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An Optical Approach for Sensing Seismic Vibrations

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ABSTRACT

This experimental study demonstrates a novel optical method which is used as a readout system for a vertical seismometer that is, based on the moiré technique. Our purpose was to build an optical seismometer whose performance is similar to seismic sensors. The oscillation system of the sensor is a spring-suspended mass which its position is monitored by moiré technique. The maximum displacement is limited by mechanical issues to a few millimeters. We used two similar overlaid grids at a small angle that, one of them is fixed to the frame of the sensor and the other one is attached to the suspended mass. Moiré pattern is illuminated with a laser diode. The laser beam passes through the moiré pattern and a narrow slit and hits on a light detector. Due to moving the oscillatory mass and the fringes movements, the light intensity on the detector varies and is recorded as voltage. A digital signal processor samples the output voltage and produces a record of the seismometer mass displacement. The response of the optical seismometer was validated through comparison of recorded waveforms with those obtained by CMG-6TD seismometer. Comparisons with conventional seismometer show that, in terms of both noise and signal fidelity, the optical approach is quite viable. Our seismometer was found to be compatible with the reference seismometer.

Keywords:
Moiré technique; Diode laser; Seismometer; Light detector

1. Introduction

The problem of measuring vibrations is a very important topic that encompasses different areas of science and technology. Vibration can be measured and characterized in terms of displacement, velocity, or acceleration [1]. A seismometer consists of a pendulum mounted on a support base [2]. The pendulum in turn is connected to a recorder, such as an ink pen. When the ground vibrates, the pendulum tends to remain still while the recorder moves, thus creating a record of the earth's movement. Seismometers are instruments designed to detect and measure vibrations of the Earth [3]. Seismometer evolved from seismoscopes, which can detect the direction of tremors or earthquakes but cannot determine the intensity or the pattern of the vibration. The earliest known device used to detect earthquakes was created by a Chinese scholar, Chang Heng, around A.D. 132. For over 1700 years, the study of earthquakes depended on imprecise instruments such as Chang Heng's [4].

The first true seismometer may have been a complex mechanism designed by the Italian scientist Luigi Palmieri in 1855 [5]. This machine used tubes filled with mercury and fitted with electrical contacts and floats. When tremors disturbed the mercury, the electrical contacts concurrently stopped a clock and triggered a device that recorded the movements of the floats, roughly indicating both the time and the intensity of the earthquake. The first accurate seismometers were developed in Japan in 1880 by the British geologist John Milne, often known as the father of seismology [6]. Together with fellow expatriate scientists James Alfred Ewing and Thomas Gray, Milne invented many different seismological devices. Today, most seismometers still rely on the basic designs introduced by Milne and his associates, and scientists continue to evaluate the tremors by studying the movement of the earth relative to the movement of a pendulum. The first electromagnetic seismometer was invented in 1906 by a Russian Prince, Boris Golitsyn [7].

However, modern sensors were built about one century ago. All sensors are based on damped oscillation systems, the inertial mass suspended on a spring or an inertial-pendulum remains the mainstay of seismometer design [8]. The frame of the sensor is fixed to the ground. During ground shaking, the movement of the mass is delayed relative to the movement of the frame. A damping mechanism restores the mass to its equilibrium position after a small transient perturbation. Besides, seismometers have a readout system to convert the suspended mass motions to a time series. The development of low-noise high-resolution seismic sensors covering the seismic signal band from milliHertz to decaHertz has been quite slow in the last decades. Although many portable, efficient and robust seismic sensors have been developed in these last decades and many new ideas and techniques are being exploited, no one has improved the characteristics of band and sensitivity of the cornerstone sensors [9].

During the last decades, different kinds of methods have been widely used for readout system, which are conventionally based on the electromechanical, capacitive, or piezoelectric principles [10- 11]. In most seismometers, the readout system consists of a moving coil-transducer that converts the motion of the mass to voltage. Nowadays, this method used in short-period seismometers, while broadband seismometers generally use a force-feedback design, which largely improves the linearity of the sensor. In this case, the inertial force is compensated by a feedback force, generated with a suitable control system and applied to the test mass using an electromagnetic transducer [9]. However, the sensor output is directly proportional to the ground acceleration. These conventional sensors have some disadvantages, for instance they are susceptible to environmental electro-magnetic (EM) noise [12].

Optical sensors are suitable to be placed where strong electromagnetic fields are applied because of their resistance to electromagnetic interference (EMI). Moreover, optical approaches have some advantages with respect to the other techniques such as higher signal to noise ratio, sensitivity and precision. In the past two decades, several fiber optic-based techniques for vibration measurement have already been utilized. Widely speaking, they can be classified into intensity modulation [13], fiber Bragg gratings (FBG) [14], Fabry-Perot interferometry [15], and Much-Zehnder [16]. However, the measurement setup was discrete and complicated.

