Nonlinear Energy Harvesting

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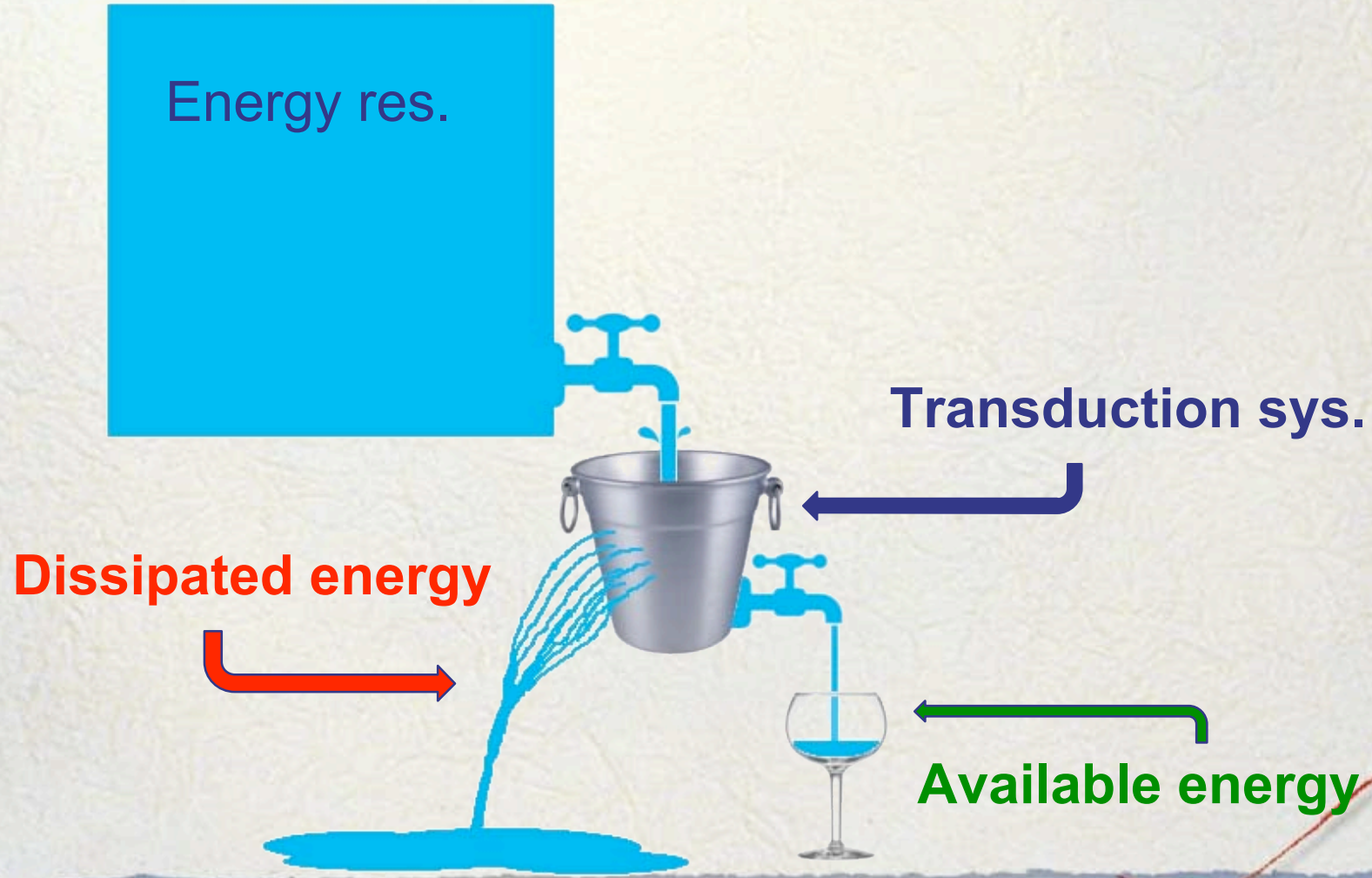
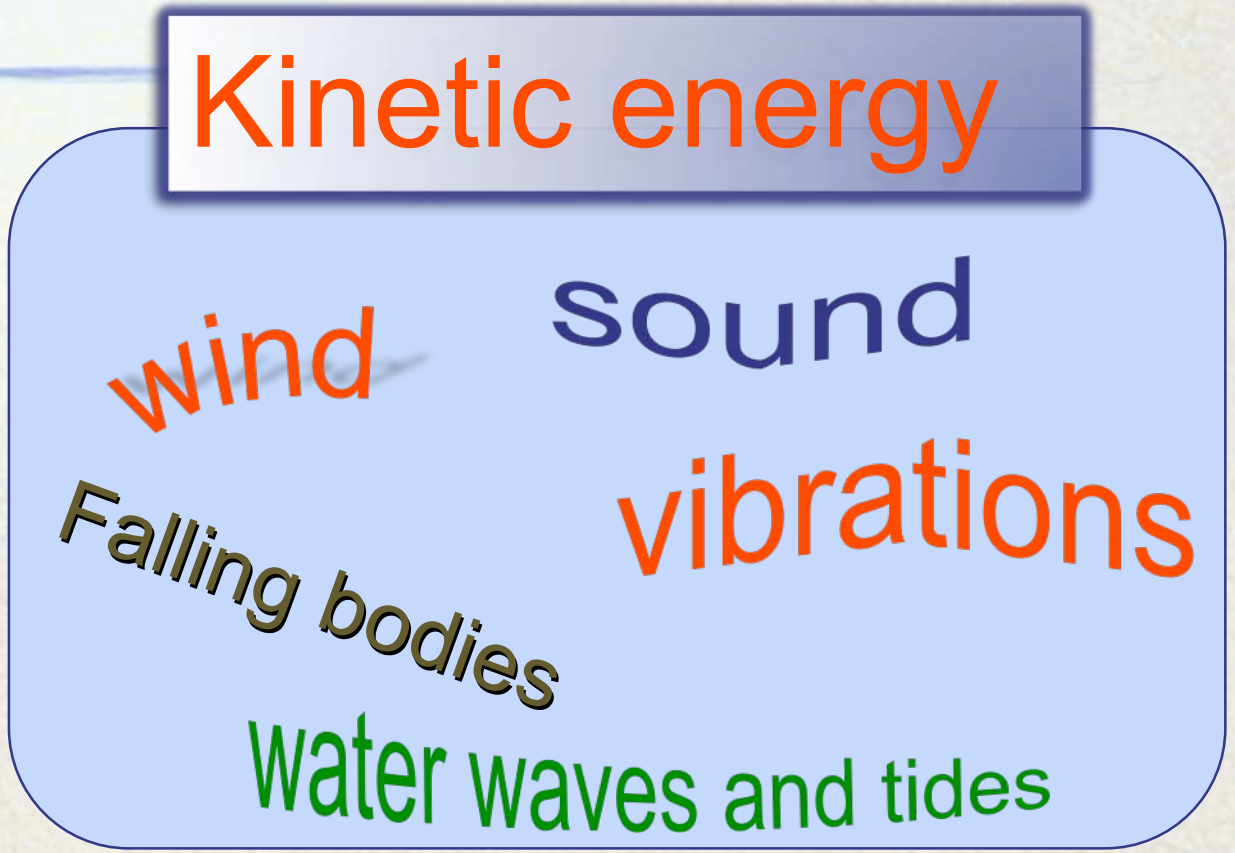
N.i.P.S Laboratory
Noise in Physical Systems

