Development of a straightness measurement and compensation system with multiple right-angle reflectors and a lead zirconate titanate-based compensation stage

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This paper presents a real-time straightness measurement and compensation system with an optical straightness measurement system and a single-axis flexure-hinge type lead zirconate titanate (PZT)-based compensation stage. The optical straightness measurement system consists of a He–Ne laser, a quadrant photodiode detector, and five right-angle reflectors. Multiple laser beam reflections between the right-angle reflectors increase the sensitivity of the straightness measurement by a factor of 6. The right-angle reflectors can be moved by the flexure-hinge type PZT-based compensation stage that is actuated by a PZT actuator to ensure that the laser beam is always projected onto the center of the quadrant detector. These two systems are integrated and fixed on a scanning stage. The resolution of the straightness measurement system is 0.1 μm. Using the real-time straightness compensation system, the straightness error of the scanning stage is fed back to the control system. The compensated straightness error of the scanning stage system was reduced from 6.5 μm to less than 1 μm. *© 2009 American Institute of Physics.* [doi:10.1063/1.3254018]

I. INTRODUCTION

The coordinated measurement machine and the profile measuring machine used a high precision displacement probe to measure the profile of a workpiece. Displacement probes are mounted on a scanning stage; the straightness error of the scanning stage is one of the main error sources. It is difficult to assemble the scanning stage with two linear guides with less than 1 μm straightness error without using a real-time measuring system, especially when the travel range exceeds 200 mm. In the off-line straightness compensated method, straightness errors are often corrected using discrete data measured by an off-line calibration measuring system.[1–5] It is necessary for the scanning stage to have good repeatability and low uncertainty.

Some studies have developed error separation methods to separate the profile of the workpiece from the straightness error of the scanning stage. The two-probe[6–9] and the three-probe methods,[10,11] called step-error separation methods, separate the straightness error from the scanning stage and the workpiece. The process of error separation requires the scanning stage to move a fixed interval between the probes. This limits the measuring points and positions of the workpiece to separate the straightness error of the scanning stage. These methods are suitable for measuring the profile of a workpiece with a fixed form, such as a cylinder or a sphere due to the fixed interval between the probes.

The real-time straightness measurement method developed in this paper uses the multiple reflection method between a collimated laser beam, five right-angle reflectors, and a quadrant detector to measure the straightness error with high sensitivity. A monochroic flexure-hinge type lead zirconate titanate (PZT) compensation stage is used to compensate for the straightness error of the scanning stage. This method can correct the straightness error induced from the scanning stage at any measuring position on the workpiece. It can thus measure workpieces with a free form.

II. STRUCTURE OF THE REAL-TIME STRAIGHTNESS COMPENSATION SCANNING STAGE

The structure of the real-time straightness compensating scanning stage is shown in Fig. 1. It is composed of three parts: (1) a real-time straightness measuring system, (2) a single-axis flexure-hinge type PZT compensating stage, and (3) the scanning stage actuated by an ac servo motor and ball screw. The single-axis compensating stage is guided by four symmetric flexure hinges and actuated by a PZT actuator. It is also used as the moving platform of the scanning stage.

A. Straightness measurement system

The real-time straightness measurement system is divided into a fixed part and a moving part. The fixed part consists of a laser, a plane mirror, a quadrant detector, and two right-angle reflectors. The moving part consists of three right-angle reflectors and a fixed holder, two angular adjustment mechanisms, a capacitance sensor and the sensor holder, and a single-axis flexure-hinge type PZT compensation stage. The structure of the moving part is shown in Fig. 2. The working principle of the straightness measurement system is shown in Fig. 3. In the proposed system, the laser beam on the fixed part is reflected from a plane mirror and reflected to right-angle reflector 1 (RA1) of the moving part. The laser beam is then reflected and horizontally shifted

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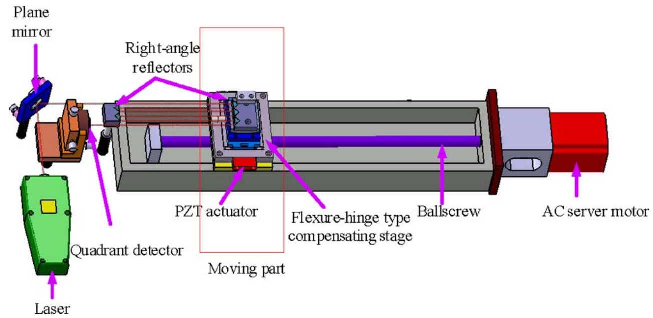

FIG. 1. (Color online) Schematic of the real-time straightness compensation scanning stage.

