Friction Control at the Nanoscale

Y. Braiman, J. Barhen, and V. Protopopescu

Center for Engineering Science Advanced Research
Computing and Computational Sciences Directorate

Oak Ridge National Laboratory

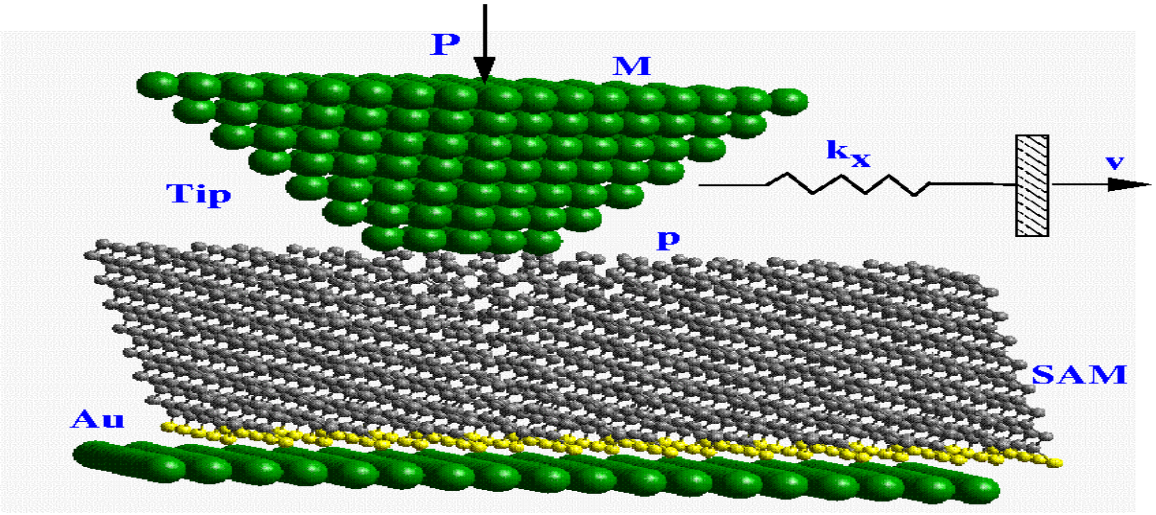
Oak Ridge, TN 37831-6355

CESAR
Center for Engineering Science Advanced Research

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Research Outline

- Develop techniques to control frictional properties of the nano-system *during sliding*
- Test algorithms with MD simulations
- Experimental implementation of friction control



Novelty of the Proposed Research

Efforts to make different lubricants are widespread around the world. In this Proposal, *we aim to make a difference*. While lubrication at the bulk has been manipulated by conventional means, the point of this proposal is very different.

We propose, *for the first time*, practical methods to manipulate friction at the nanoscale, which is impossible to manipulate by traditional methods. We will use (a) non-Lipschitzian dynamics and terminal attractor formalism; and (b) "collective structures" rather than brute-force manipulation.

We bring to this research innovative techniques that involve expertise of nonlinear dynamics. These techniques are new and revolutionary to the field of material research.

Motivation

- **Velocity (friction) control during sliding**
- **Ability to reach desired sliding velocity**
- **Achieve fast transient times**
- **The applied control is limited in strength**
- **Requires only limited accessibility**

Robustness of Friction Mechanisms

Friction is ruled by robust dynamics

good qualitative agreement between variety of models and types of interaction potentials used for a model

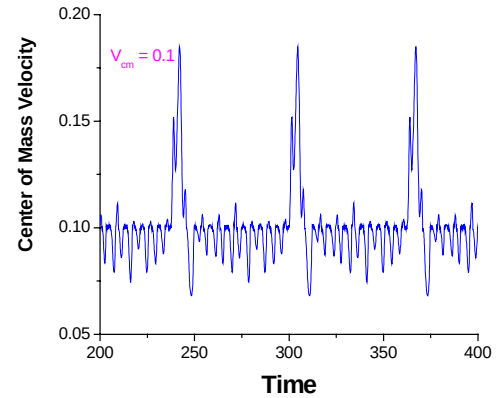
- **choice of parameters may be even more important than the choice of a model !!!**
- **Initial conditions !**

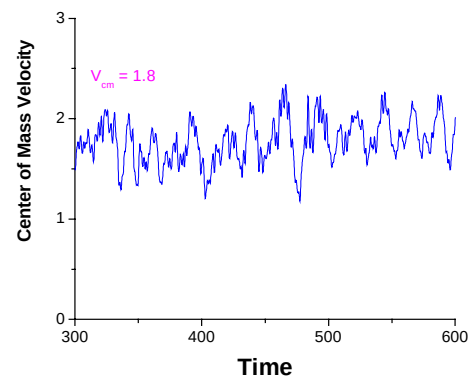
Modeling

Frenkel-Kontorova model

$$m\ddot{x}_j + \gamma\dot{x}_j = -\partial U/\partial x_j - \partial V/\partial x_j + f_j + \eta_j + C(t)$$

x_j is the position of the particle j
m is the mass of the sliding particle
M is the mass of the upper plate
γ is the dissipation coefficient
U is the interaction potential
V is the surface potential
f is the external driving force
η is the thermal noise (temperature effect)





Friction is ruled by robust dynamics

The use of good qualitative agreement between a variety of models and types of interaction potentials for a model choice of parameters may be even more portant than the choice of a del.

