Control of Friction at the Nanoscale

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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 !

Theoretical Modeling

- Phenomenological models
- F-K-Tomlinson model

$$m\ddot{X}_j + g\,\dot{X}_j = -\partial U / \partial X_j - \partial V / \partial X_j + f_j + h_j$$

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

The Model

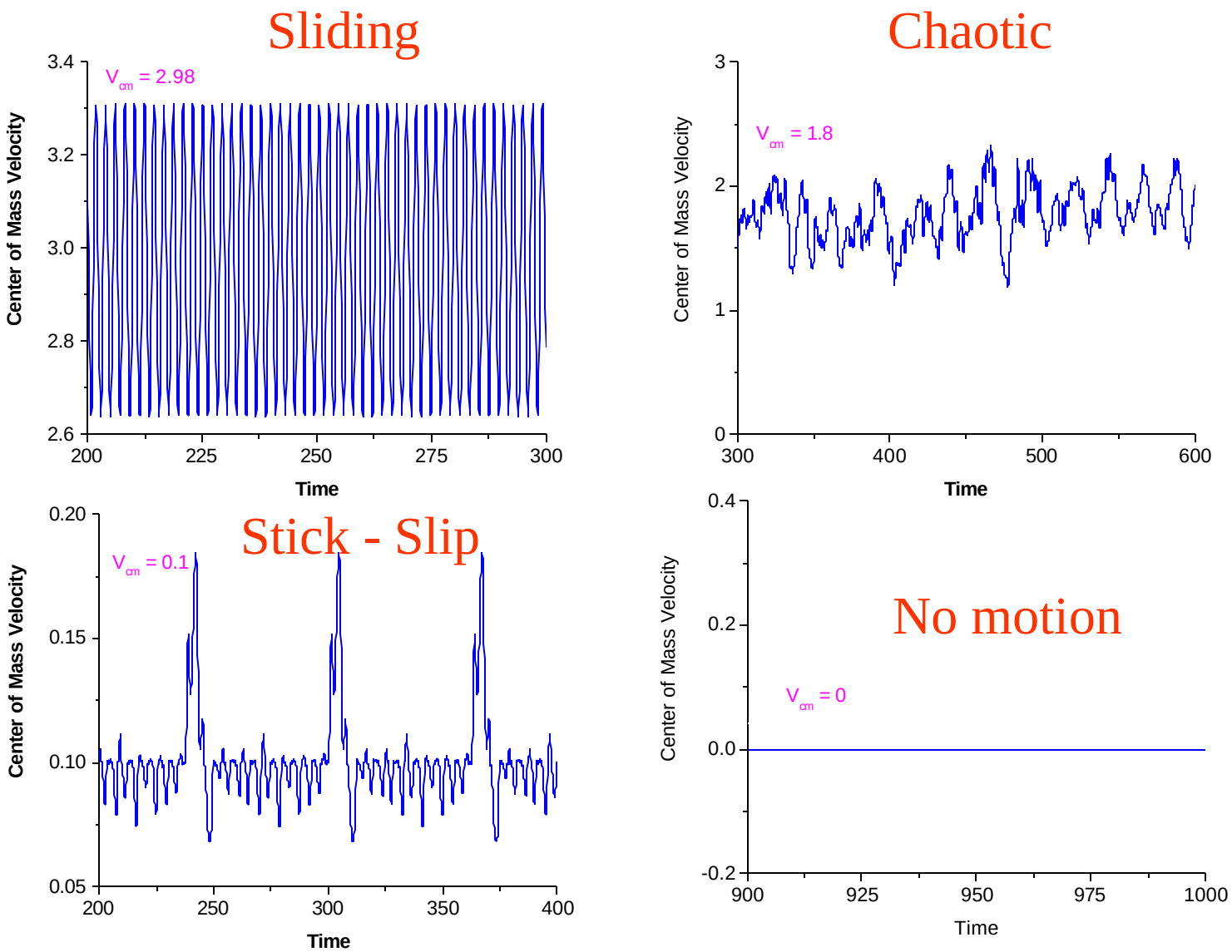
Driven Frenkel-Kontorova Model

$$\ddot{x}_j + g\dot{x}_j + \sin x_j = f + k(x_{j+1} - 2x_j + x_{j-1}) + Control$$

x_j - position of the particle j
g - single particle dissipation
f - external forcing
k - the ratio of the interparticle to substrate interactions

