

Controlling orbits in nonlinear vibration energy harvesters dynamics

How to increase nonlinear vibration energy harvesters performances based on orbit control?

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Systèmes et Matériaux pour la Mécatronique (SYMME)

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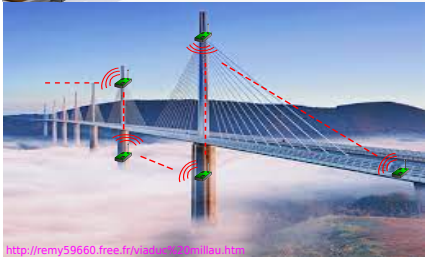
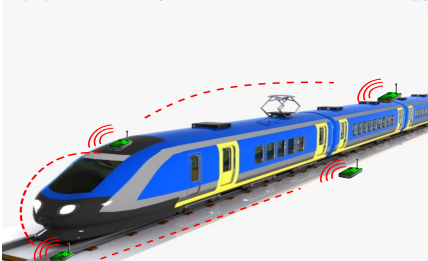
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Vibration energy harvesting motivations

Applications

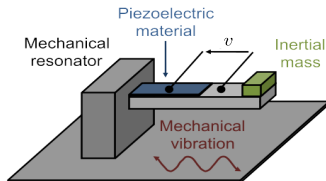
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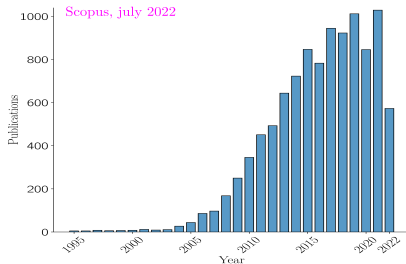
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Batteries complement (in low power electronic systems)

~ 10 μ W - 100 mW



A. Morel, Internation Solid-State Circuits Conference, IEEE 2020

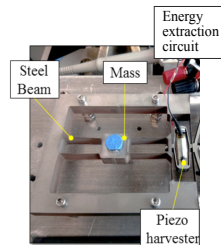
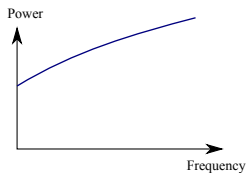
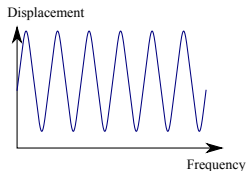
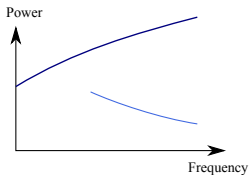
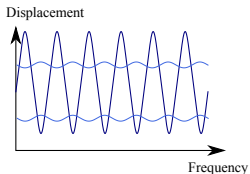


Keywords: “vibration energy harvesting”



Nonlinear Vibration Energy Harvesters (NVEH)

How to improve NVEH performance?



NVEH: bistable [1]

Applying an orbit jump strategy



Coexistence of multiple orbits of various powers



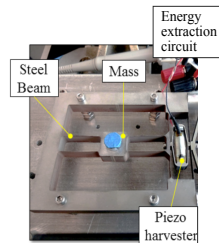
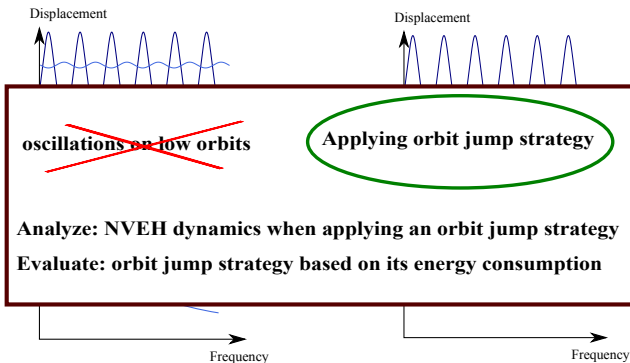
Using high power orbits



[1] T. Huguét et al., Orbit jump in bistable energy harvesters through buckling level modification (2019)

