Vibration Energy harvesting: non-linear approaches

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Summary

- Vibration energy harvesting applications and principles
- Limits of linear vibration energy harvesters
- Beyond linear VEH systems: nonlinear approaches
- Wideband technique comparison
- Conclusions

Energy harvesting applications

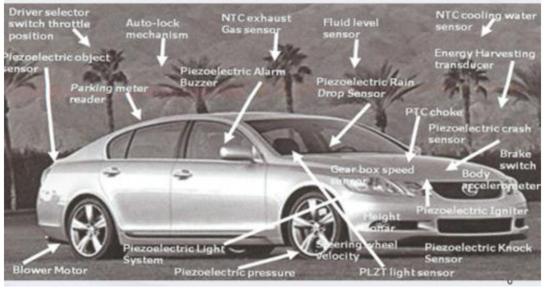
Wireless Sensor Networks

Structural Monitoring

02/07/2014 - Belo Horizonte (Brazil)
(birdge at FIAT factory)

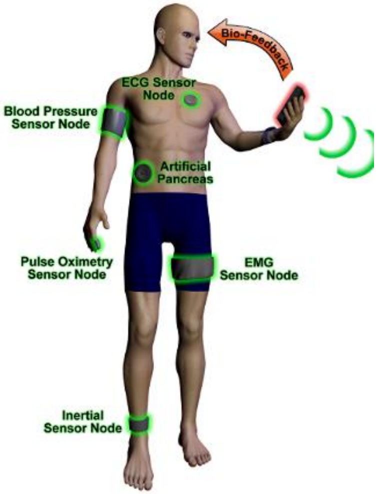
Environmental Monitoring

Transportation



Wearable sensing for health applications

Emergency medical response
Monitoring, pacemaker, defibrillators



Military applications

Energy Harvesting could enable 90% of WSNs applications (IdTechex)

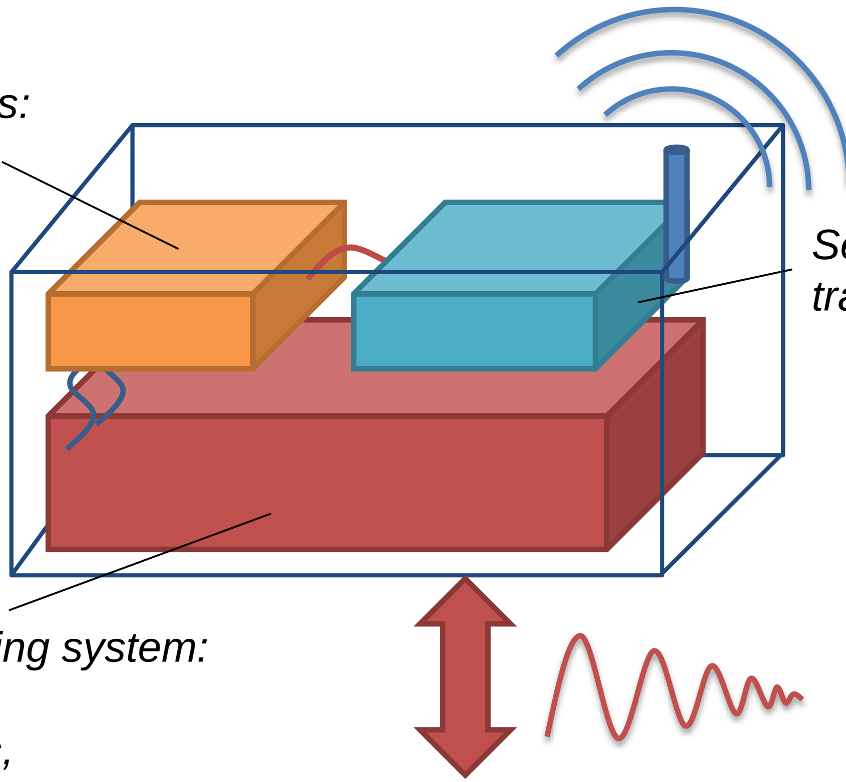
Vibration-driven wireless sensor node

Objective :

1cm^3 with less than 100 µW power consumption

Temporary storage and conditioning electrinics:

- *Ultra capacitors*
- *Rechargeable Batteries*



Sensor node and transceiver

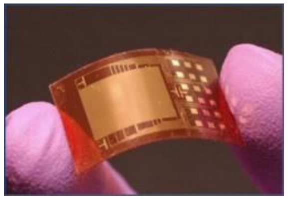
Energy harvesting system:

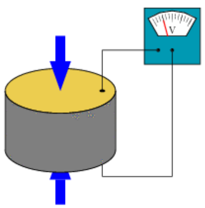
- *piezoelectric,*
- *electromagentic,*
- *electrostatic,*
- *magnetostrictive*

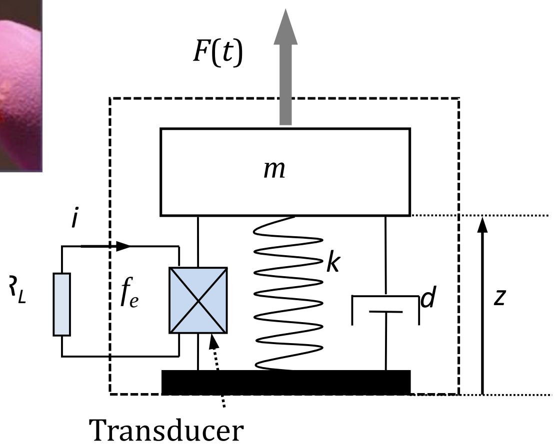
Mechanical vibrations

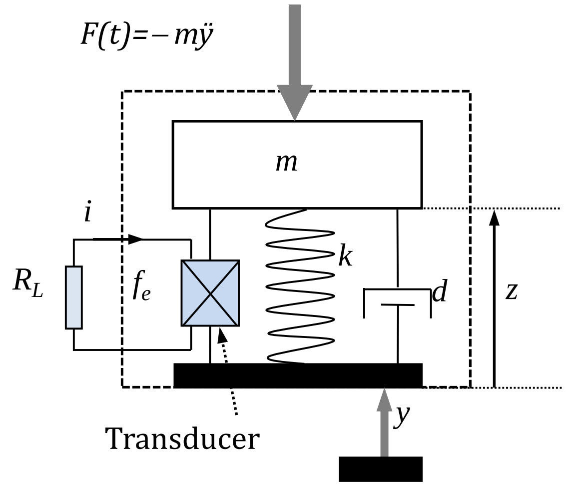
Vibration Energy Harvesters (VEHs): basic operating principles

zinc oxide (ZnO) nanowires
Wang et al. 2008





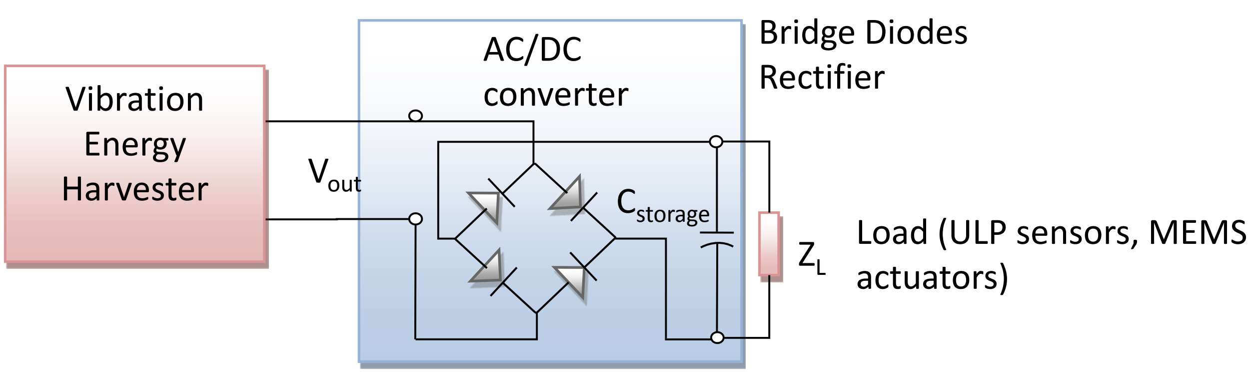




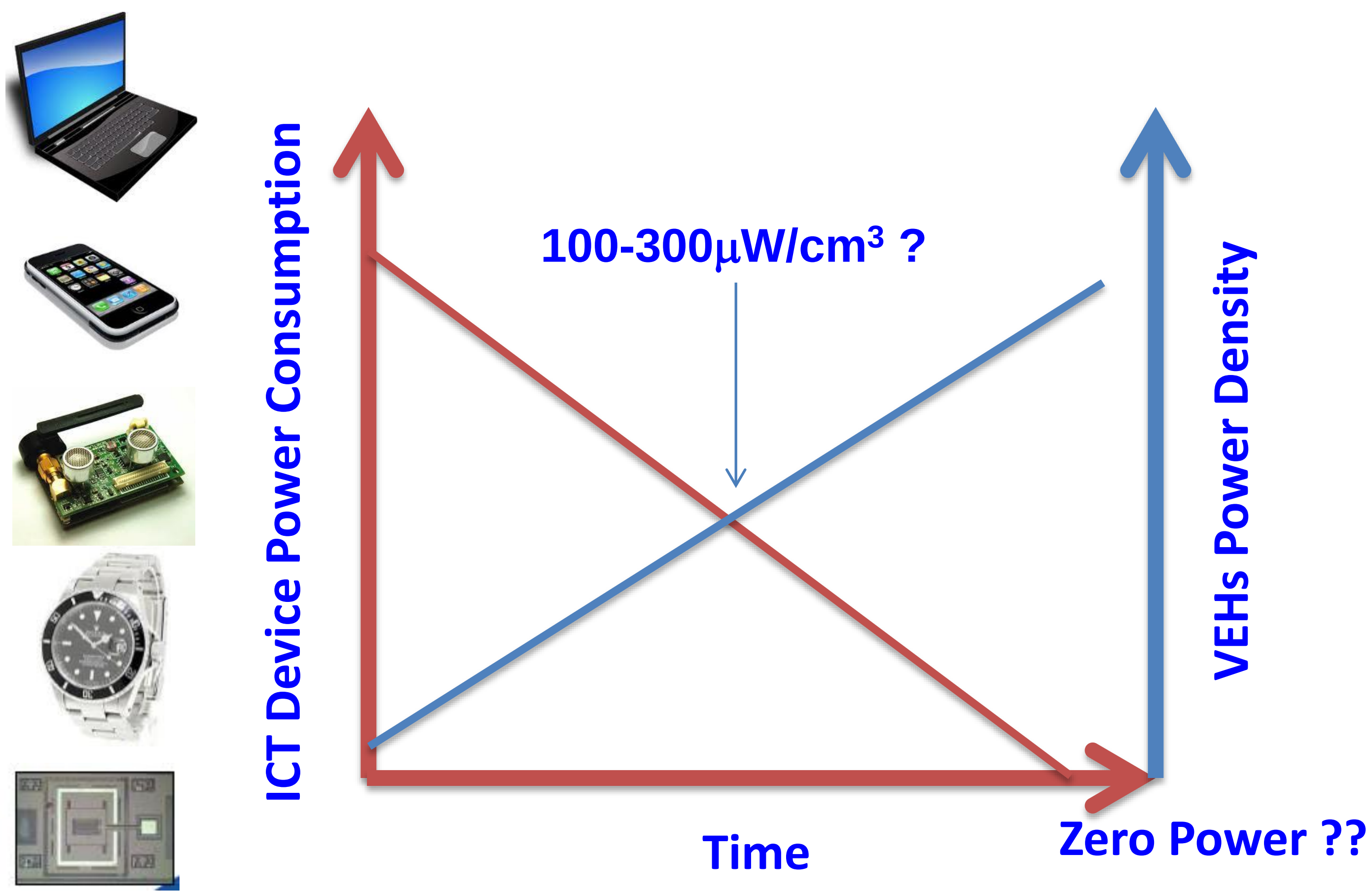
Energy harvesting from
moth vibrations
Chang. MIT 2013

Energy Harvesting from dancing

Inertial generators are more flexible than direct-force devices because they require only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

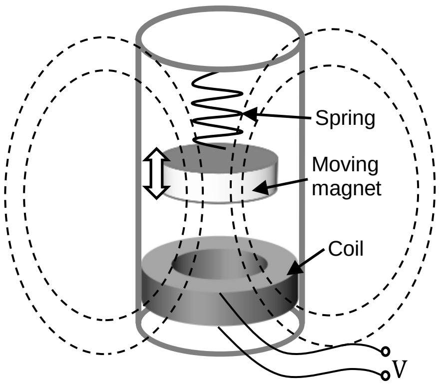


Vibration energy harvesting versus power requirements

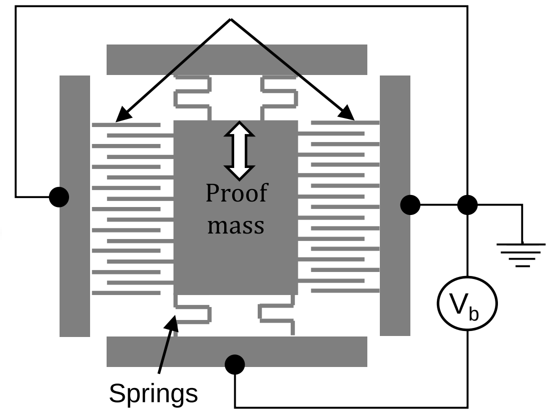


Vibration Energy Harvesters (VEHs): basic principles

Electromagnetic

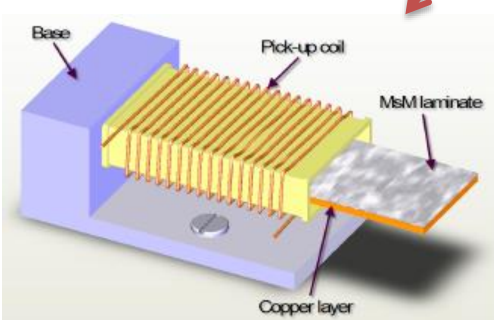


Electrostatic/Capacitive

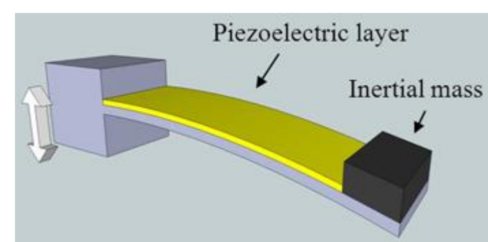


Vibration Harvesting Generator

Magnetostrictive



Piezoelectric



Conversion techniques comparison

Technique	Advantages	Drawbacks
Piezoelectric	• high output voltages • well adapted for miniaturization • high coupling in single crystal • no external voltage source needed	• expensive • small coupling for piezoelectric thin films • large load optimal impedance required (MΩ) • Fatigue effect
Electrostatic	• suited for MEMS integration • good output voltage (2-10V) • possiblity of tuning electromechanical coupling • Long-lasting	• need of external bias voltage • relatively low power density at small scale
Electromagnetic	• good for low frequencies (5-100Hz) • no external voltage source needed • suitable to drive low impedances	• inefficient at MEMS scales: low magnetic field, micro-magnets manufacturing issues • large mass displacement required.

