MÉCANISMES NON LINÉAIRES DANS DES DISPOSITIFS MEMS POUR LA RÉCUPÉRATION D'ÉNERGIE

ON THE USE OF NON-LINEAR MEMS FOR ENERGY HARVESTING

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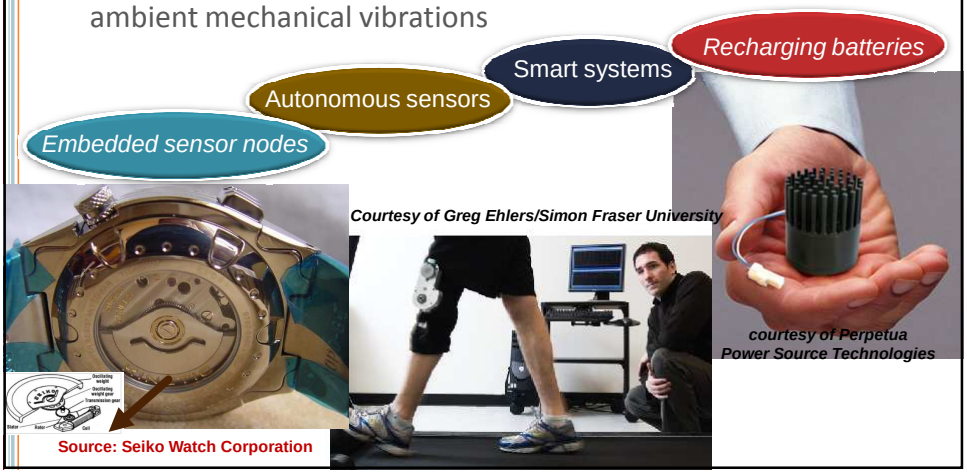
OUTLINE

- Energy Harvesting Overview
- Non-linear mechanisms & energy harvesting
  - Principle
  - Modeling
  - SDE-Matlab simulations
- The micro-machined device
  - Fabrication
  - SDE-Matlab simulations
- Experimental results
  - Set-up
  - Positioning the permanent magnet
  - Response @ optimal position
  - Transient response vs simulation

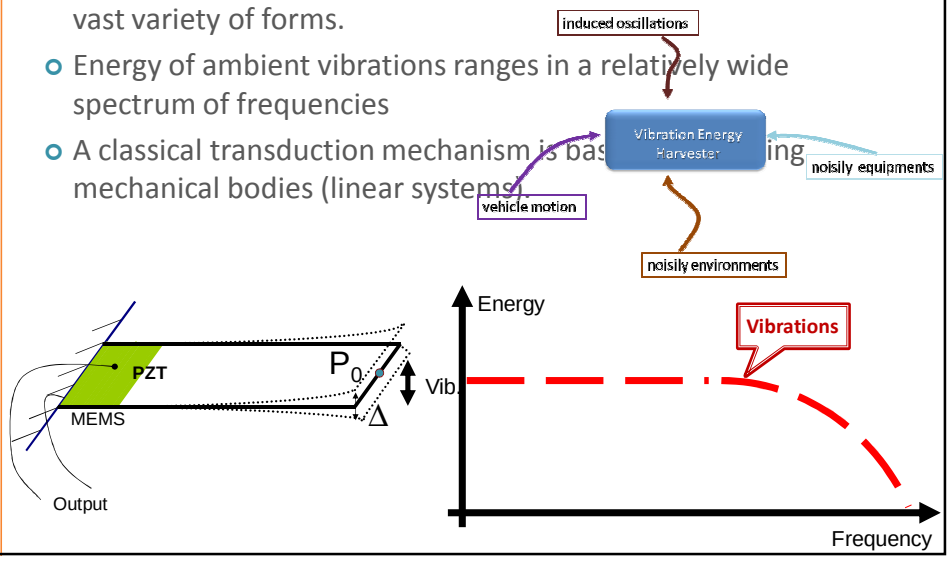
ENERGY HARVESTING OVERVIEW

- Energy harvesting materials and systems have emerged as a prominent research area…
- Here we focus on the problem of harvesting energy from ambient mechanical vibrations



ENERGY HARVESTING OVERVIEW

- In the vast majority of cases the ambient vibrations come in a vast variety of forms.
- Energy of ambient vibrations ranges in a relatively wide spectrum of frequencies
- A classical transduction mechanism is bas ing mechanical bodies (linear systems).



