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A moiré micro strain gauge

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ABSTRACT

We have built a new strain gauge based on the moiré technique. This strain gauge mainly consists of two frames that can move with respect to each other. Displacements are recorded by using the moiré technique. We use a pair of similar gratings attached to the frames. The gratings are installed in parallel without physical contact and their lines making a small angle with one another. A moiré pattern is formed due to superimposing of the gratings. A diode laser light passes through the moiré pattern and a narrow slit, and hits on a light sensor. In response to external stress, one of the gratings is displaced and, as a result, the moiré fringes move in front of the slit. Due to the fringes movements, the light intensity on the detector varies and is recorded as voltage. The voltage output can be used to measure the strain. This instrument can detect displacements of the order of micron. In this paper we show the experimental results of our instrument.

1. Introduction

A strain gauge, first invented by E. E. Simmons and A. C. Ruge in 1938 [1–3], is an instrument used to measure the surface strain of an object. The most common type of strain gauges consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object to be measured in a proper manner. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor.

Mechanical strain gauges are used to measure the movement of buildings, foundations, and other structures in civil engineering. The precision of the common types of strain gauges is low, about 0.1 mm, not enough to measure micro-deformations.

In this paper we introduce a novel strain gauge that is based on the moiré technique. Moiré pattern is defined as a series of dark and bright patterns formed by the superposition of two regular gratings. The dark and bright regions are called fringes [4]. The moiré technique has many applications in the measurement of very small displacements and light beam deflections [5,6]. The amplitude of the displacement is amplified by the moving moiré patterns. This strain gauge can be used to measure deformations in the micron scale in material sciences and civil engineering. Here we used moiré technique to measure displacements which can be used to compute the strain.

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2. Moiré technique

The moiré pattern can be created, for example, when 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 grids is placed over the other, and their lines have a small angle to each other, a new periodic structure called moiré pattern appears (Fig. 1). If the angle is increased, the separation between the bright and dark fringes and the sensitivity of the detection decrease. By choosing a small angle the sensitivity and spatial period of fringes increase. In this case, the period of moiré pattern d_m is larger than the period of gratings d

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

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.

3. Instrument design

The schematic diagram of the moiré micro strain gauge (MMSG) is shown in Fig. 2. In the MMSG two frames are used. The frames are held in front of each other by two holders. The two frames are connected by a spring. The frames can move freely. To make a moiré pattern we used two similar gratings with 20 lines per millimeter. 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

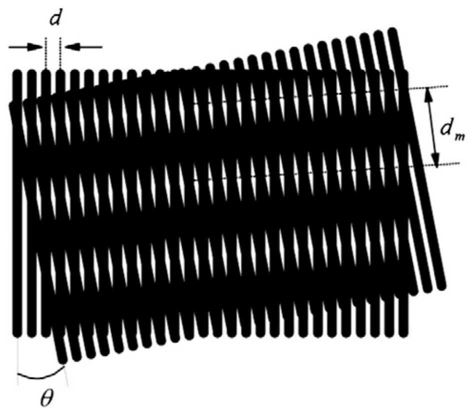

Fig. 1. A moiré pattern obtained by superposition of two gratings of equal period and their lines at angle θ.

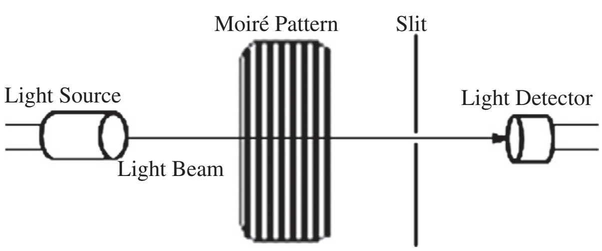

Fig. 2. Schematic diagram of the moiré micro strain gauge.

improvement in the measurement precision [5]. The angle between the lines of superimposed gratings chosen is 6°. According to Eq. (1) d_m is 0.47 mm. The gratings were attached to the frames, and held close to each other without physical contact. They can move freely so the angle of the gratings lines remains constant. A laser diode (module size 8 mm × 13 mm, wavelength 635 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 was placed in front of the light detector, and parallel to moiré fringes to narrow the laser beam. The diode, the detector, and the slit were all fixed to the instrument frame. The laser beam passes through the moiré pattern and narrow slit, before hitting on the light detector. The distance between the laser diode and the detector is 0.5 cm.

