Gas cell photoacoustic detection of ultrasound absorption

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Abstract. The photoacoustic signal generated by a 2 MHz ultrasound transducer has been detected at 500 Hz modulation frequency by an attached photoacoustic cell. A dominant mechanism for signal generation is the ultrasound absorption in the gas of the cell, where strong acoustic resonances are excited. The periodic heating by ultrasound absorption in the transducer buffer rod and subsequent thermal diffusion into the gas is a second mechanism. Experiment and theory are in reasonable accordance.

1. Introduction
Ultrasound absorbed by media is finally converted into heat. For ultrasound in the MHz range, there were different attempts to detect this heat by thermal techniques. Monchalin et al. used phase sensitive detection of the infrared radiation to determine the weak ultrasound attenuation coefficient in polycrystalline steel, which is difficult to obtain by ultrasound techniques as it can not easily be distinguished from attenuation due to scattering [1,2]. Tittmann et al. used infrared detection to measure low frequency ultrasound absorption in various materials using infrared detection [3]. Ringermacher et al. generated a low frequency thermoacoustic vibration signal which was detected by a piezoelectric transducer [4]. Other work was devoted to calibration of transducer power and used thermocouples and comparably slow heating processes to detect the heat generated by ultrasound [5,6].

The role of ultrasound absorption in the gas was only shortly mentioned in [2]. In this contribution, detection of solid and gas ultrasonic absorption by a photoacoustic (PA) cell is analysed as a function of ultrasound frequency and thermal modulation frequency.

2. Experimental
A PA cell with a cylindrical volume of 8 mm diameter and 3.5 mm height was used for the experiments. Top and bottom of the cell are formed by the transducer (or by a flat insonified sample) and by a glass window, respectively (Fig. 1a). For the experiments, a cw ultrasound signal was rectangular amplitude modulated with 50% duty cycle at frequencies of 40 Hz to 1 kHz. The PA cell has a frequency response function with a maximum at 40 Hz (given by the microphone) and a first acoustic cell resonance at 4.5 kHz. A lock-in amplifier analyses the microphone signal for oscillations at the modulation frequency.

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The ultrasound transducer consists of a piezoelectric disk mounted on a 24 mm long polymer buffer, which is forming one cell wall. It has a center frequency of $f = 2$ MHz and a bandwidth of about 1 MHz. In the experiment, a fixed modulation frequency of 500 Hz was used (which allows a good signal/noise ratio) while scanning the ultrasound carrier frequency slowly over the bandwidth of the transducer.

![Experimental arrangement of the ultrasound transducer and the photoacoustic cell.](image1)

**Figure 1.** a) Experimental arrangement of the ultrasound transducer and the photoacoustic cell. b) Sketch of signal the contributions discussed

![Photoacoustic signal at 500 Hz modulation frequency as a function of the ultrasound frequency for a broad-band probe with 2 MHz center frequency](image2)

**Figure 2.** Photoacoustic signal at 500 Hz modulation frequency as a function of the ultrasound frequency for a broad-band probe with 2 MHz center frequency

A PA signal can be detected, which shows strong peaks with a spacing of about 50 kHz (Fig. 2).

3. **Theory**

Two contributions are accounted for the signal generation in the PA cell:

3.1. **Acoustic absorption in the gas of the cell (Fig. 1b, top)**

The attenuation coefficient of air is frequency dependent and proportional to the square of the ultrasound frequency $f$: $\alpha_g = 12.66 \left(\frac{f}{\text{MHz}}\right)^2 \text{ m}^{-1}$. At 2 MHz, the acoustic wavelength $\Lambda$ in air is about
165 \mu m. The cell is forming an acoustic pipe with a resonator order of about 42 and a mode separation of 47.6 kHz. The acoustic impedance $Z_g$ of a pipe can be found to be [7]:

$$Z_g = \rho_g v_g \left| \frac{\alpha_g L - i \cdot \cos(kL) \sin(kL)}{\sin^2(\alpha_g L) + (\alpha_g L)^2 \cos^2(kL)} \right|,$$

(1)

where $\rho_g$ is the gas density, $v_g$ the speed of sound, $\alpha_g$ is the attenuation coefficient in air, $k$ the wave number in air and $L$ the length of the pipe. The part of the transducer power $P_t$ which is entering the gas is:

$$P_g = P_t \frac{(2Z_g)^2}{(Z_t + Z_g)^2},$$

(2)

where $Z_t$ is the acoustic impedance of the delay line. $P_g$ is very small compared to $P_t$. The gas pressure signal $\Delta p_g$ for a periodic power input is then

$$\Delta p_g = \gamma - 1 \frac{P_g}{V_g} \frac{1}{2 \omega_m}.$$

(3)

Here $\gamma$ is the adiabatic exponent and $\omega_m = 2\pi f_m$, where $f_m$ is the modulation frequency.