Natural Motion

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


Sliding
V_{cm} = 2.98
Center of Mass Velocity
Time
Chaotic
V_{cm} = 1.8
Center of Mass Velocity
Time
Stick - Slip
V_{cm} = 0.1
Center of Mass Velocity
Time
No motion
V_{cm} = 0
Center of Mass Velocity
Time

Values of the Sliding Velocities

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

$v = f/g$ - free sliding

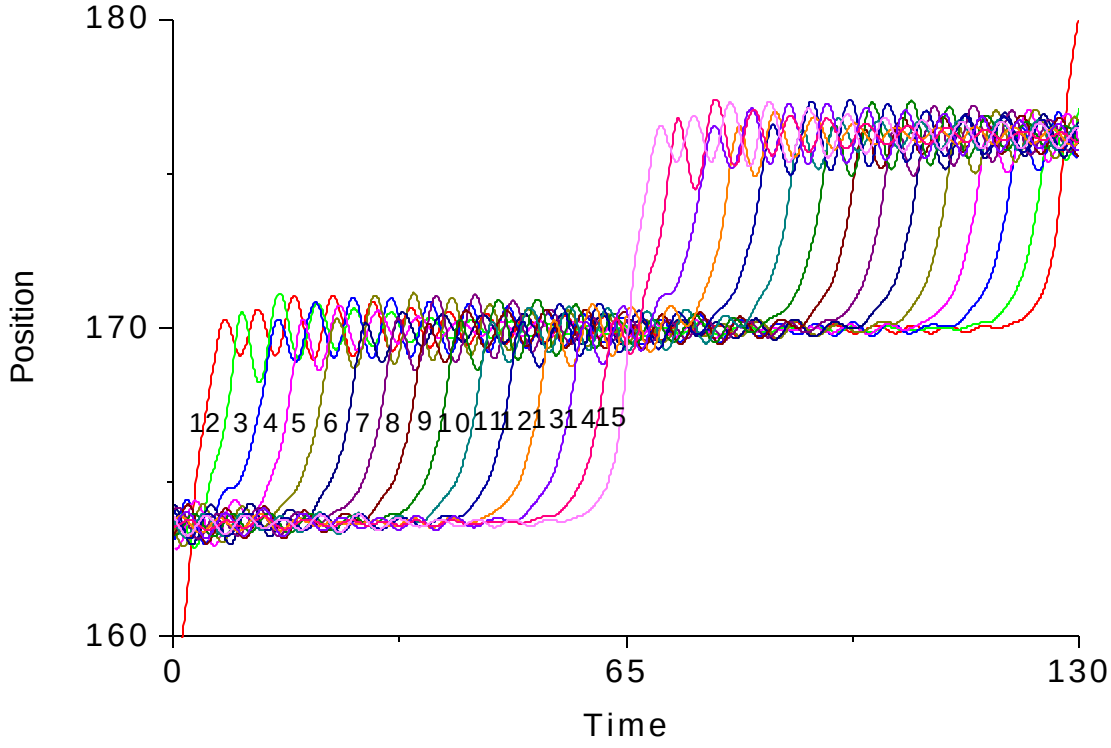
$v = v_{chaotic} = 1.8$ (just a single value
for given parameter set)

$v = kv_0$ here $v_0 = \frac{2p}{mNg}\left(\frac{p - \cos^{-1} f}{p}\right)^{1/2}(k - k_c)^{1/2}$

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)

