Introduction of micro-manipulation by adhesional force and dielectric force

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ABSTRACT

An adhered particle can be detached by dielectric force. The voltage required for the detachment is theoretically evaluated. Calculated results show fairly good agreement with experimental results. A Diagram for micro-manipulation is presented. Because the adhesion force can be evaluated by Johnson- Kendall- Roberts (JKR) approximation, the possibility and the limitation of a micro-manipulation using both the adhesion force and the dielectric force can be expressed in a diagram.

Keywords: Adhesion, detachment, dielectric force, micro-manipulation, micro-assembly, JKR

1 INTRODUCTION

Adhesional forces are theoretically well approximated by JKR theory[1], even when system has a compliance[2] and/or long range interaction is not negligible[3]. This is suggested experimentally[4,5,6] using a system constructed in UHV chamber of surface analysis apparatus[7]. The adhesion force can be used as attractive force in the manipulation of small objects.

The dielectric force seems most useful as a mechanism to generate the repulsive force in the micro-manipulation. A boundary element method (BEM) is used to evaluate the forces generated by the dielectric force. And the voltage required for the detachment is clearly expressed. Although the numerical method is used, all of the parameters are normalized and systematic evaluation is carried out [8]. The necessary conditions for the manipulation are clearly expressed in a diagram [8].

In the present paper, results of the BEM analyses are compared with experiments. Possibility and limitation of a micro-manipulation using both of the forces are discussed.

2 EVALUATION OF FORCES

The adhesion force and the dielectric force are evaluated. It is significant for the design and the control of micro-manipulation systems.

2.1 Adhesion Force

As mentioned above, the adhesion force can be approximately estimated by

$$f_{\text{adhesion}} = 1.5\Delta\gamma R \qquad (1)$$

$$\Delta\gamma = \gamma_{s1} + \gamma_{s2} - \gamma_i \qquad (2)$$

where R is the radius of the object and γ_{s1}, γ_{s2},and γ_i are respectively surface and interfacial energy of the material. γ_{s1}, γ_{s2},and γ_i are material constants[9,10,11].

2.2 Dielectric Force

The dielectric force is investigated by Boundary element method (BEM) analysis. Model used in the analysis is shown in Figure 1. The system consists of a manipulating probe, a spherical particle, and a substrate plate. The manipulator and the substrate are cylindrical assuming an axial symmetry. These objects are all conductive.

Although a numerical method is used to solve the equations, all parameters are normalized. The effect of the shape-parameters on the dielectric force is systematically evaluated. The force is independent of the size of the system. It depends on the relative shape and the relative position of the objects. The force is proportional to the second power of the applied voltage.

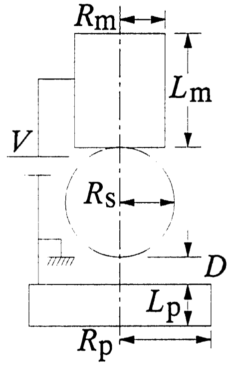


Figure 1: Model for BEM analyses

For the purpose of systematic understanding and the design of the optimal shape of the manipulator, the system without the plane is considered. Figure 2 shows the dielectric force as a function of a shape parameters of the probe. The force is normalized by the second power of applied voltage and the shape parameters are normalized by the radius of the particle. The peak of the force can be seen when the normalized radius is nearly equal unity ($R_m / R_s \approx 1$). This result suggests the existence of optimal shape of probe.

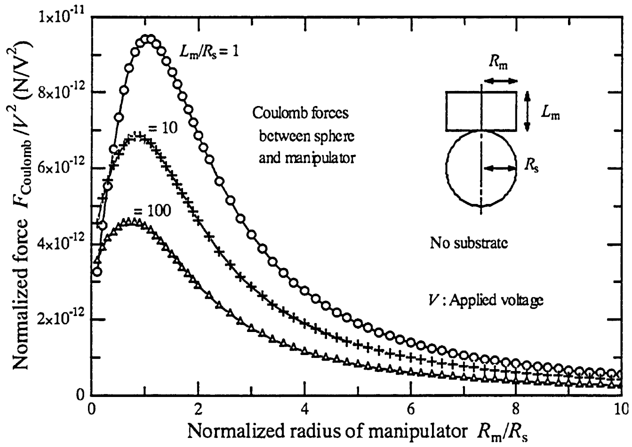
Consider the case that the system with infinite plate as the substrate. Calculations are carried out by using the mirror images. The normalized radius of the manipulator is fixed to be unity. Then, the parameters are only the length and the gap distance. In Figure 3(a), the force is plotted as a function of the gap (the distance between the sphere and the plate). Results for the normalized length L_m =1, 10, and 100 are shown in the figure.