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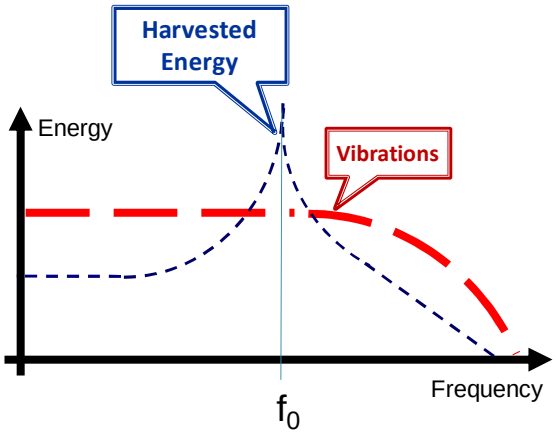
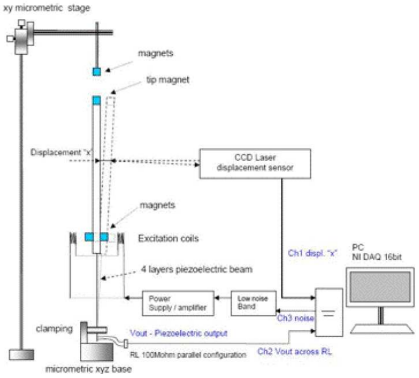


- Harvested energy is typically confined around the natural frequency of a low-pass 2nd order mechanical system.

ENERGY HARVESTING OVERVIEW

- How to increase efficiency of energy harvester?
- Damped system
  - Reduce resonance without increasing DC response
- Networked resonators to increase BW of harvested energy
  - By design
  - By process scatterings

  → array of nano-resonators
- Tunable mechanical resonators
- Non-linear system



F. Cottone, H. Vocca, L. Gammaitoni, "Nonlinear Energy Harvesting". Phys. Rev. Lett., 102 (8), 2009.

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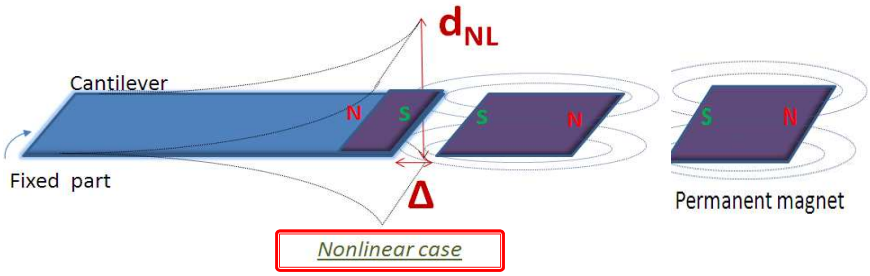
NON-LINEAR MECHANISMS & ENERGY HARVESTING

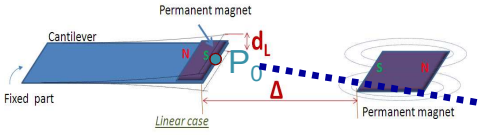
- The idea is to consider not only the device vibrations but also the nonlinear behavior of a bi-stable system to increase collected energy.
- How to obtain such a system?
  - Example: the non-linear bi-stable cantilever

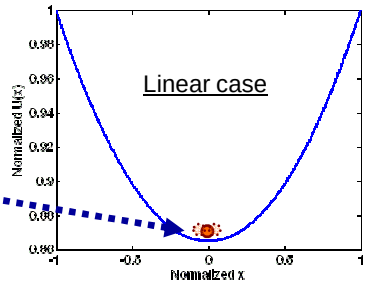


Nonlinear case

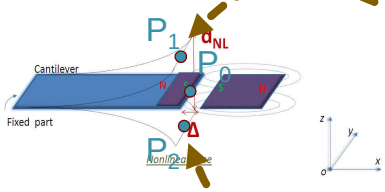
NON-LINEAR MECHANISMS & ENERGY HARVESTING

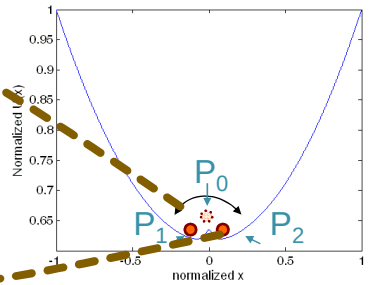
- Principle of operation





P_0 is an unstable state !





