NiPS Laboratory
Noise in Physical Systems

UNIVERSITÀ DEGLI STUDI
DI PERUGIA

Random Vibration Energy Harvesting

Francesco Cottone

NiPS lab, Physics Dep., Università di Perugia, Italy

francesco.cottone at unipg.it

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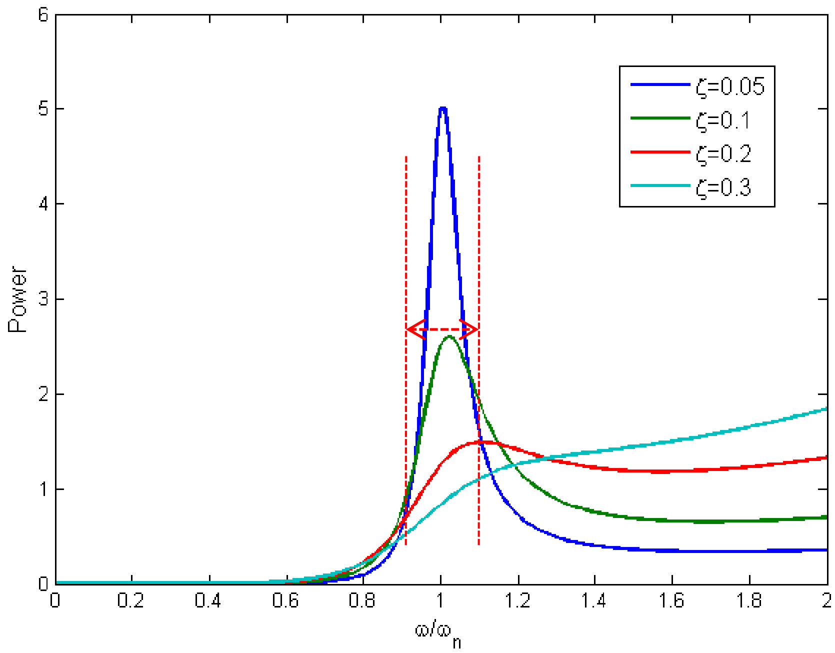
June 30th - July 3rd - Gubbio (Italy)

Outline

- Beyond linear vibration energy harvesting
- Nonlinear systems
- Examples of nonlinear devices with different conversion technology
- Final considerations

Main limits of resonant VEHs

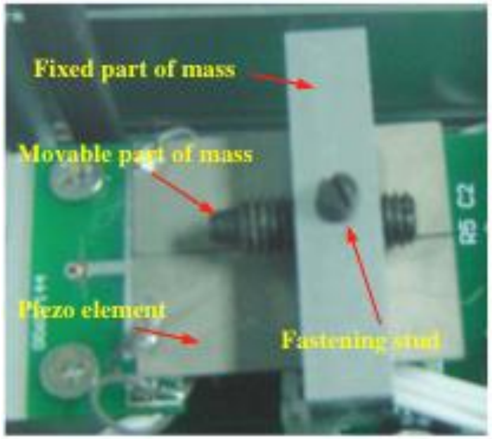
- narrow bandwidth that implies constrained resonant frequency-tuned applications
- Non-adaptation to variable vibration sources
- small inertial mass and high resonant frequency at micro/nano-scale -> most of vibration sources are below 100 Hz



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

Nonlinear systems

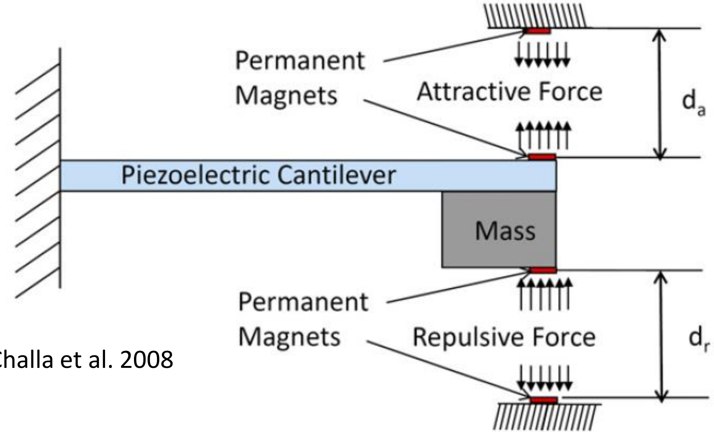
Frequency tuning



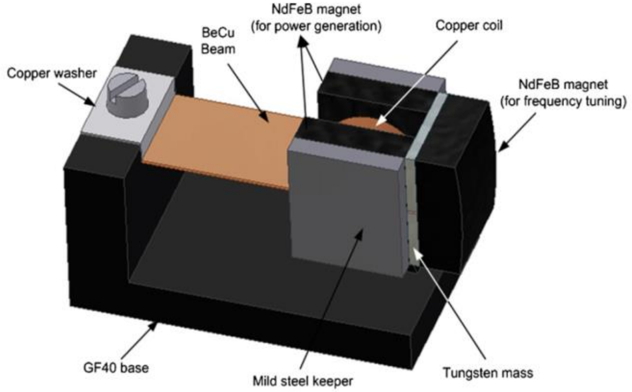
Wu et al. 2008

Piezoelectric cantilever with a movable mass

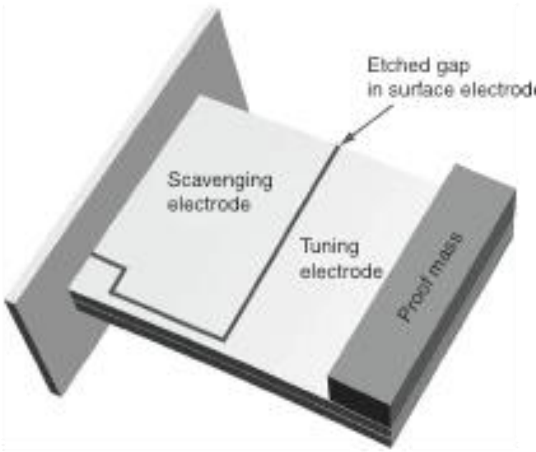
Piezoelectric cantilever with magnetic tuning



Challa et al. 2008



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



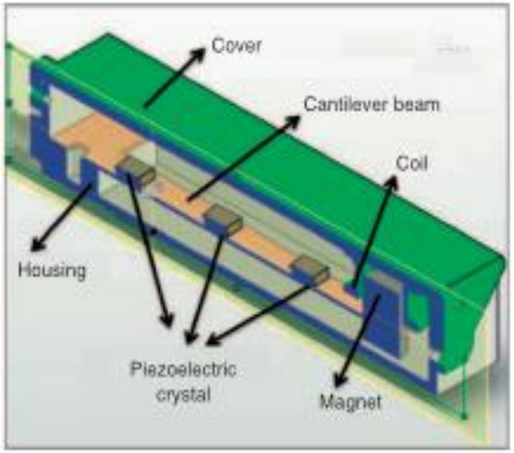
Piezoelectric beam with a scavenging and a tuning part

