Nonlinear kinetic energy harvesting

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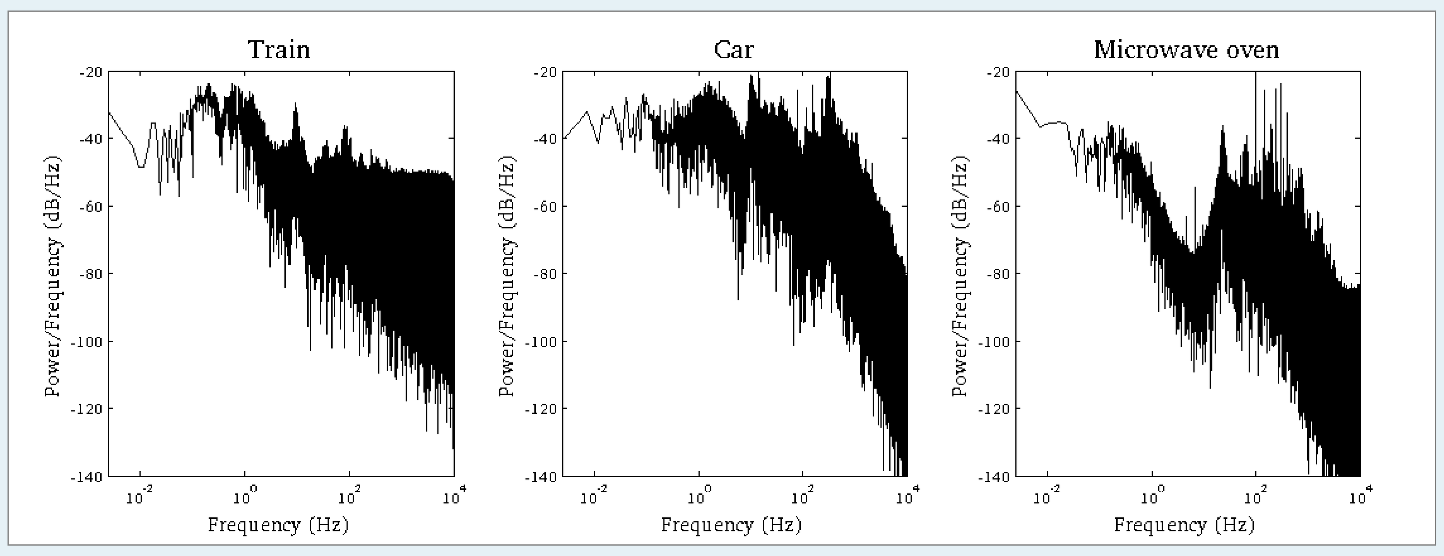
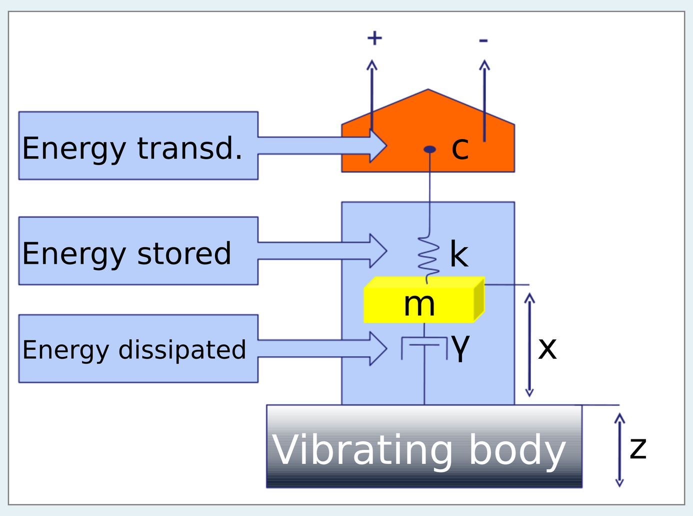
Introduction

Most of the kinetic energy present on the environment is spread in a wide frequency range with the prevalence of low frequency components.



A kinetic energy harvester is a device capable to convert the environmental vibrations into electrical power.

