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Lower detection limit of the acousto-optic effect using Optical Feedback Interferometry

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Abstract—Measurement and 3D imaging of acoustic waves through the acousto-optic effect has recently been demonstrated by means of Optical Feedback Interferometry (OFI). In this paper we study experimentally the lower limits of detection of an acoustic wave using an OFI sensor. We show that the OFI sensor exhibits a linear response to acoustic power variations, and we obtain a lower limit of detection of 83 dB rms for a planar acoustic wave at 3 kHz. We also determine the equivalent displacement, that is seen by the OFI sensor at this pressure level, to be 96 pm. A deeper understanding of the limits of the technology and the quantification of the acousto-optic effect shall help improve the applications already created for the measurement of acoustic pressure waves using OFI.

Index Terms—Optical feedback, interferometry, self-mixing, acousto-optic effect.

I. INTRODUCTION

Optical Feedback Interferometry (OFI) is a non-contact, high-precision sensing scheme which is applied to many domains of metrology. Today we find OFI in applications such as flowmetry, absolute distance measurements, vibrometry and velocimetry [1]–[6]. Compared to other non-contact sensing technologies, OFI is self-aligned, low cost and robust. Recent applications have applied the sensing scheme to the imaging of acoustic waves through the acousto-optic effect. Bertling *et al* [6] and Urgiles *et al* [7] create visual representations of standing and propagating sound waves in air, while Dubois *et al* proposed an exciting application to image pressure waves in acoustic metamaterials [8].

In these applications they measure the minute changes in the optical path between the laser and the target, through the modulation of the refractive index of air caused by an acoustic pressure wave. These changes in optical path are usually far below the half wavelength of the laser and close to the limitations of the technology. One particular challenge that has not yet been treated is the quantification of the air-pressure change in an acoustic wave using this method.

OFI operates by backscattering the laser light off a target, inducing coherent mixing of the returning light with the laser inner cavity field. The laser wave phase and amplitude is perturbed, and these perturbations are measured by the laser’s in-package photodiode. The signal provides us with information about the target the laser is pointing on. If the target is in movement, interferometric fringes are observed. A fringe appears when the target has moved a distance of half the laser’s wavelength λ [1], [5], [9].

Measurements inferior to the half wavelength of the laser has been reported. Currently the state of the art using the OFI sensing scheme is measurements of 100 pm [2], [10], [11]. Through the acousto-optic effect we measure very small changes in the optical path through the modulation of the refractive index of air in the laser beam’s path. The effect has been depicted [6], [7] but there are no evidence of quantification of the acoustic amplitude or the effect on the refractive index so far.

The refractive index of air influences the time it takes for light to travel from the laser to the target and back. P. E. Ciddor [12] made an an exhaustive model to precisely calculate the refractive index of light under given conditions. His model operates in the visible and near infrared, even for small pressure variations.

In this paper we study the dynamic range of an OFI system measuring acoustic signals using the acousto-optic effect. Furthermore, we present a model for the conversion of measured acoustic pressure through the acousto-optic effect to an equivalent displacement in order to quantify the phenomenon. In earlier studies [6], [7], pressure and frequency are controlled, but the waves undergo a free field spherical propagation. To quantify the acousto-optic effect, we have chosen to work with planar waves, where the advantages of such waves are described in sections II-A and II-B.

II. THEORY

A. OFI model and governing equations

The laser power under external feedback P_F is calculated through the well established equation

$$P_F = P_0[1 + m \cos(\omega_F \tau_{\text{ext}})] , \quad (1)$$

where P_0 is the free running laser power, m is a modulation index that depends on the target reinjection efficiency, and ω_F is the laser frequency under feedback [1], [5], [7]. An acoustic wave is a variation of air pressure with a subsequent change in refraction index n [12]. Considering a change in n , the photon round-trip time in the external cavity τ_{ext} is expressed as

$$\tau_{\text{ext}} = \tau_0 + \delta\tau \quad (2)$$

with $\tau_0 = 2n_0L_{\text{ext}}/c$ where c is the speed of light, n_0 is the refractive index of air without acoustic excitation and

