PHYSICAL REVIEW E VOLUME 59, NUMBER 5 MAY 1999

Tuning friction with noise and disorder

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(Received 9 February 1999)

We present numerical and experimental evidence which demonstrates that under certain conditions friction can be reduced by spatial disorder and/or thermal noise. We discuss possible mechanisms for this behavior. [S1063-651X(99)51405-0]

PACS number(s): 81.40.Pq, 05.40.−a, 46.80.+j

Understanding the effects of disorder on friction is of fundamental importance for a wide variety of applications [1–3]. This is a particularly significant issue since noise and disorder are ubiquitous in nature, from atomic to macroscopic length scales. Of particular importance is the limit of small velocities in which a special type of dynamics, called stick-slip dynamics [4–12], is observed in environments ranging from the atomic scale [13–16] through granular materials [17], and to the macroscopic length [4,10]. Thermal noise is inherent in any friction experiment and is commonly used to simulate the dynamics of the underlying surface [1].

The effects of static defects and randomness on friction have been studied previously by several groups [19–22]. The intuitive common wisdom is that sliding on a periodic surface is generally easier (faster) than sliding on a random surface. However, there exists evidence that indicates that randomness (thermal noise [23] or static disorder [24]) may decrease friction. Clearly, a solid theoretical understanding of the basic mechanisms leading to stick-slip dynamics, particularly of the effects of quenched disorder on stick-slip dynamics, is lacking.

The motivation of this manuscript is to study nonlinear mechanisms and to provide additional evidence showing that the friction coefficient of a chain can be tuned by the amount of either disorder and/or thermal noise. In particular, we present numerical and experimental results to demonstrate that the friction coefficient of a system can be significantly reduced by the quenched disorder and/or thermal noise.

Our nonlinear system consists of nearest-neighbor interacting particles all subject to a sinusoidal periodic or disordered potential representing the substrate and driven by the same constant external force. We write the equation of motion for the dynamics of N coupled identical particles interacting via a nearest-neighbor nonlinear Morse potential as

$$\begin{aligned}\ddot{x}_j+\gamma\dot{x}_j+\sin x_j=f+\xi_j(t)+d(x_j)+\frac{\kappa}{\beta}\{&\exp[-\beta(x_{j+1}-x_j)]\\ &-\exp[-2\beta(x_{j+1}-x_j)]\\ &-\exp[-\beta(x_j-x_{j-1})]\\ &-\exp[-2\beta(x_j-x_{j-1})]\},\end{aligned} \tag{1}$$

where f is the applied force (the same for all particles), γ is the linear friction coefficient (assumed to be constant), κ is the nearest-neighbor coupling in the array, β is the nonlinearity parameter (β^{-1} is the range over which the nearest-neighbor coupling is effectively linear), ξ_i is the thermal noise, and d_j stands for spatial disorder ($d_j=\sigma r_j$, where σ is the strength of disorder and r_j is a set of uniformly distributed random numbers in the interval $[-0.5:0.5]$). This is a simplified model of an atomic chain moving on a rough surface intended to describe in a fair qualitative way the quartz crystal microbalance (QCM) experiment for atomic scale friction measurements [25,26] and to compare predictions of numerical results with experimental observations. We performed simulations of a one-dimensional array of particles with periodic boundary conditions for an ensemble of different realizations of disorder and initial conditions. The parameter values were varied over a wide range in order to explore the robustness of the behavior. The numerical simulations were performed as follows: we first equilibrated the chain with zero external force. We then increased the external force in small increments in order to reach the asymptotic level of the driving force. Finally, we performed simulations with the thermal noise added measuring the slip time for the array to advance over a given distance. Since different realizations of disorder and different initial conditions produced different final behaviors, we averaged only on ''running'' solutions, i.e., such that the average velocity was nonzero. The thermal noise was introduced following the guidelines introduced in a Ref. [27], and we define friction coefficient of the array as $\eta=f/v_{\mathrm{c.m.}}$, where $v_{\mathrm{c.m.}}$ is the velocity of the center of mass.

