TEL AVIV UNIVERSITY אוניברסיטת תל-אביב

Atomic Scale Friction: From Understanding to Control

Michael Urbakh

School of Chemistry
Tel Aviv University
Israel

J. Klafter

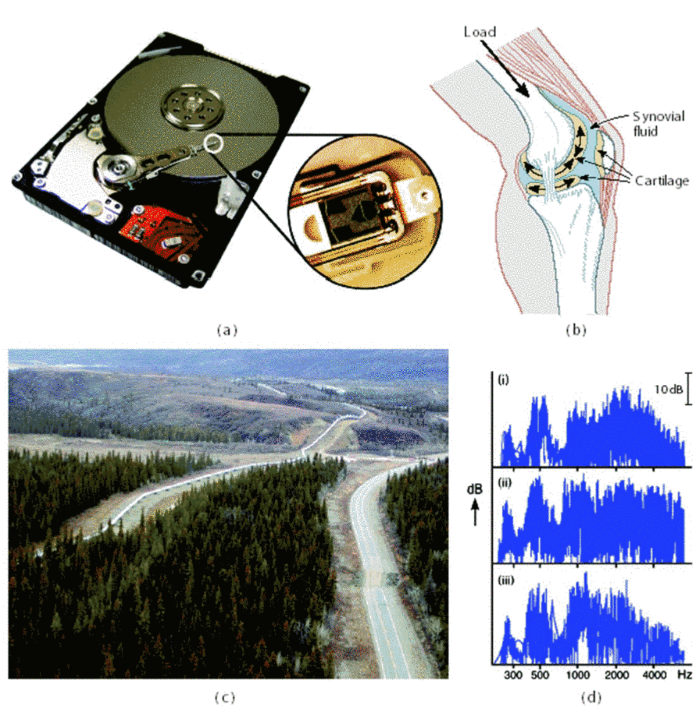
M. Rozman,
V. Zaloj,
M. Porto,
A.E. Filippov,
Z. Tschiprut

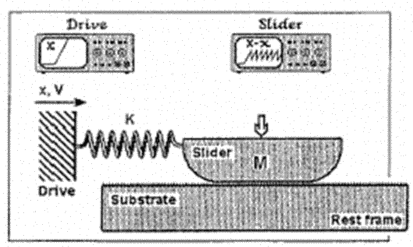
Financial support from ISF, DIP, BSF and ESF Nanotribo is gratefully acknowledged.

OUTLINE

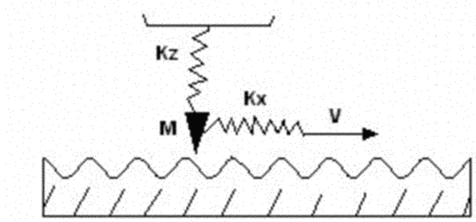
1. Motivation.
2. Experiments.
3. Modeling Friction at the Nanoscale.
4. Mechanical Control of Friction.
5. Chemical Control.
6. Conclusions.

Friction at Different Scales



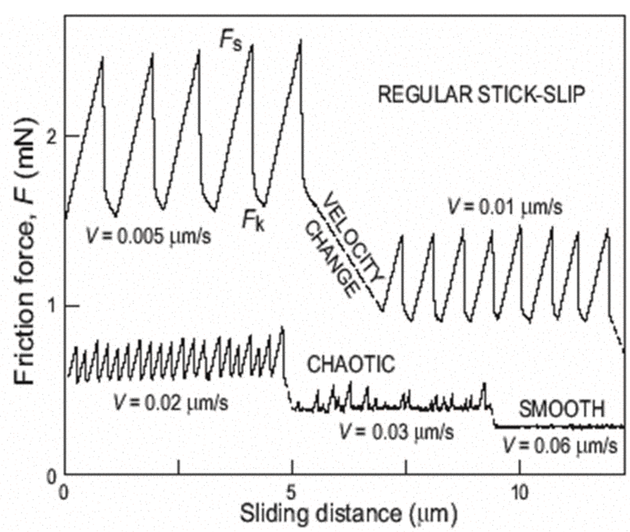


Surface Force Apparatus



Atomic Force Microscope

Experimental Observations



C. Drummond & J. Israelachvili, *Phys. Rev. E* **63,** 041506 (2001).

Experimental Observations

- Low driving velocity – solid-like behavior
- High driving velocity – liquid-like velocity

Low Velocities:
Stick-Slip Motion, F_s , F_k.

