New probing system for the nano-CMM using radiation pressure controlled microsphere

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Abstract
The circular motion probe is proposed as a new probing technique for the nano-CMM. The performances of simultaneous detection of both a position and a normal vector based on change of the elliptical orbit of the micro probe sphere are investigated experimentally. A potentiality of the circular motion probe to establish the advanced coordinate measurement of microparts is suggested by the measurement of a standard glass microsphere.

Keywords: Microprobe, radiation pressure, nano-CMM, microparts

1. Introduction
In order to assess geometrical quantities of three-dimensional (3D) shape of micro-scale components, such as dimension, size, form, orientation, location and so on, a nano-CMM (Coordinate Measuring Machine) is required to be used for coordinate metrology with nanometer order accuracy. Since a microprobe as well as the nano-CMM should be designed to satisfy such the harsh specifications as shown in Table 1, it is the most critical element to establish the nanoCMM. Therefore, to develop a new probing system with a micro probe sphere, we have been investigating the laser trapping probe [1, 2] whose principle is based on the single-beam gradient-force optical trap [3] of a micrometer size probe sphere and the vibration probing technique [4, 5, 6]. As matters relevant to the subject of making the laser trapping probe to be available in manufacturing environment, we focus our argument on the elemental properties, that is, one is trapping a probe sphere in air and the other is decreasing measurement uncertainty concerned with probing.

Table 1. Principal performance required to nano-CMM and microprobe.

<table>
<thead>
<tr>
<th></th>
<th>Measuring range</th>
<th>10 mm³</th>
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<tbody>
<tr>
<td></td>
<td>Resolution</td>
<td>10 nm</td>
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<tr>
<td></td>
<td>Accuracy</td>
<td>50 nm</td>
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<tr>
<td>Nano-CMM</td>
<td>Probe sphere diameter</td>
<td>10 μm</td>
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<td></td>
<td>Probe sphere sphericity</td>
<td>10 nm</td>
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<td></td>
<td>Sensitivity</td>
<td>10 nm</td>
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<td></td>
<td>Measuring force</td>
<td>10⁻⁶ N</td>
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<tr>
<td>Microprobe</td>
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</table>

We employ an optically trapped spacer silica particle with the diameter of 8 μm in air as the probe sphere, which has a low spring constant of about 10⁻⁵ N/m. It is forced to vibrate with several hundreds nanometer amplitude by the laser beam scanning method. Moreover, the nano-CMM using the optically vibrated microprobe is developed and the feasibility is indicated by fundamental measurement experiments [7]. On the other hand, it is difficult for the microprobe to find direction of detected surface exists because of its micro size. This generally brings about an error in the compensation of the probe sphere radius, which results

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in degradation of measurement accuracy. To overcome this problem, the circular motion probe is proposed [8]. In this paper, the performances to detect position and normal vector direction are examined experimentally.

2. Principle of circular motion probe

The principle of simultaneous detection of both a position and a normal vector is based on change of the orbit of the micro probe sphere to which circular motion in the plane perpendicular to the optical axis (XY-plane) is provided. When the circular motion probe approaches a work surface, the orbit of the probe motion is compressed perpendicular to the surface, resulting in an elliptical orbit, as shown in Fig. 1. Using probe signal in detection of the probe motion, the major and minor axes of the elliptical orbit are determined. The length of the minor axis, that is \( A_{\text{min}} \) indicated in Fig. 1, decreases with the distance between a probe sphere and a work surface due to compression of the ellipse. The position of a point on the work surface can be detected by monitoring \( A_{\text{min}} \). In addition to the length, the direction of the minor axis corresponds to the direction of the normal vector to the work surface. Then, the normal vector at the detected point is found by tracking the rotated angle with respect to \( A_{\text{min}} \).

![Fig. 1. Principle of position and normal vector detection of work surface.](image)

The probe signal is processed to obtain the length and the angle of the minor axis as follows;

1. The probe signal for the initial probe motion in circular orbit is detected as oscillating signals \( x \) and \( y \) along the \( x \)-axis and \( y \)-axis, as indicated in Fig. 1.

2. The amplitudes \( A_x \), \( A_y \) and the phase lags \( \phi \) between two oscillating signals are obtained from the oscillating signals along the \( x \)-axis and \( y \)-axis using a lock-in amplifier.

3. The minor axis angle \( \theta \) is calculated using the following equation:

\[
\theta = \frac{1}{2} \tan^{-1} \frac{2A_x A_y \cos \phi}{A_x^2 - A_y^2} \quad (1)
\]

4. The oscillating signals \( x, y \) are transformed into oscillating signals \( x', y' \) based on the rotation matrix \( R_\theta \) as:

\[
\begin{pmatrix} x' \\ y' \end{pmatrix} = R_\theta \begin{pmatrix} x \\ y \end{pmatrix}, \quad R_\theta = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}
\quad (2)
\]
(5) The amplitudes $A_x'$ and $A_y'$ are obtained from the signal $x'$ and $y'$. Then, the minor axis length $A_{\text{min}}$ is determined as the amplitude $A_y'$.

(6) A position of a work surface is sensed when $A_{\text{min}}$ drops to a predetermined level. At the same time, the normal vector angle at the detected position can be obtained from the minor axis angle calculated using equation (1).