Roundy and Zhang 2004

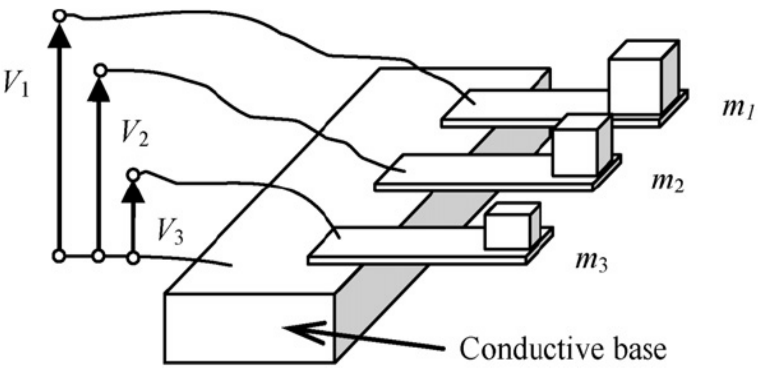
Nonlinear systems

Multimodal Energy Harvesting

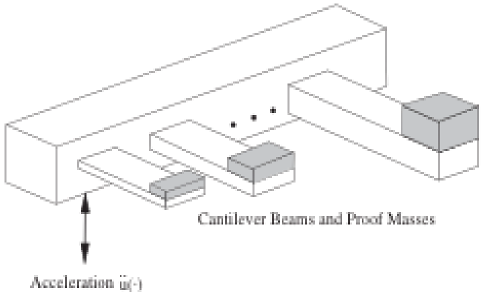
Tadesse et al. 2009



Hybrid harvester with piezoelectric and electromagnetic transduction mechanisms



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

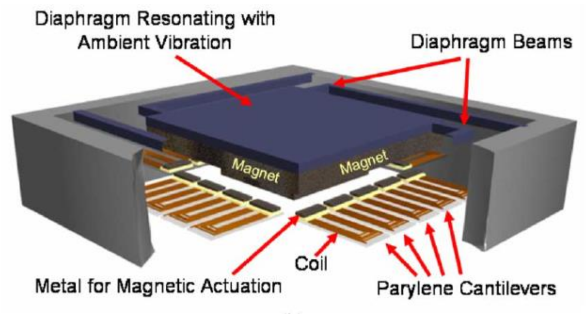


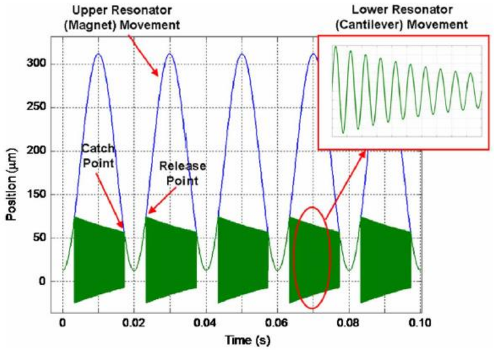
Shahruz 2006

Piezoelectric cantilever arrays
with various lengths and tip masses

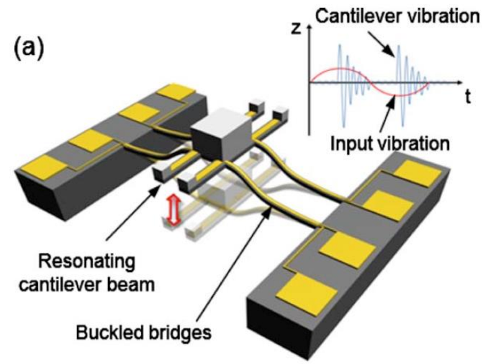
Nonlinear systems

Frequency-up conversion

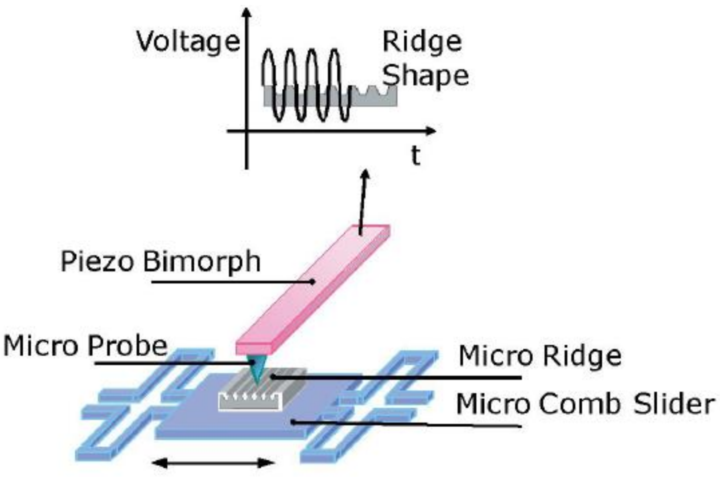




H. Kulah and K. Najafi, IEEE Sensors Journal **8** (3), 261 (2008).

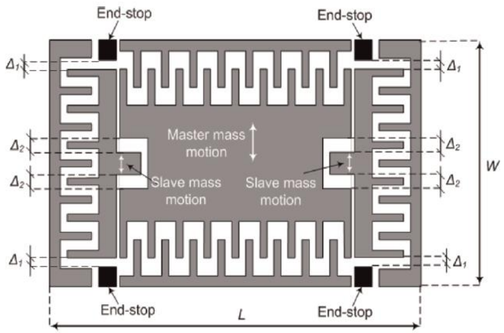


Jung, S.-M. et al. (2010). *Applied Physics Letters*



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

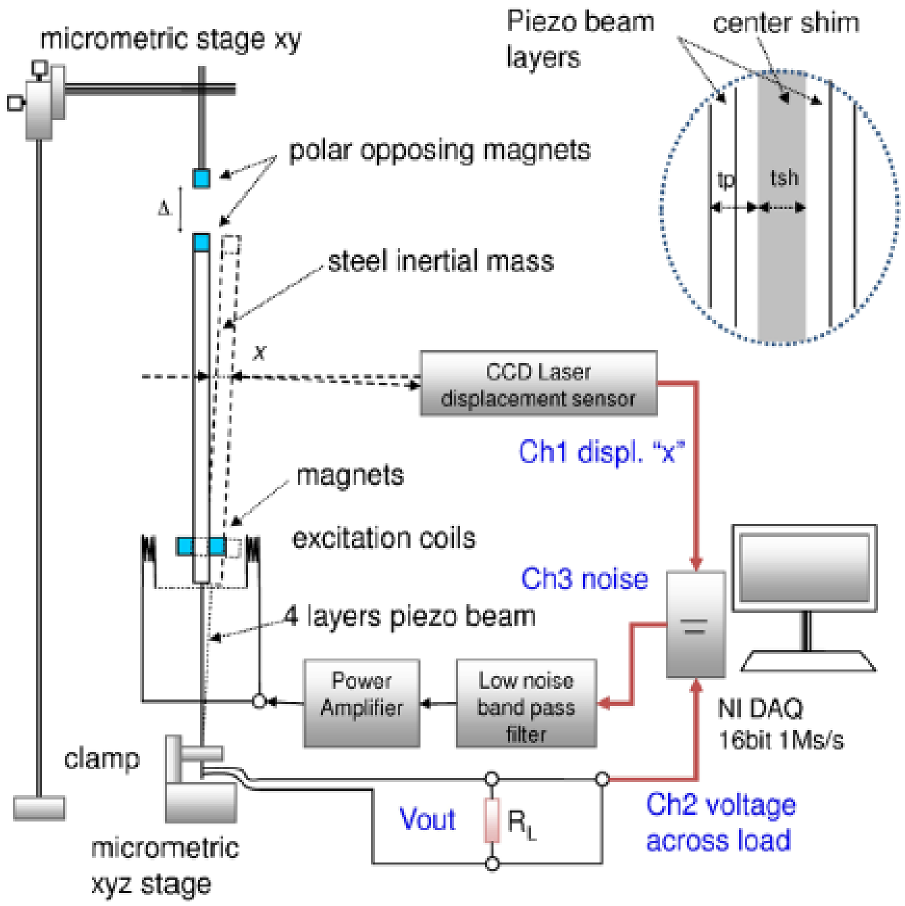
Impact electrostatic MEMS generator

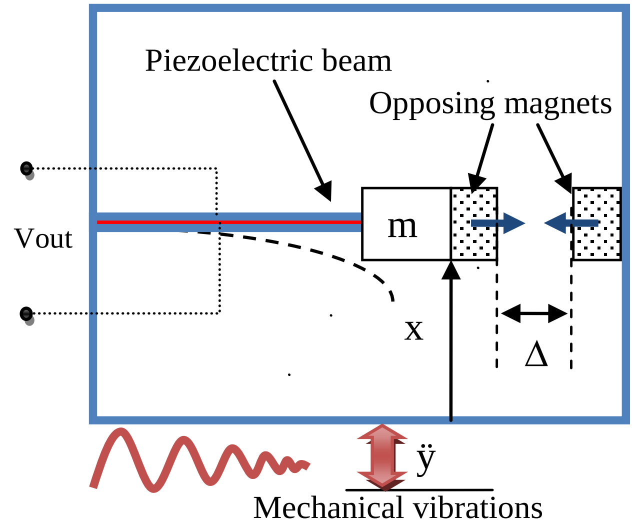


Le, C. P., Halvorsen (2012). *Journal of Intelligent Material Systems and Structures*