“Falling Domino” Dynamics

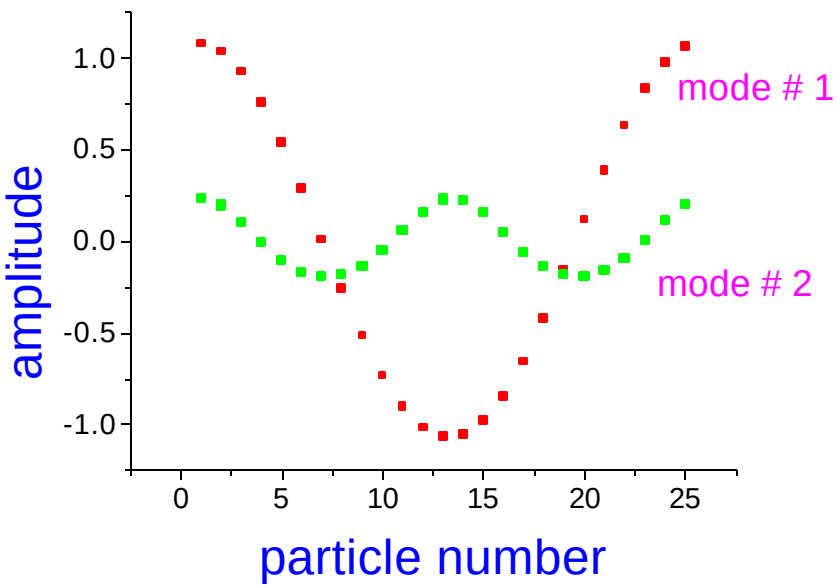


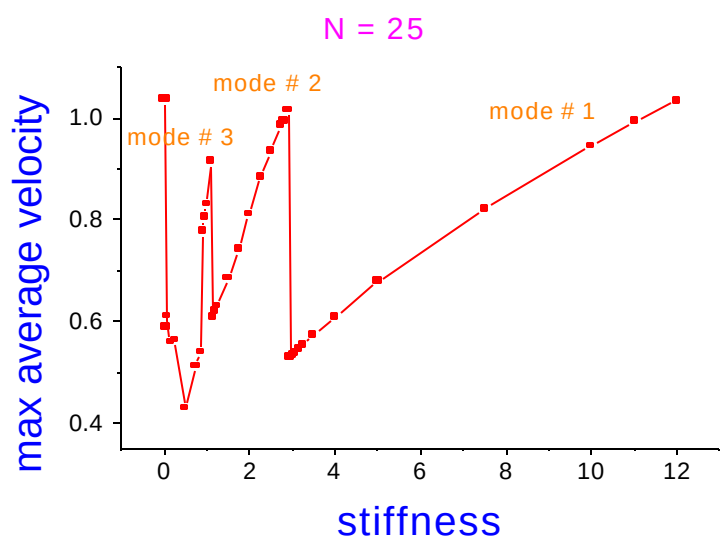
Locking of the Temporal and Spatial Dynamics (Modes)

Small size and confinement

The outcome Þ Propagation modes

Each mode is characterized by different frictional behavior

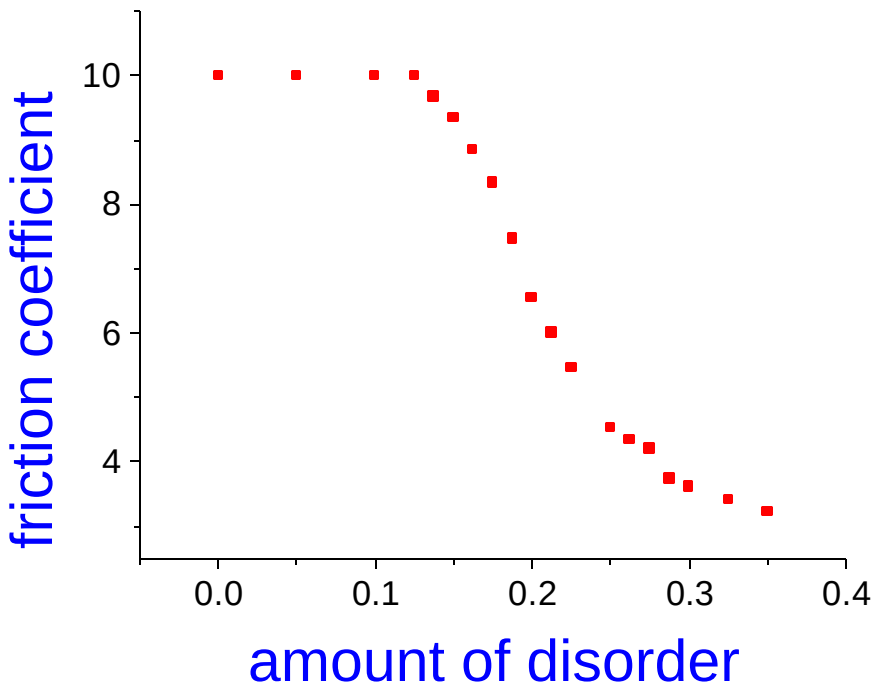




H. G. E. Hentschel, F. Family, and Y. Braiman, PRL **83**, 104 (1999).

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)