Recently, scientists used Michelson interferometry as a readout system in seismometery [8-9]. In these systems, the suspended mass motion is monitored interferometrically. In this case, the moving retroreflector attached to the suspended mass and due to a typical impulse both of them displaced. Therefore, interferometric fringes move as a result and convert to output signal finally by a light detector. The Michelson interferometery method consists of many components, making it complex and sophisticated as a readout method. However, using an appropriate optical readout system that have simple setup can be very useful and feasible in seismology.

This research has been motivated by a desire to develop a new optical readout system for seismic sensors. Toward this goal, Moiré technique is chosen because of its simplicity to implement and its precision in recording very small displacements of the Earth. These both advantages are very important in seismological applications, where it is necessary to use large number of instruments with acceptable accuracy and precision. The simplicity of the method also reduced the total cost of manufacturing optical seismometers.

Scientific explanation of this phenomenon for the first time in the seventh decade of the nineteenth century was expressed by Lord Rayleigh. He used this method for studied defects of diffraction gratings [17]. Since then, this technique was used by the scientists. Moiré techniques have expanded considerably over the past decade and are now established as important metrological tools.

The Moiré technique has many applications and used to measure variables such as displacements, rotations, curvature, and strain throughout the viewed area [18-19], light beam deflections [20] and applicability of time average geometric Moiré for elastic oscillating [21-22]. In this work, we introduce a novel precise readout system that is based on the Moiré technique. In the following, first, a brief introduction to Moiré technique is provided. The set up design and mathematical formulation of proposed readout system are provided in succeeding sections. The result of numerical simulation and experiments are also presented. At the end discussion about the results of the system is also provided.

2. Moiré Technique

Moiré technique is based on the interference obtained when two transparent plates such as two similar grids (or gratings) are overlaid at a small angle or when they have slightly different mesh sizes. For two similar and ideal overlaid grids, they can be aligned so that either no light passes, or maximum light gets through the grids. Now, if one of the plates is placed over the other and their lines have a small angle together, a new periodic structure that called Moiré pattern appears (Figure 1). The dark and bright regions are called fringes [23]. If the angle between the two gratings is increased, the separation between the light and dark fringes

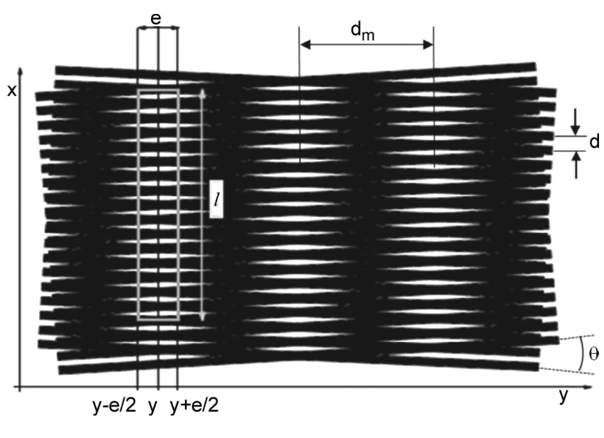

Figure 1. A moiré pattern obtained by superposition of two gratings of equal period and their lines at angle θ.

and the sensitivity decreases. By choosing a small angle, the sensitivity and fringes separability increases [24]. In this case, the period of Moiré pattern d_m is larger than the period of gratings d (Eq. 1). Displacing one of the gratings by an amount d in a direction normal to its rulings leads to a Moiré fringe shift of d_m.

Therefore, the use of Moiré technique magnifies the small displacements [25].

$$d_m = \frac{d}{2\sin(\frac{\theta}{2})} \tag{1}$$

According to the numerical simulation done in [26], the transmittance coefficient for a superposition of two gratings ($T(x, y)$) with their lines placed at angles θ to the y axes is given by [26]:

$$T(x,y) = \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} a_n a_m \times \exp\left(\frac{i2\pi}{d}[(n+m)x\cos(\frac{\theta}{2}) + (n-m)y\sin(\frac{\theta}{2})]\right) \tag{2}$$

where d is the period of grating, and a_n are the Fourier coefficients for a periodic structure. Moiré readout system can measure the amplitudes in submicron scale. In comparison with some techniques such as electromagnetic readout systems, our optical technique is free of EM noise and the power of the output signal is easier to calibrate.