High Velocities:
Smooth Sliding, Thinning.

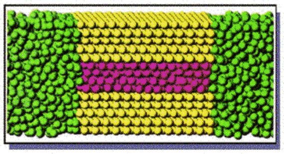
Intermediate Velocities:
Chaos.

Problems of comparison with experiments

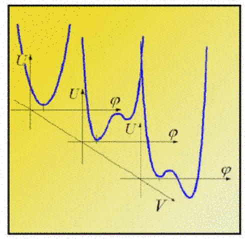
Only **macroscopic characteristics** (forces) are measured in experiments, and this information is not enough to identify a mechanism of friction (energy dissipation) and discriminate between different theoretical models.

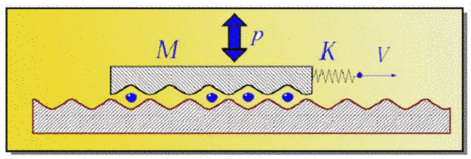
Local, space-resolved information is missing.

MD simulations



Rate-state model





"Minimalistic" model

Non-interacting particles embedded between two plates under shear

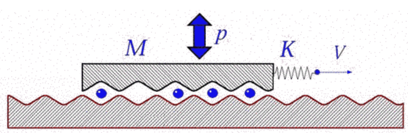


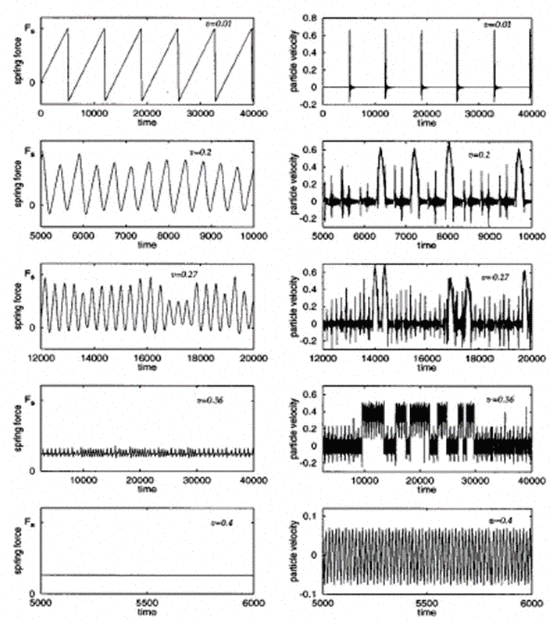
Plate motion:

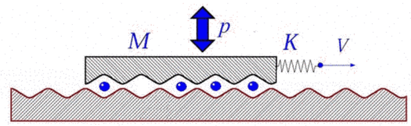
$$M\, \partial^2 X/\partial t^2 + \eta\, \partial(X - x)/\partial t + \partial U(x - X)/\partial X + K(X - Vt) = 0$$

Particle motion:

$$m\, \partial^2 x/\partial t^2 + \eta\, \partial(2x - X)/\partial t + \partial[U(x - X) + U(x)]/\partial x = f(t)$$

M.G. Rozman, M. Urbakh & J. Klafter, *Phys. Rev. Lett.* **77**, 683 (1996);
M.H. Muser, L. Wenning & M.O Robbins, *Phys. Rev.Lett.* **86**,1295 (2001).





