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Damping Nature of Vibrated Surface-Sensing Probe Controlled by Optical Radiation Pressure

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Abstract:

We have developed a non-contact surface sensing probe for a nano-coordinate measuring system. This micro-probe is controlled by optical radiation pressure. The probe sphere is oscillated and then damped near the surface by a viscous drag force. The damping nature of the probe was studied to improve the precision of the surface detection. An attempt was made to characterize the probe damping nature by the viscous drag coefficient.

Introduction

There is an increase in the demand for ultra-precise coordinate measuring systems (nano-CMM) to assess the geometrical dimensions of micro-parts. The micro-probe system is one of the most challenging components needed to establish a nano-CMM because of the scaling and other effects. We previously introduced a laser trapping technique in a novel micro-probe system [1]. This probe system has a small glass sphere (ϕ8 μm) used as the probe stylus, which is held by optical radiation pressure (Fig.1). This optically trapped probe sphere is vibrated by the optical radiation pressure, and its position is measured though the scattered light from the probe sphere. It is known that the probe vibration is damped near the measured surface by a fluidic viscous force, as shown in Fig.2 [2]. By monitoring the probe damping, a surface-sensing resolution of 30 nm was achieved without any contact with the surface [2]. Such non-contact detection has the merit of not damaging the measured surface. However, for precise detection, it is necessary to ascertain the distance between the probe and the surface. To determine this distance, the damping nature has to be carefully investigated. In this study, to determine how the probe will be damped near a surface, the oscillated probe sphere behavior near a surface was investigated.

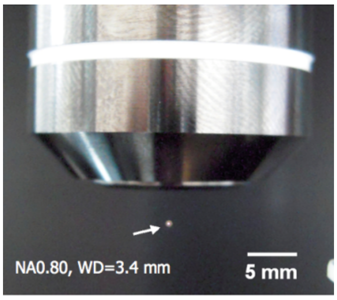


Fig. 1: Laser trapping.

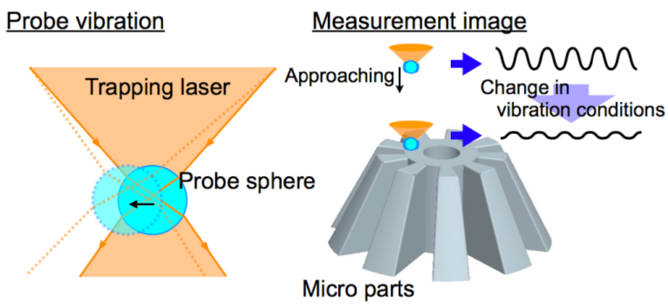


Fig. 2: Laser trapping-based micro-probe.

Dynamics model of vibrated probe

The dynamics of the oscillated probe sphere motion can be modeled using the following mass-spring-damper system:

$$m\ddot{x} + D\dot{x} + k(x - A\sin\omega t) = F(t) \tag{1}$$

where m is the mass of the sphere, D is the viscous drag coefficient, k is the spring constant, and x is the probe displacement from the equilibrium point. A and   are the oscillating amplitude and angular frequency, respectively, such that $A\sin\ t$ indicates the position of the beam waist. $F(t)$ represents the random force caused by Brownian motion. The response amplitude of the probe, X, is obtained by the following equation.

$$\frac{X}{A} = \frac{k}{\sqrt{(k - m\omega^2)^2 + D^2\omega^2}} \tag{2}$$

In the free space, the Stokes drag can be applied to the viscous drag coefficient ($D = 6\ \ r$).

Damping of oscillated probe sphere near the surface

When the probe sphere is oscillated in the vicinity of a surface, the oscillation is damped as a result of the force derived by the compression and expansion of the surrounding air, as shown in Fig.3. This damping force is described as the viscous drag force in Eq.(1). From Eq.(2), it is predicted that the response amplitude will decrease with an increase in the viscous drag coefficient, D. The viscous drag force toward the single sphere close to the wall was well studied in Ref.3. The viscous drag coefficient for a sphere oscillated parallel to a wall surface, $D_{//}$, is Faxén's law [3], which is described as follows.

$$D_{//} = \frac{6\pi\eta r}{1 - \frac{9}{16}\left(\frac{r}{h}\right) + \frac{1}{8}\left(\frac{r}{h}\right)^3 - \frac{45}{256}\left(\frac{r}{h}\right)^4 - \frac{1}{16}\left(\frac{r}{h}\right)^5} \tag{3}$$

where r is the radius of a sphere, h is the distance between the surface and center of the sphere, and   is the viscosity. The viscous drag coefficient for a sphere oscillated perpendicular to a wall, $D_{\perp}$, is given as Brenner's infinite sum formula [3]. However, Brenner's formula is not convenient because of an infinite sum. Instead, E. Schäffer proposed an approximated formula as follows [4].

