February 2006

Microparticle manipulation using inertial forces

Michael Eglin
*University of Wisconsin*

Mark A. Eriksson
*University of Wisconsin*

Robert W. Carpick
*University of Pennsylvania, carpick@seas.upenn.edu*

Follow this and additional works at: [http://repository.upenn.edu/meam_papers](http://repository.upenn.edu/meam_papers)

**Recommended Citation**
[http://repository.upenn.edu/meam_papers/88](http://repository.upenn.edu/meam_papers/88)

Publisher URL: [http://dx.doi.org/10.1063/1.2172401](http://dx.doi.org/10.1063/1.2172401)

NOTE: At the time of publication, author Robert W. Carpick was affiliated with the University of Wisconsin. Currently (June 2007), he is a faculty member in the Department of Mechanical Engineering and Applied Mechanics at the University of Pennsylvania.

This paper is posted at ScholarlyCommons. [http://repository.upenn.edu/meam_papers/88](http://repository.upenn.edu/meam_papers/88)
For more information, please contact libraryrepository@pobox.upenn.edu.
Microparticle manipulation using inertial forces

Abstract
We demonstrate controlled manipulation of large quantities of microparticles on a surface using inertial forces. Motion is induced by applying a periodic parabolic wave form to a shear-polarized piezoelectric plate coupled to a substrate on which the particles reside. Particles move in steps of 10 to 50 nm per cycle, and the particle motion is mass selective. Particle velocity is varied by changing the frequency of the wave form. Calculated inertial forces acting on the particles correspond closely to friction forces between individual microparticles and the substrate, as measured by coupling an individual particle to an atomic force microscope. The results provide insight into the characteristics of particle-surface interactions, and demonstrate the potential for controlled manipulation and separation of large collections of particles without the need for a fluid medium. (c) 2006 American Institute of Physics.

Keywords
friction, atomic force microscopy, separation, nanoparticles, nanopositioning

Comments
Copyright (2006) American Institute of Physics. This article may be downloaded for personal use only. Any other use requires prior permission of the author and the American Institute of Physics. Reprinted in Applied Physics Letters, Volume 88, Article 091913, February 2006, 3 pages. Publisher URL: http://dx.doi.org/10.1063/1.2172401

NOTE: At the time of publication, author Robert W. Carpick was affiliated with the University of Wisconsin. Currently (June 2007), he is a faculty member in the Department of Mechanical Engineering and Applied Mechanics at the University of Pennsylvania.

This journal article is available at ScholarlyCommons: http://repository.upenn.edu/meam_papers/88
Microparticle manipulation using inertial forces

Michael Eglia
Department of Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706

Mark A. Eriksson
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

Robert W. Carpickea
Department of Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706

(Received 1 July 2005; accepted 19 December 2005; published online 2 March 2006)

We demonstrate controlled manipulation of large quantities of microparticles on a surface using inertial forces. Motion is induced by applying a periodic parabolic wave form to a shear-polarized piezoelectric plate coupled to a substrate on which the particles reside. Particles move in steps of 10 to 50 nm per cycle, and the particle motion is mass selective. Particle velocity is varied by changing the frequency of the wave form. Calculated inertial forces acting on the particles correspond closely to friction forces between individual microparticles and the substrate, as measured by coupling an individual particle to an atomic force microscope. The results provide insight into the characteristics of particle-surface interactions, and demonstrate the potential for controlled manipulation and separation of large collections of particles without the need for a fluid medium. © 2006 American Institute of Physics. [DOI: 10.1063/1.2172401]
order of 10–50 nm per step, which indicates that sliding occurs only during the turnaround of the signal, as expected for the inertial mechanism. The spread in velocities and the fact that some particles remain stuck to the surface after the actuation begins is most likely due to surface imperfection of the particles and the substrate. At frequencies above a certain threshold (12 and 14 kHz for the 200 and 90 μm particles, respectively), the particle velocities are reduced. At these frequencies, the inertial forces during the smooth parabolic part of the wave form exceed the particle-substrate friction force. This creates motion in the direction opposite that intended, decreasing the mean particle velocity. If the drive frequency is increased further, random motion of the particles occurs.