At the limit when $D / R_s \rightarrow \infty$, the forces approach the values in Figure 2. At the limit when $D / R_s \rightarrow 0$, the forces approach an asymptote. The equation of the asymptote is

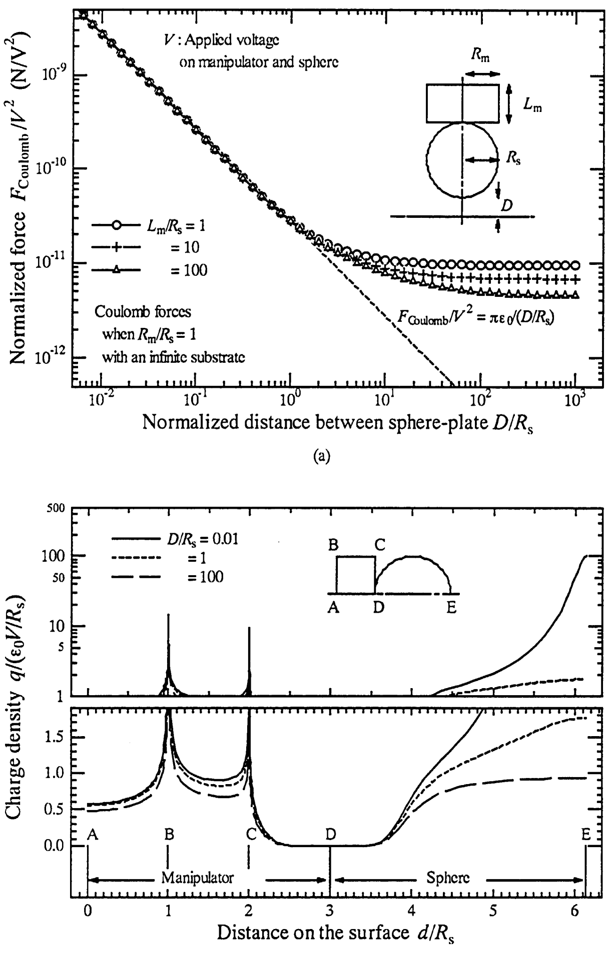
$$f_{\text{dielectric}} = \pi \varepsilon_0 R V^2 / D \qquad (3)$$

This is the analytic solution of the force between two spheres to which the voltages V and $-V$ are applied. For $D / R_s \leq 1$, the force is found to be almost equal to the Equation (3). This fact suggests that the effect of the charge on the manipulator is almost negligible for $D / R_s \leq 1$. The charge distribution is plotted in Figure 3(b) It shows that the force is due to the charge concentration near the point E.

In actual manipulation, the normalized distance D / R_s would be less than unity for the purpose of the precise manufacturing. Therefore the Equation (3) is convenient for the rough estimation of the force. Also for the purpose to generate large forces, small D is found to be required.



Firure 2 : BEM results without substrate. Dielectric repulsive forces are plotted as a function of the radius of the probe.



(a)

(b)