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

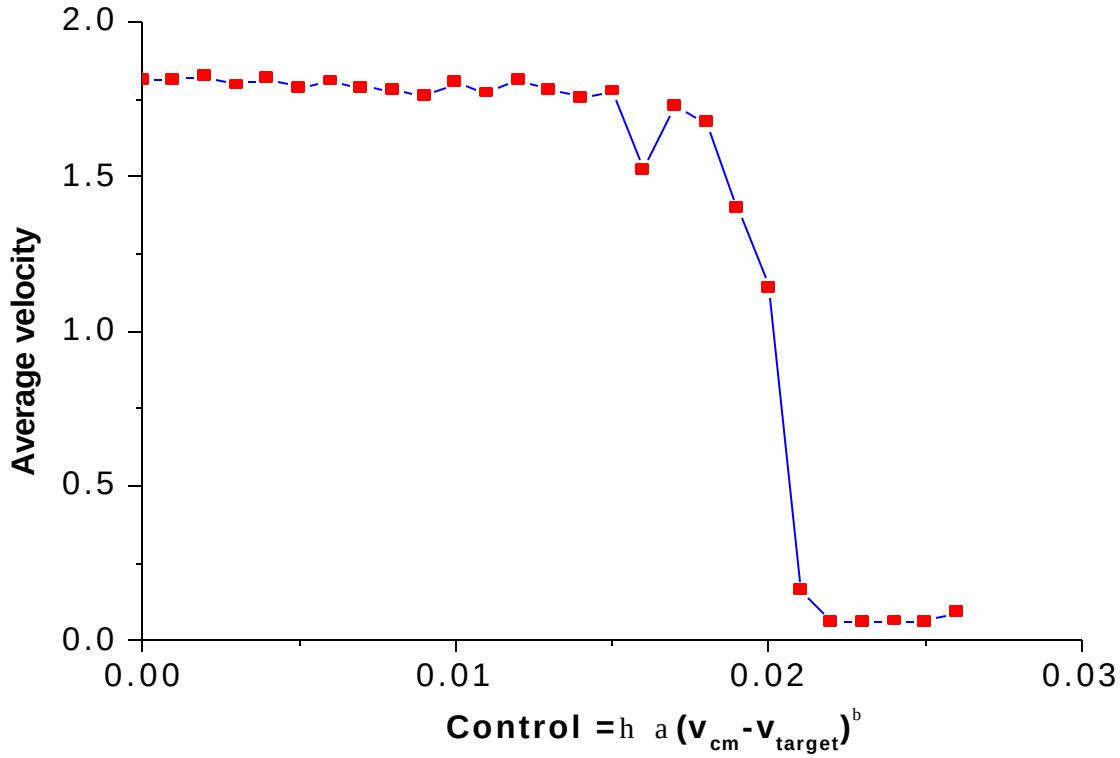
$$Control = h\,a\,(v_{target} - v_{cm})^b$$

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

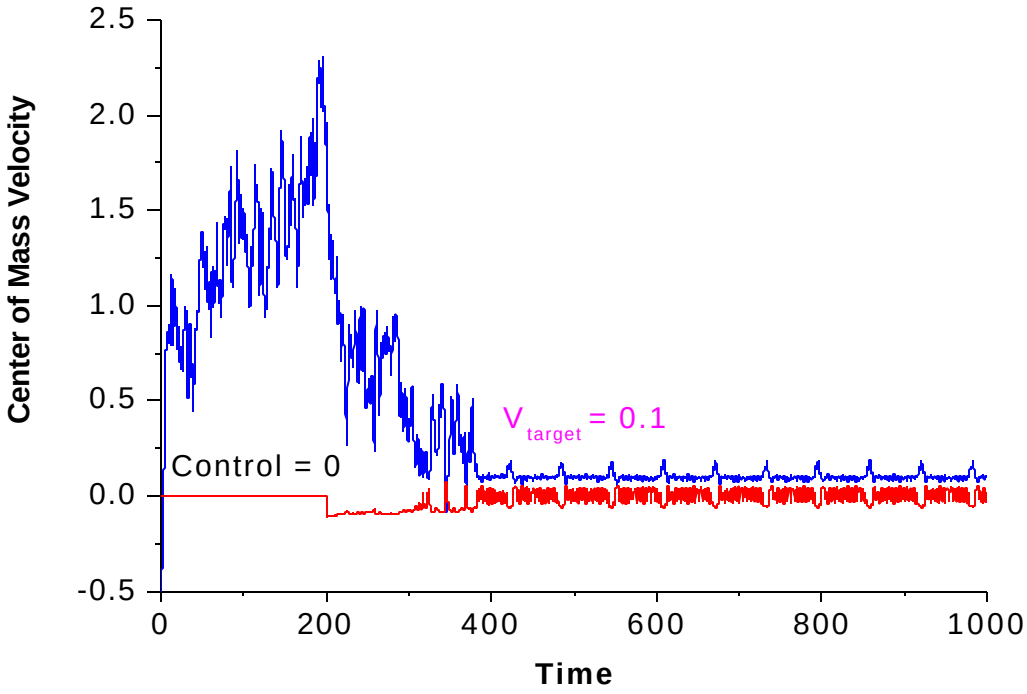
Mechanisms:
- Stabilizes already existing structures
- Creates new structures