We first describe a simple example of an array consisting of identical particles moving on a periodic potential. When the coupling constant κ is small enough (i.e., the substrate periodic potential is strong compared with interparticle interaction), nonlinearity can significantly affect the friction coefficient. This is a consequence of a property of nonlinear systems, namely, their ability to produce coexisting states with distinct average characteristics. [Equation (1) possesses many solutions depending on the initial conditions, each leading to different values of the average velocity.] Different states that manifest themselves as distinct spatial patterns can be achieved by changing the initial conditions of the system. These dynamical states affect the motion of the center of mass of the system and thereby influence the friction coefficient. Here we describe the impact on friction for a nonlinear dynamical system in the sliding and the stick-slip modes in

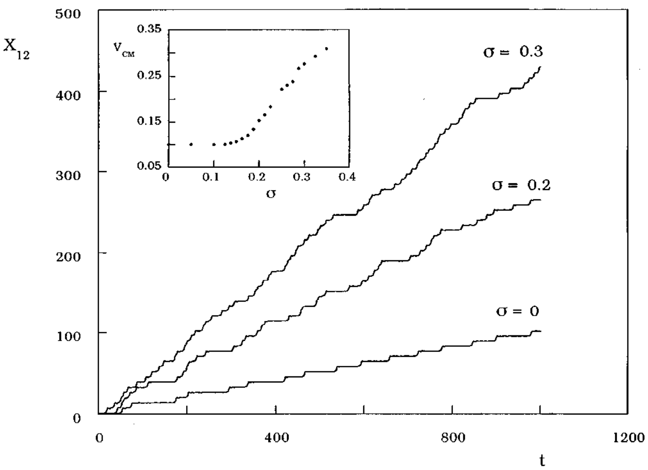

FIG. 1. Time series of the stick-slip position x_j of the particle $j=12$ in an $N=25$ particle array; the bottom curve corresponds to the identical array, the middle curve corresponds to the array with 20% of disorder, and the top curve corresponds to the array with 30% of disorder. The inset shows the average velocity of the center of mass $v_{\mathrm{c.m.}}$ as a function of the amount of disorder. The units are dimensionless.

the presence of thermal noise and quenched spatial disorder. An interesting situation arises when the external force is just slightly larger than the force necessary to initiate the motion of the chain. Static and dynamic solutions coexist in this particular regime, leading to a rich variety of possible motions (static solution - no motion, stick-slip dynamics, chaotic, or periodic sliding dynamics) [11]. In this parameter regime, the dynamics is very rich and thermal noise and quenched disorder can significantly affect the friction coefficient of the array.

We show that quenched disorder destroys the low average velocity propagating wave state by creating a new behavior with substantially higher average velocity. We concentrate on a particular mode of stick-slip motion where the array supports the propagating wave solution in which the excitation propagates from one end to another (for free end boundary conditions) or circles in the array (for periodic boundary conditions). This mode of motion can be initiated, for example, by exciting only a few particles (or just one) in the array and it is stable and robust to small noise and disorder. Figure 1 displays the time evolution of the position of a single particle (12th particle) in an array with $N=25$ (the average velocity is the same for each particle). The bottom curve shows the typical time evolution of the position of a single particle with no disorder ($\sigma=0$). The middle curve shows the time evolution in the presence of 20% disorder, while the top curve corresponds to the case with 30% disorder. The inset shows the average velocity of the array (averaged over 100 different realizations of disorder) as a function of the amount of disorder. We note that for a small enough disorder the average velocity of the array is unaltered. However, for $\sigma>12.5\%$ quenched disorder increases the velocity of the center of mass of the array (therefore it decreases the friction coefficient η). The potential effect of disorder is twofold: it may either increase the average velocity or pin the array. (To reduce the pinning effect, we introduced a small amount of thermal noise into the array.)