Energy harvesting basic ideas



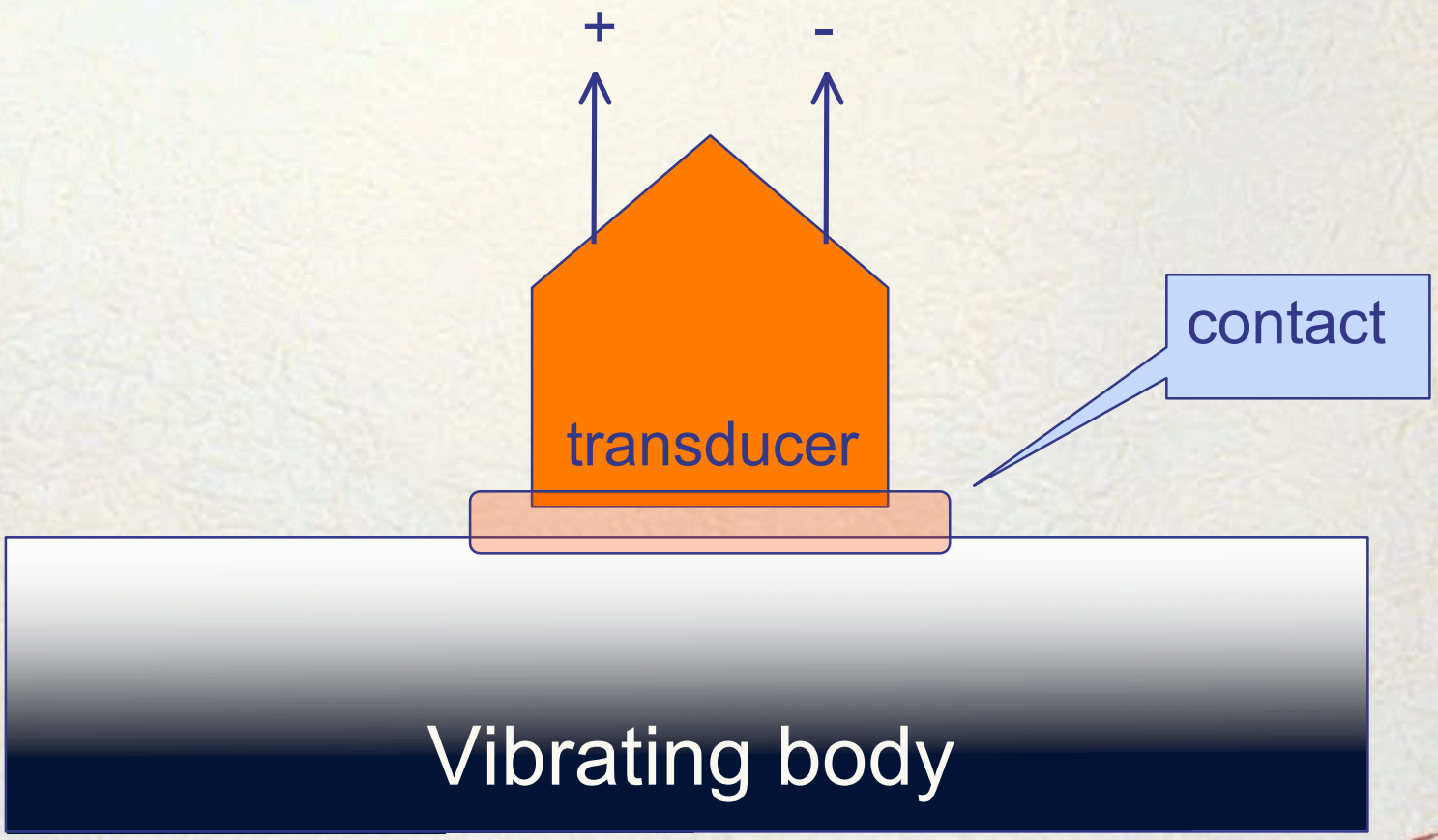
Energy harvesting basic ideas



Focus on **random vibrations** of solid bodies….

