Analyzing the shape of photoacoustic signal on audible frequency modulation

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Abstract. This paper reports the result of measurement and analysis of the shape of photoacoustic signal emitted from an object which is a piece of carbon paper, excited by a diode laser beam, which modulated by a square wave signal at audible frequency, so that acoustic measurement can be done easily and inexpensive. Here PC Real Time Audio Spectrum Analyser (RTA 168) from Virtins Technology is used to measure and record the acoustic signal. Three modulation frequencies were chosen which were 5.045, 9.576 and 14.816 Hz, all with 50% of duty cycle. The result showed that the fundamental frequency of photoacoustic signal fit to modulated laser’s signal. Measurement at 5.045Hz, as an example, showed that the shape of the photoacoustic signal fit to the model with average error of 5%. The absorption coefficient of carbon paper could also be calculated as \( \alpha = 1.49 \text{ cm}^{-1} \).

1. Introduction

The photoacoustic effect was first invented by Alexander Graham Bell as the result of his experimental attempt on 1880. This is the physical basis of the photoacoustic imaging process, in which an acoustic signal emitted due to the absorption of electromagnetic energy on an object. The electromagnetic energy can be either optical or radio signals. This technique was developed continuously as one of the non-ionization imaging methods in many fields.

The working principle of photoacoustic was a combination of optical and acoustic imaging methods. Optical imaging had a very good spatial resolution, but its performance will merely sharply decrease along with the depth of the object due to optical diffusion. Meanwhile acoustic imaging still had a good resolution for depths greater than 1 mm. Nevertheless, the result of interaction between acoustic signal and mechanical properties of material would sharply decrease in contrast of objects that had similar mechanical properties with its circumstances (for example in the case of tumor detection in tissues). The photoacoustic took advantage of optics and acoustics by emitting electromagnetic energy to the object and detected the risen effects through the occurred acoustic signal. Thus it was expected that not only optical spatial resolution would be achieved, but also subsurface acoustic penetration. Moreover, in the case of biological tissue, objects interact more with electromagnetic signals than acoustic, those make the method quite promising [1–4].
The design of a laser-based photoacoustic imaging system commonly found using laser source Nd:YAG which was combined with an Optical Parametric Oscillator (OPO) system to obtain a stable signal length, energy and pulse period. This design was proven to provide excellent photoacoustic results even though it was complicated and expensive [5]. One alternative that was quite promising as a beam source is a laser diode [6–7]. Not only cohesive and affordable, this kind of laser is available on a large number of wavelength. Several studies using laser diodes had been carried out but most of them worked above the audible area (ultrasonic). For pulse mode modulation, the ultrasonic detector used must have enough bandwidth in order to be able to detect the photoacoustic signal. Technically, designing detector like this is not easy and inexpensive [8]. The aim of this paper is to report the use of a laser diode as an optical beam source with low modulation frequency, under 20kHz. As it worked at audible frequencies, the experiments can utilize inexpensive audio recording devices. Therefore, the success of this research was expected to contribute to the development of photoacoustic imaging system with a more affordable device.

2. Theory

When the laser beam is incident on a medium, the intensity will be exponentially decreased with the depth \( z \) due to medium absorption, following the Beer-Lambert equation:

\[
F(z) = F_0 e^{-\mu_a z}
\]

(1)

Where \( F_0 \) is the intensity of the laser beam on the surface \( z=0 \) and \( \mu_a \) is the absorption coefficient of the medium. If the laser beam is a pulse with a width of \( t_p \), then from [8], the emitted photoacoustic signal can be expressed as follows:

\[
P_L(t) = \frac{B \beta}{c \rho} F_0 \mu_a e^{-1 - \mu_a c t} \frac{e^{-\mu_a c t}}{\mu_a c t}, \quad \text{for } 0 < t < t_p,
\]

(2)

\[
P_L(t) = \frac{B \beta}{c \rho} F_0 \mu_a e^{-\mu_a c t} e^{-\mu_a c t - 1} \frac{e^{-\mu_a c t}}{\mu_a c t}, \quad \text{for } t > t_p,
\]

(3)

where \( B = \) isothermal bulk modulus, \( \beta = \) thermal expansion coefficient, \( C = \) specific heat of constant volume, \( \rho = \) mass density, and \( c = \) the speed of sound in the medium. The shape of that photoacoustic signals as function of \( t \) is shown on figure 1.

![Figure 1. The shape of magnitude of photoacoustic signal related to \( t_p \).](image)

Based on figure 1, photoacoustic signal would be maximum at \( t = t_p \), so by using Eq. (2) it is acquired:

\[
P_L(t_p) = \frac{B \beta}{c \rho} F_0 \mu_a A, \quad A = \frac{1 - e^{-\tau}}{\tau}, \quad \tau = \frac{t_p}{t_S} = \mu_a c t_p,
\]

(4)

where \( A \) is stress confinement coefficient and \( t_S = (\mu_a, c)^{-1} \) is acoustic relaxation time. In the case of constant pulse energy, from Eq. (4), it could be seen that laser beam’s duration would affect the power of photoacoustic signal, the optimal result would be achieved if \( t_p < t_S \). If \( F_0 \) is a function of time as Eq. (5), then based on Eq. (4), the fluctuation of photoacoustic signal’s peaks can be expressed in Eq. (6).

\[
F_0 = F_0(t)
\]

(5)

\[
P_L(t_p) = \frac{B \beta}{c \rho} \mu_a A F_0(t)
\]

(6)

Eq. (6) shows that photoacoustic signal fluctuates following the function of the intensity of the laser.
beam, and the peak of that signal is proportional to the absorption coefficient of the medium, $\mu_a$.