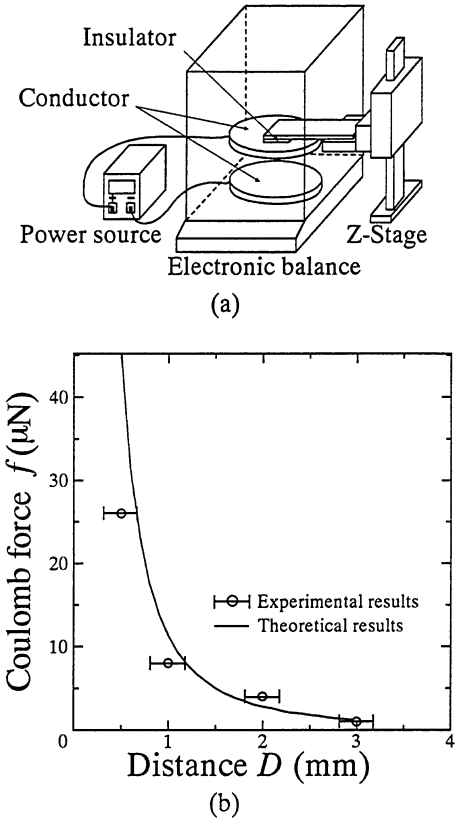
Firure 3 : BEM results with substrate. Dielectric repulsive forces are plotted as a function of the gap distance between the object and the substrate

3 EXPERIMETAL

Calculated results are compared with experiments. As for the adhesion force, detail analyses have been carried out[2~7]. Here, the theory of dielectric force is examined by comparison with experimental measurements.

3.1 Force Measurements

Using an electronic balance as shown in Figure 4 (a), dielectric force is measured and compared with BEM results. Results are plotted in Figure 4 (b). Metallic plates are 30 mm in diameter and 9 mm in thickness. They are placed with distance D and 30 V is applied between them. As shown in Figure 4(b), experimental results shows good agreement with BEM results.



(a)

(b)

Figure 4 : Dielectric force measurement and comparison with BEM result.

3.2 Flight Time Measurements

Figure 5 shows the experimental setup for measurements of flight time. After the detachment from the probe, the object fly to the substrate, being accelerated by the field. The flight time is measured by monitoring current and the flight time is measured.

At the moment of the detachment, charge stored on the object is assumed to be conservative and the flight time between them are calculated using BEM analysis.

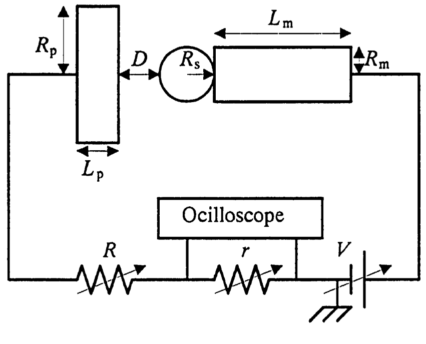


Figure 5 : Schematic illustration of experimental setup.

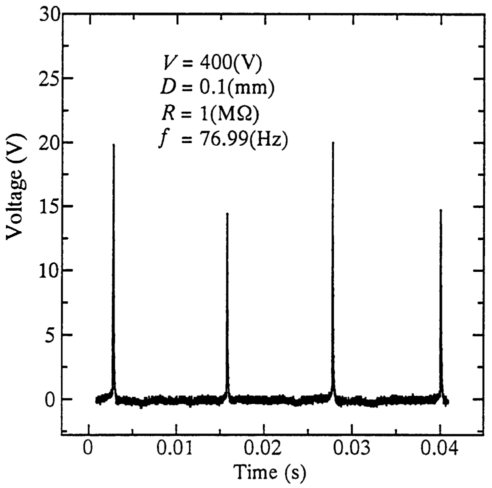


Figure 6 : Example of flight time measurement

Figure 6 shows an example recorded by the oscilloscope. Sharp peaks can be seen. It is due to charge carried by the object. Figure 7 show the comparison between experimental measurements and calculated results by BEM as a function of the voltage. τ_{u-d} is the time from probe to substrate and τ_{d-u} is the time from substrate to probe. Marks are experimental and broken lines are calculated. In the calculation of them, R is assumed to be zero. The force seems to be well calculated by BEM both in magnitude and tendency.

Figures 8 show the comparison between experimental measurements and calculated results by BEM, as a function of the resistance R of the circuit. The time constant of the circuit is enough small to affect on the flight time.