$$D_{\perp} = \frac{6\pi\eta r}{1 - \frac{9}{8}\left(\frac{r}{h}\right) + \frac{1}{2}\left(\frac{r}{h}\right)^3 - \frac{57}{100}\left(\frac{r}{h}\right)^4 + \frac{1}{5}\left(\frac{r}{h}\right)^5 + \frac{7}{200}\left(\frac{r}{h}\right)^{11} - \frac{1}{25}\left(\frac{r}{h}\right)^{12}} \tag{4}$$

Figure 4 shows the viscous drag coefficients against the distance between the probe and the surface, as calculated by Eqs.(3) and (4). Figure 5 shows the corresponding amplitude of the oscillated probe sphere. The response amplitude is normalized by the amplitude in the free

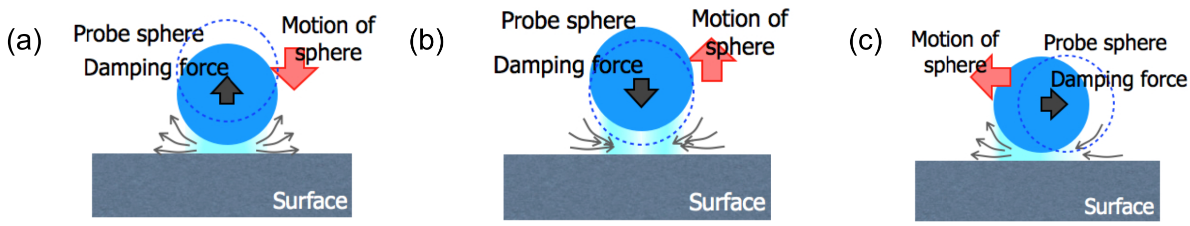


Figure 3: Probe sphere damping: (a) compression, (b) expansion, (c) shear.

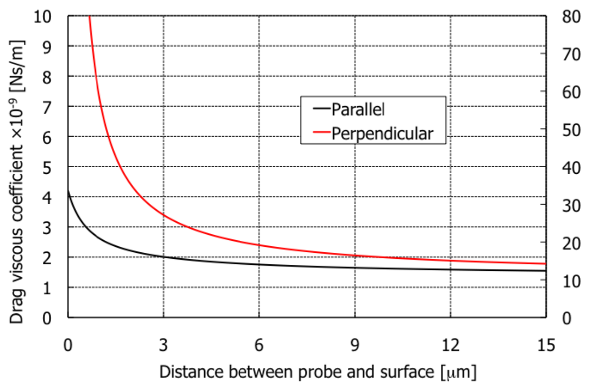


Fig. 4: Viscous drag coefficient.

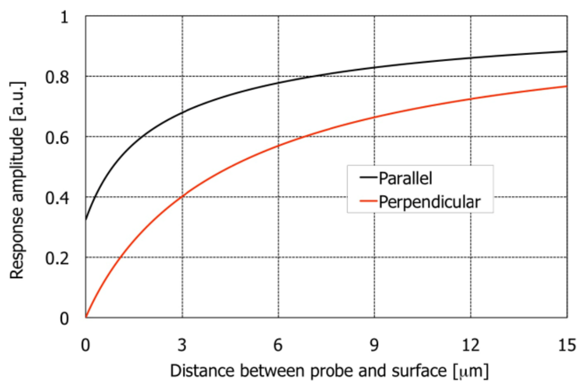


Fig. 5: Response amplitude.

space. As seen, it is important to ascertain D for the precise detections of the surface from the response amplitude damping.

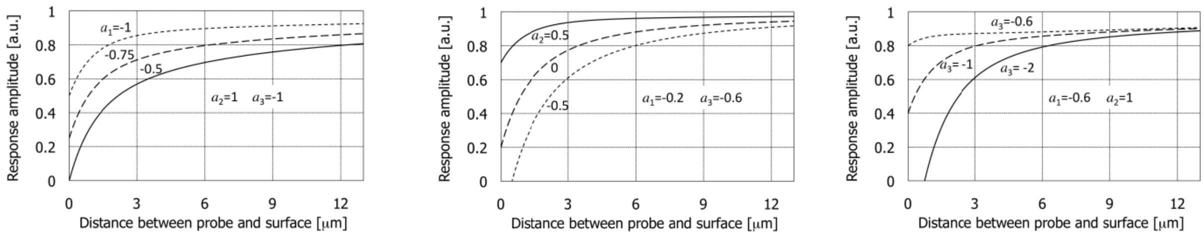
When the probe is oscillated horizontally, Eq.(3) is used for a flat surface (defined as a 0°-inclined surface). Similarly, Eq.(4) is used for a vertical surface (90°). In other cases of inclined surfaces, the viscous drag coefficient may be described such like Eq.(3) or Eq.(4). Therefore, the following equation can be used as the damping formula to generalize the damping nature of the oscillating probe for an inclined surface. The coefficients of Eq.(5), a_i, are determined from the experimental data.