NON-LINEAR MECHANISMS & ENERGY HARVESTING

- Modeling: the nonlinear system has been modeled considering a classical mass-spring-damper system, with an additive nonlinear term described by a bi-stable (double well) potential energy function. x represents the displacement of the beam, while, Ψ represents the nonlinear term that includes the elastic constant term k:

Mass of the beam

$$m\ddot{x} + d\dot{x} + \psi = f(t)$$

Damping coefficient

Stochastic source

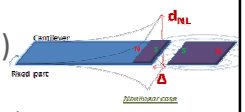
$$\Psi \triangleq \frac{\partial U(x)}{\partial x} = U'(x)$$

$$U(x) = kx^2 + (ax^2 + b\Delta^2)^{-\frac{1}{2}} + c\Delta^2$$

$$\Psi = U(x)' = \frac{\partial}{\partial x}\left[kx^2 + (ax^2 + b\Delta^2)^{-\frac{1}{2}} + c\Delta^2\right] = 2kx + \left[\frac{-\frac{1}{2}(ax^2 + b\Delta^2)^{-\frac{3}{2}}2ax}{(ax^2 + b\Delta^2)^3}\right] = -3ax(ax^2 + b\Delta^2)^{-\frac{3}{2}} + 2kx$$

NON-LINEAR MECHANISMS & ENERGY HARVESTING

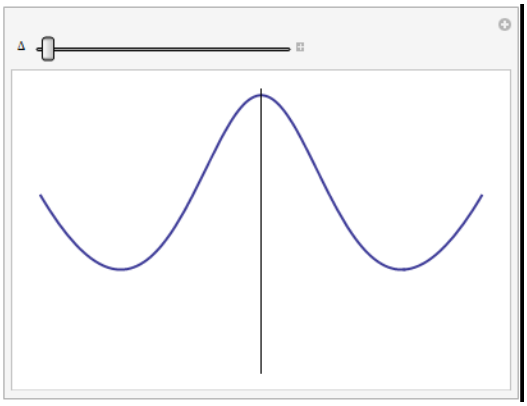
- Modeling: nonlinear dynamical model (Itô's form)



$$\begin{cases} dx_1 = x_2 dt = f_1(x)dt \\ dx_2 = \left[-\frac{d}{m}x_2 + \frac{3ax_1(ax_1^2 + b\Delta^2)^{-\frac{5}{2}}}{m} - \frac{2kx_1}{m} \right] dt + \frac{\sigma}{m} dW_t = f_2(x)dt + g_2(x)dW_t \end{cases}$$

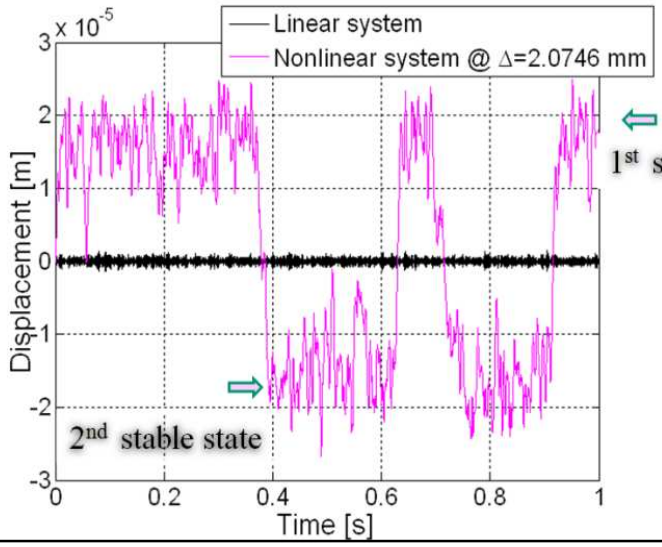
W_t: Wiener process
σ: std of the noise source

Nonlinear Term (Δ)