In the absence of disorder/noise, the original array exhibits its almost periodic stick-slip dynamics (Fig. 1, the bottom plot). Sufficient disorder/noise destroys this periodicity and results in irregular stick-slip motion in which the friction coefficient decreases (Fig. 1, the middle and top plots). In addition, the effect of disorder on the array is to create and annihilate attractors, as well as to change the size and shape of the basins of attraction. Both effects lead to a change in the average velocity [18]. In our previous example, weak disorder did not alter the average velocity underlying the robustness of the propagating structure. However, these moving structures do not exist in the presence of sufficiently large disorder; therefore, the propagating velocity of the array is high. The particular behavior trend of the array depends on both parameters and initial conditions. For example, starting with a state characterized by a high propagating velocity, the addition of quenched disorder cannot further increase the velocity of the propagation. Therefore, a sufficiently high amount of disorder added to the dynamics of a noisy array can significantly alter the friction coefficient in either direction. An interesting possibility indicating an increase in diffusion coefficient with disorder has been pointed out by Braun and Kivshar [19], where it has been argued that a single impurity can both increase and/or decrease the diffusion coefficient in a Frenkel-Kontorova chain.

We suggest a possible mechanism for the decrease in friction by disorder or thermal noise. The effect of disorder may be related to the decrease of the fluctuations in the center of mass motion. For certain solutions one can show that the average velocity of the array decreases with the increase in the center of mass fluctuations [28]. We define fluctuations from the center of mass as: $f_{av}(\sigma)=1/T\lim_{T\to\infty}\int_0^T f(\sigma)dt$, where $f(\sigma)=\Sigma_{j=1}^N\sqrt{[v_j(t)-v_{av}(t)]^2}/v_{\mathrm{c.m.}}$, $v_{\mathrm{c.m.}}$ is the center of mass velocity of the array, and $v_{av}=1/N\Sigma_{j=1}^N v_j$ is the instantaneous velocity of the center of mass. Figure 2 demonstrates the proposed mechanism, showing the fluctuations from the center of mass $f(\sigma)$ for the $N=25$ particle array with different amounts of disorder. The left-hand part of the plot corresponds to the case of no disorder ($\sigma=0$), the middle part corresponds to $\sigma=15\%$, and the right-hand part corresponds to $\sigma=30\%$. An inset shows time-averaged fluctuations from the center of mass $f_{av}(\sigma)$ in the array; clearly, an increase in the velocity of the center of mass is correlated with the decrease in the fluctuations.

We next discuss a different situation. Here we choose the parameters to better describe the dynamics of the rare gases adsorbed on silver and gold surfaces. In these cases the interparticle interaction potential is on the same order of or even larger than the substrate potential, indicating that the coupling constant κ is no longer very small and the effects of thermal noise ought to be taken into consideration. This limit suggests a different type of dynamics, whereby the array can no longer support a weakly phase-synchronized propagating structure characterized by a low average velocity. Moreover, if either the thermal noise or the driving force are large enough or the one-particle damping coefficient γ is small, the dynamics of the array is essentially a single-particle dynamics. Indeed, already for the chaotic diffusion of a single particle we found that the diffusion coefficient increases when disorder increases (indicating a decrease in the friction coefficient) [29].

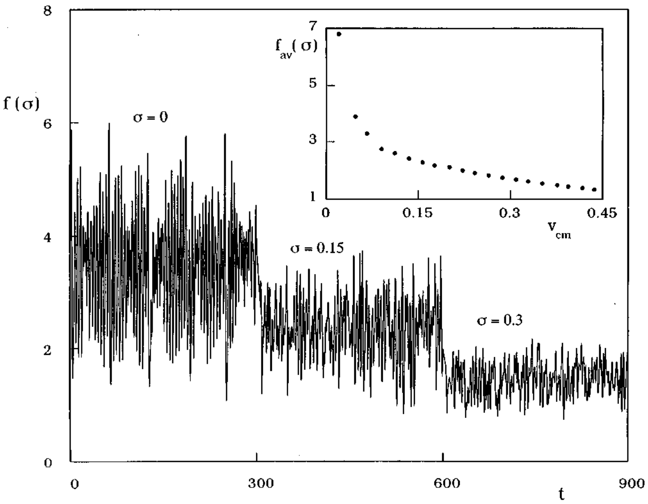

FIG. 2. Time series of the fluctuations from the center of mass $f(\sigma)$ for different amounts of disorder. The left-hand part of the plot ($t<300$) corresponds to the identical array ($\sigma=0$), the middle part ($300<t<600$) corresponds to $\sigma=15\%$, while the right-hand part ($t>600$) corresponds to $\sigma=30\%$. The inset shows the average fluctuations from the center of mass $f_{\rm av}(\sigma)$ as a function of the velocity of the center of mass $v_{\rm c.m.}$.

