

A SIMPLE OPTICAL SENSOR FOR THE STRAIGHTNESS ERROR MEASUREMENT OF A MOVING STAGE

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Abstract:

The watt balance, a metrological instrument that might provide the new definition of the kilogram, consists of a moving coil which has a tight tolerance for its straight motion. Normal straightness sensors cannot be used for the watt balance because any electronic device might disturb the magnetic field around the coil. We propose a simple optical sensor to measure out-of-straightness of a moving coil. The sensor is comprised of a cube-corner prism and a reflector having a sharp edge. When a laser beam is incident on the cube-corner prism which is located on the moving coil, any out-of-straightness movement of the coil shifts the out-coming beam. The shifted beam is partly reflected by the edge reflector and the rest of the beam transmitted. Each beam is collected into an optical fiber and sent to a balanced photo detector. The lock-in detection is used for measuring the difference of the reflected beam intensities. After obtaining the relation between the amount of beam-shift and the lock-in output signal by using the knife edge scanning method, the straightness error of a moving stage could be measured with high accuracy. In our preliminary experiment which was performed in air, the sensitivity of the sensor was 2.457 mV/nm, and the nonlinearity of the sensor turned out to be about 0.7 % for the straightness error range of $\pm 7 \mu\text{m}$.

Keywords: Straightness Sensor, Watt Balance, Edge Reflector

1. INTRODUCTION

Watt balance (WB), which is an electro-mechanical weight measuring instrument, is being developed in several countries for the purpose of providing the new definition of the kilogram based on electrical units [1-7].

WB consists of a balance, standard weight, permanent magnet, and a coil which is connected to a translation stage (Fig. 1 (a)). One of the requirements of a WB is to have a rectilinear stage for high straightness translation of the coil. To monitor the straightness of the coil motion of the WB, a non-contact, non-magnetic, vacuum compatible method is necessary. The existing method being used in the Laboratoire National de métrologie et d'Essais (LNE) of France and the Federal office of Metrology (METAS) of Switzerland, is to use a single slit where two modulated laser beams having opposite phases are focused and passed through [8-9]. The transmitted intensities of the laser beams are demodulated by a lock-in amplifier to provide the slit position relative to the beam positions.

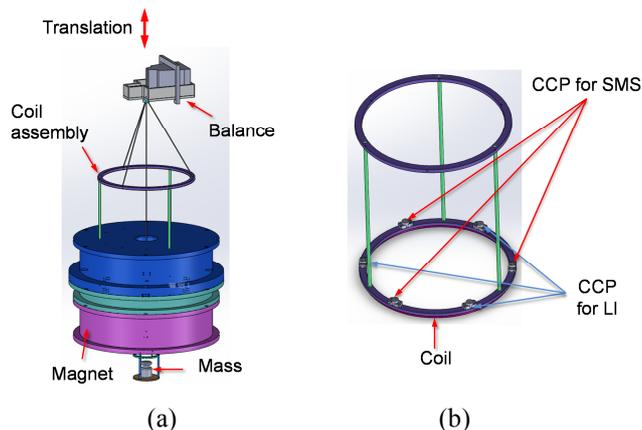


Fig. 1: Schematic diagram of the (a) watt balance, (b) coil assembly. CCP: cube-corner prism; SMS: straightness measuring sensor; LI: laser interferometer.

In this paper, we present a simple optical sensor to measure straightness of a moving coil, which is being developed in the Korea Research Institute of Standards and Science (KRISS). Key parts of the straightness measurement sensor (SMS) are a cube-corner prism (CCP) and a sharp reflecting edge which hereafter will be called as the 'edge reflector'. The principle of the SMS and the experimental results will be described in the following chapters.

2. METHOD

As shown in the Fig. 1 (b), the coil assembly carries six CCPs. Three CCPs angularly separated by 120° to each other are used for measuring position and velocity of the moving coil along the vertical axis by laser interferometers. The other three CCPs belong to three SMS, and are used for measuring the horizontal displacement of the moving coil, i.e. the out-of-straightness of the coil movement. Once the horizontal displacements of the moving coil in three directions are measured by three SMSs, the rotational motion of the coil can also be analyzed.

Figure 2 shows the schematic diagram of the SMS. A CCP is mounted on the moving coil and a laser beam is incident onto the CCP. If the motion of the coil has straightness error, the reflected light from the CCP will be displaced horizontally twice the amount of the straightness error (Fig. 3).