NON-LINEAR MECHANISMS & ENERGY HARVESTING

- SDE-matlab analysis of a non-linear mechanical system



m=0.001 kg
d=1 kg/s
k=70000 kg/s^2

@ σ= 50 mN

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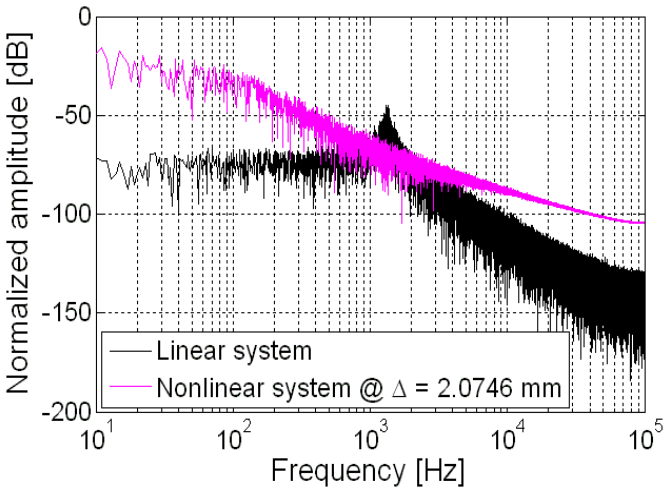

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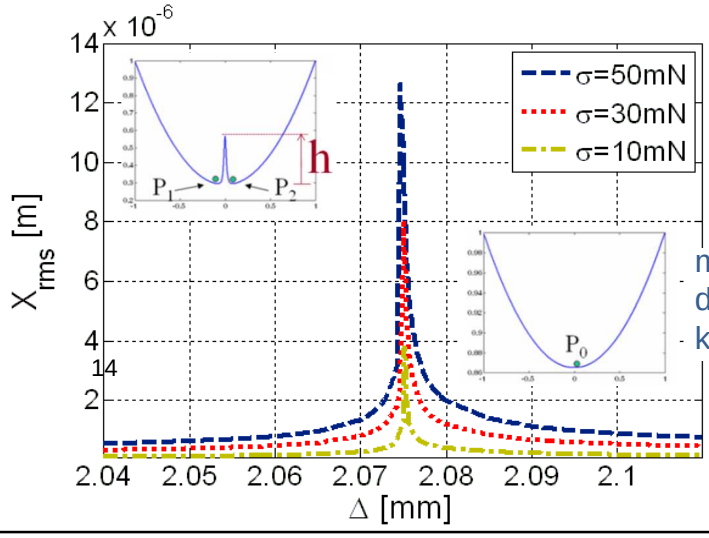

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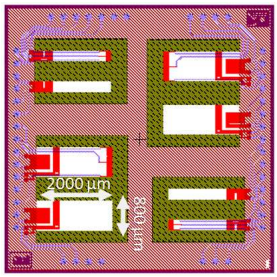
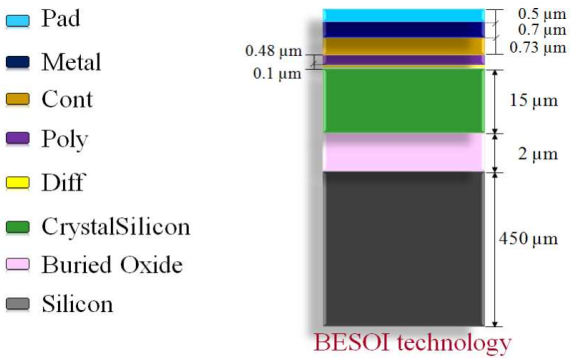
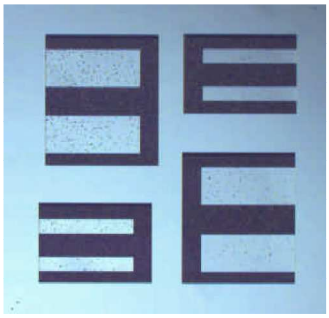
THE MICRO-MACHINED DEVICE

- SOI wafer: 15 µm c-Si layer, 450 µm carrier substrate, 2 µm buried oxide
- Front and back side DRIE etching technique
- Fabrication: CNM, Barcelona, Spain