Example of vibration sources

Human activity

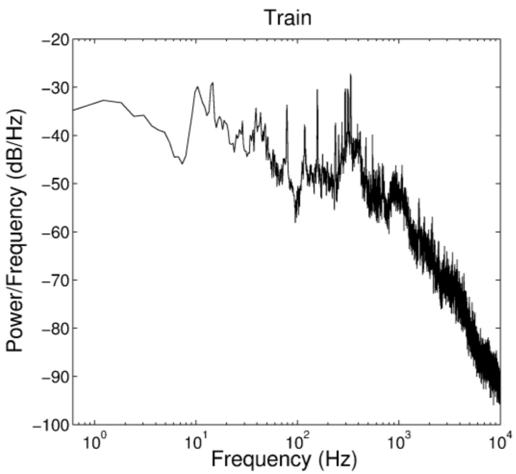
Scenario	$\overline{P}$
Taking a book off a shelf	<10 μW
Putting on reading glasses	<10 μW
Reading a book	<10 μW
Writing with a pencil	10–15 μW
Opening a drawer	10–30 μW
Spinning in a swivel chair	<10 μW
Opening a building door	<1 μW
Shaking an object	>3,000 μW

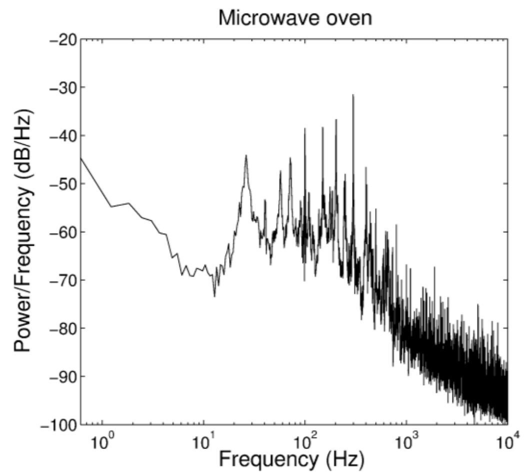
Activity	Sensing unit placement	# subjects	Median f_m (Hz)	$\overline{P}$ (μW)			Median r (Kb/s)
				[illegible]ercentile	Median	75th percentile	
Relaxing	Trouser pocket	42	N/A	[illegible]	3.1	4.8	0.6
	Waist belt	42	N/A	[illegible]	2.4	4.8	0.5
	Trouser pocket	42	N/A	[illegible]	1.4	5.9	0.3
Walking	Shirt pocket	42	1.9	[illegible]	155.2	186.0	31.0
	Waist belt	42	2.0	[illegible]	180.3	[illegible]0.3	36.0
	Trouser pocket	42	2.0	[illegible]	202.4	[illegible]4.5	40.4
Running	Shirt pocket	42	2.8	[illegible]	813.3	910.0	162.6
	Waist belt	41	2.8	[illegible]	678.3	752.8	135.6
	Trouser pocket	42	2.8	[illegible]	612.7	[illegible]7.4	122.5
Cycling	Shirt pocket	30	3.5	[illegible]	52.0	[illegible].3	10.4
	Waist belt	29	3.8	[illegible]	45.4	[illegible].2	9.1
	Trouser pocket	30	1.1	[illegible]	41.3	59.5	8.3

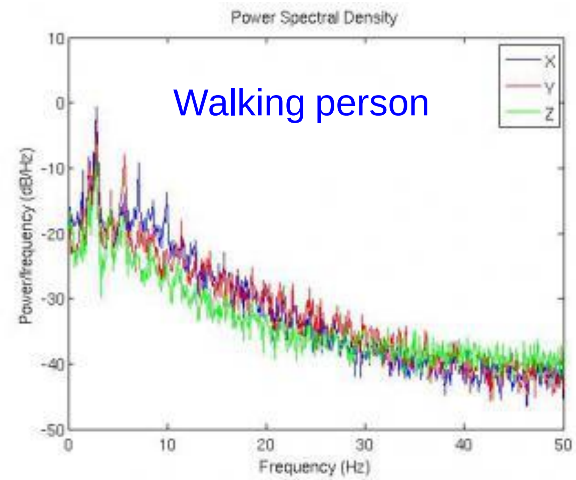
1.9
2.0
2.0
2.8
2.8
2.8
3.5
3.8
1.1
813.3
678.3

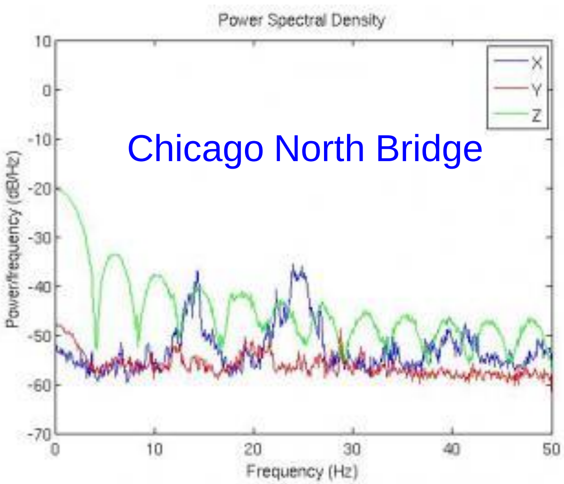
Gorlatova, M et al (2013). Movers and shakers: Kinetic energy harv[illegible]ternet of things.

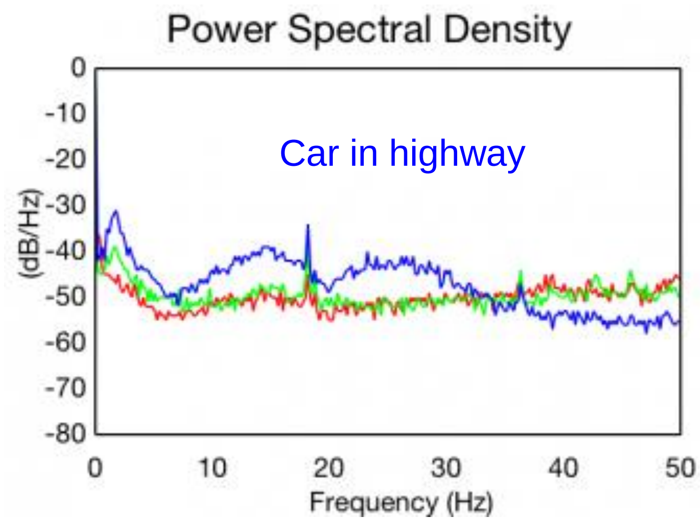
Example of vibration sources





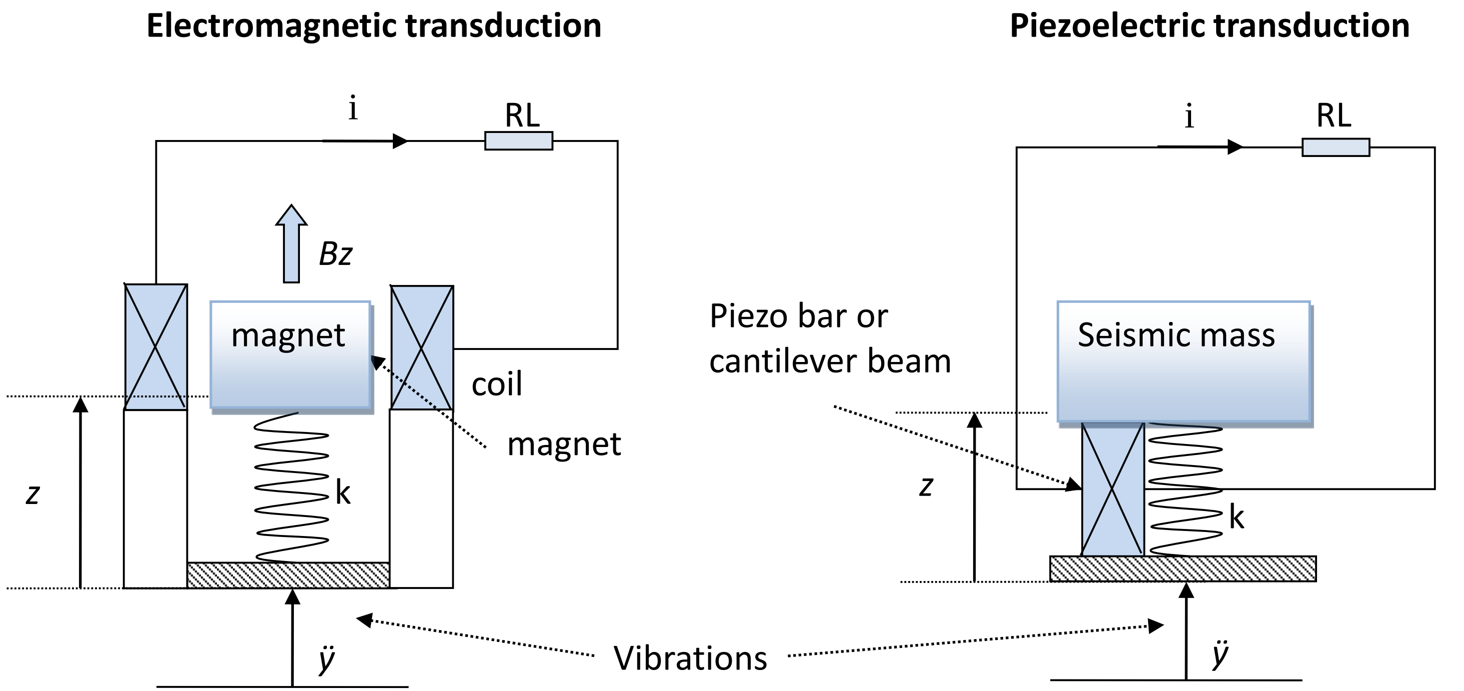






http://realvibration.nipslab.org

A general model for VEHs



$$\begin{cases} m\ddot{z} + d\dot{z} + \dfrac{dU(z)}{dz} + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda \omega_c \dot{z} \end{cases}$$

A general model for VEHs

Case of
LINEAR mechanical oscillator

$$U(z) = \frac{1}{2}kz^2 \Rightarrow \begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c\dot{z} \end{cases}$$

Laplace transform

$$\ddot{y} = Y_0 e^{j\omega t} \Rightarrow \begin{pmatrix} ms^2 + ds + k & \alpha \\ -\lambda\omega_c s & s + \omega_c \end{pmatrix} \begin{pmatrix} Z \\ V \end{pmatrix} = \begin{pmatrix} -mY \\ 0 \end{pmatrix}$$

$$\Rightarrow \quad Z = \frac{-mY}{\det A}(s+\omega_c) = \frac{-mY\cdot(s+\omega_c)}{ms^3 + (m\omega_c + d)s^2 + (k + \alpha\lambda\omega_c + d\omega_c)s + k\omega_c},$$

$$V = \frac{-mY}{\det A}\lambda\omega_c s = \frac{-mY\cdot\lambda\omega_c s}{ms^3 + (m\omega_c + d)s^2 + (k + \alpha\lambda\omega_c + d\omega_c)s + k\omega_c}.$$

Hence, the transfer functions between displacement and voltage over input acceleration are given by

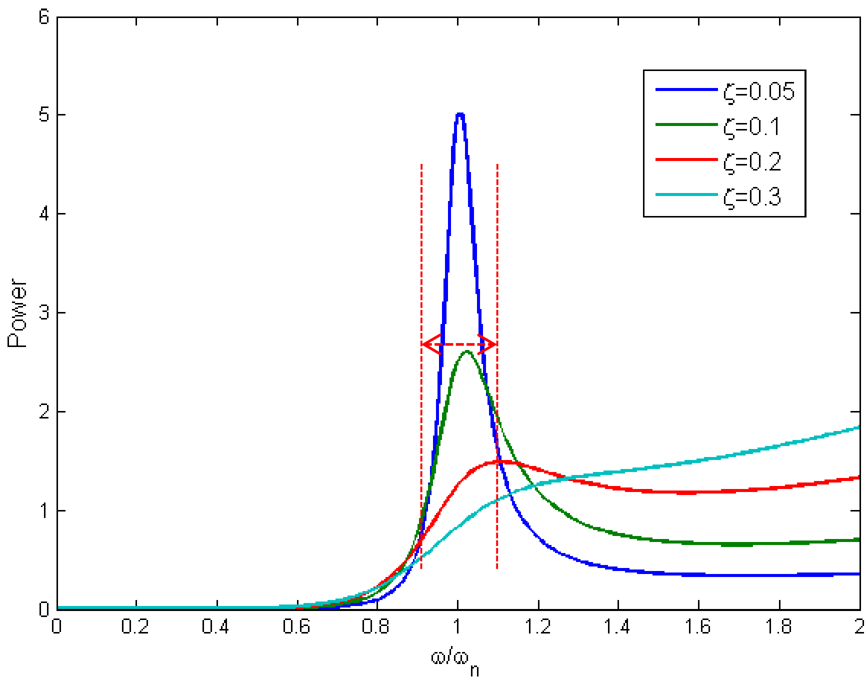
$$H_{ZY}(s) = \frac{Z}{Y}, \quad \text{(a)} \qquad H_{VY}(s) = \frac{V}{Y}. \quad \text{(b)}$$

By substituting s=jω in , we can calculate the electrical power dissipated across the resistive load

$$\Rightarrow \quad P_e(\omega) = \frac{Y_0^2}{2R_L}\left|\frac{m_2\lambda\omega_c j\omega}{(\omega_c + j\omega)(-m_2\omega^2 + d_2 j\omega + k_2) + \alpha\lambda\omega_c j\omega}\right|^2$$

Main limits of resonant VEHs

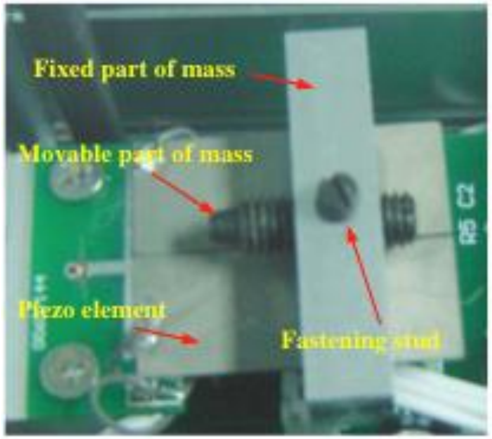
- narrow bandwidth that implies constrained resonant frequency-tuned applications
- Non-adaptation to variable vibration sources
- small inertial mass and high resonant frequency at micro/nano scale -> most of vibration sources are below 100 Hz



At 20% off the resonance the power falls by 80-90%

Beyond linear harvesting systems

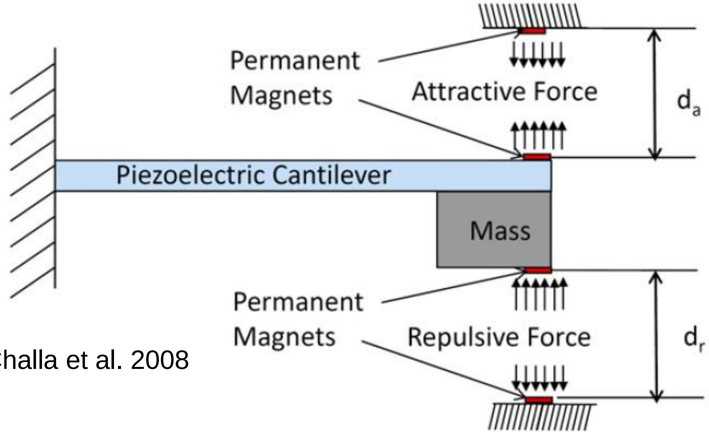
Frequency tuning



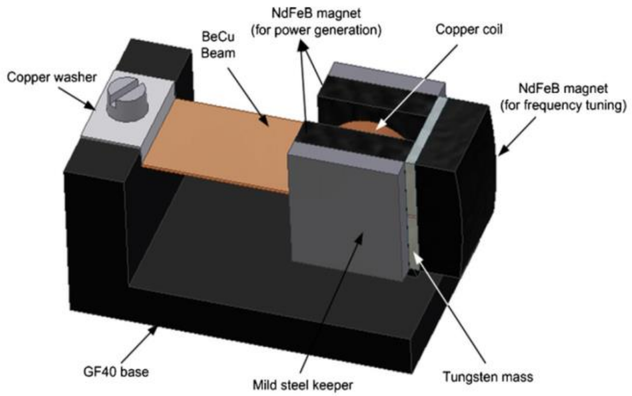
Piezoelectric cantilever with a movable mass

Wu et al. 2008

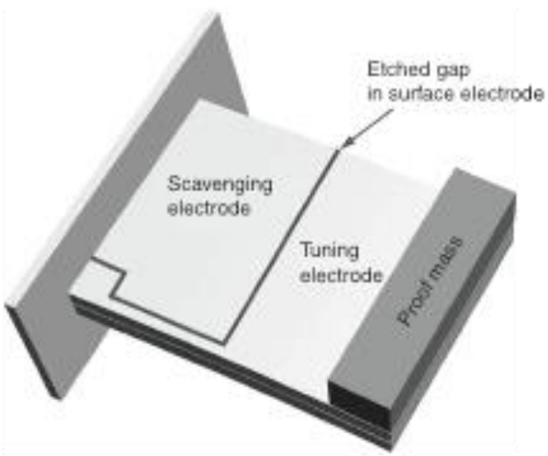
Piezoelectric cantilever with magnetic tuning



Challa et al. 2008



Zhu, et al. (2010). *Sensors and Actuators A: Physical*



Piezoelectric beam with a scavenging and a tuning part

Roundy and Zhang 2004

Beyond linear harvesting systems

Frequency tuning

Table 2. Summary of the reported resonance tuning methods.

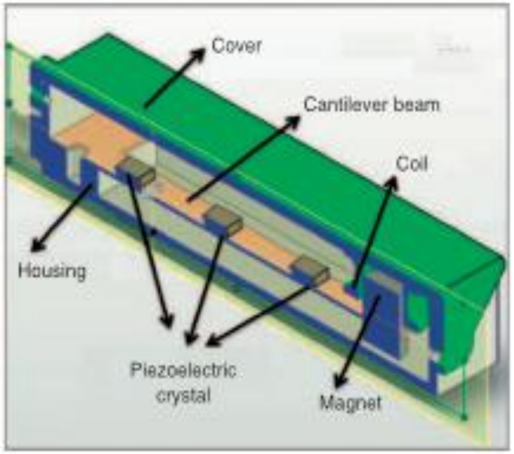
Author	Methods	Tuning range (Hz)	Tunability, $\left(\frac{\text{frequency change}}{\text{average frequency}}\right)$ (%)	Tuning load (force, distance, and voltage)	Energy or power for tuning	Automatic controller
Leland and Wright (2006)	Mechanical (passive)	200–250 (7.1 g tip mass)	22.22	Up to 65 N	–	×
Eichhorn et al. (2008)	Mechanical (passive)	292–380	26.19	Up to 22.75 N	–	×
Hu et al. (2007)	Mechanical (passive)	58.1–169.4	97.85	−50–50 N	–	×
Morris et al. (2008)	Mechanical (passive)	80–235 (can be wider)	≥98.41	≈1.25 mm	–	×
Loverich et al. (2008)	Mechanical (passive)	56–62	10.17	0.5 mm	–	×
Wu et al. (2008)	Mechanical (passive)	130–180	32.26	21 mm	–	×
Challa et al. (2008)	Magnetic (passive)	22–32	37.04	3 cm	85 mJ	×
Reissman et al. (2009)	Magnetic (passive)	88–99.38	12.15	1.5 cm	–	×
Zhu et al. (2008)	Magnetic (passive)	67.6–98	36.71	3.8 mm	2.04 mJ/mm	√
Wu et al. (2006)	Piezoelectric (active)	91.5–94.5	3.23	–	μW level (for controller)	√
Peters et al. (2009)	Piezoelectric (active)	66–89 (actuator PL140)	29.68	±5 V	150 mW (discrete control circuit)	√
Roundy and Zhang (2005)	Piezoelectric (active)	64.5–67	3.80	5 V	440 μW	×
Wischke et al. (2010)	Piezoelectric (semi-passive)	20 (10 mm long electrode)	≈6.7	−65 to +130 V	200 μJ	×