$$\delta\tau = \int_0^{L_{\text{ext}}} \frac{2\delta n(z)}{c} dz , \quad (3)$$

where z is the coordinate along the laser beam. If we consider a plane pressure wave propagating in a perpendicular direction to the laser beam, the refractive index is constant along the z axis and we can express (3) as

$$\delta\tau(t) = 2L_{\text{ext}}\delta n(t)/c \quad (4)$$

where $\delta n(t) = \delta n_{\text{max}} \sin(\omega_a t)$, with $\omega_a = 2\pi f_a$ where f_a is the acoustic frequency, and δn_{max} is the amplitude of the refractive index modulation of air in a given acoustic wave.

B. Refractive index of air

The round-trip time τ_{ext} in (1) is modulated through the change in n which is in turn modulated by the change of density of air under the effect of the acoustic pressure wave. To calculate variations of n we use Ciddor's model [12]. The model includes wavelength, pressure, temperature, relative humidity and CO_2 concentration. Since the acousto-optic induced change in the optical path produces the same effect as a change in physical path, to quantify the acousto-optic effect we calculate an equivalent displacement from the change in refractive index

$$\delta d_{\text{eq}} = L_{\text{ext}} \left(\frac{\partial n}{\partial p} \right)_{\lambda, P_0, T_0, \text{RH}_0, R_{\text{CO}_2,0}} \times \delta p \quad (5)$$

where $\partial n/\partial p$ is the change in refractive index with regards to the change in pressure, and δp is the pressure difference in an acoustic wave, measured in Pa. λ is the laser wavelength, P_0 the initial pressure, T_0 the temperature in Celsius, RH the relative humidity and $R_{\text{CO}_2,0}$ the CO_2 concentration.

The δn_{max} following (4) is calculated for a pressure change δp using Ciddor's model, and the constants ∂n and ∂p are computed. By considering planar waves, the pressure p and hence the refractive index n is evenly distributed through the entire optical axis of the laser.

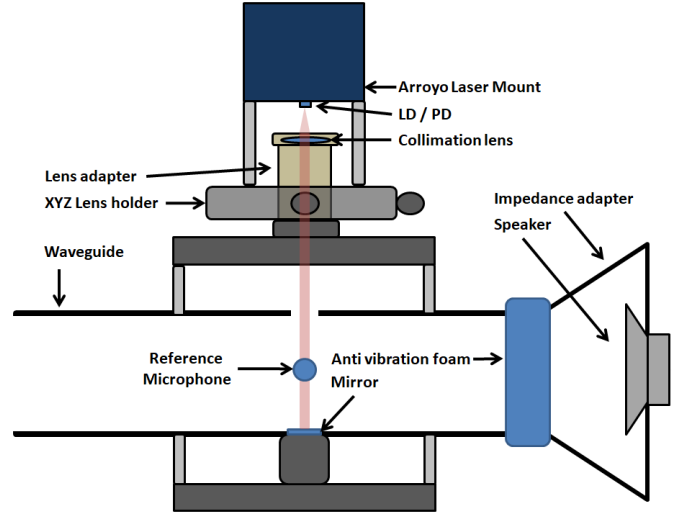


Fig. 1: Top view of experimental setup.

C. Experiment

A Distributed Feedback laser diode (1310P5DFB) emitting a transverse and longitudinal single mode at 1310 nm is mounted on an Arroyo Instruments laser mount. The mount includes a temperature control that is driven by a ThorLabs TED 200C. The laser beam is colimated by a ThorLabs C230TMD-C lens and aimed at a Thorlabs PF05-03-P01 mirror mounted in a Thorlabs KAD12F adjustable mount, 200 mm from the laser source. The mirror is aligned so that the beam is re-injected into the laser with the best achievable efficiency.