$$D = \frac{6\pi\eta r}{1+\sum_i a_i \left(\frac{r}{h}\right)^i} \quad (5)$$

When the oscillating frequency of the probe is fixed at the resonance frequency, Eq.(2) is simplified as follows.

$$X = \frac{\sqrt{mk}}{D} A \quad (6)$$

Here, the response amplitude, X, is normalized by the response amplitude of the probe in free space, X_0. In X_0, D_0 is treated as the Stokes drag, that is, $6\ \ r$. By using Eq.(5), X/X_0 can be written as



(a) a_1. (b) a_2. (c) a_3.

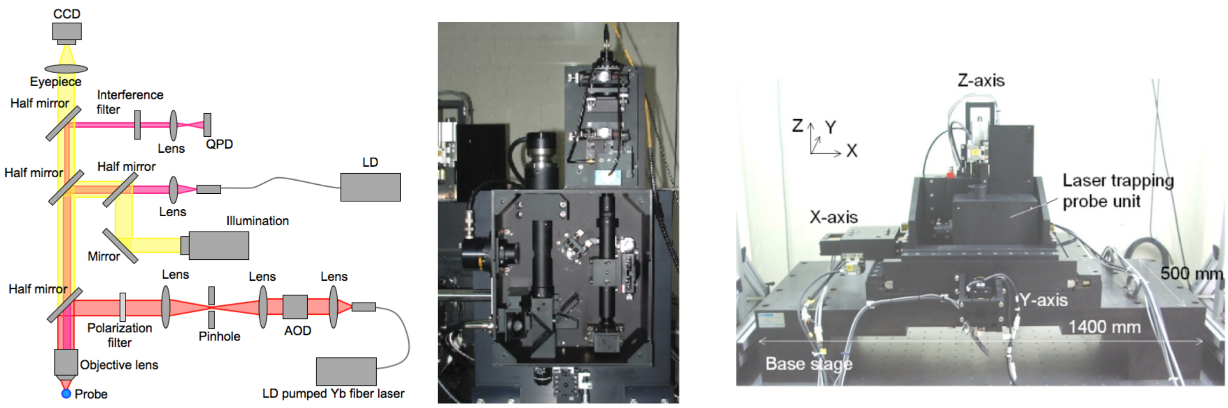
Fig. 6: Simulation of probe damping.

$$\frac{X}{X_0} = 1 + a_1\left(\frac{r}{h}\right) + a_2\left(\frac{r}{h}\right)^2 + a_3\left(\frac{r}{h}\right)^3 \tag{7}$$

For simplicity, this paper only considers terms under the third-order. Figure 6 shows some examples of the probe damping calculated from Eq.(7). a_1 mainly influences a bias of the probe amplitude, while a_2 and a_3 are related to the degree of damping. In particular, a_3 determines the steepness of the probe damping near the surface. Thus, the damping nature is characterized by the damping coefficient, a_i. By fitting Eq.(7) into the experimental data, the damping coefficients, a_1, a_2, and a_3, were experimentally determined, which characterized the damping nature of the oscillated probe sphere.

Experimental setup

The optical system for laser trapping is illustrated in Fig.7. A fiber laser (λ = 1064 nm) was employed as the light source for the laser trapping. The laser was focused using an objective lens (NA0.95). A glass microsphere with a diameter of 8 μm was used. An acousto-optic deflector (AOD) shifted the beam waist, which was used to control the probe sphere position. To measure the lateral displacement of the trapped sphere, light from the LD (λ = 640 nm) was co-axially incident on the sphere. Backscattering light from the sphere was collected



(a) Optical system. (b) Laser trapping unit. (c) The coordinate measuring system.

Fig. 7: Experimental setup.

using a photodetector. A charge-coupled device camera captured images of the trapped sphere.

