Control of Friction at the Atomic Scale

Y. Braiman,[1,2] J. Barhen,[1,2] S. Jeon,[1,3] G. Pharr[4], V. Protopopescu,[1,2] A. Rar[4], and T. Thundat[1,3]

[1] **Center for Engineering Science Advanced Research**
[2] **Computer Science & Mathematics Division**
[3] **Life Sciences Division**
[4] **Metal and Ceramics Division**
Oak Ridge National Laboratory

This research was supported by the Division of Materials Sciences and Engineering, U. S. Department of Energy, under Contract DE-AC05-00OR22725 with UT-Battelle, LLC.

Content

- Introduction
- Feedback and Non-Feedback Control of Friction
- Non-Lipschitzian Control Technique
- Numerical Demonstration of the Control
- Control of Friction by Surface Oscillations
- Experimental Demonstration of the Control
- Summary and Further Research Directions

Motivation

- **Velocity/friction force control *during sliding***
- **Ability to reach desired targeted behavior**
- **Achieve fast transient times**
- **The applied control is limited in strength**
- **Requires only limited accessibility**
- **Uses global variables**

Friction can be manipulated by applying small perturbations to accessible elements and parameters of the sliding system.

- Using a surface force apparatus, modified for measuring friction forces while simultaneously inducing normal (out-of-plane) vibrations between two boundary-lubricated sliding surfaces, load- and frequency-dependent transitions between a number of "dynamical friction" states have been observed [1].
- Extensive grand-canonical molecular dynamics simulations [2] revealed the nature of the dynamical states of confined sheared molecular films, their structural mechanisms, and the molecular scale mechanisms underlying transitions between them.
- Methods to control friction in systems under shear that enable to eliminate chaotic stick-slip motion were proposed in [3]. Significant changes in frictional responses were observed in the two-plate model [4] by modulating the normal response to lateral motion [5].
- The surface roughness and the thermal noise are expected to play a significant role in deciding control strategies at the micro and the nano-scale [6].

1. M. Heuberger, C. Drummond, and J. Israelachvili, J. Phys. Chem. B 102, 5038 (1998).
2. J. P. Gao, W. D. Luedtke, and U. Landman, J. Phys. Chem. B, 102, 5033 (1998).
3. M. G. Rozman, M. Urbakh, and J. Klafter, Phys. Rev. E 57, 7340 (1998).
4. M. G. Rozman, M. Urbakh, and J. Klafter, Phys. Rev. Lett., 77, 683 (1996), and Phys. Rev. E 54, 6485 (1996).
5. V. Zaloj, M. Urbakh, and J. Klafter, Phys. Rev. Lett., 82, 4823 (1999).
6. Y. Braiman, F. Family, H. G. E. Hentschel, C. Mak, and J. Krim, Phys. Rev. E, 59, R4737 (1999).

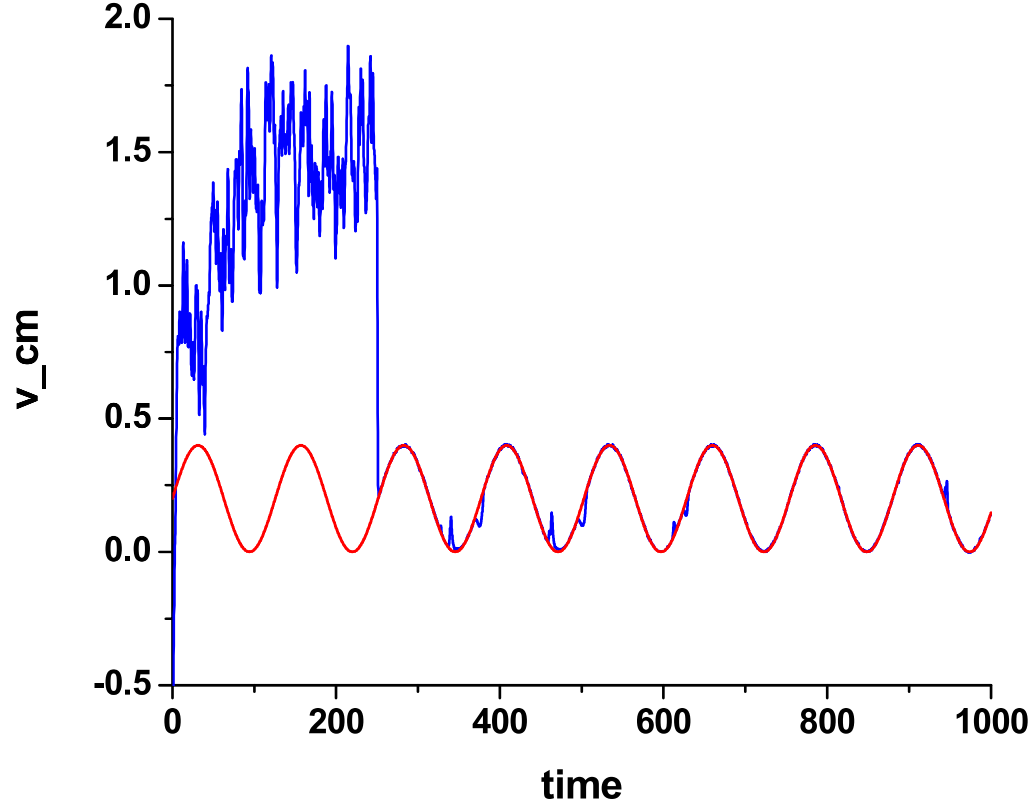
- **Experimentally, friction can be manipulated by applying in-plane and out-of-plane surface vibrations. This is realized, for example, by the use of a quartz piezo-element that oscillates the surface of frictional contact. The frequency of such an oscillation may vary from few Hz to MHz, and, perhaps to GHz limit using micro/nano cantilevers**

- **Our experiments demonstrate that already very slow (in the range of 100 Hz) vibrations can significantly alter the frictional behavior of the sliding system. This evidence strongly indicates the existence of a much slower time scale that governs the dynamics of the frictional system.**

- **From the algorithmic standpoint, friction can be controlled by applying small perturbations to accessible elements and parameters of the sliding system. Here, the challenge is to design control strategies that require only minimal accessibility.**

- **Both feedback and non-feedback means of control have been considered and speed, accessibility, and predictability considerations are those that prevail in choosing the optimal best strategy.**

Friction Control



Time series of the center of mass velocity (in dimensionless units). The red line shows the target velocity function, $v(t) = 0.2 + 0.2 \sin(0.05\, t)$, and the blue line shows the center of mass velocity. The control is applied every time step, starting at $t = 250$. The parameters are: $N = 15$, $\gamma = 0.1$, $f = 0.3$, $\kappa = 0.26$, $\alpha = 1$, $b = 0$, and $\zeta = 7$.

Non-Lipschitzian Dynamics

Lipschitz condition: the derivatives of the right-hand side of the dynamical equations with respect to the state variables is bounded

Consider: $\dot{\phi}(t) = -\phi^{1/7}$

At the equilibrium point, $\phi = 0$, *Lipschitz condition is violated, since* $\partial\dot{\phi}/\partial\phi = -(1/7)\phi^{-6/7}$ **tends to $-\infty$ as ϕ tends to zero.**

Thus the equilibrium point $\phi = 0$ is an attractor with "infinite" attraction power (terminal attractor).

Non-Lipschitzian Control of Friction
for AFM and SFM-type experiments

Attractor: $C_1(t) = \alpha(f(t)_{target} - f_m)^\beta$

Repeller:

$$C_2(t) = \rho(f_{av} - f_m)^\beta \times \mathrm{sgn}[(f_{av} - f_m)(f_m - f(t)_{target})] \times H[r - |f(t)_{target} - f_{av}|]$$