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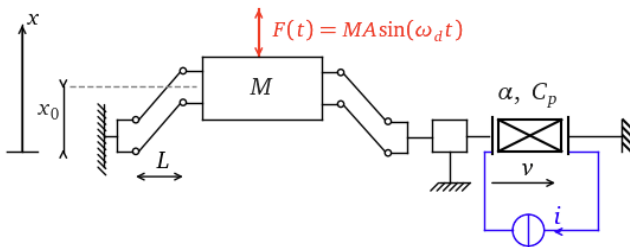


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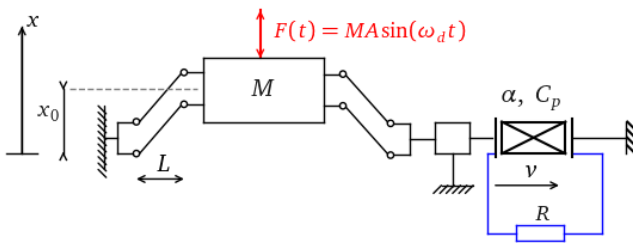
Bistable VEH forced by a sinusoidal excitation



$$\left\{ \begin{array}{l}
 \text{Mechanical resonator dynamics} \\
 \ddot{x} = -\frac{\omega_0^2}{2} \left(\frac{x^2}{x_0^2} - 1 \right) x - \frac{\omega_0}{Q} \dot{x} - \underbrace{2 \frac{\alpha}{ML} xv}_{\text{Electromechanical term}} + \underbrace{A \sin(2\pi f_d t)}_{\text{Input vibration}} \\
 \dot{v} = \underbrace{2 \frac{\alpha}{LC_p} x \dot{x}}_{\text{Piezoelectric effect}} - \underbrace{\frac{1}{C_p} i}_{\text{Harvesting term}}
 \end{array} \right. \quad \begin{array}{l} \text{Mechanical dynamics} \\ \text{Electrical dynamics} \end{array}$$



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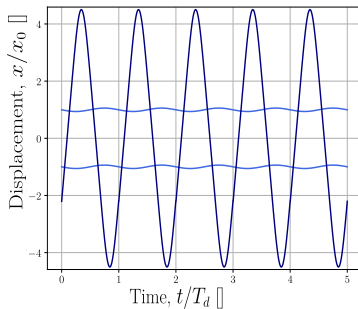
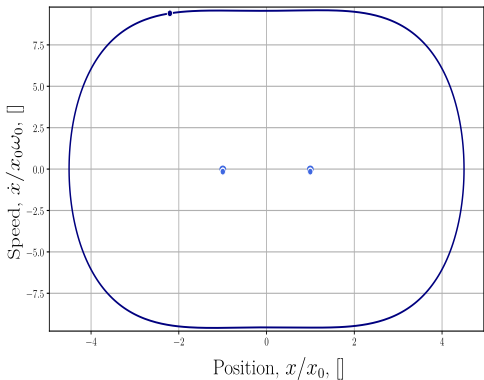
where $i = v/R$



NVEH dynamics at $f_d = 50$ Hz

H1H: Harmonic 1 High

H1L: Harmonic 1 Low

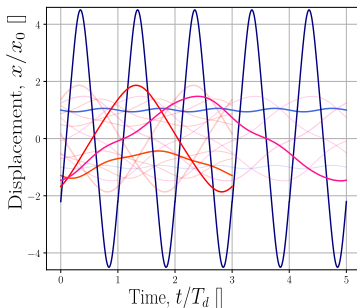
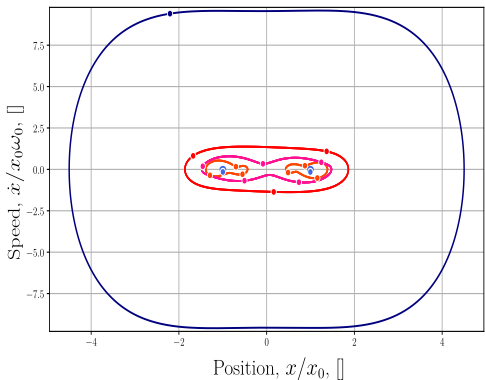