3. The Sensor Design

Among the possible and available techniques, developed in the past and available in literature and currently used in experiments of physics or in commercial instruments, the mass-spring system as an oscillator has chosen. In the following, the mechanical and optical performance of our instrument will be described.

Our optical approach has been used to make a vertical seismic sensor. The schematic diagram of designed sensor is shown in Figure (2). The oscillation system of the sensor is a spring-suspended mass whose position is monitored by Moiré technique. The mass is suspended by two identical springs placed in top and bottom of the mass and fixed into a frame. In this work, the springs of a commercial geophone (SE-10, made by Sunfull Company) have been used to build sensors

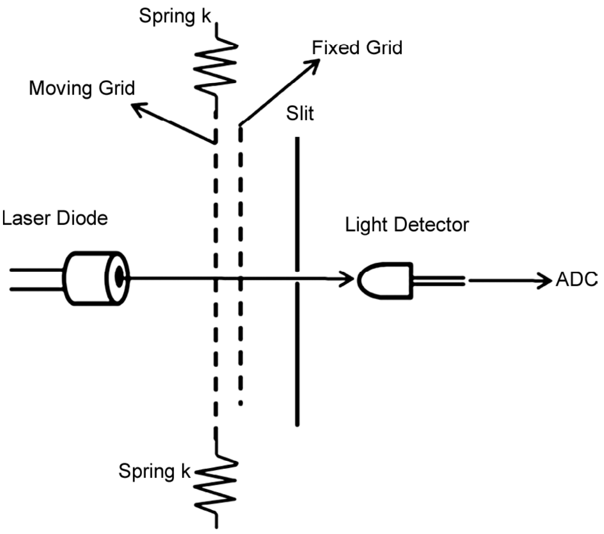

Figure 2. The schematic diagram of optical readout system.

oscillation system. The suspended mass has 12 gr and has held vertically. The natural frequency of the oscillation system is 10 Hz. Many materials have analyzed to build mechanical part of the sensor that consists of main frame, suspended mass, holders, and others. However, it was found out that, Aluminum and Copper Beryllium are the best choice. Finally, aluminum alloy 7075- T6 has chosen to build the first prototype. The reasons of this choice are mainly due to the fact that beyond the good thermal conductivity, the immunity to electromagnetic field, the high strength and low friction characteristics, the aluminum is a material not expensive and its machining is relatively easy and cheap [9].

To monitor the suspended mass position during the oscillations, Moiré technique has been used. To form Moiré pattern, two similar Ronchi gratings with 20 lines per millimeter have been used. One of them attached to a frame that is as the suspended mass and the other one is attached to a frame that fixed to the sensor's frame. The gratings were held close to each other without physical contact and the angle between the lines of superimposed gratings chosen is 6°. When the angle between the lines of superimposed gratings is less than 6°, the d_m / d ratio is larger than 10, which will result in a corresponding improvement in the measurement precision [27]. According to Eq. (1), d_m is 0.48 mm. Gratings can move freely so the angle of their lines remains constant.

To detect and convert the movement of suspended mass to an output voltage, a laser diode (module size 8 mm×13 mm, wavelength 650 nm, input voltage 3 V, power 1 mW) was placed in front of the gratings and a light-detector (silicon photodiode VTP1188s) faced the laser source from the opposite side. A narrow vertical slit (20 μm) that is parallel to Moiré fringes was placed in front of the detector to narrow the light beam. The initial position of the slit is halfway between two adjacent dark and bright Moiré fringes. The diode, the detector and the slit were fixed to the instrument frame. The laser beam passes through the Moiré pattern and the slit before hitting on the light detector.

The distance between the laser diode and the detector is 3 cm. As we know, damping is an important factor for seismic sensors. Damping for our sensor is provided by viscous oil, which is placed at the bottom of the sensor. Figure (3) shows our instrument.

