Four Degree-of-Freedom Geometric Error Measurement System with Common-Path Compensation for Laser Beam Drift

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A precision four-degree-of-freedom measurement system has been developed for simultaneous measurement of four motion errors of a linear stage, which include straightness and angular errors. The system employs a retro-reflector to detect the straightness errors and a plane mirror to detect the angular errors. A common-path compensation method for laser beam drift is put forward, and the experimental results show that the influences of beam drift on four motion errors can be reduced simultaneously. In comparison with the API 5D laser measuring system, the accuracy for straightness measurement is about ±1.5μm within the measuring range of ±650μm, and the accuracy for pitch and yaw measurements is about ±1.5 arc-seconds within the range of ±600 arc-seconds.

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1. Introduction

A moving table along a specified axis will inherently have errors in six degrees of freedom, which are three linear errors (linear positioning, horizontal straightness, vertical straightness) and three angular errors (pitch, yaw and roll). For a typical three-axis machine center, there are twenty-one geometric errors that are required to measure step by step according to the relevant criteria. Current technology for the measurement of these errors employs the laser interferometer such as HP5529.[1] This whole measurement process often takes a long time as each error should be calibrated separately, and the measurement uncertainty could increase as the process time increases. Besides, the measurement accuracy could not be assured as the operators and the measuring environment change every alignment of measurement apparatus. There are some other reports for multi-error measurement systems published in recent years.[2-10] The works by K.C.Fan from National Taiwan University and the works by Ni et al from University of Michigan are representative. At present, there is a commercially available 5/6D measuring system from Automated Precision Inc.API.[11]

As it is known, the accuracy of a laser collimation measurement system can also be greatly limited by the factor of beam drift which generally results from the temperature gradient of the laser source and also the air turbulence. Some researches have been carried out to find ways to compensate the measurement error produced by the laser beam drift.[12-14] However, in the most cases, the compensation beam is not in a common-path with the measurement beam, and the measurement beam and the compensation beam are not relative totally, the compensation results are not so ideal. Besides, the influence on the all motion errors can not be reduced simultaneously with the current methods.

In this paper, a newly developed system for simultaneously measuring four-degree-of-freedom errors of machine tools is introduced. A single-mode fiber-coupled laser module is used to eliminate the beam drift of the laser source. Only a cube corner retro-reflector and a beam splitter are adopted in the moving target in order to sense the straightness errors and angular errors (pitch and yaw) respectively and simultaneously. A simple common-path compensation method for laser beam drift is put forward, and a 2D position-sensitive detector and a lens are used to monitor angular drift of the laser beam. The experimental results are given and show that the influences of beam drift due to the air turbulence on all four motion errors can be reduced simultaneously.

2. Principle of Measurement

2.1 Common-Path Measurement and Compensation for Laser Beam Angular Drift

Fig. 1 shows the diagram of common-path compensation system of beam angular drift. A collimation laser beam reaches the retro-reflector (RR) and is reflected back to a lens, and then it is focused to a 2D position-sensitive detector (PSD). If there is the angular drift of the laser beam $\Delta\alpha$ in the plane xoz, the laser spot position on the x-direction of PSD will be changed Δx. In the same way, when there is the angular drift $\Delta\beta$ in the plane yoz, the position of laser spot on the PSD will be changed Δy. The angular drift of a laser beam is small, usually less than 30 arc-seconds, and the angle of laser beam drift in the two directions can be obtained as

$$\Delta\alpha = \tan^{-1}\left(\frac{\Delta x}{f}\right) \approx \frac{\Delta x}{f} \qquad (1)$$
$$\Delta\beta = \tan^{-1}\left(\frac{\Delta y}{f}\right) \approx \frac{\Delta y}{f}$$

Where f is the focal length, Δx and Δy is the spot position changes in two directions on the PSD