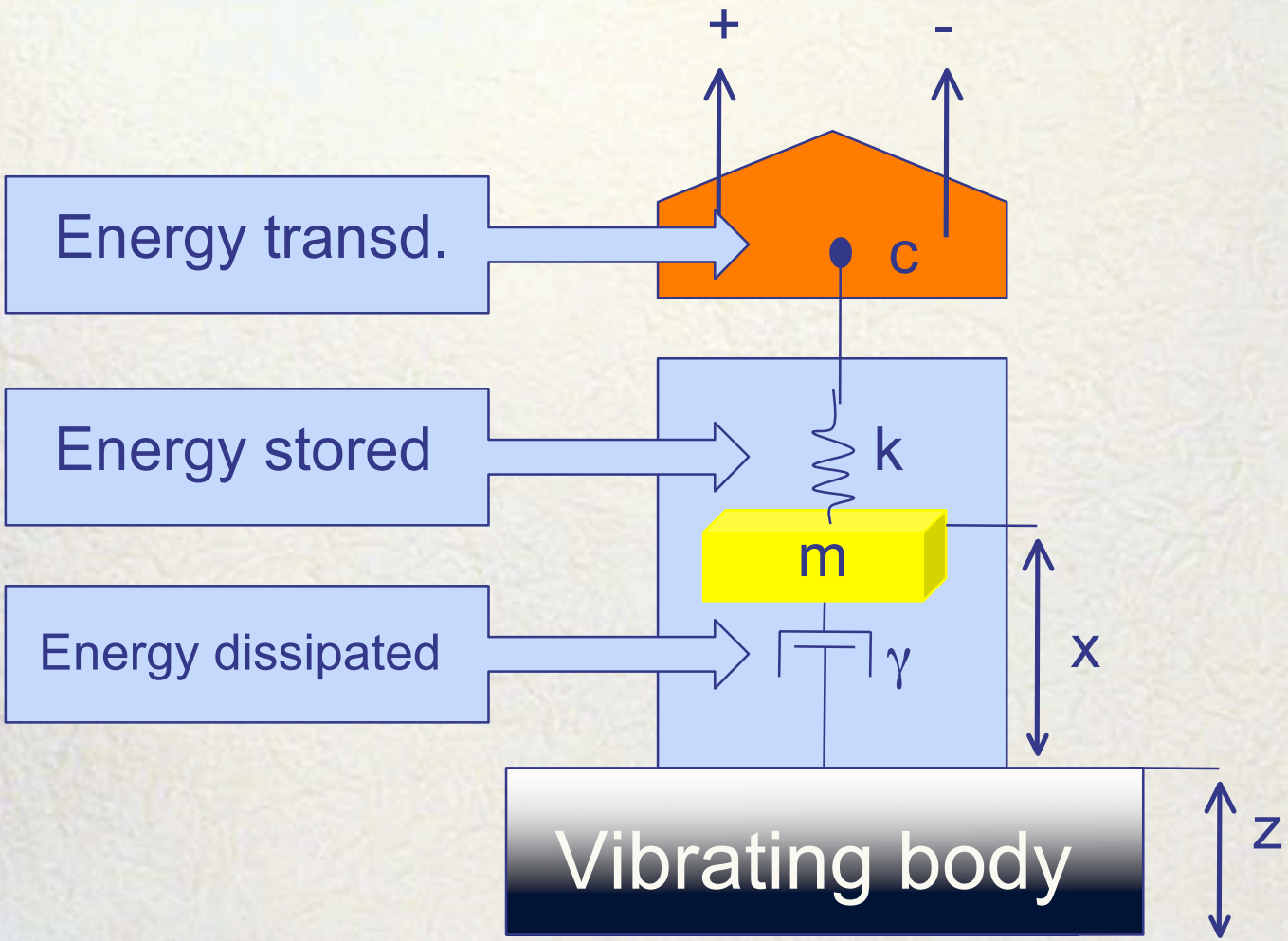
Noise energy harvesting

Basic Scheme

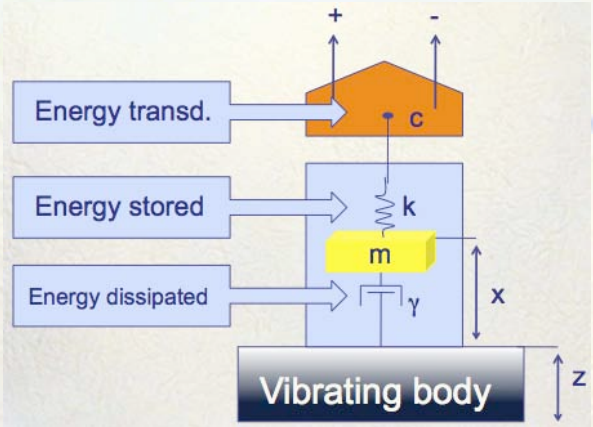


Noise energy harvesting

Dynamical model



Noise energy harvesting



Dynamical model

Details depend on the physics…

$$m\ddot{x} = \frac{dU(x)}{dx} \#\dot{x} \; c(x,V) + \; z$$

$$\dot{V} = F(\dot{x},V)$$

Equations that link the vibration-induced displacement with the Voltage

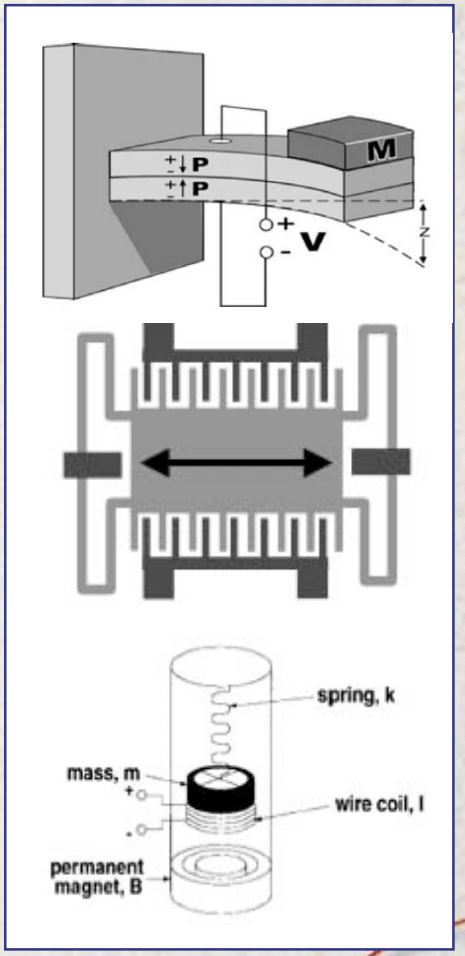
Noise energy harvesting

Transduction mechanisms

1. Piezoelectric: dynamical strain is converted into voltage difference.

2. Capacitive: geometrical variations induce voltage difference

3. Inductive: dynamical oscillations of magnets induce electric current in coils



Noise energy harvesting

Transduction mechanisms

1 Piezoelectric: dynamical strain is converted into voltage difference.

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z$$

$$\dot{V} = K_c\dot{x} - \frac{1}{\tau_p}V$$

The Physics of piezo materials

The available power is proportional to V^2

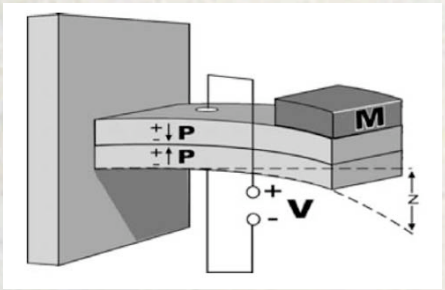
Noise energy harvesting

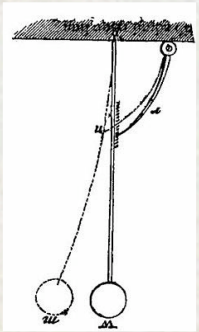
Linear systems

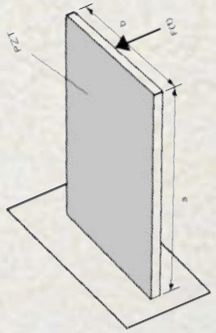
When $U(x) = \frac{1}{2} k x^2$ it is called a linear system

Linear systems have some interesting features… (and engeneers like them most)

1) There exist a simple math theory to solve the eq.s
2) They have a resonant behaviour (resonance freq.)
3) They can be “easily” realized with catilevers and pendula





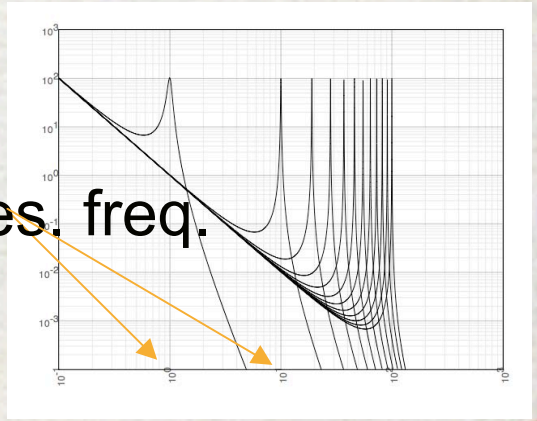


Noise energy harvesting

Linear systems

For a linear system the transfer function presents one or more peeks corresponding to the resonace frequencies and thus it is efficient mainly when the incoming energy is abundant in that regions…

This is a serious limitation when you want to build a small energy harvesting system…



Why ?!!

Noise energy harvesting

Linear systems

For two main reasons…

(1) the frequency spectrum of available vibrations instead of being sharply peaked at some frequency is usually very broad.