Nonlinear systems

Bistable systems

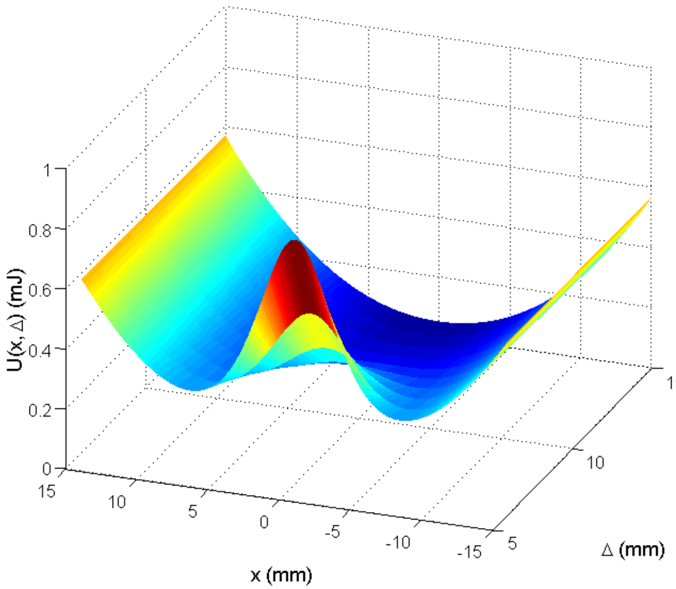


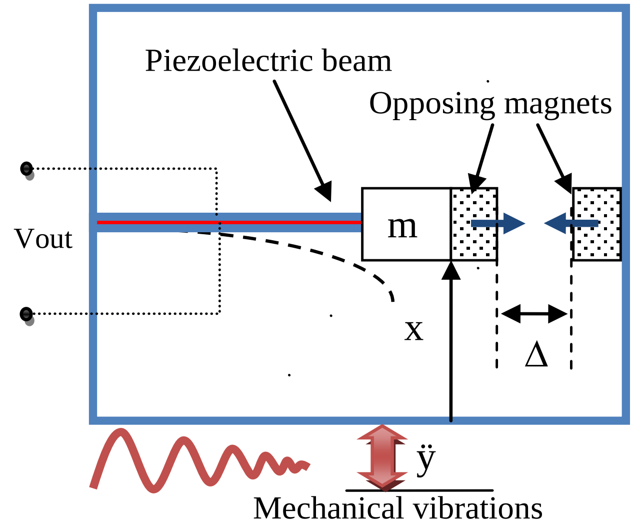


Cottone, F., H. Vocca & L. Gammaitoni, Nonlinear Energy Harvesting. *PRL,* 102 (2009).

Nonlinear systems

Bistable systems





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

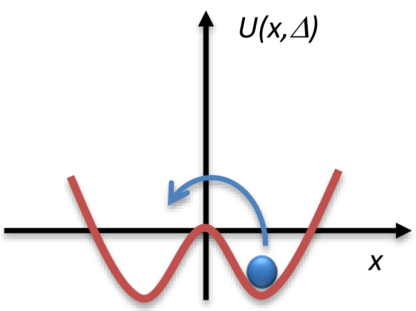
$$\begin{cases} m\ddot{x}(t)+\delta\dot{x}(t)+K_{eff}x(t)+\dfrac{\partial U(x,\Delta)}{\partial x}+K_vV(t)=-m\ddot{y}(t) \\ \dot{V}(t)+\dfrac{1}{\tau}V(t)=K_c\dot{x}(t); \qquad \tau=R_LC_p \end{cases}$$

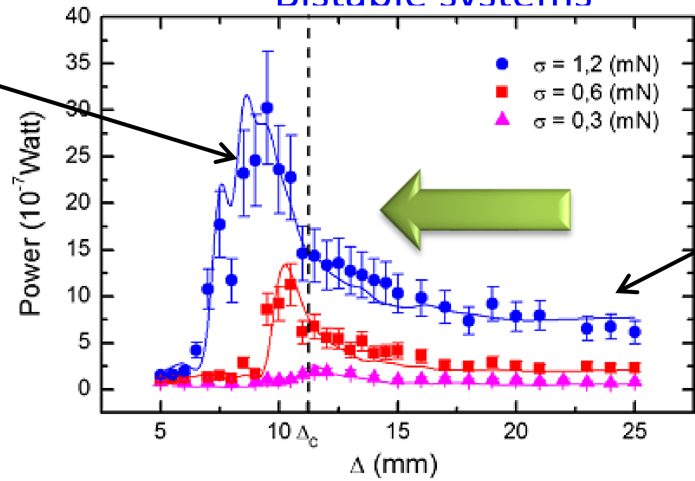
Cottone, F., H. Vocca & L. Gammaitoni. *PRL,* 102 (2009).

Nonlinear systems

Bistable systems

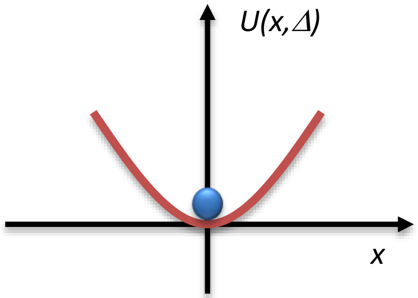
Bistable: inter-well and intra-well oscillations

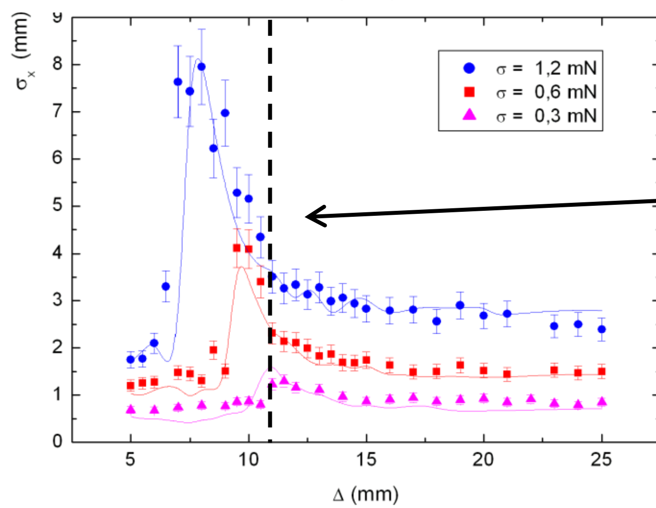




Resonant monostable

Δ=25mm

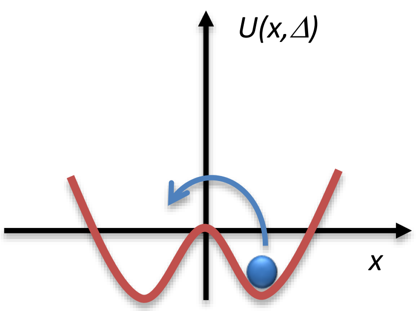


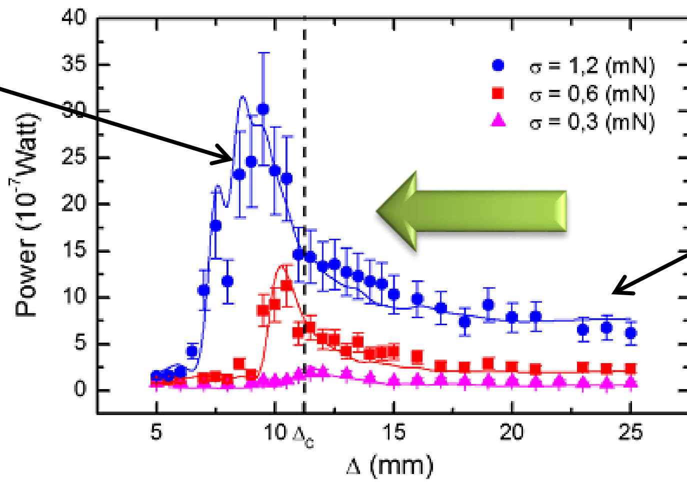


Bifurcation point

Nonlinear systems

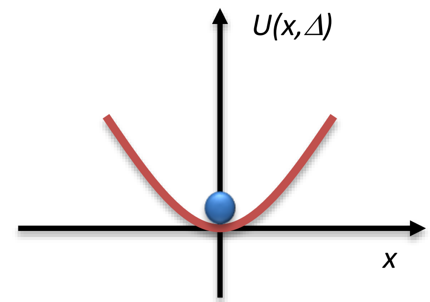
Bistable: inter-well and intra-well oscillations