$$H(z) = 1 \; for \; z > 0, \text{ and } H(z) = 0 \; for \; z < 0$$

$$\beta = 1/(2n+1), \; n = 1, 2, 3, \ldots$$

Control: $C(t) = C_1(t) - C_2(t)$

Non-Lipschitzian Control of Friction
for QCM-type of experiment

Attractor: $f_1(t) = \alpha(v(t)_{target} - v_{cm})^{\beta}$

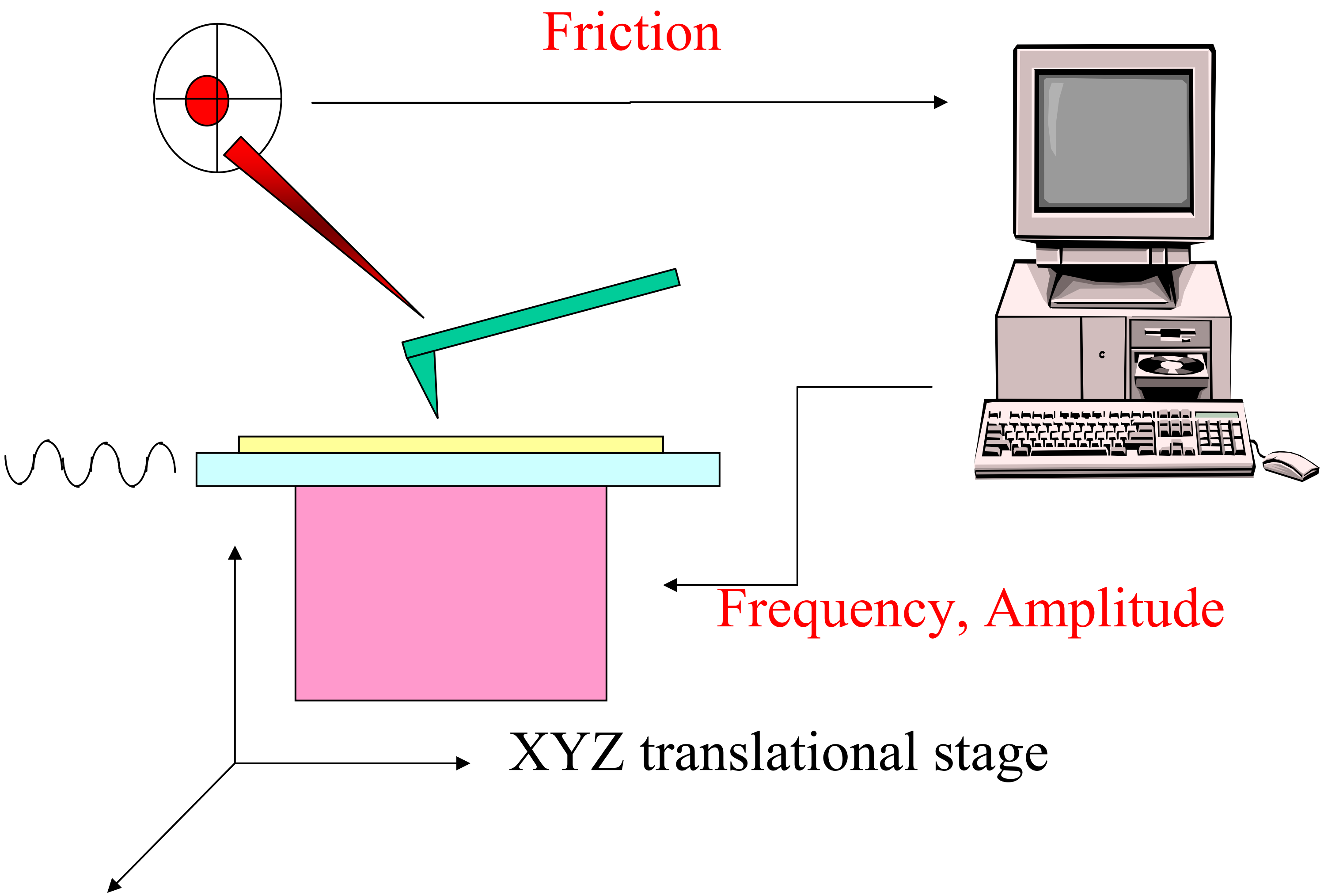
Repeller:

$$f_2(t) = \rho(v_{av} - v_{cm})^{\beta} \times \mathrm{sgn}[(v_{av} - v_{cm})(v_{cm} - v_{target})] \times H[r - |v_{target} - v_{av}|]$$

$$H(z) = 1 \; for \; z > 0, \text{ and } H(z) = 0 \; for \; z < 0$$

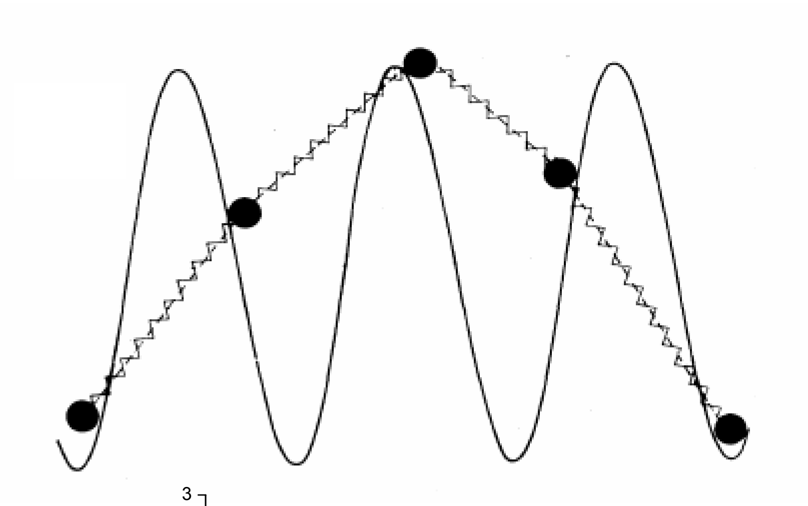
$\beta = 1/(2n+1), \; n = 1, 2, 3, \ldots$

Control: $f_c(t) = f_1(t) - f_2(t)$

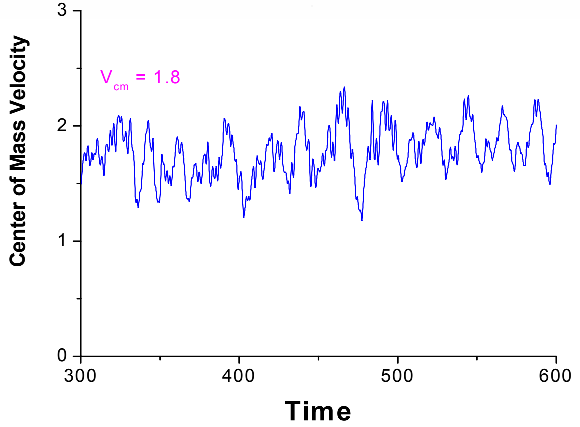

Friction
Frequency, Amplitude
XYZ translational stage

Friction Control - a Model

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



x_j is the position of the particle j
m is the mass of the sliding particle
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)



Control:

$$C(t) = \alpha (v(t)_{target} - v_{cm})^{\beta}$$

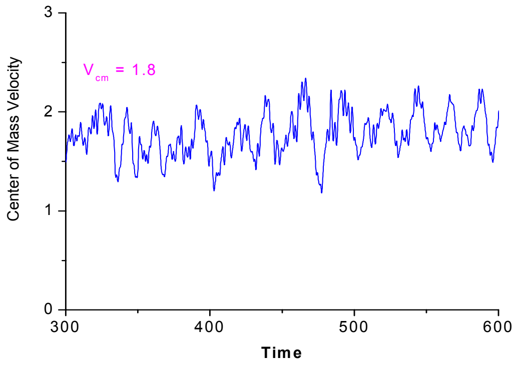
$$\beta = 1/(2n+1),\ n = 1, 2, 3, \ldots$$