The numerical results are presented in Fig. 3, where we show cumulative distributions of slip times for $\sigma=0\%$, 2.5%, and 5%. Our sample was based on 500 repetitions of different realizations of disorder. Addition of disorder results in shifting the distribution toward smaller slip times, clearly indicating a decrease in friction.

We now describe experimental work that is in qualitative agreement with the previous numerical results. In particular we show that the friction associated with the sliding of solid and liquid krypton (Kr) films on disordered gold substrates is substantially lower than on ordered gold substrates. The gold substrates on which the measurements were performed were prepared by depositing gold films onto polished quartz substrates held at 80 and 300 K, the 80 K samples being the more disordered of the two. The samples were scanned by

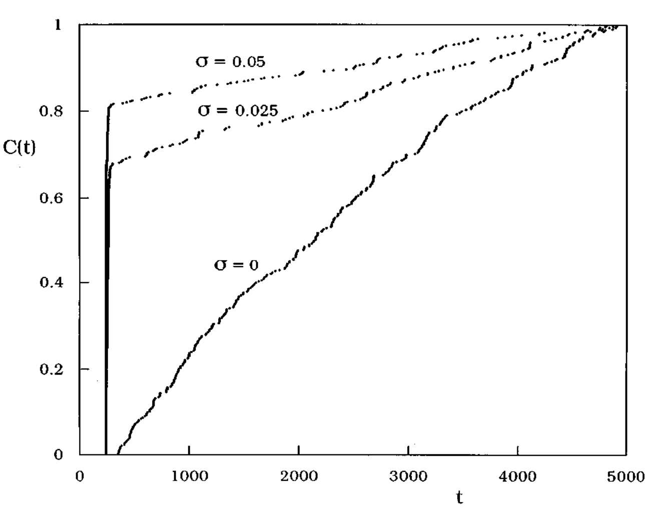

FIG. 3. Cumulative slip time distributions ($\sigma=0$, 0.25, 0.05) for the $N=25$ particle array. The bottom curve corresponds to the identical array ($\sigma=0$), the middle curve corresponds to $\sigma=2.5\%$, while the top curve corresponds to $\sigma=5\%$.

