

Estimation of measuring uncertainty for optical micro-coordinate measuring machine

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Based on the evaluation principle of the measuring uncertainty of the traditional coordinate measuring machine (CMM), the analysis and evaluation of the measuring uncertainty for optical micro-CMM have been made. Optical micro-CMM is an integrated measuring system with optical, mechanical, and electronic components, which may influence the measuring uncertainty of the optical micro-CMM. If the influence of laser speckle is taken into account, its longitudinal measuring uncertainty is 2.0 μm , otherwise it is 0.88 μm . It is proved that the estimation of the synthetic uncertainty for optical micro-CMM is correct and reliable by measuring the standard reference materials and simulating the influence of the diameter of laser beam. With Heisenberg's uncertainty principle and quantum mechanics theory, a method for improving the measuring accuracy of optical micro-CMM through adding a diaphragm in the receiving terminal of the light path was proposed, and the measuring results are verified by experiments.

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For the measurements of dimension, shape, and position errors of industrial products, coordinate measuring machine (CMM) is an indispensable tool, which is widely used in manufacturing industry. Statistic data show that 70% measurements of geometrical quantities can be accomplished by CMM. With the development of microfabrication and nanotechnology in the latest decade, the miniaturization of the electromechanical products is becoming a trend, the sizes of which are in the range from several millimeters to several centimeters with tolerance of submicron or nanometer scale. The conventional CMM with larger measuring scale and relatively lower measuring accuracy cannot satisfy the requirements for small sizes and tolerances, so the development of a micro-CMM with an accuracy of sub-micrometer and even nanometer is an urgent affair. For the evaluation of measuring accuracy of micro-CMM, its measuring uncertainty is evaluated in this paper based on the related principle for conventional CMM^[1-3].

There are many factors that affect measuring accuracy of micro-CMM during a measuring process, so the combined measuring uncertainty^[4] is synthesized by the measuring uncertainties of the measured items, which may be estimated by two methods, types A and B, which are defined as the determination of measuring uncertainty components by statistical analysis of measuring data and probability distribution based on empirical or information, respectively. For exactly estimating uncertainty components of all influence factors, the analysis of the relationship between influence factors and measuring results is needed. If all uncertainty components of influence factors are obtained, the uncertainty can be calculated. In general, if quantity y is determined by quantities x_1, x_2, \dots, x_N , namely

$$y = f(x_1, x_2, \dots, x_N), \quad (1)$$

the measuring uncertainty u_c of y is a combined value of

all uncertainty components, which may be expressed as

$$u_c = \sqrt{\sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 (u_{x_i})^2 + 2 \sum_{1 \leq i < j} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \rho_{ij} u_{x_i} u_{x_j}}, \quad (2)$$

where ρ_{ij} is a correlation coefficient between uncertainties of x_i and x_j . If the uncertainties of x_i and x_j are independent, Eq. (2) can be simplified as

$$u_c = \sqrt{\sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u_{x_i}^2}. \quad (3)$$

According to the above principles and based on the uncertainty estimation principle of the conventional CMM, the analysis of measuring errors and the determination of the measuring uncertainty for micro-CMM are carried out. Micro-CMM is a complicated measuring system with optical, mechanical, and electronic elements, so its measuring accuracy is influenced by the optical, electrical, mechanical, and environmental factors. Because most of the measuring uncertainties induced by mechanical, electronic, and optical systems are un-correlated or weakly correlated, Eq. (3) is employed for analyzing and estimating the measuring uncertainty of micro-CMM in this paper.

The measurement of micro-CMM in z direction is performed with laser dot arrays scanning mode and regular-reflective triangulation, whose resolution is higher than the conventional vertical triangulation. It is suitable to measure ultra-precision machined surfaces, micro-electro-mechanical-system (MEMS) devices, linewidth and step height in integrated circuit (IC). Micro-CMM is mainly composed of six parts, as shown in Fig. 1.

Through analyzing the structure of micro-CMM, we can get the measuring uncertainties of the main influence factors as follows. 1) u_1 and u_2 are the measuring

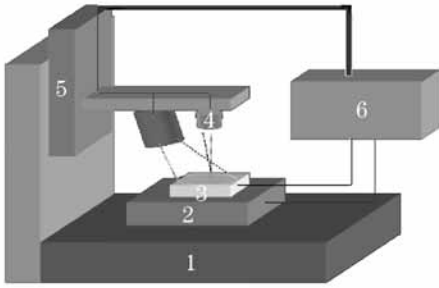


Fig. 1. Schematic diagram of micro-CMM. 1: working bench; 2: macro-driving platform driven by step motors for the larger measuring scale; 3: piezoelectric ceramic micro-driving platform for precision positioning; 4: high accuracy laser displacement sensor and controlling unit; 5: Z stepper and elevator sliding bench; 6: industrial control computer.