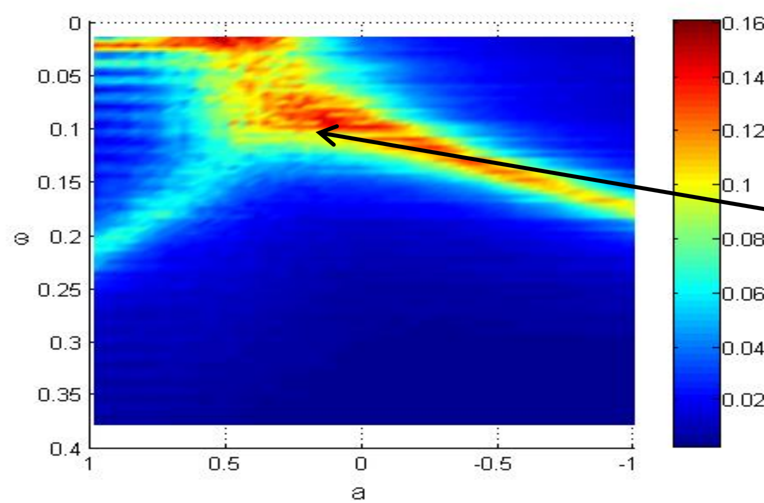




Resonant monostable

Δ=25mm



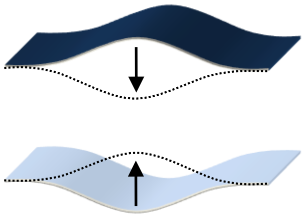


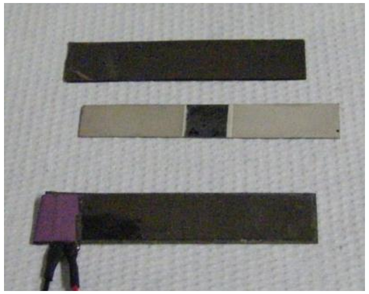
Bandwith enhancement when interwell jumps occur