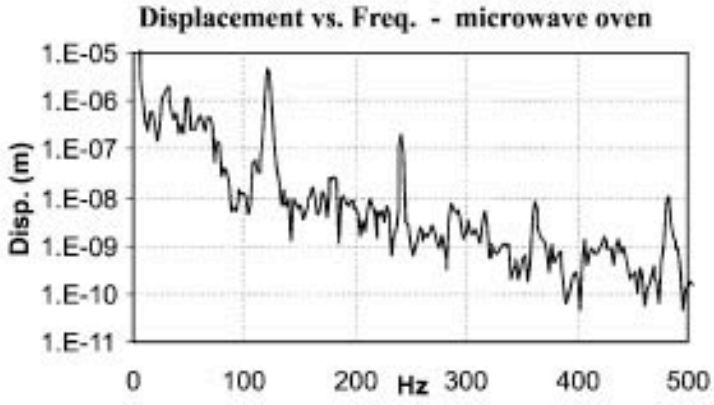
(2) The frequency spectrum of available vibrations is particularly rich in energy in the low frequency part… and it is very difficult, if not impossible, to build small low-frequency resonant systems…

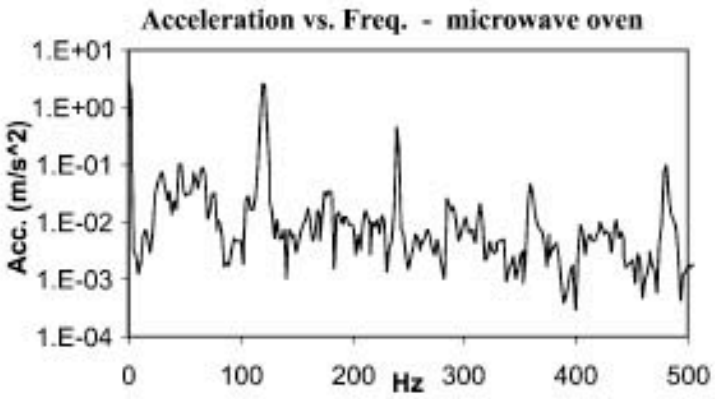
Let's see some examples…

Noise energy harvesting

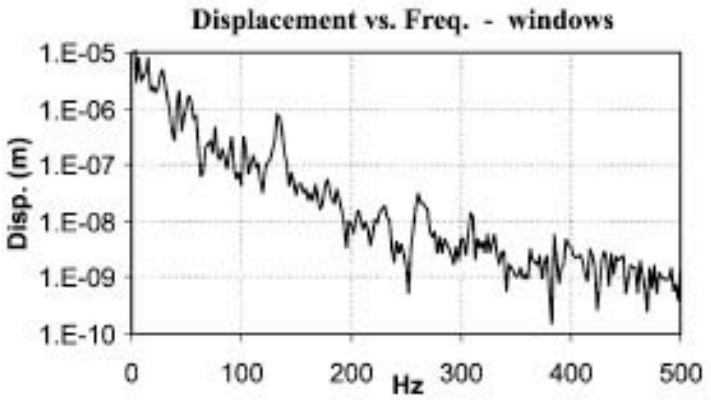
S. Roundy et al. / Computer Communications 26 (2003) 1131–1144