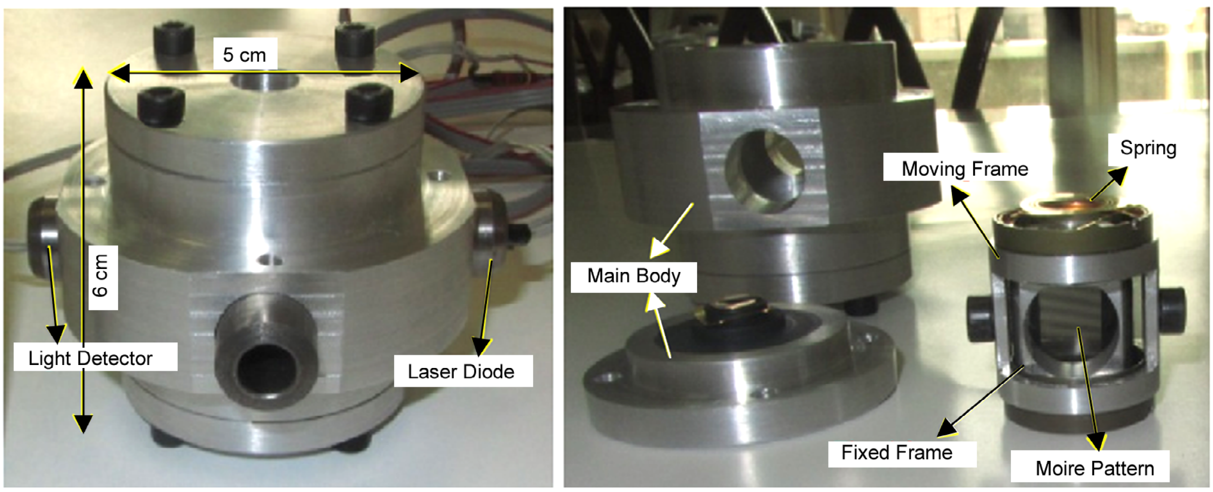

Figure 3. The optical seismic sensor based on the moiré technique.

4. Determination of Seismic Pulses Amplitude

In seismology, scientists desire the displacement of the ground (or time derivatives thereof) relative to a quasi-inertial space a practically unobtainable reference frame [8]. The amplitude of ground vibration can help seismologists and other scientists in earth's interior studies. Capability of seismic sensor to determine the amplitude as precise as possible is very important. As we know, the seismic sensors record the displacement of the suspended mass instead of real ground displacement. Determination of the real amplitude is related to readout system of the sensor. For example, a coil-magnet readout system that is used in most seismic sensors, cannot record the real displacement because the output of this system belongs to magnetic flux changing. In these sensors, the motion of coil and magnet relative to each other leads to a change in the magnetic flux passing through the coil. Therefore, according to Faraday's law of induction, the flux changing produces an electrical signal in coil that is sensitive to the velocity of suspended mass (coil or magnet). We believed that optical approach can help us to solve this problem. This opens the door to optical readout systems. More details can be found in [8]. This has led us to an optical seismometer consisting of a spring-suspended mass whose position is monitored by Moiré technique.

Due to base excitation on oscillation system, one of the gratings moves with respect to the other one. Therefore, the Moiré fringes pass through the laser light, and the intensity of light varies on the detector varies between two maximum and minimum values as a result of the bright and dark Moiré fringes passing in front of the laser beam, respectively. The motion of the suspended mass results in a much larger motion of the Moiré fringes. The average intensity of a light beam ($\bar{I}$) through a slit of width e and length l oscillating with angular velocity ω in front of the fringes is given by [26]:

$$\bar{I}(t) = I_0\, l\left[\frac{1}{4} + 2\sum_{n=1}^{+\infty} a_n^{\,2}\, sinc\left(\frac{\pi n e}{d_m}\right)\times \cos\left(\frac{2\pi n\left(A\exp(-\gamma t)\sin(\omega t+\varphi)\right)}{d_m}\right)\right] \quad (3)$$

where I_0 is the initial intensity of laser beam, γ is the natural damping constant of the oscillator, t is time and A is the amplitude of suspended mass displacement. For a displacement larger than the gratings period the light power on the detector is triangular and periodic. However, the value of displacement of one of the gratings with respect to the other one is equal to the amplitude of the oscillations. In this case, phase changing in output time series identifies the oscillation phase changing. The amplitude of suspended mass displacements can be deriving from the time series by:

$$A = (N+\delta)d, \quad (4)$$

where d is the period of gratings that is 0.05 mm, N is the number of complete period in time series occurs in the first quarter of oscillation period (or occurs between two subsequence phase changing) and δ is the fraction of one complete period that occurred at the end of first quarter of oscillation. We can derive δ by Eq. (5):

$$\delta = \begin{cases} \dfrac{(2n-1)}{4} + \dfrac{1}{2\pi}\sin^{-1}\left(\dfrac{V_m - |V|}{V_m}\right), & if\ n = 1\ or\ 2 \\ \dfrac{1}{2\pi}\sin^{-1}\left(\dfrac{|V|}{V_m}\right), & if\ n = 0 \end{cases} \quad (5)$$

where n is the number of extrema in δ (that can be 0, 1 and 2), V_m is the value of maximum amplitude of output voltage due to the passing of the Moiré fringes in front of the light detector, and V is the value of output voltage at the phase change in time series.