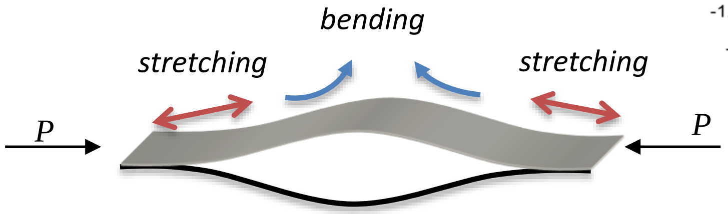
Nonlinear systems

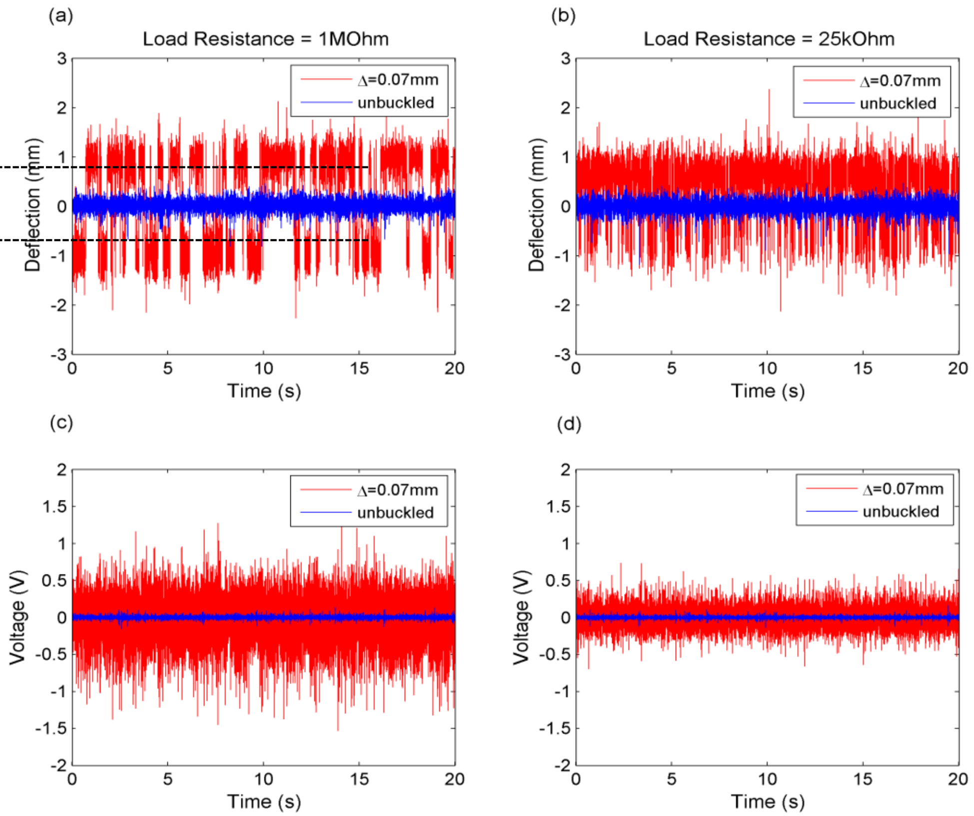
Buckled beam piezoelectric harvesters

Snapping between buckled states



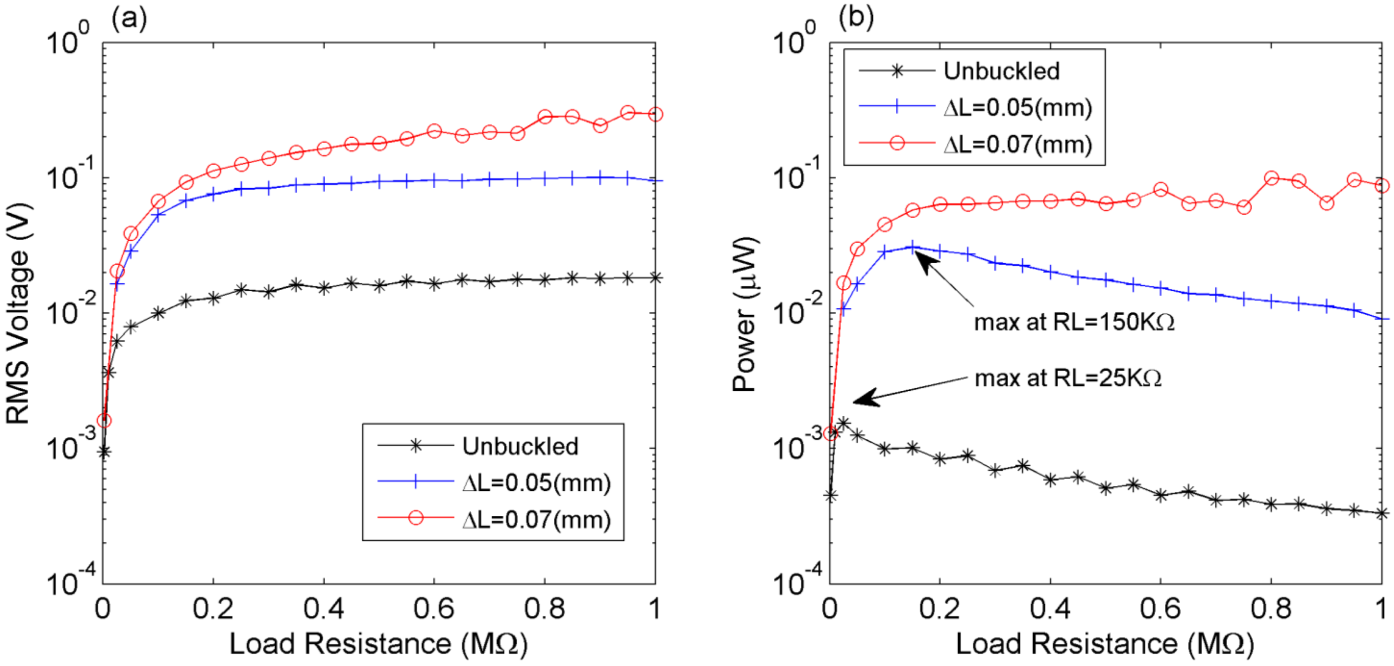






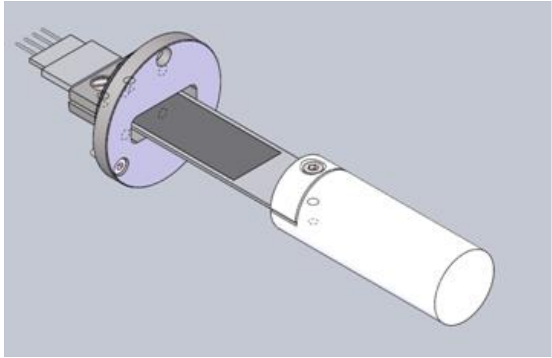
Nonlinear systems

Buckled beam piezoelectric harvesters

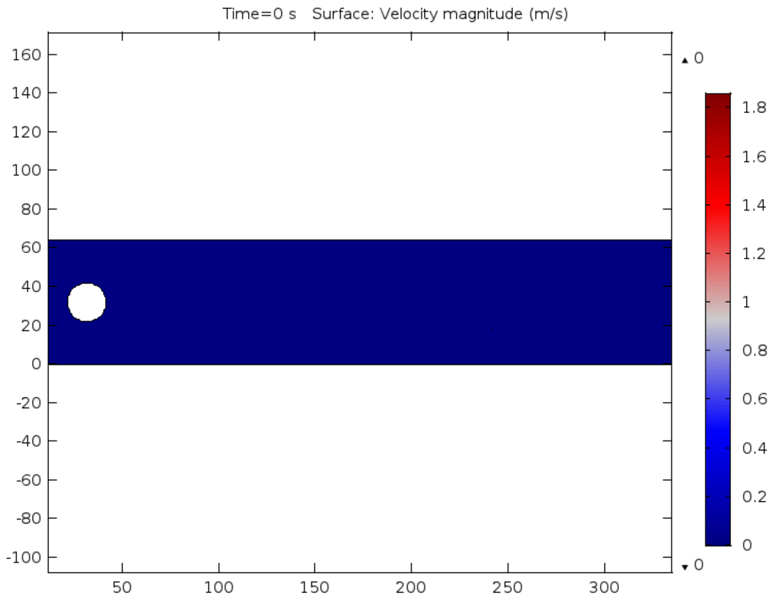


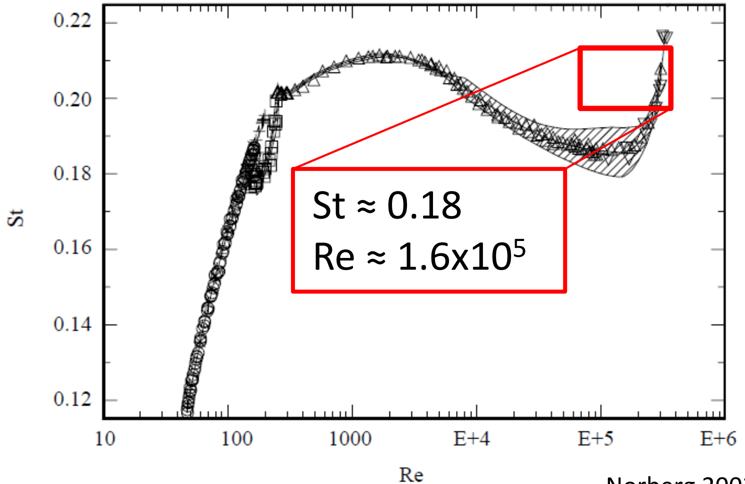
Cottone, F., L. Gammaitoni, H. Vocca, M. Ferrari & V. Ferrari, Smart materials and structures, 21, 2012.

Nonlinear systems



Numerical simulation: d=2cm, U=0.7 m/s





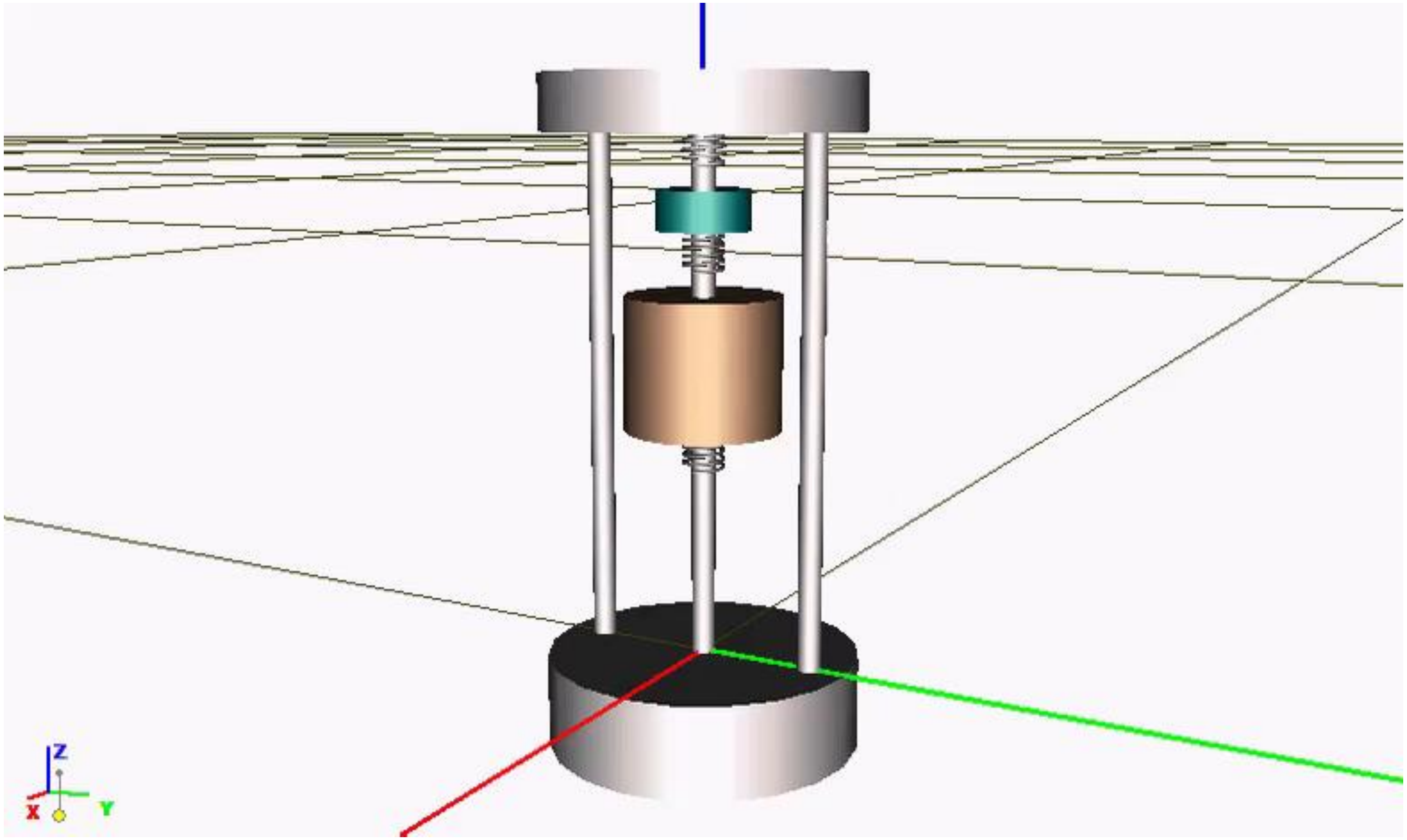
Norberg 2003

Von Karman vibrations by turbulence from a cylindrical object.

- Strouhal number $\mathrm{St} = \frac{f_S\, d}{U},$
- Reynolds number $\mathrm{Re} = \frac{\rho U d}{\mu},$

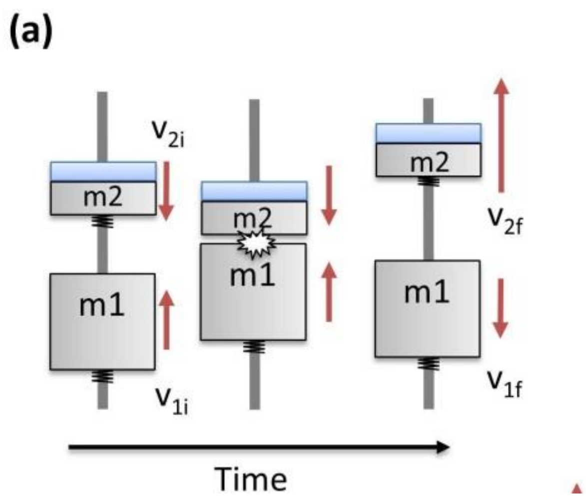
Nonlinear systems

Velocity-amplified mulitple-mass EM VEH



Nonlinear systems

Velocity-amplified mulitple-mass EM VEH



$$v_{2f} = \frac{(e+1)m_1 v_{1i} + (m_2 - em_1)v_{2i}}{m_1 + m_2}$$

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

the final velocity of the smaller mass is

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

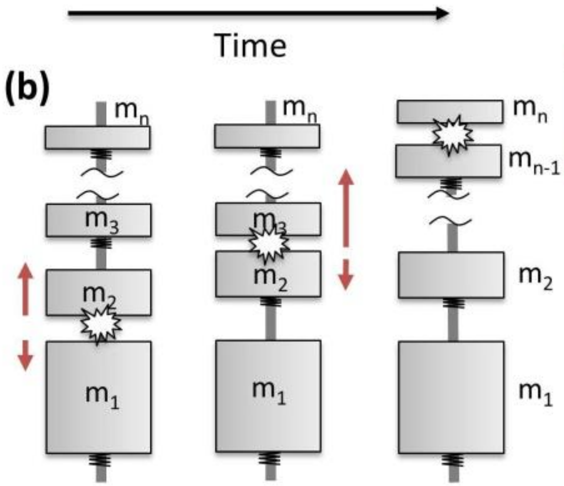
In the case of equal but opposite initial velocities

