P-S Time Observation based on Laser Interferometer Seismic Signal Data

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Abstract

In seismic signal detection, it is important to detect seismic wave and P-S wave arrival time. Seismometers or accelerometers which are used as seismic wave measurement system have some limits to detect seismic signal. In order to overcome these limits, we propose the seismic wave measurement device based on a heterodyne laser interferometer. Heterodyne laser interferometer is used as the distance measurement device which has measurable range from nanometer to several meters. Therefore we model seismic wave detection system based on heterodyne laser interferometer to measure P-S time for epicenter. Finally, we use STA/LTA algorithm to detect P-S time accurately. It is shown that heterodyne laser interferometer can be used as seismic detection device.

Keywords: Heterodyne Laser Interferometer, STA/LTA Algorithm, P-S Time, Seismic Signal

1. Introduction

Nowadays, there are many natural disasters such as typhoon, earthquake, tsunami, *etc*. Earthquake happens suddenly and moves fast. In order to prepare for the earthquake, we need for fast and accurate seismic signal detection. The mainly used devices to measure seismic wave are seismometer or accelerometer [1-2]. 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 [3] proposed a seismometer based on a fiber-optic interferometry which has a high sensitivity. Wu [4] proposed Fiber Bragg Grating (FBG) based accelerometer which is robust to EMI, and has a signal multiplexing capability. Gevorgyan [5] suggested the single-layer open-flat-coil (OFC) oscillator-based sensitive platform technology to overcome the defect of seismometer and accelerometer. Acernese [6] described a new low-frequency seismic sensor by using Michelson interferometer. Loh [7] proposed the interferometric accelerometer which consists of a suspended bulk-micromachined proof mass with protruding fingers. Araya [8] suggested the highly sensitive wideband seismometer based on the laser interferometer.

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.
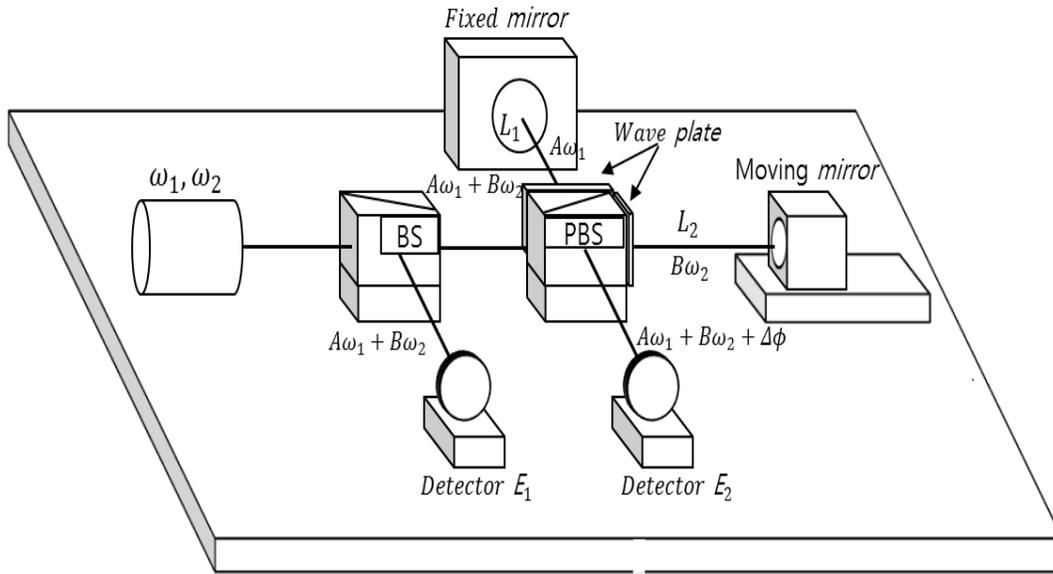

Figure 1. Heterodyne laser interferometer

2. Heterodyne Laser Interferometer

Heterodyne laser interferometer emits laser light source which consists of two orthogonal beams with difference frequencies [9-10]. 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 $A\omega_1 + B\omega_2$. The reference beam is collected by a photo detector A. The intensity of reference electric fields from detector A can be expressed as follows

$$E_{A1} = \frac{1}{\sqrt{2}} A e^{j(\omega_1 t + \phi_A)}$$

$$E_{A2} = \frac{1}{\sqrt{2}} B e^{j(\omega_2 t + \phi_B)}$$

(1)

