A laser straightness measurement system using optical fiber and modulation techniques

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Abstract

In this paper a laser straightness measurement system is proposed. Using the characteristics of travelling straight and parallel, a new diode laser system utilizing optical fiber and modulation techniques was developed. This optically aligned beam is used to establish a reference line for the straightness measurement of any mechanical system. A four-quadrant photo detector was used to receive the laser beam. A phase sensitive detecting technique was adopted to process the opto-electrical signals from the detector. A single board microcomputer employing an 8098 processor was developed to conduct all data acquisition and signal processing. The influence from disturbing lights, circuit drift and beam drift can be removed from the system. The system was calibrated using an HP5528 laser interferometer. Results showed good accuracy of 0.3 µm within the range of ±100 µm and pointing stability of 0.3 µm at a 1 m distance was obtained. Two practical testing examples are carried out on a CMM and a grinding machine, respectively. Repeatability of both tests was found within 0.5 µm. This low-cost system has been successfully applied to the straightness measurement of a precision CMM. © 2000 Published by Elsevier Science Ltd.

Keywords: Straightness measurement; Optical fiber; Modulation; Accuracy

1. Introduction

The term "straightness error" is generally used to refer to many aspects of engineering quality, such as workpiece straightness, motion straightness, etc. Optical measurements of straightness errors have been widely used in the field of engineering metrology. Two kinds of methods are commonly adopted. One uses the optical axis as a virtual line, a straightness datum that can be

established by means of various optical accessories [1]. These instruments include: autocollimators, alignment telescopes and optical theodolites. The other method employs a laser beam to generate a reference line, which has the properties of small divergence and high intensity. An early system involved using a He–Ne laser of 633 nm in association with a beam expander to facilitate the alignment measurement [2]. The intensity center of the beam was taken as the reference point whose position was examined using a four-quadrant detector or a CCD camera. An accuracy of 10^{-5} was achieved [3–5]. Many other methods were developed with high alignment accuracy, such as the polarimetry method [6], the polarizing method [7,8], the optical compensation method [9], and the Zeeman laser interferometer method [10,11]. Recently, a laser diode was adopted for straightness measurement since it is small in size and low in power. An accuracy of several PPM was gained [12,13].

Besides the air turbulence and temperature gradient in the testing environment, the accuracy of a laser straightness measurement system can also be limited by such factors as beam drift, disturbance from lights in the operating site and drift in the electrical circuit. In this research, a newly developed system using an optical fiber and a modulation technique is introduced. The beam output from a single mode optical fiber can eliminate the beam drift and isolate the heat generated from the laser source. A modulated beam whose frequency is set far away from that of any potential light disturbance is used to suppress the influence from light disturbance. All signals which share serially the same signal processing channel can also eliminate the DC drift and gain drift of the signal processing circuit. A single board microcomputer employing an 8098 processor was developed to conduct all data acquisition signal processing. Having removed all possible system noises, calibration tests using an HP5528 laser interferometer demonstrated that an accuracy of 0.3 μm within a ±100 μm measuring range and a pointing stability of 0.3μm at a distance of 1 m could be achieved. Experimental tests on one CMM and one machine tool have also shown good repeatability of only 0.5 μm.

2. Principle of laser diode and optical fiber alignment

It is well known that the propagation of a laser beam through an optical fiber forms an optical field. The optical field distribution of the emergent beam from a single-mode optical fiber is fixed in the form of a symmetrical Bessell distribution. If the coupling laser beam has an angular or lateral drift, the intensity of the emergent beam will be altered, but the original distribution of the optical field is maintained. If the emergent end of the fiber coupler is positioned solidly, the angular and lateral drift of the laser beam can be eliminated.

Fig. 1 shows the block diagram of a laser diode and optical fiber straightness measurement system. The LD power supply provides a modulated driving current. A modulated laser beam from the laser diode is coupled to a piece of single mode optical fiber. The beam output from the fiber end passes through a collimating lens to form a collimated and parallel wave front. The intensity center of the beam is taken as the reference point whose position is continuously detected using a four-quadrant detector.