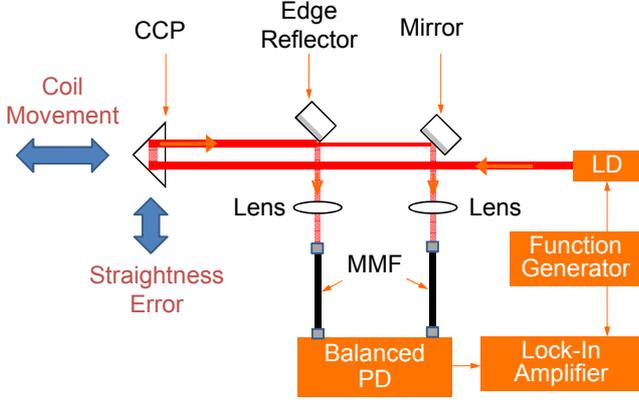


Fig. 2: Schematic diagram of the SMS. CCP: cube-corner prism; MMF: multimode optical fiber; LD: laser diode.

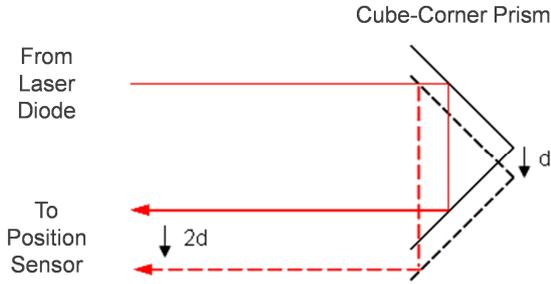


Fig. 3: Double shift of the laser beam when the corner cube prism is displaced.

The out-coming beam from the CCP is headed to a reflector having a sharp edge so that about half of the beam is reflected by the edge reflector. Both the reflected and the transmitted beams are separately collected by optical fibers which are connected to a balanced photo detector.

The power of the reflected beam when the beam center is displaced from the edge of the reflector by x , can be expressed as

$$P_r = \frac{P_i}{2} \left[1 + \operatorname{erf} \left(\frac{-\sqrt{2}x}{w} \right) \right], \quad (1)$$

where $\operatorname{erf}()$ is the error function, P_i is the power of the input beam, and w is the beam waist of the laser beam.

Thus the power difference measured by balanced photo detector will be

$$P_r - P_t = P_i \times \operatorname{erf} \left(\frac{-\sqrt{2}x}{w} \right), \quad (2)$$

where P_t denotes the power of the transmitted beam.

Figure 4 shows the plot of reflected power, transmitted power, and their difference as a function of x . The power difference is linear in x when the shift of the CCP is less than quarter of the laser beam waist. Since the expected out-of-straightness of the moving coil is about $10 \mu\text{m}$, the SMS can be applied for the WB as the out-of-straightness measurement sensor.

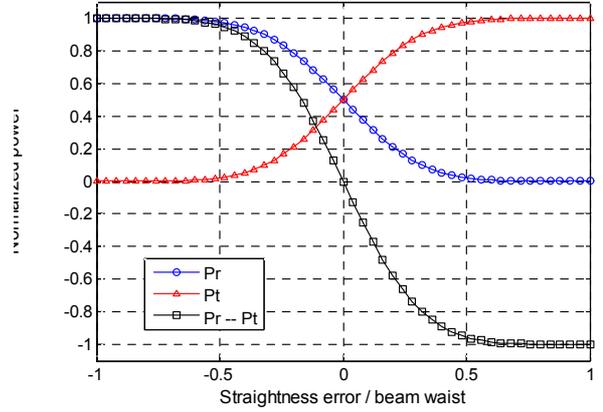


Fig. 4: Plot of the powers of the reflected and transmitted beams from the edge reflector, and their difference.

3. EXPERIMENTS

3.1 Experimental Setup

The experimental setup of the SMS is shown in Fig. 5.

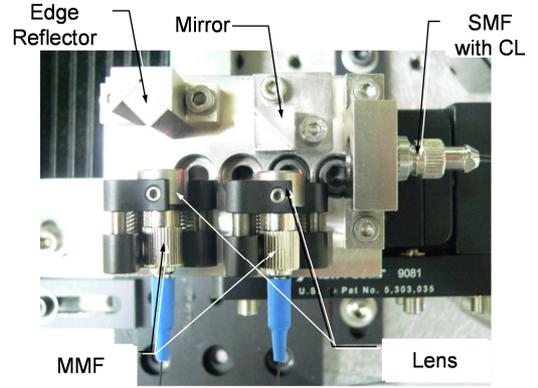


Fig. 5: Photo of the SMS. The cube-corner prism is not shown in the photo. SMF: single mode fiber; CL: collimation lens; MMF: multimode fiber.