Tang et al. 2010

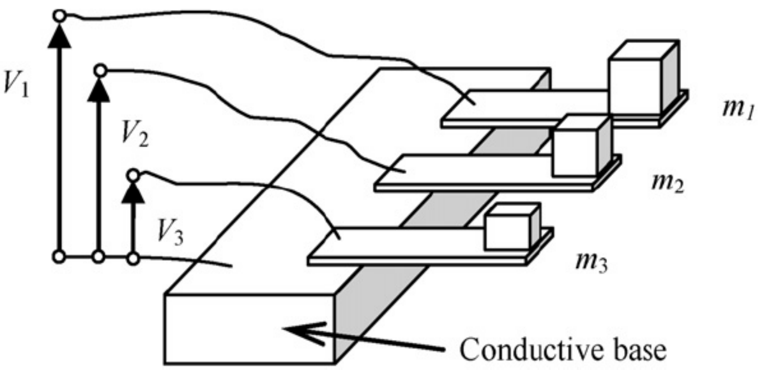
Beyond linear harvesting systems

Multimodal Energy Harvesting

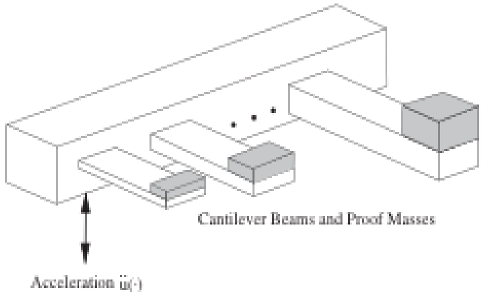
Tadesse et al. 2009



Hybrid harvester with piezoelectric and electromagnetic transduction mechanisms



Ferrari, M., et al. (2008). *Sensors and Actuators A: Physical*

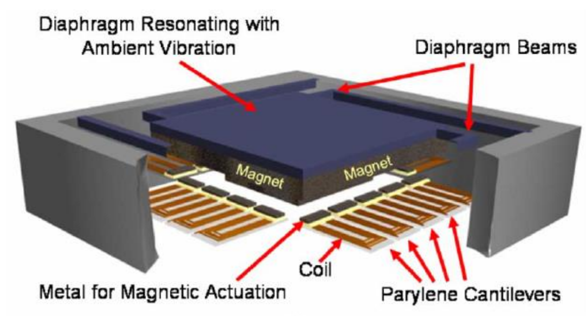


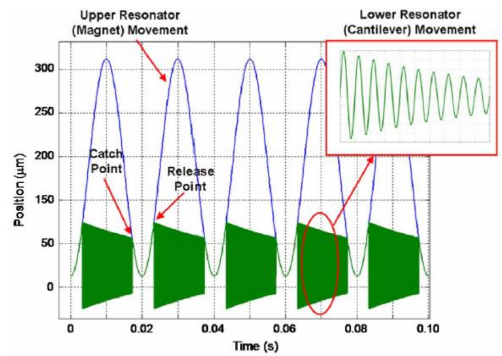
Shahruz 2006

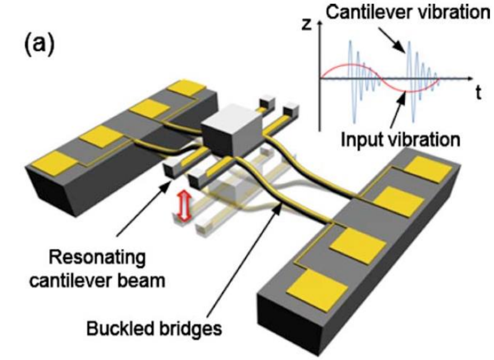
Piezoelectric cantilever arrays
with various lengths and tip masses

Beyond linear harvesting systems

Frequency-up conversion

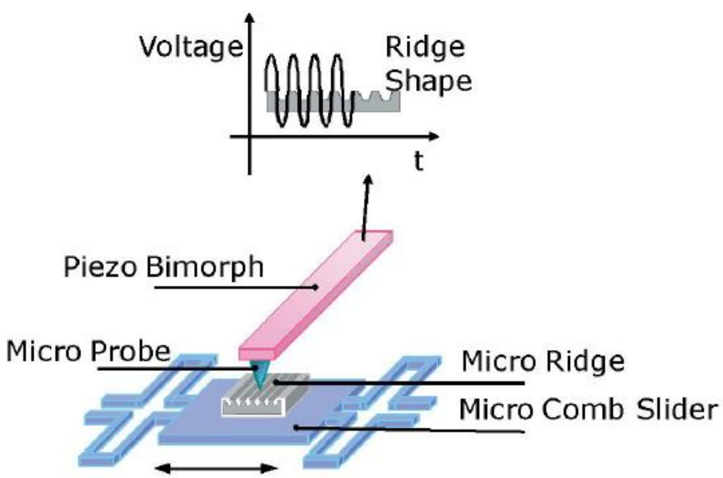






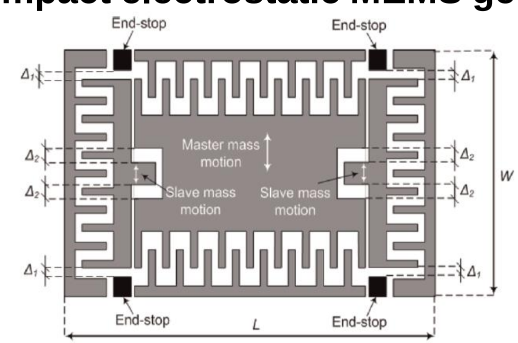
H. Kulah and K. Najafi, IEEE Sensors Journal **8** (3), 261 (2008).

Jung, S.-M. et al. (2010). *Applied Physics Letters*



D.G. Lee et al. IEEE porc. (2007)

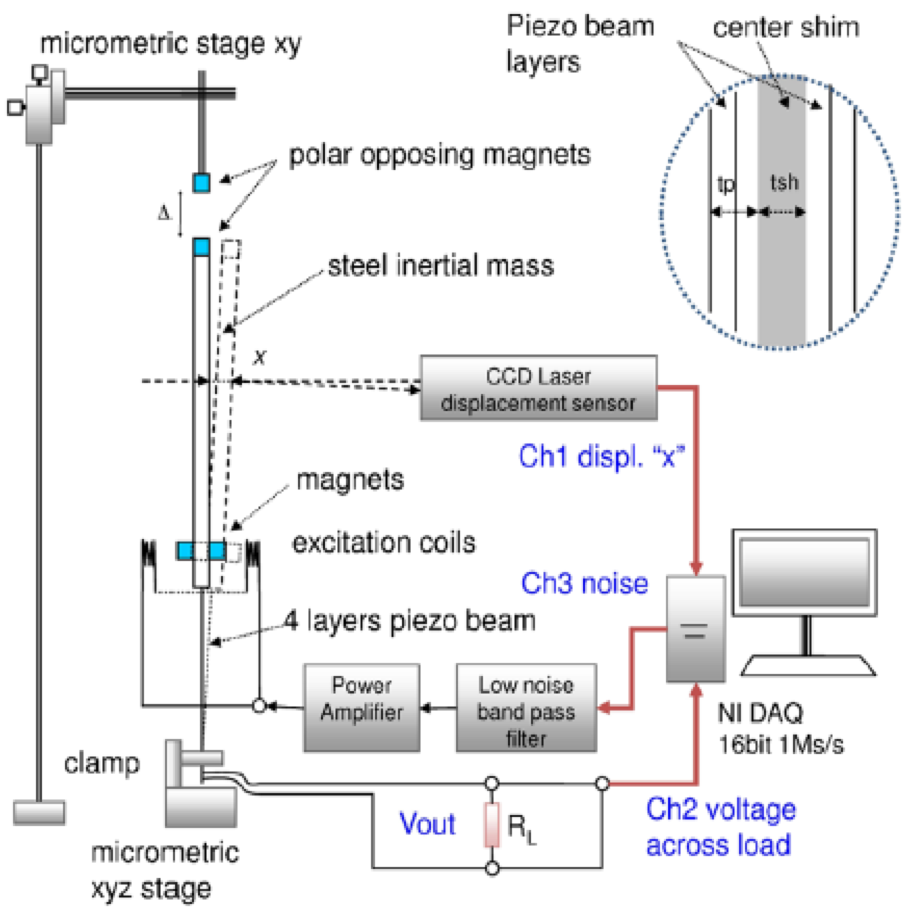
Impact electrostatic MEMS generator

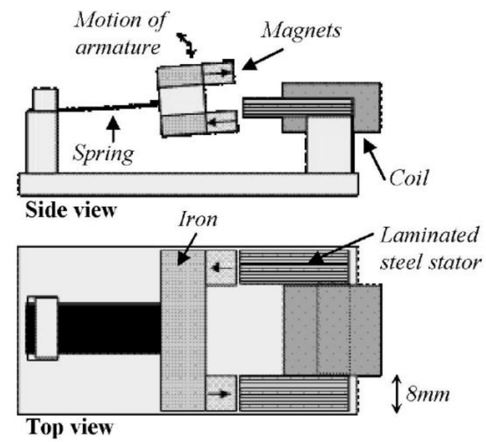


Le, C. P., Halvorsen (2012). *Journal of Intelligent Material Systems and Structures*

Beyond linear harvesting systems

Nonlinear systems



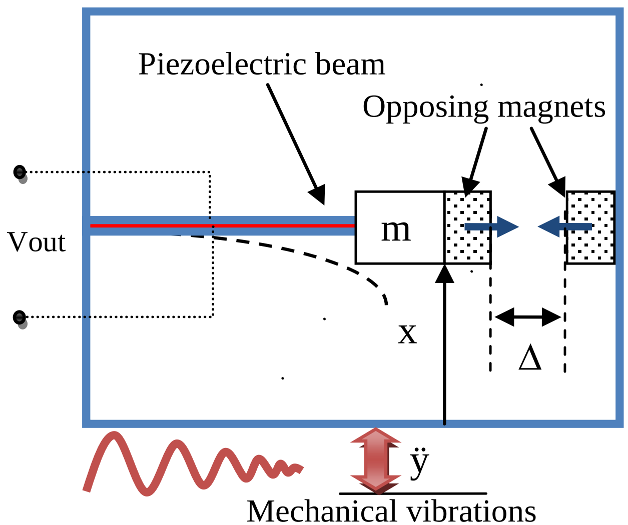


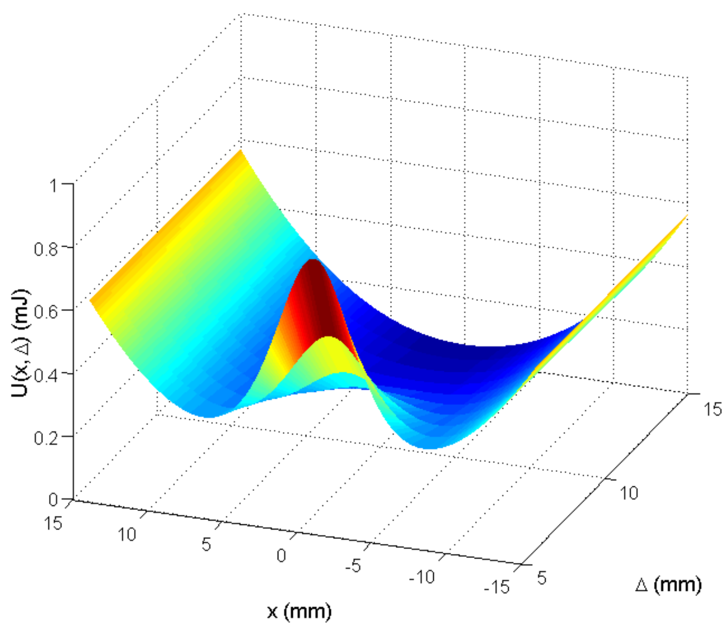
Burrow, S.G and Clare, L.R. IEEE porc. (2007)

Cottone, F., H. Vocca & L. Gammaitoni, Nonlinear Energy Harvesting. *PRL,* 102 (2009).

Beyond linear harvesting systems

Nonlinear systems for vibration energy harvesting





Magneto-elastic potential

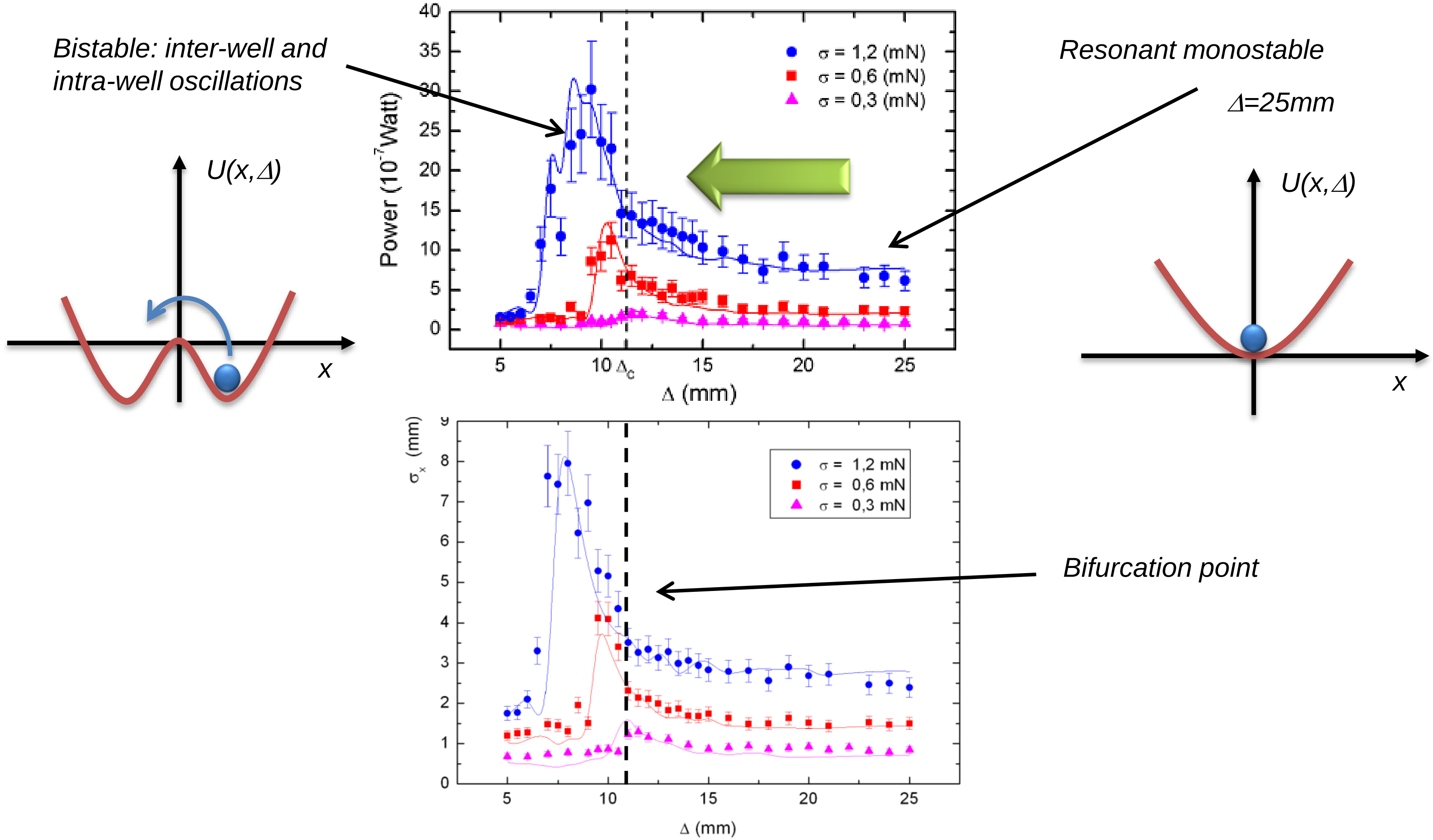
$$U(x,\Delta) = \frac{1}{2}K_{eff}x^2 + \frac{\mu_0}{2\pi}\frac{M_1M_2}{(x^2+\Delta^2)^{3/2}}$$

Governing equations of a single-DOF piezo-magnetoelastic model

$$\begin{cases} m\ddot{x}(t) + \delta\dot{x}(t) + K_{eff}x(t) + \dfrac{\partial U(x,\Delta)}{\partial x} + K_v V(t) = -m\ddot{y}(t) \\ \dot{V}(t) + \dfrac{1}{\tau}V(t) = K_c\dot{x}(t); \qquad \tau = R_L C_p \end{cases}$$

Cottone, F., H. Vocca & L. Gammaitoni, Nonlinear Energy Harvesting. *PRL,* 102 (2009).

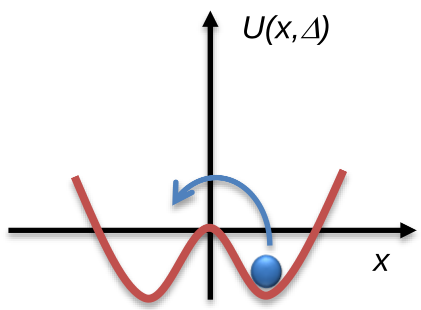
Bistable oscillators for vibration energy harvesting

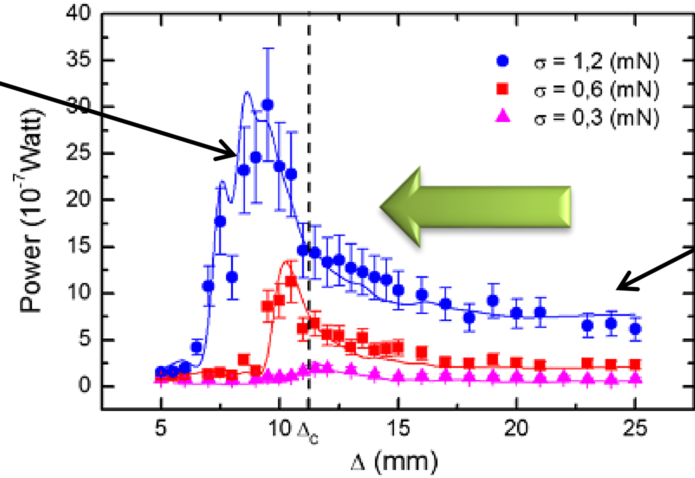


Cottone, F., H. Vocca & L. Gammaitoni, Nonlinear Energy Harvesting. *PRL,* 102 (2009).

