Seismic Wave Detection based on Laser Interferometer for P-S Time Measurement

Minwoo Lim, Kyunghyun Lee, Jungkeun Oh, Kwanho You

Sungkyunkwan University, Suwon, 440-746, Korea
{didwktlr, naman2001, ojkorea, khyou}@skku.edu

Abstract. In seismic wave measurement part, the accuracy of measurement data is very critical. Current seismic wave detection systems are based on seismometers or accelerometers. The basic structure is usually based on a piezoelectric sensor which has a limited measurement accuracy. To overcome this defect, we propose the heterodyne laser interferometer as a seismic wave measurement device. Laser interferometer is used in ultra-precision measuring field. We model the seismic signal detecting system to measure P-S time which is an important factor to estimate epicenter. Moreover, we measure the P-S time by using STA/LTA algorithm. We prove the performance of a seismic wave detection system based on laser interferometer.

Keywords: Laser interferometer, STA/LTA algorithm, seismic wave, P-S time

1 Introduction

Nowadays, in seismic signal measurement, the accuracy is a crucial factor. Seismometers or accelerometers are the most common sensors to measure a seismic signal. These apparatuses consist of electronic sensors which are based on piezo-electricity and piezo-resistive effect. However, there exist limitations of low resolution and narrow bandwidths.

In order to solve this problem, Gardner [1] proposed a seismometer based on a fiber-optic interferometry which has a high sensitivity. Wu [2] proposed Fiber Bragg Grating (FBG) based accelerometer which is robust to EMI, and has a signal multiplexing capability. Gevorgyan [3] suggested the single-layer open-flat-coil (OFC) oscillator-based sensitive platform technology to overcome the defect of seismometer and accelerometer.

In this paper, we propose a seismic signal detection method based on a laser interferometer system. Laser interferometer is a displacement measuring device. Using laser Doppler effect, laser interferometer measures distance. It is used for precision length measurement applied in the fields of semiconductor manufacture and robotics. Moreover, it covers a wide displacement range, from sub–nanometer (nm) to several meter scale. This paper is written as follows: In section 2, we analyze a laser interferometry system. Section 3 explains an STA/LTA algorithm, P-wave and S-wave. The performance is demonstrated by a simulation in section 4. The conclusion appears in section 5.

2 Heterodyne laser interferometer

Heterodyne laser interferometer emits laser light source which consists of two orthogonal beams with difference frequencies [4-5]. The laser light is divided by the beam splitter (BS) into two beams. One is the reference signal and the other is the measurement signal. The laser lights are denoted by $A\vec{l}_1 + B\vec{l}_2$.

The measurement beam is divided by a polarizing beam splitter (PBS) as $A\vec{l}_1$ and $B\vec{l}$. One signal ($A\vec{l}_1$) is reflected by a fixed mirror. The other signal ($B\vec{l}_2$) is reflected by a moving mirror. These signals are collected by a photo detector B. With no additive error, the intensity of measurement beam is represented as follows.

$$E_{A} = \frac{1}{2} A e^{j(\vec{l}_1 t + \theta_A)}$$

$$E_{B} = \frac{1}{2} B e^{j((\vec{l}_2 t) + \theta_B)} \tag{1}$$

The output signal collected by a photo detector B is proportional to wave intensity.

$$I_m \propto (E_{B1}+E_{B2})(E_{B1}+E_{B2})^* = \frac{1}{2}(A_A^2 B_B^2) + AB + \cos[wt(\Delta\theta) + \theta_B] \tag{2}$$

where $\Delta\vec{l}$ is defined as $\Delta\vec{l} = \vec{l}_2 - \vec{l}_1$. $\Delta\theta$ is the frequency difference caused by

Doppler effect.

Using a high pass filter, we eliminate DC components. To measure the phase in high accuracy, we use a lock-in amplifier to obtain phase information. Moreover, the multiplied results pass through a low-pass filter. Then, they are represented in sine and cosine waveforms.

$$I_x \propto \frac{AB}{2}\cos\theta,$$

$$I_y \propto \frac{AB}{2}\sin\theta \tag{3}$$

We can obtain θ as follows,

$$\theta = \tan^{-1}\left(\frac{I_y}{I_x}\right) \tag{4}$$

Finally, we can determine the difference in the optical length ($\Box L$) by using the equation of $\Box L = \Box \lambda / 4 \Box n$. λ is the mean of wavelength, n is a refractive index, and $\Box L$ is the difference of length between a fix mirror and a moving mirror.