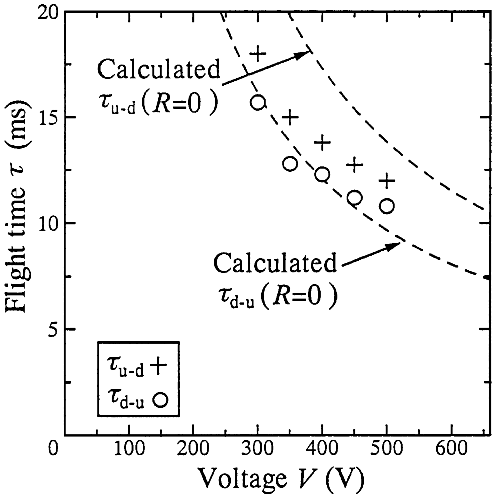


Figure 7 : Experimental results of flight time compared with BEM analyses

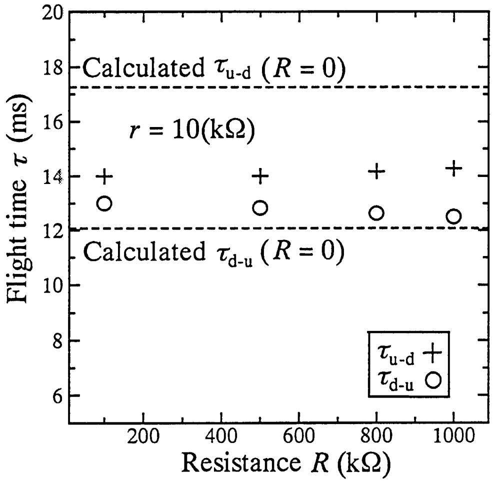


Figure 8 : Experimental results of flight time compared with BEM analyses

As shown in Figures 7 and 8, BEM results show fairly good agreement with experimental results. This fact suggests that the estimation by Equation (3) is a good approximation of the dielectric forces.

4 DIAGRAM FOR MANIPULATION

Since the adhesion force can be evaluated by the Equation (1) and the dielectric force can be evaluated by Equation (3), the voltage required for the detachment can be obtained from

$$f_{\text{dielectric}} > f_{\text{adhesion}} \tag{4}$$

therefore, the voltage required for the detachment can be re-written as

$$V \cong 4.12\times10^{5}\sqrt{\Delta\gamma D} \tag{5}$$

For ideal interface the work of adhesion $\Delta\gamma$ is in the order of 1 [9~11]. In usual manipulation, $\Delta\gamma$ is smaller than 1. Even in the ultra high vacuum chamber with a spattering system, it is not often to measure $\Delta\gamma$ =1. And $\Delta\gamma$ =0.01 is more probable for actual surfaces with some roughness and/or some contamination. Therefore, $\Delta\gamma$ would be about in the order from 0.01 to 1.

This relation is plotted in Figure 6. As shown in the figure, the required voltage is obtained as a function of the gap distance D. The threshold depends on the work of adhesion between the objects. In actual manipulation, the voltage should be determined considering the electric discharge and the tunneling current. The precise control of gap distance D is found to be significant for the processing.

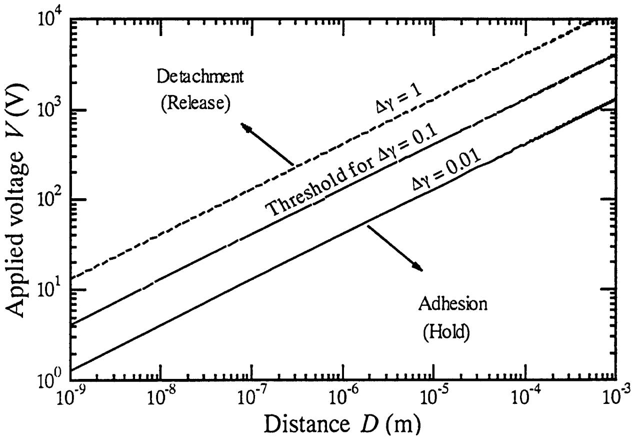


Figure 6 : Diagram for micro-manipulation

5 CONCLUSION

The dielectric force generated by applied voltage from is discussed by using the BEM. The required voltage for the detachment is clearly expressed. The BEM analyses are in good agreement with experimental results. In order to generate larger forces, smaller distance between object and substrate is required and the control of the distance is found to be significant. The force is proportional to the second power of the applied voltage. The larger voltages lead to the larger forces. The threshold is expressed in a diagram. We have to determine the applying voltage considering an electric discharge, and a tunnelling current.

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