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

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

Nonlinear systems

Velocity-amplified mulitple-mass EM VEH

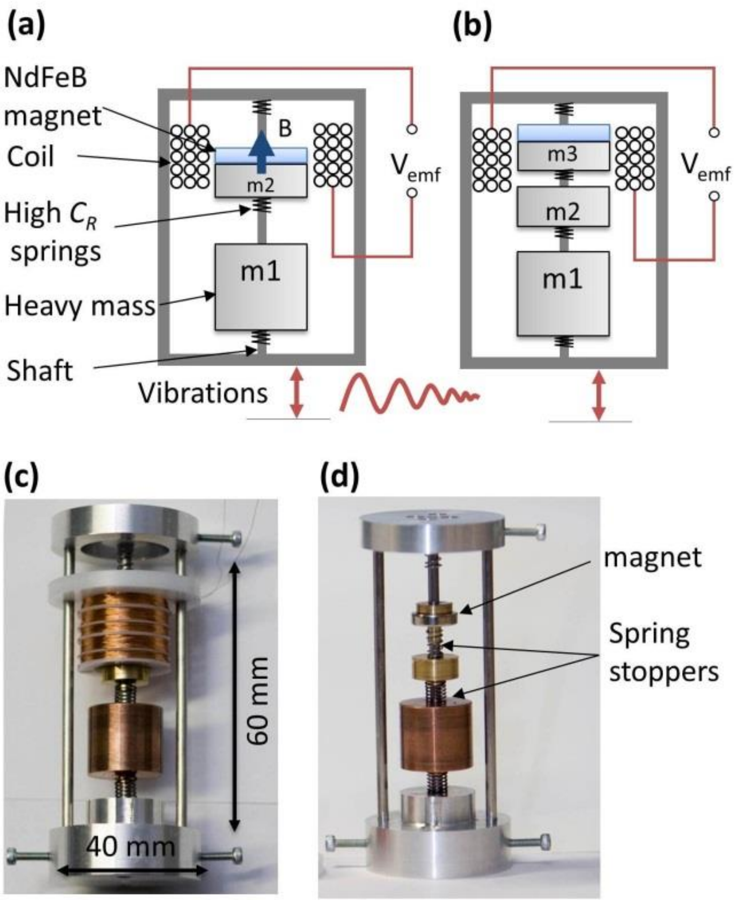


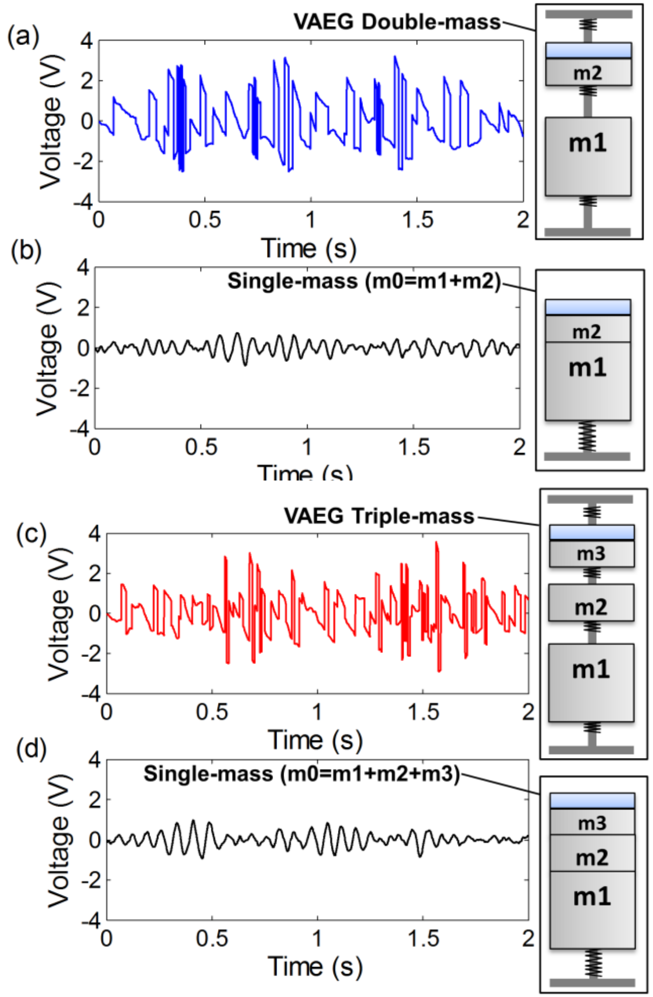
For a series of n−bodies of progressively smaller mass that impact sequentially, the velocity gain is proportional to n.
(Rodgers et al., 2008)