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

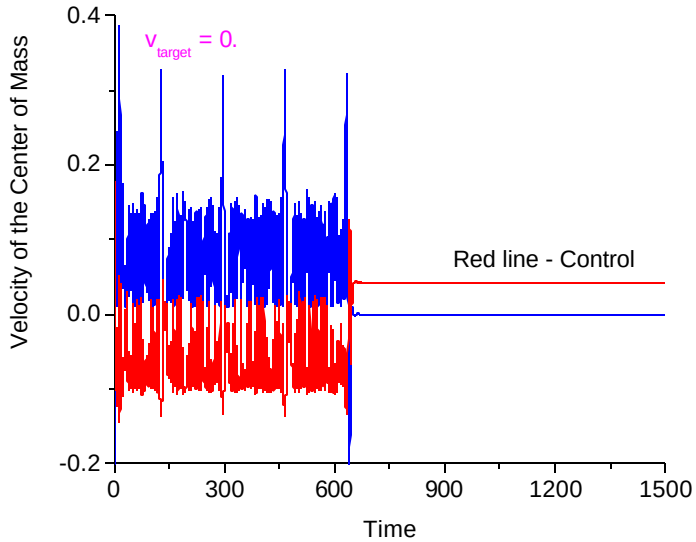
Strength of the Control

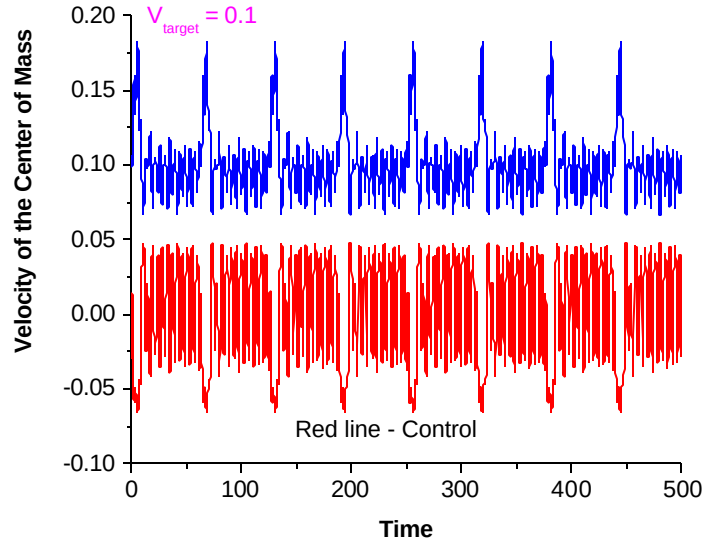