Driven Two-Wave Potential Model

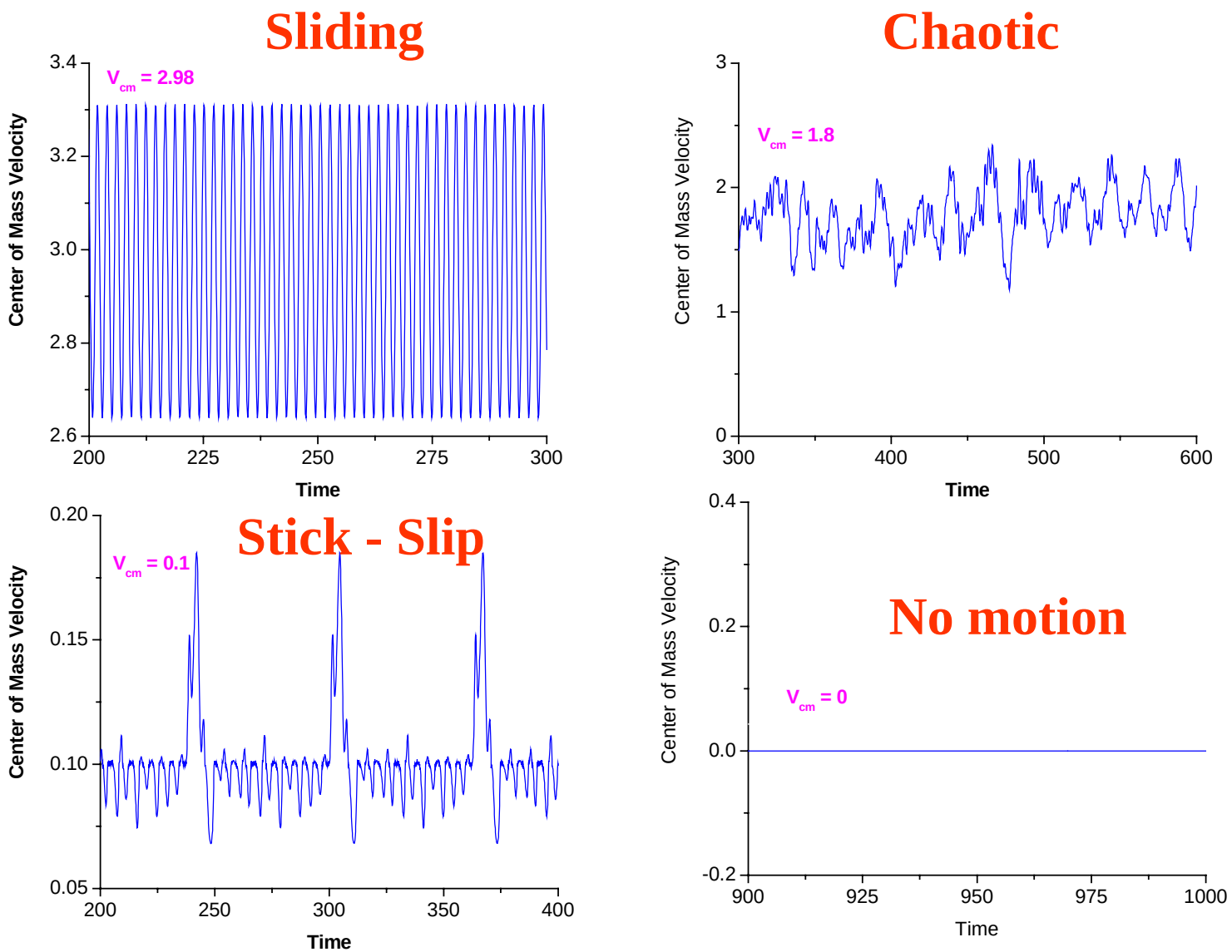
$$M\ddot{X} + \sum_{i=1}^{N}\gamma(\dot{X} - x_i) + K(X - Vt) + \sum_{i=1}^{N}\frac{\partial V(x_i - X)}{\partial X} = Control$$

$$m\ddot{x}_i + \gamma(2\dot{x}_i - \dot{X}) + \sum_{\substack{j=1\\ i\neq j}}^{N}\frac{\partial U(x_i - x_j)}{\partial x_j} + \frac{\partial V(x_i)}{\partial x_i} + \frac{\partial V(x_i - X)}{\partial x_i} = 0$$

F. Family, H. G. E. Hentschel, and Y. Braiman, J. Chem. Phys. B 104, 3984 (2000);
H. G. E. Hentschel, F. Family, and Y. Braiman, Phys. Rev. Lett. 83, 104 (1999).

Natural Motion

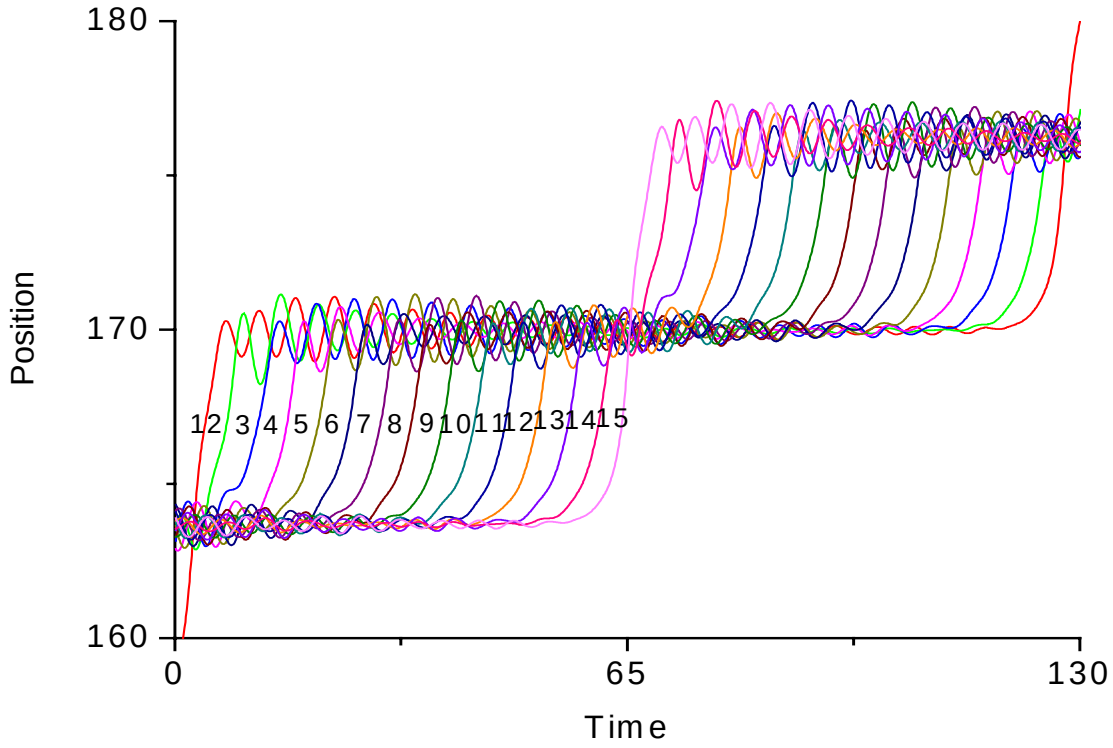
- **Free Sliding:** $v \approx f/\gamma$
- **No sliding (fixed point):** $v = 0$
- **Low velocity (stick - slip) motion:** $v = O(0.1)$
- **Chaotic motion:** $0 < v < f/\gamma$