5. Experimental Results

Many experiments have carried out to investigate the performance of the optical seismometer. The method of test is basically comparison the waveform of optical sensor with a co-located reference sensor. The reference sensor in this study is CMG-6TD sensor by Guralp Company. The performance of the sensors has tested by investigation their unit impulses response. Both sensors were exposed to many impulses and these experiments carried out in a non-isolated environment to have environmental vibrations, too. In this case we were able to study the response of new sensor in real conditions. A 12 bit ADC has been used with sampling rate of 60 sps.

Figure (4) shows a part of sensors output to unit impulses. As we can see, there is a good agreement between two traces in response to received vibrations. Also, it is observed that, the first motions in optical sensor traces are clearer than those in 6TD output and beside this, the signal to noise ratio in optical seismometer responses is more than conventional seismometer which is very important in seismometery. These results well illustrated in Figure (5). Also, Figure (6) shows first part of Figure (5) to illustrate more details of both sensors output. As we can see, the sensitivity in low amplitudes of optical sensor is more than the conventional sensor. The power spectrum for both sensors responses has been investigated. Figure (7) shows the power spectrum of identical traces of sensors. It is visible that, in comparison with conventional seismometer the sensitivity of optical sensor is quite proper. Also, results show that, in higher and mid frequency is more and in lower frequency less than 6TD. The natural frequency for our sensor (10 Hz) is more than 6TD (0.1 Hz).

In the following, we have investigated the noise level of our optical seismometer in comparison with reference seismometer. The different methods used to estimate self-noise of seismic sensors have made it difficult to do side-by-side comparisons of their performance. This lack of a self-noise estimate standard makes it difficult to assess when a sensor's self-noise is above the manufacturer's specifications,

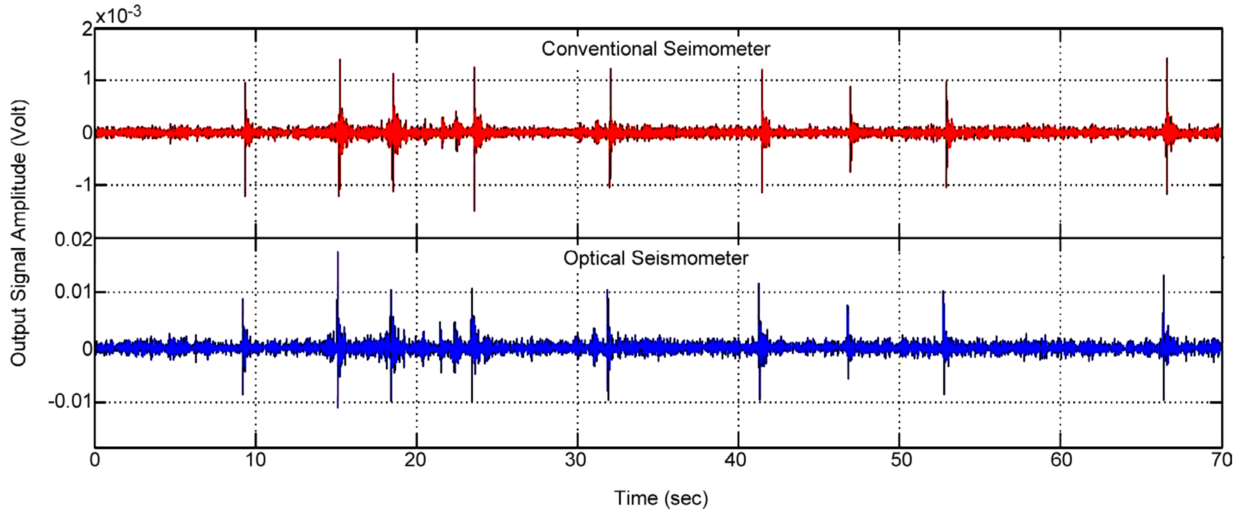

Figure 4. The output time series of conventional and optical seismometer to the unit impulses response.