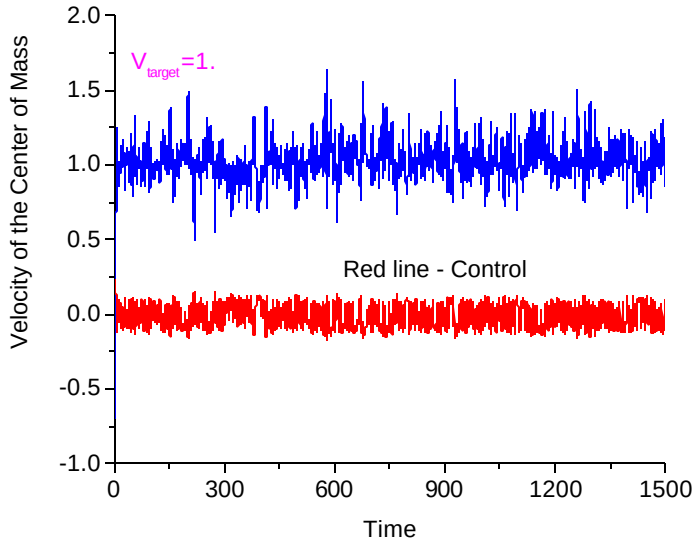
Fast Transient Times

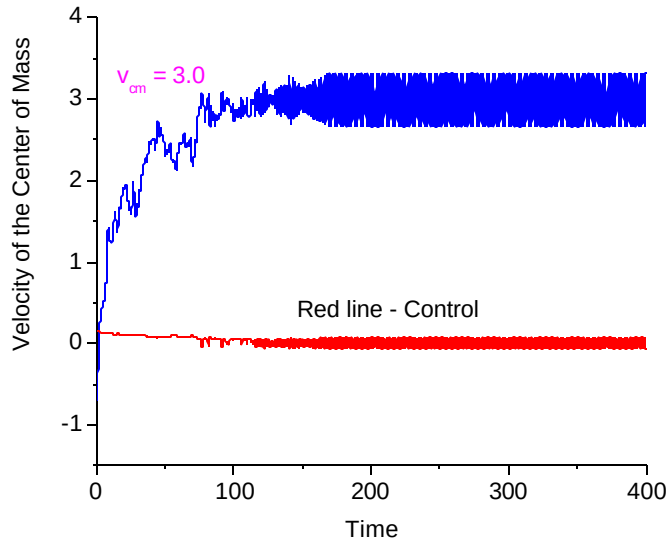


Performance of the Control Algorithm

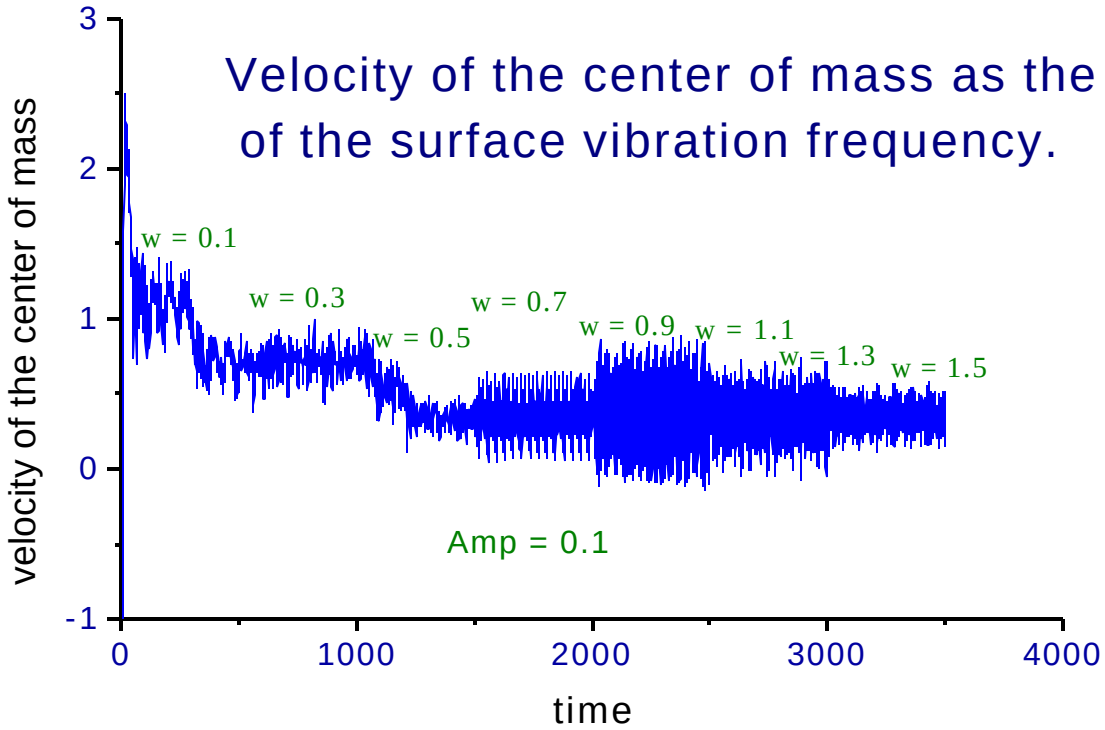