CESAR
Center for Engineering Science Advanced Research

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

“Falling Domino” Dynamics



CESAR
Center for Engineering Science Advanced Research

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Values of the Sliding Velocities

Only particular values of velocities
of the "uncontrolled motion" can be observed:

$v = f/\gamma$ - free sliding

$v = v_{chaotic} = 1.8$ (just a single value
for given parameter set)

$v = kv_0$ here $v_0 = \frac{2\pi}{mN\gamma}\left(\frac{\pi - \cos^{-1} f}{\pi}\right)^{1/2}(\kappa - \kappa_c)^{1/2}$

N is the number of particles
and k is an integer

Y. Braiman, F. Family, and H. G. E. Hentschel,
Phys. Rev. E 53, R3005 (1996)

Friction Control During Sliding

- Feedback techniques - external perturbations

Benefits:
- Ability to continuously vary the average sliding velocity
- Fast transient times

- Non-feedback techniques - periodic perturbations

$$Control = \eta\alpha(v_{target} - v_{cm})^{\beta}$$

$\eta = 1$ if $v_{target} < v_{cm}$
-1 if $v_{target} > v_{cm}$

Mechanisms:
- Stabilizes already existing structures
- Creates new structures

J. Barhen, S. Gulati, and M. Zak, IEEE Computer June 1989, pp 67-76

Feedback Control Algorithm

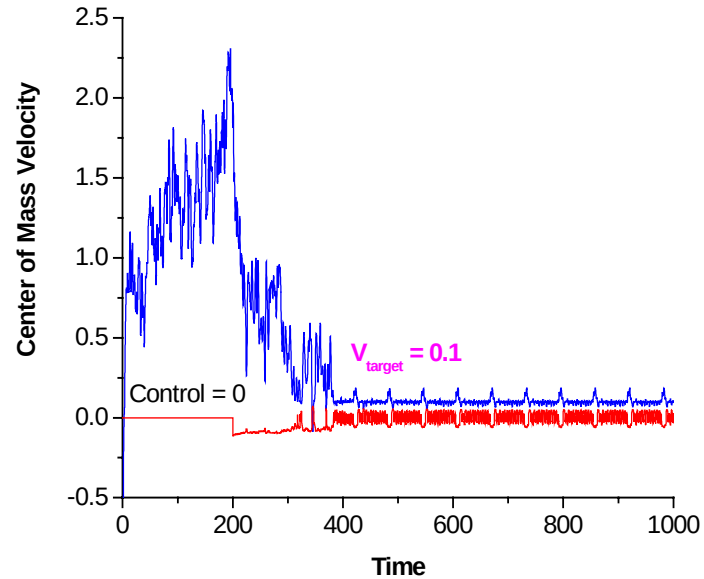
Use terminal attractor formalism (applied in neural nets)

$$Control = c_0 \alpha (v_{cm} - v_{target})^{\beta}$$

$$c_0 = -1 \text{ if } v_{cm} > v_{target} \text{ and}$$

$$c_0 = 1 \text{ if } v_{cm} < v_{target}$$

$$\beta = 1/n, \; n = 3, 5, 7.....$$



Benefits:

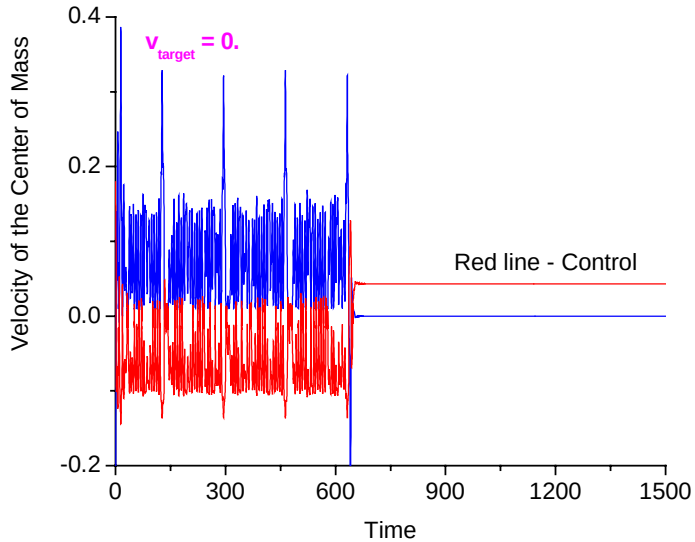
- **Ability to drive friction to a desired value**
- **Fast transient times**
- **Accessibility - requires only the measurement average quantities**

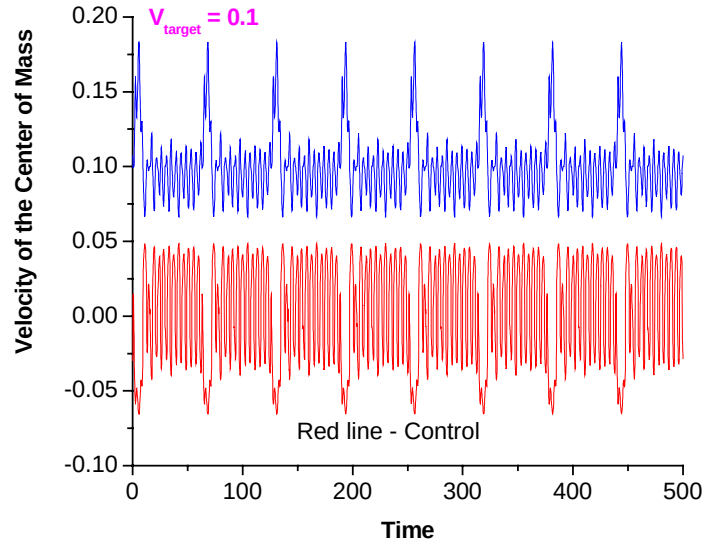
Y.Braiman, J. Barhen, and V. Protopopescu, "Control of Friction at the Nanoscale", Submitted to Phys. Rev. Lett. (2002).