3. Experimental setup

The optical system arrangement is illustrated in Fig. 2(a). The light source used for trapping the probe is a Nd:YAG laser ($\lambda=1064$ nm, CW mode, linear polarization). The beam diameter of the laser is expanded using a relay lens unit to have the same diameter as the entrance pupil of an objective lens (100×, 0.95 N.A. and W.D. 0.3 mm). After passing through a beam splitter, it reaches the objective lens and a silica microsphere with a diameter of 8 µm is trapped at the focal spot of the laser beam. The acousto-optic deflector (AOD) deflects the propagating direction of the laser beam for the probe oscillation. In order to acquire the position of the probe, a He-Ne laser light ($\lambda=632$ nm) illuminates a probe sphere. Light backscattered from the probe sphere is delivered to a position sensitive detector (PSD) that detects the spot position on the detector plane. For precise measurement, lock-in detection is applied, so that the probe signal from the PSD is processed with the oscillating signal feed to the AOD. Setting of a work and initial positioning of the probe sphere to the work are done with assistance of microscopic observation as shown in Fig. 2(b).

![Fig. 2. Schematic diagram of the experimental setup;](image)

(a) Optical system, (b) Work and probe approach.

![Fig. 3. Orbital change of the probe motion near a surface.](image)

4. Fundamental properties of circular motion probe

The orbit of the circular motion probe changing near the cleavage surface of an as-cleaved silicon wafer (Fig. 2(b)), which has the smoothness of atomic level, is examined. In a few micrometers before the probe contacts the work surface, the amplitude of the perpendicularly oscillated probe to the work surface is damped more than the parallel-oscillated probe [9]. This implies that the circular motion of the probe is compressed into an elliptical motion near the surface. The measurement result of the orbital change of the circular motion probe is shown in Fig. 3. An oscillating frequency of 1800 Hz and an amplitude of 500 nm are used as oscillation conditions. The measured distance between the probe and the surface is set at 4 µm (near contact), 5 µm, 7 µm, and far from the surface respectively, where the probe radius is 4 µm. While approaching to the work surface, the ellipticity in the orbit compressed perpendicular to the surface is getting more and more obvious. It is also confirmed that the direction of the minor axis on the elliptical orbit keeps the normal direction of the surface.
To investigate the resolution of the position sensing, the minor axis length of the elliptical orbital is measured at intervals of 50 nm. For each plot, data is taken 50 times and the mean value and standard deviation are calculated. Fig. 4(a) shows that the minor axis length as a function of the distance between the probe and the surface in about 5 μm from the initial position. Fig. 4(b) shows the detail in the vicinity on the work surface. The gradient indicates the sensitivity of the probe for position detection. The minor axis length decreases to 57 nm with an approach distance of 1.1 μm. Thus this probe performs with a sensitivity of 0.018 μm/nm and the standard deviation of the minor axis length is 1.1 nm. Therefore, the resolution of position detection estimated based on the obtained gradient and standard deviation is approximately 39 nm in this study.

![Diagram showing minor axis length changing with probe traveled distance near a work surface](image)

**Fig. 4.** Minor axis length changing with probe traveled distance near a work surface; (a) Plots of minor axis length and distance, (b) Change of minor axis length near the work surface in several hundreds nanometer.

The performance for the normal vector sensing is examined by measuring the surface inclination. As a work, the tilted cleavage surface at various angles: 1°, 12°, 23°, 32° and 43° is used. The given tilt angle α is estimated by image processing using microscopic CCD images, as shown in Fig. 5. Fig. 6 shows the measured minor axis angle θ while the probe approaches the surface in the x-direction. The data is acquired at intervals of 50 nm. For each probing, the error is within a few degrees. It is thus experimentally proved that the circular motion probe has an ability to measure the normal vector of the work surface with an accuracy of a few degrees.

![Diagram showing inclination angle and experimental setup](image)

**Fig. 5.** Experimental arrangement of probe approaching to a work with inclination angle.

![Diagram showing measurement results of minor axis angles](image)

**Fig. 6.** Measurement results of minor axis angles of the elliptical probe motion.
5. Measurement of a standard glass microsphere

In order to verify the feasibility of the circuler motion probe, the measurement of a position with a normal vector is carried out using a standard glass microsphere (Duke Scientific) which has the NIST traceable diameter of 168 μm with the standard deviation of 8 μm. Fig. 7 shows experimental arrangement of the probing with the work. The probe approaches the work in the y-direction on an arbitrary z-plane near the center of the sphere with the speed of 42 nm/s. Measurement results of the coordinates and the normal vector angles are shown in Fig. 8. Most of all positions on the sphere surface can be detected without deviations depending on probing direction to the surface. The measured normal vector angles agree well with the angles which are calculated from the regression circle base on measured coordinates. Consequently, the circuler motion probe has a potentiality to establish the advanced coordinate measurement of microparts using the nano-CMM.

![Image](image_url)

Fig. 7. Experimental arrangement of the probe sphere approaching to a glass microsphere.

![Image](image_url)

Fig. 8. Measurement results of the coordinates and the normal vector angles of the glass microsphere.

6. Conclusion

In this paper, a novel probing technique for a nano-CMM using the circular motion of an optically trapped microsphere has been described. In order to verify the validity of the circular motion probe, measurements of the position and the normal vector of a cleavage surface are performed. It is suggested that the circular motion probe can detect a position of the work surface with a resolution of 39 nm and can simultaneously measure the normal vector with an accuracy of a few degrees. Moreover, a potentiality of the circuler motion probe is demonstrated by the measurement of a standard glass microsphere with the NIST traceable diameter of 168 μm.

References