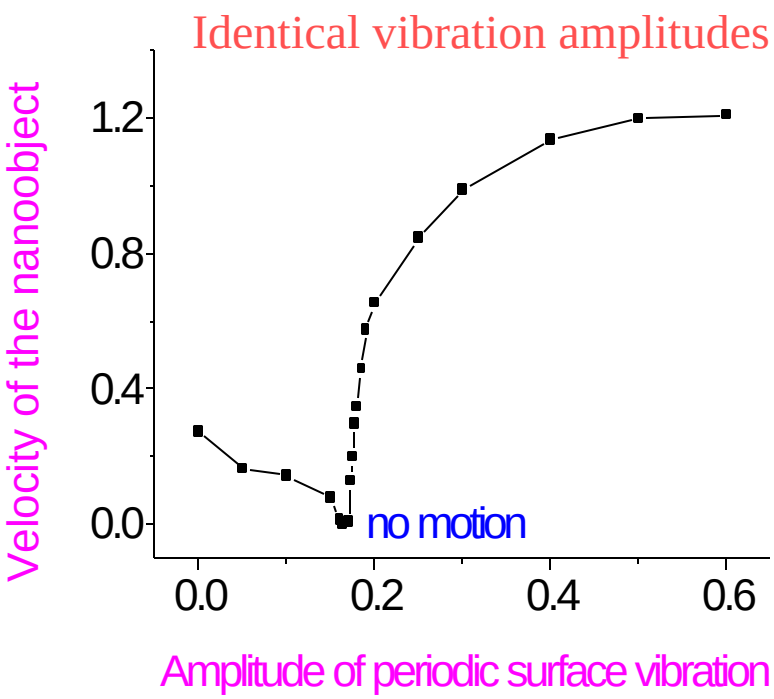


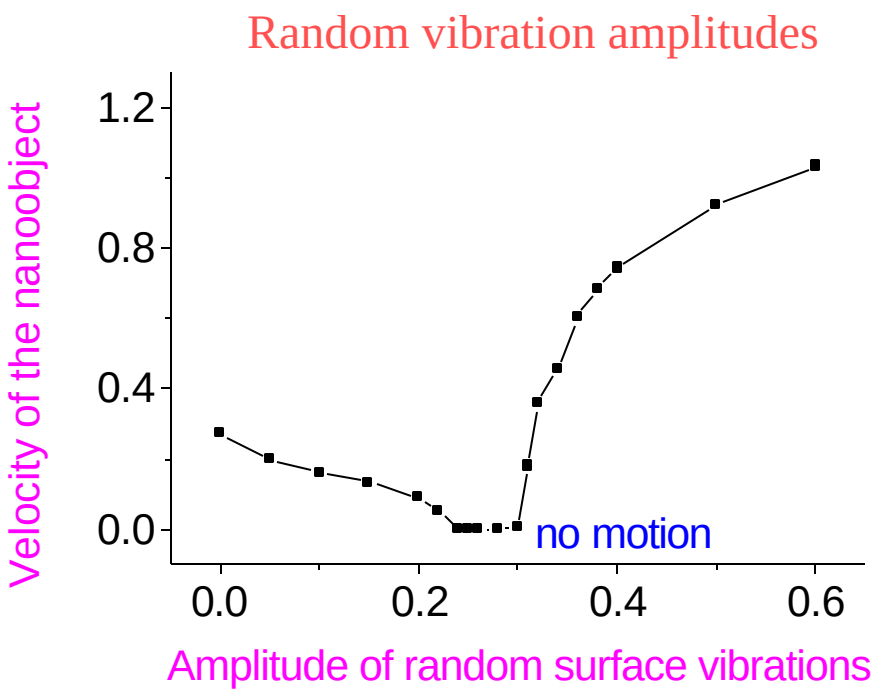
Friction Control by Surface Vibrations



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).