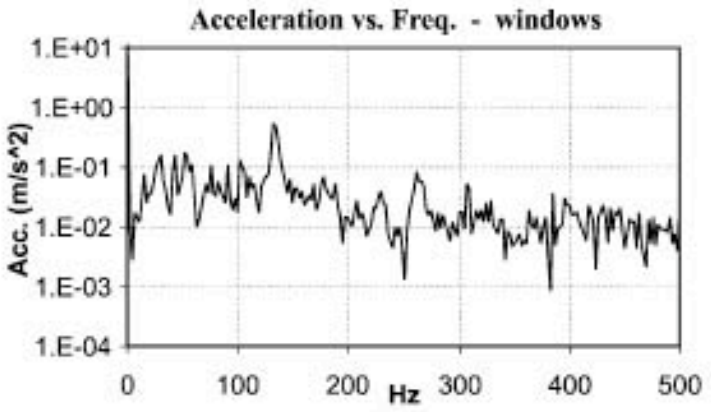
Microwave Casing





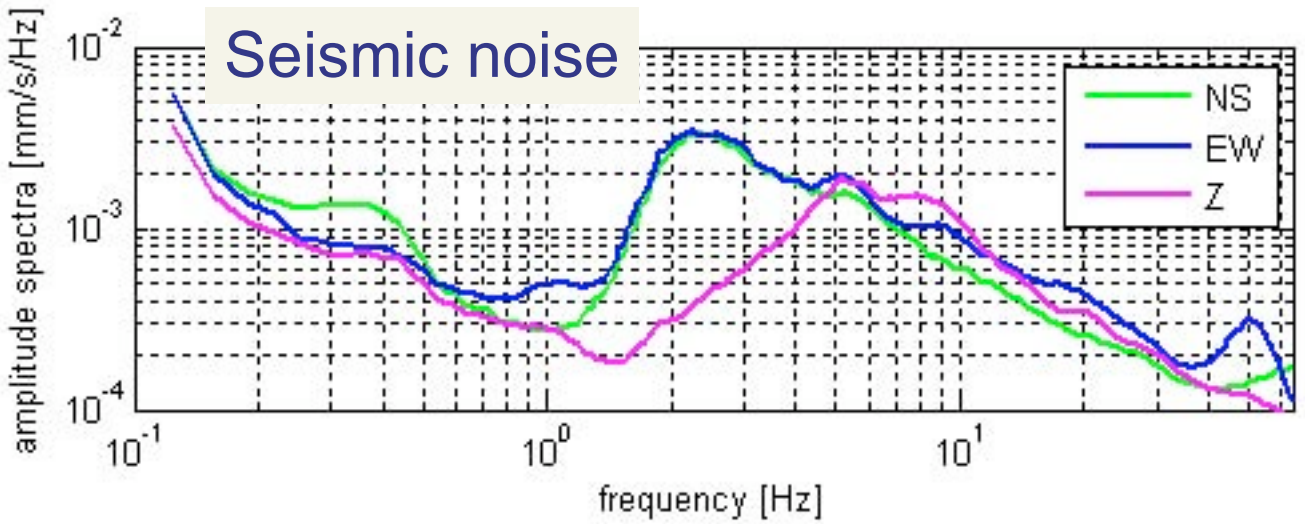
Windows Next to a Busy Street



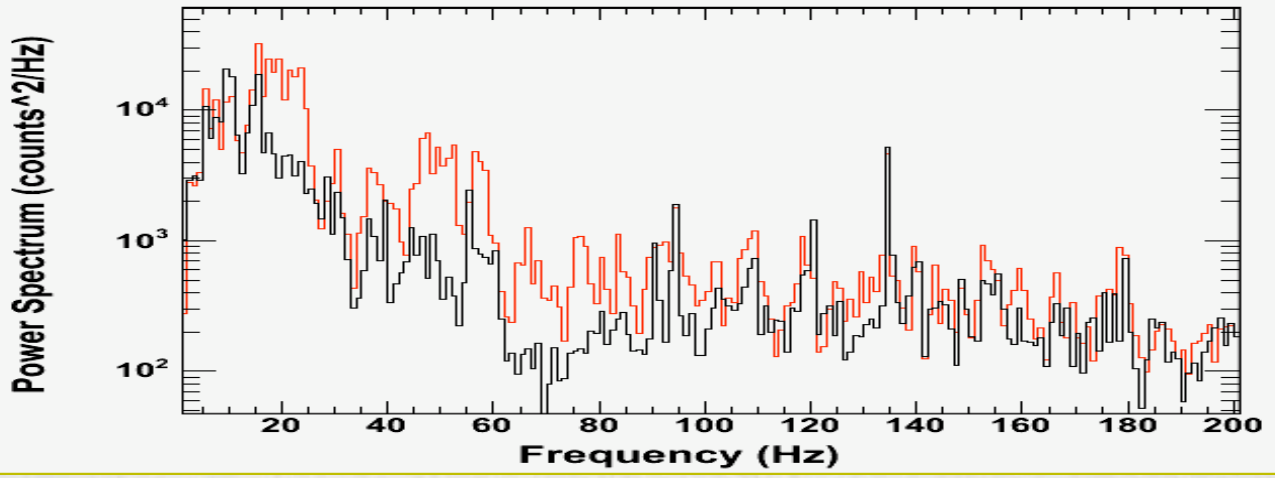


Noise energy harvesting

Seismic noise

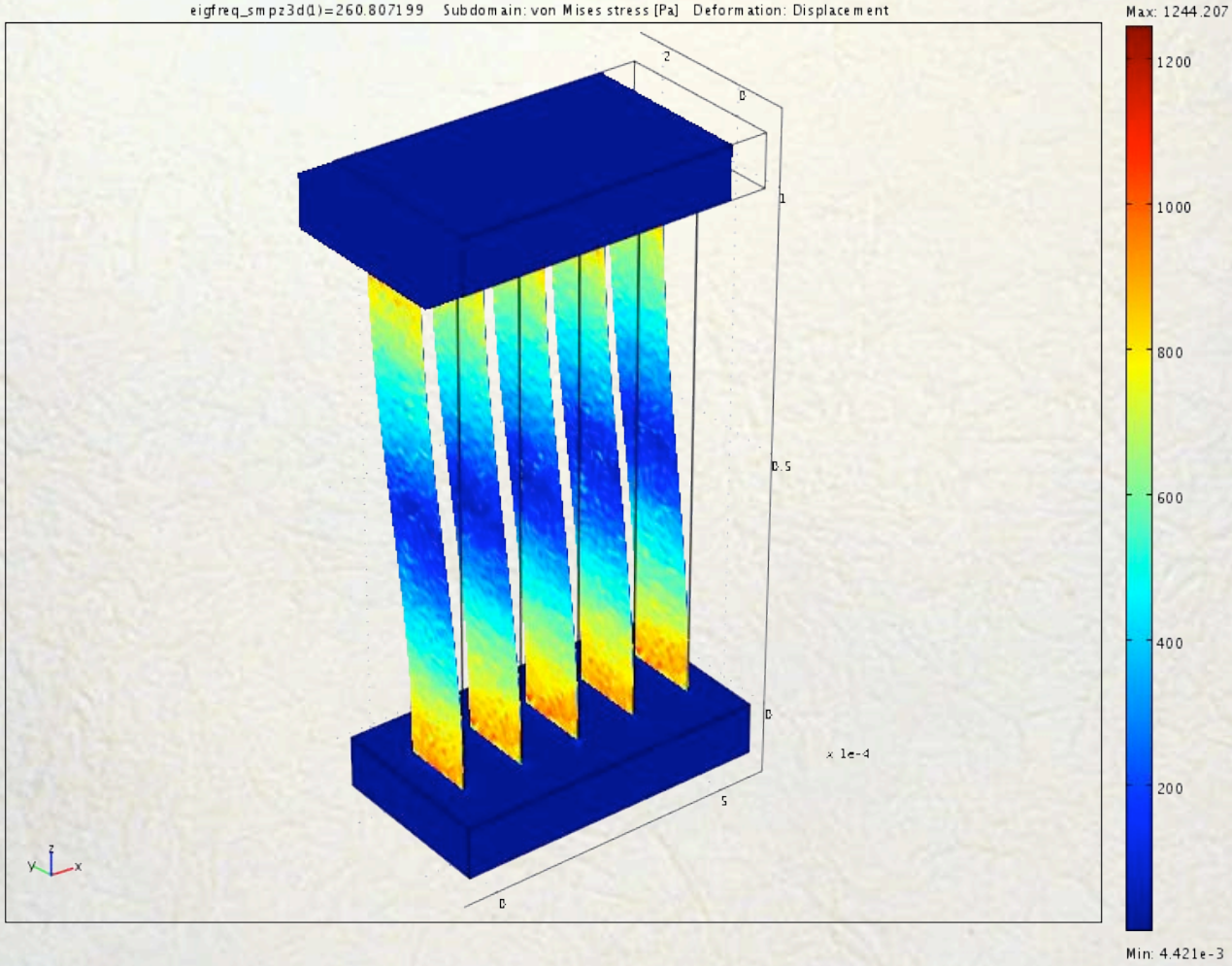


Acoustic noise – quiete working env.



Noise energy harvesting

Micro energy harvesting system…



25 μm thick
1 mm high

Freq. 10 KHz

Noise energy harvesting

Wish list for the perfect vibration harvester

1) Capable of harvesting energy on a broad-band
2) No need for frequency tuning
3) Capable of harvesting energy at low frequency

1) Non-resonant system
2) “Transfer function” with wide frequency resp.
3) Low frequency operated

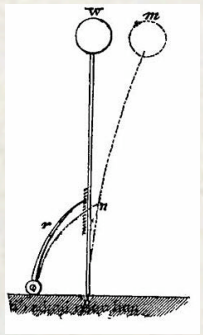
Noise energy harvesting

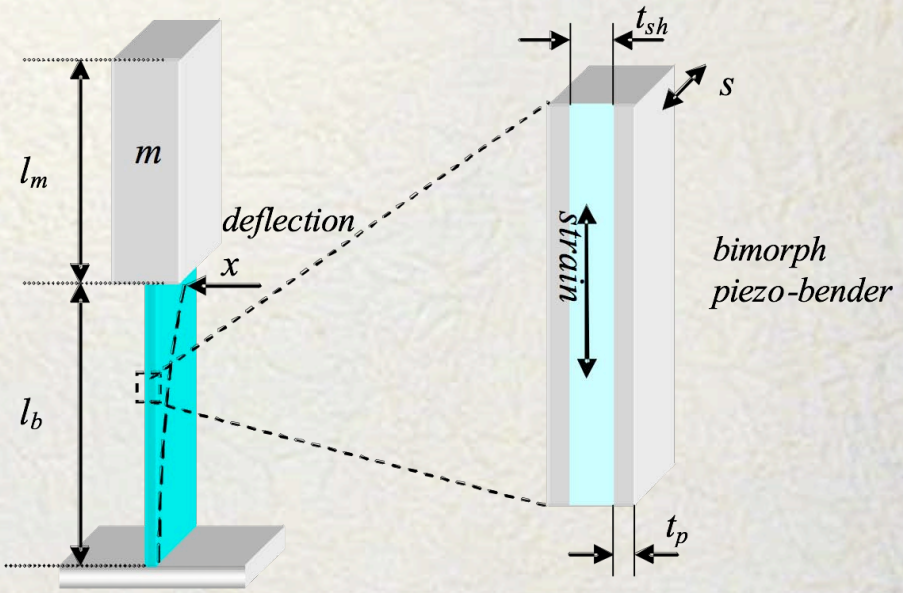
NON-Linear mechanical oscillators

1) Non-resonant system
2) “Transfer function” with wide frequency resp.
3) Low frequency operated