3.2. Thermal piston effect due to a periodically heated transducer delay line (Fig. 1b, bottom)

The attenuation coefficient of the buffer polymer is frequency dependent and also proportional to the square of the ultrasound frequency: $\alpha_t = 5.25 \ (\mu\text{MHz})^2 \ \text{m}^{-1}$. The transducer delay line material is periodically heated by ultrasound absorption. The delay line surface generates a classical thermal piston contribution by heat flow into the gas and subsequent gas expansion. The absorbed power density $q_t$ in the delay line material close to the cell is given by:

$$q_t = 2\alpha_t (1 + \frac{(Z_g - Z_i)^2}{(Z_g + Z_i)^2})I_l,$$

(4)

where $\alpha_t$ is the ultrasound attenuation coefficient and $I_l$ the incident sound intensity in the buffer. The acoustic wavelength in the buffer is large compared to the thermal diffusion length $\mu_b$ of the buffer and $\mu_g$ of the gas at 500 Hz modulation frequency. The effusivity of the air is small compared to that of the buffer. The temperature oscillation $\theta_t$ resulting from this volume heated region is then:

$$\theta_t = \frac{1}{2} \frac{a_t}{\rho_t c_t} \frac{1}{\omega_m}.$$

(5)

Here, $\rho_t$ is the density and $c_t$ the specific heat capacity of the buffer material. Finally, the gas pressure signal $\Delta p_p$ due to the thermal piston contribution is:

$$\Delta p_p = \gamma - 1 \frac{\rho g c g}{V_g} \frac{1}{2 \omega_m} \theta_t.$$

(6)

4. Discussion

The gas absorption effect has a modulation frequency dependence $\sim \omega_m^{-1}$, whereas the thermal piston effect has a frequency dependence $\sim \omega_m^{-1.5}$. This should lead to a relatively stronger thermal piston effect at lower modulation frequencies.
Fig. 3 shows a calculation based on equations (1)-(6) using literature data for the material parameters and assuming an incident acoustic power of 1 W into the cell diameter.

![Diagram showing calculated pressure signal in the photoacoustic cell at 500 Hz modulation frequency as a function of the ultrasound frequency for a broad-band probe. Solid line: gas absorption part. Dashed line: thermal piston part.]

The acoustic resonances resulting from gas absorption dominate the total signal at lower frequencies. The acoustic attenuation coefficients of gas and solid, which are strongly increasing with frequency, lead to decreasing resonance peak heights but to an increasing thermal piston contribution with increasing frequency. Compared to the experiment (Fig. 2), the thermal piston contribution is not or only weakly visible. This may be due to an overestimation of the assumed ultrasound absorption coefficient for the buffer rod. The transducer band-with curve has not been considered in the model, which leads to some deviations. Moreover, both contributions have different signal phase, therefore not necessarily leading to purely additive superposition.

In conclusion, this kind of “sono-acoustic” detection may be a fast and simple tool for calibration of strong acoustic sources in the MHz regime.

References
[1] J.-P. Monchalin and J. F. Bussière, In: “Nondestructive methods for material property determination”, C. O. Ruud and R. E. Green (eds.), (Plenum Press New York 1984) 289-298
[2] J.-P. Monchalin, J. F. Bussière and L. Bertrand, Can. J. Phys. 64, 1059 (1986)
[3] B. R. Tittmann and R. S. Linebarger, Proc. 1984 IEEE Ultrasonic Symposium, 762-765
[4] H. I. Ringermacher and J. S. Heyman, Proc. 1981 IEEE Ultrasonic Symposium, 840-843
[5] B. Fay, M. Rinker, Proc. DGZfP Jahrestagung 1993, 994-998
[6] M. R. Myers and B. A. Herman, IEEE Trans. Ultrasonics, Ferroelectrics and Freq. Control 49 (2002) 565-572
[7] L. Kinsler, A. Frey, A. Coppens, and J. Sanders, “Fundamentals of acoustics”, (John-Wiley & Sons, New York 1982)