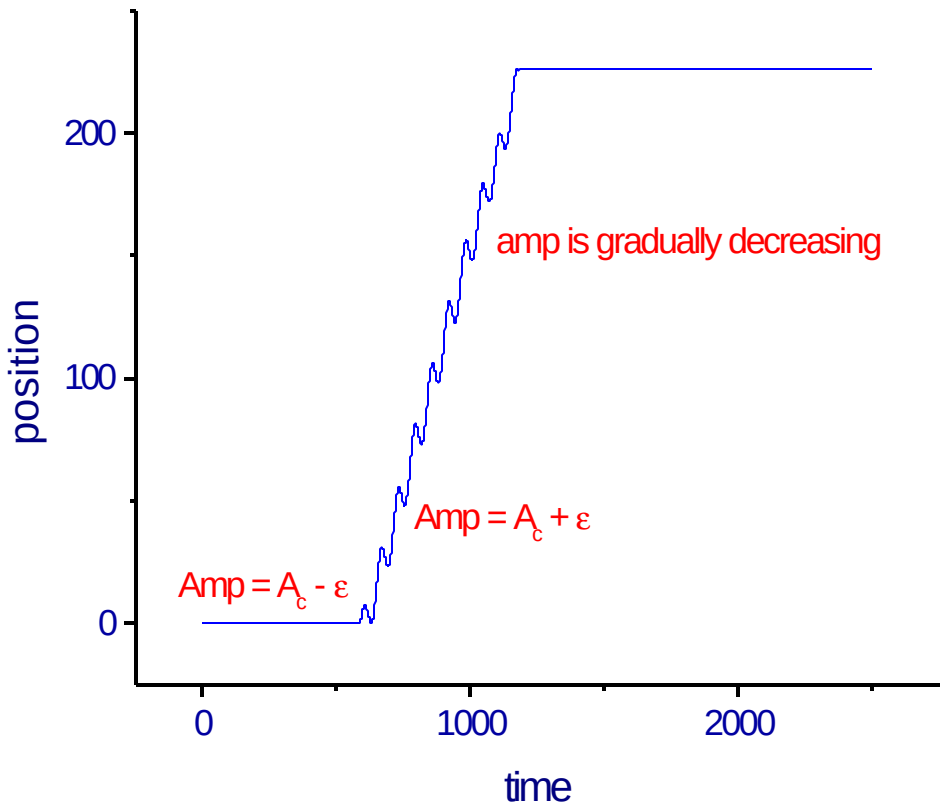
Demonstration of the Effect of Surface Vibrations

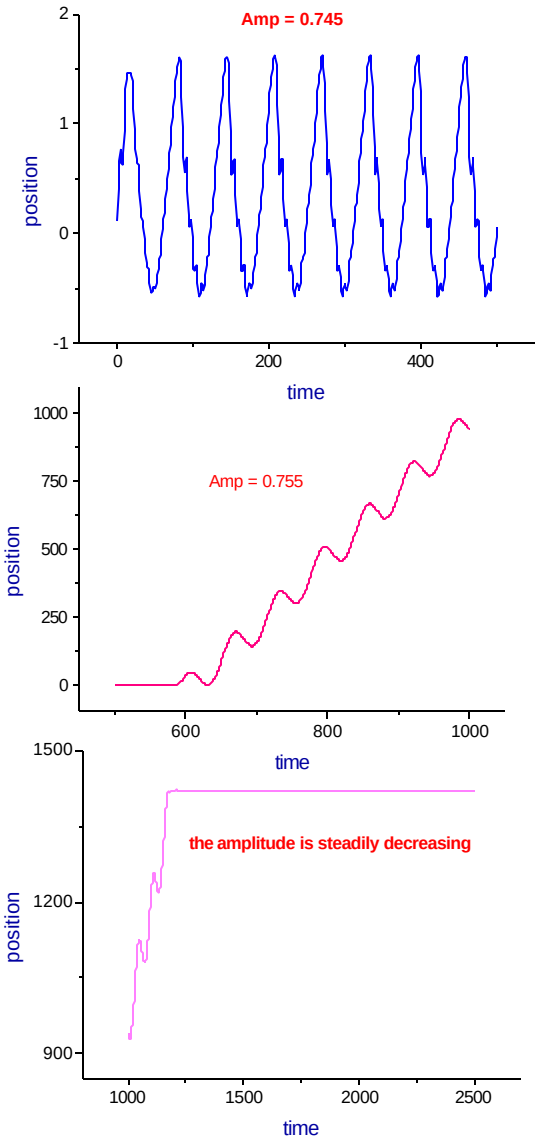




Velocity is controlled by the amplitude of surface vibrations.

Transition to Sliding Behavior





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.

Partial Travel Support - DARPA/MTO