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Design and Construction of a Seismometer Based on the Moiré Technique: Detailed Theoretical Analysis, Experimental Apparatus, and Primary Results

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ABSTRACT— **We have built a vertical seismometer that works based on the moiré technique. One grating is attached to the suspended mass and one to the frame of the instrument. The two gratings are in relative motion, and the resulting moiré pattern magnifies this motion. The intensity of a light beam passing through the moving moiré fringes changes with time, and a light detecting system converts this power fluctuation into a voltage signal. From this voltage signal the time series of ground motion is obtained. We investigated the performance of the instrument theoretically, as well as experimentally. Our instrument can measure the amplitude of oscillation through moiré magnification. It is free from EM environmental noise, has adjustable sensitivity and dynamic range, and has simple and straightforward design. Furthermore, we introduce a novel way of data acquisition from moving moiré patterns.**

KEYWORDS: Moiré pattern, seismometer, recording system, ground displacement, transmission function, time series

I. INTRODUCTION

Seismometers work based on damped oscillation of an inertial pendulum system consisting of a proof mass attached to a spring. The frame of the instrument is fixed to the ground. During ground shaking, the movement of the mass is delayed relative to that of the frame. In most seismometers, the recording system consists of a moving coil-transducer that converts the motion of the mass to voltage signal. This electromagnetic recording system is susceptible to environmental EM noise. Recently, mechanical and interferometric techniques have been used in the readout system of seismometers [1]-[2]. These techniques have high accuracy of measurement, but complicated set-up. In this work, we present a recording system for a vertical seismometer based on the moiré technique. A moiré pattern is produced when two periodic structures, such as line gratings, are overlaid and rotated relative to one another by a small angle. The moiré technique has diverse applications in the measurement of displacements and light deflections, such as strain measurement [3], landslide monitoring [4], vibration of large scale structures study [5], atmospheric turbulence studies [6]–[8], wavefront sensing [9]-[11], modulation transfer function of optical devices such as printing systems [12], measurement of the spectrum of light sources [13] and so on. It improves the precision of measurements remarkably, and the required instrumentation is usually simple and inexpensive.

II. INSTRUMENT DESIGN

The design of our instrument is similar to that of a commercial geophone. It consists of an external aluminum case which houses two aluminum frames (Fig. 1). The internal frame is fixed to the case. The external frame is attached to the case through two springs from top and bottom, and acts as the suspended mass of the instrument.

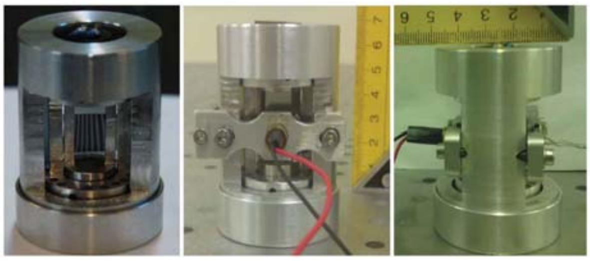

Fig. 1 (Color online) Left and middle, front view of the instrument before and after installation of the diode, slit, and light detector, respectively. Right, side view of the instrument.

We used the springs of a Weihai Sunfull geophone model SE-10 in our instrument, and made the mass of the suspended frame as close as possible to that of the mass of model SE-10 [14]. The instrument has a height of 56 .5 mm and a diameter of 45 mm. The SE-10 model had a natural frequency of 10 Hz. We attached one Ronchi grating to the suspended frame and one to the internal frame. The lines of the two gratings are almost horizontal and make a small angle with each other. The gratings were held close to each other without physical contact, and allowed to move freely in parallel. As a result, moiré fringes are formed. The lines of the fringes are vertical, perpendicular to the bisector of the lines of the two gratings (Fig. 2). The vertical movement of the gratings is magnified by a corresponding horizontal movement of the moiré fringes. A 1 mW laser diode was placed in front of the gratings, and a light detector (photodiode) faced the laser source from the opposite side. A narrow vertical slit was placed in front of the detector to narrow the light beam. The slit and detector are close to each other and to the gratings to minimize the laser beam diffraction effect from the gratings. Values of the laser beam diameter and the slit are not affecting the results when their values are large enough in comparing to the gratings periods. Meanwhile it should be mentioned that, by increasing the laser beam power, the output of the detector is increased and its effect is removed by normalization of the detector signal. Fig. 3 shows a schematic diagram of this setup. The diode, the detector, and the slit were all fixed to the instrument frame. During the motion of the suspended mass, the moiré patterns pass through the laser light and, as a result, the intensity of the light varies. The detector records these variations as a voltage signal, and a 14 -bit A/D card converts it into a digital time series.