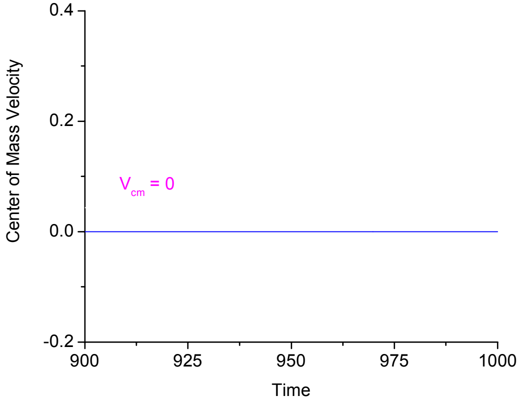
The Model

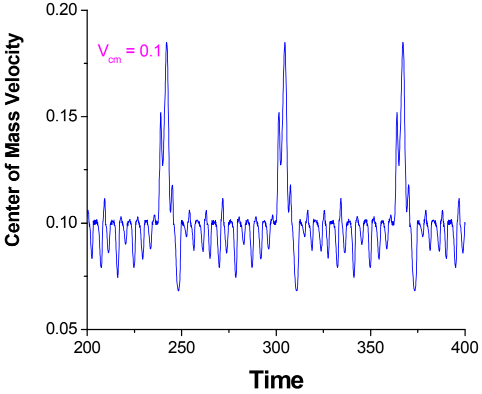
Driven Frenkel-Kontorova Model

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

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

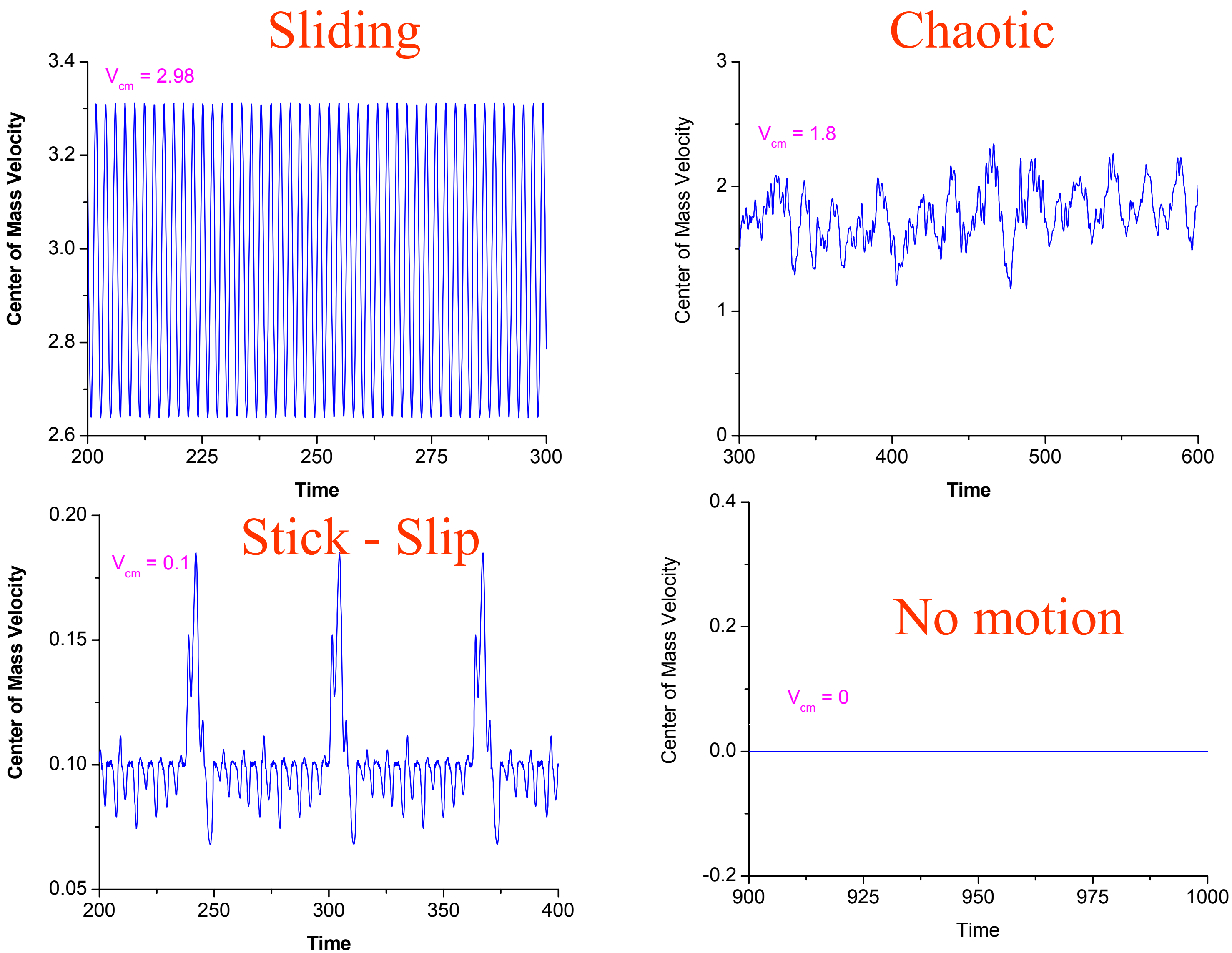






Natural Motion

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



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:

$v = f/\gamma$ - free sliding

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

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

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)

Demonstration of Friction Control

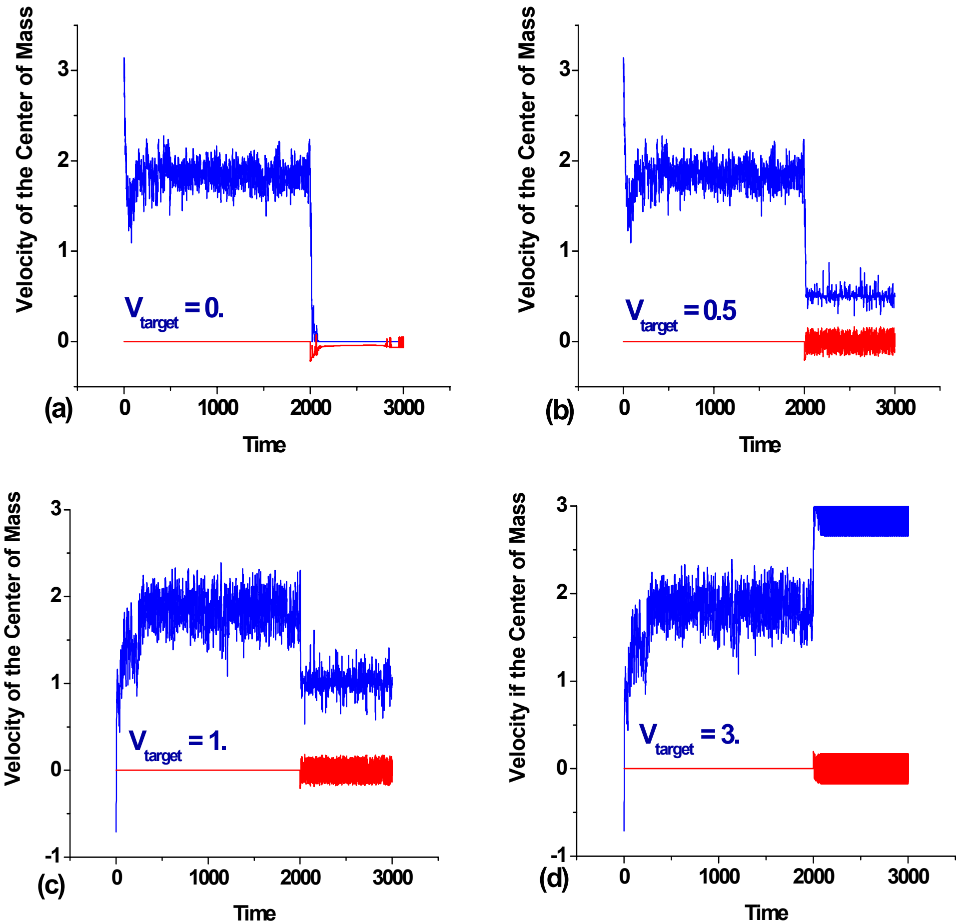


Figure: Performance of control algorithm for four values of the center of mass velocity (0, 0.5, 1.0, and 3.0) for a 15 - particle array. **Control was initiated at *t=2000***. Blue lines show time series of the center of mass velocities, while red lines show the control. In all cases, the desired behavior was rapidly achieved. All the units are dimensionless and initial conditions were chosen randomly.

1. New algorithm developed

- –fast and efficient
- –enables to induce any arbitrarily chosen behavior compatible with the system's dynamics.

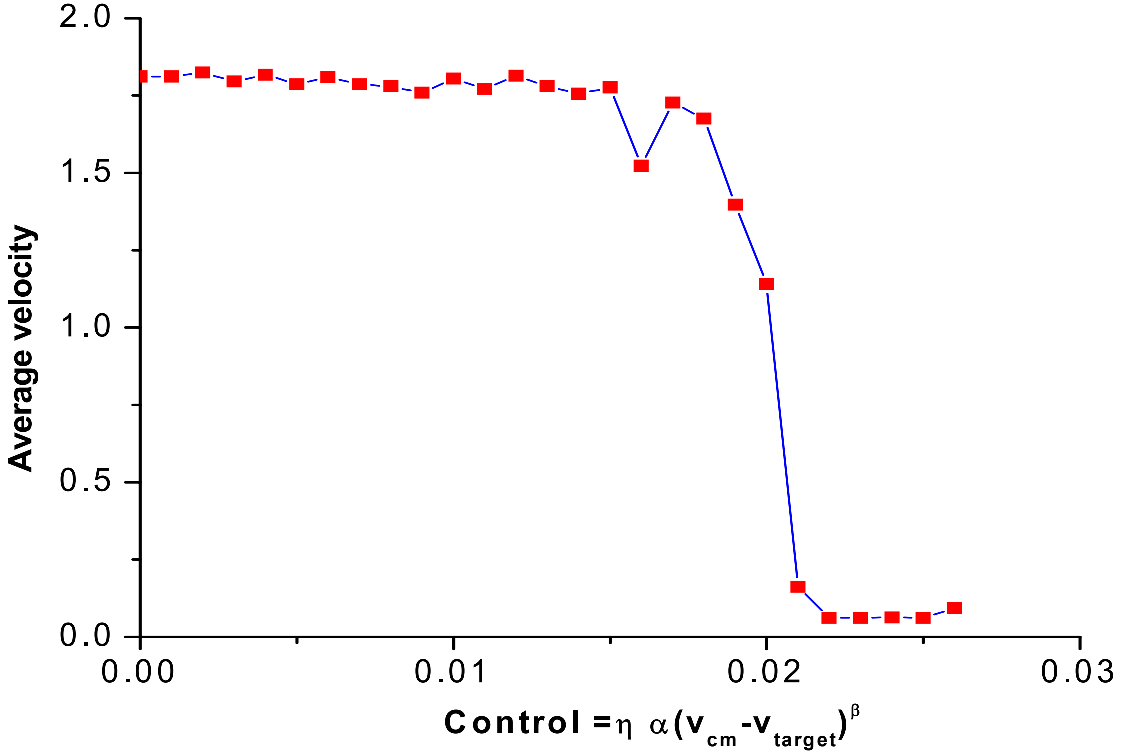
2. Methodology is based on two original concepts:

- – non-Lipschitzian dynamics
- – global behavior targeting

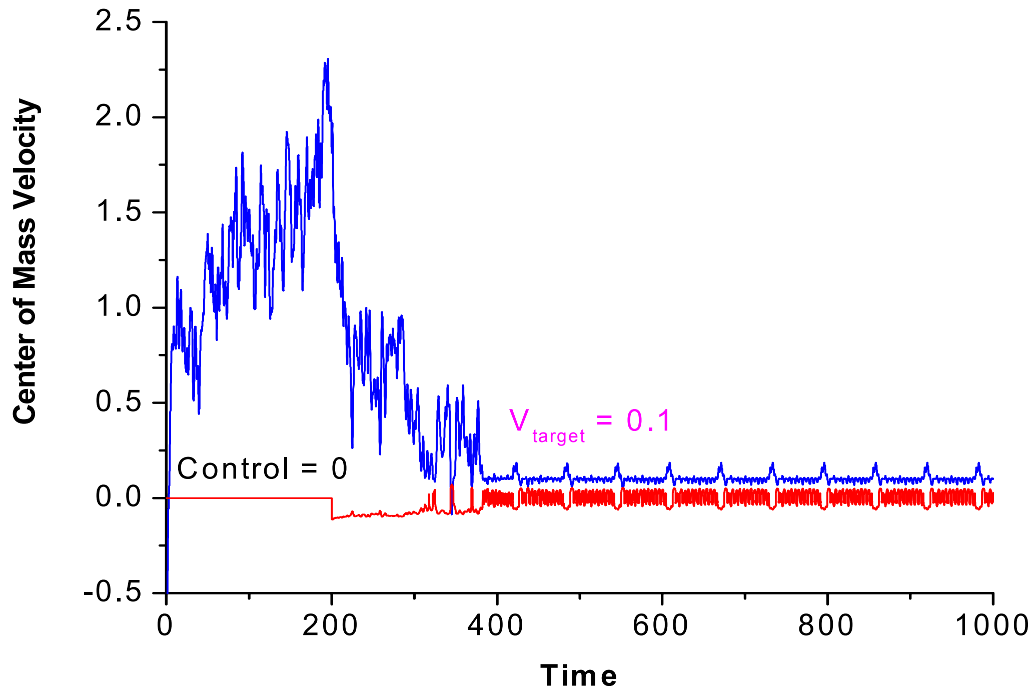
3. Quickly reaches targeted behavior.