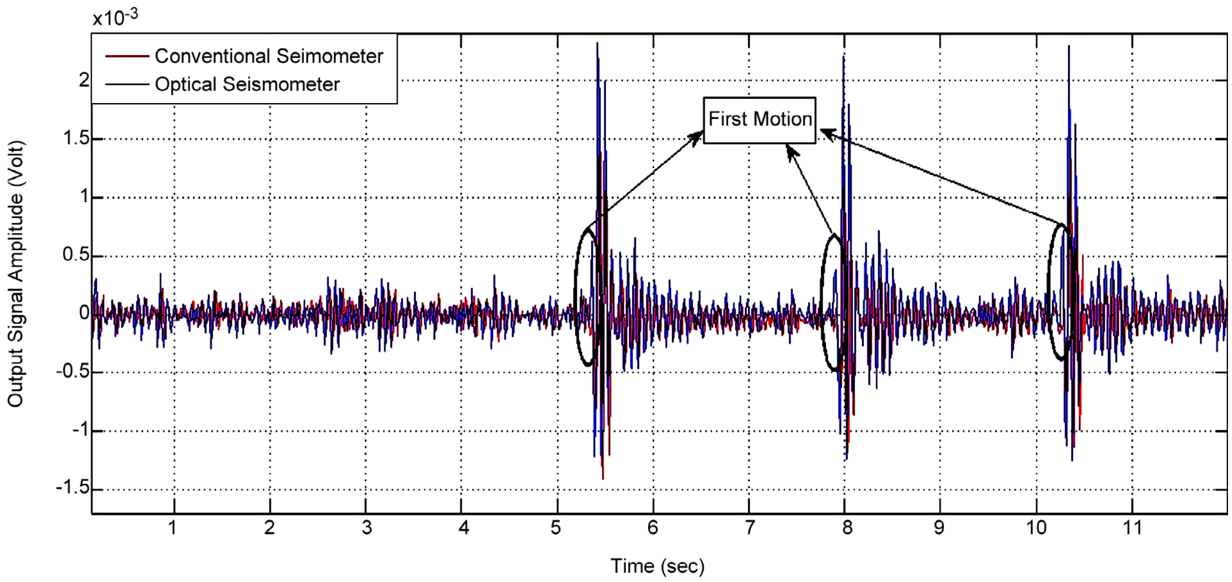

Figure 5. The conventional and optical seismometer output signals that are superimposed. The first motions in optical seismometer output are clearer in comparison with the 6TD output. The first motions of both outputs are shown by ellipses.

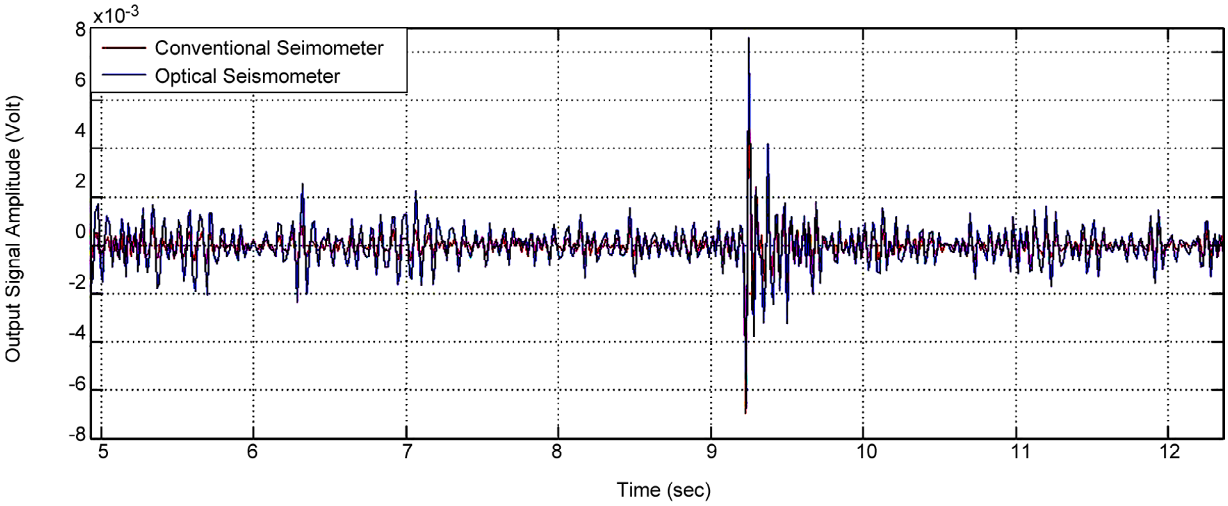

Figure 6. First part of Figure (5) to illustrate more details of both sensors output.