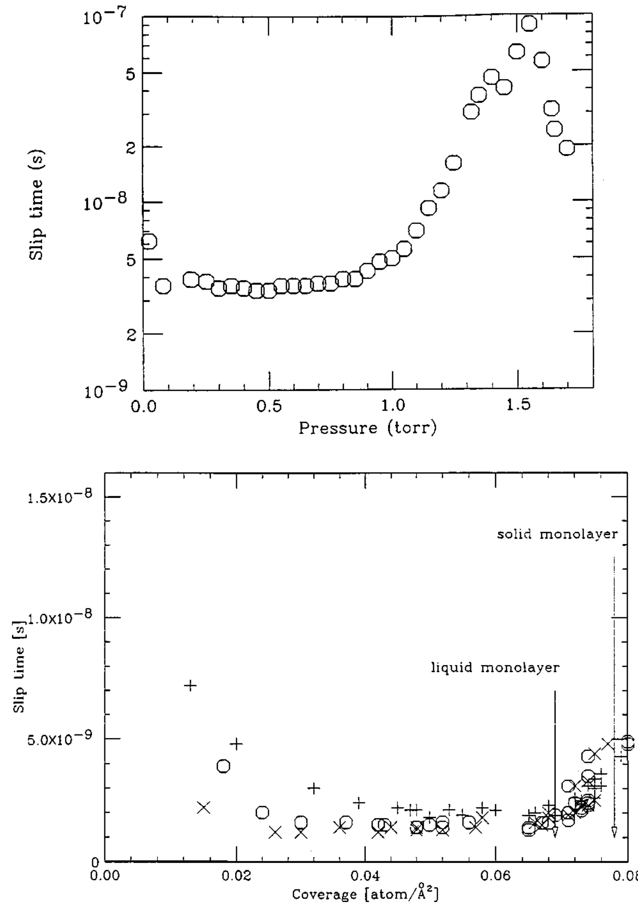

FIG. 4. Slip time vs film coverage for the 300 K sample (bottom). Symbols x, o, and + represent data recorded at different velocities having a ratio of 1, 2, and 3. Slip time vs pressure for the 80 K sample (top). (The film adsorbed on the 80 K sample has decoupled from the motion to such an extent that accurate estimates of film coverage are difficult to obtain.) The data for the 80 k sample are nonetheless clearly 1 to 2 orders of magnitude greater than those obtained for a typical 300 K sample.

tunneling microscopy, and in order to characterize the texture of the samples in a quantitative manner, the surface topologies were analyzed within the framework of self-affine fractal geometry [31]. Roughness exponents for both the 80 and 300 K samples fell within experimental error of $\alpha=0.55$, the primary difference between the two substrates being the range of scaling exhibited, rather than the roughness exponent itself. In particular, the scaling exhibited by the samples deposited at low temperatures extended to shorter, nearly atomic, length scales, while the 300 K sample did not.

Friction measurements were performed on these substrates by cooling them to 77 K and then adsorbing krypton from the gas phase. The adsorption produced a change in the resonant frequency of the microbalance. This change was proportional to the fraction of the mass of the condensed film, which was able to track the oscillatory motion of the underlying substrate on account of the interfacial friction forces. Amplitude shifts in the oscillation were also present, because of the frictional shear forces exerted on the surface electrode by the adsorbed film. The characteristic slip times τ, and the friction coefficients (i.e., shear stresses per unit velocity) η, were obtained from the relations [25] $\delta(Q^{-1})$

$=4\pi\tau\delta f$, $\eta=\rho_2/\tau$, where ρ_2 is the mass per unit area of the adsorbate and τ corresponds to the time at which the sliding speed of the krypton decreases to $1/e$ of its original value.

Slip time versus pressure for the 80 K sample (top) and slip time versus film coverage for the 300 K sample (bottom) are depicted in Fig. 4. The 300 K data consists of points recorded at different vibrational amplitudes of the QCM [30]. The intention here was to assure that the 300 K data exhibited no major dependence on amplitude (and thus sliding speed), since the 80 and 300 K sets were unlikely to be carried out at exactly the same amplitudes of vibration. The film adsorbed on the 80 K sample decoupled from the oscillatory motion of the microbalance to such an extent that accurate estimates of film coverage were difficult to ascertain. The data for the 80 K sample were nonetheless clearly 1 to 2 orders of magnitude greater than those obtained for a typical 300 K sample, indicative of substantially lower friction for the more disordered system.

We have presented numerical and experimental evidence that quenched disorder and thermal noise can decrease friction. The opposite, more intuitive outcome whereby friction is increased by noise/disorder have been observed also, indicating that the array dynamics is highly complex. The behavior of the sliding system appears to be sensitive to the range of parameters describing the sliding chain and the substrate. This suggests the possibility of controlling frictional behavior [32,33]. Indeed, it has been demonstrated experimentally [34] and in the full-scale molecular dynamics simulations [35] that frictional properties of the sliding system can be significantly altered by applying very small external perturbation. Further studies are required to elucidate control mechanisms leading to decrease or increase of friction.

Y. Braiman would like to thank Dr. R. F. Fox for valuable discussions regarding the addition of thermal noise to numerical simulations, Dr. V. Protopopescu for his helpful comments and suggestions on the manuscript, and M. Popescu for his help with the graphics. This work was supported in part by the U.S. Office of Naval Research (F.F), by the Engineering Research Program of the U.S. DOE Office of Basic Energy Science under Contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation (Y.B.), and by the National Science Foundation under Grant No. DMR-9705259 (J.K.).

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