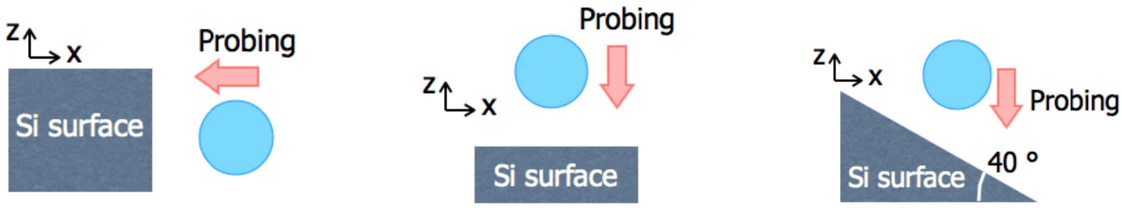
The laser trapping unit was produced as a compact unit (Fig.7(b)) that was mounted on a precise three-axis stage (Fig.7(c)). A shaft motor was employed to drive the stage. Linear scales were used to monitor the stage motion, and the scale resolution was 0.14 nm. The stroke of the stage was 40 mm. The repeatability and accuracy were less than 10 nm and 30 nm, respectively.

Experimental procedure

Probing experiments were conducted to determine the coefficients of Eq.(5). The trapped probe sphere was brought close to different surfaces: a 40° inclined surface, vertical surface (90°), and flat surface (0°). A smooth silicon wafer (Ra < 1 nm) was used as a sample surface. The probe sphere was horizontally oscillated at an amplitude of 200 nm and a frequency of 2100 Hz, which was the resonance frequency. The approach speed was 5.0 µm/s. The approach direction was normal to the surface for the vertical and flat surfaces (Fig.8(a)(b)). In the case of the 40° inclined surface, a vertical approach was used for the probe sphere (Fig.8(c)). The response amplitude was monitored while probing.

Experimental result

The experimental results are shown in Fig.9, along with fitting curves. The coefficients, a_1, a_2, and a_3, experimentally obtained from the fitting curves, are shown in Table 1. As seen, the damping curves for 0° and 90° seem similar, but the damping coefficients are clearly different. This indicates that they had different damping natures. The a_3 value for 90° is much smaller than that for 0°, while the a_2 for 0° is smaller (even negative), which indicates that the response amplitude for 90° is more steeply damped than that for 0°. On the other hand, from Fig.9, it can be seen that there is a big difference between 40° and 90°. The degree of damping seems to be responsible for this difference, which is known from the coefficients of a_2 and a_3.



(a) Vertical surface. (b) Flat surface. (c) 40° inclined surface.

Fig. 8: Approaching experiments.

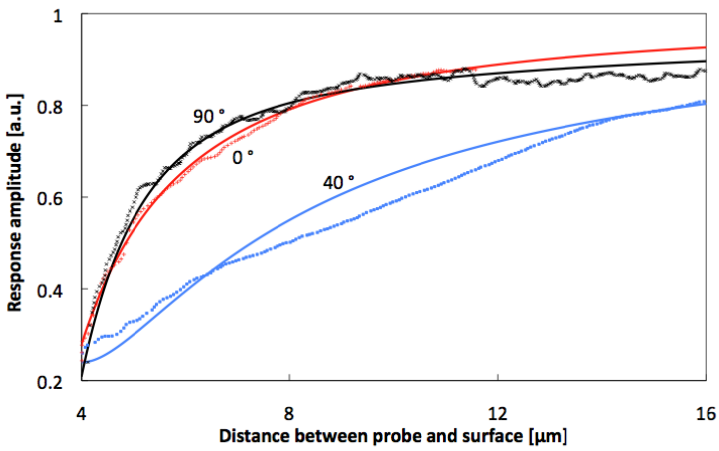


Fig. 9: Probe damping on inclined surfaces.

Table 1: Coefficients of damping.

Surface	Damping coefficient		
	a_1	a_2	a_3
0 °	-0.19	-0.38	-0.15
40 °	-0.55	-1.19	0.98
90 °	-0.59	1.00	-1.30

Thus, it is shown that the damping nature of the laser-trapped micro-probe seems to be characterized by comparing the damping coefficients.

Conclusion

In this paper, the damping nature of an oscillated laser trapped micro-probe was discussed. The probe sphere damping near a surface is caused by a viscous drag force. Therefore, it was revealed that the probe damping can be simply characterized by the coefficients of the polynomial for the viscous drag coefficient. Future work will be more dedicated to gathering data for probe damping against various surfaces in terms of the inclined angle, surface roughness, surface relative humidity, and so on.

References

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