Y. Braiman, J. Barhen, & V. Protopopescu, Physical Review Letters 90, 094301 (2003).

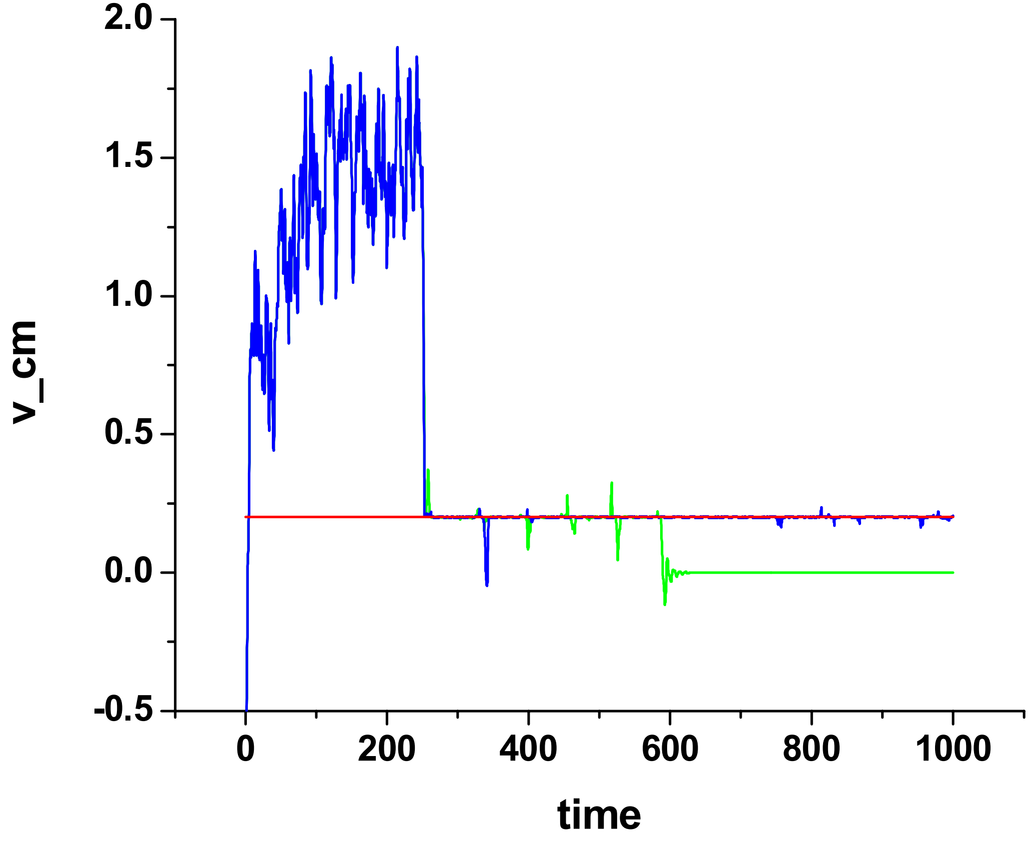
Strength of the Control



Fast Transient Times

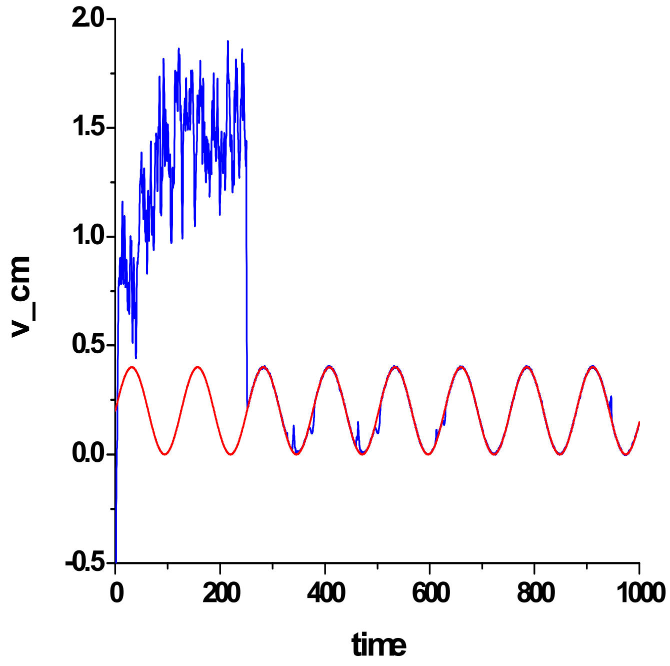


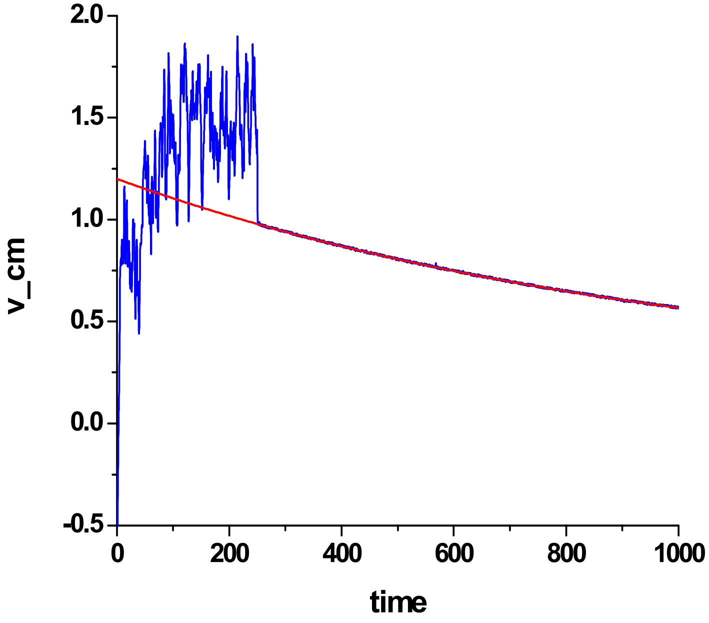
Effect of the Repeller



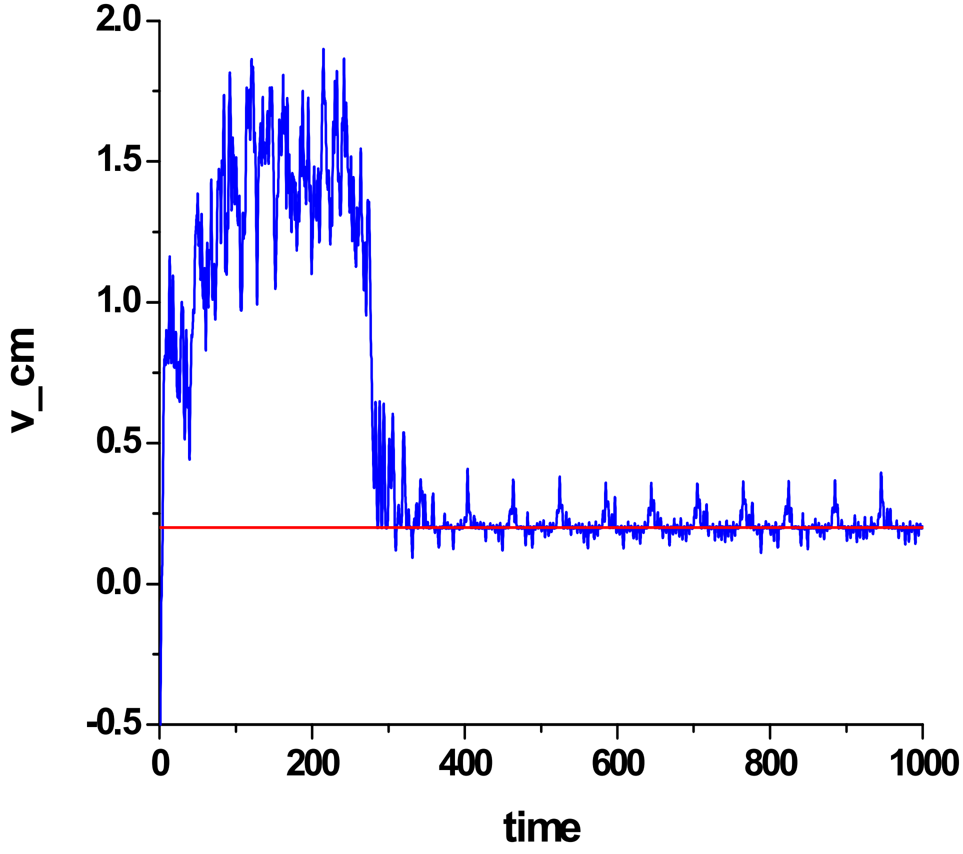
V. Protopopescu & J. Barhen, accepted to Chaos (2004).