Bistable oscillators for vibration energy harvesting

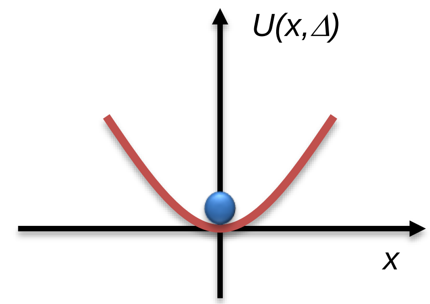
Bistable: inter-well and intra-well oscillations

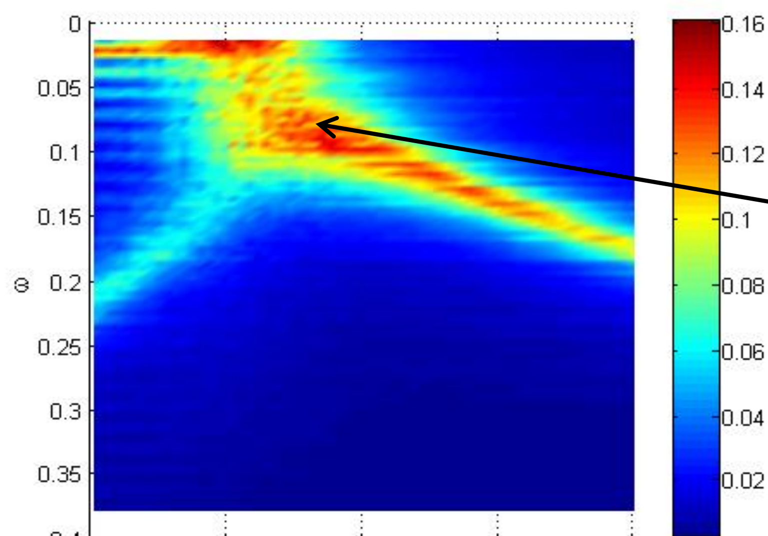




Resonant monostable

Δ=25mm





Bandwith enhancement when interwell jumps occur

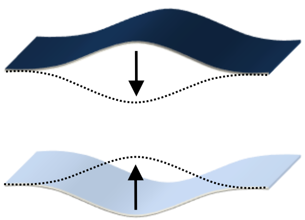
Cottone, F., H. Vocca & L. Gammaitoni, Nonlinear Energy Harvesting. *PRL,* 102 (2009).

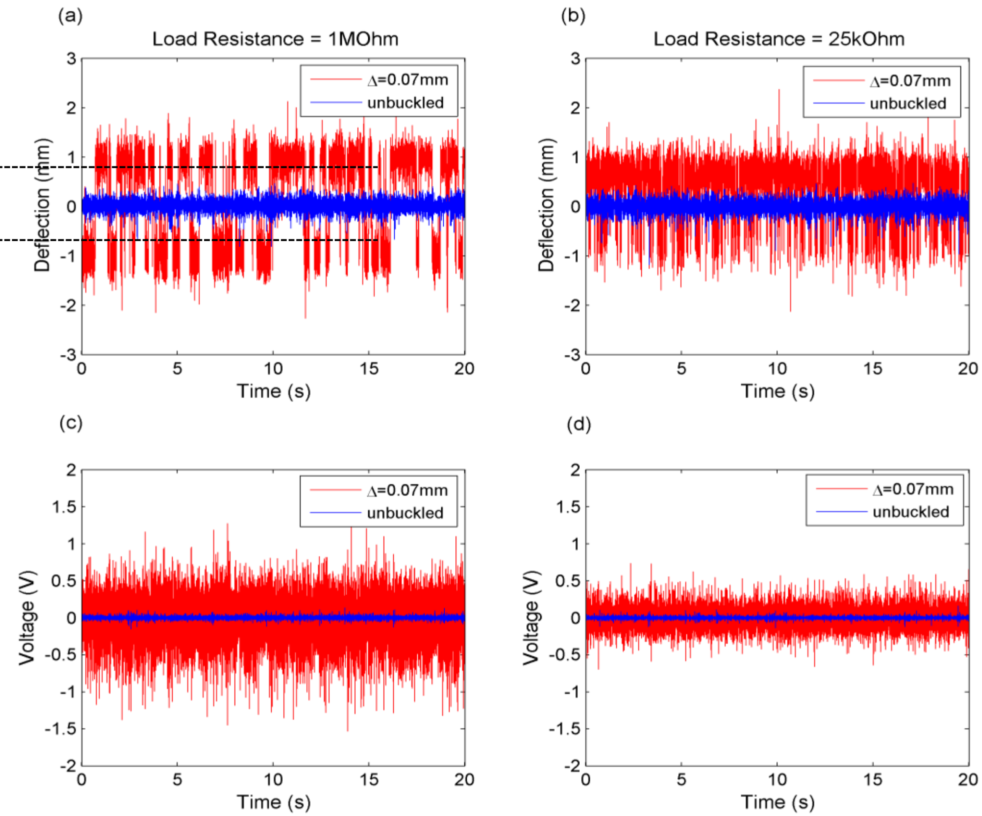
Bistable oscillators for vibration energy harvesting

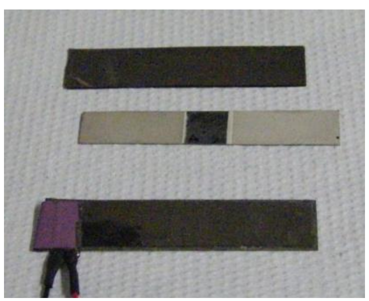
Buckled beam piezoelectric harvesters

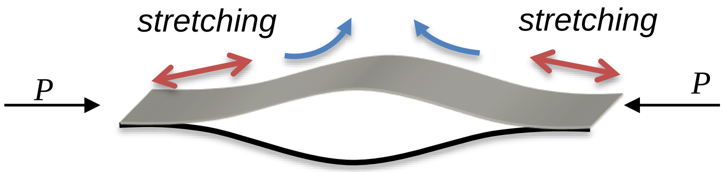
Cottone, F., Gammaitoni, L., Vocca, H., Ferrari, M., & Ferrari, V. (2012). *Smart materials and structures, 21*(3), 035021

Snapping between buckled states





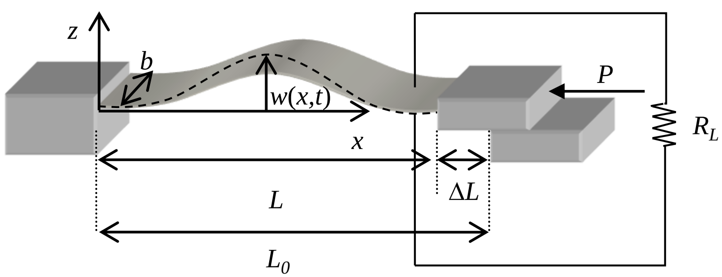


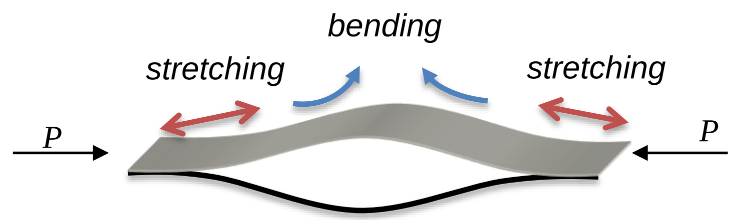


Bistable oscillators for vibration energy harvesting

Buckled piezoelectric beams

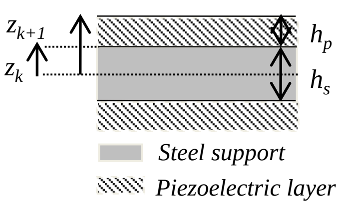
$$w(x,t)=w_1(x)+v(x,t)$$

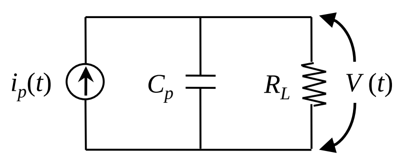




the initial buckling shape function is

$$\psi(x)=h_0(1-\cos(2\pi x/L))/2$$





by applying Euler-Lagrange equations

$$\frac{d}{dt}\left(\frac{\partial \mathfrak{L}}{\partial \dot q}\right)-\frac{\partial \mathfrak{L}}{\partial q}=F(t),\qquad \frac{d}{dt}\left(\frac{\partial \mathfrak{L}}{\partial \dot\lambda}\right)-\frac{\partial \mathfrak{L}}{\partial \lambda}=I(t)$$

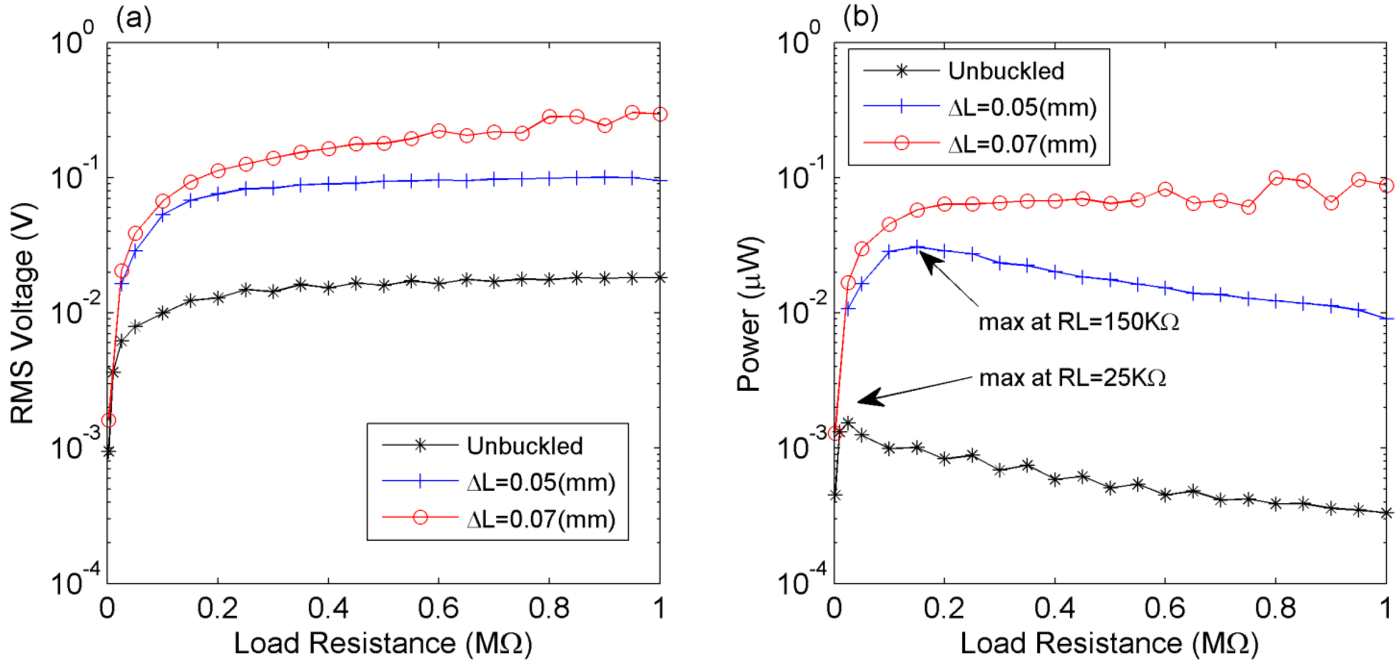
gives two coupled second order nonlinear differential equations governing the motion of the piezoelectric buckled beam

$$\begin{cases} m\ddot q + c\dot q + k_3 q^3 + (k_2 - k_1 V)q + k_0 V = -\eta \ddot z, \\ \ddot V + \dfrac{2}{R_L C_p} V = 2\dfrac{k_0}{C_P}\dot q - 2\dfrac{k_1}{C_P} q\dot q. \end{cases}$$

Where the output voltage is related to the flux linkage $V=-\dot\lambda$

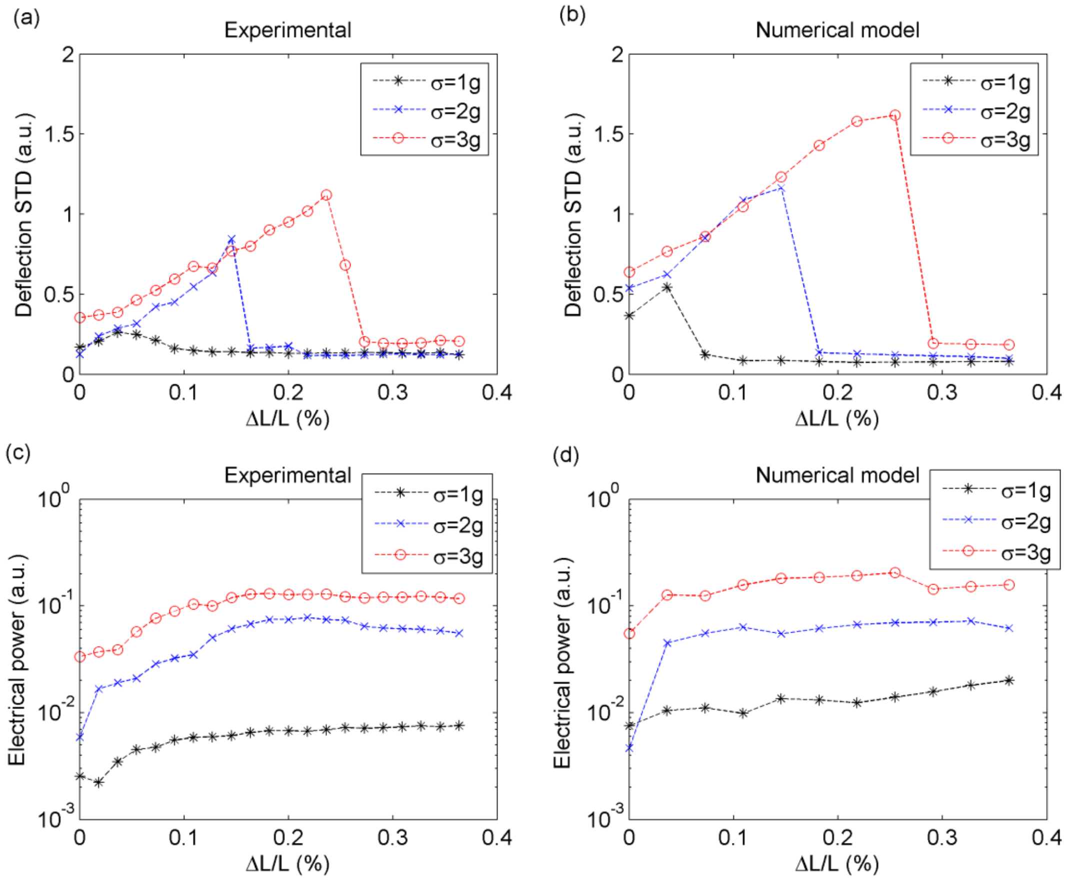
Bistable oscillators for vibration energy harvesting

Experimental and numerical results



Cottone, F., L. Gammaitoni, H. Vocca, M. Ferrari & V. Ferrari (2012)
Piezoelectric buckled beams for random vibration energy harvesting. Smart materials and structures, 21.

Bistable oscillators for vibration energy harvesting



Cottone, F., L. Gammaitoni, H. Vocca, M. Ferrari & V. Ferrari (2012)
Piezoelectric buckled beams for random vibration energy harvesting. Smart materials and structures, 21.

Nonlinear electromagnetic generators for wide band vibrational energy harvesting

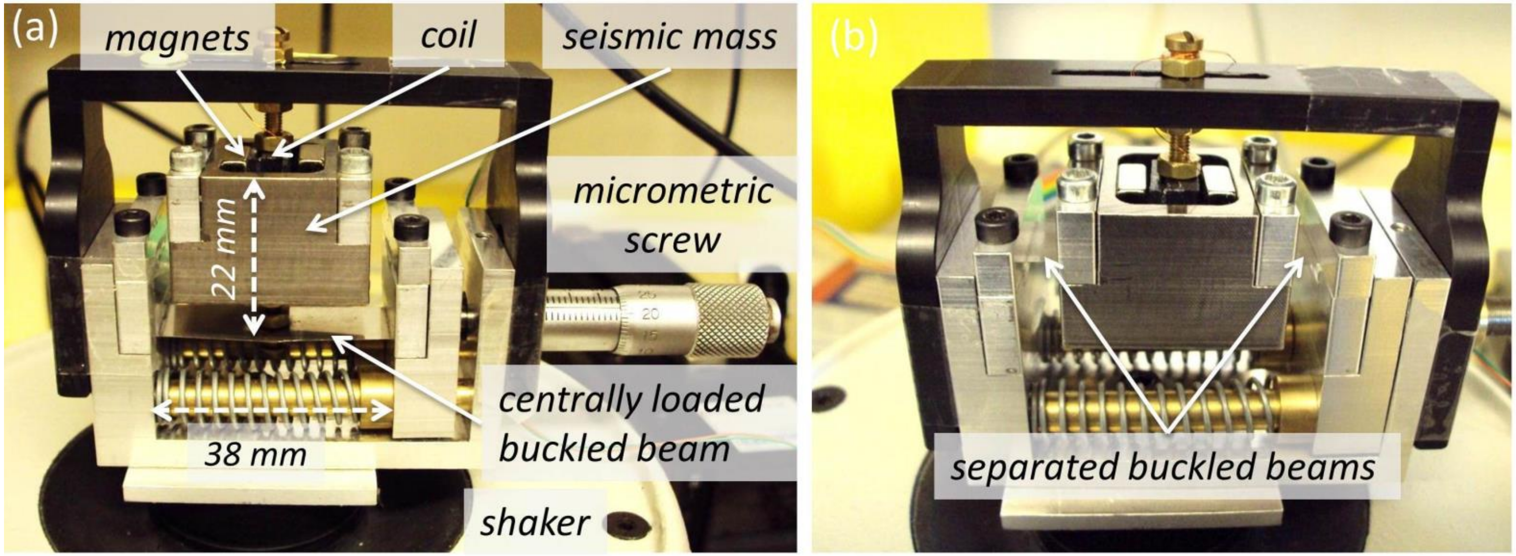


Figure 2. Photographs of the BEMG prototype for the (a) single centrally loaded-beam clamping configuration, (b) double-beam clamping configuration, and (c) scheme of the testing equipment.
BEMG: beam electromagnetic generator; PC: personal computer; DAQ: data acquisition.