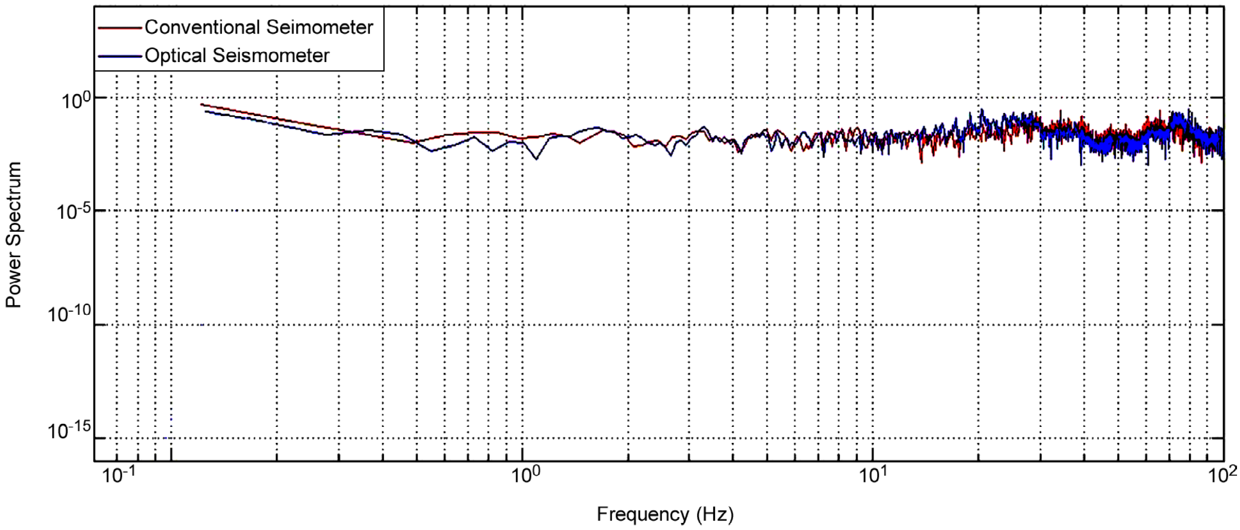

Figure 7. The power spectrums of identical outputs of conventional and optical seismometer. It is a good agreement between both power spectrums.

indicating a possible problem with the sensor or noisy site conditions [28]. In sensor development it is important to be able to compare a prototype sensor's self-noise to that of known self-noise levels of a reference sensor. With the above in mind, we used a standard method to estimate self-noise of seismic sensors. We have been used Welch's Method to estimate an averaged PSD, then multiply by bandwidth (1/3 or 1/2-octave) and take square root to get RMS estimate. The details of our processing method are as follows: for both sensors we have compared waveforms of duration over 4500 seconds of non-stop quiet data. Our Welch method uses a Hanning window taper for windows. Figure (8) shows the waveforms and the power spectrum density (PSD) of both sensors. Also, Figure (9) shows the ANSS-Recommended low-gain noise analysis for both optical and reference seismometers.

As we know from seismological point of view, it is important to know polarity of the ground displacement. In this sensor to determine the polarity of seismic pulses, the light beam passes through the bright and dark fringes at rest (suspended mass is at rest) so that the intensity of the light received by the light detector is on average. As the suspended mass moves, the direction of the motion (polarity) can be detected by changing the intensity of the light beam toward darker (negative polarity) or brighter (positive polarity) zone.