2 STA/LTA algorithm for P-S time measurement

Generally, seismic waves consist of P-wave, S-wave and surface wave. P-wave is a longitudinal wave and arrives first. S-wave is a transverse wave and arrives secondly. Surface wave moves along surface and is the last to arrive. By using the difference of P-wave and S-wave arrival we can measure the distance of epicenter. Therefore, we use the STA/LTA algorithm to calculate P-S time.

The STA/LTA algorithm which is a standard trigger method in seismic recorders measures the ratio of energy density between short-term and long-term [6]. This algorithm estimates a seismic signal in two moving time window. If the amplitude of a seismic signal is defined as $a(t)$, the short-term average is represented as

$$STA(l) = \frac{1}{n_s} \sum_{t=l-n_s}^{l} a(t) \tag{5}$$

where n_s is the length of time window for short-term average. Similarly, the longterm average is represented as

$$LTA(l) = \frac{1}{n_l} \sum_{t=l-n_l}^{l} a(t) \tag{6}$$

where n_l is the length of time window for long-term average

The short-term average measures the instant amplitude of the seismic signal. While the long-term average calculates the real time average of seismic wave amplitude. Therefore it is less sensitive to a slow increase in energy. The STA/LTA algorithm measures the signal-to-noise ratio. The time when the STA/LTA ratio is over the user-defined threshold value is used to calculate the P-S time.

4 Simulation

In this section, we demonstrate the application of seismic signal measurement based on a laser interferometer and apply STA/LTA algorithm to measure the P-S time. Wavelength (λ) is set as 632.991 nm and refractive index (n) is 1.00000002665. By using the laser interferometer equation, we can measure the seismic wave movement.
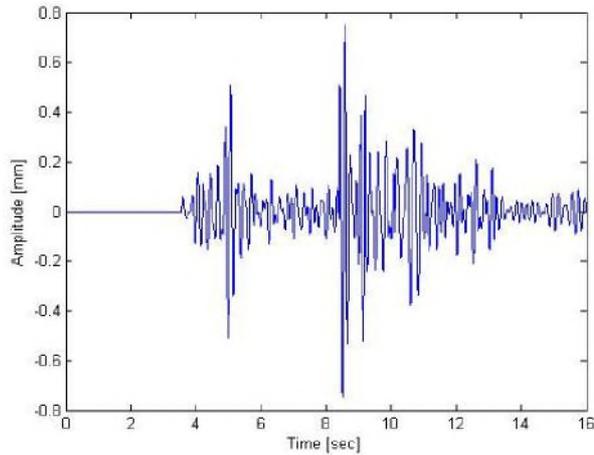
Fig. 1. Seismic signal measured by laser interferometer

Fig. 2 shows the application of STA/LTA algorithm in simulated data. We set up the window length of LTA as 10 times of STA and the threshold value as 2 times of average of STA/LTA. When STA/LTA value is over the threshold value, we can detect the P-wave arrival time and S-wave arrival time, respectively. P-and S-wave arrival time are measured as 3.6s and 8.4s. If the velocity of P-wave is 8km/s and the velocity of S wave is 4km/s, we can determine that epicentral distance is 38.4km by using the equation of $D = (V_P V_S / V_P - V_S) T_{PS}$. D is epicentral distance. V_P is P-wave velocity. V_S is S-wave velocity. T_{PS} is P-S time.
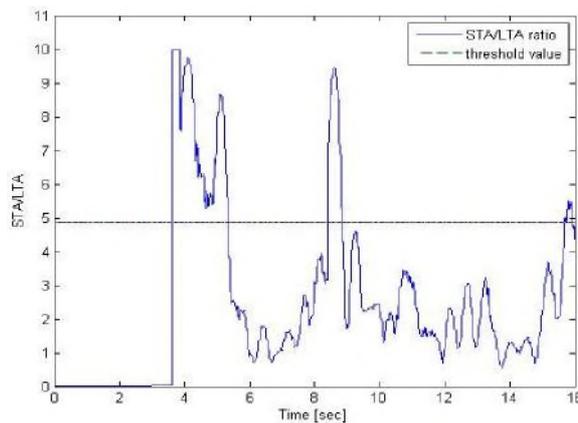

Fig. 2. STA/LTA ratio

5 Conclusions

In this paper, we purpose a seismic signal measurement method by using a heterodyne laser interferometer. Laser interferometer can measure the length using its intensity signal. By using a laser interferometer, we can detect the seismic wave in length scale and enhance the measurement accuracy in seismic signal detection. In order to prove the proposed P-S time detection algorithm, we set up the system modeling. Moreover, we use STA/LTA algorithm to measure P-S time. We confirm that laser interferometer can measure seismic signal as a seismometer.

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