The output signal intensity I_r measured by photo detector A is

$$I_r \propto (E_{A1} + E_{A2})(E_{A1} + E_{A2})^*$$
$$= \frac{1}{2}(A^2 + B^2) + AB\cos[\Delta wt + (\phi_B - \phi_A)]$$

(2)

The measurement beam is divided by a polarizing beam splitter (PBS) as $A\omega_1$ and $B\omega_2$. One signal ($A\omega_1$) is reflected by a fixed mirror. The other signal ($B\omega_2$) 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.

$$E_{B1} = \frac{1}{\sqrt{2}} A e^{j(\omega_1 t + \phi_A)}$$

$$E_{B2} = \frac{1}{\sqrt{2}} B e^{j(\omega_2 t + \phi_B + \Delta\phi)}$$

(3)

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

$$I_m \propto (E_{B1} + E_{B2})(E_{B1} + E_{B2})^*$$

$$= \frac{1}{2}(A^2 + B^2) + AB\cos[\Delta wt + (\phi_B - \phi_A) + \Delta\phi]$$

(4)

where $\Delta\omega$ is defined as $\Delta\omega = \omega_2 - \omega_1$. $\Delta\phi$ is the frequency difference caused by Doppler effect. Using a high pass filter, we eliminate DC components. Then, the AC components of I_r and I_m remain as follows.

$$I_{r,ac} \propto AB\cos(\Delta\omega t),$$

$$I_{m,ac} \propto AB\cos(\Delta\omega t + \Delta\phi)$$

(5)

To measure the phase in high accuracy, we use a lock-in amplifier to obtain phase information. $I_{r,ac}$ and $I_{m,ac}$ signals are calculated through a multiplier. Signal I_r is divided into two signals. One has the same phase with I_r and the other is 90 degree shifted I_r. Each signal is multiplied by I_m. We can obtain phase information which is needed to measure length. Moreover, the multiplied results pass through a low-pass filter. Then, they are represented in sine and cosine waveforms.

$$I_x \propto \frac{AB}{2}\cos\Delta\phi,$$

$$I_y \propto \frac{AB}{2}\sin\Delta\phi$$

(6)

We can obtain $\Delta\phi$ as follows,

$$\Delta\phi = \tan^{-1}\left(\frac{I_y}{I_x}\right)$$

(7)

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

The intensity signals of I_x and I_y is expressed as sine and cosine functions in Eq. (6). In an ideal circumstance, Lissajous' figure forms a circle in the $I_x - I_y$ plane. The trajectory of intensity according to the change of phase is plotted in Figure 2.
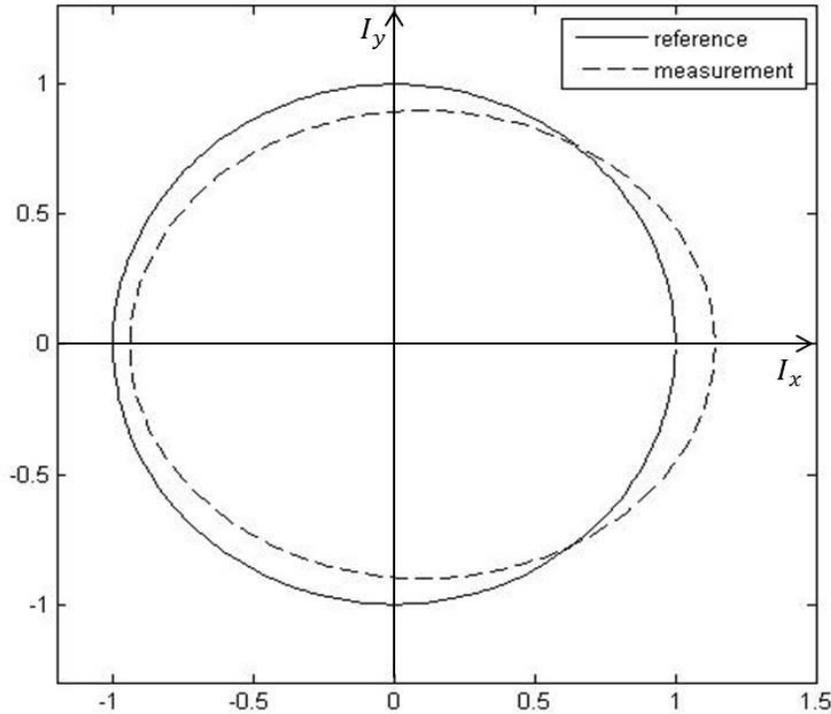
Figure 2. $I_x - I_y$ **plane**