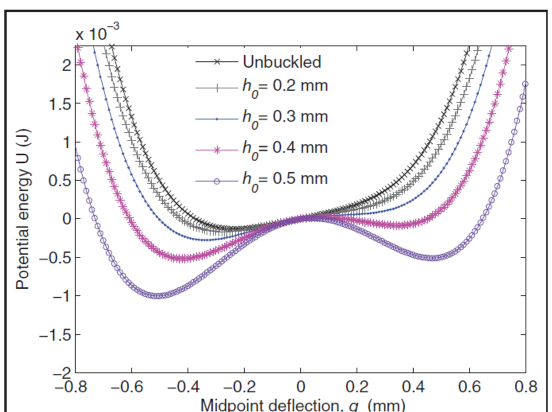


Figure 3. Potential energy of the system for increasing values of buckling height h_0.

$$\frac{d^2\tilde{q}(\tau)}{d\tau^2}+\frac{1}{Q}\frac{d\tilde{q}(\tau)}{d\tau}+\tilde{q}(\tau)+\tilde{q}^3(\tau)+\tilde{V}(\tau)=-\frac{d^2\tilde{y}(\tau)}{d\tau^2},$$

$$\frac{d\tilde{V}(\tau)}{d\tau}+\frac{1}{\gamma}\tilde{V}(\tau)=k_{em}^2\frac{d\tilde{q}}{d\tau},$$

$$\gamma=\omega_0/(\omega_R+\omega_L) \qquad k_{em}^2=\frac{\lambda^2}{k_1L_c}=\frac{(Bl)^2}{k_1L_c}. \qquad k_{pz}^2=\frac{\alpha^2}{k_1C_0}$$

Nonlinear electromagnetic generators for wide band vibrational energy harvesting

Bandwidth enhancement of 2.5x with bistability at 0,2 grms

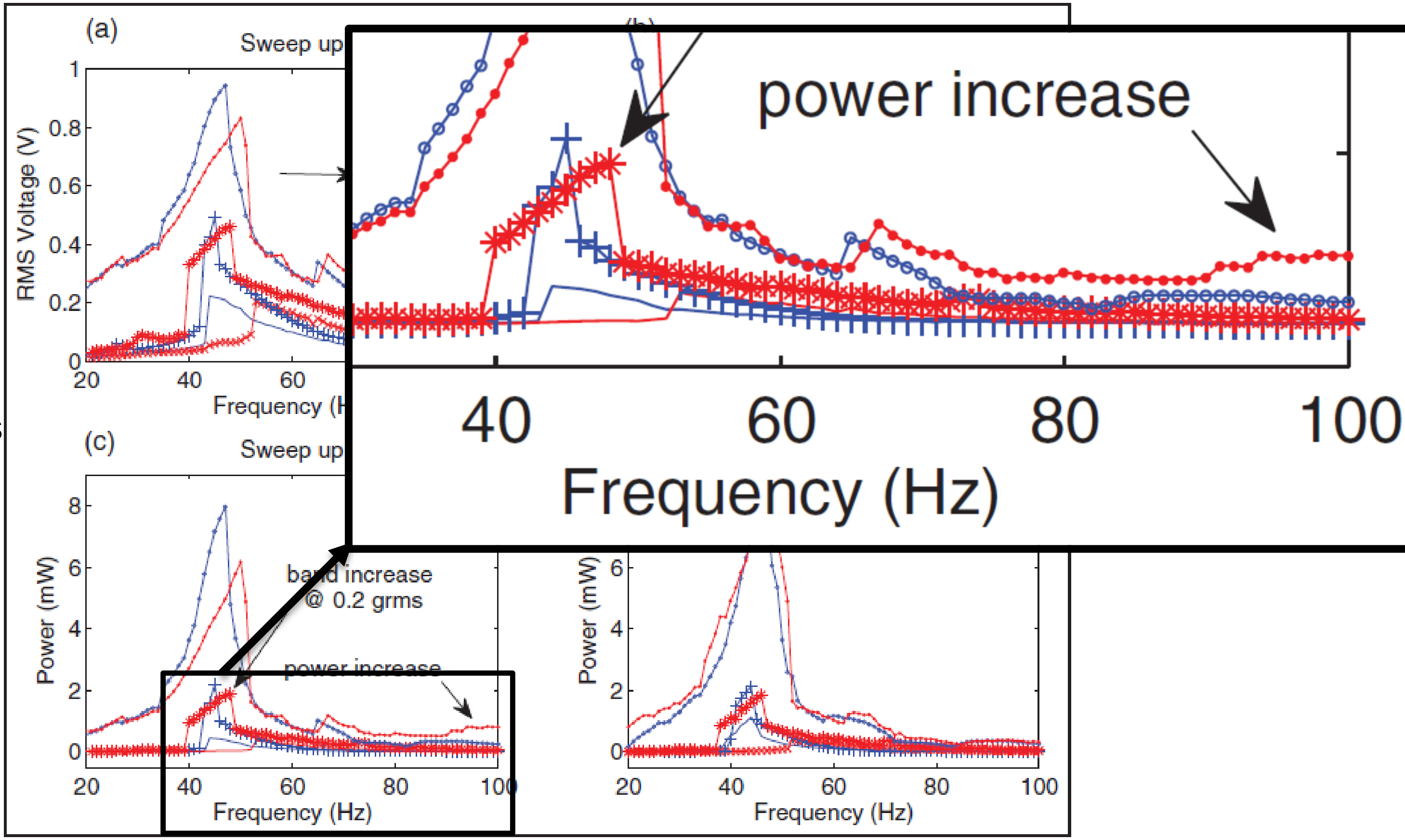
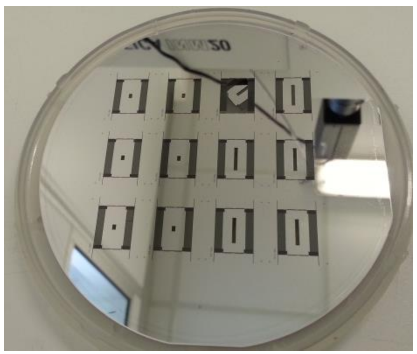


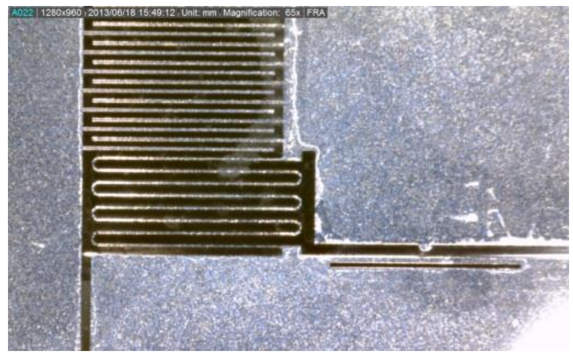
Figure 6. Experimental comparison of unbuckled- and buckled-beam (h_0 = 0.3 mm) generators for up (left column) and down (right column) frequency sweeps with acceleration amplitudes of 0.1, 0.2, and 0.5 g_{rms}. (a and b) *rms* voltage and (c and d) the corresponding power dissipated across the optimal load resistance R_L = 112 Ω.
rms: root mean square.

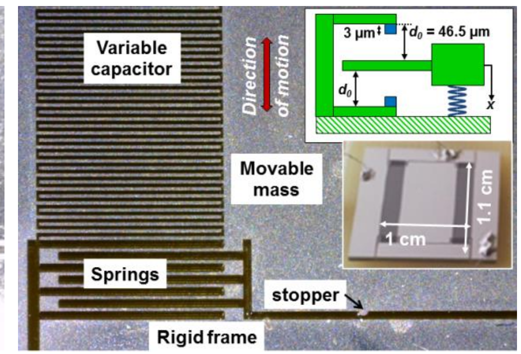
Electrostatic generators

Université Paris-Est, ESIEE Paris,

Silicon MEMS-based electrostatic harvesters.







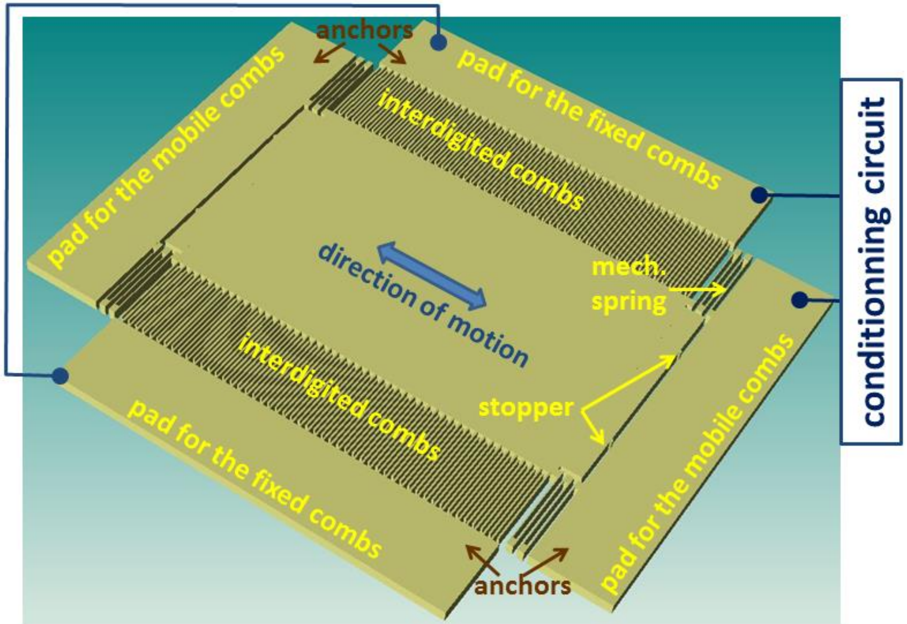
- **Cottone, F.,** Basset, P., Guillemet, R., Galayko, D., Marty, F. and T. Bourouina. Non-linear MEMS electrostatic kinetic energy harvester with a tunable multistable potential for stochastic vibrations, (2013) Conf. Proceeding. IEEE TRANSDUCERS 2013.

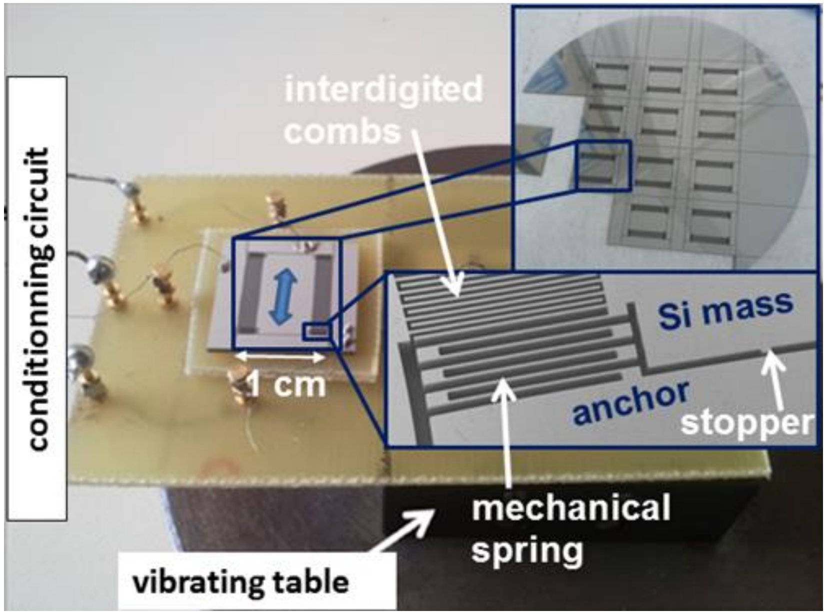
- **Cottone, F.,** Basset, P., Guillemet, R., Galayko, D., Marty, F. and T. Bourouina. Bistable multiple-mass electrostatic generator for low-frequency vibration energy harvesting, (2012) Conf. Proceeding. IEEE MEMS (2013).

- R., Guillemet, Basset., P, Galayko, D., **Cottone, F**., Marty, F. and T. Bourouina. Wideband MEMS electrostatic vibration energy harvesters based on gap-closing interdigitated combs with a trapezoidal cross section, (2012) Conf. Proceeding. Accepted for publication at IEEE MEMS 2013.

- **Cottone, F.**, Basset, P., Vocca, H. and Gammaitoni, L. Electromagnetic buckled beam oscillator for enhanced vibration energy harvesting, Conf. Proceeding. 2012 IEEE International Conference on Green Computing and Communications, Conference on Internet of Things, and Conference on Cyber, Physical and Social Computing. (2012).

Nonlinear MEMS electrostatic kinetic energy harvester





Guilllemet, R., Basset, P., Galayko, D., Cottone, F., Marty, F., & Bourouina, T. (2013). *Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on* (pp. 817-820): IEEE.

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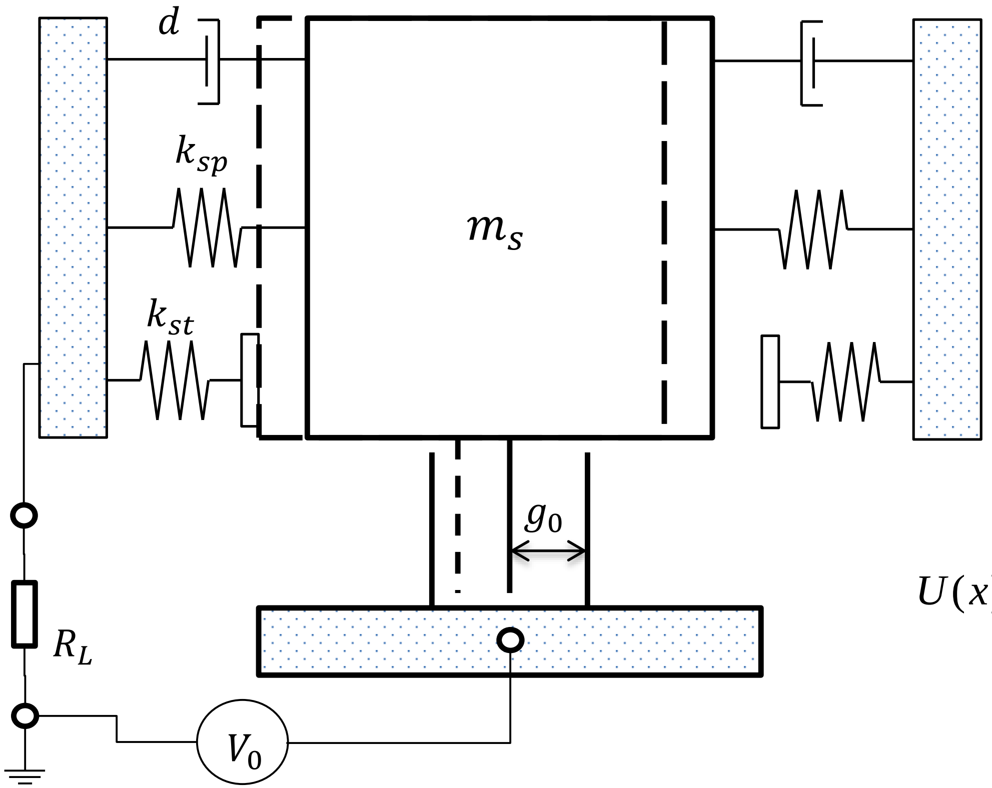
Basset, P., Galayko, D., Cottone, F., Guillemet, R., Blokhina, E., Marty, F., & Bourouina, T. (2014). *Journal of Micromechanics and Microengineering 24(3), 035001*

Nonlinear MEMS electrostatic kinetic energy harvester

Mathematical modeling



Governing equations

$$m\frac{d^2x}{dt^2}+\left(c_a+c_i\right)\frac{dx}{dt}+\frac{dU(x)}{dx}=-m\frac{d^2y}{dt^2},$$