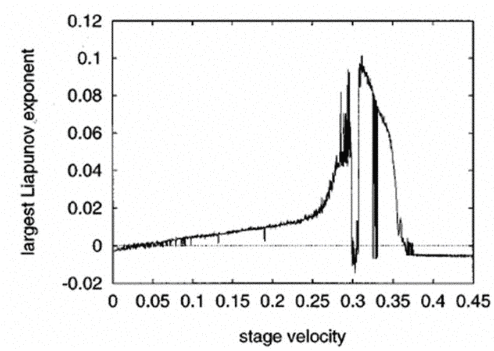
M.G. Rozman, M. Urbakh & J. Klafter, *Phys. Rev. Lett.* 77, 683–686 (1996),

Predictions:

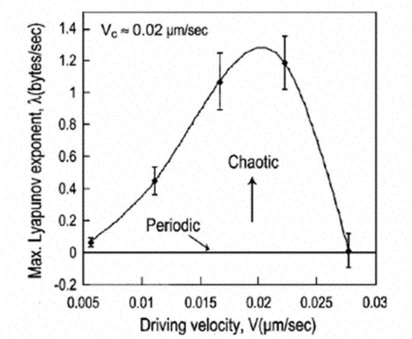
- Chaotic Behavior of Sheared Systems.
- New Phases of Motion
  (two types of sliding, inverted stick-slip motion, …).
- Dependencies of Frictional Properties on Mechanical Parameters.
- Mechanical Control of Friction.

Chaotic Behavior of Sheared Systems

Theory



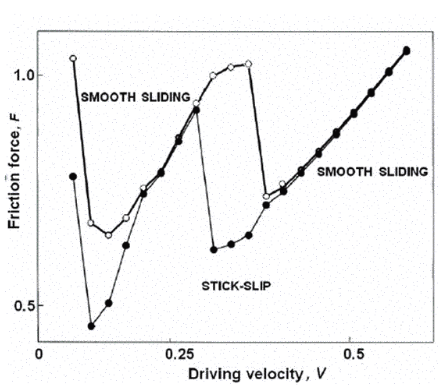
Experiment



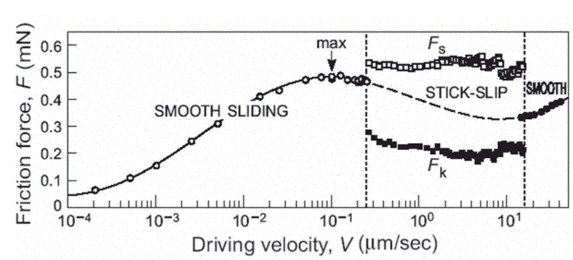
M. Urbakh, J. Klafter, D, Gourdon & J. Israelachvili, ***Nature***, 430, 525 (2004).

New Phases of Motion

Theory



Experiment



M. Urbakh, J. Klafter, D, Gourdon & J. Israelachvili, ***Nature***, 430, 525 (2004).

Controlling Frictional Forces

1. Mechanical Control:

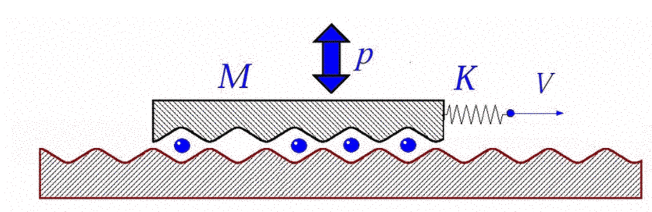
- modulation of normal load
- lateral vibrations

2. Chemical Control:

- supplementing base lubricants by friction modifier additives.

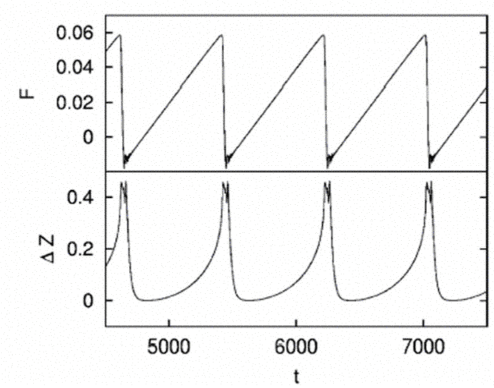
Mechanical Control

1. Modulation of normal load



M.G. Rozman, M. Urbakh & J. Klafter, *Phys. Rev. E* **57**, 7340–7343 (1998).