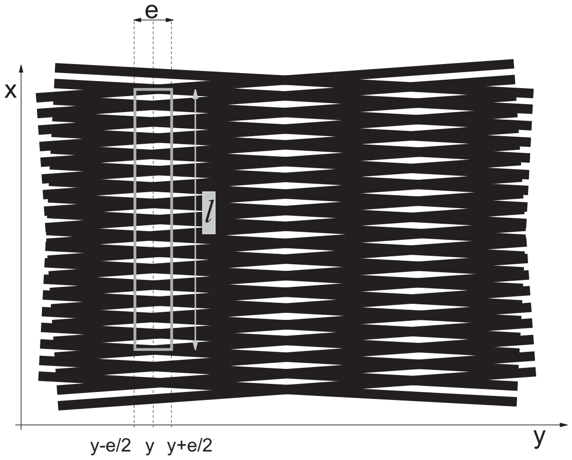

Fig. 2. Moiré pattern formed by superimposing two similar gratings. The white box is the slit [15].

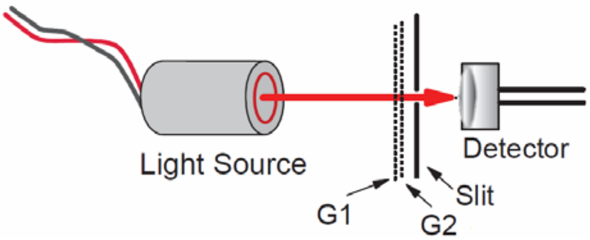

Fig. 3. A schematic diagram of the optical setup of the instrument, G1 and G2 are the two gratings.

III. MATHEMATICAL FORMULATION

In the theoretical considerations, the transmission function of a Ronchi grating with lines perpendicular to axis of the coordinate system is given by

$$t(x) = \sum_{n=-\infty}^{+\infty} a_n \exp\left(\frac{2\pi inx}{d}\right), \tag{1}$$

where d is the period of grating, a_n are the Fourier expansion coefficients of the Ronchi grating, and n is an integer number. Referring to Fig. 2, the transmission function for a superposition of two gratings with their lines placed at angles $\theta/2$ and $-\theta/2$ to the y axis is given by:

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

For $n = -m$, a periodic moiré pattern is formed whose period d_m, is larger than d:

$$d_m = \frac{d}{2\sin(\theta/2)}. \tag{3}$$

The moiré fringes are parallel to the x axis. Fig. 4(a) shows the plot of the transmission function averaged over x. The distance between two successive peaks constitutes the moiré fringe period. The detector measures the spatial average of the light over its aperture or over the width of the incident beam, whichever is smaller. If the period of the moiré fringes is smaller than the smaller of aperture and beam width, then the fringe displacements will be lost by the detector. To avoid this problem, we put a narrow vertical slit in front of the detector to reduce the size of the beam. The amount of light passing through the slit of length l and width e with its central line at y (Fig. 2) is given by:

$$P(y) = I_0 \int_{-l/2}^{l/2} dx \int_{y-e/2}^{y+e/2} T(x,y)dy, \tag{4}$$

where I_0 is the illuminating irradiance of the beam incident on the pattern.