Illuminating a position in the active area of the detector, the beam causes ohmic current in each cell of the quadrant and flows to its corresponding cathode. If the beam has a lateral displacement relative to the detector, the light flux in each cell will change. Assuming that a beam of
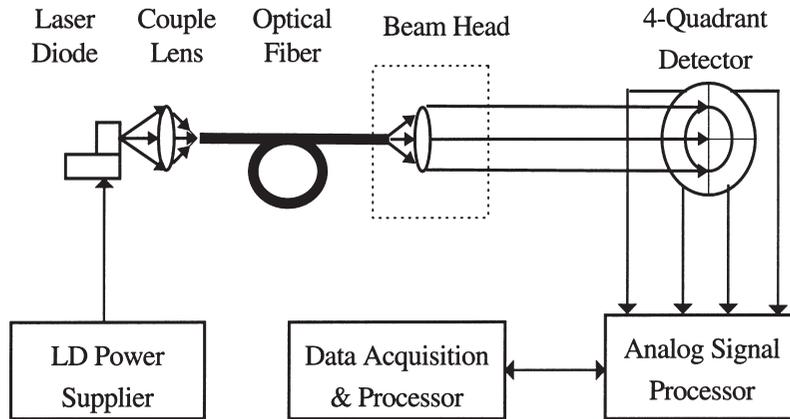
Fig. 1.   Diagram of the laser alignment system using a laser diode and optical fiber.

perfectly uniform intensity is used, the relationship between the displacement and the currents is determined using [14]

$$x=k\frac{(i_1+i_4)-(i_2+i_3)}{\sum i_{1,2,3,4}} \quad y=k\frac{(i_1+i_2)-(i_3+i_4)}{\sum i_{1,2,3,4}} \tag{1}$$

where x, y are the displacements in the x and y axes, respectively; i indicates the output current of the corresponding cathode, and k is a proportional constant. Ideally, the linearity of a quadrant detector should be quite good. However, because the beam intensity is in the form of a Bessell distribution, the detector may deviate to some extent from the ideal transfer characteristic. In practice, such a deviation can be experimentally calibrated using a high accuracy laser interferometer.

3. Electrical signal processing and position detecting

As shown in Fig. 2, the electrical signal processing circuit for a quadrant detector includes: pre-amplifiers, an averager, a differential/proportional amplifier, analog switches, narrow band
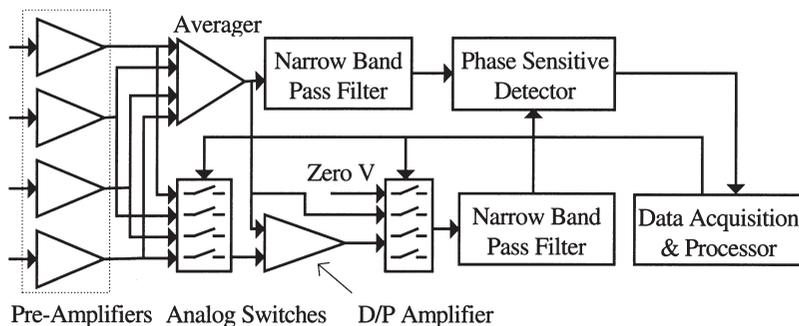
Fig. 2.   Diagram of the electrical signal processor.

filters, a phase-sensitive detecting circuit, an A/D converter, and a data acquisition and processing unit.

Because of some disturbing lights reaching the detector while the alignment beam is incident on it, the current from each cell can be expressed as:

$$i_j = I_j \sin \omega t|_{j=1,2,3,4} + \sum_{n=0}^{\infty} A_n \sin(\omega'_n t) \tag{2}$$

where I_j is the amplitude of the jth signal caused by the alignment beam and ω is the frequency of the modulation. The last term of the above equation represents noise signals caused by disturbing lights. When the beam projects right onto the center of the detector, the signal output from all of the quadrant cells are equal to each other. If the beam has a lateral displacement, some of the signals will increase while the others will decrease. The averaged signal can be considered as a kind of bias. Due to the existence of this bias, the magnification of signals from the detector will be limited. In order to increase the resolution we use a differential and proportional circuit to remove the bias from all of the signals. In this case the signals are determined using:

$$\begin{cases} i_a = \dfrac{\sum I_{1,2,3,4}}{4} \sin \omega t + \sum_{n=0}^{\infty} \bar{A}_n \sin(\omega'_n t) = I_a \sin \omega t + \sum_{n=0}^{\infty} \bar{A}_n \sin(\omega'_n t) \\ \\ i_{dj} = k_p(I_a - I_j) \sin \omega t|_{j=1,2,3,4} + \sum_{n=0}^{\infty} (A_n - \bar{A}_n) \sin(\omega'_n t) \end{cases} \tag{3}$$

where i_a is the average of the four signals, i_{dj} is the output of the differential/proportional circuit, and k_p is the gain coefficient of the circuit. If a high resolution is desired, we can choose a large k_p.