Example…

Inverted pendulum



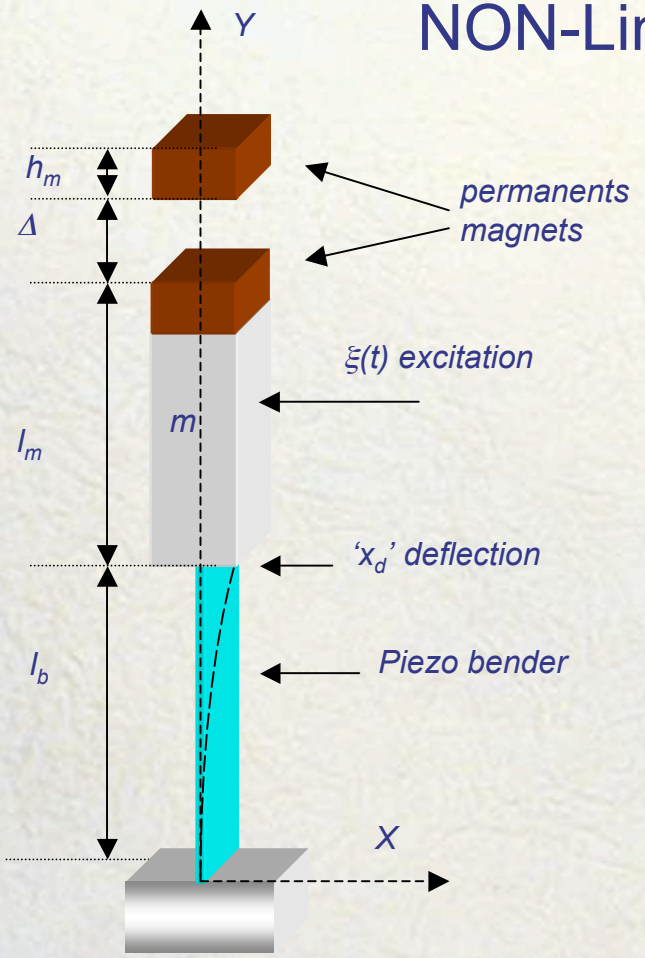


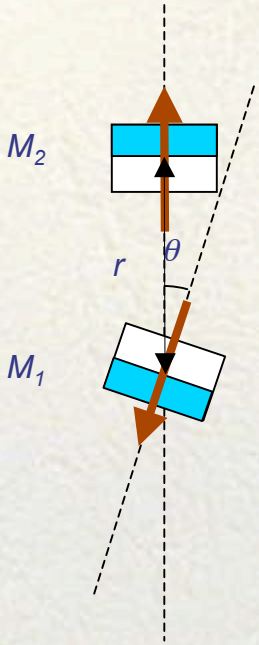
F. Cottone, PhD Thesys, Perugia 2007

Noise energy harvesting

NON-Linear mechanical oscillators

NON-Linear Inverted pendulum





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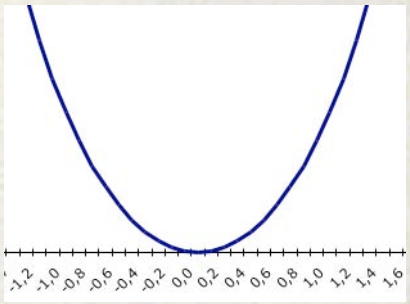
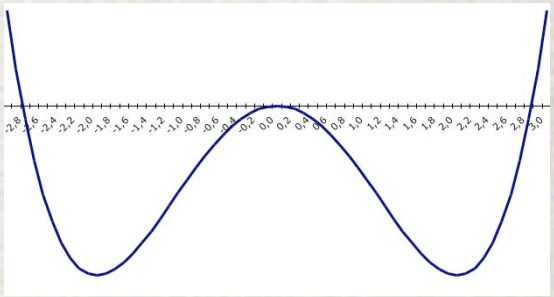
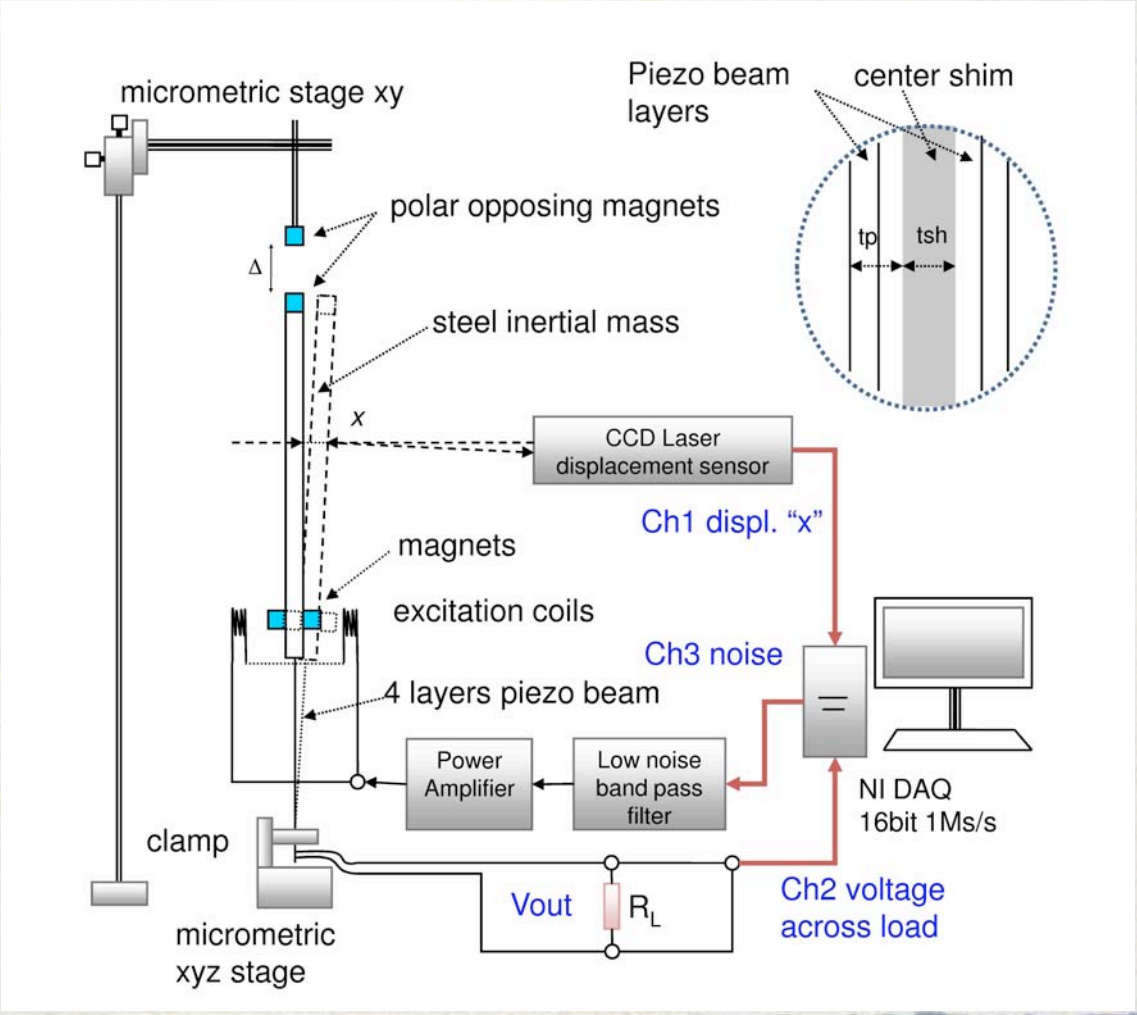