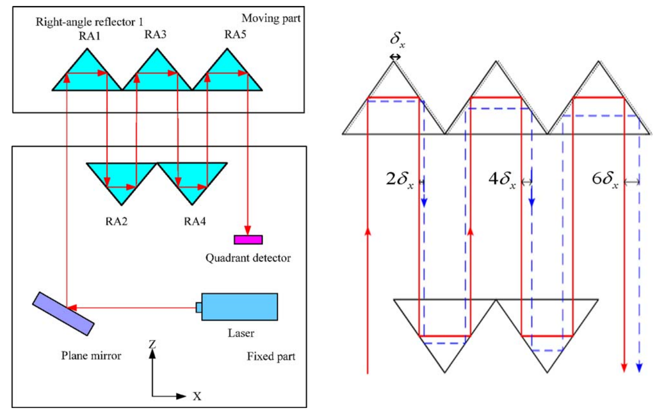

FIG. 3. (Color online) Measuring principle of the straightness measurement system.

from RA1 and projected to right-angle reflector 2 (RA2). After three cycles of reflection and horizontal shifts, the laser beam is projected onto the quadrant detector of the fixed part. When the scanning stage is moved, the laser beams with multiple reflections and horizontal shifts induced from the straightness error of the stage change the spot position of the laser beam on the quadrant detector. The straightness error of the scanning stage can be measured from the spot positions of the quadrant detector.

When the right-angle reflector is shifted by horizontal displacement δ_x, the laser beam reflected from the reflector is shifted by $2\delta_x$. Thus, the sensitivity of the straightness measurement is improved by a factor of 2. In our system, the sensitivity of the straightness measurement can be improved by a factor of 6. The straightness can be calculated using

$$\delta_x = \frac{K_x V_X}{6}, \quad \text{horizontal straightness}, \tag{1}$$

where V_x is the voltage of the spot position on the quadrant detector and K_x is the proportional gain (displacement/voltage).

B. Flexure-hinge type PZT compensation stage

The flexure-hinge type PZT-based single-axis compensation stage with one degree of freedom of motion is shown in Fig. 4. The flexure-hinge mechanism uses a notched hinge, thus providing smooth and continuous motion without any friction. The design uses eight notched hinges for a symmetrical structure and little parasitical motion. The important parameters of the notched hinge include the notch radius, R, and the thickness, t, and height, h, of the notched hinge. In our design, R is 1.5 mm, t is 0.9 mm, and h is 12 mm. The stage is made of medium carbon steel (S45C) and is processed using wire electrical discharge machining. Commercial CATIA software (Dassault Systems) was used for the simulation of the single-axis compensation stage. In the simulation, the stage was elongated to move 30 μm, which is a little longer than the real displacement (25 μm) of the piezoelectric actuator. The simulation results of the deformation and stress analysis using the finite element method are shown in Fig. 5. The results show that the displacement of the inner stage increased uniformly and that the yaw angular displacement is very small. The maximum stress of the compensation stage was about 2.07×10^8 N/m^2, which is smaller than the yield strength. The stress was concentrated on the eight symmetric notch hinges. The experimental test for the yaw angular error of the real stage is shown in Fig. 6. The maximum angular error is less than 0.5 arc sec. The result shows the good symmetrical structure of the designed stage. The natural frequency of the real stage was tested by applying an impulse signal to the stage and using the fast Fourier transform (FFT) to determine the natural frequency. An impulse signal was generated by beating the stage with a rubber hammer. The FFT of the natural frequency response is shown in Fig. 7. The figure shows a natural frequency of around 634 Hz. Thus, the stage can be used for dynamically correcting the straightness error at a bandwidth of 60 Hz.

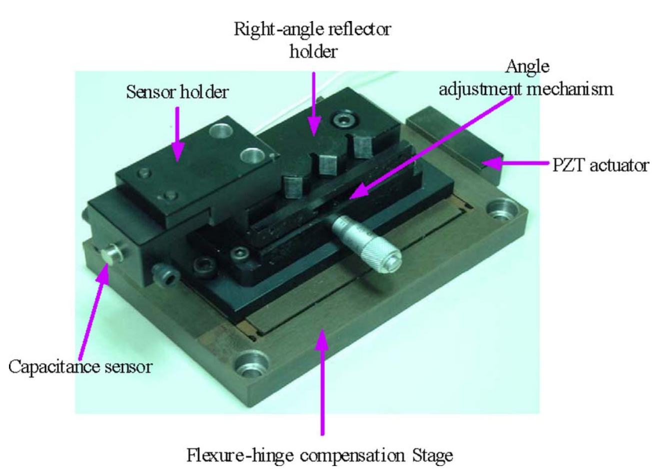

FIG. 2. (Color online) Single-axis flexure-hinge type PZT compensation stage with the capacitance sensor and reflection part of the straightness measurement system.