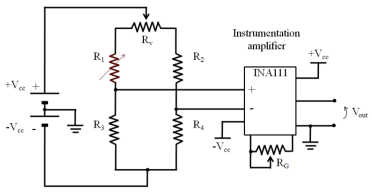


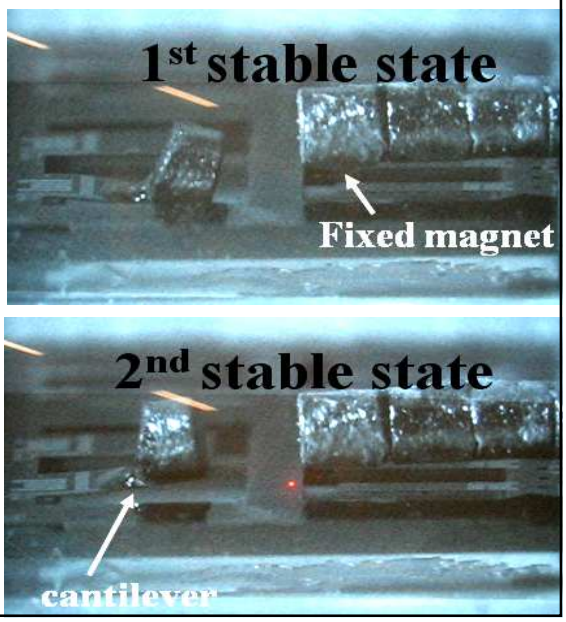




THE MICRO-MACHINED DEVICE

- Bi-stable SOI cantilever beam
  - After gluing a magnet, bi-stable behavior is obtained
  - Displacement is electrically-measured through strain gauges

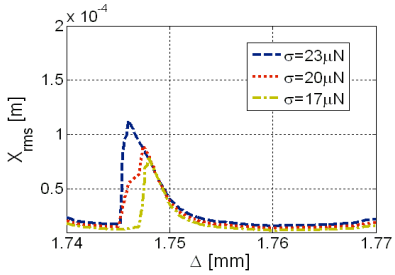


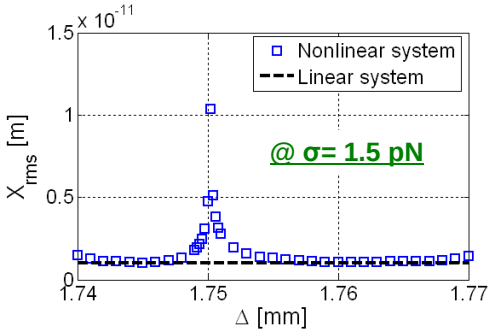


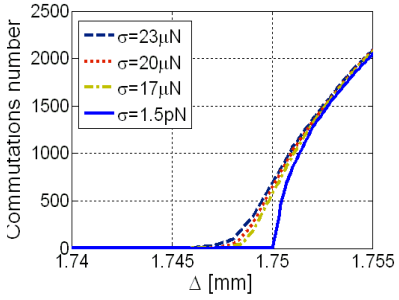
THE MICRO-MACHINED DEVICE

- SDE-matlab analysis of a SOI cantilever beam

m=1e-8 kg
d=1e-5 kg/s
k=15 kg/s²





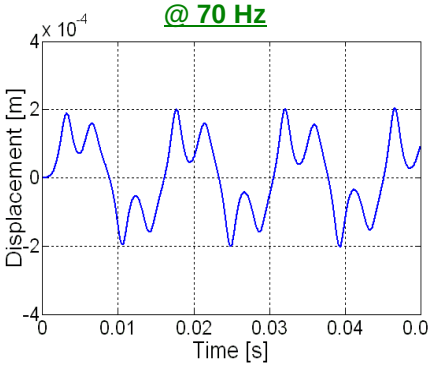


THE MICRO-MACHINED DEVICE

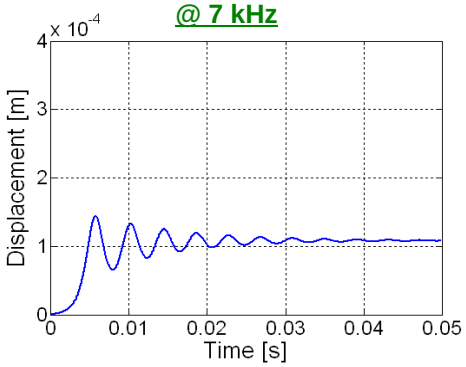
- SDE-matlab analysis of a SOI cantilever beam
  - displacement of the beam excited by a sinusoidal waveform having an amplitude of 17mN