● H1L ● H1H



NVEH dynamics at $f_d = 50$ Hz

H1L: Harmonic 1 Low **H1H:** Harmonic 1 High **SH3L:** Subharmonic 3 Low
SH3H: Subharmonic 3 High **SH5H:** Subharmonic 5 High

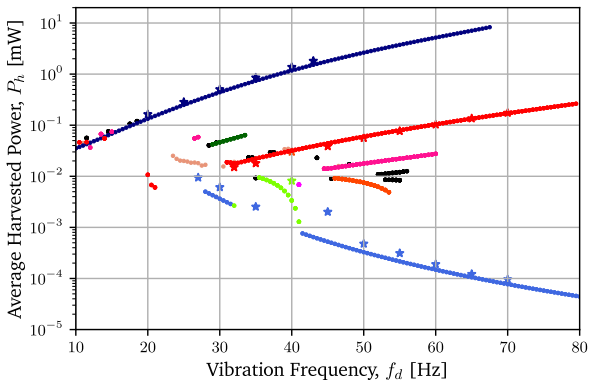


● H1L ● H1H ● SH3L ● SH3H ● SH5H



Average harvested power versus vibration frequency

H1H: Harmonic 1 High **H1L:** Harmonic 1 Low **SH3H:** Subharmonic 3 High

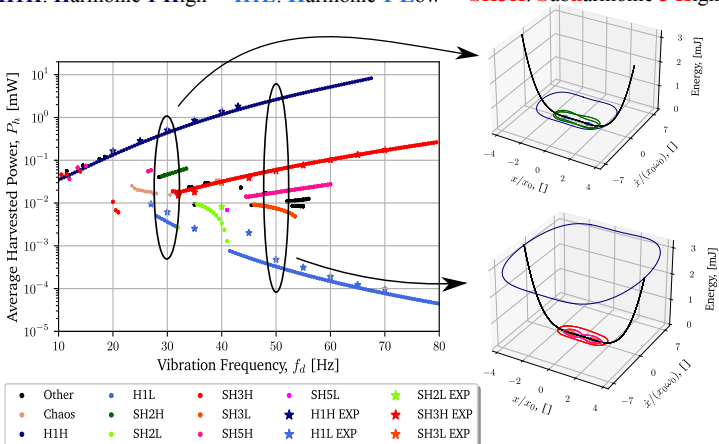


- | | | | | |
|---------|--------|--------|-----------|------------|
| ● Other | ● H1L | ● SH3H | ● SH5L | ★ SH2L EXP |
| ● Chaos | ● SH2H | ● SH3L | ★ H1H EXP | ★ SH3H EXP |
| ● H1H | ● SH2L | ● SH5H | ★ H1L EXP | ★ SH3L EXP |



Average harvested power versus vibration frequency

H1H: Harmonic 1 High **H1L:** Harmonic 1 Low **SH3H:** Subharmonic 3 High

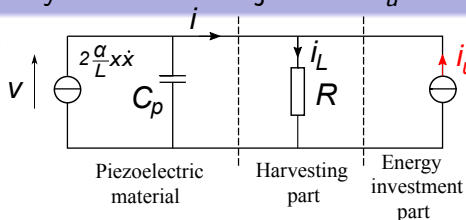


- ▶ the more $f_d \nearrow$, the more it is interesting to implement orbit jump
- ▶ $f_d < 25$ Hz: it is not necessary to implement an orbit jump strategy



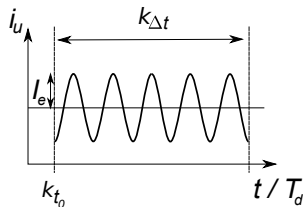
Electrically-induced orbit jump by a current injection i_u

$$\begin{cases} \ddot{x} = -\frac{\omega_0^2}{2} \left(\frac{x^2}{x_0^2} - 1 \right) x - \frac{\omega_0}{Q} \dot{x} - 2 \frac{\alpha}{ML} xv + A \sin(2\pi f_d t) \\ \dot{v} = 2 \frac{\alpha}{LC_p} x \dot{x} - \frac{1}{C_p} i_L + \frac{1}{C_p} i_u \end{cases}$$