In order to assure planar waves, the acoustic waves are injected into a cylinder of diameter 55 mm and length 0.5 m. The acoustic wave is generated by a Visatron FRS 8 speaker, driven by a Renkforce SAP-702 amplifier that is mounted inside an acoustic impedance adapter of length 130 mm at the end of the waveguide. The interferometric system is fixed on the waveguide at 200 mm from the inlet. A G.R.A.S 46AE metrologic microphone is inserted into the waveguide over the laser beam, flush with the inner wall as to not perturb the pressure wave. The acoustic signal is acquired by an ACOEM 04dB acquisition card connected to the microphone.

The ensemble laser - waveguide - mirror, is placed on vibration absorbing foam to reduce potential vibrations propagating through the optical table. The impedance adapter and speaker is attached to the waveguide through absorbent foam to reduce vibrations due to the mechanical movement of the speaker membrane. Two PCB 352C18 accelerometers are fixed on the distant sensor parts: one on the laser mount, the other on the mirror mount.

Once acquired, the accelerometer signals are integrated two times before being subtracted from one another to compute the relative displacement.

To determine the linearity and minimal detection level of the system, a continuous sinusoidal acoustic signal with frequency 3 kHz is sent through the waveguide and the OFI signal is recorded for signal amplitudes ranging from 70 dB_{rms}

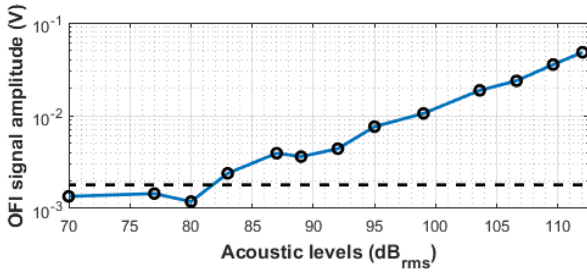


Fig. 2: Blue line: Sensor signal power for acoustic pressures. Dashed black line: Noise level of the sensor.

(0.09 Pa) to 112 dB_{rms} (11.26 Pa). The signals are acquired and filtered using a 2nd order Butterworth bandpass filter with cutoff frequencies $f_{c1} = 2.7$ kHz and $f_{c2} = 3.3$ kHz. An FFT is calculated for each signal, and the amplitude of the 3 kHz peak is recorded.

D. Numerical simulations

Using (5) we can calculate an equivalent displacement for an acoustic pressure wave under a given set of conditions. With an OREGON WMR89 weather station we measure the temperature to be 20°C and the relative humidity to be 35%. The atmospheric pressure is 101.325 kPa, the laser's wavelength is 1310 nm and the CO₂ quantity is set to 450 ppm as proposed in [12]. We calculate the refractive index n over the pressure range of a class one metrological sonometer (65 kPa to 110 kPa) with mentioned parameters as input, and we derivate to obtain ∂n for use in (5). Using the same input parameters we can simulate the variation of pressure in an acoustic wave and calculate the equivalent displacement for any given acoustic power.

III. DISCUSSION

In Fig. 2 we observe the system's response to acoustic pressure levels. When we decrease the acoustic power from 70 dB_{rms} to 112 dB_{rms} the response is fairly linear before flattening out at the bottom. The system's response to acoustic the pressures 87 dB_{rms} - 92 dB_{rms} remains at a similar level. This is possibly caused by a change in ω_F (1), due to a perturbation in the laser current, change in laser temperature, or to vibrational perturbations. The lowest detectable acoustic amplitude is 83 dB_{rms} which is recorded with an amplitude of 2.4 mV by the OFI system.

Fig. 3 shows the theoretical relationship between the amplitude of a plane acoustic wave in Pascals that passes through the laser beam, and the equivalent displacement in nanometers, as calculated using the model in [12]. Plotted in a dashed blue line in the same figure we observe how the sensor's response the acoustic pressure follows the theoretical curve in a linear fashion.

Using (5) we calculate that a 11.26 Pa zero to peak acoustic pressure wave corresponds to an equivalent displacement of 1.64 nm zero to peak. The lowest detectable amplitude in our experiment is 0.4 Pa zero to peak and is calculated to be 58 pm in equivalent displacement zero to peak.