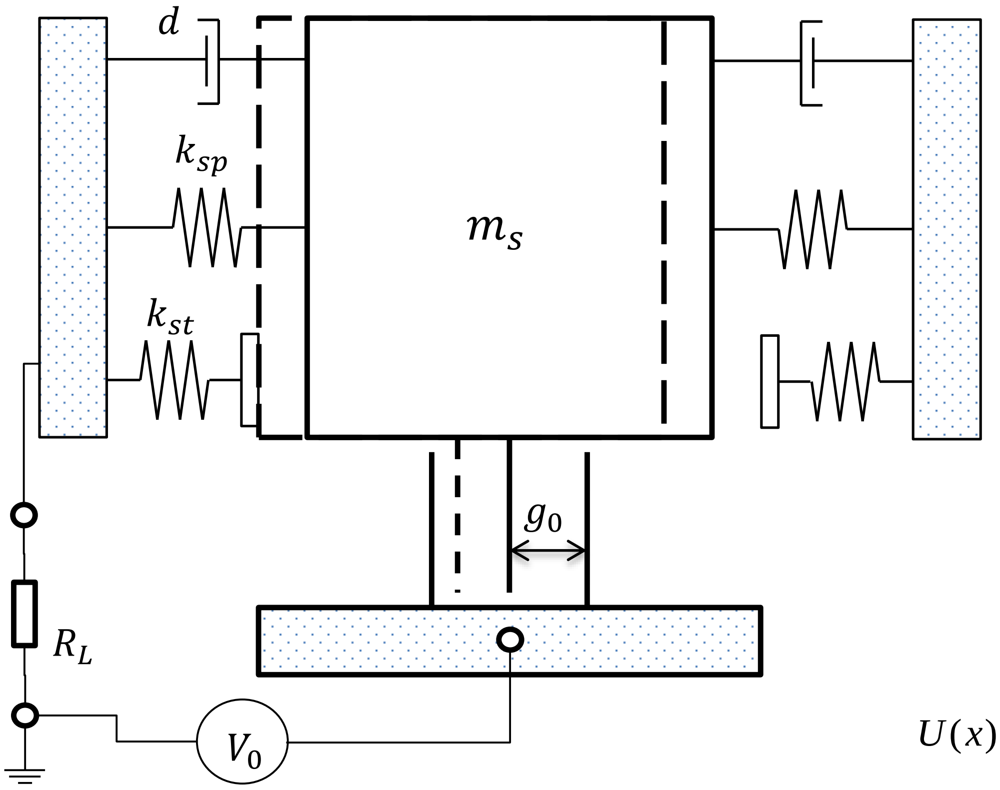
$$R_L\frac{d}{dt}(C\cdot V)+V=U_0,$$

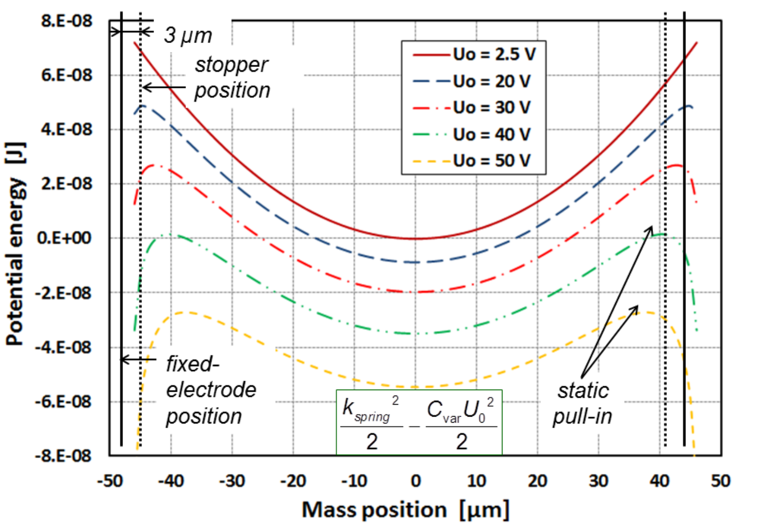
$$U(x)=\begin{cases}\frac{1}{2}k_{sp}x^2-\frac{1}{2}C(x)U_0^2, & \text{for } |x|<x_{\lim}\\ \frac{1}{2}(k_{sp}+k_{st})x^2-\frac{1}{2}C(x)U_0^2, & \text{for } |x|\geq x_{\lim}\end{cases}$$

$$C(x)=C_{par}+\varepsilon N_f l_f\frac{1}{2r}\left[\ln\left(\frac{d_0-x+2hr}{d_0-x}\right)+\ln\left(\frac{d_0+x+2hr}{d_0+x}\right)\right],$$

Nonlinear MEMS electrostatic kinetic energy harvester

Mathematical modeling



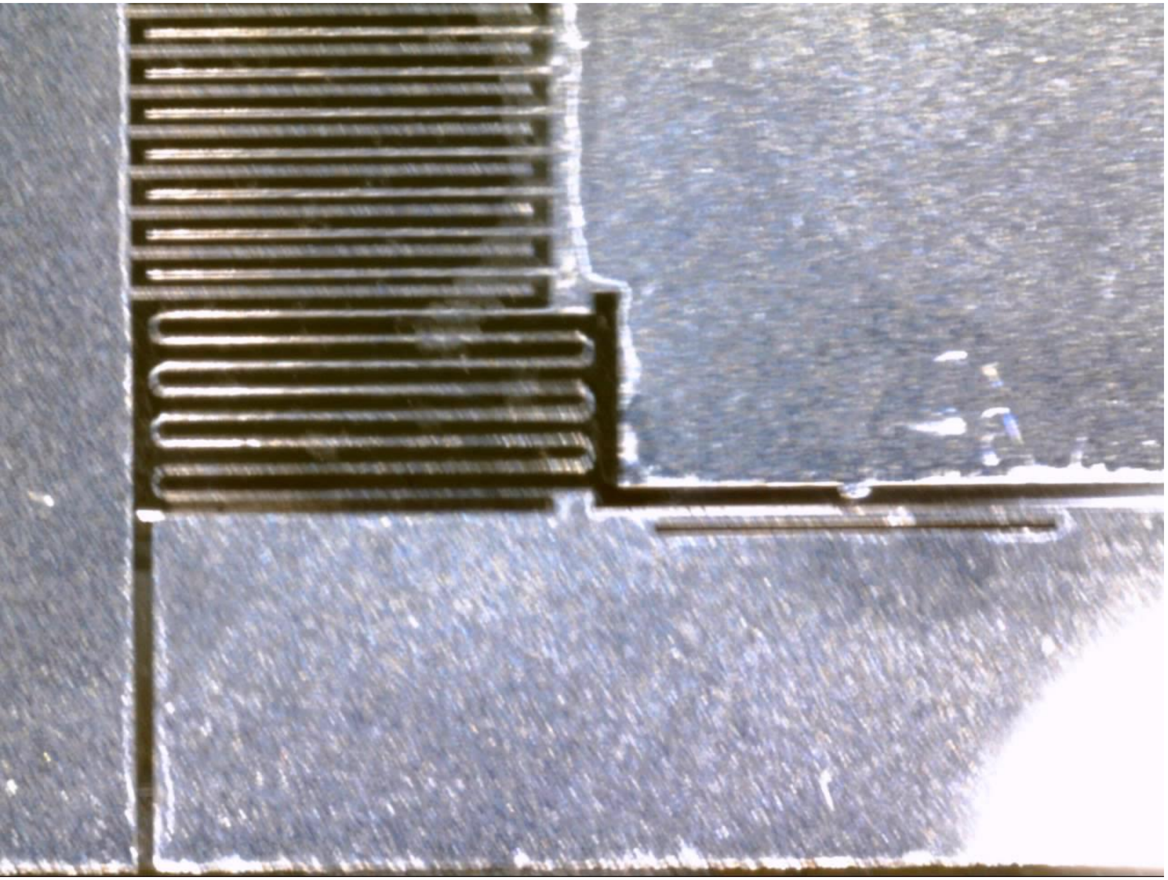


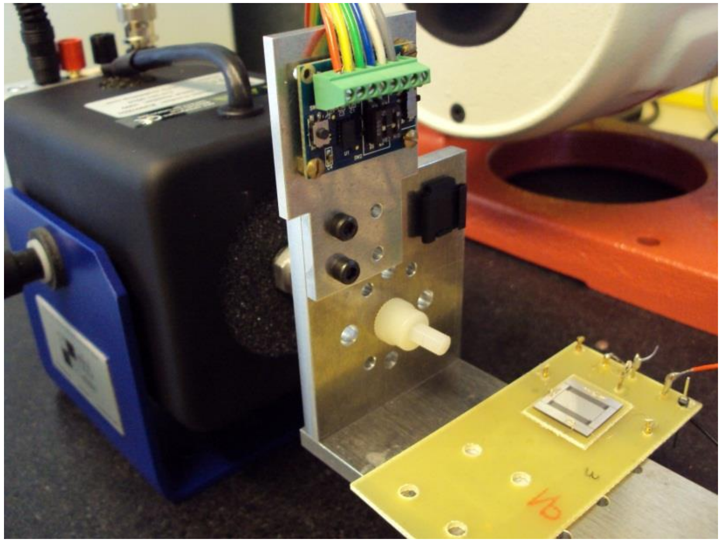
$$U(x) = \begin{cases} \frac{1}{2}k_{sp}x^2 - \frac{1}{2}C(x)U_0^2, & \text{for } |x| < x_{\lim} \\ \frac{1}{2}(k_{sp}+k_{st})x^2 - \frac{1}{2}C(x)U_0^2, & \text{for } |x| \geq x_{\lim} \end{cases}$$

Electrostatic generators

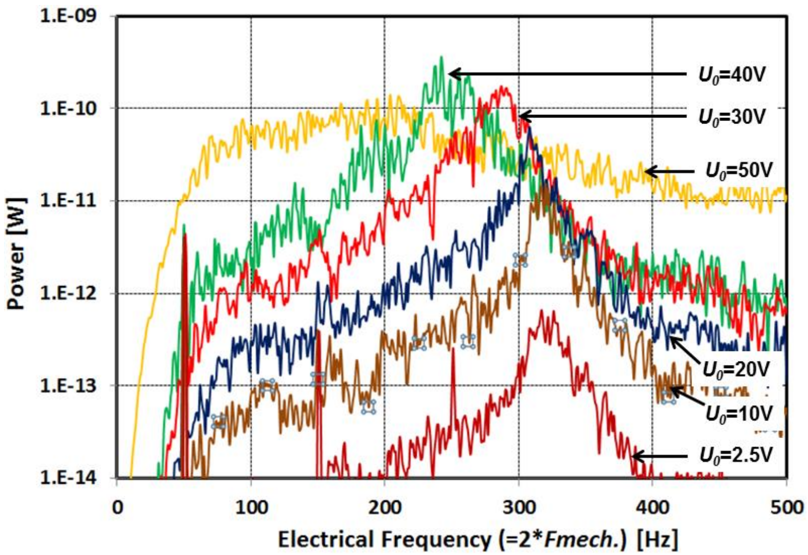
F. Cottone, P. Basset Université Paris-Est, ESIEE Paris,

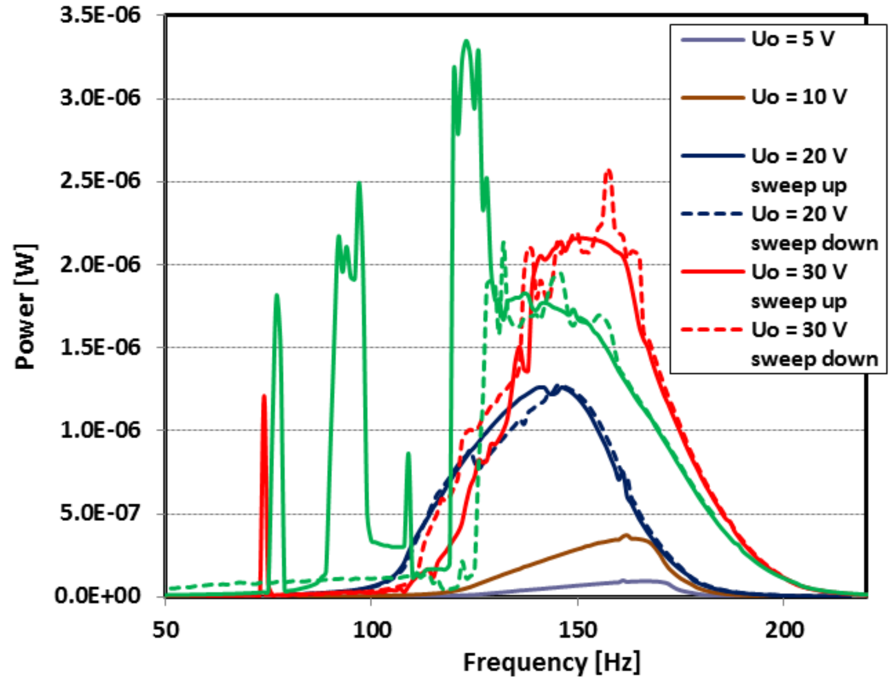
Silicon MEMS-based electrostatic harvesters.





Nonlinear MEMS electrostatic kinetic energy harvester





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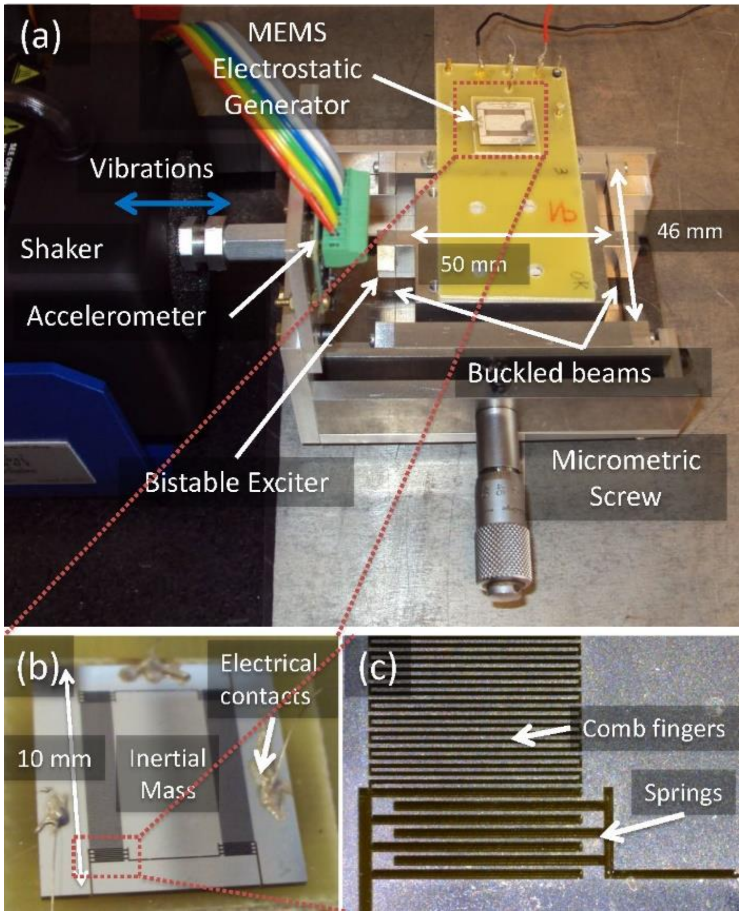
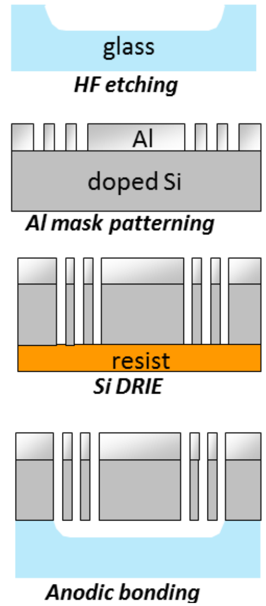
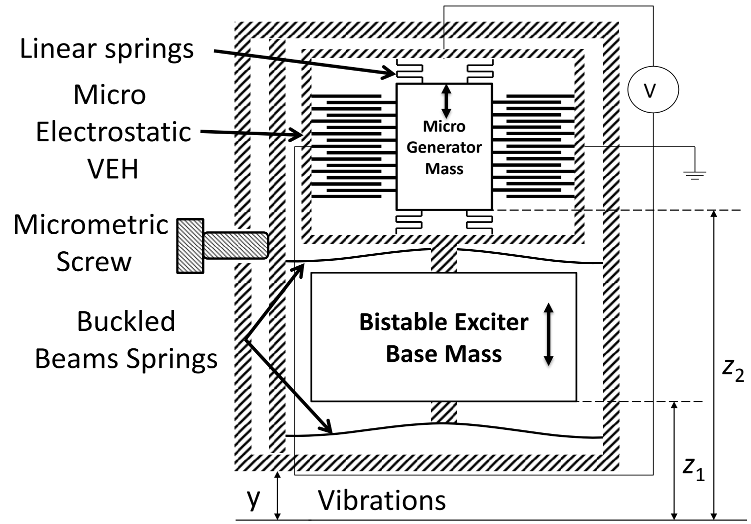
Bistable multiple-mass electrostatic generator for low-frequency vibration energy harvesting