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

Nonlinear systems

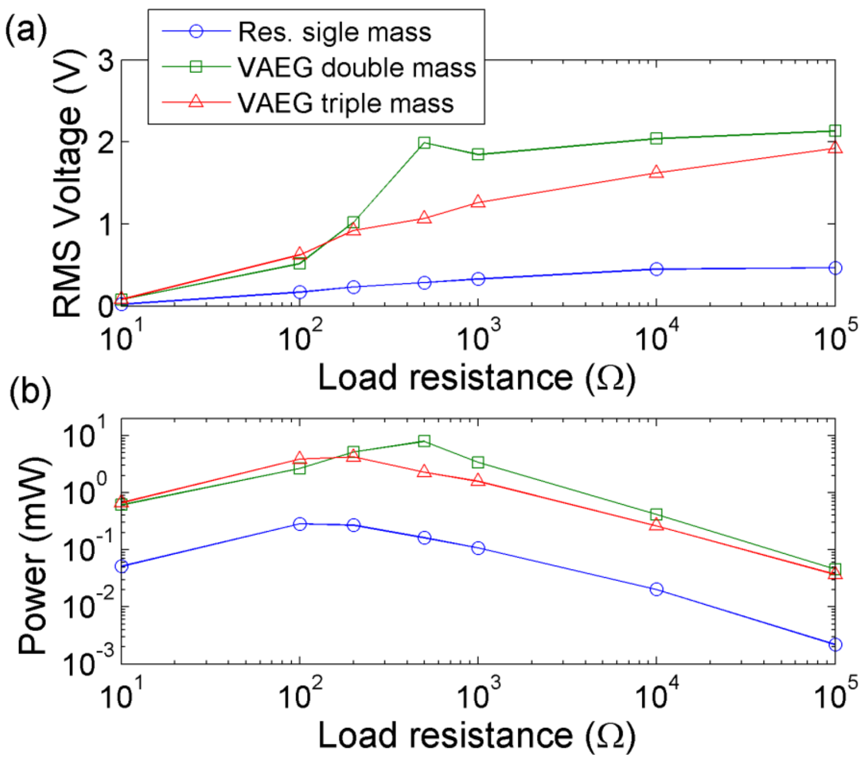
Velocity-amplified mulitple-mass EM VEH

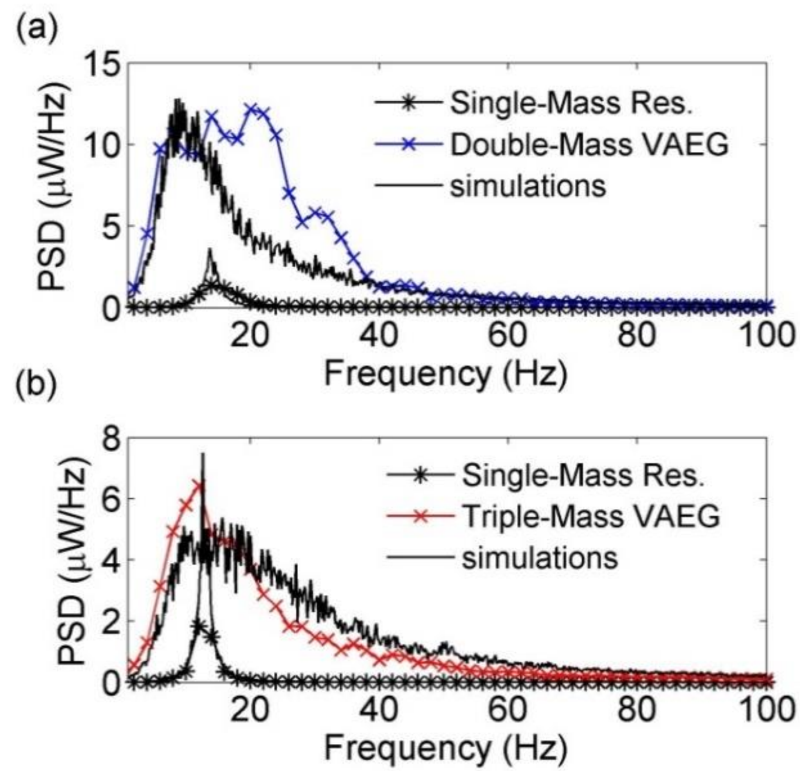




Nonlinear systems

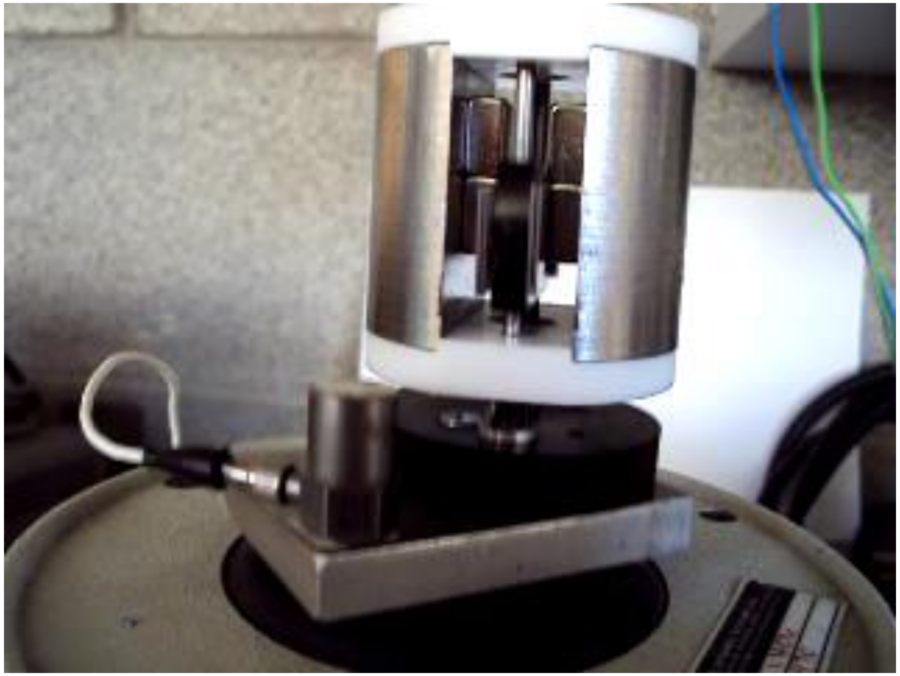
Velocity-amplified mulitple-mass EM VEH





Nonlinear systems

Velocity-amplified mulitple-mass EM VEH

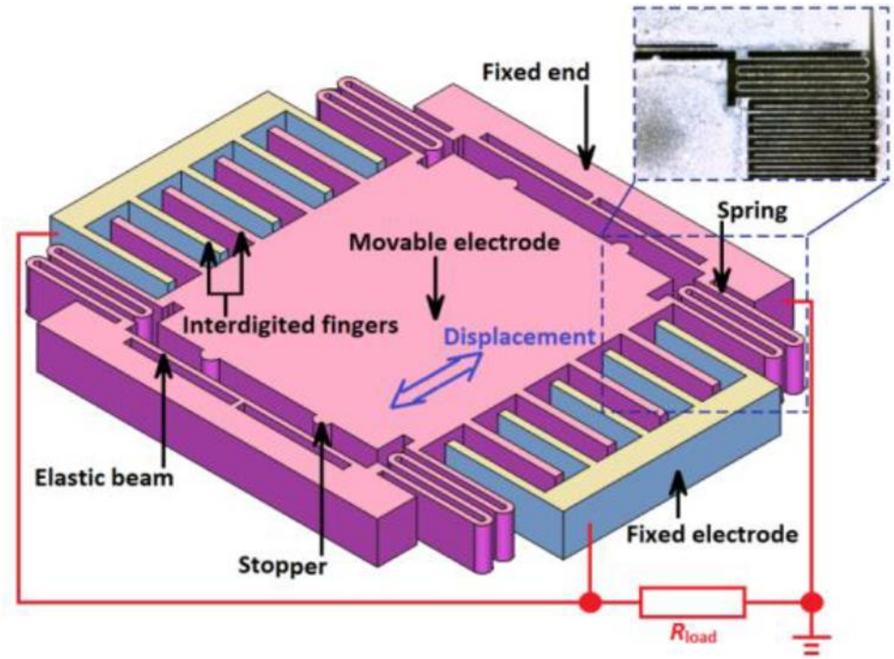


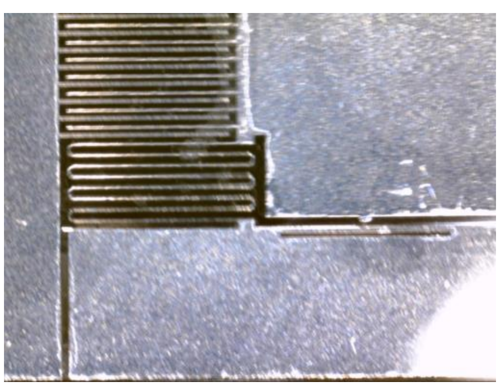
Prototype 2
with transversal magnetic flux

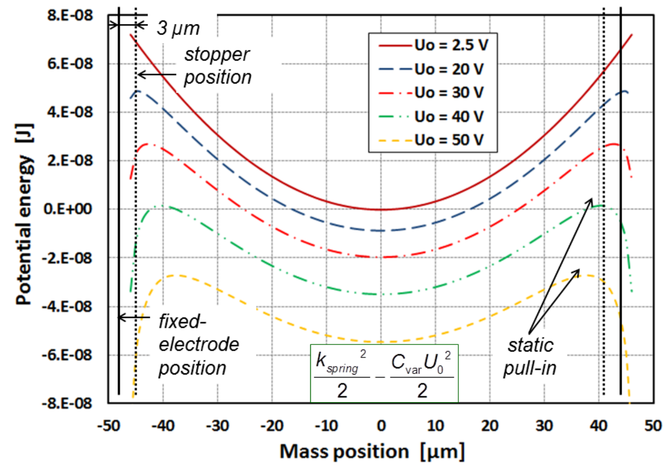
University of Limerick (Ireland) and Bell-Labs Alcatel (USA).

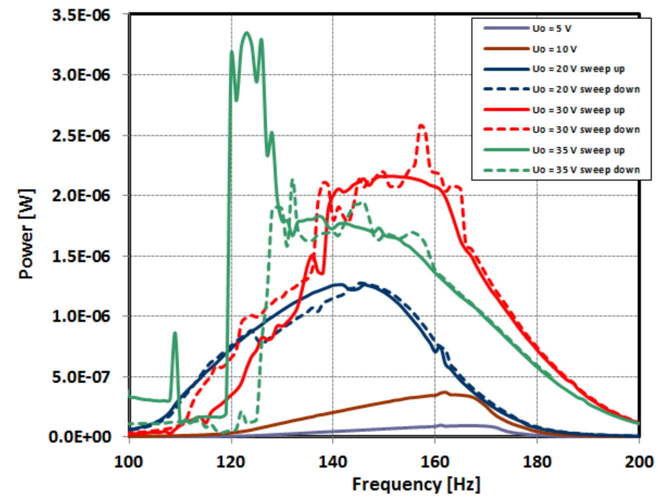
F. Cottone, G. Suresh, J. Punch - "*Energy Harvesting Apparatus Having Improved Efficiency*". US Patent n. 8350394B2