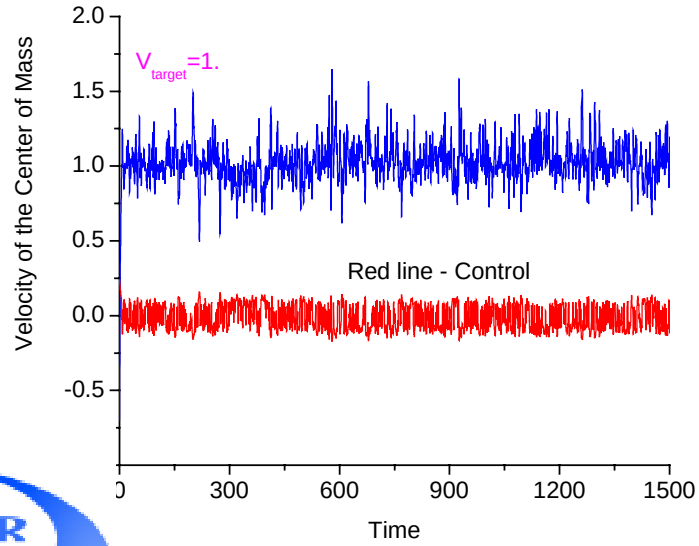
CESAR Center for Engineering Science Advanced Research

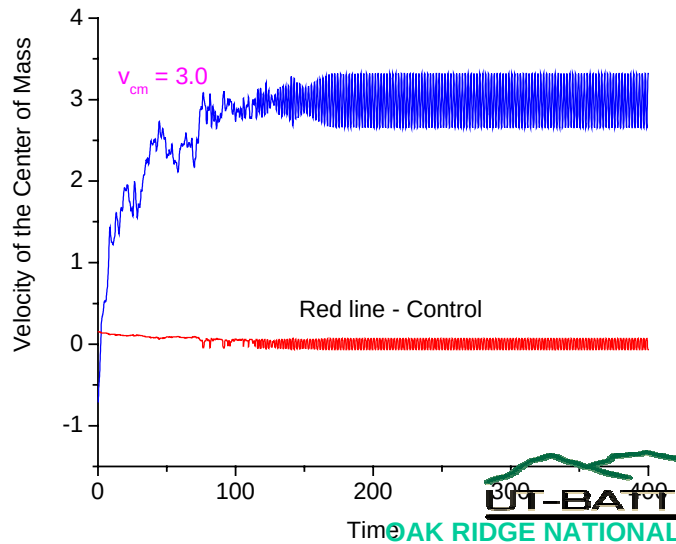
UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Performance of the Control Algorithm