The output signals from each cell include both signals from the beam and disturbing lights, however only the part of the signal in which the frequency is equal to the modulation beam is desired. In this system a phase-sensitive detecting technique is used to demodulate the amplitudes of the signals. For eliminating these disturbing lights, the modulating frequency of the beam is set far away from the frequencies of the disturbing lights and a narrow band pass filter, whose central frequency equals the modulation frequency, is used. Having been demodulated, the amplitudes of the signals are converted into digital signals using a 12-bit A/D converter. By controlling the analog switches in sequence, the data acquisition and processing unit can obtain signals from each cell of the detector, the average signal and the null signal serially. All of these signals can be expressed as:

$$\begin{cases} i_1 = k_d k_p(I_a - I_1) + i_{DC} \\ i_2 = k_d k_p(I_a - I_2) + i_{DC} \\ i_3 = k_d k_p(I_a - I_3) + i_{DC} \\ i_4 = k_d k_p(I_a - I_4) + i_{DC} \\ i_s = k_d I_a + i_{DC} \\ i_0 = i_{DC} \end{cases} \tag{4}$$

where k_d indicates the gain of the PSD circuit. The position or displacement equation in Eq. (1) can be rewritten as:

$$\begin{cases} x=k\dfrac{(i_1+i_4)-(i_2+i_3)}{i_a}=kk_p\dfrac{(I_1+I_4)-(I_2+I_3)}{I_s-I_0} \\ \\ y=k\dfrac{(i_1+i_2)-(i_3+i_4)}{i_a}=kk_p\dfrac{(I_1+I_2)-(I_3+I_4)}{I_s-I_0} \end{cases} \tag{5}$$

From this equation, we know that the disturbing signals and the drift of DC and electrical gain are all removed.

4. Experimental setup and results

According to the operation principle, an experiment setup was established. In this setup, a 670 nm laser diode pigtailed with a single mode optical fiber was used. The four-quadrant detector adopted was the model SD-386-22-21-251 from the Silicon Detector Corporation. The CPU for the data acquisition and processor was an 8098 chip from the Intel Corporation. In order to achieve a high Q value from the narrow band-pass filter, a switch capacity filter MF10 from National Semiconductor was used. The 12-bit A/D converter used was an AD1674 from the Analog Device Corporation. The measuring range of the experimental setup was set to be ±100 μm.

We put both the laser unit of the straightness measurement system and the four-quadrant detector, which was equipped with a PI micro-displacement stage, on the top of an optical bench. The distance between them was about 1 m. An HP5528 laser interferometer was used to calibrate the accuracy of the lateral displacement of the detector. Fig. 3 demonstrates good linearity of our
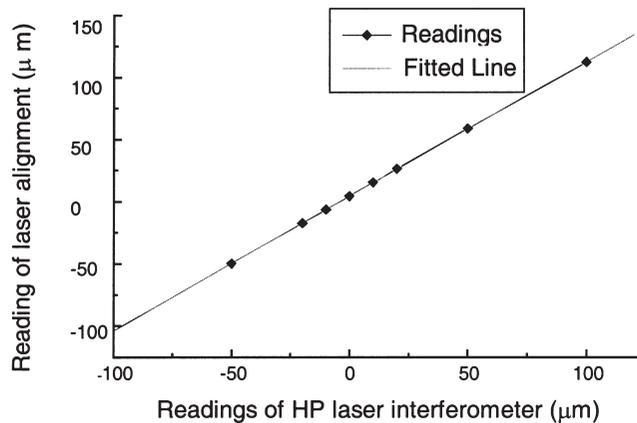
Fig. 3.   Accuracy calibration results using an HP interferometer.
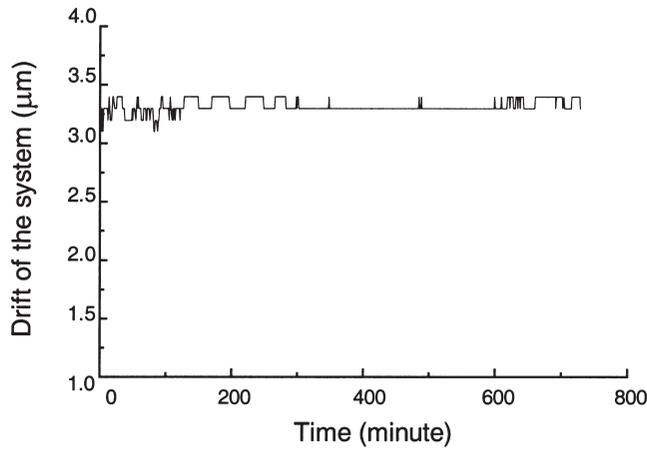
Fig. 4.   Results of pointing stability test.