This is a preliminary setup to validate the operational principle of the SMS. The dimension of the sensor module (excluding the CCP) shown in Fig. 5 is $74 \text{ mm} \times 54 \text{ mm}$. A laser beam from a laser diode at the wavelength of 650 nm which is modulated with the frequency of 10 kHz is carried through a single mode fiber to the SMS. Collimated laser beam is headed to a CCP which is mounted on a movable stage. The returning beam is split by the edge reflector into two directions. Both beams are separately focused into multimode optical fibers whose output is connected with a balanced photo detector. The modulated voltage of the balanced photo detector is demodulated by a lock-in amplifier. In this way, the DC voltage proportional to the straightness error of the moving stage is produced. For proper conversion of the output voltage to the straightness error, the conversion factor must be found. This conversion factor is also called the sensitivity of the SMS.

3.2 Sensitivity of the SMS

A laser interferometer is used to obtain the conversion factor. As shown in Fig. 6, a homodyne laser interferometer is installed near the SMS. The fixed mirror shown in the figure is an aluminium coated zerodur mirror used for the interferometer.

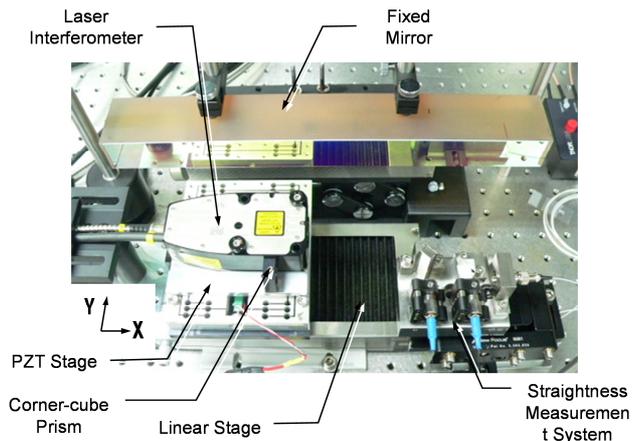


Fig. 6: Experimental setup for the measurement of sensitivity of the SMS.

The interferometer module and the CCP are sitting on two stages: a Y-axis flexure stage driven by a piezoelectric transducer (PZT), and a linear X-axis stage driven by a motor. The straightness error was simulated by translating the Y-axis stage. By applying voltages to the PZT, both the CCP and interferometer body were translated up to 15 μm . The output voltage of the lock-in amplifier and the reading of the laser interferometer were simultaneously recorded. Fig. 7 shows an example of the measurement results.

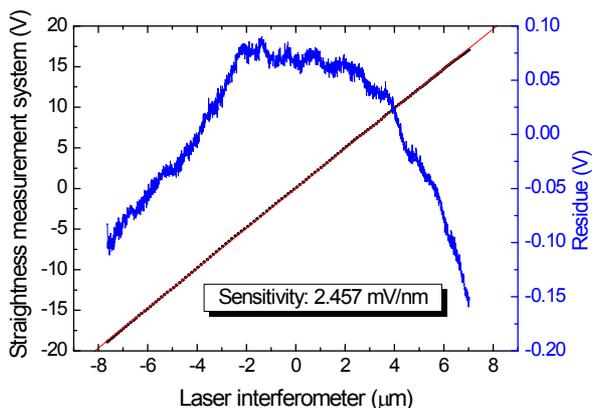


Fig. 7: Measurement results of the conversion factor of the SMS. The straight line shows the linear relation between the readout of the laser interferometer and the SMS output. The other graph shows the residue from the linear fit.

The conversion factor was found to be 2.457 mV/nm, and the SMS showed good linearity in the range of -7 μm to 7 μm . The residue from the linear fit is also shown in Fig. 7. The residue is about 230 mV and corresponds to 94 nm in

straightness error. Thus the nonlinearity of the SMS is about 0.7 %.

