the refractive index change dominates over the unwanted physical mirror movement by a factor of

10,000 or 80dB. The non-linearity caused by the superposition of the two effects is negligible. Also note that this is only true for the Eigenfrequency; if the etalon is excited at a frequency unequal to one of its Eigenmodes, the effect will even be much smaller.

3.3 Microphone in liquid media (hydrophone)

Furthermore, the performance in liquid media is investigated, since the membrane-free optical microphone can also be used as a hydrophone.

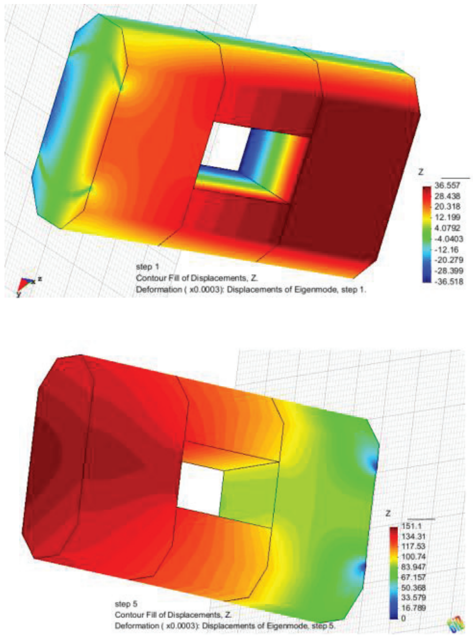

Figure 5 – Two distinct Eigenmodes of the optical microphone in water. The Eigenfrequencies are 25.6kHz (upper image) and 158kHz (lower image)

It is found that the Eigenfrequencies in liquids are approximately the same as in air. For the lowest Eigenmode (25.6kHz), the effect of the mirror excursion is somewhat alleviated, since the laser beam is limited to the center of the mirror, where the excursion essentially is equal to zero. However, disregarding this effect, the sound pressure required at the location of the etalon in order to physically move the mirror by 1fm at this lowest mode amounts to $160dB_{rel.\ 1\mu Pa}$ (equivalent to 100Pa). For the Eigenmode at 158kHz, it is $172dB_{rel.\ 1\mu Pa}$ (equivalent to 400 Pa). Here again, these values can be compared to the optical path length change induced by the refractive index change. It is found that the refractive index change dominates over the unwanted physical mirror movement by approximately 92dB or a factor of more than 40,000. Once more, the non-linearity caused by the superposition of the two effects is negligible.

3.4 Discussion of simulation results

In the first place, it is found that the (intended) effect of refractive index change of the medium dominates over the contribution of mechanical mirror movement. It might be somewhat surprising that this significant difference is even more pronounced in liquids than in air. Since the acoustic impedance of water is more similar that of glass (the etalon material) than if compared to airborne operation, where a larger index gap (between air and glass) exists, one might assume that structure-borne vibration couple into the physical cavity easier if operated in liquid. However, the opposite is found.

With sound pressure p, acoustic impedance Z, sound particle velocity v, and excursion ξ, one can write:

$$p = Z \cdot v = Z \frac{d\xi}{dt} \quad (1)$$

For a harmonic oscillation, this can be written as

$$p = Z \cdot j\omega\xi \quad (2)$$

Hence, at an equal particle excursion ξ, a higher sound pressure is required for higher impedance. In other words: for the optical microphone, to generate the same structure-borne impact, a higher sound pressure is required in water than in air. This difference is quite significant since the impedance of air is much lower than the impedance of water: Z_{air}=413 Ns/m³, Z_{water}= $1.4 \cdot 10^6$ Ns/m³.

4. APPLICATION EXAMPLES

4.1 Early field tests of the optical sensor

Two application examples for the membrane-free optical microphone shall be given, one for airborne sound and one for liquid-based sound.