system with only 0.3 µm error within the range of 200 µm. Fig. 4 shows the drift of the system over 12 h with the pointing stability about 0.3 µm only.

5. Applications

The experimental setup of the straightness measurement of a CMM is shown in Fig. 5, in which the laser unit is mounted on the granite table of a CMM and the four-quadrant detector is attached to the spindle. The bridge is commanded to move step-by-step so that the system can detect the

1. Laser diode

2. Adjustable table

3. 4-Q detector
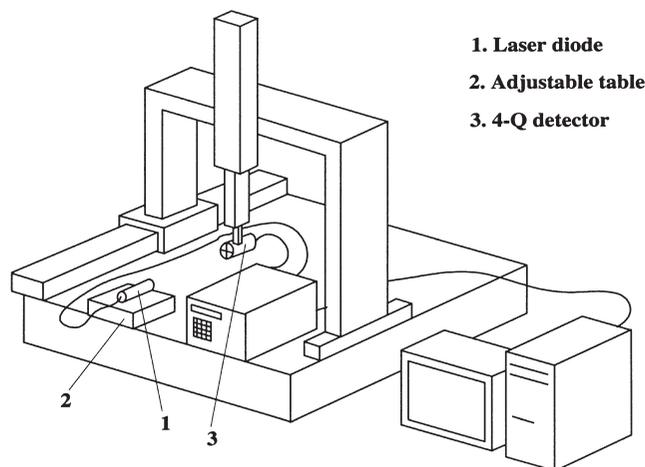
Fig. 5.   Setup of straightness measurement on a CMM.
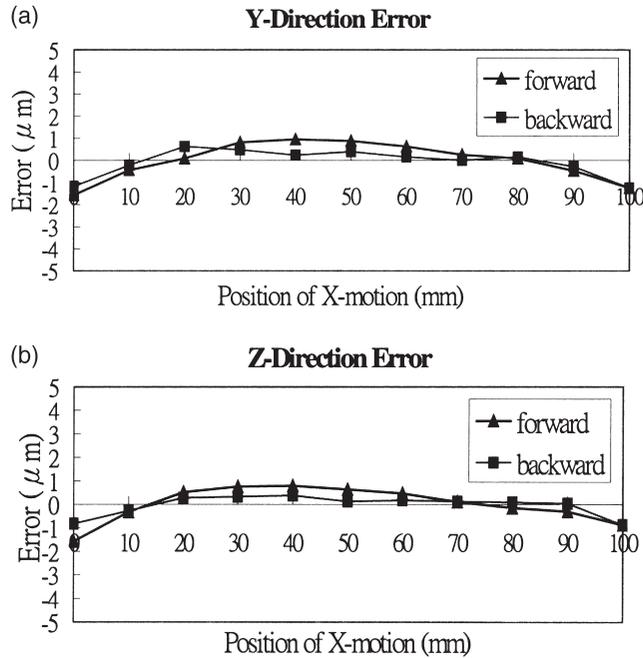
Fig. 6.   (a) Tested CMM horizontal straightness errors. (b) Tested CMM vertical straightness errors.