3. 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 [11]. STA/LTA algorithm uses two moving time windows. To calculate the STA/LTA algorithm, the absolute amplitude of each seismic signal data is used. Next, the average of absolute amplitude is calculated by each window size. By using the average of absolute amplitude, we can obtain a value defined as STA/LTA ratio. In STA/LTA algorithm, we need to determine several factors such as STA window duration, LTA window duration, STA/LTA trigger threshold level, and STA/LTA detrigger threshold level. Moreover, to optimize triggering of seismic recorder, we set up these parameters which are trigger filters, pre-event time (PEM), post-event time (PET), and trigger voting scheme.

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 [12-14]. 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

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

(8)

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

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

(9)

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.
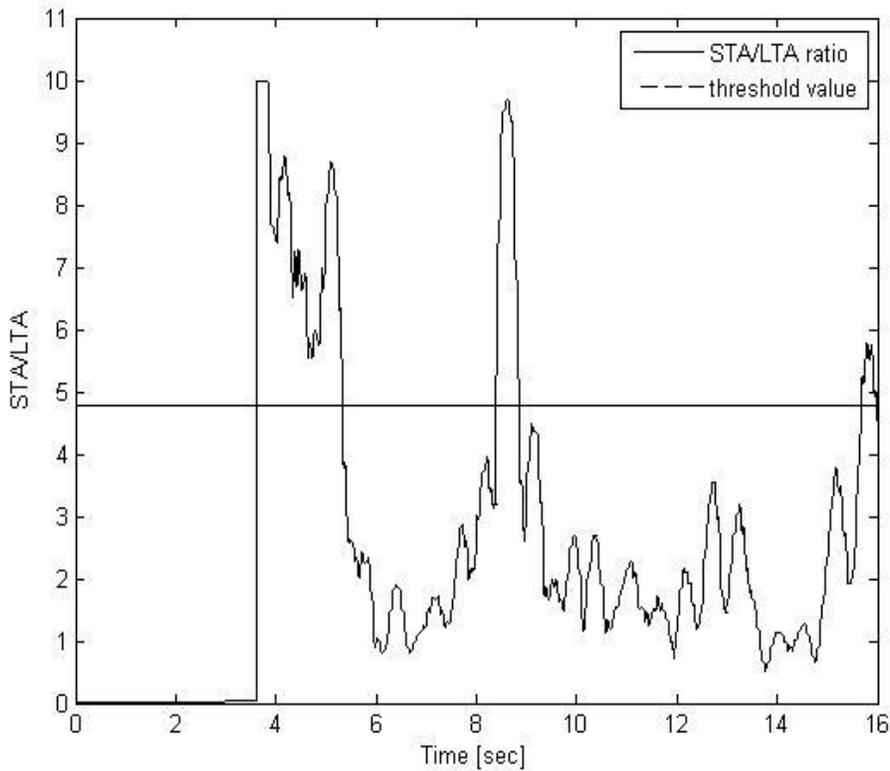
4. Simulation