3.3 Variation of the Sensitivity along the X Axis

We evaluated the variation of the conversion factor of the SMS over the whole stroke of the moving stage. Since the range of coil movement is designed to be about 50 mm, we performed the experiment described in section 3.2 with the CCP placed at various positions in the x axis. The linear stage carrying the CCP and the interferometer module was translated from 0 to 60 mm with 10 mm steps. At each position, the conversion factor was measured. The results are shown in Fig. 8.

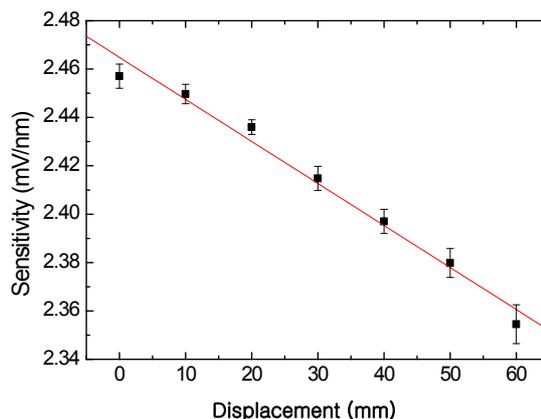


Fig. 8: Variation of sensitivity of the SMS over various position of the CCP.

Although very small (0.4 % over the whole range), the results show slight decrease in the sensitivity with increasing displacement of the stage. This is thought to come from the fact that the diameter of the laser beam is not constant but increases along the x axis according to the following equation

$$w(x) = w_0 \sqrt{1 + \left(\frac{\lambda x}{\pi w_0^2}\right)^2}, \quad (3)$$

where λ is the wavelength of the laser and w_0 is the beam waist of the laser beam. Depending on the size of the laser beam, the same amount of shift of the CCP will produce different fractional change in the optical power reflected or transmitted by the edge reflector. Optimal determination of the beam size should be performed to make a tradeoff between the high sensitivity and non-variability of the sensitivity.

3.4 Resolution of the SMS

By applying a square wave voltage to the PZT, the flexure stage was periodically translated back and forth with amplitude of 20 nm. The displacement of the stage was measured with both the laser interferometer and the SMS. As can be seen from Fig. 9, steps of 20 nm are clearly resolvable. With our preliminary setup, the resolution of the SMS is roughly 20 nm, and more experimental examinations are to be made.

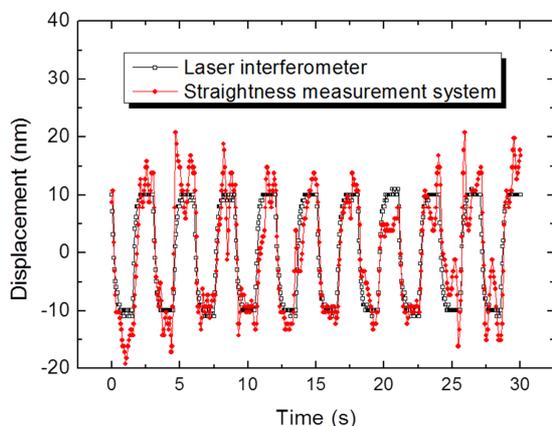


Fig. 9: Resolution of the SMS. Displacement of 20 nm is clearly measurable.

4. CONCLUSION

A simple optical sensor module to measure out-of-straightness of a moving coil of a WB is proposed. The sensor is comprised of a CCP and a reflector having a sharp edge. When an intensity modulated laser beam is incident on the CCP which is located on the moving coil, out-of-straightness of the moving coil shifts the out-coming beam, which is partly reflected by the edge reflector and the rest of the beam transmitted. Each beam is collected by a separate multimode optical fiber and sent to a balanced photo detector. The lock-in amplifier demodulates the modulated detector signal to obtain the DC voltage value proportional to the difference of the two photo detector outputs. This voltage is translated to straightness error by multiplying it with the conversion factor obtained by a laser interferometer.

Since the sensor uses a single beam, it is very convenient to perform the optical alignment. The SMS is a non-contact type, non-magnetic, and vacuum compatible sensor which does not disturb the magnetic field around the coil, and thus can be used for the watt balance experiment.

In our preliminary experiment which was performed in air, the sensitivity and the resolution of the SMS were 2.457 mV/nm and 20 nm, respectively. The nonlinearity of the SMS turned out to be about 0.7 % for the straightness error range of $\pm 7 \mu\text{m}$. Since the new idea on the SMS has been verified, the system will be upgraded for better performance.

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