Normal-Lateral Coupling

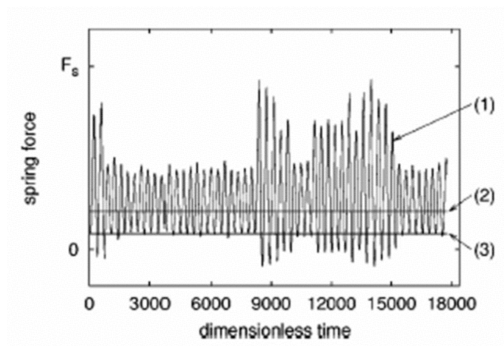


V. Zaloj, M. Urbakh & J. Klafter, J. *Phys. Rev. Lett*. **82**, 4823–4826 (1999).

Two goals:

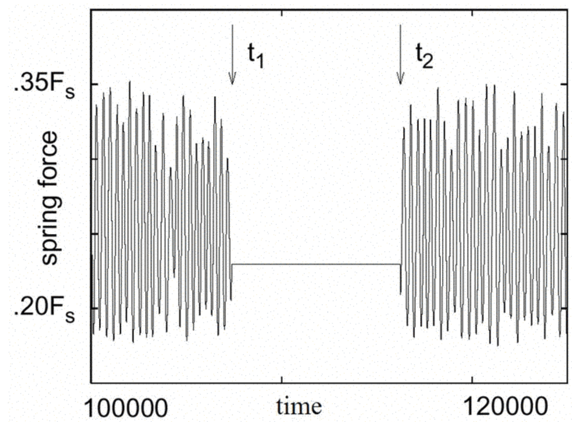
- **decrease frictional forces,**
- **achieve smooth sliding at low driving velocities.**

high technological importance for micromechanical devices, where the early stages of motion and the stopping processes, which exhibit stick-slip, pose a real problem



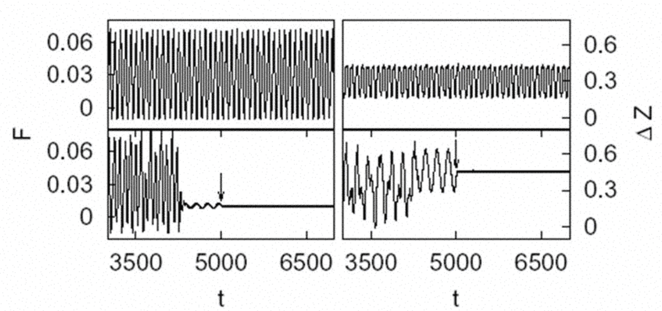
Main idea:

To stabilize unstable sliding states for low driving velocities, $V<V_c$, where one would expect chaotic stick-slip motion.



M.G. Rozman, M. Urbakh & J. Klafter, *Phys. Rev. E* **57**, 7340–7343 (1998).

Control through application of harmonic oscillations



V. Zaloj, M. Urbakh & J. Klafter, J. *Phys. Rev. Lett.* **82**, 4823–4826 (1999).

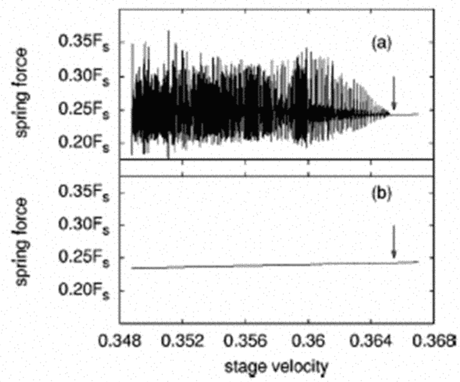
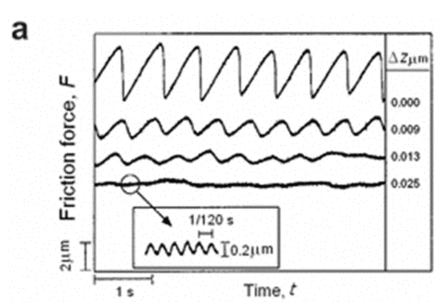
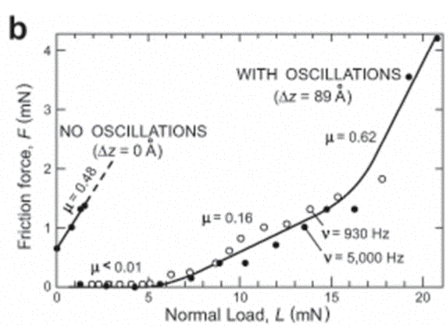