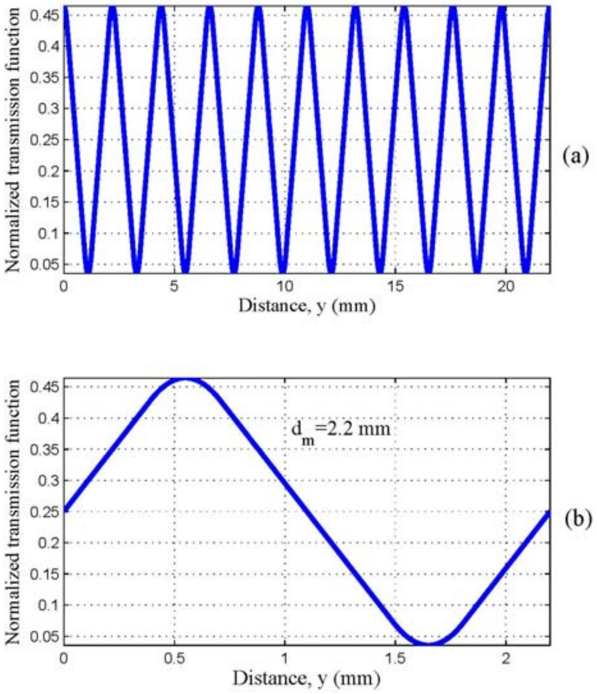

Fig. 4. (a) The normalized transmission function averaged over x for moiré fringes are parallel to the x axis, (b) The transmission function in a periodic of moiré pattern averaged over x when $\varphi_0 = \pi/2$, for which the equilibrium position of the optical detection system will be midway between two adjacent dark and bright moiré fringes.

Inserting Eq. 2 in Eq. 4, we have:

$$P(y) = I_0 \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} a_n a_m \times \int_{-l/2}^{l/2} \exp\left[\frac{2\pi i}{d}(n+m)\cos\left(\frac{\theta}{2}\right)x\right]dx \times. \int_{y-e/2}^{y+e/2} \exp\left[\frac{2\pi i}{d}(n-m)\sin\left(\frac{\theta}{2}\right)y\right]dy \tag{5}$$

The transmitted light measured by the detector with linear response for a uniform illumination of the set can be expressed as $\mathrm{V(y)} = \beta\,\mathrm{P(y)}$, where β is a constant depending on the detector gain. For large enough l in comparing to the gratings' period d, the first integral in Eq. 5 vanishes except for $m = -n$ [6] when it becomes equal to l and the output of the detector can be expressed as:

$$V(y) = \beta l I_0 \sum_{n=-\infty}^{\infty} a_n a_{-n} \int_{y-e/2}^{y+e/2} \exp\left(\frac{2\pi iny}{d_m}\right)dy, \tag{6}$$

where d_m is given by Eq. 3. Here we assume that the diameter of the laser beam is also large enough in comparing to the gratings' period *d*. Taking into account that the Ronchi grating has an even transmission function, i.e. $a_n = a_{-n}$, we obtain [6]:

$$V(y) = \beta l I_0 \sum_{n=-\infty}^{\infty} a_n^2 \int_{y-e/2}^{y+e/2} \exp\left(\frac{2\pi i n y}{d_m}\right) dy . \qquad (7)$$

Evaluating the integral in Eq. 7 leads to:

$$V(t) = \beta e l I_0 \sum_{n=1}^{\infty} a_n^2 \operatorname{sinc}\left(\frac{\pi n e}{d_m}\right) \exp\left(\frac{2\pi i n y(t)}{d_m}\right). \qquad (8)$$

For a Ronchi grating $a_0 = 1/2$. The real part of $V(y)$ is:

$$V(t) = \beta e l I_0 \times \left[\frac{1}{4} + 2\sum_{n=1}^{\infty} a_n^2 \operatorname{sinc}\left(\frac{\pi n e}{d_m}\right) \cos\left(\frac{2\pi n y(t)}{d_m}\right)\right]. \qquad (9)$$