4.2 Corona noise measurement

In an industrial project, the noise emission induced by a 380kV high-voltage power line was to characterize. Corona discharge, especially in the presence of light rain or fog, leads to a significant emission of noise. This source of noise may signify a major challenge in course of Environmental Impact Assessments. In prior work, characterization of corona noise was conducted with a focus on *immission* measurement, since a considerable safety distance between conventional microphones and the power line has to be respected while performing the measurements. In order to asses a more favorable signal-to-noise ratio, a source or *emission* measurement is preferred. Hence, the optical microphone was employed to monitor corona noise at a distance of 30cm form the power lines, where the sensor’s immunity to electromagnetic interference is key.

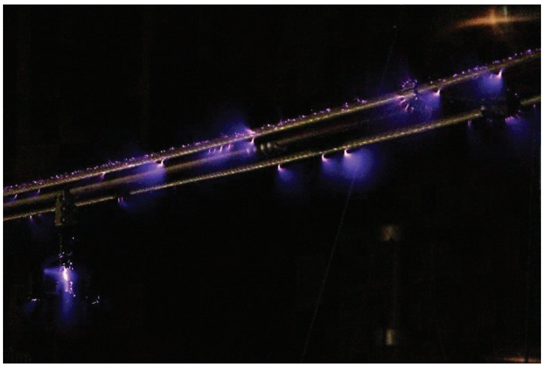

Figure 6 – Optical microphones are placed at a distance of 30 cm from power lines. (Photo courtesy of APG, Austria)

4.3 Photoacoustic imaging

The optical microphone, if used as a hydrophone, may be especially suitable in the fields of Photoacoustic Imaging (PAI), a currently emerging market and a hot topic. For this purpose, the cavity between the two mirrors is filled with liquid, which may be any fluid such as water, oil, or an index matching substance. Comparative benchmark tests showed that the optical hydrophone exceeds the similar-sized, best-in-class, medical ultrasound piezo sensor in terms of signal-to-noise ratio. A noise equivalent input pressure of <1Pa was repeatedly demonstrated over a 25MHz bandwidth for a sensor volume of smaller than 0.1mm³ (3). To our knowledge, this value is unprecedented for liquid coupled ultrasound sensors based on piezo or optical detection methods. Reaching high sensitivity over a broad frequency range is a key feature with clear benefits to the PAI application, since it directly impacts on image quality and measuring time. In cooperation with Vienna Medical University (Center for Medical Physics and Biomedical Engineering, Prof. Drexler), first results include images of zebrafish and resolution targets (3). Also refer to figure 7.

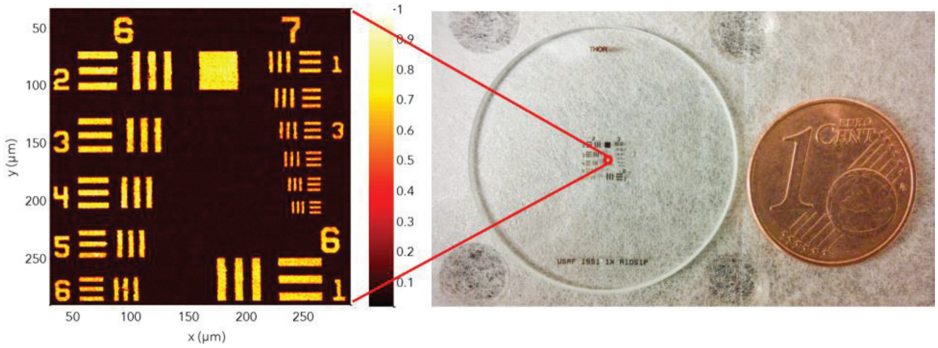

Figure 7 – Photoacoustic image of the standardized US Air Force resolution target imaged with XARION sensor Eta L. The magnified rectangular area has dimensions of 0.3mm by 0.3mm.

5. CONCLUSIONS

In this study, the influence of structure-borne vibrations on the membrane-free optical microphone have been investigated. It is found that the intended sensor signal induced by change of refractive index significantly dominates over the unwanted movement of the mirror structures. The effect is more pronounced in liquid than in air, which is due to the small excursions due to the high acoustic impedance of the liquid.

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