Sinusoidal current injection:

$$i_u(t) = \begin{cases} I_e \sin(\omega_e t + \psi_e), & \text{for } t/T_d \in [k_{t_0}, k_{t_0} + k_{\Delta t}] \\ 0, & \text{otherwise} \end{cases}$$



5 orbit jump parameters:

$$(k_{t_0}, k_{\Delta t}, I_e, \psi_e, \omega_e)$$

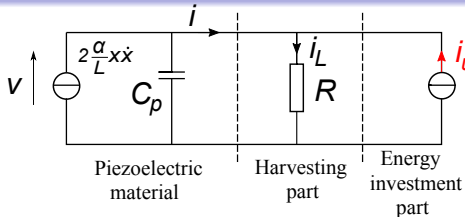
Injected energy:

$$E_{inj} = \int_{t_0}^{t_0 + \Delta t} v(t) \cdot i_u(t) dt$$



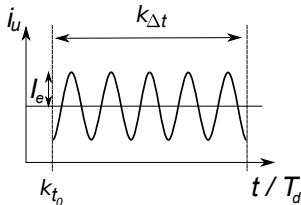
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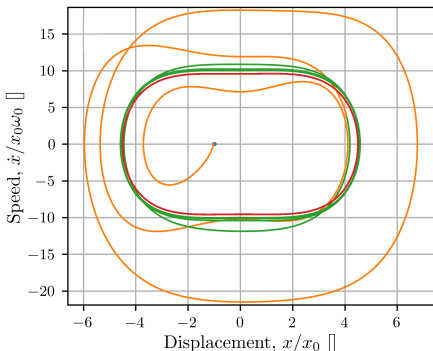
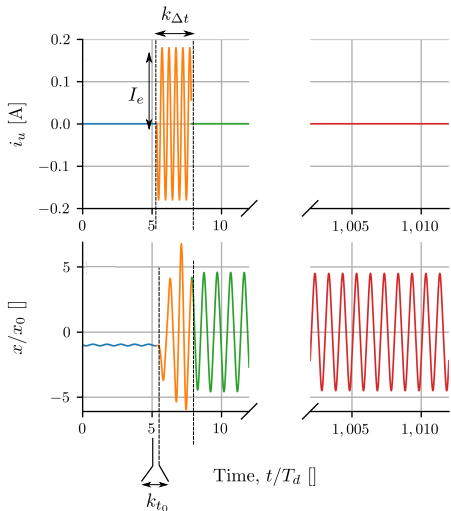
Invested energy:

$$E_{\text{inv}} = \int_{t_0}^{t_0 + \Delta t} [v(t) \cdot i_u(t) - v(t) \cdot i_L(t)] dt$$



Sinusoidal injected current i_u : $f_d = 50$ Hz

$$(k_{t0}, k_{\Delta t}, I_e, \psi_e, \omega_e) = (0.35, 2.5, 0.18, 1.6\pi, 2\omega_d)$$