When one of the gratings is displaced with respect to the other one moiré fringes passes through the laser light without any deformation because the angle of grating is constant. The intensity of the light varies as a result. The variations of light intensity are recorded by a light detector as a time series. The output of the light detector is electrical voltage.

Variations of the output voltage are showing displacement of one of the gratings with respect to the other one, as a result of deformation in objects. Figs. 3 and 4 show our instrument.

4. Determination of the displacement amplitude

Due to an external stress on the MMSG, one of the gratings moves with respect to the other one. The moiré fringes pass through the laser light, and the power of light varies on the detector. The light power 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. For a displacement larger than the gratings period, the light power on the detector is triangular and periodic. Over a half period the measured power is linearly proportional to the displacement. Theoretical detail concerning linear behavior of the transmission function of the moiré pattern versus displacement can be found in [6]. Also, a similar theoretical investigation is reported in [7], where a method for submicron displacements measurement is suggested by measuring the autocorrelation of transmission function of a

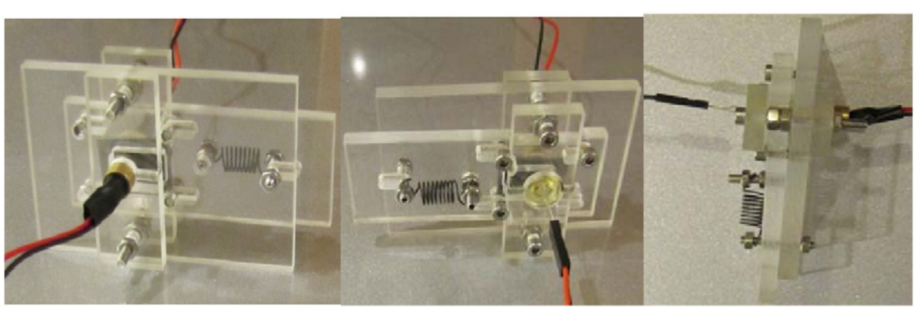

Fig. 3. The moiré micro strain gauge in three different views.

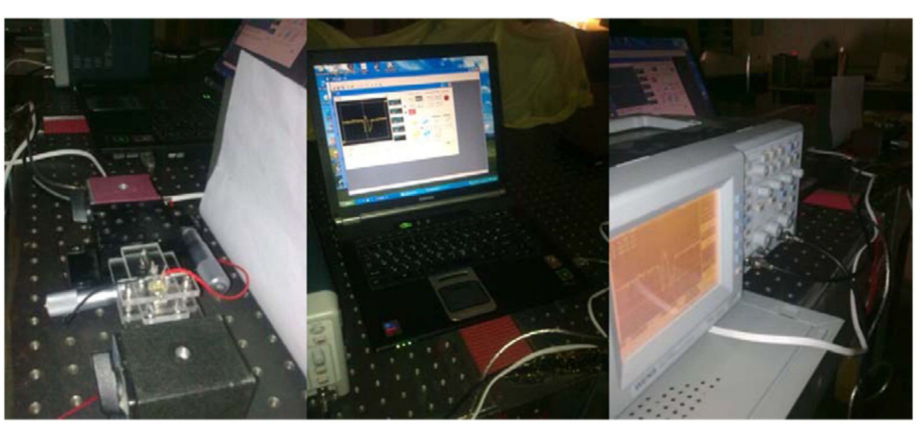

Fig. 4. The set up for the experiments.

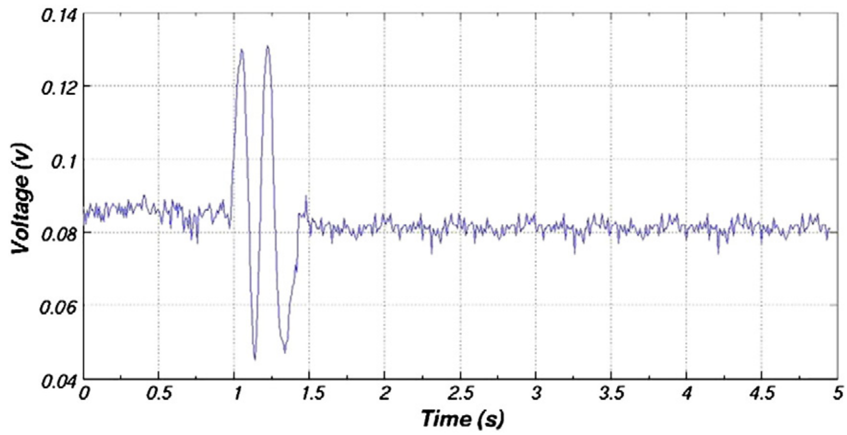

Fig. 5. Output of the moiré strain gauge for a spring compression of 0.1 mm.