Control Towards Desired Functional Behavior

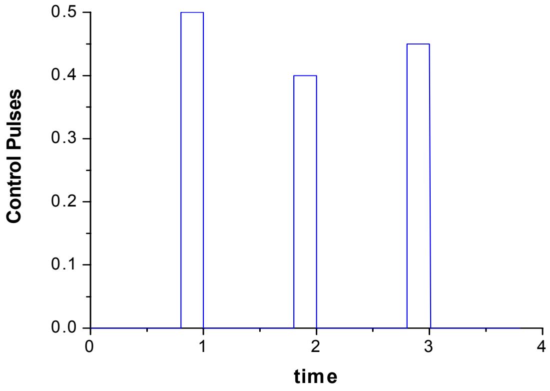




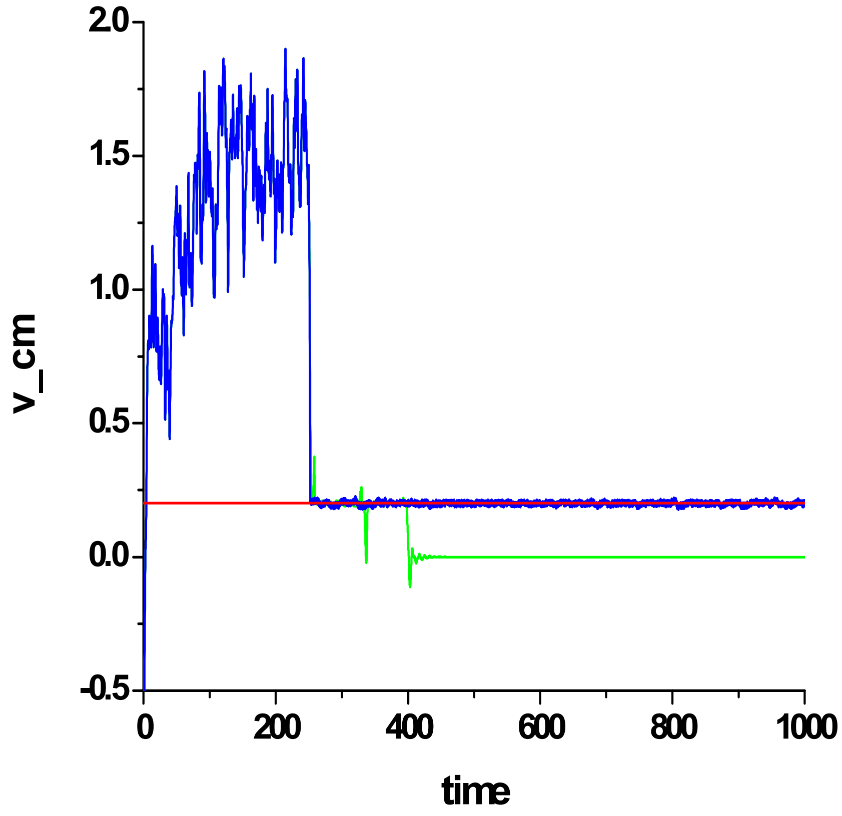
Pulsed Control



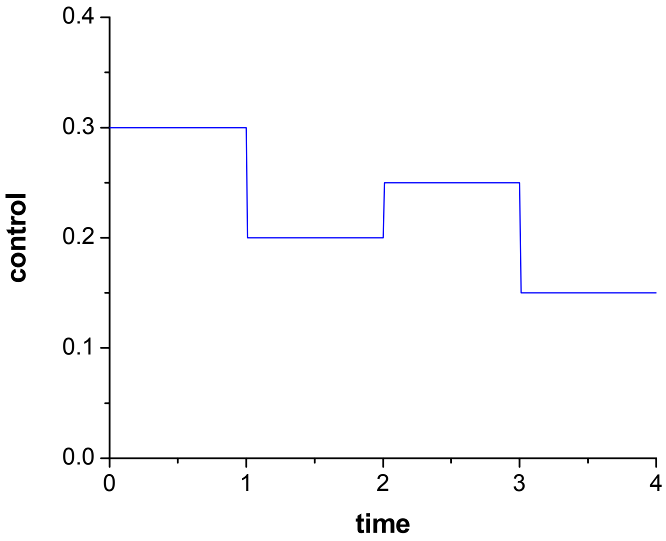
Pulsed Control Schematic

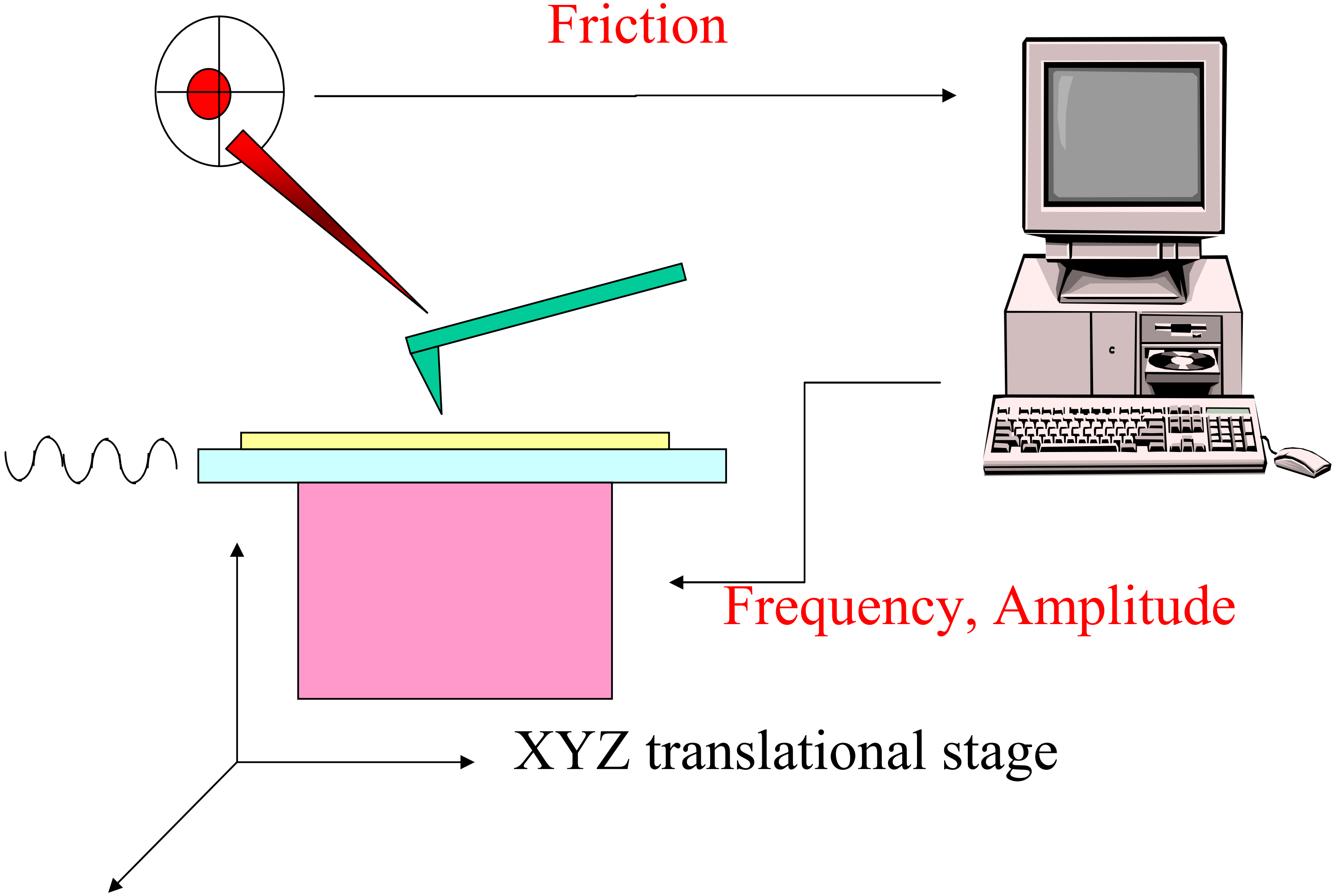


Step-Like Control

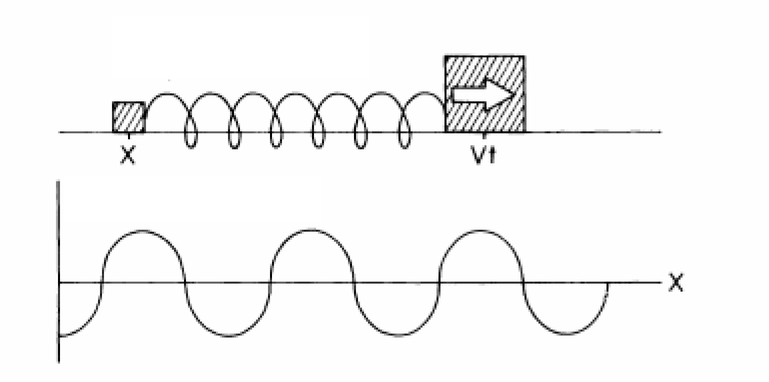


Step-Like Control Schematic




Friction
Frequency, Amplitude
XYZ translational stage

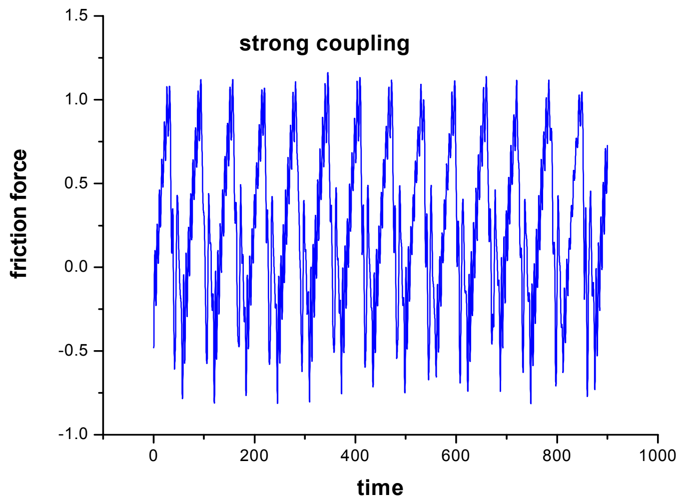
Modeling the AFM Motion

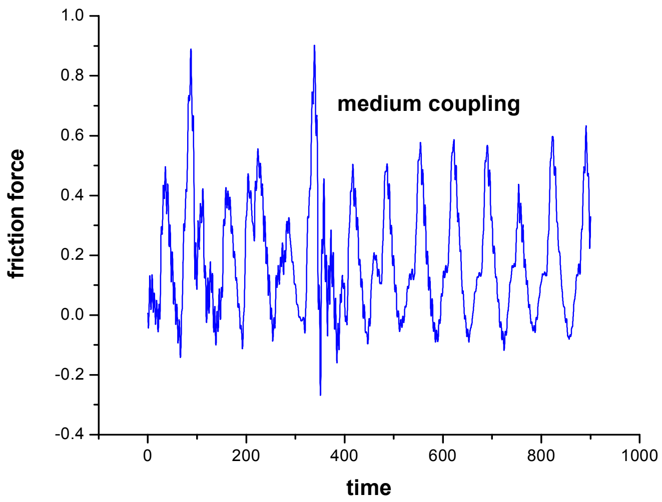


$$\ddot{x} + \gamma \dot{x} + \sin x = K(vt - x)$$

J. S. Helman, W. Baltensperger, and J. A. Holst, Phys. Rev. B 49, 3831 (1994)

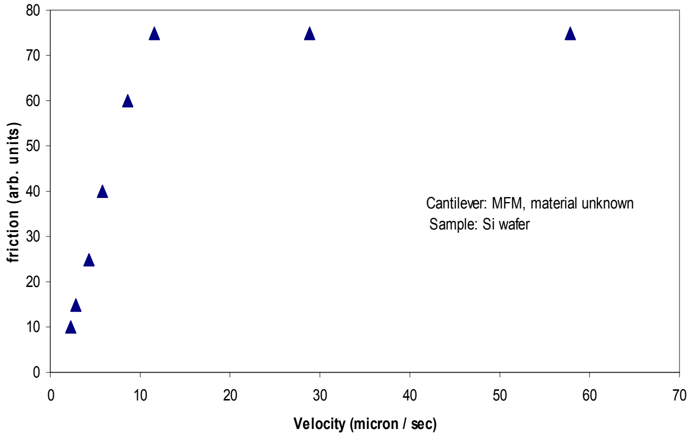
$$\ddot{x}_j + \gamma \dot{x}_j + \sin x_j = K(vt - x_{cm}) + F_{\text{int}}(x_{j+1}, x_j) + F_{\text{int}}(x_{j-1}, x_j)$$