The actual surface displacement of the silicon substrate and the particle-substrate friction force is measured with glass particles attached to AFM cantilevers (so-called colloidal probes\(^1\)). 70 μm glass particles are glued to commercial AFM cantilevers with an UV curable epoxy resin (NOA61, Norland Products, NJ) using a home-built micromanipulation stage. The cantilever spring constants are calibrated in normal and torsional mode with the added mass method.\(^2,13\)

The surface displacement during actuation of the piezo is measured by bringing the colloidal probe into contact with the substrate with its long axis perpendicular to the shear direction of the piezo. A drive voltage small enough to prevent slip of the particle is applied to the piezo and the surface displacement is calculated from the lateral deflection signal of the AFM. During these experiments, scanning of the AFM scanning piezo itself is turned off. Figure 3 shows the drive voltage (a), the surface displacement (b), and the surface acceleration (c) (calculated from b) after smoothing the data with a running average). The maximum displacement occurs at time \(t_1\) [Fig. 3(a)], approximately 10 μs after the maximum in the drive signal. There is also a broadening of the peak to a width \(\Delta t\) and thus a reduction of the maximum acceleration. These effects are due to hysteresis which is inherent to piezoelectric materials, and this limits the inertial force that can be applied.

The inertial force \(F_i\) on the particle at the cusp is calculated by \(F_i = ma\) with \(m\) being the particle mass and \(a\) the surface acceleration. If we model the acceleration as constant during the time period \(\Delta t\) at the peak of the displacement [Fig. 3(b)], it can be approximated by \(a = \Delta v/\Delta t\). \(\Delta t\) is measured from Fig. 3(b) and found to be 15 μs for all drive frequencies and amplitudes used in our experiments. The change in surface velocity is estimated by \(\Delta v = v_1 - v_2\), with \(v_1\) and \(v_2\) the velocities at the beginning and end of the time period \(\Delta t\) [Fig. 3(b)]. The velocities are calculated from Eq. (1). The inertial force acting on a particle with diameter \(D\) and density \(\rho\) is

\[
F_i = m \frac{v_1 - v_2}{\Delta t} = \frac{8\pi d^3 \rho D^3}{3\Delta t}.
\]

To estimate the inertial forces necessary to move particles placed on a substrate, we slowly increase the drive amplitude, and observe the amplitude at which the particles start to move. In three independent experiments with 70 μm glass particles, with a parabolic drive of 12 kHz, the first particle motion is observed at 19±6 V, which according to Eq. (2) equals 54±17 nN. At full drive amplitude (71 V, or 200 nN) 80%±7% of all particles are observed to move.

These forces are compared to friction forces measured for individual particles with the colloidal probe AFM.\(^14\) Friction is measured from the first moment of contact between the particle and the surface (Fig. 4), with only a small normal force applied. The threshold force for particle movement is approximately 54±17 nN. In three independent experiments with 70 μm glass particles, a threshold force of approximately 50±20 nN is observed. At full drive amplitude (71 V, or 200 nN) 80%±7% of all particles are observed to move.
load of 1.0±0.5 nN besides the additional 45±13 nN of adhesion acting. After a rapid increase during contact formation, a slow increase with sliding distance occurs, which levels off after ~100 µm of sliding. Two separate measurements with individually prepared cantilevers with 70 µm particles attached exhibit initial friction forces of 25 and 45 nN, respectively, and the forces level off at 40 and 140 nN, respectively. These forces correspond well to the inertial force of 54±7 nN at which the first particles start to move on the actuated substrate, and the upper limit of these forces is in the range where a large fraction of the particles move on the substrate. The spread of the friction forces for the two particles shows that friction is dependant on the particular particle, which has also been observed in single-particle adhesion measurements by Heim et al.15 This is consistent with our observation that under the same drive conditions some particles move while others do not, which as stated above is likely due to surface imperfections, which indeed are observed in electron micrographs of the particles’ surfaces.

We demonstrate a way to induce motion of large numbers of microparticles on a surface with no carrier medium. The method is simple and versatile, with the only prerequisite that the combination of particle mass and substrate acceleration must produce enough inertia to overcome the friction force of the particle/substrate interface. By coupling an AFM directly to individual glass particles, we measure the friction force between the particles and the substrate, and find good agreement between a simple analytical model and the measured behavior of the actuated particles. A further reduction of the particle size being moved can be achieved by the use of piezoelectric materials with lower hysteresis to increase the surface acceleration or by reducing frictional forces between particles and the substrate.

The authors acknowledge Dr. In-Ha Sung for preparing the colloidal probes, and T. Swenson and C. Torres for assistance with sample preparation, piezocharacterization, and data acquisition. This work was supported by The U.S. Department of Defense, Army Research Office, Chemical Sciences Division, under Contract No. DAAD19-03-1-0102, and by the NSF under Grant Number DMR-0094063.