The moiré fringes have a damped oscillatory movement of the form $y(t) = A(d_m/d)\exp(-\gamma t)\sin(\omega_d t)$, where *A*, $(d_m/d)A$, γ, and ω_d are the amplitude of displacement of the suspended mass relative to the instrument case, maximum moiré fringe displacement with respect to the instrument case, natural damping constant, and angular frequency of the damped oscillator, respectively. ω_d is given by:

$$\omega_d = \omega\left(1-\gamma^2\right)^{1/2}, \qquad (10)$$

where ω is the angular frequency of the undamped oscillator. Alternatively, one can view the fringes as fixed and the diode, the slit, and the detector having an oscillatory movement. Now the output of the detector is given by:

$$V(t) = \beta e l I_0 \times \left[\frac{1}{4} + 2\sum_{n=1}^{\infty} a_n^2 \operatorname{sinc}\left(\frac{\pi n e}{d_m}\right) \cos\left(\frac{2\pi n y(t)}{d_m} + \varphi_0\right)\right]. \qquad (11)$$

where φ_0 is the initial phase corresponding to the position of the slit with respect to the moiré pattern. For the purpose of determining the polarity of the first motion, the optimum value of φ_0 is $\pi/2$, for which the equilibrium position of the optical detection system will be midway between two adjacent dark and bright moiré fringes, Fig. 4(b). With this arrangement, the polarity of the first motion can easily be determined from the time derivative of *V(t)*.

IV. NUMERICAL SIMULATION

Fig. 5 shows the simulated time series of the normalized power, $\frac{V(t)}{\beta e l I_0}$, recorded by the detector (Eq. 11), in response to a unit impulse at $t = 0.1\,\mathrm{sec}$. In this plot we used values of $d = 0.1mm$, $d_m = 2.22mm$, $e = 0.1mm$, and $\omega = 20\pi \quad (f = 10Hz)$), which are close to those of the real instrument. Also, typical values of $A = 0.5mm$, $\phi_0 = \pi/2$, and $\gamma = 0.03$ were used.

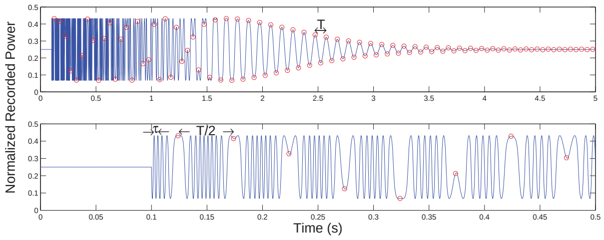

Fig. 5. (Color online) Simulated time series of normalized power recorded by the light detector in response to a unit impulse at t = 0 .1 sec. Bottom plot shows the beginning part of the time series. Red circles denote the phase discontinuities. T is the period of the oscillator. τ is the passage time of one moiré fringe by the detector.

The given value of $d_m = 2.22mm$ corresponds to an angle 2.58 degrees between the lines of the gratings. In the experiments, we fixed this angle to have a constant value for d_m. Furthermore, small changes on d_m do not affect the results. Because when the first grating is displaced in a direction perpendicular to its ruling direction with a value of *d*, the resulting moiré fringes will move a value of d_m. This rule is not affected by any changes of the angle between the lines of the gratings. Also, the value used for the damping factor is a typical value however it is not far from the real instrument damping factor. The simulated time series shows a periodic behavior marked by intermittent equal-distance phase discontinuities (red circles). These points correspond to the turning points of the oscillator. The interval between adjacent phase discontinuities is equal to the half-period of the oscillator, *T*/2. The number of periods between each two discontinuities indicates the number of fringes passing by the detector. Depending on the amplitude of the oscillator, each time interval contains a number of full periods, *N*, plus a fraction of a period, *δ*. The amplitude is given by:

$$A = (N + \delta)d.$$

Due to damping, the number of periods between successive phase discontinuities gradually decreases. When the amplitude is less than *d*, the fringes are displaced by only a fraction of their period and so $N = 0$. In this case, the oscillator amplitude is directly proportional to the output amplitude and it can be calculated from $A = \delta d$.

We can derive δ by the following formulas [3]:

- when *V* is increasing and $V > V_0$ (in the first quarter of the period):

$$\delta = \frac{1}{4}\frac{(V - V_0)}{(V_{\max} - V_0)}, \tag{12}$$

- when *V* is decreasing (in the second and third quarters of the period)

$$\delta = \frac{1}{4} + \frac{1}{2}\frac{(V_{\max} - V)}{(V_{\max} - V_{\min})}, \tag{13}$$

- when *V* is increasing and $V < V_0$ (in the fourth quarter of the period)

$$\delta = \frac{3}{4} + \frac{1}{4}\frac{(V - V_{\min})}{(V_0 - V_{\min})}, \tag{14}$$

where, $V_{\max}$ and $V_{\min}$, are the maximum and minimum amplitude of the detector output voltage, respectively, *V* is the amplitude value at the end of the measurement and V_0 is the initial value of the amplitude (see Fig. 4 (b)). Here, the initial position of the slit is half-way between two adjacent dark and bright moiré fringes so that $V_0 = \frac{V_{\max} + V_{\min}}{2}$.

