Reducing Friction by Normal Oscillation of the Surface

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Abstract:

We studied the effect of periodic and random normal surface oscillations on friction in an atomic force microscope experiment. Oscillation frequency was varied in the range of 1–100 KHz, and oscillation amplitude was varied in the range of a few nanometers. We observed a reduction of a few orders of magnitude in friction coefficient due to the oscillations. Very low values (of the order of 0.01) of friction coefficient were measured. The friction coefficient shows minimal value at the oscillation frequency of 10 KHz (the resonance frequency of the apparatus was measured as 20.7 KHz), indicating that the decrease in friction is due to dynamical effects of sliding materials. Remarkably, friction coefficient was also significantly decreased by applying random oscillations.

Friction between surfaces in contact is a longstanding and very important, yet unsolved, problem. Because of the complexity and multidisciplinary nature of the phenomenon, numerous factors play a key role in describing the relative sliding of adjacent surfaces; therefore, it is a multifaceted problem to address. In particular, the outstanding complexity significantly affects our ability to predict and control frictional sliding, properties that are highly desirable for a variety of technological applications including micro-electro-mechanical systems (MEMS), computer recording systems, and miniature motors and actuators.

Friction can be affected by the application of small perturbations to accessible elements and parameters of the sliding system [1–8]. Implementation of a desirable level of control, though, requires a priori knowledge of the strength and timing of the perturbations. Such techniques are, in general terms, not developed yet. Therefore, phenomenological studies of the effects of small perturbations applied to sliding are important.

Recently, Heuberger et al. [1] (experimental) and Gao et al. [2] (full-scale molecular dynamics computer simulation) showed that friction in thin-film boundary-lubricated junctions can be reduced by coupling small-amplitude (of the order of 1Å) directional periodical mechanical oscillations of the confining boundaries to the molecular degree of freedom of the sheared interfacial lubricating fluid. Using a surface force apparatus modified to measure friction forces while simultaneously inducing normal (out-of-plane) vibrations between two boundary-lubricated sliding surfaces, load- and frequency-dependent transitions between “dynamical friction” states have been observed [1]. In particular, regimes of vanishingly small friction at interfacial oscillations were found. Methods to control friction in systems under shear that enable the elimination of chaotic stick-slip motion were proposed by Rozman et al. [3]. Significant changes in frictional responses were observed in the two-plate model [4] by modulating the normal response to lateral motion [5]. In addition, surface roughness and thermal noise are expected to play a significant role in deciding control strategies at the micro and the nano scales [6, 7].

In this manuscript, we study the effect of surface oscillations, both periodic and random, on frictional properties of surfaces, using an atomic force microscope (AFM). Since the first measurement of friction with an AFM by Mate et al. [9], the AFM has been widely used to measure the frictional properties of materials on the nanometer scale [10, 11]. Our results showed a significant (few orders of magnitude) reduction in the friction force as a result of surface oscillations. As in the surface force apparatus experiment [1], we observed vanishingly small values of the friction coefficient of the order of 0.01. We demonstrate that periodic as well as random oscillations result in a significant decrease in friction coefficient.

Mercaptopropionic acid was purchased from Aldrich and used without any further purification. It was selected as a boundary lubricant because of its simple structure and hydrophilicity. An atomically smooth mica surface was cleaved, and a 2.5-nm thickness of chromium and a 30-nm thickness of gold layers were sequentially deposited on it. A self-assembled monolayer of mercaptopropionic acid was formed on a fresh gold surface by dipping the gold-coated mica into a 1-mg/ml concentration of ethanol solution overnight. After being thoroughly rinsed with ethanol and completely dried with clean nitrogen, the substrate was immediately mounted on a piezoelectric actuator. The amplitude and frequency of vertical oscillation by the actuator were controlled with a digital function generator.

For friction measurement, an AFM (Multimode, Digital Instrument, Santa Barbara, CA) with a quadrant position-sensitive detector was used. A diode laser is focused on the end of the cantilever and aligned to reflect the laser beam to the center of the detector. Proportional and integral gains of a feedback loop were set to low values because high values can exert a large influence on the lateral force measurement. As the cantilever scans on the surface, the friction between the lever and the surface twists the cantilever, and the reflected laser beam moves out from the center position. The larger the friction value, the larger the difference between the trace and retrace appears. Scan speed and scan size were fixed at 1.97 Hz and 100 nm, respectively, throughout the measurements.

Figure 1 shows the friction loops at a fixed frequency of 10 KHz and various amplitudes of vertical oscillation against time. The upper and lower curves represent

trace and retrace in standard AFM measurements, respectively. The bigger the difference is, the more pronounced the friction is. Although the accurate amplitude of the vertical vibration is not measured at this high frequency, its amplitude-to-voltage parameter is about 1 nm/V at low frequency, and the amplitude is linearly dependent on the applied voltage in the given frequency. The difference starts to decrease even at a low driving voltage of 0.1 V and reaches an almost negligible value at 1 V.

Figure 2(A) summarizes the friction coefficients at various frequencies and amplitudes. Friction coefficient, μ, is calculated from $\mu = \alpha F/L$ where F and L are a friction force and a normal load in voltage, respectively. F is calculated from the difference between trace and retrace in Fig. 1, and L is fixed at 2 V throughout the experiment. Since the spring constants of flexure and torsion are different, the ratio of the spring constants, α, should be considered. Here, α is assigned to be 30 based on the previous experiment using the same structure for the silicon cantilever [12]. At a low frequency of 1 Hz, the friction is not much affected by the oscillation, regardless of the amplitude, because the vertical oscillation is slower than the scanning speed of the cantilever. The friction starts to decrease significantly above 100 Hz, and the minimum friction coefficient appears at 10 KHz. However, the friction coefficient increases again above 10 KHz. This tendency is more apparent in Fig. 2(B), where the friction coefficient is plotted against the logarithm of the frequency at a fixed amplitude of 4 V. The inset of Fig. 2(B) is the same plot as Fig. 2B but is plotted against the linear frequency.

Since the mechanical resonance of the instrument plays an important role in the measurement, the resonance response of the apparatus was measured to confirm whether the minimum friction coefficient is related to the mechanical resonance. A lock-in amplifier (Stanford Research Systems, Sunnyvale, CA) was used to drive the piezoelectric actuator instead of the function generator, and it scanned from 1 to 100 KHz. Figure 3 shows that the resonance peak appears at 20.7 KHz; that is far higher than the frequency where the minimum friction was achieved. Moreover, the inset of Fig. 3 shows that the amplitude is almost constant or decreases slightly up to 1 KHz; that implies that the friction decrease at this frequency range is not related to the resonance response of the system. The spikes at 60, 120, and 180 Hz come from electronic noise.

Figure 4 shows how the amplitude of random oscillation affects the friction coefficient on a bare gold surface. In our experiment, random noise from a function generator was applied to a piezoelectric actuator. A spectrum analyzer confirmed that the noise was truly random up to 100 KHz. As the amplitude of the vertical oscillation increases, the friction coefficient decreases, approximately following the first-order exponential decay which signifies that a single energy dissipation mechanism plays a role during the measurement. The decreasing tendency of the friction coefficient on bare gold is similar to that on mercaptopropionic acid, but the absolute friction coefficient on mercaptopropionic acid is smaller than that on bare gold because of the lubrication.

In summary, a significant reduction in friction coefficient has been observed as a result of a very small amplitude of surface oscillation in the KHz frequency range. Both periodic sinusoidal as well as random oscillations result in a significant decrease of friction coefficient, indicating the robustness of the effect. The significance of this result may be attributed to both fundamental and application aspects. Eliminating the need to select a proper range of oscillation frequencies (that may be very narrow) to achieve the desired effect significantly relaxes constraints on the implementation of such a method of friction control and indicates the robustness of the effect and the applicability to systems other than the AFM.

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Figures Captions

Figure 1. Friction loops were measured with various amplitudes of vertical oscillation at a fixed frequency of 10 KHz. The difference between the trace (upper curve) and the retrace (lower curve) represents the friction force.

Figure 2. (A) Friction coefficients are measured at various amplitudes and frequencies of vertical oscillation, ■ : 1 Hz, ● : 10 Hz, ▲ : 100 Hz, ▼ : 1 KHz, ◆ : 10 KHz, ◄ : 20 KHz, ►: 50 KHz, ★ : 100 KHz. (B) Friction coefficients at fixed driving amplitudes of 4 V are plotted against the logarithm of the driving frequency. Inset shows the same plot, but against the linear frequency.

Figure 3. Mechanical resonance response of the system has been measured using a lock-in amplifier and shows the resonance peak at 20.7 KHz. Inset magnifies the response below 1 KHz.

Figure 4. The effect of the amplitude on a bare gold surface was measured by applying a random noise function to the piezoelectric actuator. As the amplitude increases, the friction coefficient decreases, following the first-order exponential decay.

Fig 1

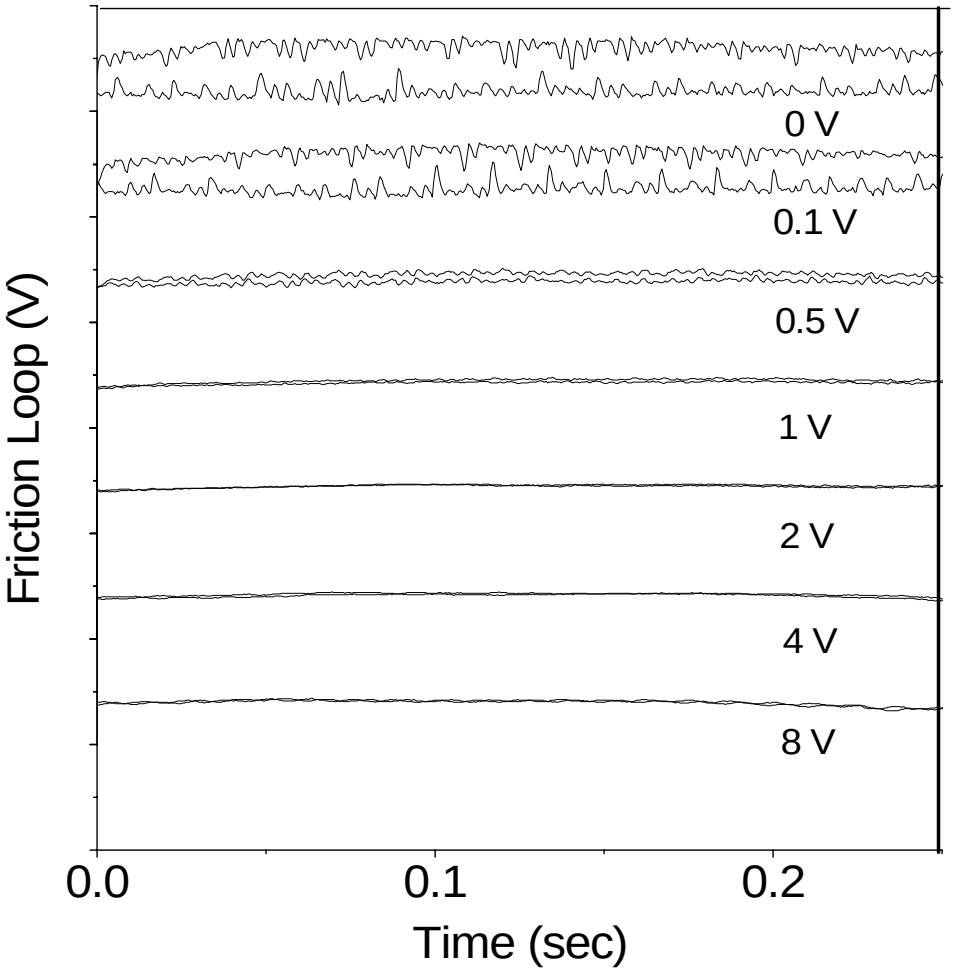
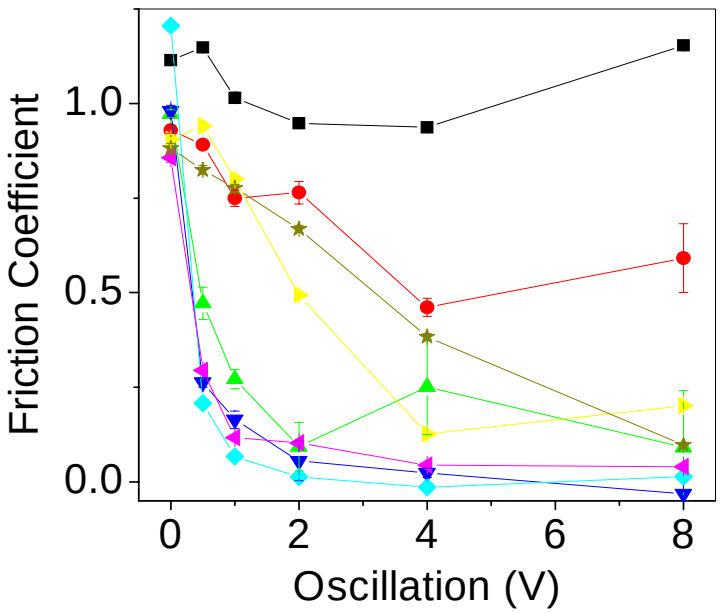


Fig 2

A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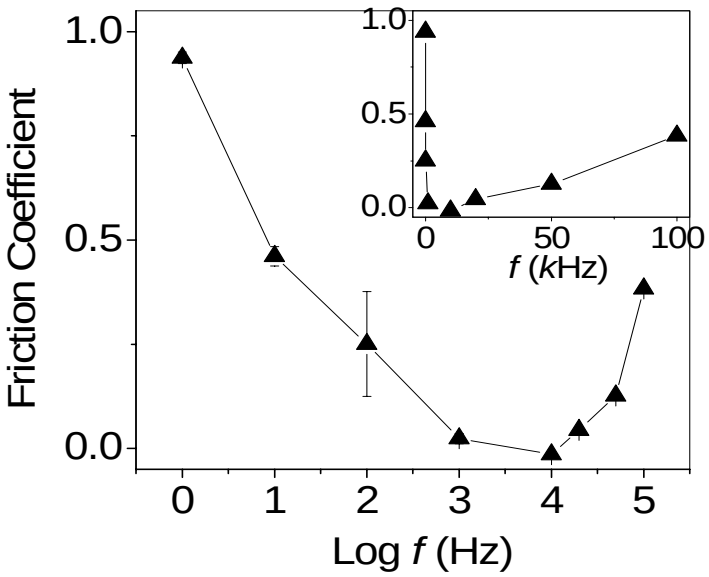
0.0
0
2
4
6
8
Oscillation (V)

B


Friction Coefficient
1.0
0.5
0.0
0
1
2
3
4
5
Log f (Hz)
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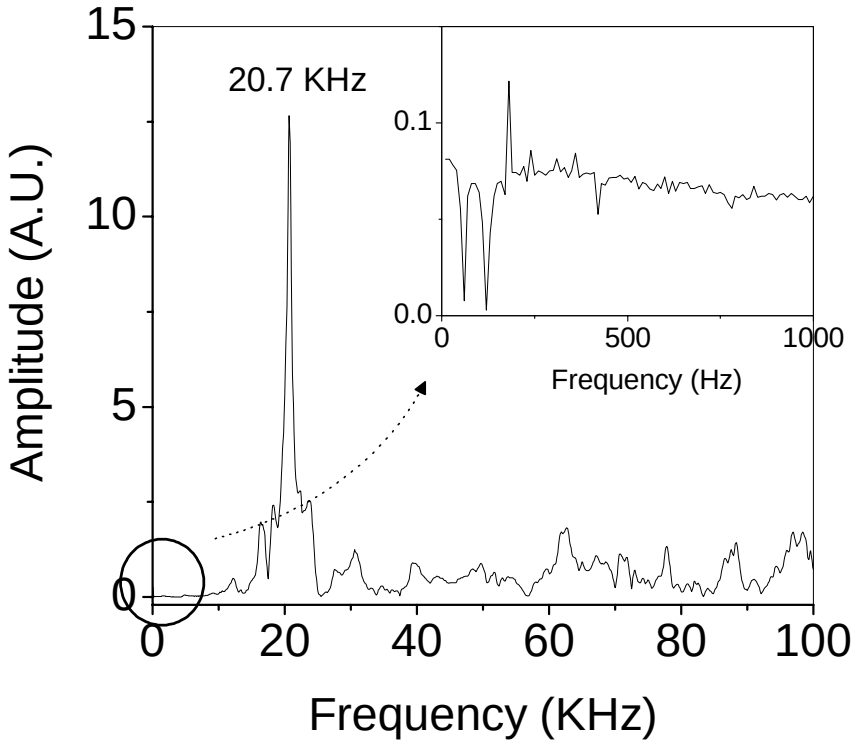
0.5
0.0
0
50
100
f (kHz)

Fig 3


15
10
5
0
Amplitude (A.U.)
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20
40
60
80
100
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0.0
0
500
1000
Frequency (Hz)
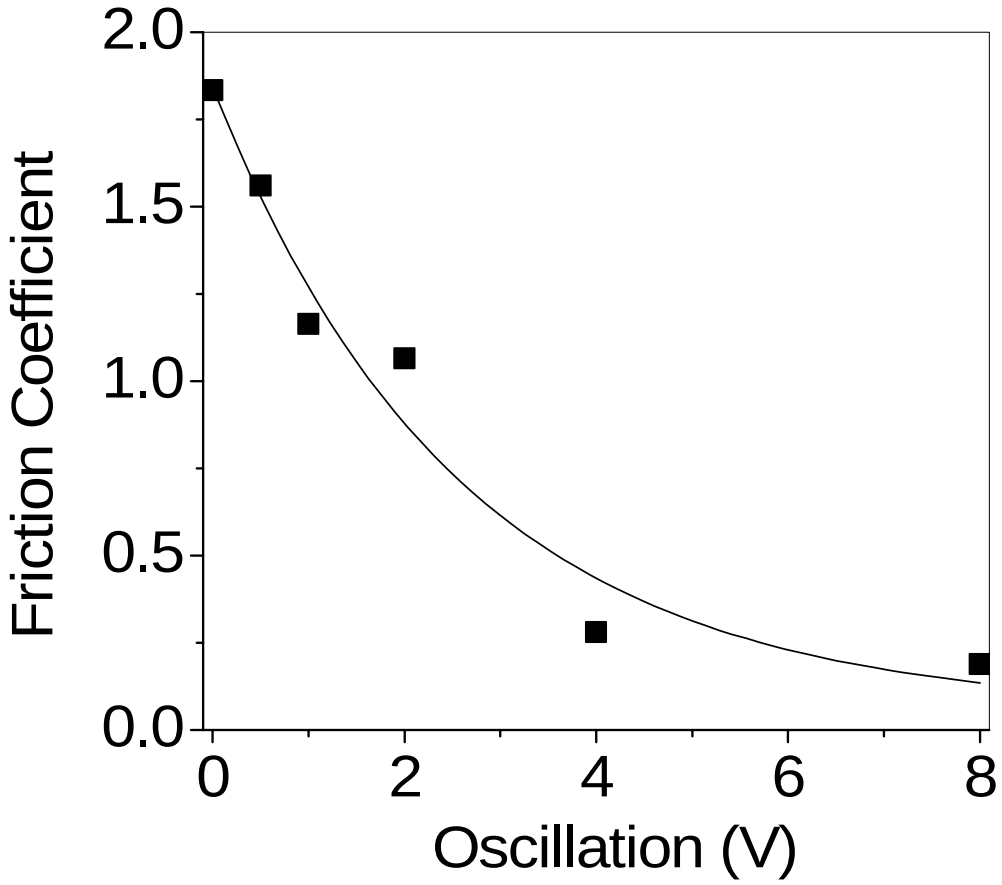
Fig 4