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. Figure 3 presents the seismic signal detection with laser interferometer.
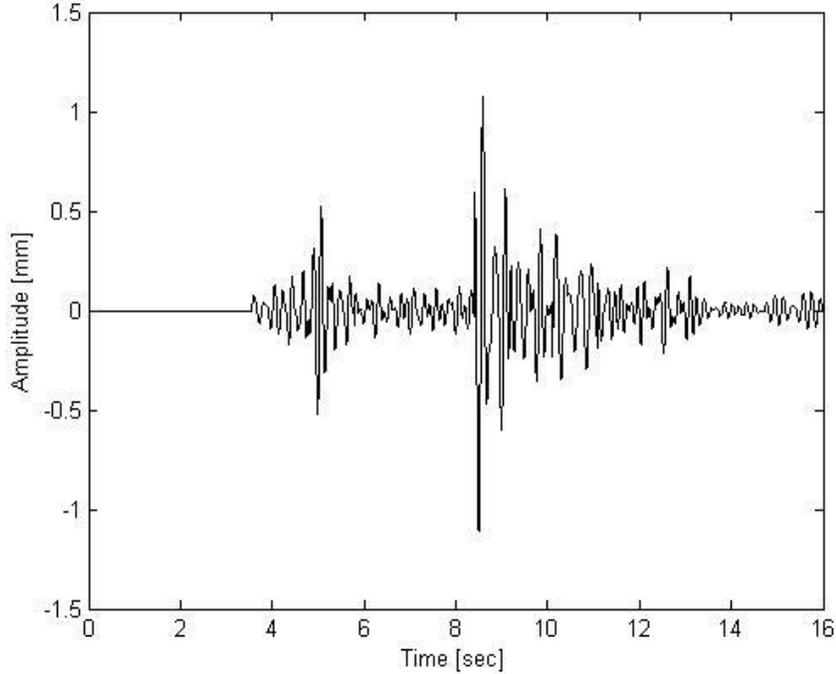
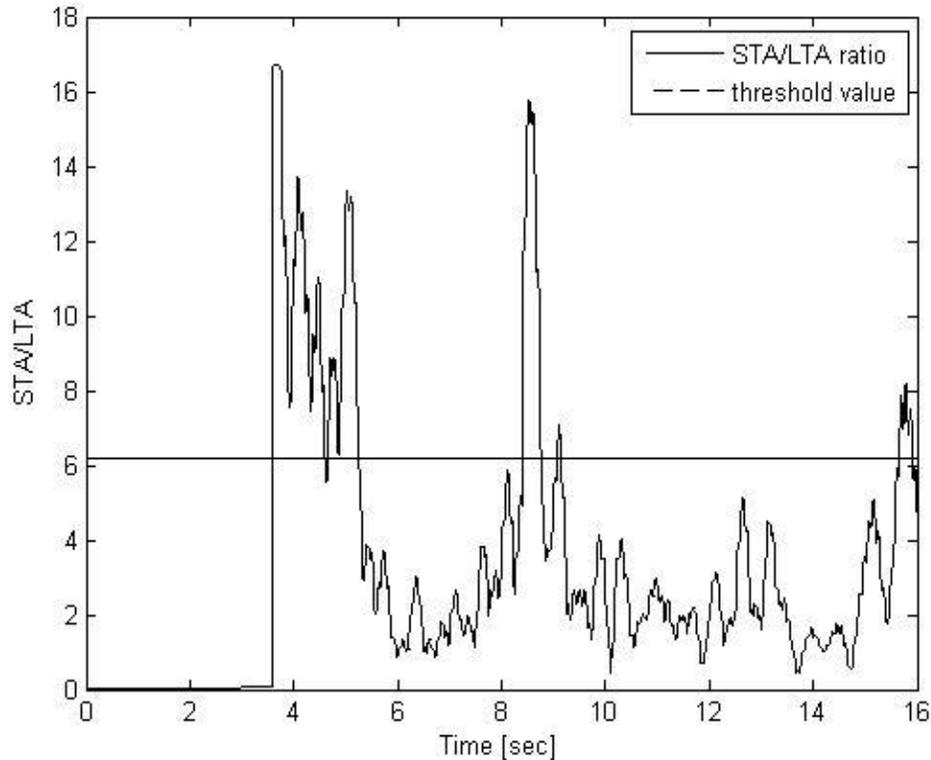**Figure 3. Seismic signal measured by laser interferometer**

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.

Figure 4 shows the application of STA/LTA algorithm in simulated data to set STA window size of 400. 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.

Figure 4. STA/LTA ratio with window size of 400

Figure 5 shows the application of STA/LTA algorithm in simulated data to set STA window size as 300. LTA window size is the same size as in Figure 4. The threshold value sets two times of STA/LTA ratio. We measure the P-wave arrival and S-wave arrival time again. Each P-S arrival time was measured as 3.6s and 8.4s, respectively. We assumed the same velocity of P-wave and S-wave in Figure 4. Then, we can determine the epicentral distance. The result of the epicentral distance with a window size of 300 is almost equal to that of a window size of 400. However, STA value with a small window size is more sensitive. Therefore, it shows more fluctuations according to various STA/LTA ratio and has more occurrences when STA/LTA ratio is above the threshold value. It shows a steep slope at P-wave arrival time and S-wave arrival time.

Figure 5. STA/LTA ratio with window size of 300

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.

Acknowledgements

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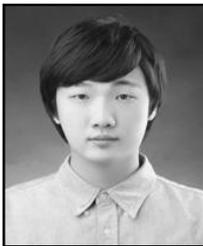
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