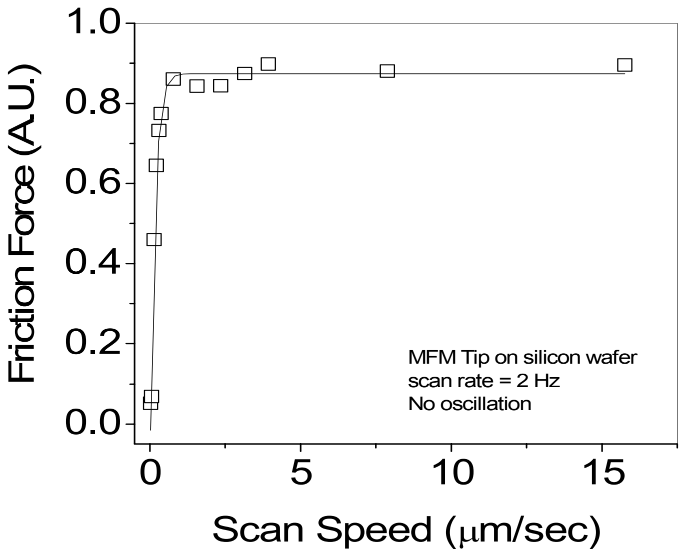




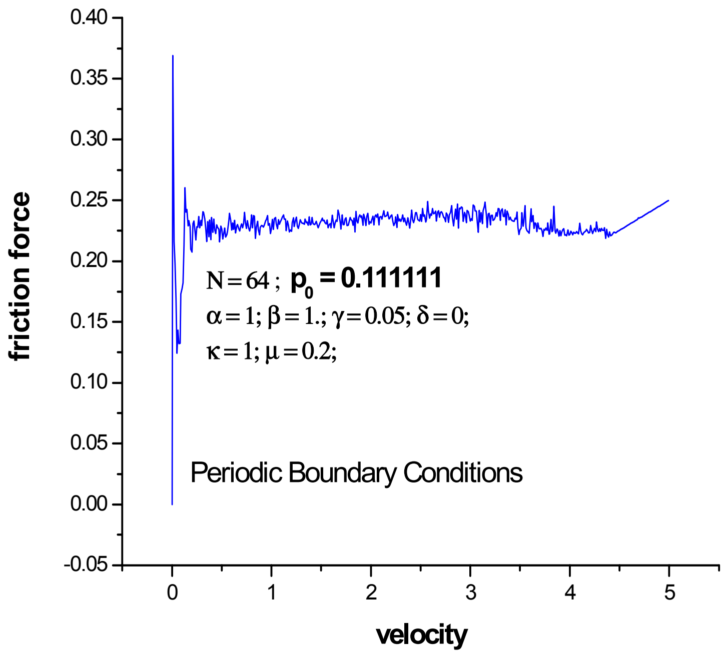
Friction force – Velocity Dependence

Experimental

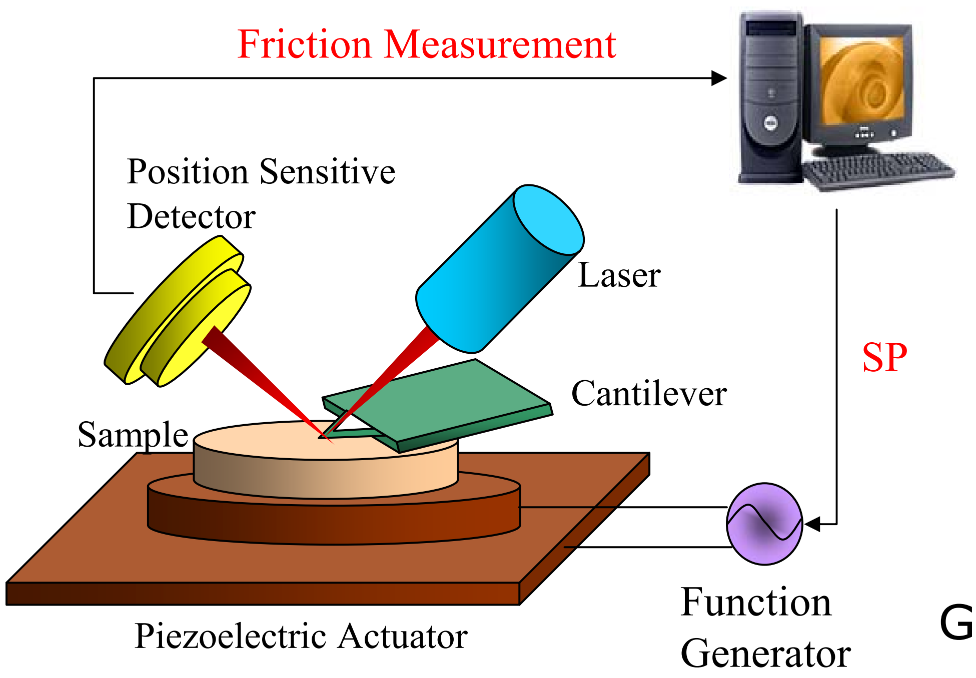


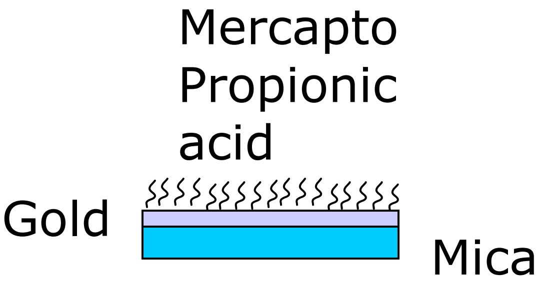


Numerical Simulations



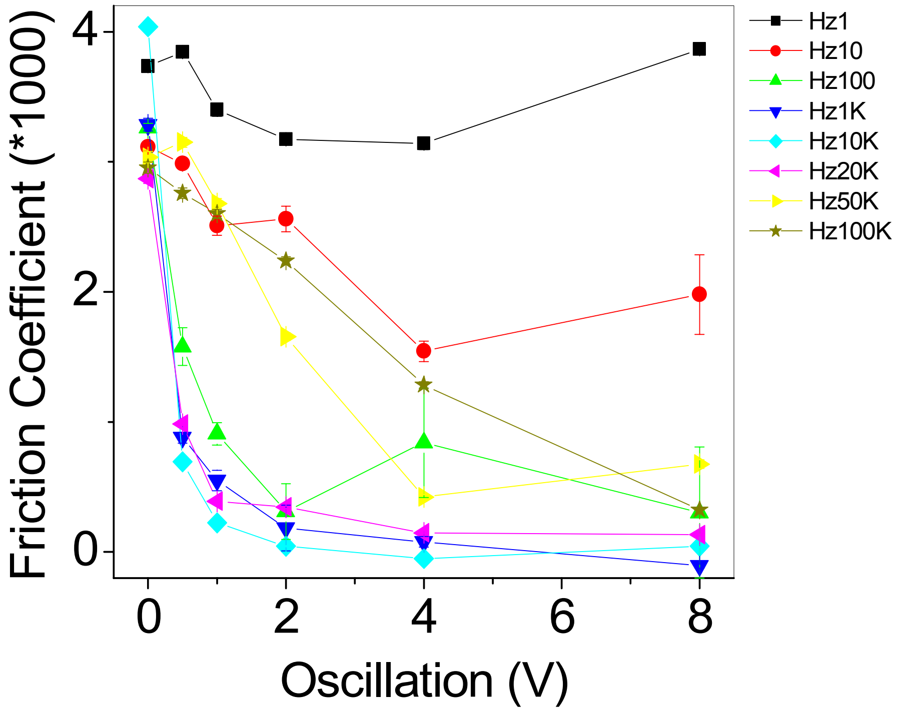
Experimental Setup



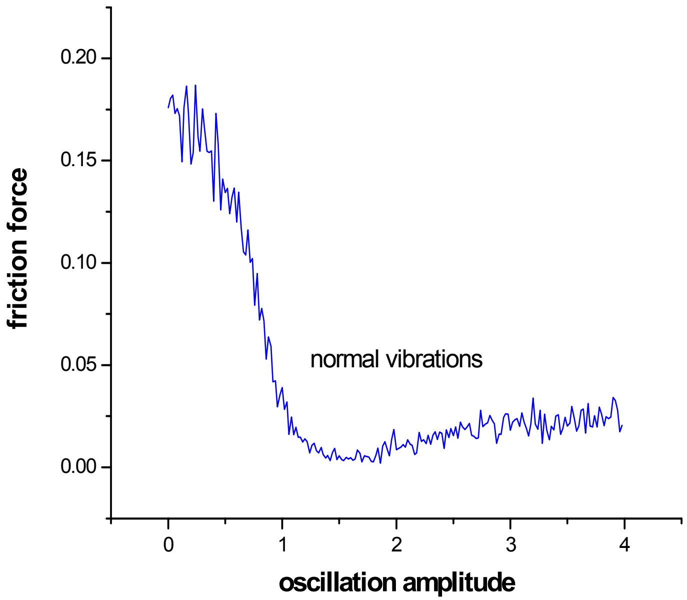


Dependence on Oscillation Amplitude

Experimental

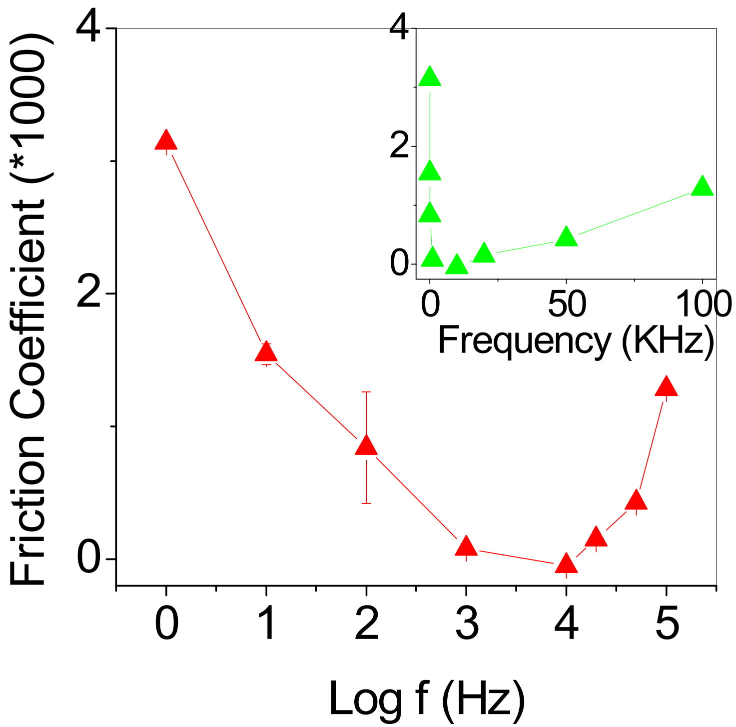


Numerical Simulations

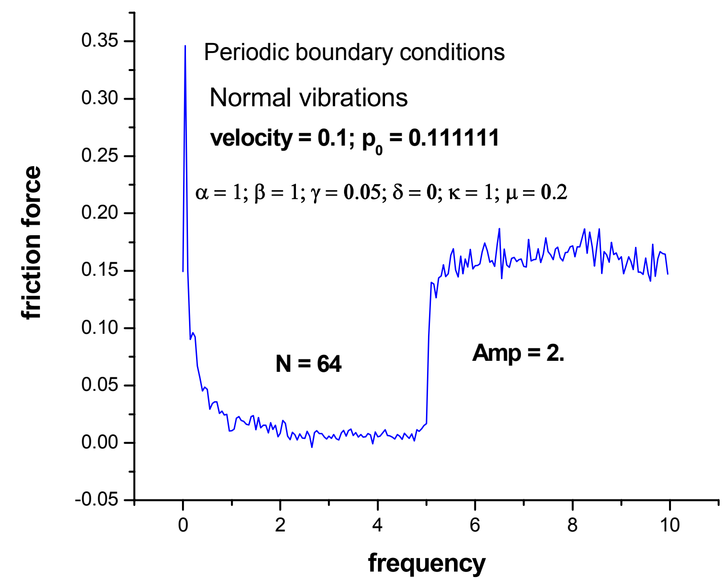


Dependence on the Frequency of Oscillations

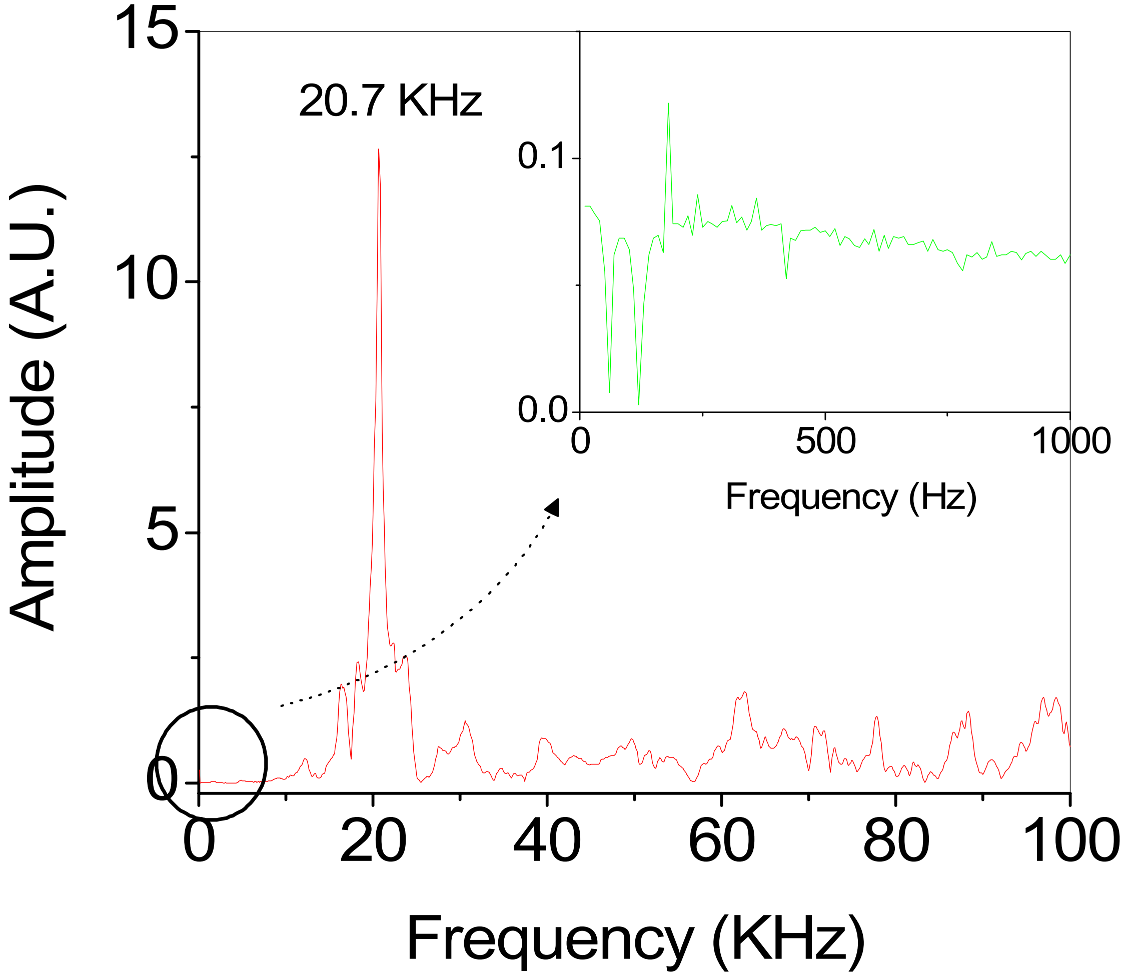
Experimental



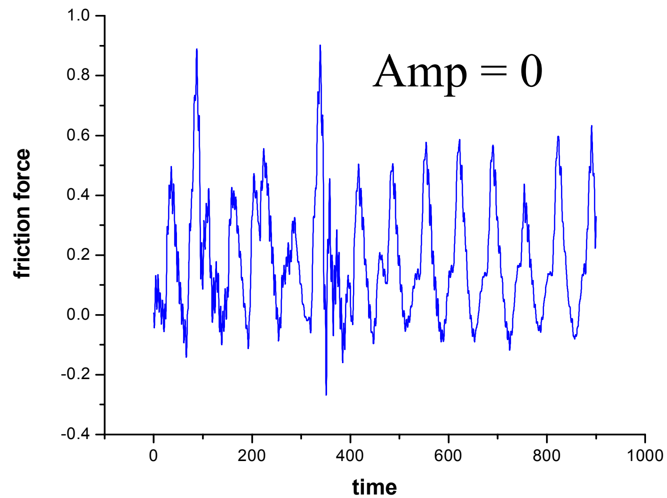
Numerical Simulation

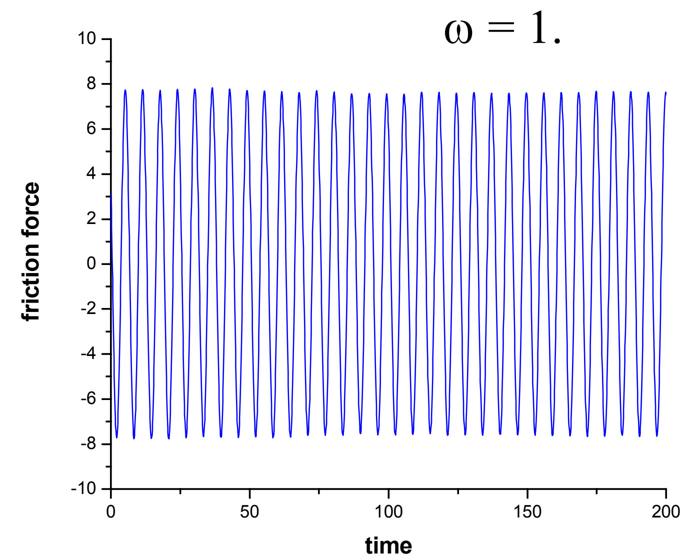


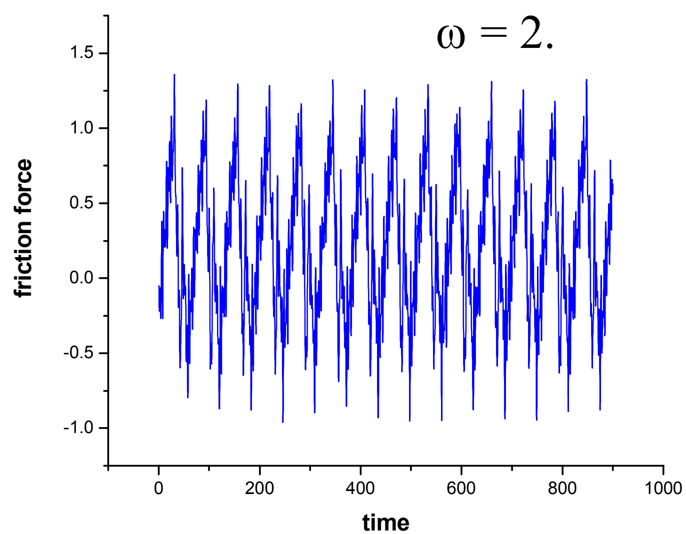
Resonance Response

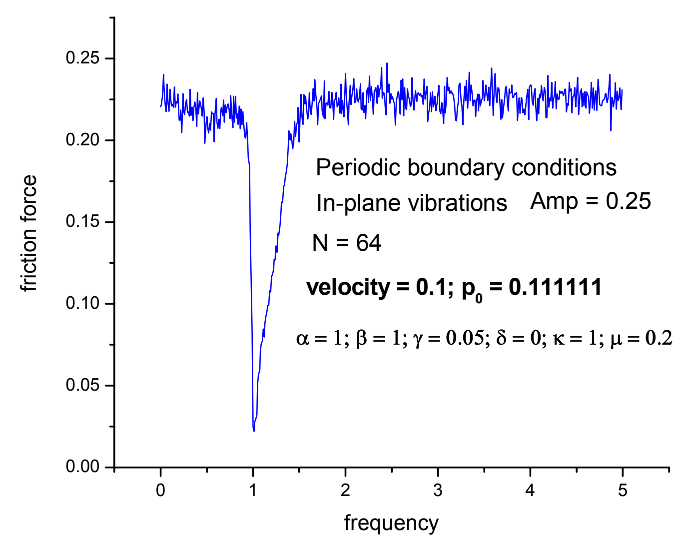


Effect of Lateral Oscillations









Summary

We derived the properties of a general control algorithm for quantities describing global features of nonlinear extended mechanical systems. The control algorithm is based on the concepts of non-Lipschitzian dynamics and global targeting. We showed that:

- **(i)** **Certain average quantities of the controlled system can be driven – exactly or approximately – towards desired targets which become linearly stable attractors for the system's dynamics;**
- **(ii)** **The basins of attraction of these targets are reached in very short times; and**
- **(iii)** **While within reasonably broad ranges, the time-scales of the control and of the intrinsic dynamics may be quite different, this disparity does not affect significantly the overall efficiency of the proposed scheme, up to natural fluctuations.**