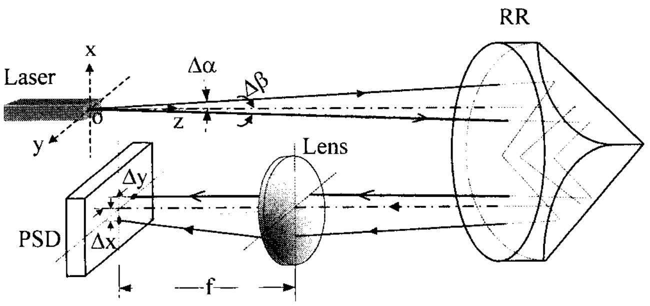


Fig. 1 Diagram of common-path measurement of beam angular drift

2.2 Straightness Error Measurement

Fig. 2 shows the diagram of straightness errors measurement system with the common- path beam drift compensation in the plane xoz. The system consists of a fixed unit and a moving unit. The laser beam reflected back from RR is split into two beams by the beam splitter (BS1). The beam reflected by BS1 reaches a quadrant detector (QD) and is used to detect the straightness errors. It is the measurement beam. The beam that transmits through BS1 reaches PSD and is used to measure the beam angular drift. It is the compensation beam. So the measurement beam and the compensation beam are in the common path.

In the instance of non angular drift, when a stage is moved along the axis of travel with a certain lateral distance ΔX, the beam reflected by the RR will be shifted on the corresponding QD by a distance of $2\Delta X$.[15] If there is the angular drift of $\Delta\alpha$, the beam position changes on the QD will be ΔX_1, and the straightness error in the direction of X can be obtained after compensation for beam drift as

$$\Delta X = \frac{\Delta X_1}{2} \pm l \times \Delta\alpha \qquad (2)$$

Where $\Delta\alpha$ is given by the Equation (1), l is the moving distance, and the sign (±) is chosen according to the actual measurement.

The straightness error in the direction of Y can be gotten in the same way.

$$\Delta Y = \frac{\Delta Y_1}{2} \pm l \times \Delta\beta \qquad (3)$$

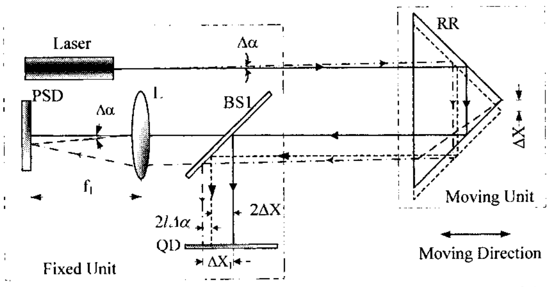


Fig. 2 Diagram of straightness errors measuring with beam drift compensation

2.3 Measurement of Pitch and Yaw

Fig. 3 shows the schematic diagram of measurement of the angular errors with common-path beam drift compensation in the plane xoz. A half-plane mirror (BS3), a lens (L2) and a PSD2 are adopted to detect the angular errors of pitch and yaw.

In the instance of non angular drift, when a stage is moved along the axis z with a pitch angle α_2, the ray angle reflected from BS3 will change $2\alpha_2$, thus the spot position of the reflected beam which is focused on PSD2 will change about $2f_2\alpha_2$ if the α_2 is small. Similarly, if there is the angular drift of $\Delta\alpha$, the spot position of the reflected beam which is focused on PSD2 will change ΔX_2. Thus, the pitch α_2 after compensation can be obtained by

$$\alpha_2 = \frac{\Delta X_2}{2f_2} \pm \frac{\Delta\alpha}{2} \qquad (4)$$

Where $\Delta\alpha$ is given by the Equation (1), f_2 is the focus length of lens L2, and the sign (±) is chosen according to the actual measurement.

The yaw β_2 can be obtained in the same way.

$$\beta_2 = \frac{\Delta Y_2}{2f_2} \pm \frac{\Delta\beta}{2} \qquad (5)$$

Where ΔY_2 is the spot position change on PSD2 in the direction of Y.