uncertainties induced by linear error of motion of step motor and workbench's flatness error, respectively. During measuring, Z step motor is immovable, so we do not consider the linear error of motion of Z step motor. The linear error of X - Y step motors is obtained using the minimum area envelopment method. Through repeated experiments and uncertainty estimation with type A, $0.24\text{-}\mu\text{m}$ uncertainty within $100\text{-}\mu\text{m}$ stroke is gotten. Similarly, the uncertainty induced by workbench is $0.12\text{ }\mu\text{m}$ within $100\text{ }\mu\text{m}$. 2) u_3 is the measuring uncertainty induced by linear error of motion of piezoelectric ceramic, which is $0.32\text{ }\mu\text{m}$ within $100\text{-}\mu\text{m}$ stroke through a number of experiments and type A estimation. 3) u_4 is the measuring uncertainty induced by the repeated positioning error of piezoelectric ceramic, which is 10 nm with type B estimation based on detecting report of the factory. 4) u_5 is the measuring uncertainty induced by fixing squareness error of laser displacement sensor. It can generate measuring error in measuring displacement Δ , which includes tangential and normal errors induced by squareness errors α_{xz} and α_{yz} , respectively. Obviously, squareness error of laser displacement sensor is equivalent to tilting error of object plane, the normal error can be expressed as^[5]

$$\delta\Delta = \Delta \frac{R^2}{a^2} \left(1 + 2 \frac{\Delta}{a} \cos\theta \right) [\tan\theta - \tan(\theta - \beta)], \quad (4)$$

where R and β are the radius of observation lens and the tilting degree of object plane, respectively, a is object distance, θ is the angle of the incident rays with respect to the observation axis. According to type B estimation, when $\alpha_{xz} = \pm 0.5^\circ$, $u(\Delta_{xz}) = 0.7\text{ }\mu\text{m}$; when $\alpha_{yz} = \pm 0.5^\circ$, $u(\Delta_{yz}) = 0.3\text{ }\mu\text{m}$. 5) u_6 is the measuring uncertainty induced by data sampling system composed of opto-electronic converter, signal amplifier, signal filter, analog/digital (A/D) converter and RS232 serial port communication. It is not easy to estimate and has little influence to measurement. Here, we mainly take care of uncertainty induced by A/D conversion. Laser displacement sensor has a minimum resolution of $0.32\text{ }\mu\text{m}$, so the display value appears within interval $[(x_i - 0.32/2), x_i + 0.32/2]$ with equal probability and the uncertainty is $u_6 = (0.32/2)/\sqrt{3} = 0.092\text{ }\mu\text{m}$ according to type B estimation. 6) u_7 is the measuring uncertainty induced by environment. Micro-CMM is located in thermostatic chamber, adopting stable power supply, active

and passive insulating vibration technology to realize vibration insulation effectively, so this uncertainty can be ignored. 7) u_8 is the measuring uncertainty induced by laser speckle. When a laser beam is projected onto object surface, optical field of every point of imaging plane is a convolution of optical fields in small area of object plane according to point expansion function of optical system. If the aperture of illumination lens is bigger than that of observation lens, or surface roughness of object is rough enough in comparison with the laser wavelength, the scattering field of object surface complies with circle complex Gauss distribution. The light wave interference leads to random fluctuation of optical field of imaging points and forms speckle noise, resulting in uneven distribution of intensity of imaging plane, then the measuring uncertainty is brought. According to the limit of diffraction, the diameter of focus beam may be expressed as

$$d \approx \frac{\lambda}{\sin u_i}. \quad (5)$$

When the diameter of laser beam is $d \approx 10\text{ }\mu\text{m}$, the wavelength $\lambda = 670\text{ nm}$, the illumination numerical aperture (NA) $\sin u_i = 0.067$, and the incident angle $\theta = 63^\circ$, the measuring uncertainty induced by speckle can be calculated as^[6]

$$u(\Delta) = \frac{1}{2\pi} \frac{\lambda}{\sin u_i} \frac{1}{\sin\theta} = \frac{1}{2\pi} \frac{0.67}{0.067} \frac{1}{\sin 63} = 1.79\text{ }\mu\text{m}. \quad (6)$$

It is clear that if illumination NA becomes larger and the diameter of laser beam becomes smaller, the uncertainty will be smaller. In addition, the diameter of beam is not a constant within longitudinal measuring range, it will result in some measuring error, but this variation is quite small, the uncertainty can be ignored.