Whish list for perfect 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

Vibration harvester model

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

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

$U(x)$ Is the energy **stored**

$\gamma\dot{x}$ Accounts for the energy **dissipated**

$K_v V$ Accounts for the energy **transduced**

ξ_t Accounts for the **input** energy

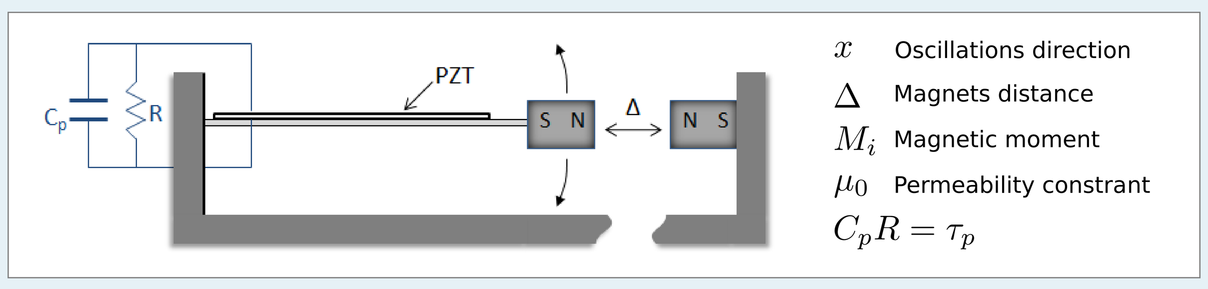
Two conditions have to be met in order to have a maximum in the V_{rms}:
1) the x_{rms} has to be as large as possible
2) the x_{rms} amplitude has to be transduced into V_{rms} with minor losses and this can happen if V can follow closely the evolution of x.

Due to the high-pass filter effect of second equations, with a cut-on frequency determined by $w_p=1/\tau_p$, in order to have most of the motion x_{rms} transduced into the voltage V it is important that most of the energy in x is located at frequencies larger than w_p.