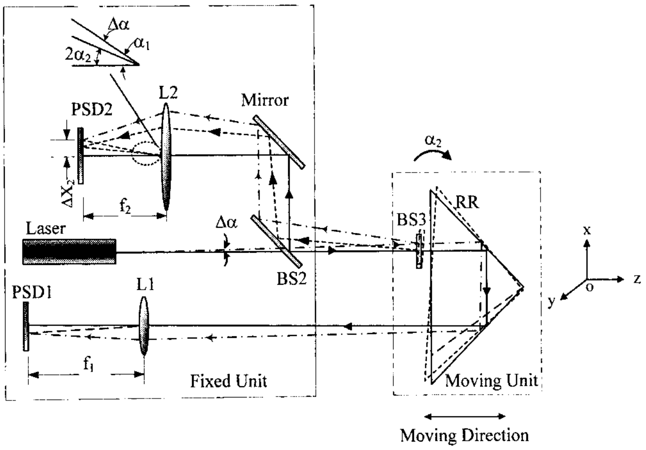


Fig. 3 Schematic diagram of angular errors measuring with beam drift compensation

2.4 System configuration for simultaneously measuring 4DOF with Common-path Drift Compensation

Fig. 4 shows the schematic diagram of the system for simultaneously measuring four-degree-freedom (4DOF) with Common-path Beam Drift Compensation. A single-mode fiber laser module is used as the light source to eliminate the beam drift of the laser source and to isolate the to heat generated from the laser source, and in this way, the beam stability is increased greatly. The 4DOF measurement system is mainly composed of two parts. One is a moving unit which consists of BS3 and RR that are used to sense the angular errors and straightness errors, the other is a fixed unit that includes three subsystems, one is consists of BS2, a mirror, a lens L2

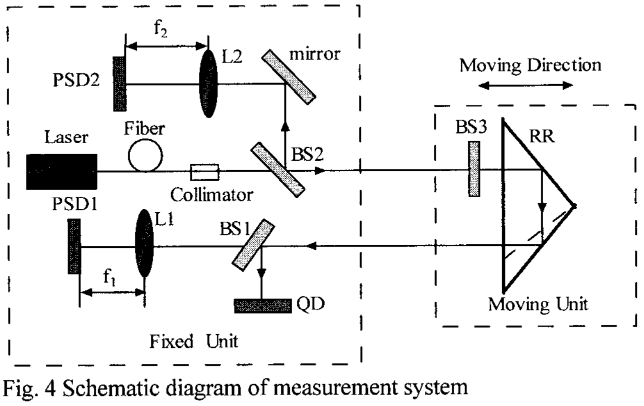


Fig. 4 Schematic diagram of measurement system

and a PSD2 and is used to detect angular error sensed by the BS3, the second is consists of BS1 and a QD and is used to detect straightness error sensed by RR, the third is consists of BS1, a lens L1 and PSD1 and is used to detect angular drift of laser beam. The measurement principles have been introduced above.

3. Experimental results

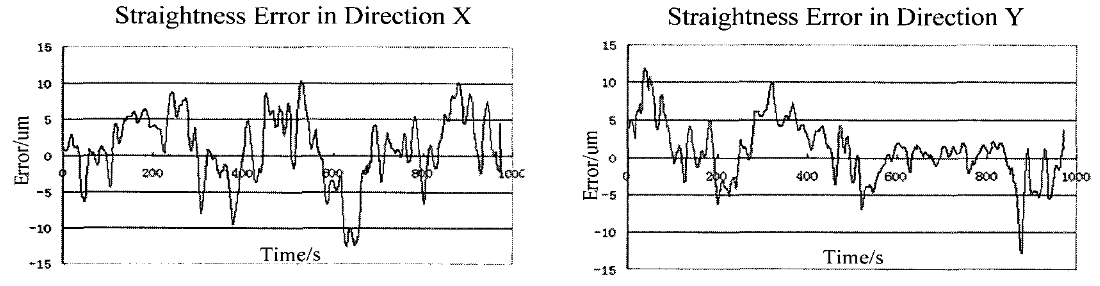
3.1 Beam Drift Compensation Test

To evaluate the effect of the common-path compensation method for the laser beam drift under different conditions, some experiments have been done in the temperature of 18°C±2°C. When the distance target is eight meters away, the results of straightness stability measurement is shown in Fig. 5, which indicates that the maximum fluctuation decreases from 25μm to 12μm and the accuracy can be increased by about 50% within a measurement period of about 16minutes. Furthermore, when the distance target is ten meters away, the results for the yaw and pitch measurements shown in Fig.6 indicate that the maximum fluctuation decreases from 10 arc-seconds to 3 arc-seconds and the accuracy can be increased by about 65% within a measurement period of about 40 minutes.

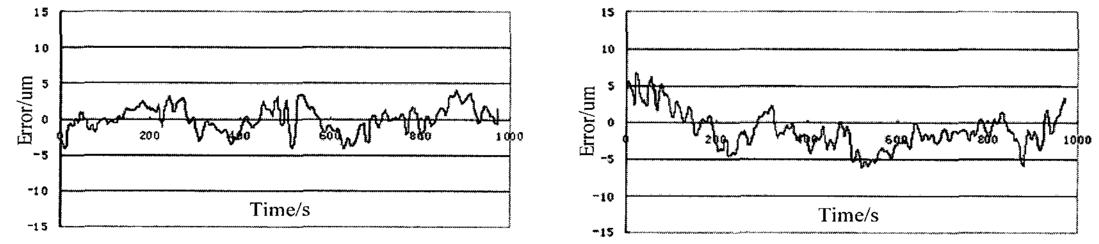
3.2 Calibration Test

The measuring heads of 4DOF system and API system are mounted on an x-y stage, and the calibrations of straightness errors are performed. Fig. 7(a) and (b) shows the results. The maximum deviation of horizontal straightness is found to be from -1.1μm to 1.2μm within a measurement range of ±650μm. The maximum deviation of vertical straightness is found to be from -1.0μm to 1.4μm within the range of ±600μm.

The calibrations of angular errors were carried out with the measuring heads of two systems mounted on a rotary table which can be rotated with pitch angle and yaw angle. The results are shown in Fig. 7(c) and (d). The maximum deviations are from -1.5 arc-seconds to 1.5 arc-seconds for the yaw error and from -1.3 arc-seconds to 1.4 arc-seconds for the pitch error within the range of ±600 arc-seconds.

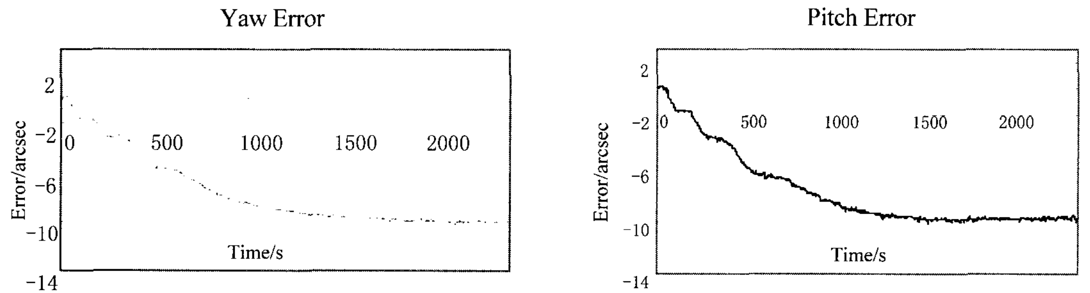


(a) Before Compensated (c) Before Compensated

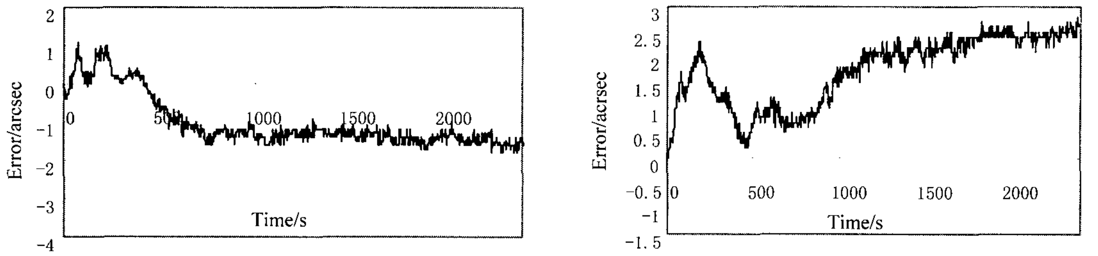


(b)After Compensated (d)After Compensated

Fig. 5 Straightness error comparison experiments results



(a) Before Compensated (c) Before Compensated



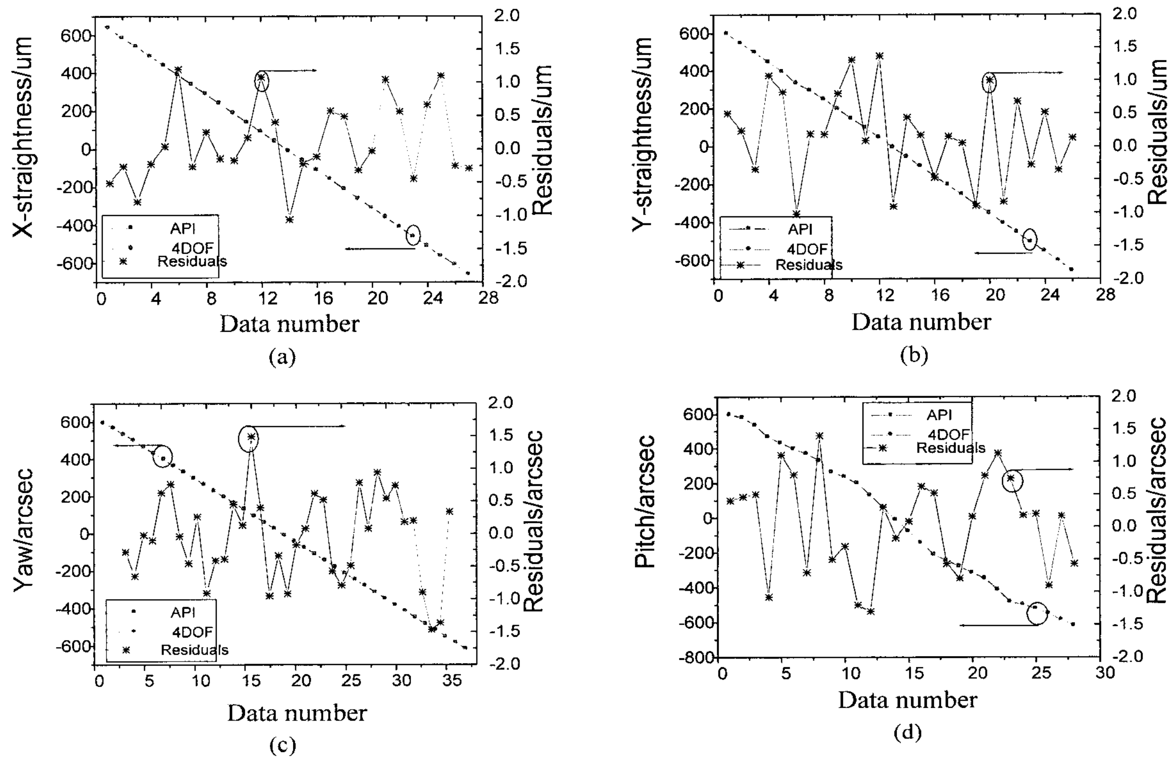
(b) After Compensated (d) After Compensated

Fig. 6 Yaw and pitch error comparison experiments results

3.3 Comparison Test

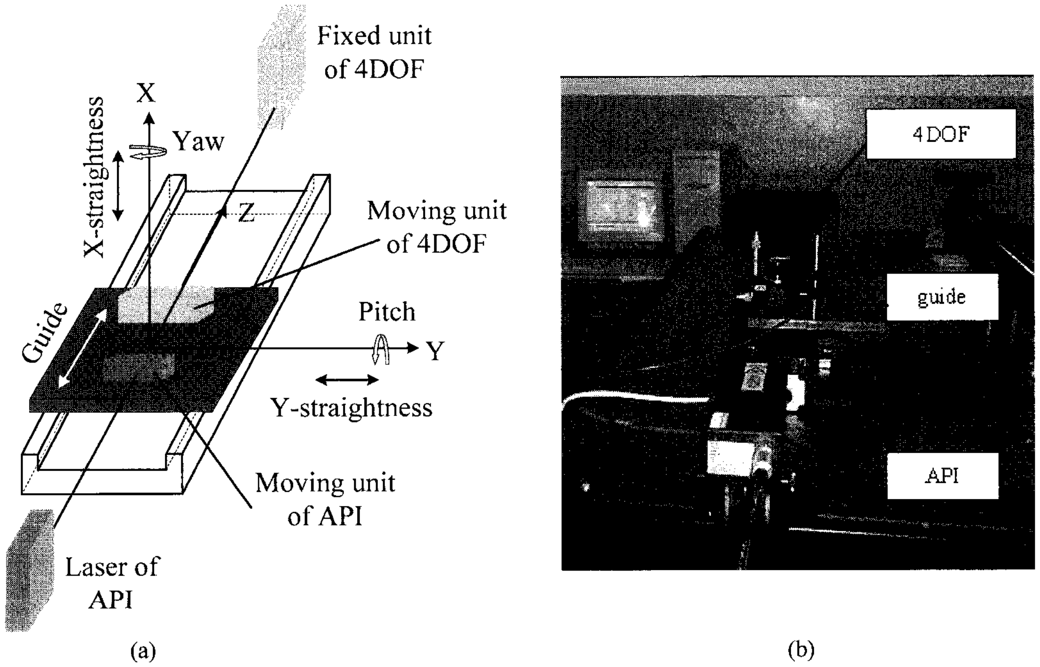
The motion errors of a linear guide were tested with 4DOF system and API system simultaneously in the temperature of 18°C±2°C. The system diagram and the photo of the experimental set-up are showed in Fig. 8(a) and (b). Both measuring heads of two systems are mounted on a linear guide, which is moved for a travel of 1000mm with an increment of 100mm. The four-degree-of-freedom including horizontal and vertical straightness errors, pitch and yaw angular errors can be measured simultaneously. The results are showed in Fig.9. The maximum residual errors are about from -2.4μm to 1.1μm and from -3.9μm to 3.8μm for the horizontal and vertical straightness errors respectively, and the maximum residual errors are about from -1.8 arc-seconds to 1.3 arc-seconds and from -2.8 arc-seconds to 2.4 arc-seconds for yaw and pitch errors.

In fact, a model guide that is just placed in a optical platform shown in Fig. 8 (b) was used a test object, and it has a much lager straightness errors than a real linear guide used in machine tools. The two measuring heads of 4DOF and API system can not be placed at the same position on the model linear guide is the main reason for producing a difference between the two measurement systems.