3. Experiments
The experiments were using audio recording device by Virtins Technology comprised of (figure 2):
- Measurement Microphone (ECM999, bandwidth 20 Hz - 20 kHz)
- XLR cable
- XLR-to-USB Sound Card (sampling rate 48 kHz, 16bit)
- USB Cable
- Recording Software

The microphone was placed behind the object, which is a piece of carbon paper, inline with the laser beam, as depicted in figure 3.

![Figure 2](image1.png)

Figure 2. Instruments used for recording photoacoustic signal.

![Figure 3](image2.png)

Figure 3. Schematic of the experimental system used for measuring photoacoustic signal.

Laser’s pulse frequency controller is used as laser beam modulator. Modulation process was done electronically because of its easy design and capability to achieve higher frequency compared to mechanical modulator (rotating disc). The modulator was based on ATMEGA8535 microcontroller, commanded by a computer to control the frequency. The experiment was shown on figure 4.

4. Result and discussion

4.1 The effect of modulation frequency
The experiment is aimed to measure spectrum frequency of photoacoustic signal related to laser source modulation, using 50% duty cycled square wave signal. As depicted in figure 4, the intermittent laser
beam is directed onto the object, which emits acoustic signal that recorded by microphone. The recorded data and modulation signal would be analyzed using Fourier transformation. As shown in figure 5, the spectrums did not only consist of the fundamental frequencies of the square wave signals but also of neighboring frequencies. This is because each of the square waves signal was not perfectly square, so standard deviation ($\sigma$) was used as frequency spreading indicator near the fundamental frequency as shown in table 1. In these experiments, square waves with frequencies of 5.045, 9.576, and 14.816 Hz were applied respectively, to modulate the laser beam. The recorded signals and their spectrum frequencies were shown on figure 5.

![Figure 4. Photo of laser beam hit the object which is in line with the microphone.](image)

| Table 1. Standard deviation of modulated laser signal and photoacoustic. |
|------------------|-------------|-------------|
| Frequency (Hz)   | $\sigma_{\text{Laser}}$ | $\sigma_{\text{PA}}$ |
| 5.045            | 0.12        | 0.18        |
| 9.576            | 0.20        | 0.30        |
| 14.816           | 0.14        | 0.20        |

According to figure 5, both modulation signal and recorded data had similar fundamental frequencies for all experiments. These results were in accordance with equation (7), which showed that the fluctuation of photoacoustic signal was only determined by modulated laser’s frequency, if all other parameters were held constant. Despite the fact that there were a increase of standard deviation, which is implied that photoacoustic energy was distributed to other frequency besides fundamental. As the result, the peak of fundamental photoacoustic signal would be decreased. It might be caused by the imperfect square wave signal for modulation, which contains many frequency around its fundamental. Each frequency interacted photo acoustically then resulted in responses that widened the photoacoustic frequency spectrum, hence enlarged the standard deviation.
Figure 5. Spectrum frequencies of modulation signals (red) and recorded signals (blue), with three modulation frequencies, (a) 5.054, (b) 9.576, and (c) 14.816 Hz respectively.

4.2 The models of photoacoustic signal
Still using the same data, we chose a modulation frequency value (5045 Hz) in order to observe the shape of its photoacoustic signal. With this frequency modulation, there was around 9 observation points on every period, using 44.100 Hz sampling frequency. Thus it was expected that signals information are not lost, according to Nyquist theorem. Then to reduce noise, as much as 100 signals were separated, averaged, and normalized. The result was fitted to the modelling data based on equation (2) and (3). Modelling curve was set by changing $\mu_a$ value, in order to minimized error between model and measurement. The best result was shown on figure 6. Using $t_p = 99 \mu s$ (half of a laser modulation period) and 5000 m/s as the speed of sound on solid material, the value of $\mu_a$ of the object could be found $1.49 \text{ cm}^{-1}$. The average error between model and measurement was 5%. With this small error, it was concluded that the model was successfully drew the physical process of photoacoustic.

5. Conclusion
This paper shows that the fundamental frequency of photoacoustic signal fits to the modulation frequency of the laser beam. By applying square waved signal for modulation, the spectrum frequency was widened as the result of frequency components around its fundamental. This led to decrease the peak of photoacoustic signal because of energy distribution. It could be lessen by applying smoother modulation signal such as sinusoidal. By applying the existed model, we was able to predict the absorption coefficient material of carbon paper, through model fitting. Therefore, audible frequency
photoacoustic method is able to be developed for more complex imaging.

![Figure 6](image)

**Figure 6.** Normalized of the recorded photoacoustic signals (dot), and of the model (line).

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