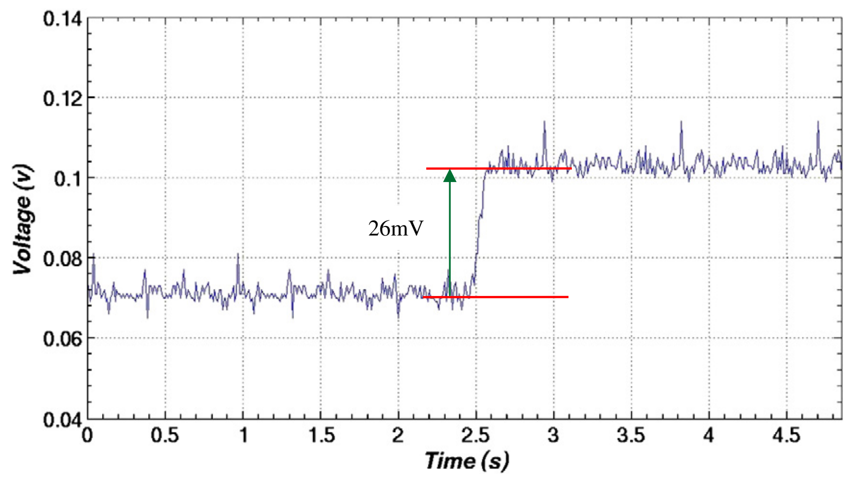

Fig. 6. Output of the moiré strain gauge for a spring compression of 5 mm.

grating. The value of displacement of one of the gratings with respect to the other one is equal to the value of compressing or stretching in the MMSG. We can derive the amplitude of displacement from the time series by:

$$\Delta l = (N+\delta)d, \tag{2}$$

where N is the number of complete period in time series, δ is the fraction of one complete period that occurred, and d is the period of gratings that is 0.05 mm. We can derive δ by:

$$\delta = \begin{cases} \frac{1}{4}\frac{(V-V_0)}{(V_{max}-V_0)}, & \text{when V is increasing and } V > V_0 \text{ (in the first quarter of the period)} \\ \frac{1}{4}+\frac{1}{2}\frac{(V_{max}-V)}{(V_{max}-V_{min})}, & \text{when V is decreasing (in the second and the third quarters of the period)} \\ \frac{3}{4}+\frac{1}{4}\frac{(V-V_{min})}{(V_0-V_{min})}, & \text{when V is increasing and } V < V_0 \text{ (in the fourth quarter of the period)} \end{cases} \tag{3}$$

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. Here, the initial position of the slit is halfway between two adjacent dark and bright moiré fringes so that $V_0 = \frac{V_{max}+V_{min}}{2}$.

5. Experimental results

We carried out two experiments to investigate the performance of our instrument. We subjected the strain gauge to an external stress by a micro stepper device. The step of the micro stepper is 1 μm. In the first experiment a 0.1 mm displacement was applied to the spring (twice the period of the gratings). Fig. 5 shows the output of the MMSG. As we can see, there are two complete periods, since two fringes pass through the beam. Therefore N = 2 and δ = 0 and according to Eq. (2) $\Delta l = 0.1$ mm. In the second experiment the value of spring displacement was 5 μm that is a fraction of the grating period. Fig. 6 shows the response of the MMSG. The variation of output voltage is about 26 mV. In this case $N = 0$, and from Fig. 6 and Eqs. (2) and (3) and Δl is estimated as 5.6 μm. Based on signal to noise ratio of the voltage in Fig. 6, the uncertainty of the measurements is 1 μm. The signal to noise ratio can be increased by increasing the power of the laser source. The results have very good agreement with the applied displacements.

6. Conclusion

We have presented a new mechanical strain gauge based on the moiré technique. The measurement range of our instrument is 1 μm to 2 cm and the resolution is 1 μm. This strain gauge is designed for detecting the micro deformations created by the external stress. The applications of moiré strain gauge vary from geological studies or civil engineering to materials or metallurgy engineering. Our instrument is easier to install, and insensitive to environmental conditions such as temperature fluctuations. In the moiré strain gauge we can vary the sensitivity to detect the displacement by varying the gratings period, the angle between the rulings of the gratings. Also we can enhance the output of detector by enhancing the power of light source and enhancing the proportion of signal to noise.

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