XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

LASER TRAPPING MICRO-PROBE FOR NANO-CMM

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Abstract: Nano-CMM is required to evaluate tolerance and dimension of the component parts of micromachines by coordinate measurement of submillimeters size 3-D shapes. This paper discusses a micro-probe technique for the nano-CMM, the so-called laser trapping micro-probe. The principle to detect a three dimensional position is based on the nature of an optically trapped particle and interferometer method. An optically trapped silica particle in air is used as a micro-probe sphere. Practical positional detection method is established based on experimental analysis of fringe intensity changes while a probe sphere is approaching to a workpiece. Measurements of a glass microsphere used as particle size standards is demonstrated to verify the validity of the laser trapping micro-probe. Measurement results show that the laser trapping probe has a possibility to measure submillimeters size 3-D shapes of such as microparts.

Keywords: Microparts, Laser trapping, Nano-CMM probe

1 INTRODUCTION

Microfabrication or micromachining technology has been steadily improving as photolithography technology enhanced or modified for creating small three-dimensional (3D) structures with dimensions ranging from millimeters to submicrometers has matured. To obtain and maintain compatibility of standardized microcomponents in practical use it is necessary to evaluate geometrical quantities of micromachined 3D shape with manometer order accuracy in microfabrication systems. The nano-CMM (Coordinate Measuring Machine) [1] is proposed to use for coordinate metrology of microparts. However, to establish it a positional sensing probe with satisfying sensitivity of higher than 10 nm and measuring force of less than 10^{-5} N must be developed. We have been developing the new probe technique for the nano-CMM, that is called the laser trapping micro-probe [2, 3] whose principle is based on single-beam gradient-force optical traps [4] of a small particle and microscope interferometers.

In this paper, fundamental characteristics on the practical positional detection based on an intensity change of the fringe generated by Linnik interferometer are demonstrated. Using the experimentally introduced positional detection method, the measurements of a glass microsphere with NIST traceable mean diameter are performed. The measuring results show the validity of the laser trapping micro-probe as positional sensing probe for the nano-CMM.

2 PRINCIPLE OF LASER TRAPPING MICRO-PROBE

The principle of the probe is based on an optically trapped small dielectric particle and Linnik interferometer for detecting a displacement of a probe sphere. Figure 1 shows dynamical behavior of an optically trapped small dielectric particle used as a probe sphere. As an initial state, a probe sphere retains a stable position under application of trapping force F_t that is the resulting force of all radiation pressures f_i produced by focused laser beam, as shown in Figure 1(a). If some external force F_e applied to the probe sphere (Figure 1(b)), then the balance is broken dynamically and the probe sphere begins to shift. At this moment, the trapping force changes with the radiation pressure distribution depending on the illumination conditions for the probe sphere position. When F_e is released (Figure 1(c)), the probe sphere is accelerated in the direction of the original position and is finally recovered to the initial stable position precisely. As discussed above, an optically trapped small dielectric particle acts as a probe sphere, which is sensitive to external force given by interactions with a workpiece. Positional detection is determined with the shift Δ of a probe sphere caused by the external force F_e as shown in Figure 2. Actually, detecting displacement δ on the probe sphere's top surface enables us to notify a shift Δ, for example typical translation from Δ to δ at the point P_o is shown in Figure 2(a) and (b) in case of the probe approache in vertical or horizontal direction. In general, it is illustrated in Figure 2(c) that a shift Δ in an arbitrary direction is detectable as displacement δ' at a point P' on the top surface of the probe sphere. Non-contact sensing of this displacement δ’ is performed using Linnik interferometer that generates a fringe pattern changing with a displacement. Moreover, employing full information included in the fringe pattern reflecting a displacement at not just one point but everywhere on a probe sphere’s top surface, it promises to attain high sensitivity required to a positional sensing probe for the nano-CMM. Figure 3 shows the fundamental configuration of Linnik type microscope interferometer. A beam-splitter divides the wave from the light source into two, one segment traveling to the left and one downward. Each wave passes through an object lens which have almost the same optical quality as another one. The part of the wave passing through the left object lens is reflected by a reference mirror and deflected by the beam-splitter toward the detector. And the part of the wave passing through the down object lens is reflected by a probe sphere's surface and passes through the beam-splitter again. Thus the two waves are united and a concentric circular fringe pattern is produced on the detector.