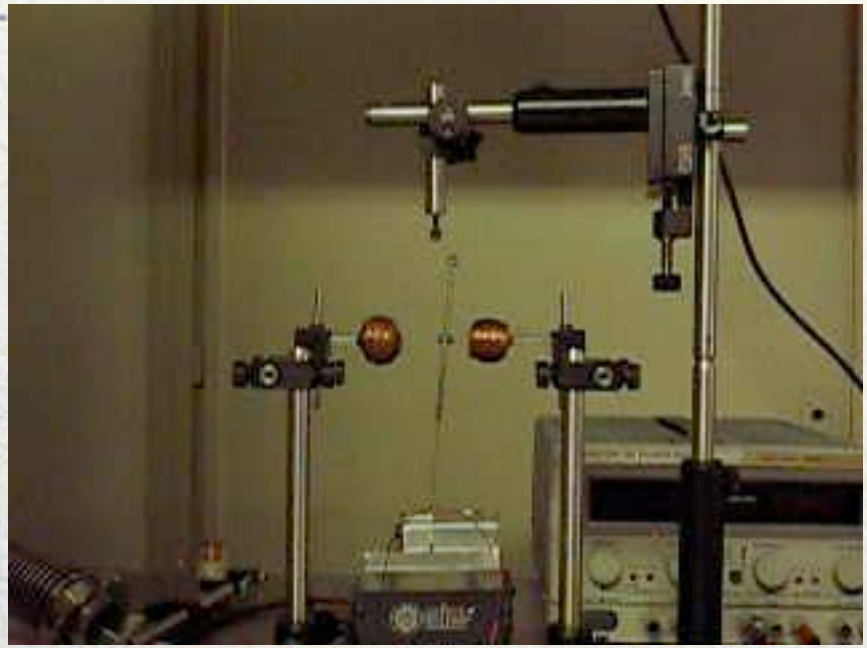
Noise energy harvesting

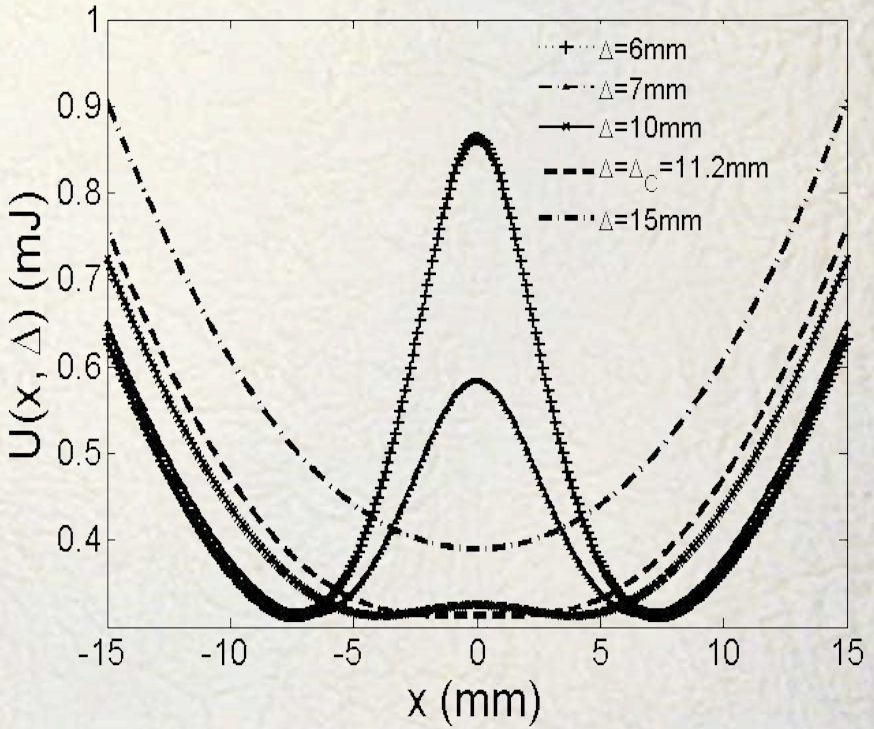
NON-Linear mechanical oscillators



Noise energy harvesting

NON-Linear mechanical oscillators



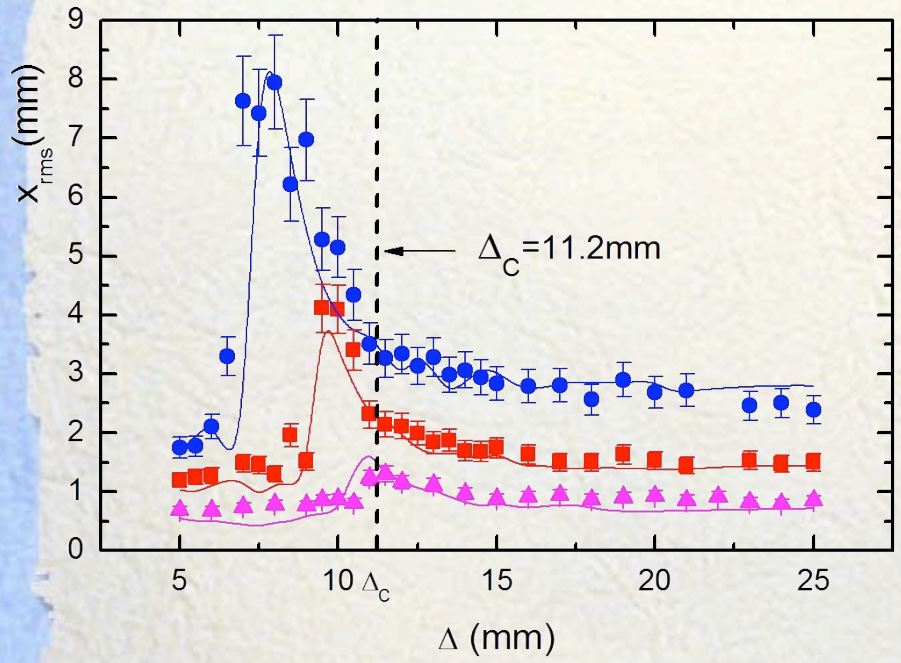


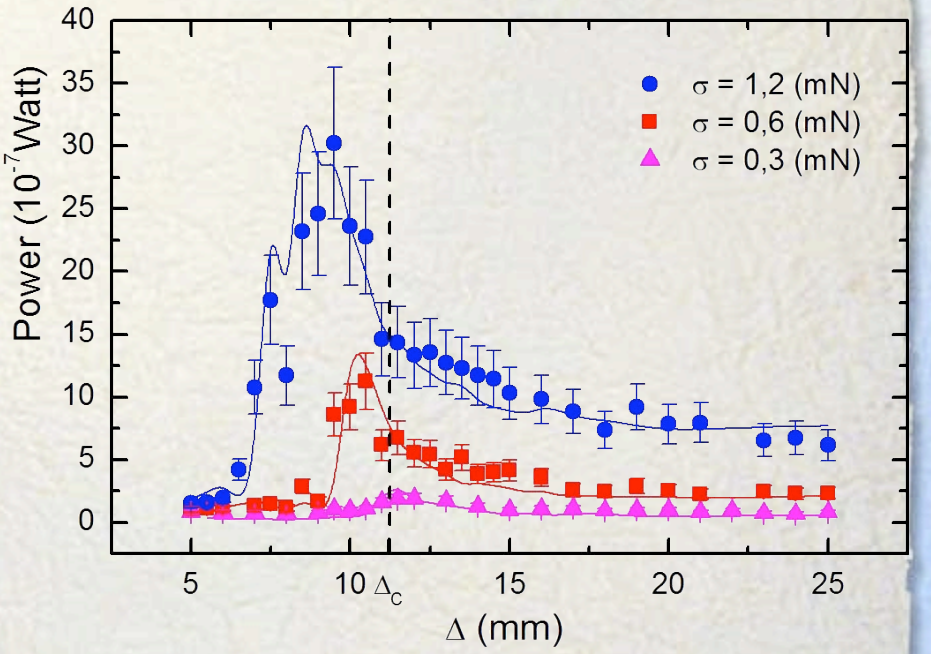
http://www.nipslab.org/node/1676

Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni
Physical Review Letters, 102, 080601 (2009)