V. EXPERIMENTAL RESULTS

We studied the response of the instrument to a unit impulse in several experiments carried out under identical conditions. The results confirmed the repeatability of the experiment. Fig. 6 shows a typical output of the instrument. Comparison with Fig. 5 reveals very good agreement between experiment and theory. In the experiment, due to the inertia of the instrument, the response to the impulse is somewhat delayed. This explains the small difference between the beginning parts of the two time series. In this particular example, for the initial complete oscillations, about 12 moiré fringes pass by the slit, and $N = 6$, $n = 0$. These values can be obtained by fitting Eq. 11 to the experimental data. The sampling rate of the recording system was 1000 samples/sec. From the data, values of 0.008 and 0.096 sec were obtained for τ and *T*, respectively. Then the initial amplitude of oscillation is 0.30 mm. Because of effects like the inertia of the oscillator, and the broadening of the incoming pulse, there are some irregularities in the beginning of time series. Thus we evaluate τ and *T* after the first phase discontinuity. We investigated the noise response of the instrument. Fig. 7 shows the output of the detector to environmental noise.

The dark noise fluctuation of the system was determined to be around 6 mV. The minimum measurable amplitude is given by $A_{\min} = \frac{d}{2SNR}$, where SNR is the signal-to-noise ratio calculated by dividing the maximum signal output fluctuation by that of the dark noise. From Fig. 6, signal fluctuation is about 60 mV, which gives SNR=10 and $A_{\min} = 5\mu m$. The SNR and so the measurement precision can be easily improved by increasing the power of the light source. The minimum measurable amplitude can be also estimated using $A_{\min} = e\left(d/d_m\right)$, where for the given values of $d = 0.1mm$, $d_m = 2.22mm$, and $e = 0.1mm$ we get gain the value $A_{\min} = 0.5\mu m$.

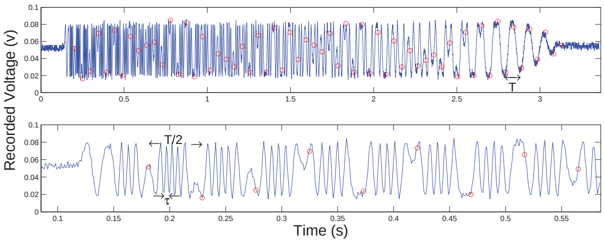

Fig. 6. (Color online) The output of the instrument in response to a unit impulse. Figure details are the same as those in Fig. 5.

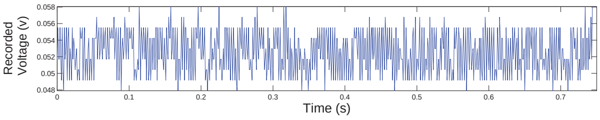

Fig. 7. (Color online) The detector responses to environmental noise.

VI. CONCLUSION

In this paper, we have presented a vertical seismometer that employs the moiré technique for its readout system. We employed the magnification of the moiré technique to measure ground displacements. Our technique allows us to extract the amplitude of oscillation from the time series of the output. The dynamic range and sensitivity of detection are adjustable by merely changing the angle between the rulings of the gratings. In conventional seismometers, the response may get saturated at large amplitudes due to the proportionality of output to the amplitude of oscillation. Whereas in our instrument, the increase of amplitude of oscillation, only changes the number fringes passing by the slit, without increasing the amplitude of the output. Thus, saturation is irrelevant. Another advantage of our instrument is that its optical readout system is free of EM noise, whereas conventional instruments that use EM readout system are in general vulnerable to EM noise. Furthermore in this work, we have presented a new method for data acquisition from moving moiré patterns. Our instrument is very simple and compared to other optical methods the implementation of the technique is straightforward.

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