out-of-straightness of the motion. Fig. 6(a) plots the error diagram of the horizontal straightness with respect to the least-squares line, and Fig. 6(b) is the result of vertical straightness error. The repeatability is within 0.5 μm. The second application is on a grinding machine. Fig. 7 shows the photo of the measurement setup in which the laser unit is attached to the spindle and the four-quadrant detector is mounted onto the worktable through a six-axis adjustable table. Quite
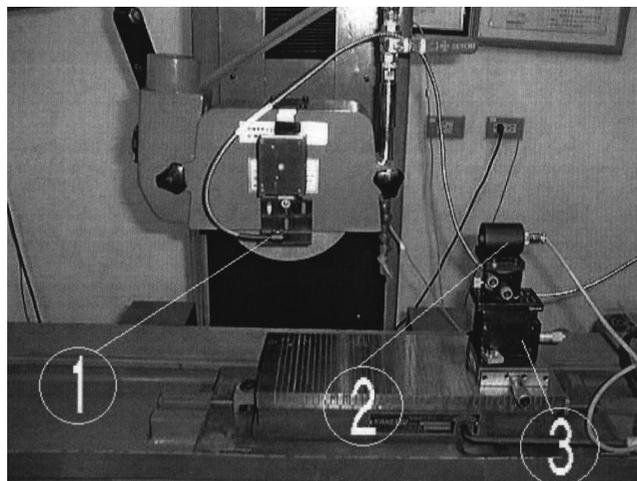
Fig. 7.   Photo of the straightness measurement of a grinding machine: (1) laser diode; (2) 4-Q detector; (3) adjustable table.

repeatable straightness errors, within 0.5 μm, can be seen in both axes, as shown in Fig. 8(a) and (b).

If we mount a corner cube onto the moving part and let the beam reflect back to the four-quadrant detector which is fixed near the laser head, the moving part can then be wireless which eliminates any induced pushing and pulling errors of the wire. Such a system will be more stable and the sensitivity will even be doubled [8,15].

6. Conclusions

Optical and electrical drifts at the operational site are considered to be major sources of error, which limit the stability of the laser alignment system. In our newly developed system, with the implementation of the optical fiber and modulation techniques, these influences can all be reduced to a minimum. A high accuracy system is thus achieved. The advantages of this system are:

1. the alignment beam from the optical fiber is proven to be a drift free beam. The heat source from the laser diode is isolated at the same time. The stability of the alignment is maintained;
2. the modulation–demodulation technique eliminates the noise from disturbing lights and electrical signals;
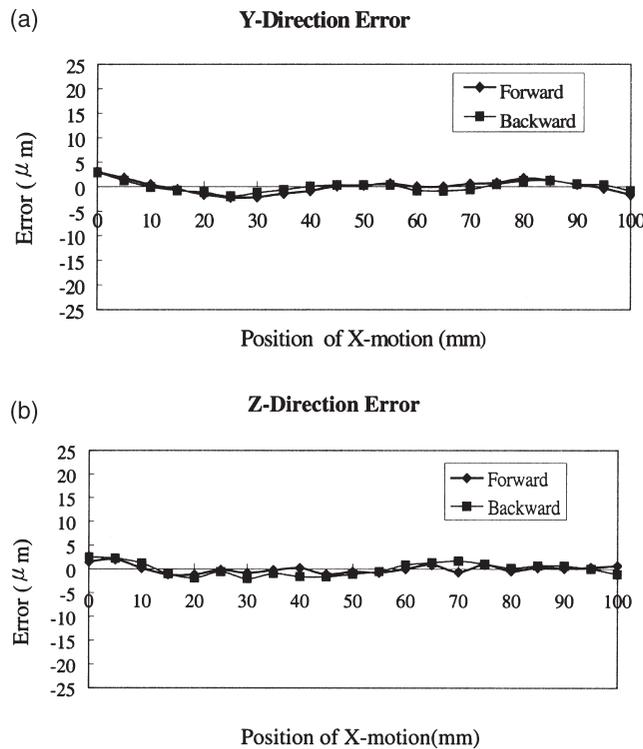
Fig. 8.   (a) Tested horizontal straightness errors of the grinding machine. (b) Tested vertical straightness errors of the grinding machine.

3. the signal processing channel sharing technique suppresses the DC and gain drift in the circuits;
4. it has good accuracy of 0.3 μm in 200 μm measurement range, good pointing stability of 0.3 μm for 12 h at 1 m distance, and good repeatability of 0.5 μm in both the x and y axes;
5. it is compact in size, cheap in cost, and easy to install.

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