- before jump
- during jump
- transient after jump
- last $10 T_d$ convergence

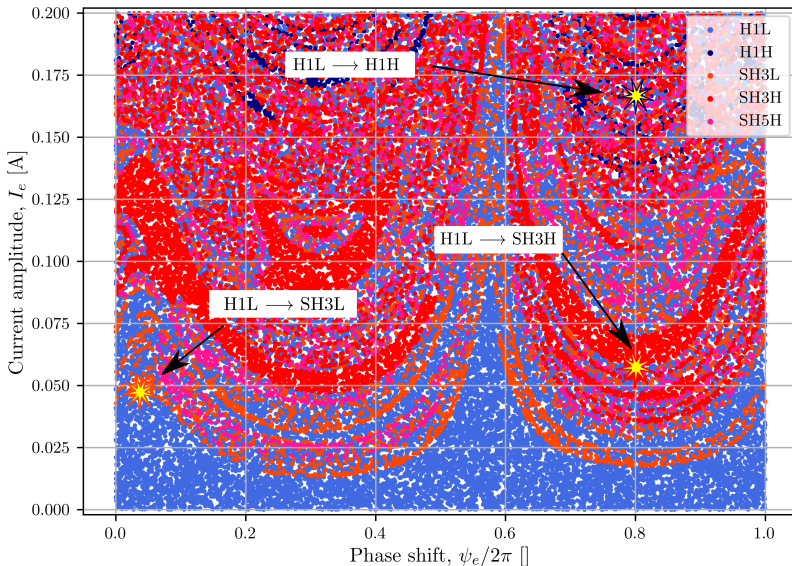


$E_{inv} \approx 40$ mJ

Time to recover the invested energy: $15 T_d$

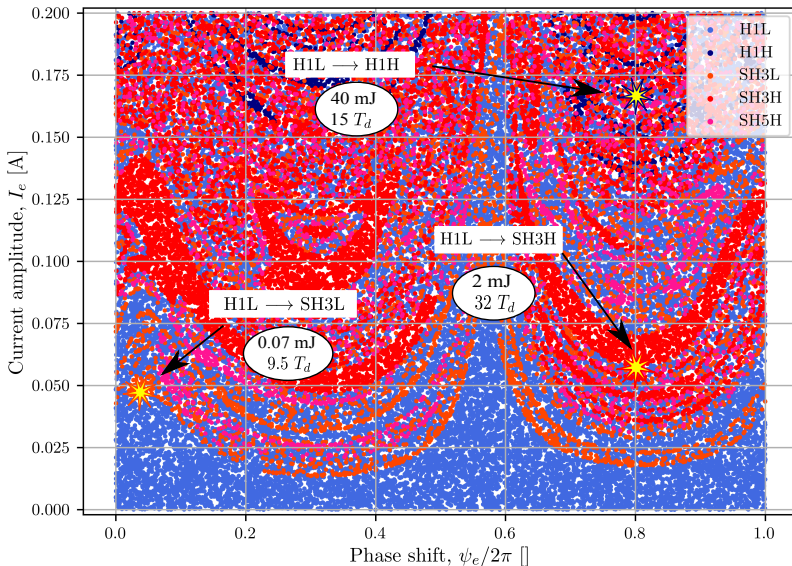
Map: $f_d = 50$ Hz

$(k_{t0}, k_{\Delta t}, I_e, \psi_e, \omega_e) = (0.35, 2.5, I_e, \psi_e, 2\omega_d)$