m=1e-8 kg
d=1e-5 kg/s
k=15 kg/s^2

@ 70 Hz



@ 7 kHz



@ σ= 17 mN

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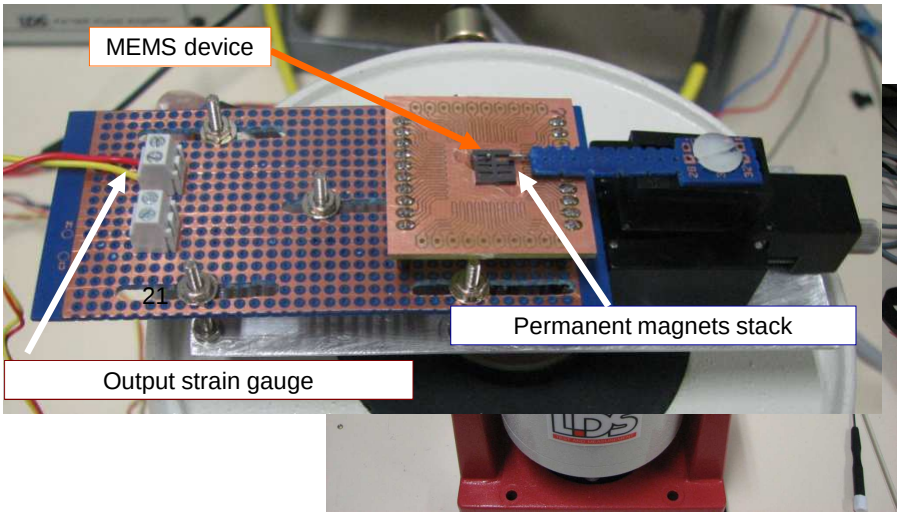
EXPERIMENTAL RESULTS