FIG. 4. Time oscillations of the spring force for the deceleration of the driving stage: (a) without control, (b) under control. Spring force is presented in units of static friction force, $F_s = 2\pi U_0 / b$ [8]. For convenience the stage velocity (instead of time) is indicated on the axis. Vertical arrows indicate the critical velocity v_c.

M.G. Rozman, M. Urbakh & J. Klafter, *Phys. Rev. E* **57**, 7340–7343 (1998).

Experiments

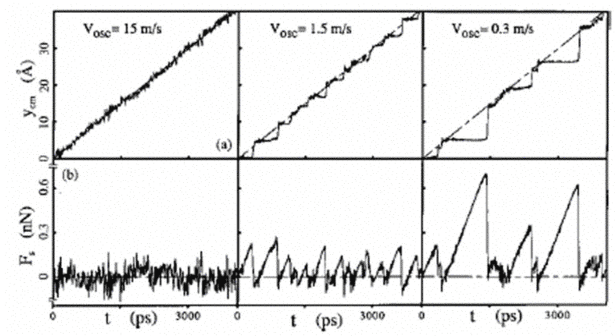




A. Cochard, L. Bureau & T. Baumberger, *Trans. ASME* **70**, 220 (2003).

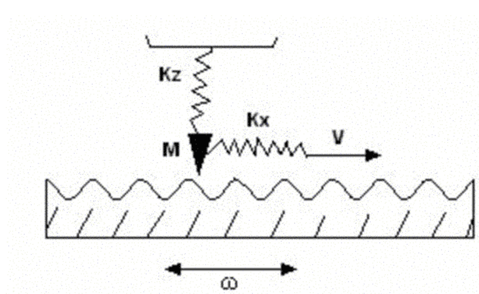
M. Heuberger, C. Drummond & J.N. Israelachvili, *J. Phys. Chem. B* **102**, 5038 (1998).

Large-scale MD simulations



J. P. Gao, W.D. Luedtke & U. Landman, *J. Phys. Chem. B* **102**, 5033 (1998).

2. Effect of lateral vibrations



Z. Tschiprut, A. E. Filippov & M. Urbakh, *Phys. Rev. Lett*. 95, Art. No. 016101 2005.

E.Riedo, E.Gnecco, R.Bennewitz, E.Meyer, and H.Brune, PRL, 2003.

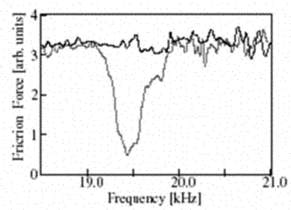
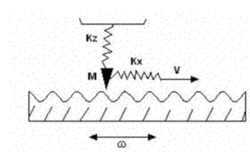


FIG. 3. Friction force vs frequency of the external oscillations at $v = 8\ \mu m/s$ (continuous line) and $v = 150\ \mu m/s$ (dashed line). The applied load is $F_N = 15$ nN in both cases.