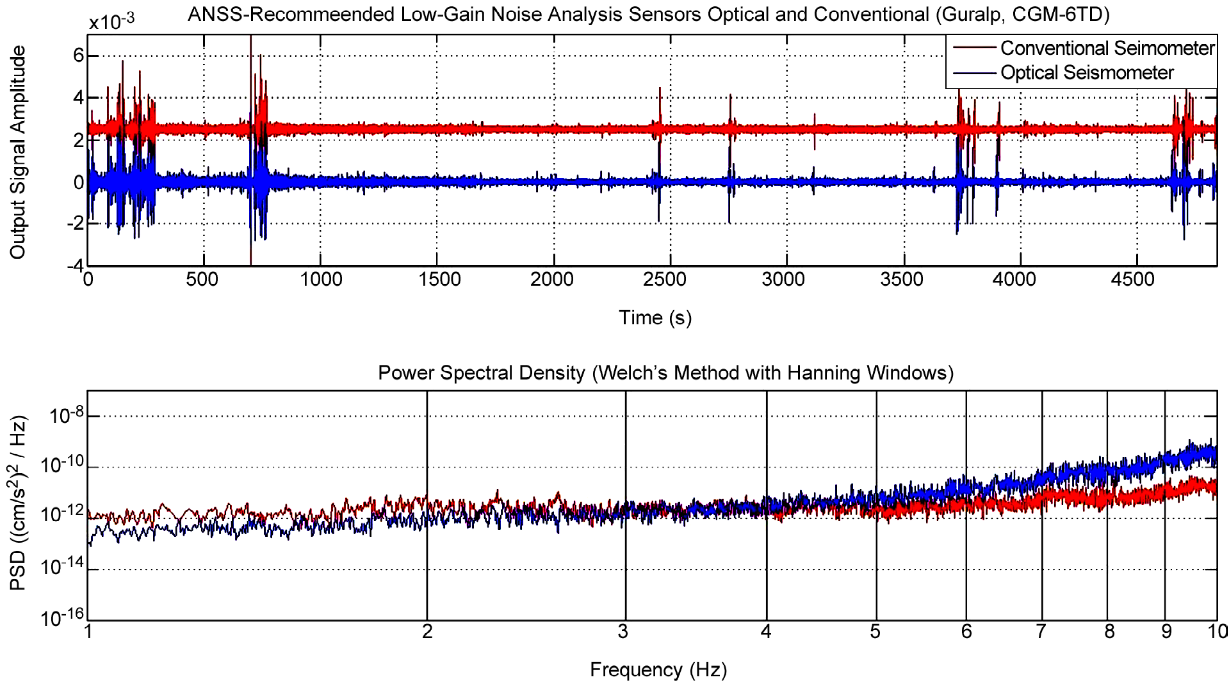

Figure 8. The waveforms and the power spectrum density (PSD) of both optical (blue) and CGM-6TD (red) sensors.

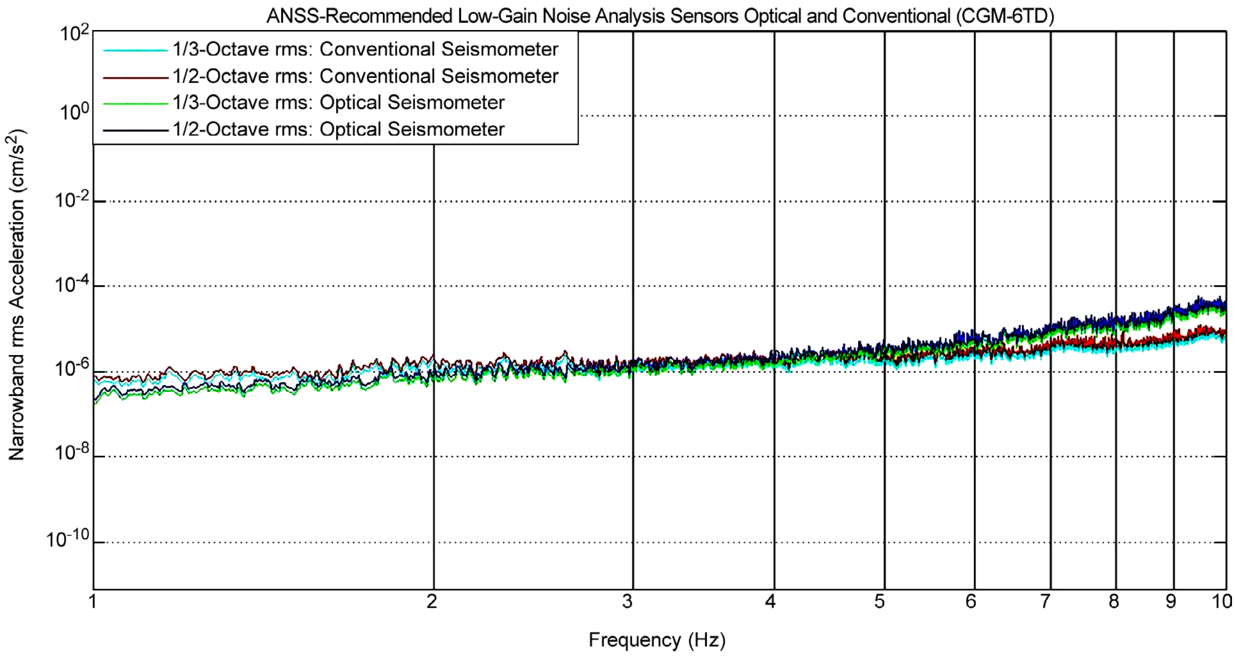

Figure 9. ANSS-recommended low-gain noise analysis for both optical and reference seismometers.

6. Conclusion

In this paper a new optical seismic sensor have described which is based on the Moiré technique and developed for geophysical applications. Adding an optical element to a vertical seismometer allowed us to monitor its mass position with high resolution. This sensor is a short period seismometer with natural frequency of 10 Hz. Preliminary tests, performed on optical seismometer and a conventional seismometer, are reported and discussed in this paper. The results show the good performance of optical seismic sensor. Moiré seismometer has some advantages respect to conventional seismometers that consist of high sensitivity, the first motions in its output are clearer in comparison with the 6TD output. Furthermore, its output is largely free of EM noise. In this sensor we can vary the sensitivity by varying the gratings period and the angle between the rulings of the gratings. Also we can amplify the output signal of sensor by enhancing the power of light source. Research is continuing in the development of this optical seismometer to other types of seismometers with other frequency bands.

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