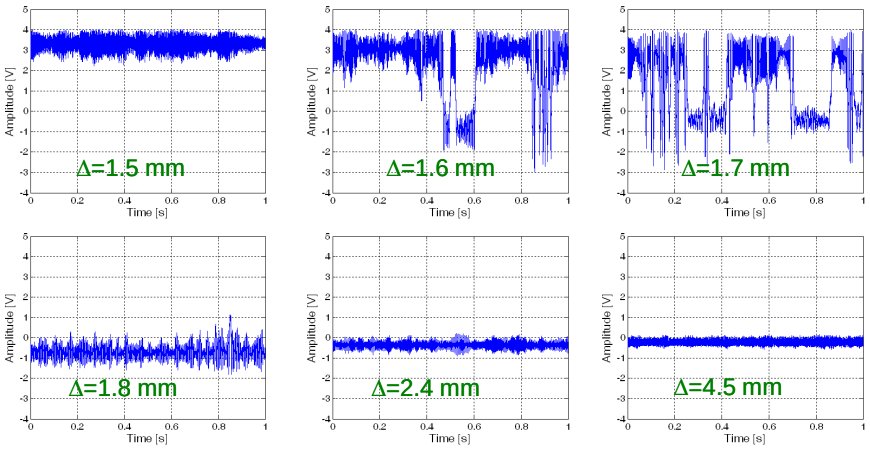
- Experimental set-up



EXPERIMENTAL RESULTS

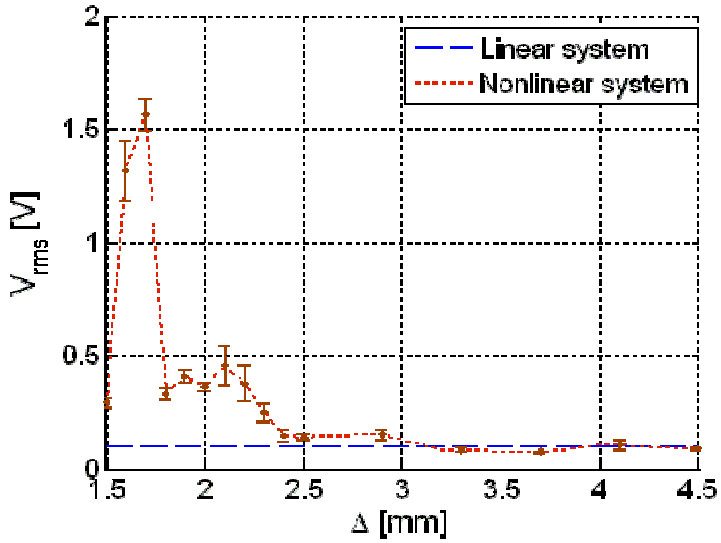
- Positionning the permanent magnet

@ 0.88 g / σ=20 µN



EXPERIMENTAL RESULTS

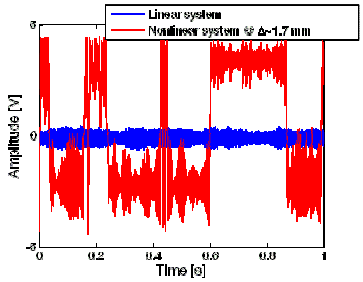
- Positionning the permanent magnet @ 0.88 g / σ=20 µN

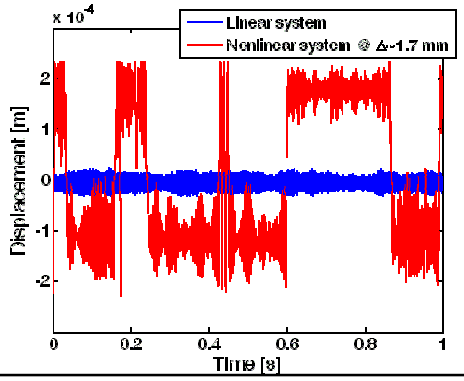


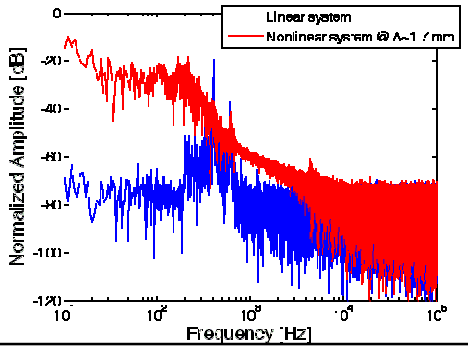
EXPERIMENTAL RESULTS

- Response @ optimal distance of permanent magnet

@ 0.88 g / σ=20 µN

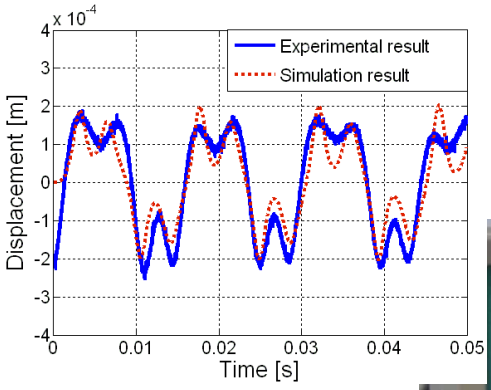




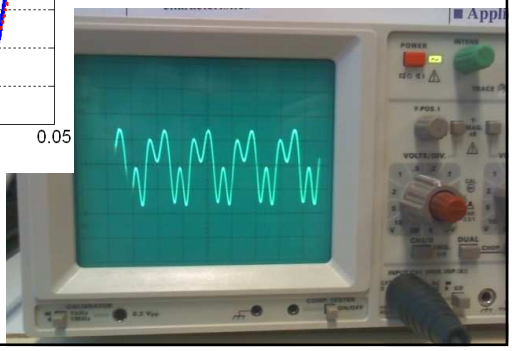


EXPERIMENTAL RESULTS

- Transient response: experimental result vs simulation



@ 70 Hz



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CONCLUSIONS AND FUTURE TRENDS

- Bi-stability seems a promising principle to increase efficiency of energy harvesters
- A micro-machined BESOI device has been designed and fabricated

- Modeling *vs* experimental are in-line
- Magnet deposition relates to craft arts
- Very sensitive to magnet positioning

→ a micro-machined device with embedded piezoelectric and magnetic foil materials will be realized.