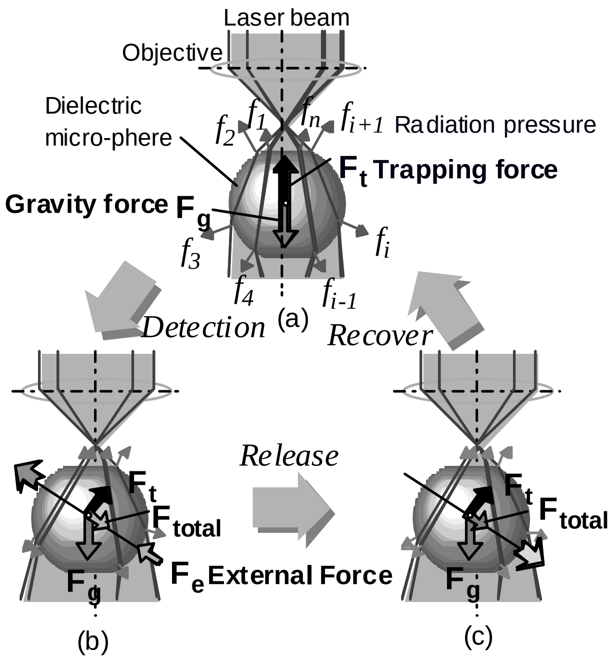


Figure 1. Dynamical behavior of laser trapping micro-probe

3 MEASUREMENT SYSTEM AND WORKPIECE

Figure 4 represents the schematic diagram of the measurement system specifically designed for trapping a particle in air, observing the trapped particle and measuring the fringe pattern. In addition, The main specifications of the principal components and glass microspheres used for a workpiece are listed in Table 1. The system is composed of the laser trapping optical system with the Q-switch/Nd: YAG laser with wavelength of 1064nm, the Linnik type microscope interferometer consisting the microscope objective with numerical aperture (N.A.) of 0.95 and the xyz-stage with positioning accuracy of 5nm, which is driven by PZT actuators. The YAG laser beam is deflected by a dichroic mirror toward a microscope objective, then focused to a silica particle used as a probe sphere. It has certified diameter of about 8μm and highly accurate sphericity. The silica particles scattered on a glass plate are firmly adhered to the surface by affection of adsorption. So, it is necessary to break the

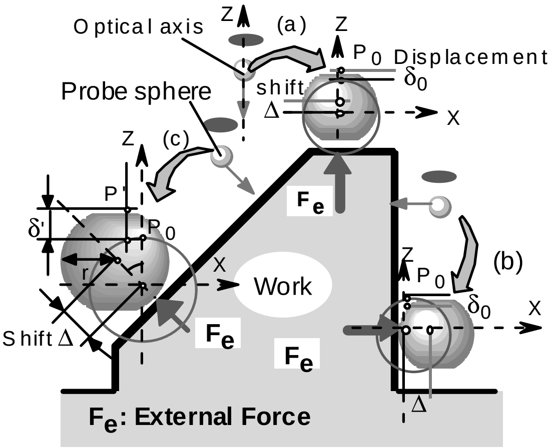


Figure 2. Shift ofprobe sphere by interaction between probe and work

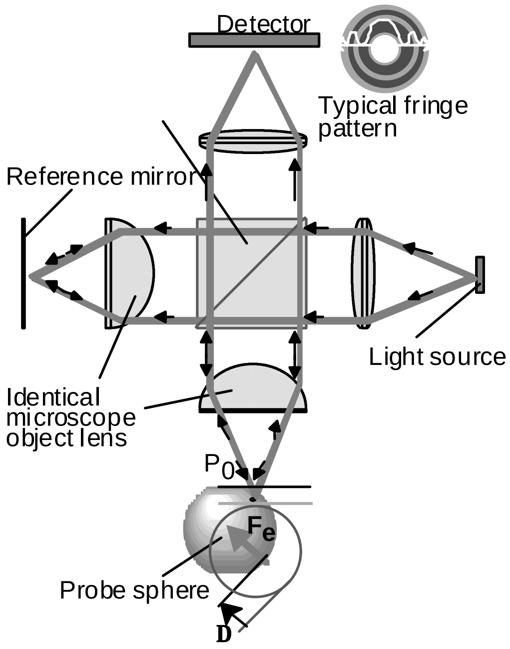


Figure 3. Configuration of Linnik interferometer

adsorption with concentrating high energy of Q-switch pulse emission, an average power of 3.6 W. After releasing the silica particle from the adsorption, it is levitated with radiation pressure produced by reflection from the glass plate. Once the silica particle is levitated in air, it is possible to keep a stable position even if laser emission mode is switched from Q-switch pulse emission mode to CW emission mode with low power of less than 100mW. A He-Ne laser with wavelength of 633 nm is utilized as the interference light source. The beam travels through an optical fiber and is deflected by a cube beam-splitter. A dichroic mirror divides the wave into two, one segment traveling to a reference mirror with flatness of 1/10 of wavelength and the other to the probe sphere. The reference mirror is positioned using a PZT stage with the same positioning accuracy as the xyz-stage. The top view of a trapped probe sphere is obtained using a microscope component with the magnification rate of 500X at a CCD area sensor. This magnification rate is high enough to measure the fringe spacing with satisfying the resolution. The fringe image data detected by the CCD area sensor is processed by a personal computer with an image memory. Manipulation of the probe is observed using the microscope unit in the lateral direction. The workpieces are uniform glass microspheres with calibrated mean diameters 168 ± 8.48 μm traceable to the Standard Meter through the National Institute of Standards and Technology (NIST). The probe position is fixed and approaching to a workpiece is performed with relative movement given by the xyz-stage on which the workpiece is set.

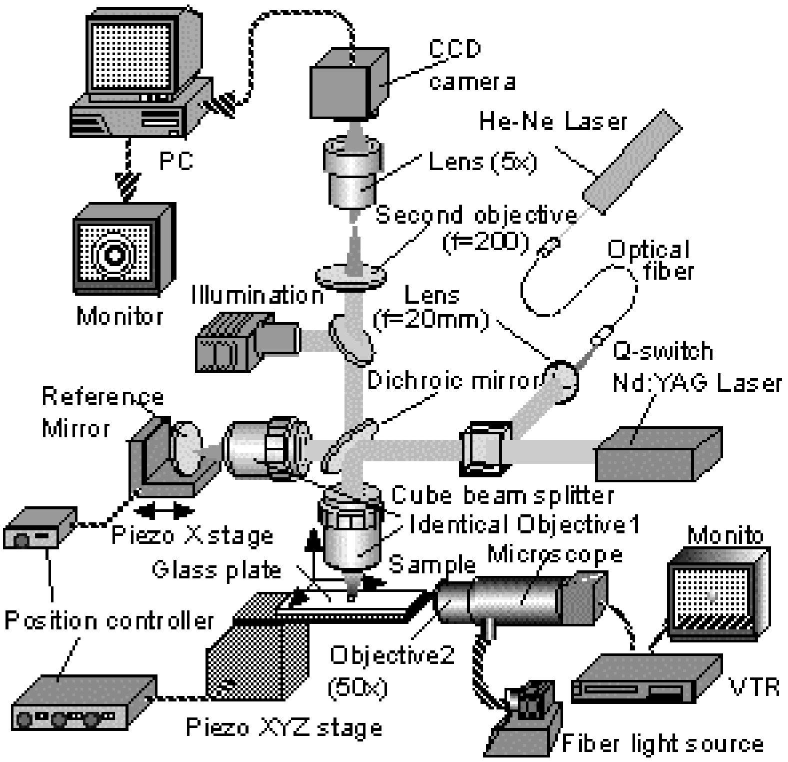


Figure 4. Schematic diagram of laser trapping probe experimental

4 CHARACTERISTICS OF FRINGE INTENSITY CHANGE

To investigate optical properties of the fringe pattern induced by Linnik interferometer, fundamental experiments to measure the fringe intensity changing with a shift of the reference mirror and a probe sphere are carried out.

Figure 5 shows a typical fringe pattern observed when a probe sphere is at a stable position. A concentric circular pattern is formed. This pattern is caused by initial optical path differences between the reference mirror surface and the probe sphere surface, which is determined by the surface profile of the probe sphere. As indicated in the magnified picture in Figure 5, the intensity distribution for the cross section in the radial direction repeats bright and dark such as the first bright (B1) and the second dark (D2). In order to measure the fringe intensity without errors caused by noises and fluctuation, the normalized intensity I (%) is introduced. Intensity level is determined by a percentage such as a maximum peak intensity I_{max} of 100 and minimum peak intensity I_{min} of 0, that is, I (%) is given by,

$$I_{\%}= (I - I_{min})/ (I_{max}-I_{min}) \qquad (1)$$

Figure 6 (a) shows the experimental procedures for checking how fringe intensity follows a shift of the reference mirror and the probe sphere. Part A and Part B of Linnik interferometer in Figure 6(a) illustrate the situations mentioned below. The fringe intensities of B1 and D2 are measured with giving a displacement by 20nm step up to 500nm to the reference mirror or the probe sphere fixed onto the glass plate surface set on the xyz-stage. A probe sphere is adjusted at the initial position while the fringe intensity change depending on the reference mirror is measured, and vice versa. The reference mirror moves in the x-direction and the probe sphere in the z-direction. Figure 6 (b) and (c) show the

Table 1. Experimental conditions

Objective 1 (100X) (Nikon CF IC EPI Plan)	N.A. W.D. Focal length	0.95 0.30 mm 2.00 mm
He-Ne Laser (interferometer light source)	Wave Length Power (max)	633 nm 30 mW
Q-swich/Nd:YAG Laser (laser trapping light source)	Wave Length Power (max) Peak power (max): Q-switch puls mode	1064 nm 15 W 50 kW
Probe sphere (Spacer silica for LCD)	Material Mean diameter Standard deviation Refractive index Density	Silica 7.99 µm 0.1 µm 1.44 2.0 g/cm^3
Piezo XYZ stage: Workpiece Piezo X stage: Reference mirror	Resolution: Feedback piezo actuator	5 nm
Glass microsphere: NIST traceable mean diameter (Workpiece)	Material Certified mean diameter Standard deviation Refractive index Density	Soda lime glass 168 ± 8.4 µm 7.5 µm 1.51@589nm 2.42 g/cm^3

measurement results of the intensities changing with a x-position of the reference mirror and with a z-position of the probe sphere, respectively. In Figure 6 (b), both of B1 and D2 repeat peak and valley with a shift of the reference mirror. Based on theoretical consideration of an optical path difference, the intensity change meets the turning over from bright (dark) to dark (bright) in the interval of about 158 nm, that is, 1/4 of wavelength. The turning over follows the optical path difference approximately near a focal point but becomes a little bit shorter as far from the focal point. These results show that the reference mirror should be adjusted near the focal point for obtaining the fringe pattern approximately changing with the optical path difference. On the other hand, the fringe intensity changing with a shift of the probe sphere reaches the turning over in the interval longer than the theoretical optical path difference as shown in Figure 6 (c). This difference results from oblique incidence illumination to the spherical surface adding to an effect of numerical aperture [5]. However, the fringe intensity changes with the shift of the probe sphere without irregularity. Using this characteristic of a fringe intensity change, it is possible to detect positions by sensing the shift of a probe sphere caused by external force with the interactions between a probe sphere and a workpiece.

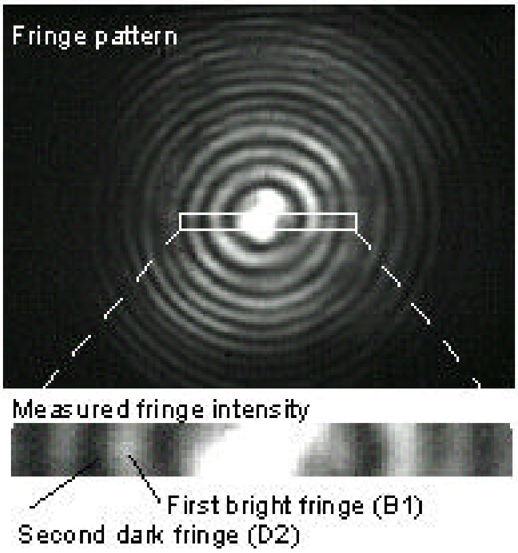
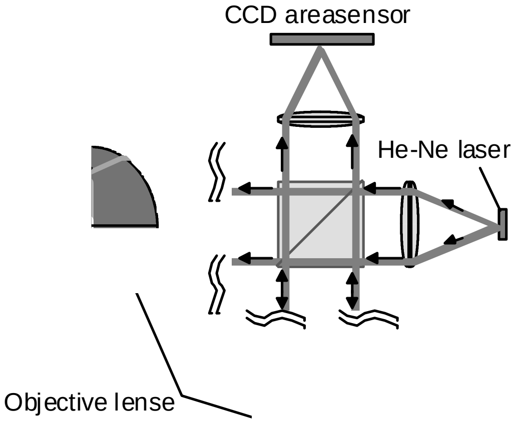
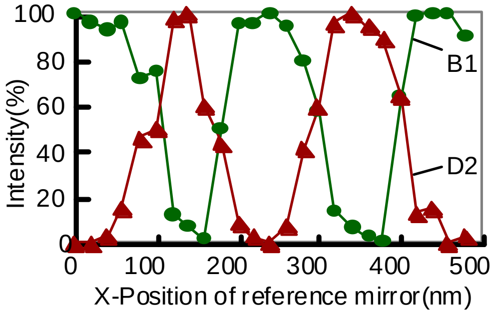


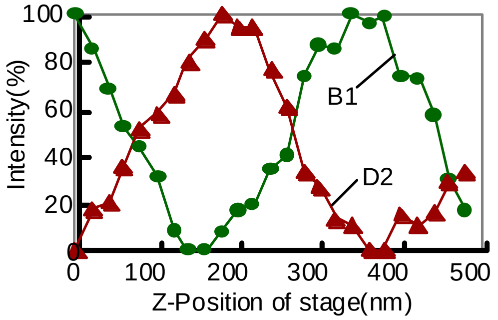
Figure 5. Fringe pattern for probe sphere at stable position



(a) Changing reference mirror position in Part A and probe sphere position in Part B.



(b) Change of fringe intensity with reference mirror.



(c) Change of fringe intensity with probe spherer.

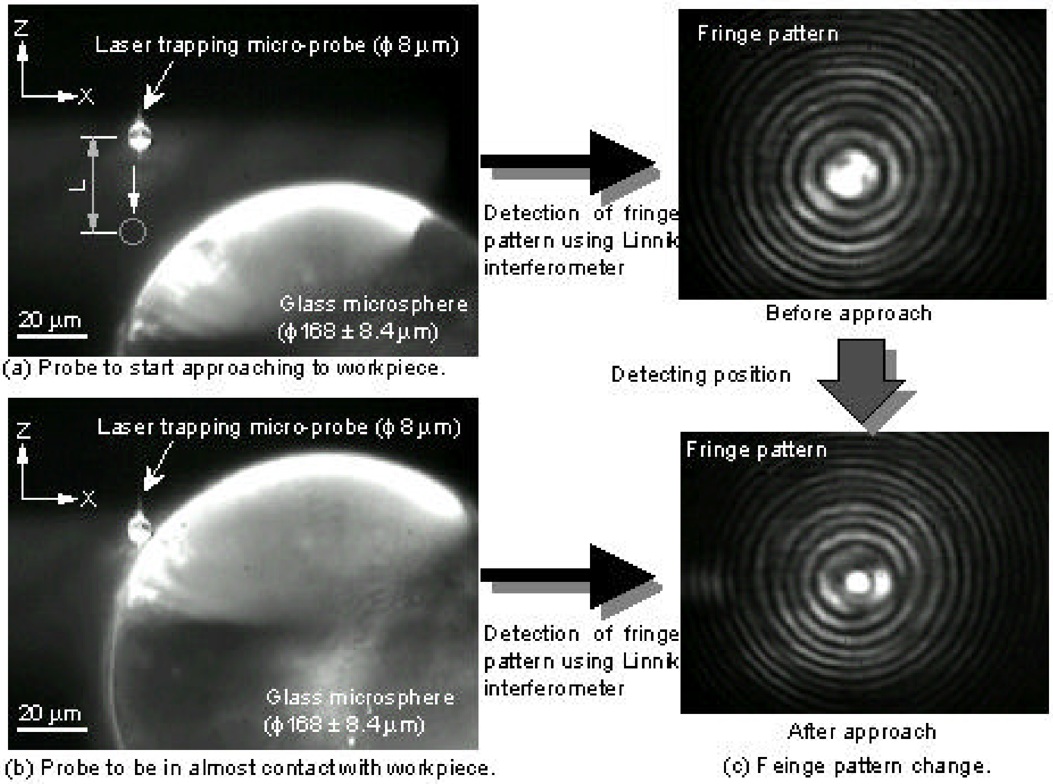
Figure 6. Fringe intensity measurements generated by Linnik interferometer.

5 PRACTICAL POSITIONAL DETECTION

It is successfully achieved that a probe sphere is trapped in air and the fringe pattern is generated together with it. Using this probe, the fringe properties with probe access to a workpiece is experimentally investigated. To verify the validity of positional detection based on a fringe change, a glass microsphere used as particle size standards is measured.

5.1 Positional detection based on fringe intensity change

The fringe properties show that the fringe intensity changes with a shift of the probe sphere and reach the turning over at a z-directional displacement between 150 and 200 nm. If any external force acts on a probe sphere at a nearest position to a workpiece including contact, it is expected to catch the turning over of the fringe intensity with a shift of a probe sphere. The fundamental experiment is carried out to find the fringe properties with a probe approximating to a workpiece. Figure 7 shows the microscopic images of the three-dimensional trapped probe sphere in air and the approach to the glass microsphere with the corresponding fringe patterns. The probe is given in the z-directional approach to the glass microsphere as shown in Figure 7 (a). When the probe sphere is the very nearest position to the glass microsphere as shown in Figure 7(b), the fringe intensity meets the turning over as indicated in Figure 7(c). The initial position is set to be about 20 µm away from the glass microsphere surface and the first bright fringe intensity B1 changing with a distance L from the initial position is measured. As indicated in Figure 8 showing the measurement results, the normalized intensity decreases steadily from near L=10 µm as the probe loses the remainder of a distance to contact with the surface. And finally the intensity touches a bottom at about L=18 µm and at this moment the probe sphere displaces more than 158 nm. Assuming unidentified short-range force giving a displacement to the probe sphere with an interaction between a probe sphere and a workpiece, these fringe properties make it possible to establish non-contact sensing of a position. Consequently, the laser trapping micro-probe can detect a position based on fringe intensity change such as the turning over of the first bright fringe.



(a) Probe to start approaching to workpiece.

(b) Probe to be in almost contact with workpiece.

(c) Feinge pattern change.

Figure 7. Fringe pattern change while being close to workpiece

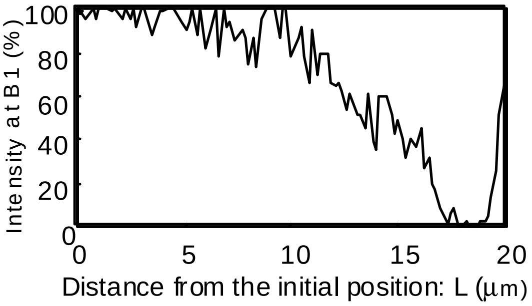


Figure 8. Measurement results of fringe intensity change

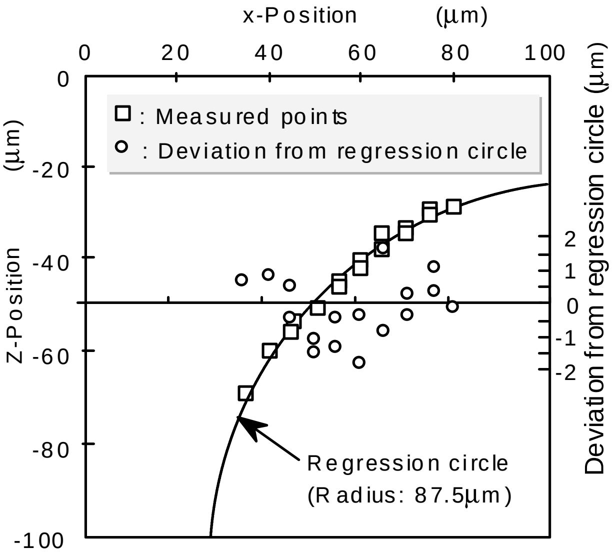


Figure 9. Measurement results of glass microsphere using laser trapping micro-probe

5.2 Measuring experiment

Based on the principle to detect a position, the coordinate measurement of the maximum cross section is carried out using a standard glass micro-sphere with the specifications shown in Table 1. Each position is measured twice by probing in the z-direction. Because of restrictions for microscopic observation and probe operation, the measuring region is limited to a quarter part of the sphere. Figure 9 shows the measured point data plot, the regression circle calculated using least square method and deviations of individual measured point from the regression circle. The radius 87.5 μm of the regression circle agrees with the nominal radius of 84 ± 4.24 μm within uncertainty. Moreover, the mean deviation of 0.005 μm is obtained and we found that the measured points are fairly fitted to a circle. Therefore the measurement result suggests that the laser trapping micro-probe has a potentiality as a positional sensing probe for the nano-CMM with high sensitivity.

6 CONCLUSIONS

To establish the laser trapping micro-probe for the nano-CMM, the characteristics of the fringe pattern generated by the Linnik interferometer and the positional detection method using an optically trapped probe sphere in the atmosphere are studied experimentally. The fringe intensities change with a shift of the reference mirror and the probe sphere. When the probe sphere displaces more than 158 nm the fringe intensities turn over from bright (dark) to dark (bright). A displacement of the probe sphere caused by an external force with the interaction between the probe sphere and the workpiece can be detected using the fringe intensity change. Measurement results of the fringe intensity while the probe accesses to a workpiece show that the laser trapping micro-probe enables non-contact sensing of a position based on the turning over of the first bright fringe. Using this experimentally introduced positional detection method, measurements of a glass microsphere with NIST traceable mean diameter of 168 ± 8.48 μm are performed. The measured points are fairly fitted to the regression circle within the mean deviation of 0.005 μm and the radius 87.5 μm of the regression circle agrees with the nominal radius. These results demonstrate a potentiality of the laser trapping micro-probe as a positional sensing probe for the nano-CMM.

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