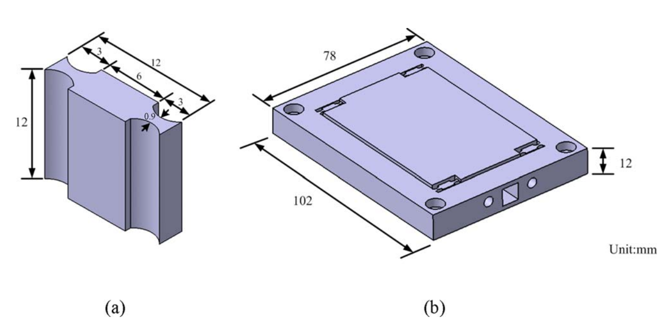

FIG. 4. (Color online) Dimensions of the single-axis flexure-hinge type PZT compensation stage. (a) The flexure-hinge and (b) the single-axis compensation stages.

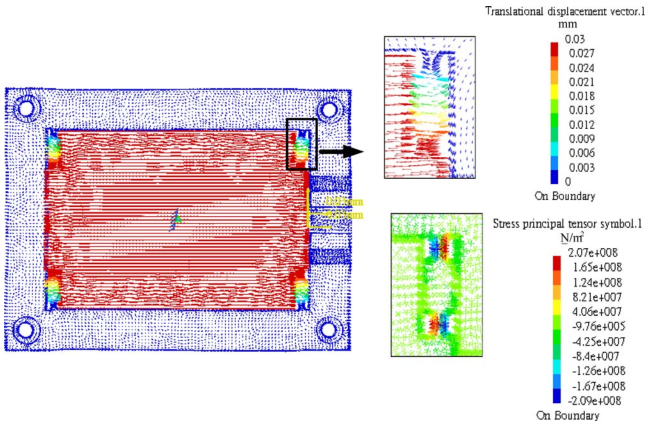

FIG. 5. (Color online) Simulation results of the finite element analysis using CATIA software.

C. Scanning stage actuated by an ac servo motor and ball screw

A ball screw and two linear guides are used in the scanning stage. The motor of the scanning stage is an ac brush motor (Sanyo P5). A digital driver (Elmo CEL-15/1660I) is connected to the motor and the control hardware. The control system includes software (MATLAB/SIMULINK) and a dSPACE processor (DS1104). The working range and the resolution of the scanning stage are 250 mm and 0.25 μm, respectively. A proportional-integral-derivative (PID) controller was designed for the scanning stages.

III. CONTROL SYSTEM

The control systems include the controller of the scanning stage and the controller of the straightness compensation stage. The software and hardware are MATLAB/SIMULINK, a dSPACE processor (DS1104), a digital driver (Elmo CEL-15/1660I), and a high gain voltage amplifier (PosiCon-150-3-A). The piezoelectric actuator (PSt150/7*7/20), with a 25 μm stroke range, and the amplifier (PosiCon-150–3-A) were made by Piezomechanik GmbH.[12] Figure 8 shows the control flow of the straightness compensation scanning stage. The digital driver drives the motor in the scanning stage; the feedback system is the encoder of the motor. The PID controller was designed for the scanning stages. The high gain voltage amplifier actuates the piezoelectric actuator in the PZT-based compensation stage. The real-time straightness measuring system measures the horizontal straightness error of the scanning stage which is fed back to the control system to move the three right-angle reflectors on the PZT-based compensation stage. The PI controller was designed for the straightness compensation stage. During the scanning process, the compensation stage keeps the laser spot on the center of the quadrant detector.