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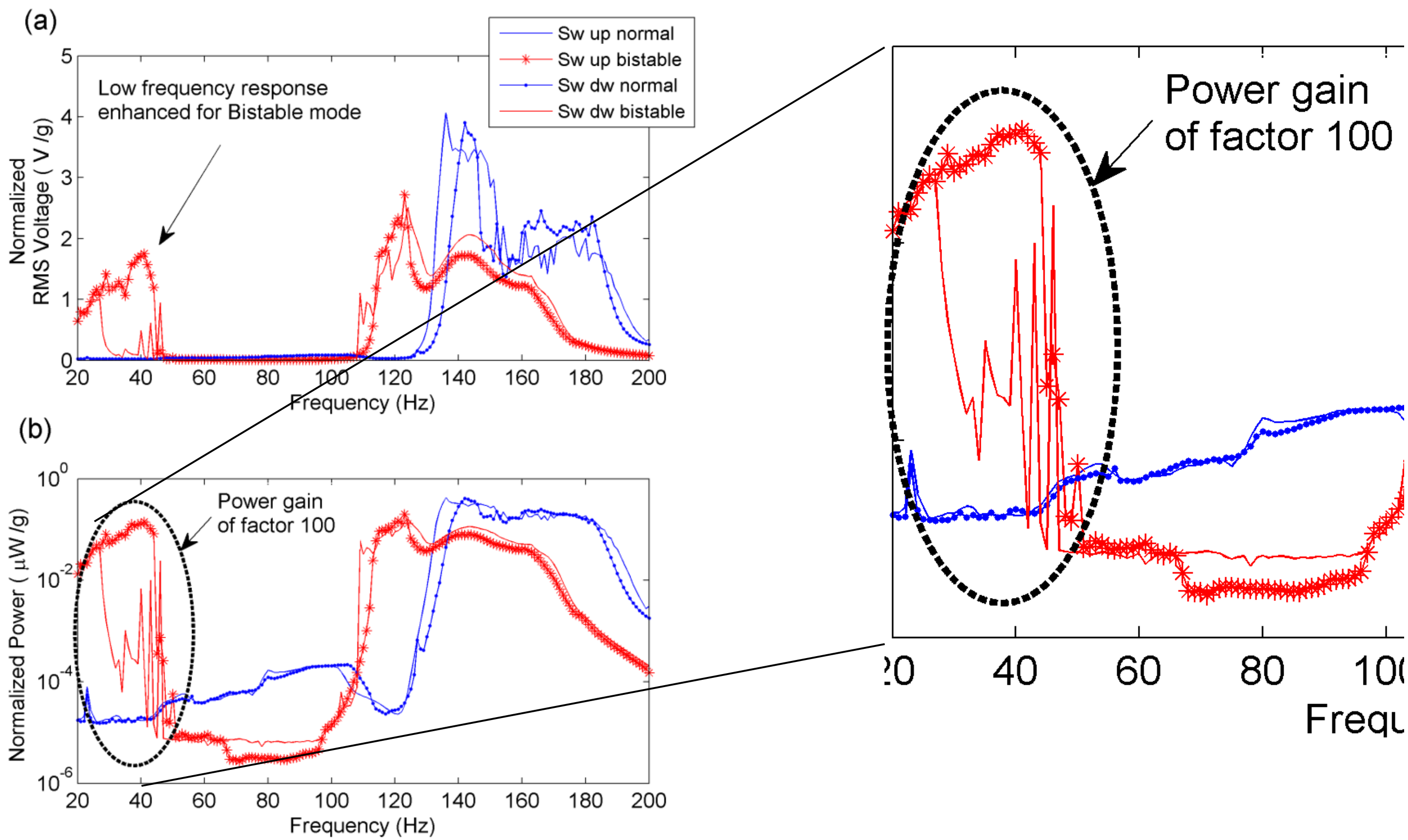

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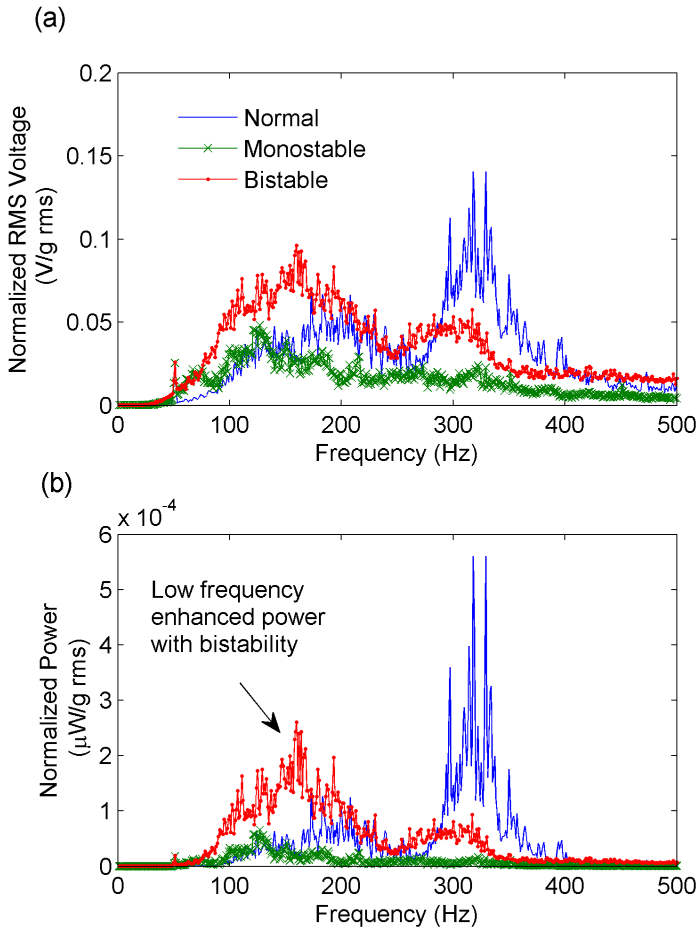

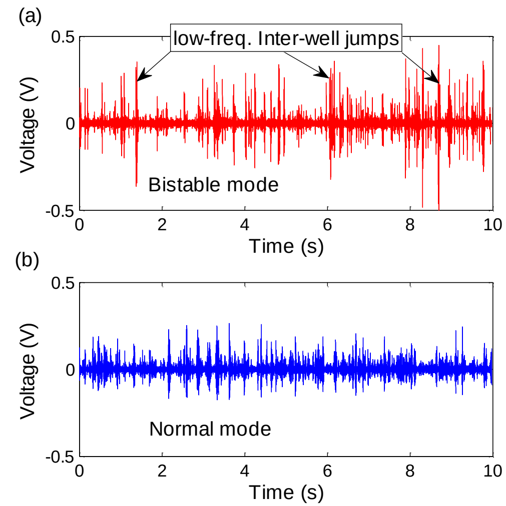

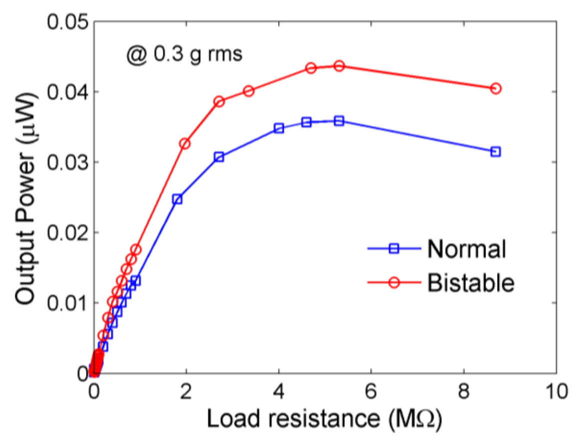

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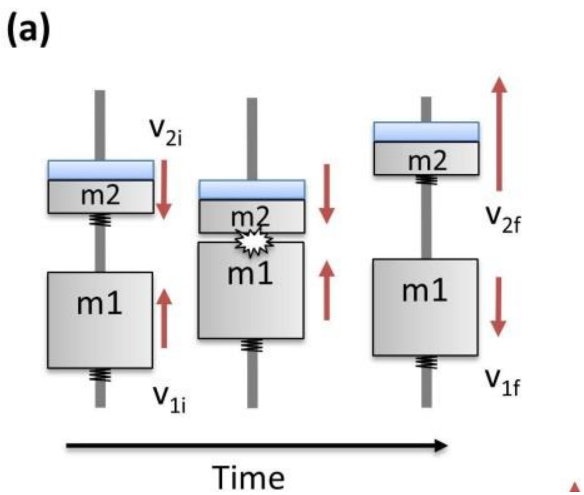
Beyond linear harvesting systems

Velocity-amplified mulitple-mass EM VEH



$$v_{2f} = \frac{(e+1)m_1 v_{1i} + (m_2 - e m_1) v_{2i}}{m_1 + m_2}$$

if $e = 1$ and in the limit of $m_1 / m_2 \rightarrow \infty$,

the final velocity of the smaller mass is

$$v_{2f} = 2v_{1f} - v_{2i}.$$

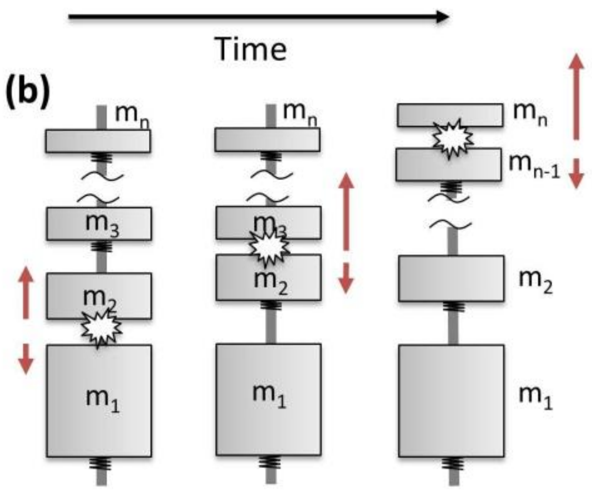
In the case of equal but opposite initial velocities

$$v_{2f} = -3v_{2i},$$

which represents a gain **factor of 3x** in velocity.

Beyond linear harvesting systems

Velocity-amplified mulitple-mass EM VEH



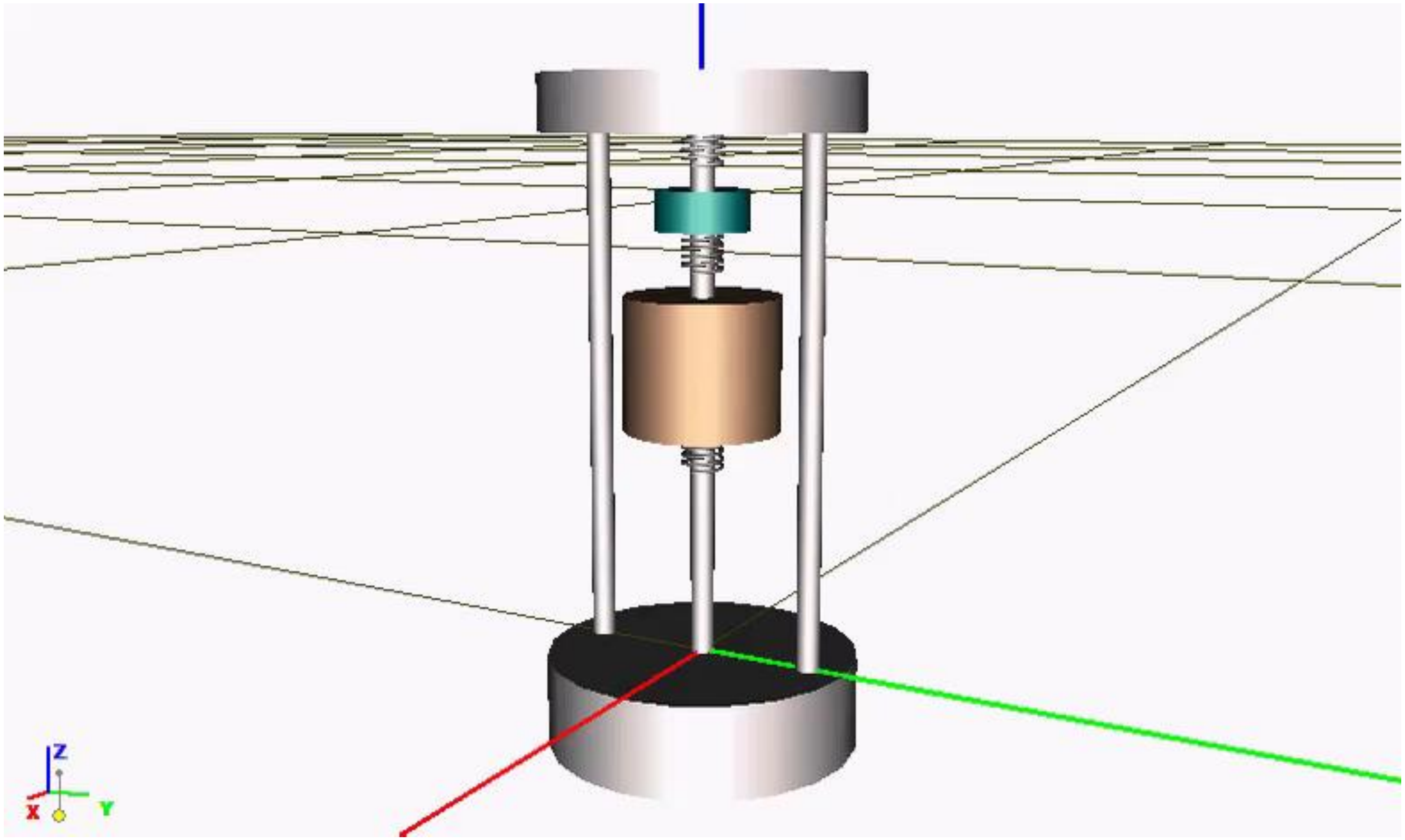
For a series of *n*–bodies of progressively smaller mass that impact sequentially, the velocity gain is proportional to *n*.

(Rodgers et al., 2008)

$$G_n = (1 + e_{1,0}) \prod_{k=2}^{n} \left(\frac{1 + e_{k,k-1}}{1 + r_{k,k-1}} \right) - 1$$