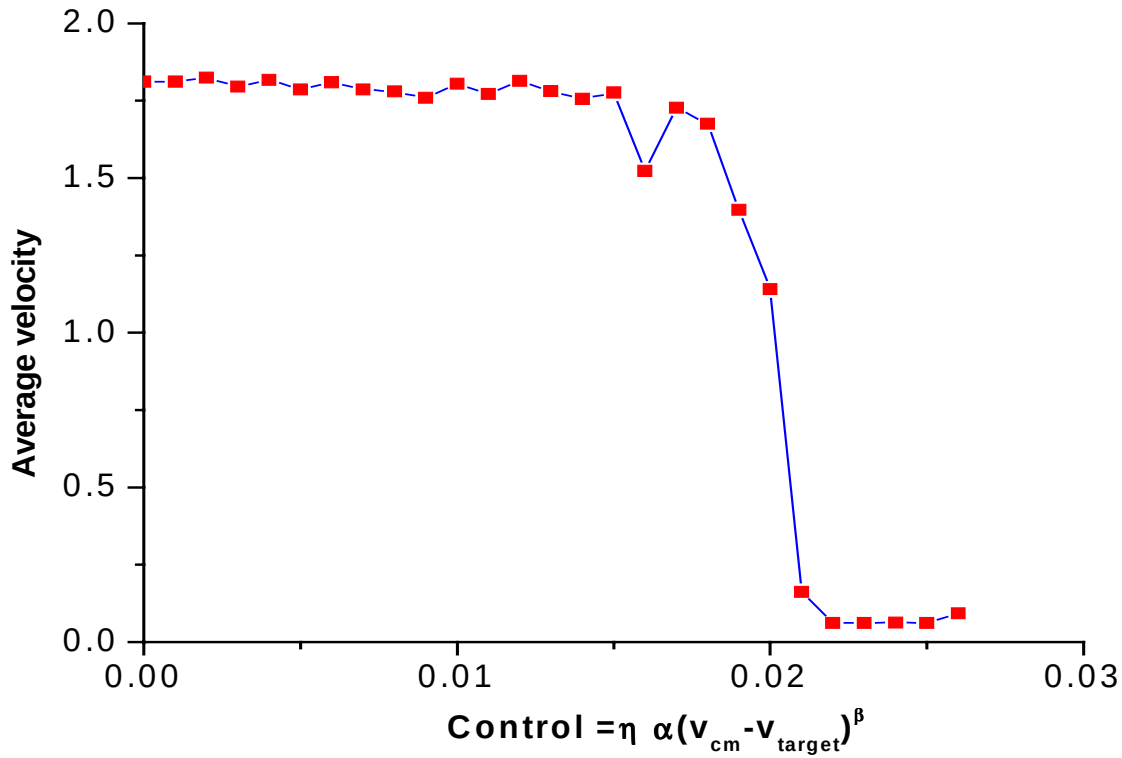




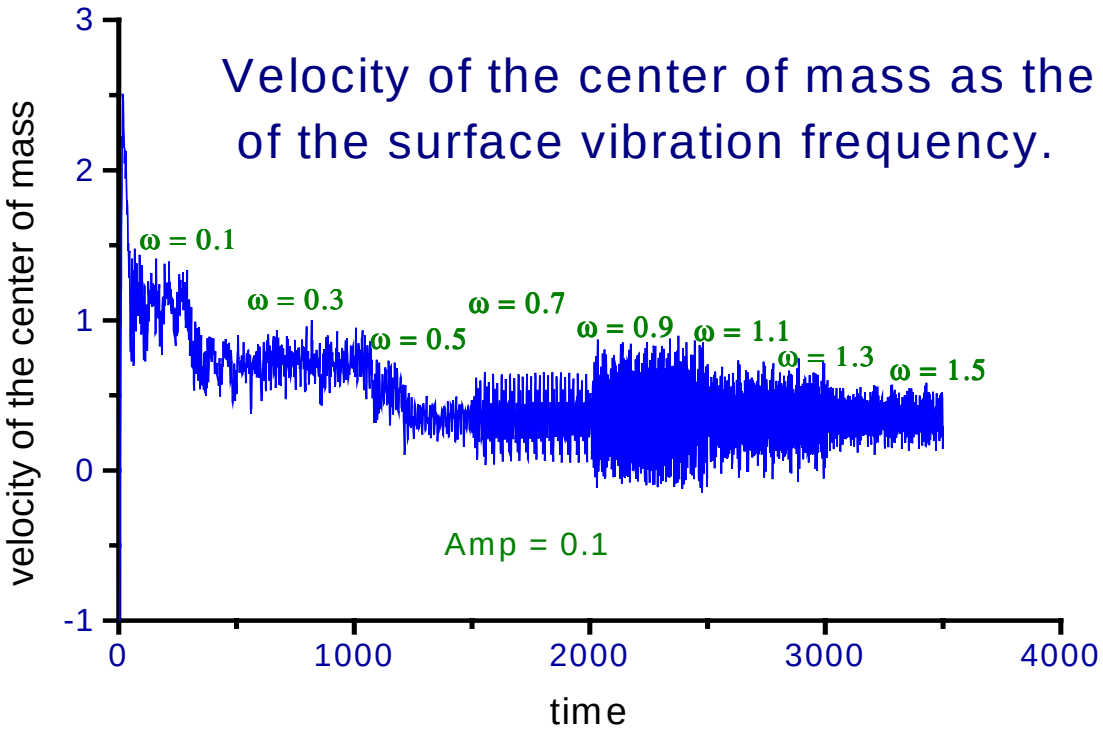




Strength of the Control

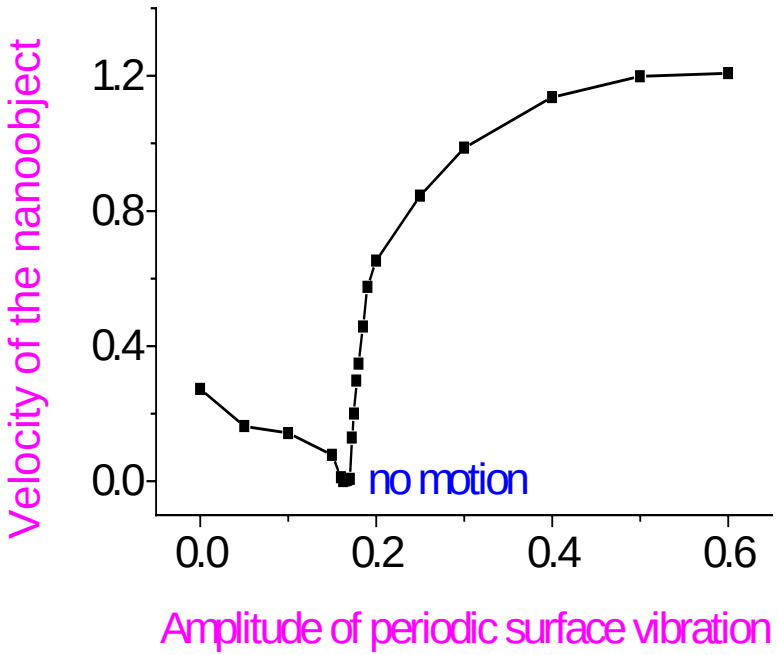


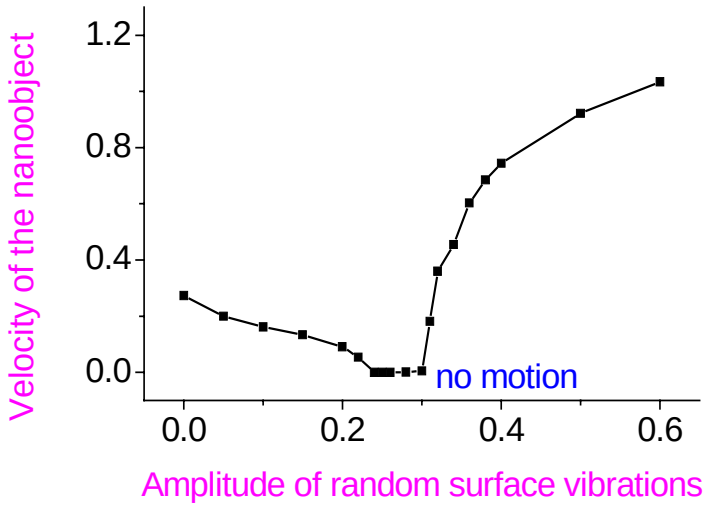
Friction Control by Surface Vibrations



M. Heuberger, C. Drummond, and J. Israelachvili, J. Chem. Phys. B 102, 5038 (1998);
J. Gao, W. D. Luedtke, and u. Landman, J. Phys. Chem. B 102, 5033 (1998);
M. G. Rozman, M. Urbakh, and J. Klafter, Phys. Rev. E 57, 7340 (1998);
F.-J. Elmer, Phys. Rev. E 57, R4903 (1998).

Theoretical Demonstration of the Effect of Surface Vibrations





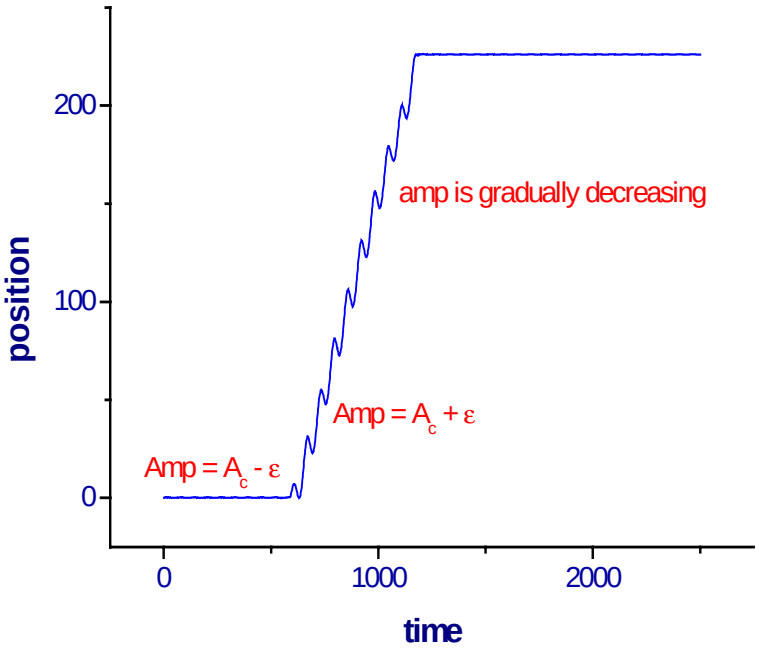
- Velocity is controlled by the amplitude of surface vibrations.
- Non-feedback control