(a) (b) (c) (d)

Fig. 7 Calibration test results with API system
(a) Horizontal straightness (b) Vertical straightness (c)Yaw error (d) Pitch error



(a) (b)

Fig. 8 Set-up for comparison test with API measuring system
(a)Set-up diagram (b)Photo of the experimental set-up

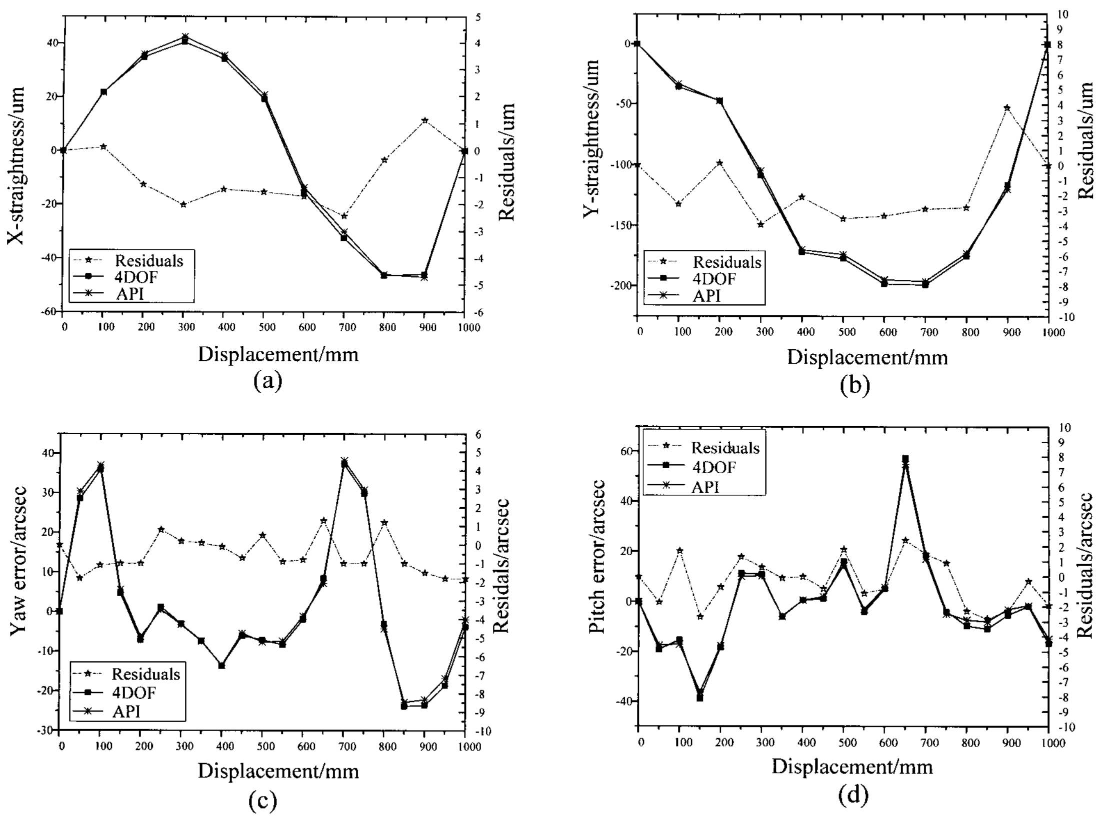


Fig. 9 Comparison results with API system
(a) Horizontal straightness (b) Vertical straightness (c)Yaw error (d) Pitch error

4. Conclusions

This paper presents a simple system that is able to simultaneously measure the motion errors in four-degrees-of freedom of a linear stage. A common-path compensation method for laser beam drift was successfully integrated. The proposed measurement method was verified and the performance of the measurement system was evaluated in the experiment. The stability test showed that the measurement error induced by laser angular drift can be reduced greatly using common-path compensation method. Moreover, the comparison experimental results showed that the developed system has the accuracy of ±1.5μm within the measurement range of about ±650μm in measuring straightness error, and ±1.5 arc-seconds within the range of ±600 arc-seconds in measuring pitch and yaw.

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