THE MODEL



$$M\ddot{x}(t) = -\eta_x(z)(\dot{x}(t) - \dot{x}_0(t)) - \partial U(x - x_0, z)/\partial x + F_{ext}^x + f_x$$

$$M\ddot{z}(t) = -\eta_z(z)\dot{z}(t) - \partial U(x - x_0, z)/\partial z + F_{ext}^z + f_z$$

Potential and dissipation coefficients

$$U(x,z) = U_0\left[1 + \sigma \sin\left(\frac{2\pi}{b}(x - x_0)\right)\right]\exp(1 - z/\lambda) \qquad \eta_{x,z}(z) = \eta_{x,z}^0 \exp(1 - z/\lambda)$$

External spring forces

$$F_{ext}^x = K_x(Vt - x(t)) \qquad F_{ext}^z = K_z(z_0 - z(t))$$

Oscillatory drive

$$x_0 = A\sin(2\pi\omega t)$$

Important parameters:

Inertia plays a role of the driving force, $F_{driv} = (2\pi)^2 mA\omega^2 \sin(2\pi\omega t)$

The frequency of the small oscillations of the tip in the periodic potential $\omega_0 = (1/b)\sqrt{U_0/m}$

For $m = 10^{-11} kg,\ U_0 = 0.25eV,\ b = 0.5nm \Rightarrow \omega_0 \approx 100kHz,$

Other parameters

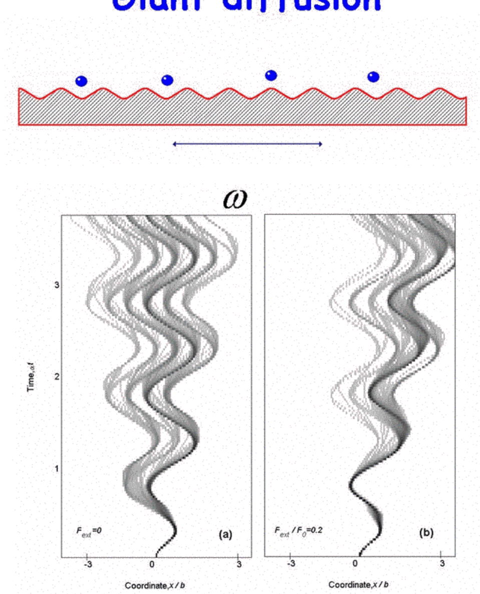
$\Omega = \omega/\omega_0, \quad V/b\omega_0 \approx 0.1, \quad \eta_{x,z}/m\omega_0 \approx 1 \div 3, \quad k_B T/U_0 \approx 0.01 \div 0.1$

Spring constants:

$$K_x < 4\pi^2 U_0/b^2, \quad K_z < U_0/\lambda^2$$

Giant diffusion

Diffusion

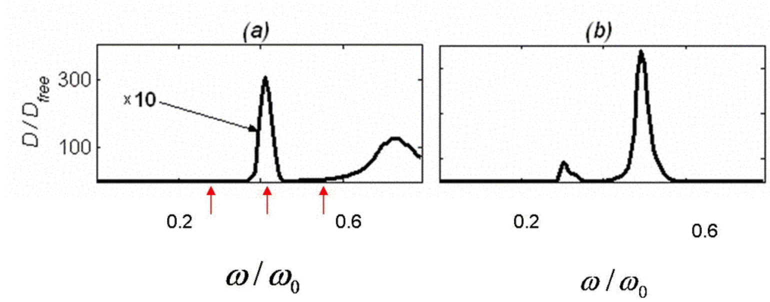


Migration

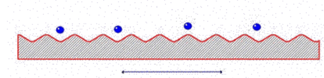
Time evolution of the particle density distribution