Nonlinear energy harvester

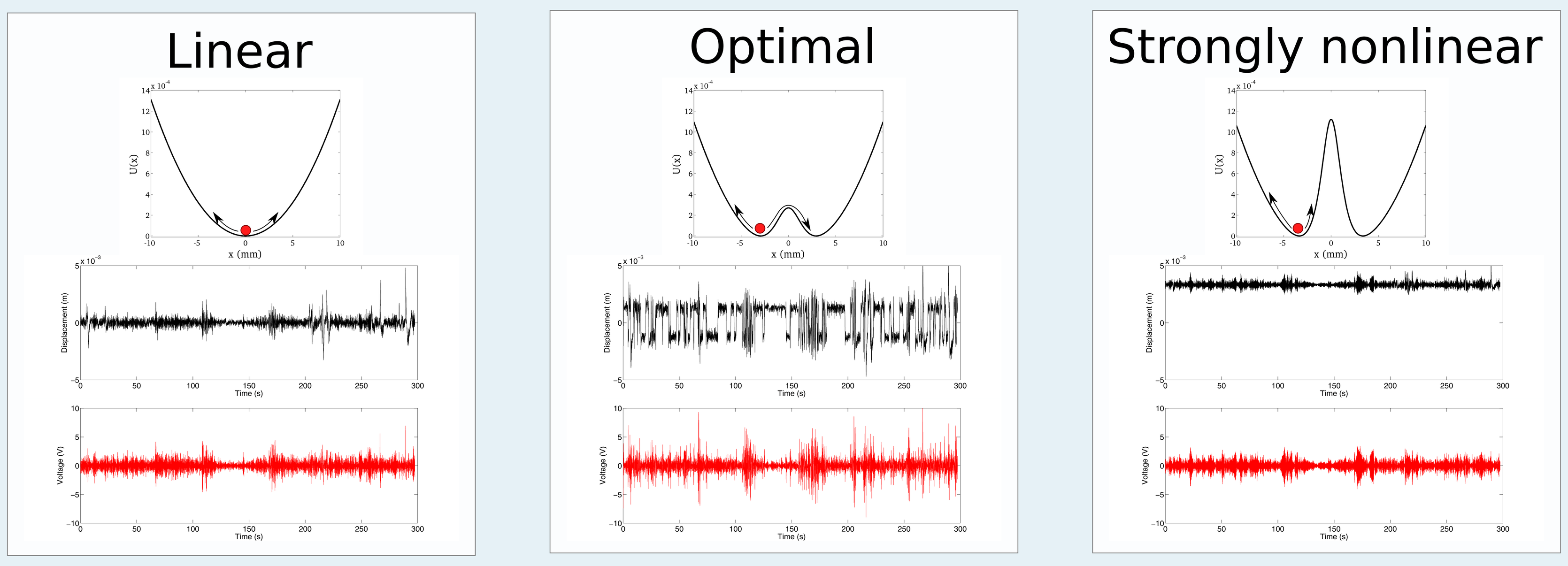
Harvester scheme

The dynamics of the inverted pendulum tip can be modified with the introduction of an external magnet placed at a certain distance Δ and with polarities opposed to those of the tip magnet. The external magnet introduces a force dependent from Δ that opposes the elastic restoring force of the bended beam.



The potential energy function of the nonlinear cantilever can be represented by the following equation:

$$U(x) = \frac{1}{2}kx^2 + \frac{\mu_0}{2\pi}\frac{M_1 M_2}{(x^2+\Delta^2)^{3/2}}$$

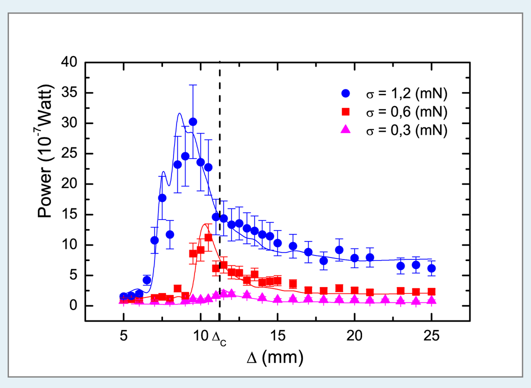


decreasing distance beetween magnets

When the external magnet is far away, the cantilever behaves like a linear oscillator (first panel). This situation accounts well for the traditional piezoelectric vibration-to-electric energy converters. When Δ is small enough the random vibration makes the pendulum swing in a more complex way characterized by iter-well and intra-well oscillations (second and third panels).

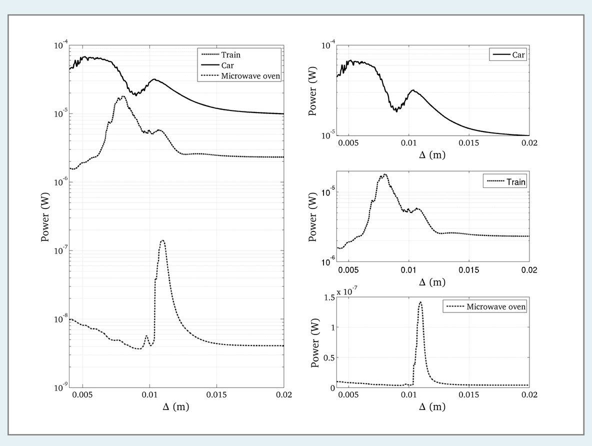
Results

Experiment & Simulation



Left: output power versus magnets distance using as external force exponentially correlated noise.

Simulation with real vibrations



Right: simulation results of the cantilever piezoelectric oscillator. Mean electric power as a function of the magnets distance for the three real vibrations data sets presented above.

Conclusions

Nonlinear vibration harvesters, based on the exploitation of the dynamical features of stochastic bistable oscillators, can outperform standard linear oscillators in real-world applications. These results are not limited to the few specific cases presented here, but can be generalized to a vast class of vibration signals where the vibration spectrum is spread in a wide frequency range. This results are not limited only to the piezoelectric energy conversion principle but can be applied also to other principles, e.g. capacitive and inductive. This study can be applied also to micro and nano scale.

[1] **The benefits of noise and nonlinearity: Extracting energy from random vibrations** - L. Gammaitoni, I. Neri and H. Vocca - Chemical Physics Volume 375, Issues 2-3 Pages 435-438
[2] **Noise Harvesting** - L. Gammaitoni, F. Cottone, I. Neri and H. Vocca - AIP Conf. Proc. - Volume 1129, pp. 651-654
[3] **Nonlinear oscillators for vibration energy harvesting** - L. Gammaitoni, I. Neri and H. Vocca - Appl. Phys. Lett. 94, 164102 (2009)
[4] **Nonlinear Energy Harvesting** - F. Cottone, H. Vocca and L. Gammaitoni - Phys. Rev. Lett. 102, 080601 (2009)