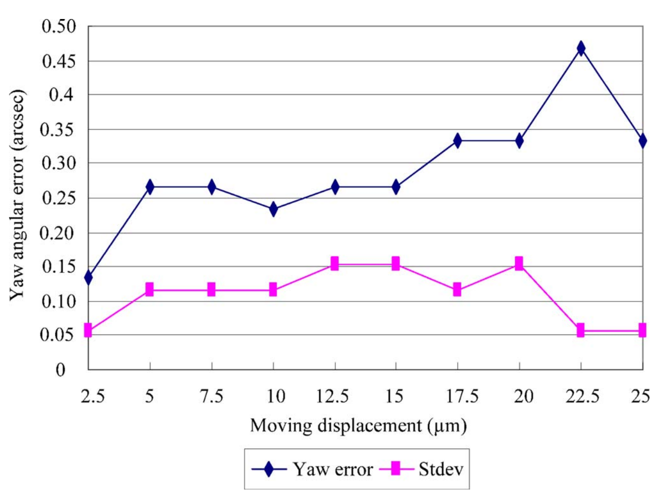

FIG. 6. (Color online) Verification of yaw angular error of the PZT compensation stage.

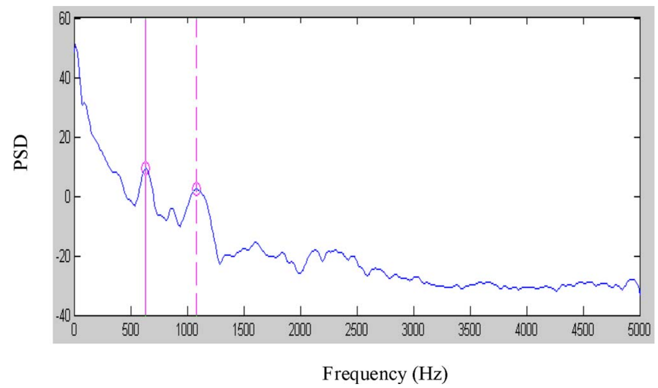

FIG. 7. (Color online) Frequency spectrum of the impulse response of the PZT compensation stage.

The error signal between the straightness measuring system and the compensation stage can be expressed as

$$e = \delta_c - \delta_x. \tag{2}$$

The actuated signal input to the motor of the compensated stage can be expressed as

$$u = K_p e + K_I \int e dt, \tag{3}$$

where the δ_c is the reference command of the compensated straightness and K_p and K_I are the controller gains.

Before the real-time straightness compensation process, the PZT stage was tested with a PI controller. The control system generated a control signal in a feedback loop. The scanning stage did not move. The feedback signal was measured from the straightness measurement system. The step response with a 5 μm displacement is shown in Fig. 9. The

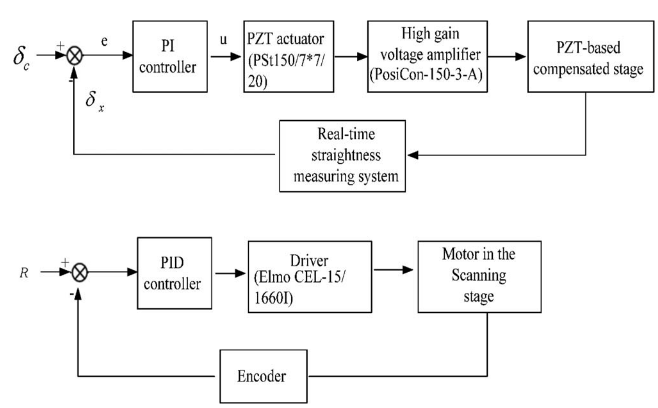

FIG. 8. Control flow of the real-time straightness compensation scanning stage.

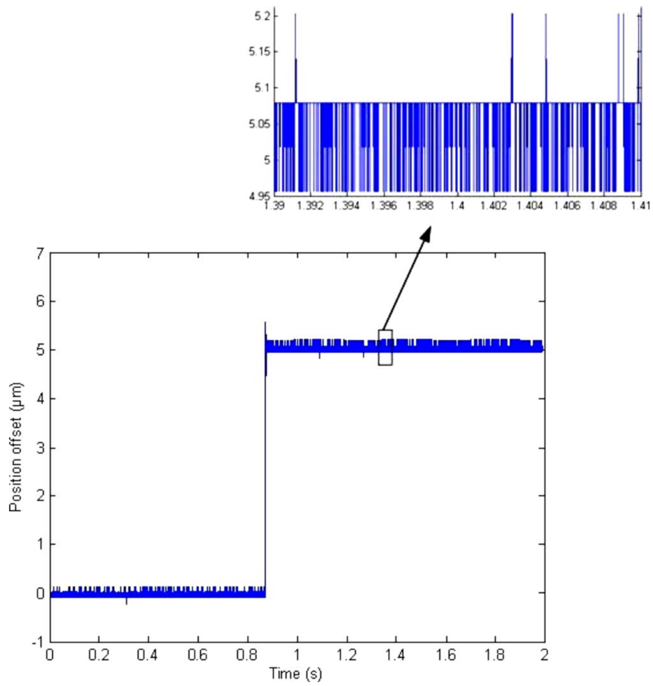

FIG. 9. (Color online) Step response of the PZT compensation stage with 5 μm displacement.

solid line represents the control signal itself, while the actual performance for translation displacement is shown as the variance of 4.96–5.08 μm around the 5 μm. The rising time was estimated to be less than 0.01 s. The steady state error was about 0.12 μm.