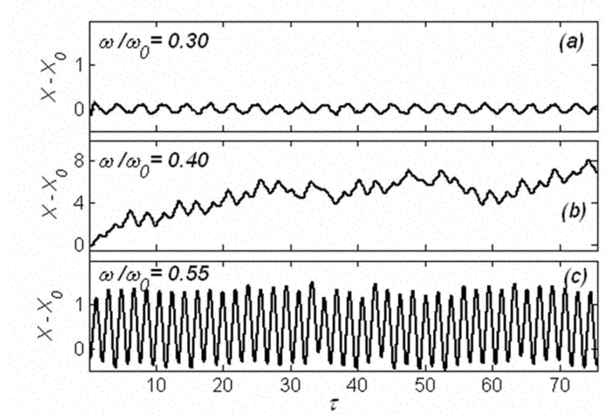
Surface diffusion, D/D_{free}

$A/b=1$ $A/b=2$



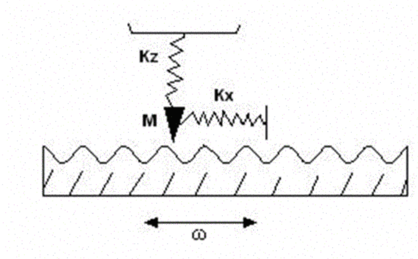
Particle trajectories

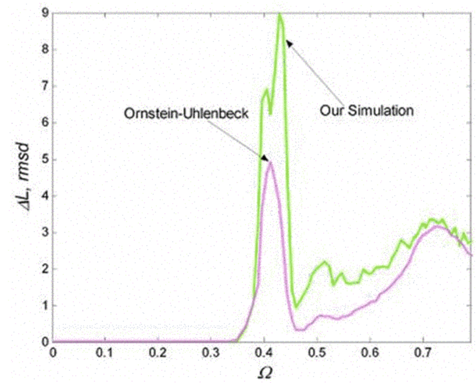




x-x_0 is the particle displacement with respect to the minimum of the particle-surface potential

How to observe this effect experimentally?

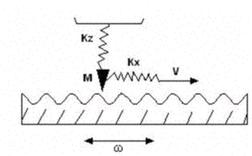


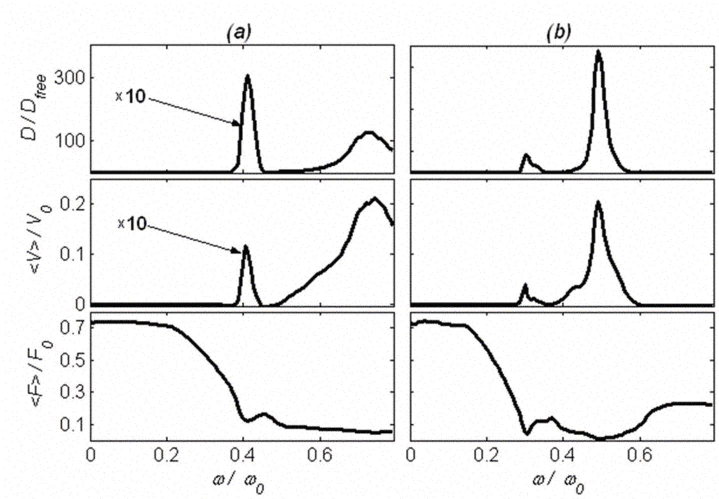


Ornstein-Uhlenbeck model gives

$$\Delta L_{OU} = \sqrt{D_{free}\eta_x / K_x}$$

Effect of lateral vibrations on transport and friction (1D)





Diffusion

Migration

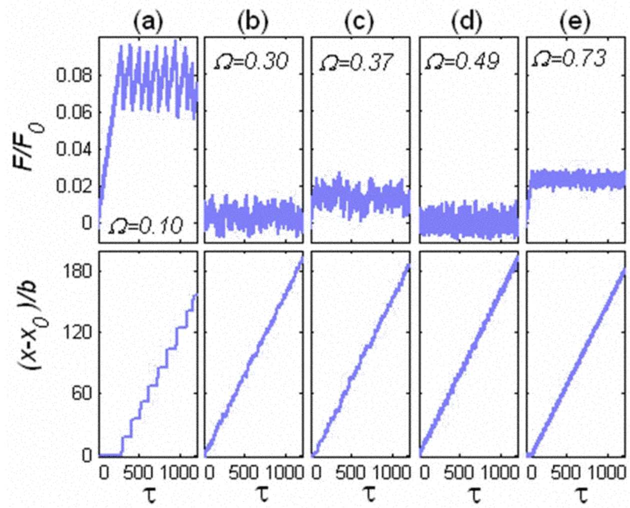
$F_{ext} = 10^{-2} F_0$

Mean frictional force

$$F_0 = 2\pi U_0 / b$$

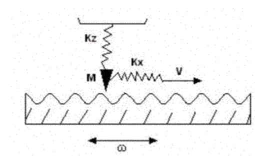
Time series of the spring force and tip displacement