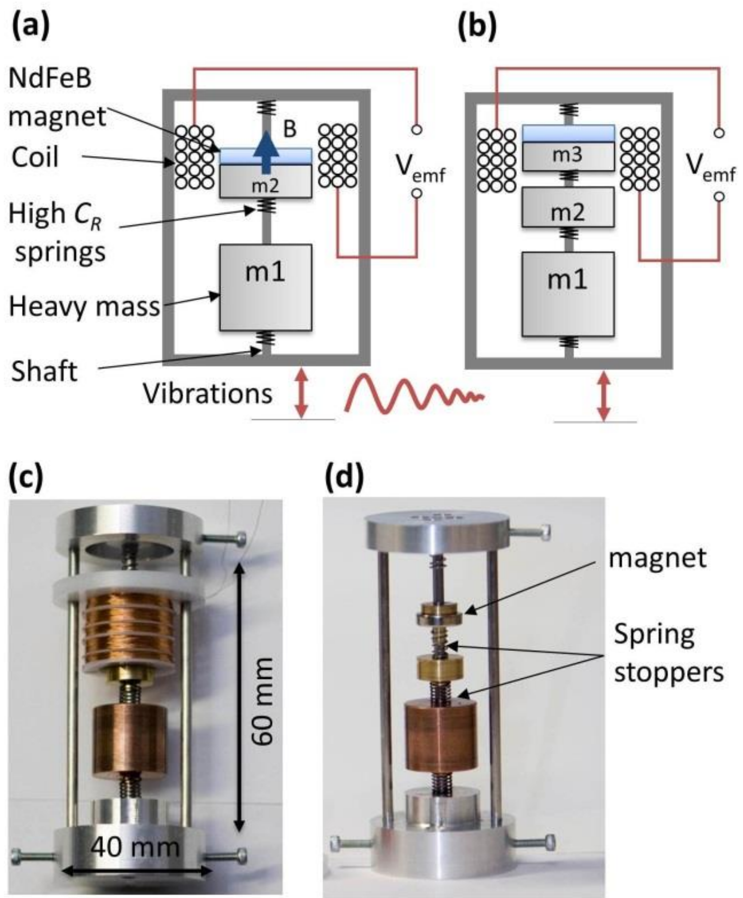
Beyond linear harvesting systems

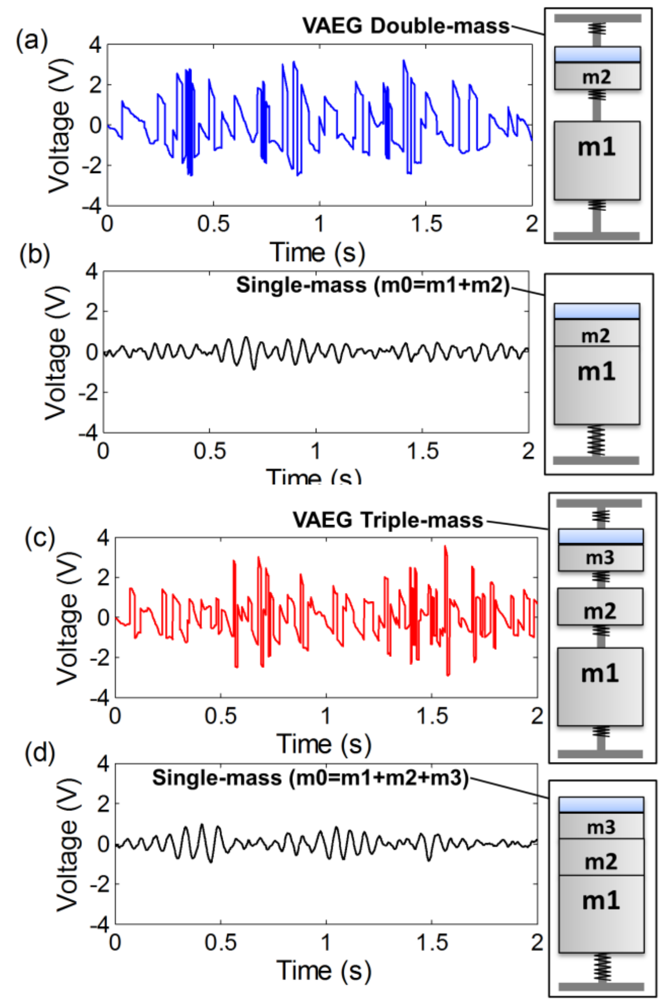
Velocity-amplified mulitple-mass EM VEH



Beyond linear harvesting systems

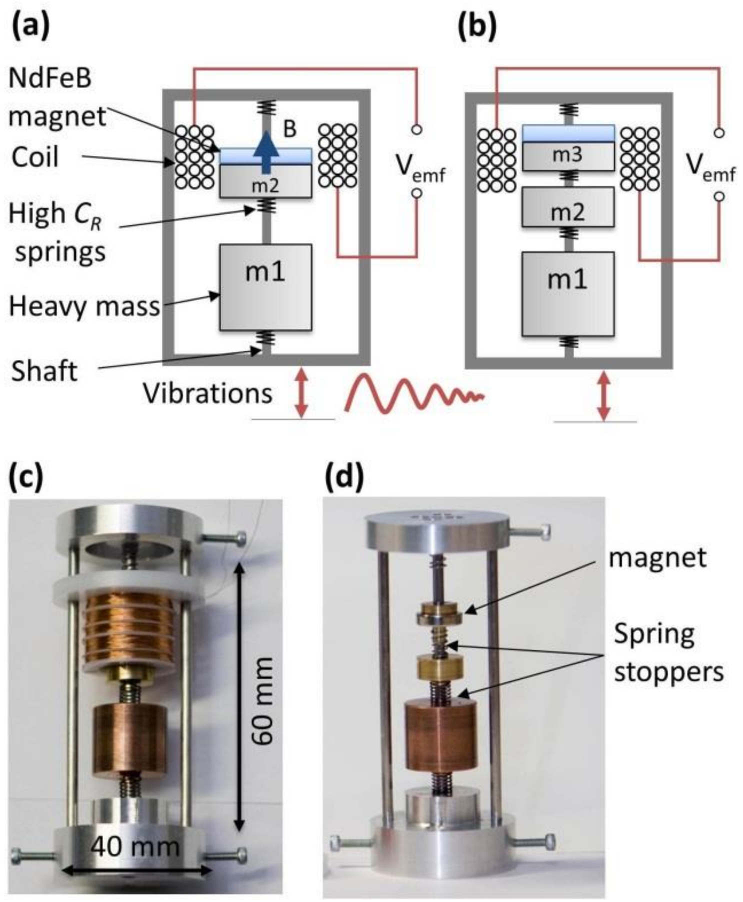
Velocity-amplified mulitple-mass EM VEH

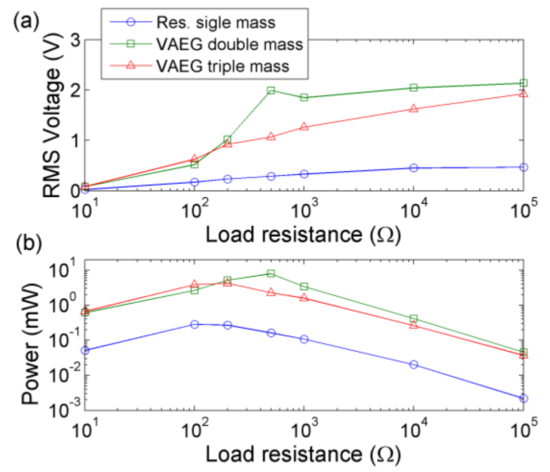


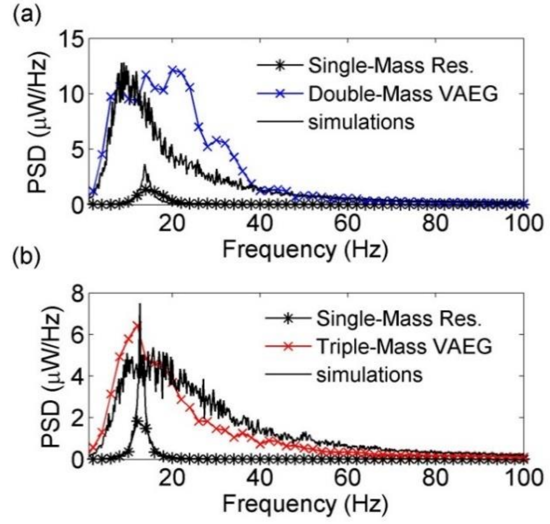


Beyond linear harvesting systems

Velocity-amplified mulitple-mass EM VEH

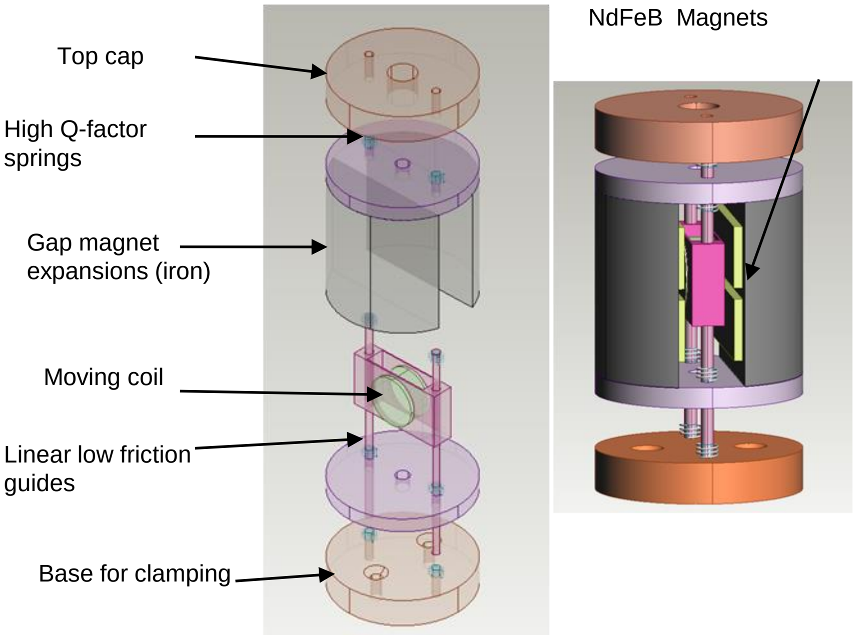




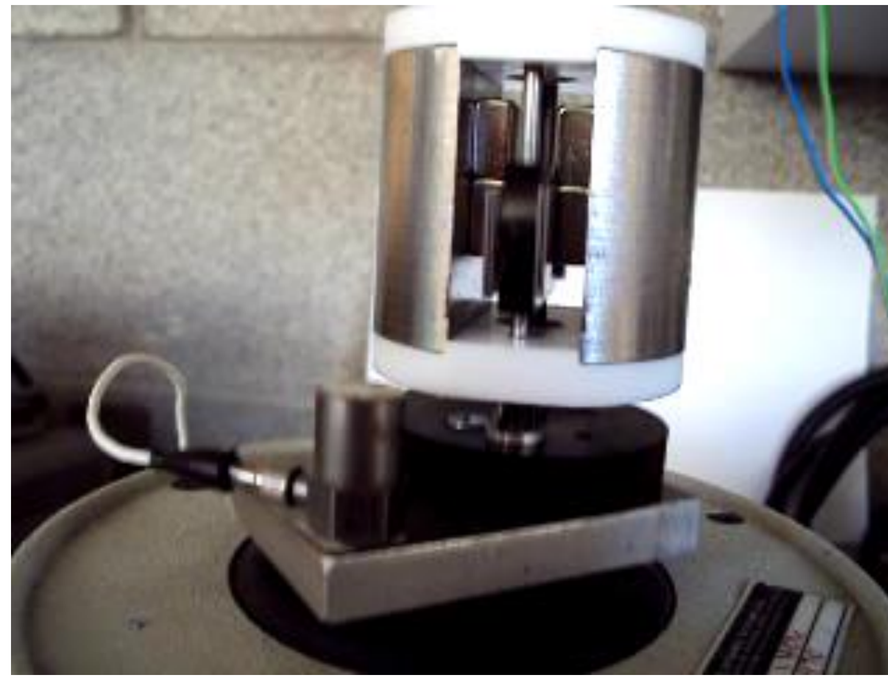


Beyond linear harvesting systems

Velocity-amplified mulitple-mass EM VEH



Prototype 2 with transversal magnetic flux

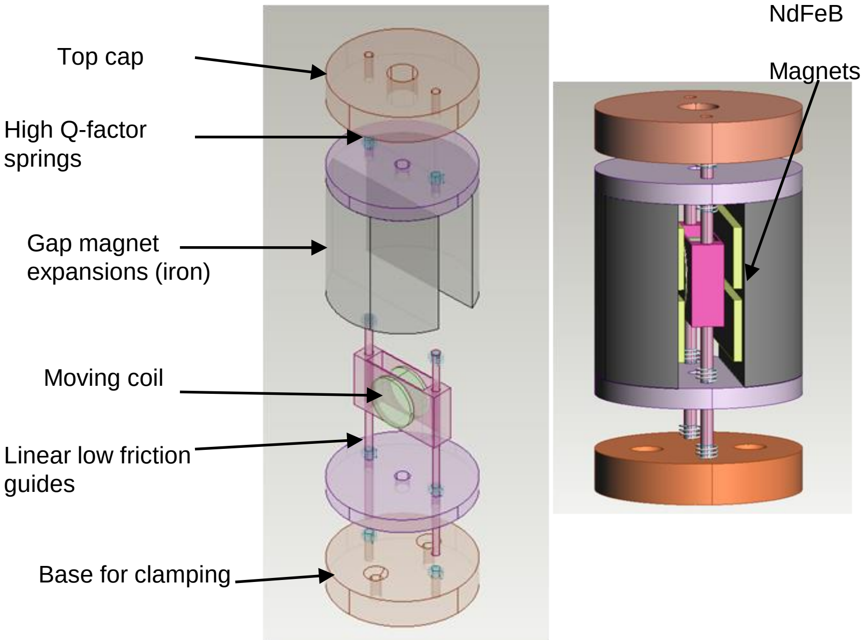


University of Limerick (Ireland) and Bell-Labs Alcatel (USA).

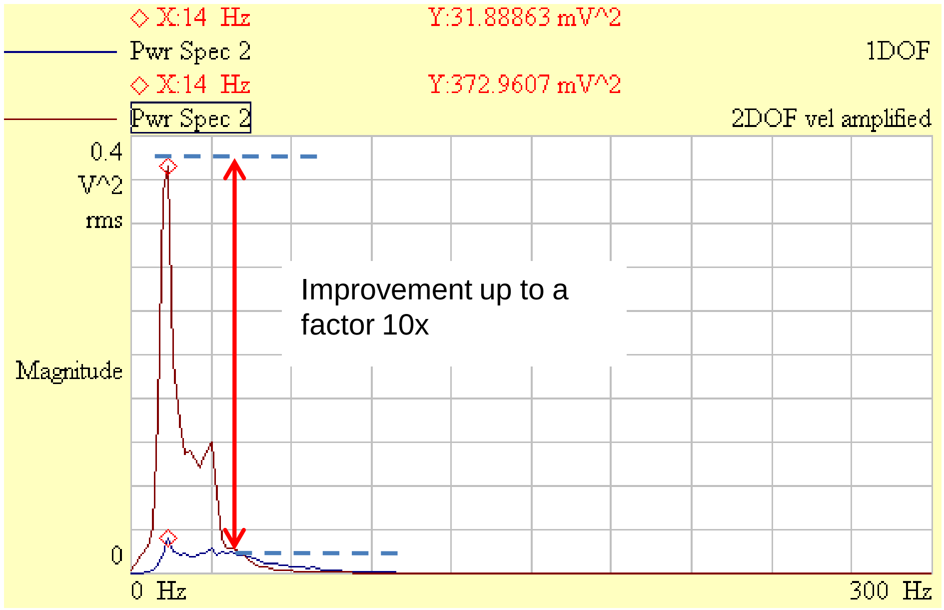
F. Cottone, G. Suresh, J. Punch - "*Energy Harvesting Apparatus Having Improved Efficiency*". US Patent n. 8350394B2

Beyond linear harvesting systems

Velocity-amplified mulitple-mass EM VEH



Prototype 2 with transversal flux linkage



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Comparison of various approaches

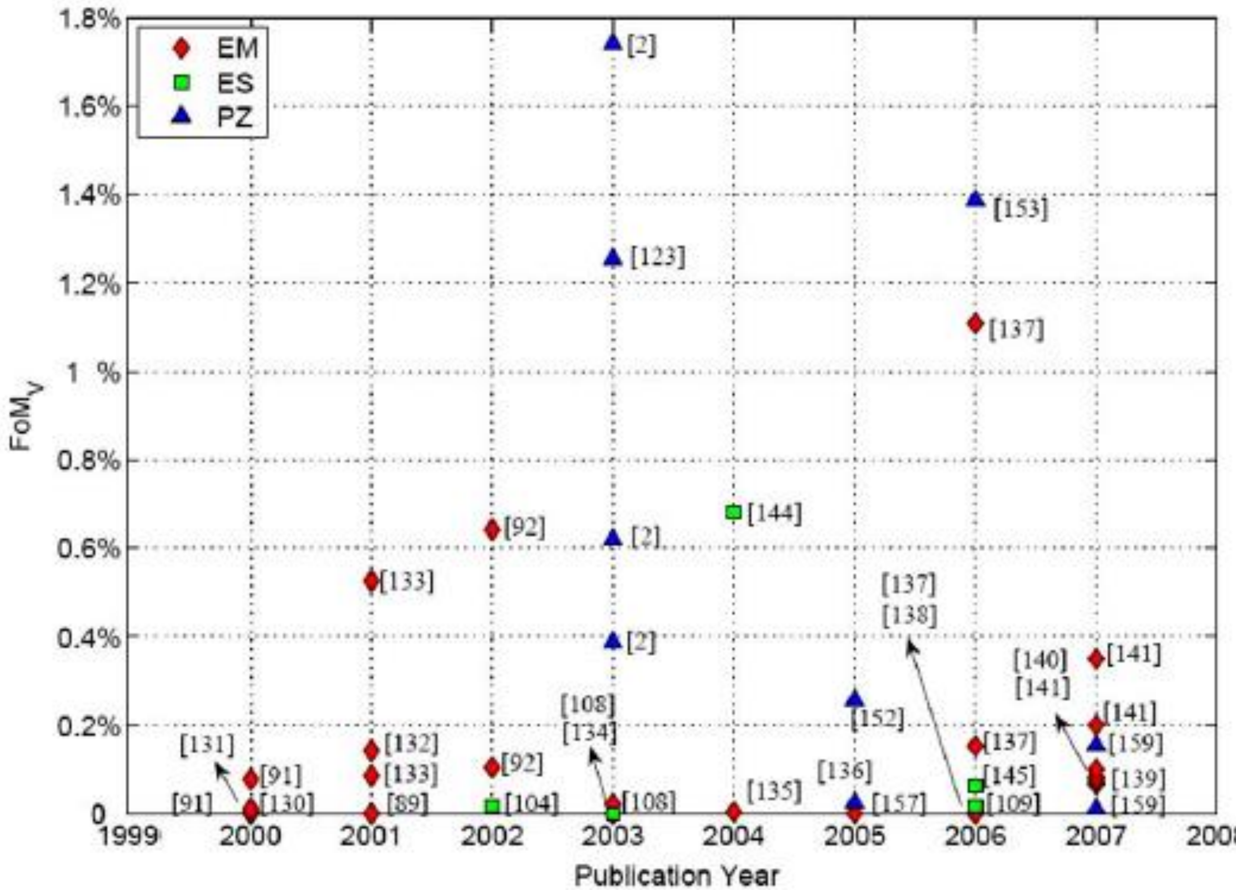
Strategies	Advantages	Disadvantages
Mechanical tuning	• High efficiency	• Extra system and energy are required • Responds to only one frequency at a time • Slow response to a change in a vibration frequency
• Change dimension	• Does not affect damping	• Difficult to implement • Not suitable for tuning *in situ*[a]
• Change centre of gravity	• Does not affect damping	• Not suitable for tuning *in situ*
• Change spring stiffness continuously	• Suitable for *in situ* tuning	• Consumes energy when generators work at resonance
• Apply axial load (change spring stiffness intermittently)	• Easy to implement • Suitable for *in situ* tuning • No energy is required when generators work at resonance • Damping is not affected when the tensile load is applied	• Increased damping when the compressive load is applied
Electrical tuning	• Easy to implement • No energy is required when generators work at resonance • Suitable for *in situ* tuning	• Low tuning efficiency
Widen bandwidth	• No tuning mechanism required • Respond to different frequencies at the same time • Immediate response to a change in vibration frequency	• Complexity in design
• Generator array	• Damping is not affected	• Complexity in design • Low volume efficiency
• Use mechanical stopper	• Easy to implement	• Fatigue problem • Decrease in the maximum output power
• Coupled oscillators	• Easy to implement	• Decrease in the maximum output power
• Nonlinear generators	• Better performance at excitation frequencies higher than resonant frequency	• Complexity in design • Hysteresis
• Bi-stable structure	• Better performance at excitation frequencies much lower than resonant frequency	• Complexity in design

[a] Tuning while the generator is mounted on the vibration source and working.

Zhu, D., Tudor, M. J., & Beeby, S. P. (2010).

Performance metrics

$$\mathrm{FoM_V} = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{Au} Vol^{\frac{4}{3}} \omega^3}$$



Bandwidth figure of merit

$$\mathrm{FoM_{BW}} = \mathrm{FoM_V} \times \frac{\delta\omega_{1\ \mathrm{dB}}}{\omega}$$

Frequency range within which the output power is less than 1 dB below its maximum value

Mitcheson, P. D., E. M. Yeatman, et al. (2008). "Energy harvesting from human and machine motion for wireless electronic devices." Proceedings of the IEEE **96**(9): 1457-1486.

Conclusions

- Most of vibrational energy sources are random and present low frequency content.

- Linear vibration energy harvesters are limited and application dependent.

- The efficiency of Vibration Energy Harvesting can be improved with nonlinear approaches such as:
  - Freqeuncy tuning
  - Multimodal systems
  - Freqeuncy-up converters, impacting masses
  - Bistable nonlinear systems

- There's plenty of room for improvement at level of
  - nonlinear dynamics,
  - material properties,
  - miniaturization procedures,
  - efficient conditioning electronics.

- In general nonlinear systems like bistable/multistable oscillators are the best choice for wideband vibration harvesting

Technical challenges

- **Miniaturization issues:** improving coupling coefficient at small scale and power density
  - Improvements of piezoelectric-material properties
  - Improving capacitive design
  - Increasing remanent magnetic filed in micro magnets
  - Research on electrets

- **Efficient conditioning electronics**
  - Mechanical rectification ?
  - Efficient Integrated design
  - Power-aware operation of the powered device

Research activities done in collaboration with