Noise energy harvesting

NON-Linear mechanical oscillators



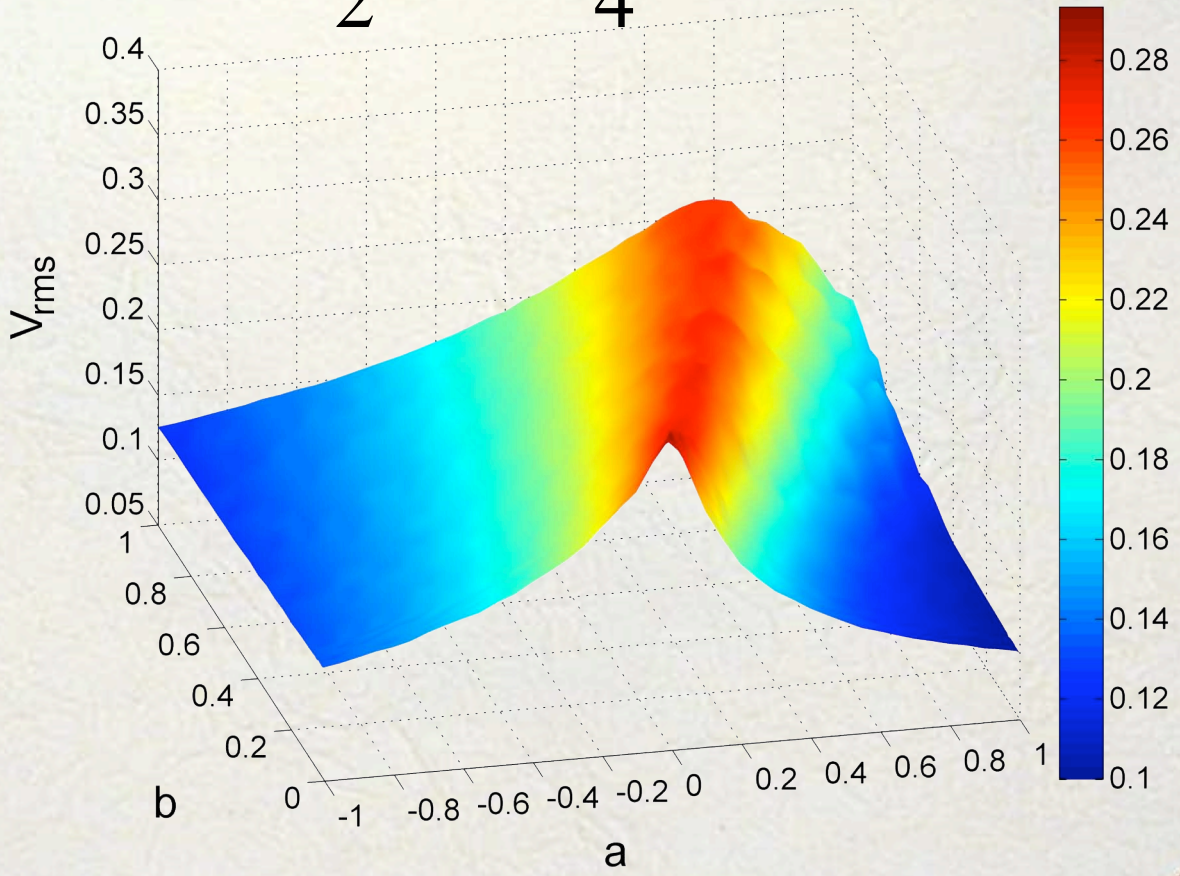


Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni , Physical Review Letters, 102, 080601 (2009)

Noise energy harvesting

Non-linear systems

$$U(x) = -\frac{1}{2}ax^2 + \frac{1}{4}bx^4$$ Duffing potential



L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

Noise energy harvesting

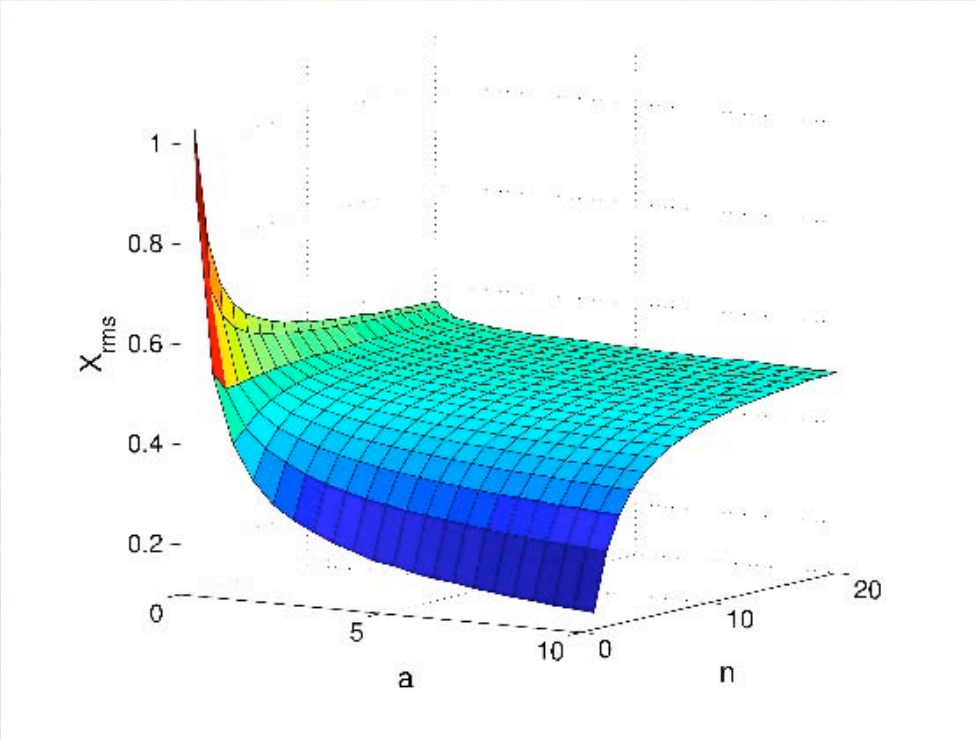
Only bistability???

A more general monostable potential…

$$U(x) = ax^{2n}$$

$$with: a > 0$$

$$n = 1,2,...$$



$$a_{th} \approx \frac{D}{4} = \sigma^2 \tau$$

L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

To think about…

1) Non resonant (i.e. non-linear) mechanical oscillators can outperform resonant (i.e. linear) ones*
2) Non-linear systems are more difficult to treat
3) Bistability is not the only nonlinearity available…

* **wisepower technology** patent. For more info see: www.nipslab.org, www.wisepower.it