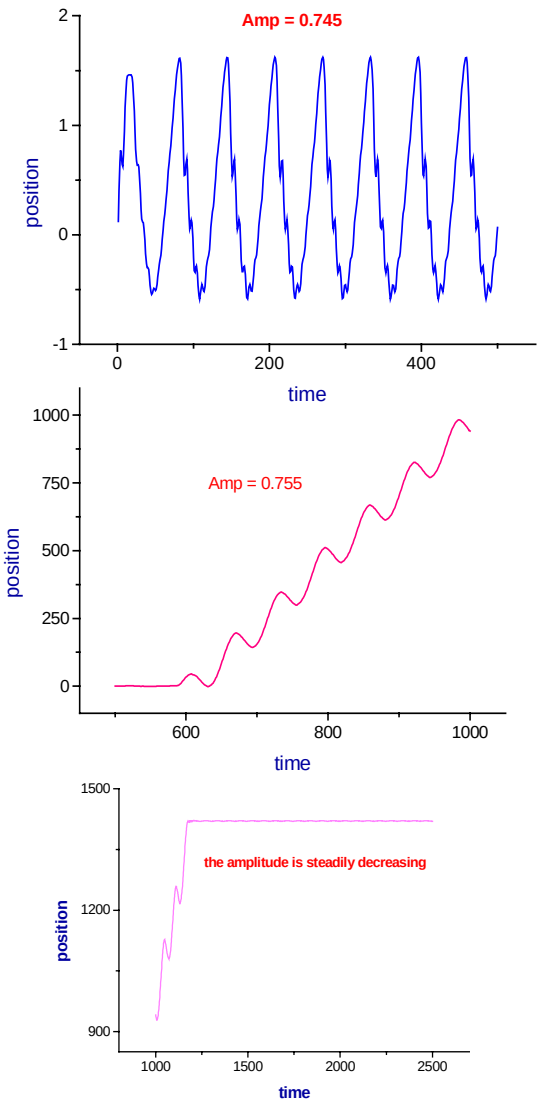
CESAR
Center for Engineering Science Advanced Research

Y. Braiman, J. Barhen, and V. Protopopescu, "Friction Control by Surface Vibrations" (in preparation).

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Transition to Sliding Behavior



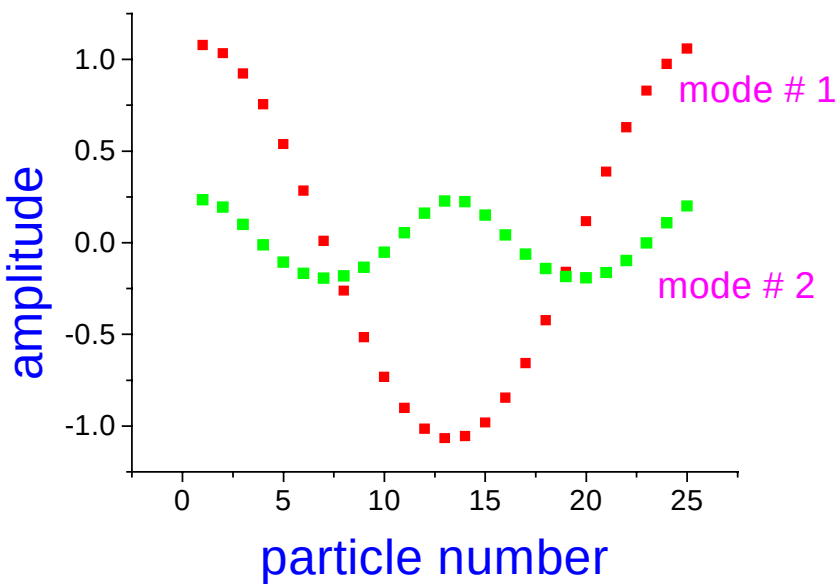


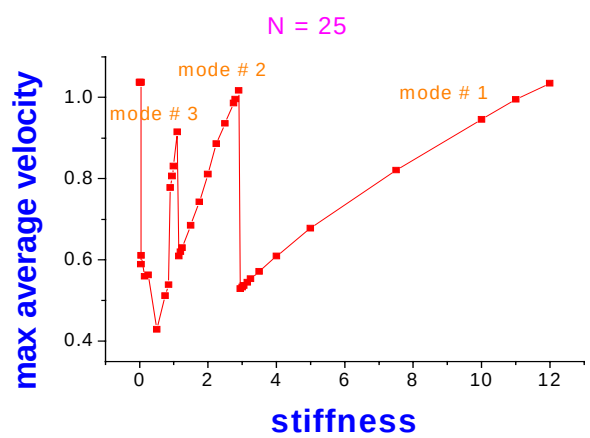
Locking of the Temporal and Spatial Dynamics (Modes)