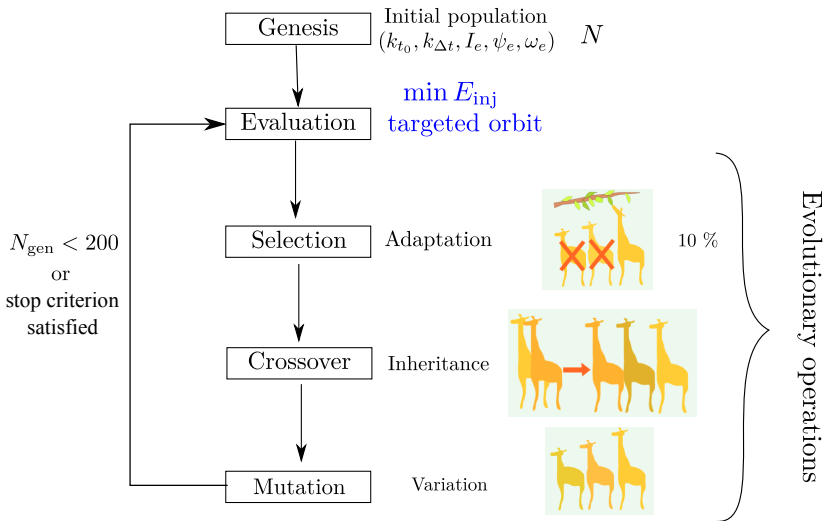


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Evolutionary Algorithm

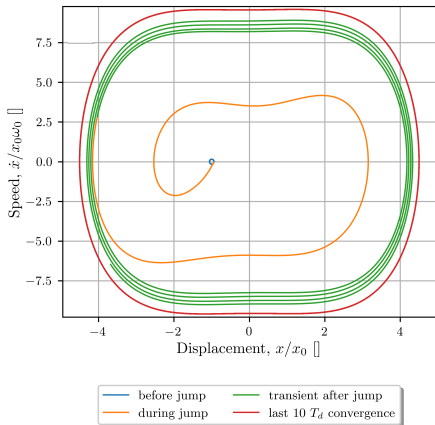
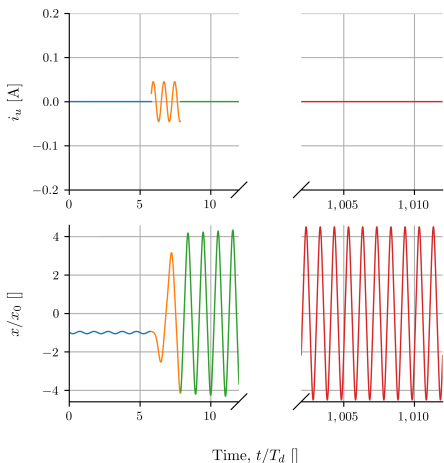


Illustrations: http://igm.univ-mlv.fr/~dx/XPOSE2013/leroux_genetic_algorithm/fonctionnement.html



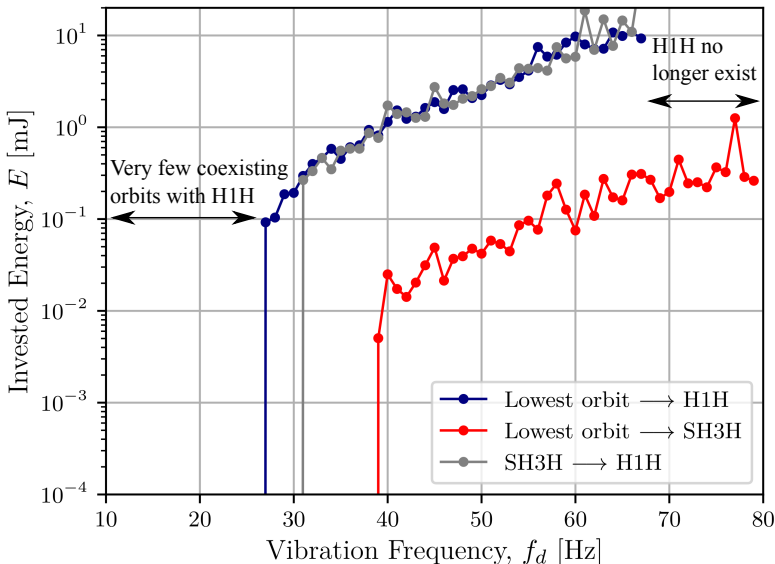
Optimized solution: 50 Hz

$$(k_{t0}, k_{\Delta t}, l_e, \psi_e, \omega_e) = (0.8, 2.08, 0.04, 2.49, 415.34)$$


 $E_{\text{inv}} \approx 2.2 \text{ mJ}$

 Time to recover the invested energy: $0.85 T_d$

Optimal invested energy versus vibration frequency



Conclusion and perspectives

Analysis tool electrically-induced orbit jump strategies:

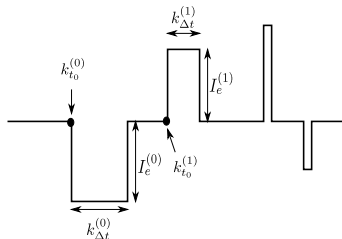
- ▶ Optimize orbit jump strategy using an evolutionary algorithm
- ▶ Simulate orbit jump strategy not specifically electrically-induced (e.g., buckling jump)

To follow: Consider more complex current injection waveform

- ▶ generic injected current with $3N$ dof:

$$i_u(t/T_d) = \sum_{n=0}^{N-1} I_e^{(n)} \Pi_{k_{\Delta t}^{(n)}} \left(t/T_d - k_{t_0}^{(n)} \right)$$

$$N \geq 1$$



- ▶ Smooth this generic current with a spline interpolation



Thank you for your attention!



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