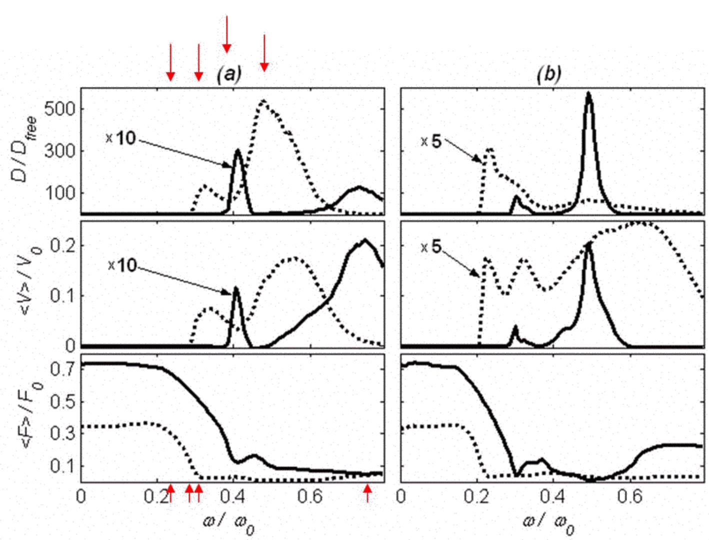
A=2



$$K_x b^2 / \left((2\pi)^2 U_0 \sigma \right) = 3.2 \cdot 10^{-3}$$

Normal-Lateral Coupling





Diffusion

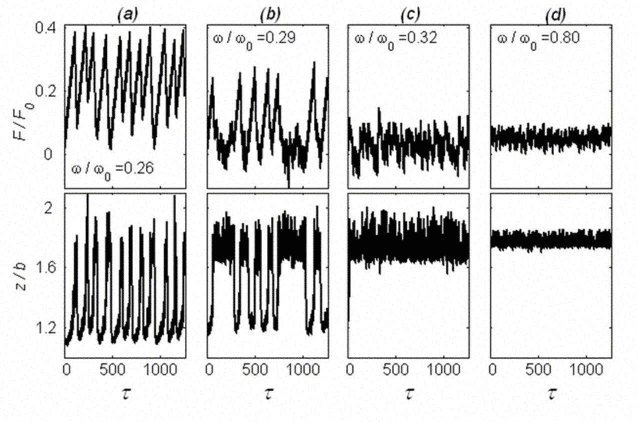
Migration

$F_{ext} = 10^{-2} F_0$

Mean frictional force

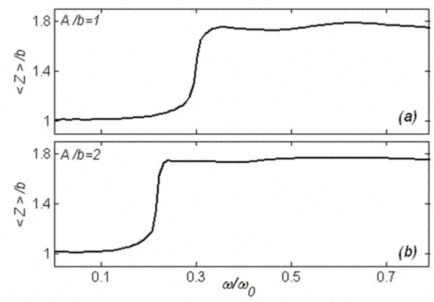
—— 1D, - - - including normal motion

Frictional traces



Frictional force and normal displacement of the tip; A=1, $K_z \lambda^2 / U_0 = 0.63$

Dilatancy transition



Tip-surface separation as a function of the frequency

In conclusion

- Minimalistic models enabled predictions to be made that were later verified experimentally.
- Manipulation by mechanical excitations, when applied at the right frequency, amplitude and direction, allows to reduce the friction force, to eliminate stick-slip motion and to achieve sliding at low driving velocities.
- Mixing the embedded layer with additives does not only reduce friction, but it also makes it possible to control the regimes of motion.
- Control of friction is technologically important for micromechanical devices, where the early stages of motion and the stopping processes, which exhibit stick-slip, pose a real problem.