IV. CALIBRATION FOR REAL-TIME STRAIGHTNESS COMPENSATION SCANNING STAGE

A. Calibration of the real-time straightness measurement system

The calibration process was directly conducted in the scanning stage. The PZT stage moved the right-angle reflectors and the displacement was measured by a capacitance sensor with a resolution of about 50 nm. The horizontal displacement of the laser beam was measured by the quadrant detector. The calibration results, shown in Fig. 10, indicate

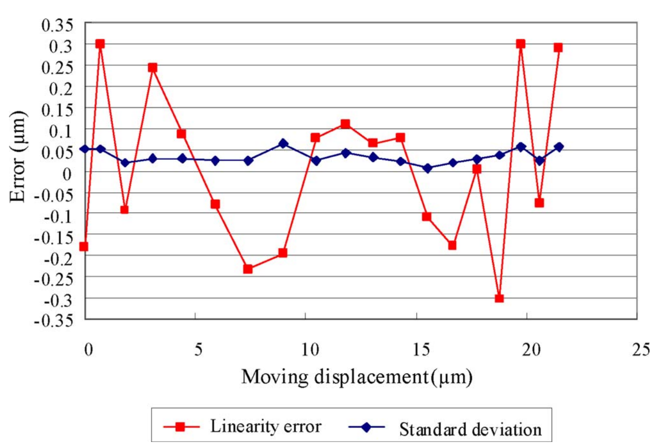

FIG. 10. (Color online) Linearity error and the standard deviation of the proposed straightness measurement system.

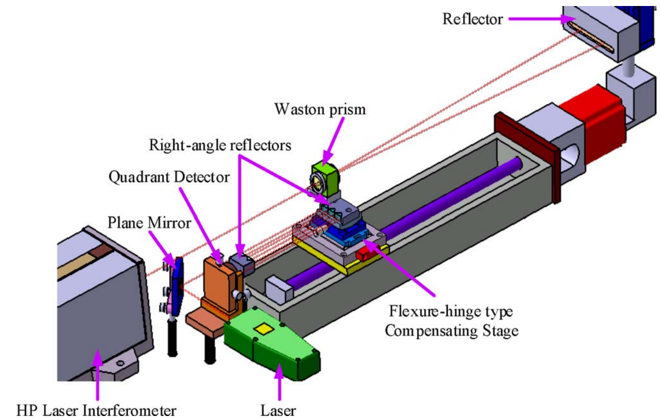

FIG. 11. (Color online) Setup of the calibrating system for the real-time straightness compensation scanning stage.

that the proportional gain of the quadrant detector was 0.082 V/μm and that the linearity error of the quadrant detector was under ± 0.3 μm within the measuring range of 22 μm. The standard deviation was about 0.07 μm.

B. Straightness error measurement of the scanning stage

Figure 11 shows the complete experimental setup of the straightness measurement and compensation system and the verification system of the laser interferometer straightness calibration system. An HP laser interferometer and the proposed straightness measuring system for straightness calibration were set on the scanning stage. In this straightness measuring experiment, measurements were performed by moving the scanning stage a distance of 200 mm with increments of 20 mm, for three runs. Figure 12 shows that the straightness error of the scanning stage was 6.5 μm. The standard deviation of the scanning stage was 0.4 μm. The residual error between the HP laser interferometer and the proposed straightness measurement system was less than 0.6 μm within the measuring range of 200 mm.