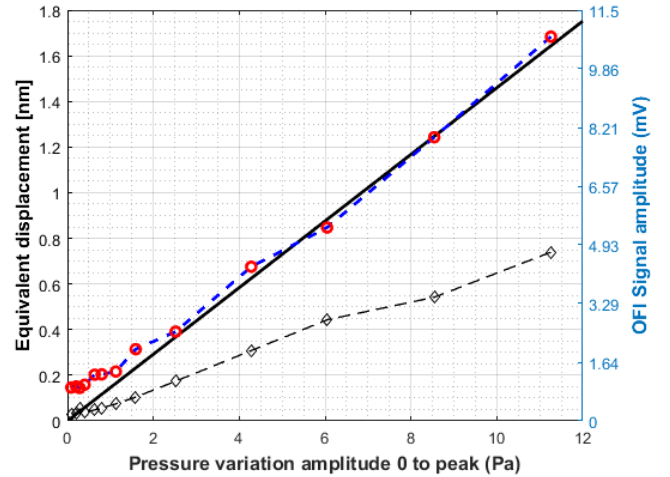


Fig. 3: Black solid line (left axis): Simulated equivalent displacement for given pressure variations. Black striped line (left axis): Differential movement between laser mount and mirror mount for given pressure variations. Blue striped line (Right axis): Sensor response for measured acoustic pressure

For each acoustic power we use the accelerometers to estimate relative displacement between the mirror and the laser. We observe a modulation of the relative distance at the acoustic frequency which is 3 kHz. In Fig. 3 we observe how the relative amplitude between the laser mount and the mirror mount descends linearly with the acoustic pressure. When injecting the 11.26 Pa zero to peak pressure wave into the system, we observe a 0.74 nm zero to peak relative movement between the laser mount and the mirror mount. As such we consider the vibrational levels too strong to be negligible. The average relative movement of the system is 0.038 nm zero to peak at the lowest detectable acoustic power of 0.4 Pa zero to peak. Therefore we calculate a new lower limit of detection for the system by adding the measured vibrational displacement to the theoretical equivalent displacement, and we obtain 96 pm zero to peak, that is similar to the lowest reported values for vibration OFI sensing in the literature. Thus we account for the possible perturbation due to vibrations in the system.

IV. CONCLUSION

We have studied the response of an OFI sensing system measuring the acousto-optic effect for different amplitudes of acoustic pressure variation. A model was established to convert the measured acoustic pressure amplitude to an equivalent displacement. Using planar acoustic waves made it possible to control and accurately measure the pressure p along the optical axis of the laser. The system was designed so that the acoustic waves were completely planar in order to calculate the equivalent displacement using the model.

We have found that there is a linear relationship between the optical power variation and the acoustic pressure variations. Due to vibrations in the system the relative distance between the laser mount and the reflector mount is modulated at the

acoustic frequency. We have determined the lowest detectable acoustic amplitude detectable, taking into account these perturbations. The lowest detectable optical path variation we are able to detect with our system is 96 pm when the acoustic wave pressure variation is 0.4 Pa. The relative movement due to vibrations is 38 pm and the calculated equivalent displacement is 58 pm. In [2] the lower threshold of vibration reported is 0.1 nm, giving our system essentially the same performances. In order to eliminate the effect of the vibrations the experiment is to be improved so that the laser and mirror mounts no longer are in contact with the waveguide. The acoustic generator should be placed on vibration absorbent foam in order to eliminate vibrations propagating through the optical table.

A future perspective is to continue the development of our model to make it compatible with spherical free-field acoustic waves. Such a model would be of great advantage when studying the acousto-optic effect using OFI, and could even be applied to previous studies already published. In doing so we could, using OFI, create a non-contact, cost effective and accurate measurement instrument for the quantification of free-field acoustic pressure waves. As the instrument would be non-contact, the wave would not be perturbed as it is measured.

V. ACKNOWLEDGMENTS

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