Small size and confinement

The outcome $\Rightarrow$ Propagation modes

Each mode is characterized by different frictional behavior

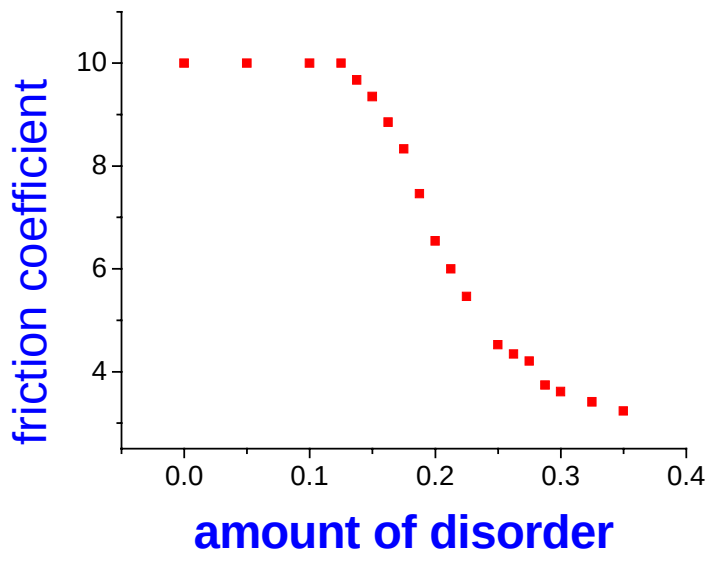




H. G. E. Hentschel, F. Family, and Y. Braiman, PRL 83, 104 (1999).

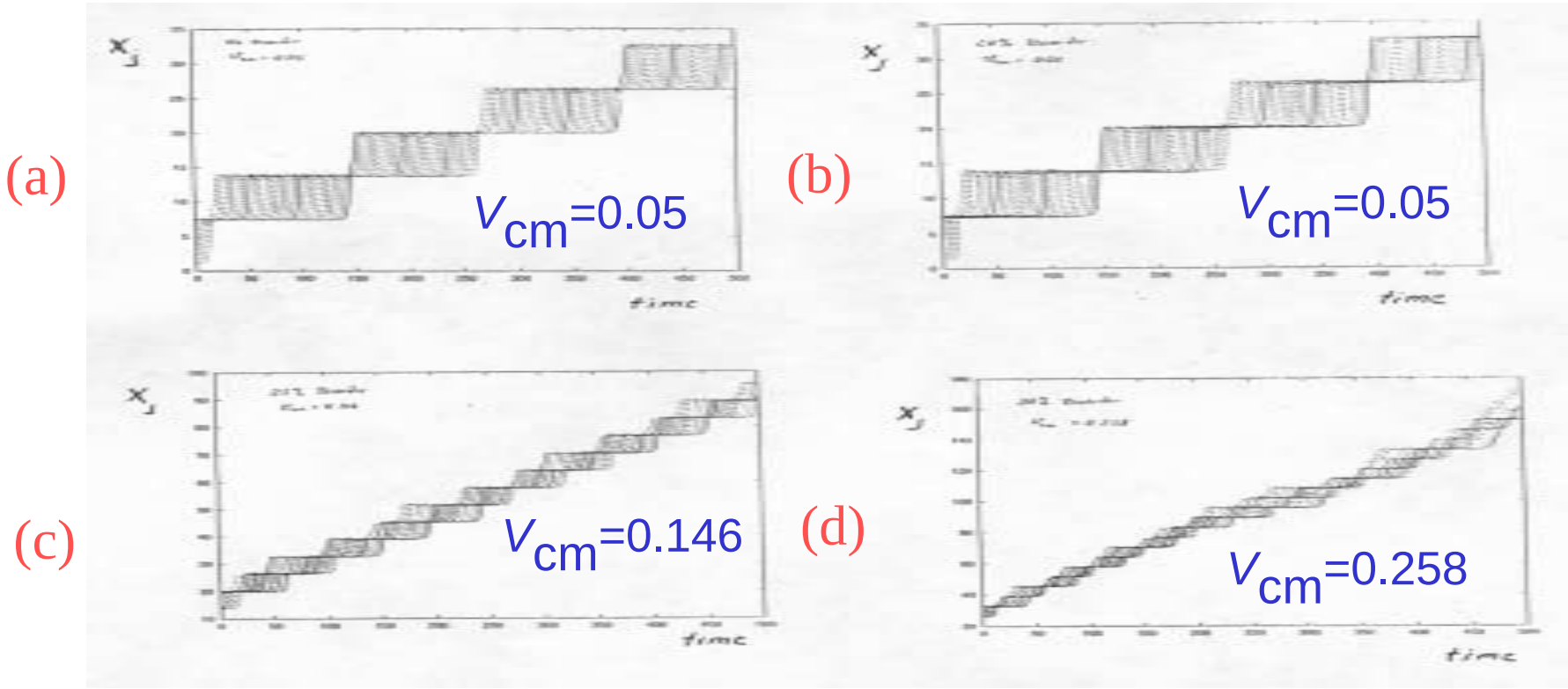
Sliding on Disordered Substrate

Friction coefficient can be significantly reduced
(by orders of magnitude) when sliding on irregular surfaces



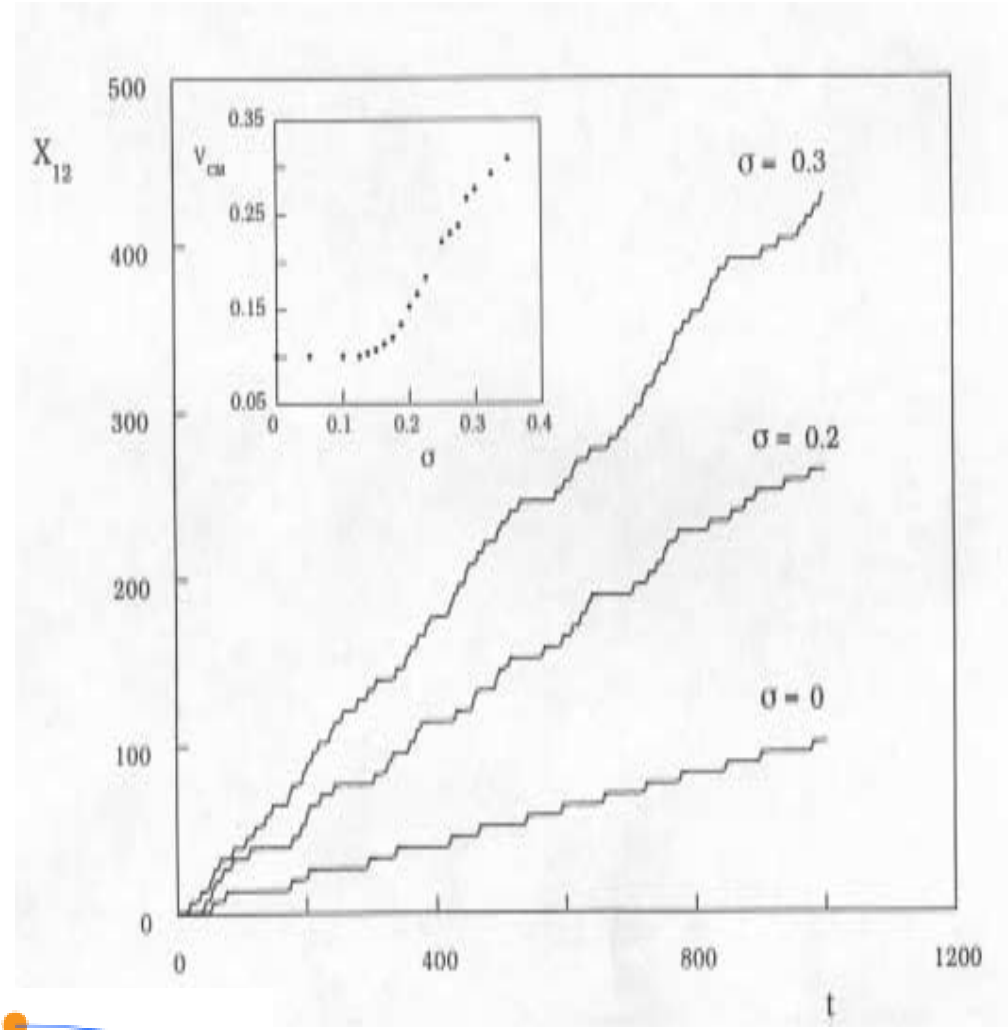
Y. Braiman, F. Family, H. G. E. Hentschel,
C. Mak, and J. Krim, PRE 59, R4737 (1999)