According to the analysis above, we may obtain the combined uncertainties as follows. 1) Taking account of laser speckle, the combined uncertainty of z axis can be calculated by

$$u_c(z) = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 + u_6^2 + u_8^2}.$$

Substituting the items by the values obtained before, we can get $u_c(z) = 2.0\text{ }\mu\text{m}$. If the influence of laser speckle is ignored, the combined uncertainty of z axis $u_c(z) = 0.88\text{ }\mu\text{m}$. 2) The combined uncertainty of x axis may be expressed as

$$u_c(x) = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2}.$$

Substituting the items in the equation by the corresponding values, we can get $u_c(x) = 0.42\text{ }\mu\text{m}$. Similarly, we can get the combined uncertainty of y axis, that is, $u_c(y) = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2} = 0.42\text{ }\mu\text{m}$.

In order to prove the estimation of uncertainty validity and calibrate micro-CMM, the measuring standard reference material (SRM) was adopted and the results measured by micro-CMM and scanning electron microscope (SEM) were compared. SRM was fabricated by micromachining technology, which has a series of grooves and steps with different amplitudes and wavelengths on

a silicon wafer by dry etching technique.

Figure 2 is a photograph of SRM under optical microscope. Figures 3 and 4 are two section profiles measured by SEM (JSM-6460, JEOL, Japan) and micro-CMM, respectively. Through comparison of these two figures, we can see the influence of laser beam. The laser beam has an area-averaging effect which affects the lateral resolution of measuring system, and causes perpendicular edge

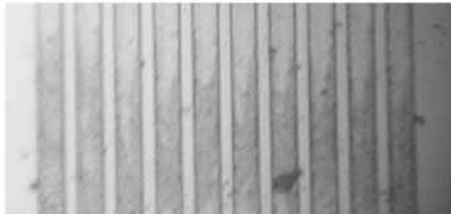


Fig. 2. Planar photograph of SRM observed under optical microscope.

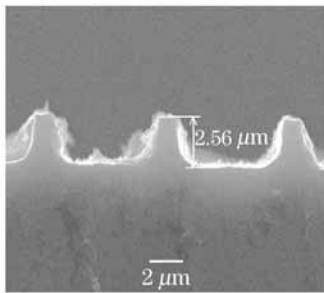


Fig. 3. Measurement of SRM measured by SEM.

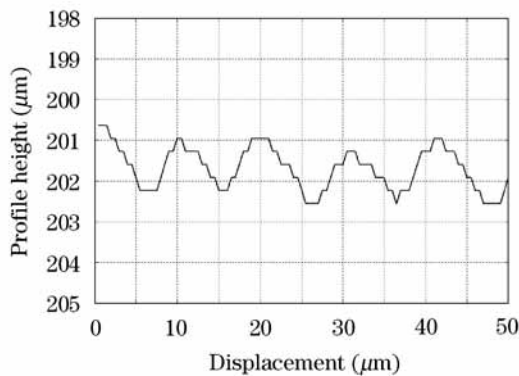


Fig. 4. Measurement of SRM measured by micro-CMM.

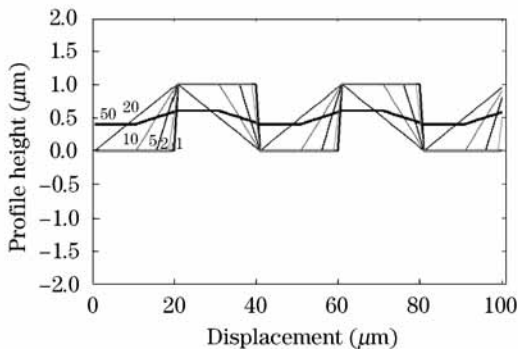


Fig. 5. Simulation results of influence of diameter of laser beams. Curves represent the results for beams with different diameters, “1” stands for one length unit.

of steps and grooves becoming slope edge, and makes widths of grooves become small, but it has a little influence on pitch measurement. This results measured by micro-CMM agree well with the simulation results of laser beam influence shown in Fig. 5. It is clear that the measuring result has larger distortion with larger beam diameter. The step height is $1.69 \mu\text{m}$ measured by micro-CMM, and $2.56 \mu\text{m}$ by SEM. Through numbers of experiments and data processing, we obtained the uncertainty of $0.79 \mu\text{m}$. This value is smaller than the uncertainty of $0.88 \mu\text{m}$, which was calculated under the condition of ignoring influence of laser speckle. In fact, we can find that surface of SRM fabricated through dry etching is smooth from SEM photograph. According to Fig. 3, the surface roughness $R_a=1.0 \mu\text{m}$, and the wavelength is $0.67 \mu\text{m}$, so it does not satisfy the condition^[7] that roughness adequately bigger than wavelength and cannot cause laser speckle, thus the influence of speckle can be neglected. The pitch is 10.56 and $11.2 \mu\text{m}$ measured by SEM and micro-CMM, respectively. The uncertainty is $0.52 \mu\text{m}$, which is less than the expansion uncertainty of $0.84 \mu\text{m}$ when $u_c(x) = 0.42 \mu\text{m}$ and $k = 2$.

In general, object surface is a random rough surface. When rays are projected onto the surface, the reflect rays include regular-reflective rays and stray rays. The stray rays will degrade the signal-to-noise ratio (SNR) and bring harmfulness to measurement. The stray rays mostly include multi-reflective rays coming from lens, especially the second reflective rays, scattered rays coming from edge of lens, and other stray rays from environment. All these rays reach into detector and produce an additional light intensity distribution which reduces the contrast of imaging plane and limits the resolution of measuring system. In order to overcome this optical deflection, an aperture diaphragm is added, which exactly locates at the front focus plane of observation lens. The aperture diaphragm has two functions: filtering the diffusion reflective rays for improving imaging quality and enhancing the resolution of measuring system, and forming an “imaging deep light path” which enlarges the depth of focus and improves measuring accuracy. The possible loss of light energy caused by the diaphragm should be paid attention to. Therefore, the adaptive gain module in laser displacement sensor to ensure reliable imaging should be adopted. Adding an aperture diaphragm in receiving terminal can filter stray rays and thus improve the SNR of receiving rays, as shown in Fig. 6. According to quantum mechanics, the reciprocal value of SNR of measuring system is equal to $1/\sqrt{n}$, where n is the number of photons arriving at detector. Falconi^[8] gave the formula of the uncertainty of position of imaging points on detector

$$u(\delta) = \frac{1}{\sqrt{n}} \times \frac{1}{2\pi} \times \frac{\lambda}{\sin u}, \tag{7}$$

where $\sin u$ is the NA of observation lens, λ is laser wavelength. If the SNR is improved, the uncertainty of position of imaging points will reduced, and the measuring accuracy will be enhanced. Figure 7 is the profile of a standard gauge block measured with aperture diaphragm, and the profile in Fig. 8 was measured without

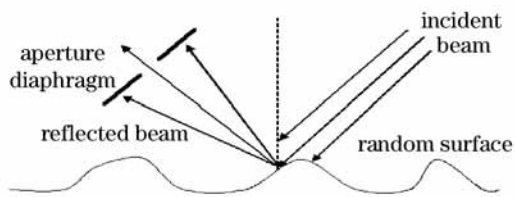


Fig. 6. Schematic of adding an aperture diaphragm in receiving terminal.

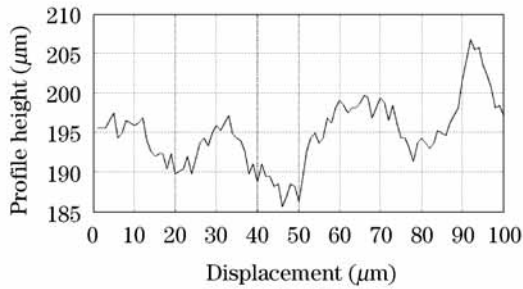


Fig. 7. Measuring result of gauge block surface through adding an aperture diaphragm.

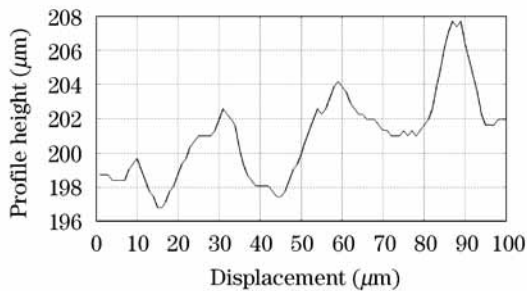


Fig. 8. Measuring result of gauge block without aperture diaphragm.

aperture diaphragm. In the former, one can distinguish more fine structure.

Through analysis and estimation of measuring uncertainty of three dimensions for micro-CMM, the mea-

suring uncertainty of z axis is $1.71 \mu\text{m}$ considering the laser speckle and $0.88 \mu\text{m}$ without considering laser speckle. The experimental results show that speckle is a prominent factor, which affects measuring accuracy in laser measurement, and some effective methods to reduce speckle should be adopted. Domain averaging annealing^[9] and aperture internal scanning^[10] are potential methods. Fitting the gray distribution of image-spot with multinomial, and calculating the gray gravity center for determining precision location of imaging points, we can make the resolution reach sub-pixel and improve the measuring accuracy. It was proved that the estimation of measuring uncertainty for micro-CMM is valid through measurement of SRM and simulation experiments.

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