V. COMPENSATION RESULTS AND DISCUSSION

In the real-time straightness compensation process, the compensation stage keeps the laser spot on the center of the quadrant detector. Thus, the laser paths of the straightness

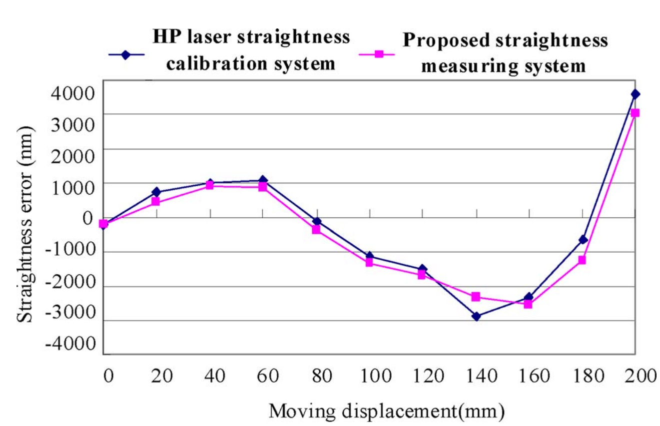

FIG. 12. (Color online) Verification results of the HP straightness calibration system and the proposed straightness measurement system.

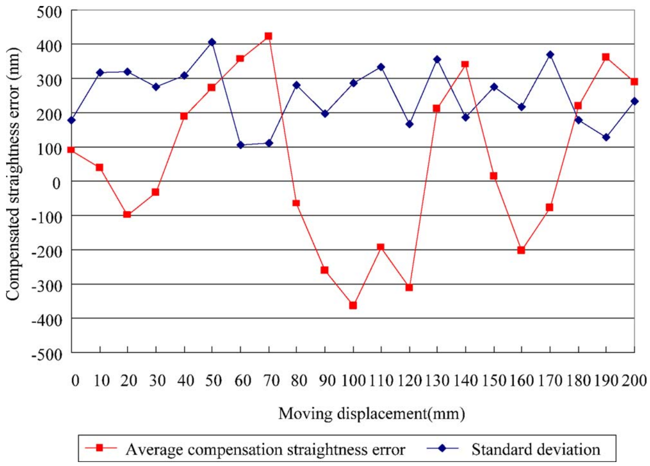

FIG. 13. (Color online) Real-time straightness error compensation results measured by the HP laser interferometer system.

measurement system have to be adjusted to be parallel to the moving axis of the scanning stage. A lack of parallelism between the laser beam and the moving axis will result in incorrect real-time straightness error compensation, which will affect the straightness measurement of the workpiece. The adjustment process is described in the steps below.

(1) The scanning stage is moved from 0 to 200 mm and the data from the quadrant detector is recorded.
(2) The trend line for the data is calculated using the least-squares regression fit to estimate the lack of parallelism.
(3) The reflection mirror is adjusted to increase parallelism and steps 1 and 2 are repeated.

After the adjustment, five experimental tests were performed using the real-time straightness error compensation of the scanning stage. The input command of the PZT compensation stage was set to be zero ($\delta_c = 0$). Figure 13 shows the straightness error compensation results measured by the HP laser interferometer system. The straightness error of 6.5 μm was reduced to be less than 1 μm. The standard deviation was about 0.5 μm. The real-time straightness error compensation scanning stage can thus separate the straightness errors at any measurement position of the scanning stage to be less than 1 μm. The experimental results also show that implementing the proposed system with a displacement probe is feasible for measuring the straightness error of a workpiece. The proposed method is simple, direct, and effective for measuring the profile of both fixed form and free form workpieces.

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[1] Hewlett Packard Co. Ltd., Product Overview, 2000.
[2] Renishaw Co. Ltd., Performance measurement brochure, 2007.
[3] J. Ni, P. S. Huang, and S. M. Wu, Trans. ASME, J. Eng. Ind. **114**, 362 (1992).
[4] K. C. Fan and M. J. Chen, Precis. Eng. **24**, 15 (2000).
[5] C. H. Liu, W. Y. Jywe, C. C. Hsu, and T. H. Hsu, Rev. Sci. Instrum. **76**, 055110 (2005).
[6] H. Tanaka, K. Tazawa, M. O-hori, and H. Sekiguchi, CIRP Ann. **30**, 455 (1981).
[7] K. Tazawa, H. Sato, and M. O-hori, ASME J. Mech. Des. **104**, 587 (1982).
[8] D. J. Whitehouse, U.S. Patent No. 4,084,324 (1978).
[9] H. Tanaka and H. Sato, Trans. ASME, J. Eng. Ind. **108**, 176 (1986).
[10] E. H. K. Fung and S. M. Yang, Meas. Sci. Technol. **11**, 1515 (2000).
[11] W. Gao, J. Yokoyama, H. Kojima, and S. Kiyono, Precis. Eng. **26**, 279 (2002).
[12] See Piezomechanik GmbH, http://www.piezomechanik.com.