Disorder - Enhanced Synchronization



Time series of positions of all the particles in N=25 particle array for:
(a) the identical array; (b) 20% of disorder;
(c) 25 % of disorder; (d) 30 % of disorder

Sliding is Faster on Disordered Surfaces



The position of a particle #12 in array as a function of time.

The bottom curve corresponds to the identical array.
The middle curve corresponds to to the arrays with 20% of disorder,
The top curve corresponds to the array with 30% of disorder.

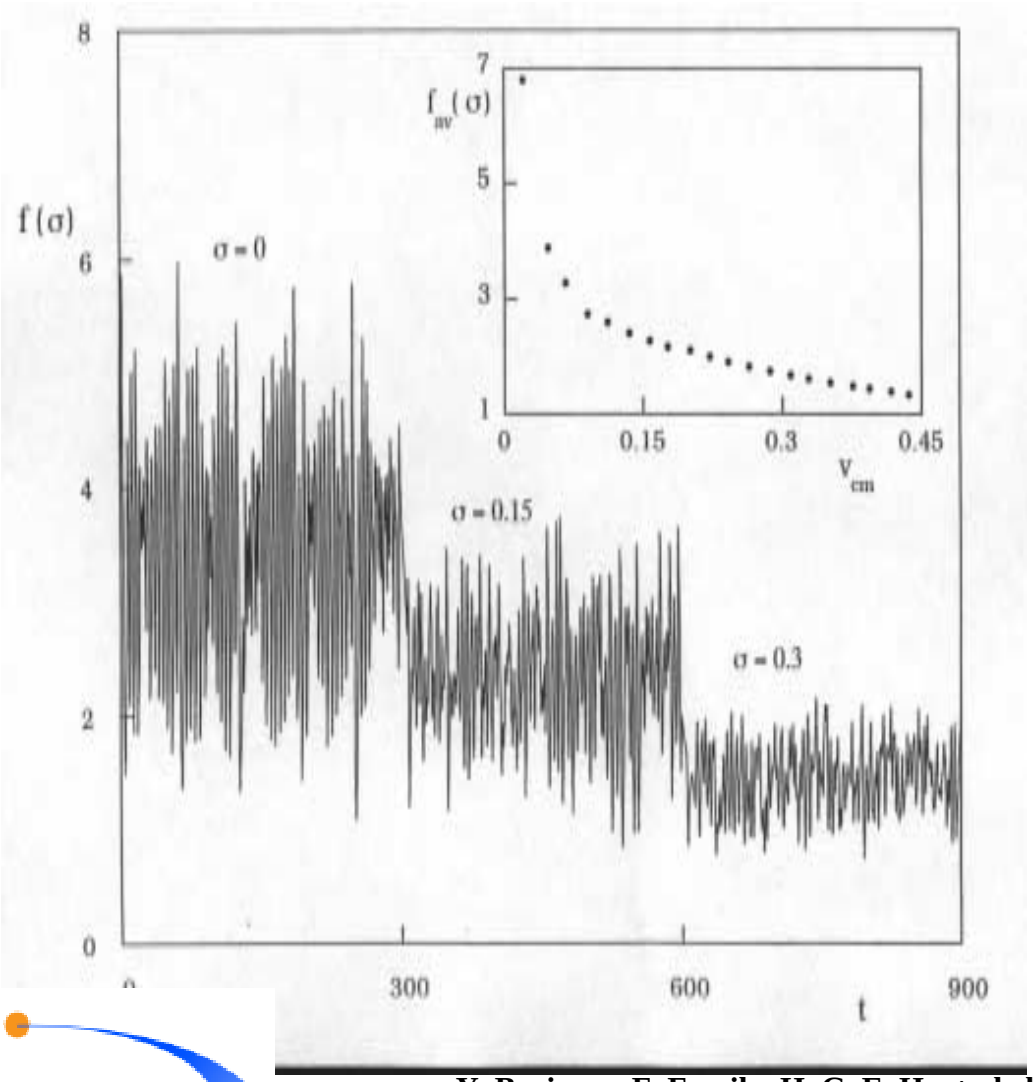
The inset shows the average velocity of the center of mass as a function of the amount of disorder

CESAR
Center for Engineering Science Advanced Research

Y. Braiman, F. Family, H. G. E. Hentschel, C. Mak, and J. Krim, PRE 59, R4737 (1999)

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Sliding is Faster for a Better Synchronized Array



Time series of the fluctuations from the center of mass f(σ) for different amounts of disorder.

The left-hand part of the plot corresponds to the identical array.
The middle part corresponds to σ=15%.
The right-hand part corresponds to σ=30%.
The inset shows the average fluctuations from the center of mass as the function of the velocity of the center of mass.

Y. Braiman, F. Family, H. G. E. Hentschel, C. Mak, and J. Krim, PRE 59, R4737 (1999)

Summary

We proposed control algorithm that enables us to control the average velocity (friction coefficient) of the chain *during sliding*.

Benefits:

- **Ability to continuously vary the average sliding velocity**
- **Ability to reach desired sliding velocity**
- **Fast transient times**
- **The applied control is limited in strength**
- **Requires only limited accessibility**

Mechanisms:

- **Stabilizes already existing spatial structures**
- **Creates new spatiotemporal structures**

Acknowledgements

This research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences. The Oak Ridge National Laboratory is managed for the U.S. DOE by UT-Battelle, LLC, under contract No. DE-AC05-00OR22725.

CESAR
Center for Engineering Science Advanced Research

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY