THE MICROPROBE FOR NANO-POSITIONAL DETECTION USING OPTICALLY FORCED VIBRATION METHOD

Y. TAKAYA, M. NISHIKAWA, S. TAKAHASHI and T. MIYOSHI
Osaka University, 2-1 Yamadaoka Suita, 565-0871 Osaka, JAPAN

1. INTRODUCTION

As seen in various type of microsystems such as micromechanical system, microoptical system, three-dimensional LSI, MEMS(Micro-Electro-Mechanical System), MOEMS(Micro-Opto-Electro-Mechanical System), technical trends of microfabrication include increasing diversification and complexity of processes, combination of different processes, and multifunction. In contrast, quantitative evaluation technique of geometrical quantities such as size, dimensions, and tolerances has not been established yet. The establishment of assessment technologies for three-dimensional micromanufacturing accuracy is an urgent issue.

To assess geometrical quantities of micromachined 3-D shape based on coordinate metrology with nanometer order accuracy, nano-CMM [1] as a three dimensional coordinate measuring machine with the measuring range of mm and accuracy of nm order. As the microprobe satisfying harsh requirements for nano-CMM, we have been developed the laser trapping probe [2] [3] whose principle is based on the single-beam gradient-force optical trapping technique [4] and the Linnik type microscope interferometer. We employ an optically trapped 8µm spacer silica particle as the probe sphere, which has a low spring constant of about 10^{-5}N/m. In the previous system, interferometric sensing is not robust to complex motions of the probe sphere resulting from dynamical effects in microscopic region, for example, electro static effect, adsorption, heat fluctuation, Brownian motion, etc. Therefore, it is difficult to decrease measurement uncertainty in positional sensing. To overcome this problem, we propose a vibrational microprobe driven by radiation pressure as an active sensing method.

The work reported in this paper deals with fundamental characteristics of the newly developed laser trapping probe introducing an optically forced vibration method. The experimental system is developed and fundamental experiments are performed to investigate characteristics of the vibrational microprobe. An optically trapped silica particle in air is used as a microprobe sphere with the diameter of 8.0µm. Frequency response to external excitation is obtained in 2 kHz. The spring constant of the probe is estimated by measuring frequency response. Finally, we demonstrated approach to a glass microsphere with 168µm diameter.

2. PRINCIPLE OF OPTICALLY FORCED VIBRATION METHOD

Fig. 1 shows the principle of the laser trapping probe for nano-CMM using optically forced vibration method. An optically trapped small dielectric particle in air is used as a microprobe sphere. It is sensitive to external force generated by interactions with a workpiece and has the same dynamical properties as a positional detection probe. As the source of the trapping beam, Nd:YAG laser light formed annular is used. The probe sphere retains a stable position against gravity when applied with trapping force (Fig.1(a)). Improving the stability of the trap using annular beam trapping technique, a probe sphere can be forced to oscillate by the driving force exerted by radiation pressure. As the source of the driving beam, the light from the laser diode (LD) traveling through the center of the annular beam is used (Fig.1(b)). The driving force is changed by modulating the intensity of LD emission. An optically trapped small dielectric particle in forced oscillation state is useful for the positional detection probe (Fig.1(c)). Consequently, a position can be detected based on changes of oscillating frequency (Fig.1(d)).
3. EXPERIMENTAL SETUP

Schematic diagram of the laser trapping probe system based on the optically forced vibration technique is illustrated in Fig. 2. The system is composed of a trapping optical system, a driving optical system for optically forced oscillation of a probe sphere, a detecting optical system for monitoring the oscillating status.

The light with wavelength of 1064nm is emitted from Q-switch/Nd:YAG laser and is annular shaped by an obstruction. The laser beam is deflected by polarized beam splitter (PBS2), after through PBS1, then focused by an objective with N.A. of 0.95 on a silica particle with 8µm diameter. The silica particle on the glass plate can only be levitated in air with the concentration of the high energy of the Q-switch pulse emission, after which the probe sphere can be maintained at a stable position in the CW emission mode with a low power of less than 100mW. The modulated light with wavelength of 687nm from LD is joined with the YAG laser light at PBS1 and travels through the center of the annular beam. Then it is focused on a silica particle after deflected by PBS2. The backscattered YAG laser light from a trapped particle passes through IRTF with eliminating LD light. The light deflected by DM is collected by a lens, then detected using PD. Oscillating condition is monitored by output signal from PD. Positioning of a workpiece is performed using an xyz-stage with positioning accuracy of 5nm, which is driven by PZT actuators.

4. FUNDAMENTAL EXPERIMENTS

4.1 Annular beam trapping

Fig. 3 shows annular beam generation for stable trapping. Trapping force is the resulting force of a pulling component and a pushing component, as indicated in Fig. 3(a). A pulling component is exerted by the light with a large incident angle and a pushing component by the light with a small incident angle, that is, the light around the optical axis in the focused beam. A pulling component in the trapping force is more dominant for annular beam than Gaussian beam, therefore, annu-
lar beam enables more stable trap. Moreover, annular beam is advantageous for driving the trapped particle in the condition that the pushing component in annular beam is smaller than Gaussian beam. Methods to generate annular beam and its intensity profile are shown in Fig.3(b). Incident beam from YAG laser is obstructed using a circular opaque disk[5]. This method makes it possible to simplify the system. Transforming efficiency is low, however the annular beam is obviously more effective to trap a particle than Gaussian beam. The bright spot seen in the center of the generated annular beam is caused by diffraction. This diffraction spot has so small size and low intensity that trapping stability is not influenced. As indicated in Fig.3(b), the intensity profile has good rotation symmetry, this beam property is important to trap stably.

4.2 Vibration properties of the probe

The probe sphere is driven by modulated LD light in addition to annular beam trapping to confirm vibration of the trapped probe sphere in air. Fig. 4 shows measurement results of oscillating behavior of the probe sphere. The LD laser light is given the sinusoidal modulation at the amplitude of 12mW and the frequency of 23Hz. The voltage output from the photodetector is obtained by detecting the backscattered light from the probe sphere. And the voltage output is reflecting the Z directional displacement of the probe sphere, when the axis of the trapping beam is in the Z direction. We can recognize the periodical signal resulting from vibration of the probe sphere in Fig. 4 (a). The voltage output from the photodetector is processed using a FFT analyzer in real time to analyze the vibration in the spectral domain. The power spectral density for the voltage output from the photodetector is obtained as Fig.4(b). From the peak at 23.75 Hz in the power spectral density distribution, we can confirm that the frequency response corresponding to the sinusoidal modulation of LD laser light is obtained. This is supported by no response seen in the power spectral density distribution without modulation also.

The optically trapped particle can be modeled as a mass in a three-dimensional harmonic potential[6]. The laser trapping probe has two spring constants, one is the axial and the other in the radial direction. For the axial movement of the trapped particle, a differential equation modeling is given by,

\[ m \ddot{z} + D \dot{z} + k_z z = F \]  

(1)

where \( k_z \) is the spring constant in the axial direction, \( m \) is the mass of the particle, \( D \) is the viscous
drag coefficient of the surrounding medium, and $F$ is the external driving force. According to the Stokes Law, a spherical particle that moves in air at low velocity undergoes a viscous drag, and its Stokes drag coefficient is given by,

$$D = 6 \pi \eta r$$

(2)

where $\eta$ is the viscosity of the surrounding medium, and $r$ is the radius of the particle. The following amplitude response $|\vec{R}|$ is deduced from Eq. (1).

$$|\vec{R}| = \frac{\text{Const.}}{\sqrt{\left(1 - \left(\frac{f}{f_n}\right)^2\right)^2 + \left(2 \frac{\zeta}{f} \frac{f}{f_n}\right)^2}}$$

(3)

Here, $f_n$ is the resonance frequency without viscous damping and $\zeta$ is the viscous damping term. Using $\zeta = D / \left(2 \sqrt{m k_z}\right)$, by measuring the frequency response of the oscillating amplitude and performing a least-squares fitting according to Eq. (3), we can determine the term $f_n$ and further obtain the axial spring constant $k_z$ using the relation

$$f_n = \frac{\sqrt{k_z/m}}{2 \pi}$$

(4)

Fig. 5 indicates the measured amplitude response for the sinusoidal modulation at frequencies ranging from 50Hz to 2kHz and the least-squares fitting curve.
measured data is performed by employing constant values according to the experimental conditions: the radius of the probe sphere $r = 4.0 \times 10^{-6}$ m, the mass of the probe sphere $m = 5.0 \times 10^{-13}$ kg, the viscosity of air $\eta = 1.81 \times 10^{-5}$ Pa·s and the viscous drag coefficient of air $D = 1.36 \times 10^{-9}$ N·s/m. Substituting the deduced value of the resonant frequency $f_n = 870$ Hz from the least-squares fitting into Eq.(4), we obtain the axial spring constant $k_z = 1.6 \times 10^{-5}$ N/m.

4.3 Positional detection

In order to verify the performance of the vibrational microprobe as a positional sensitive probe, we conducted an experiment to approach the probe sphere to a glass microsphere with 168µm in diameter. Fig. 6 shows investigation of positional detection using the change of vibrational status of the probe sphere by approaching it to a glass microsphere. In this experiment, the probe particle is forced to vibrate at a frequency of 500Hz. The probe sphere is moved toward the glass microsphere in the Z direction at the X position of about 40µm from the center of the sphere (Fig.6(a)). The microscopic images of the probe sphere at the initial position and reaching at Z=4000nm are indicated in Fig.6(b). Relative displacement between the probe sphere and the glass microsphere is given by moving the sample stage.

Fig. 7 shows measurement results of the peak power in Fourier spectra of the voltage output from the photodetector changing with the vibration status for verifying positional detection principle. Fourier spectra of a monitoring signal of vibrating probe sphere are measured while approaching it to the glass microsphere. While the probe sphere is moving from z=0nm to z=4900nm, the spectra keeps a peak at the modulating frequency of 500Hz. However, we can recognize that the peak vanishes at z=4925nm. On the other hand, the probe sphere returns to z=4900nm, then the peak appears again. This means that the probe comes in contact with the work surface in 25nm. We confirmed that the chane of spectrum changes has high repeatability and is independent of an inclination angle of the work surface. These results show that our method has the possibility to have positional sensing accuracy of less than 25nm.
5. CONCLUSIONS

Fundamental characteristics of the newly developed laser trapping probe introducing an optically forced vibration method were experimentally investigated. We have achieved three dimensional trapping of a microprobe sphere in air with the annular beam generated by using an obstruction. The probe sphere in annular beam trapping was oscillated using the LD laser light with the sinusoidal modulation. We confirmed it by measuring the voltage output from the photodetector detecting the backscattered light from the probe sphere. Amplitude response for the sinusoidal driving force at frequencies ranging from 50Hz to 2kHz were measured. From the obtained resonant frequency, we could estimate the axial spring constant $k_z$ of the laser trapping probe as $1.6 \times 10^{-5}$ N/m. Finally, we suggested that our method has the possibility to have an accuracy of less than 25nm from the measurements of the vibrational status while the probe sphere is approaching to the glass microsphere.

REFERENCES