Nonlinear MEMS electrostatic VEH

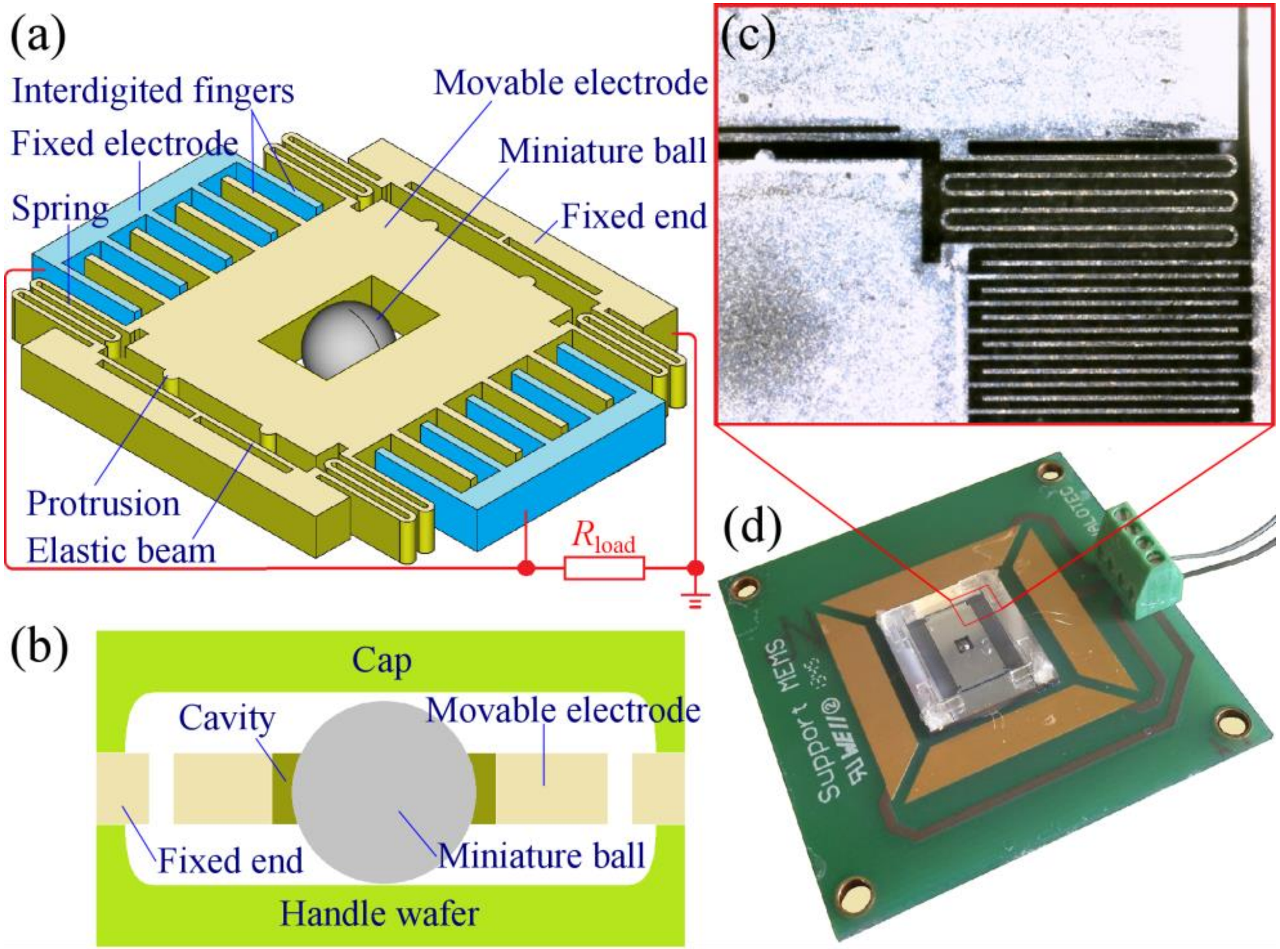








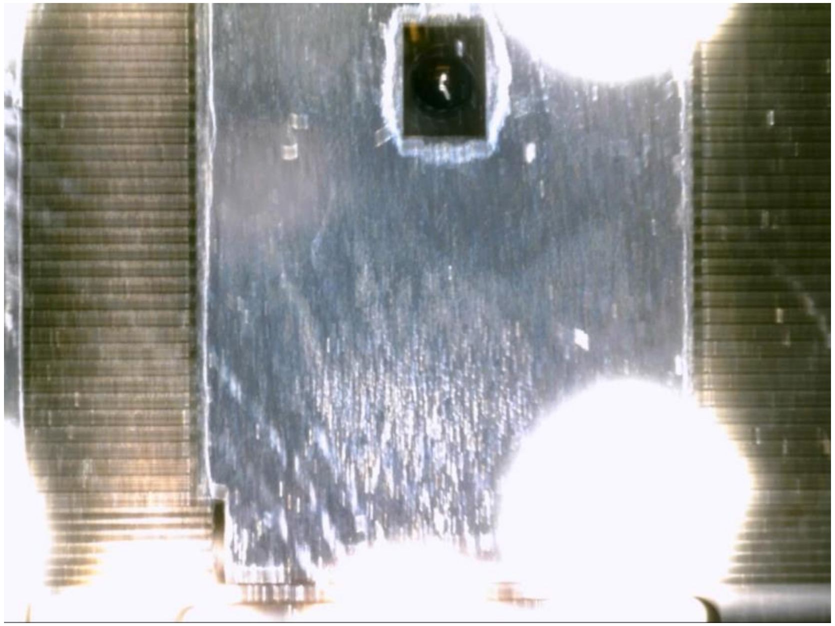
Nonlinear MEMS electrostatic VEH



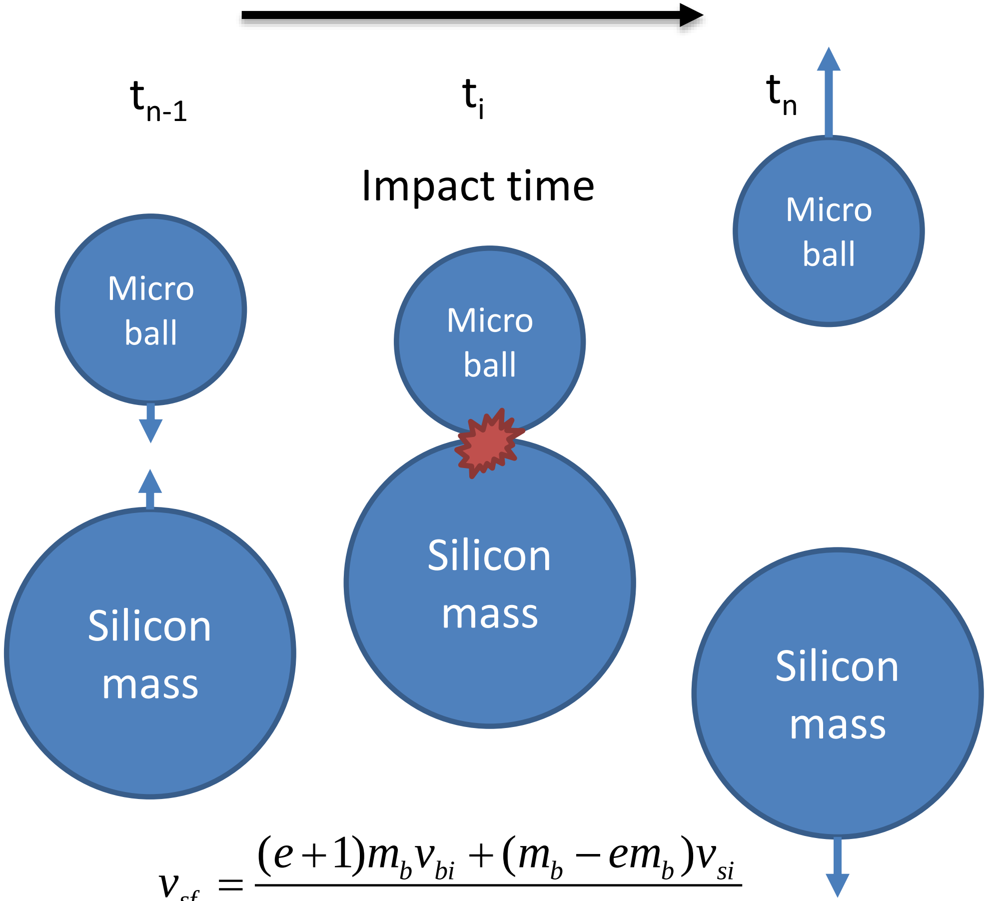
Y. Lu, F. Cottone, S. Boisseau, F. Marty, D. Galayko, and P. Basset, Appl. Phys. Lett. 107, 20 (2015).

Low-frequency MEMS electrostatic VEH

Experimental test



Working principle

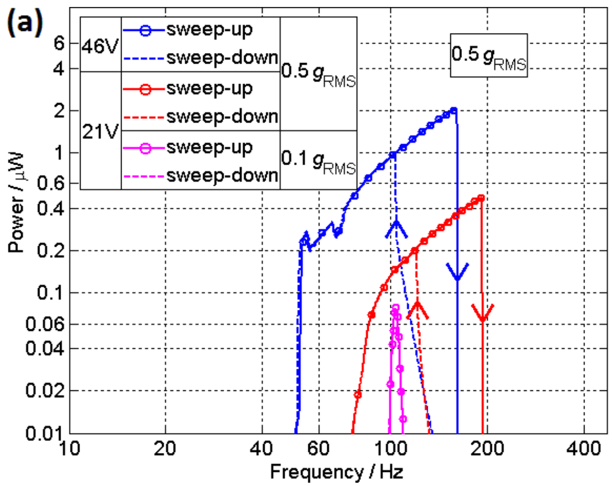


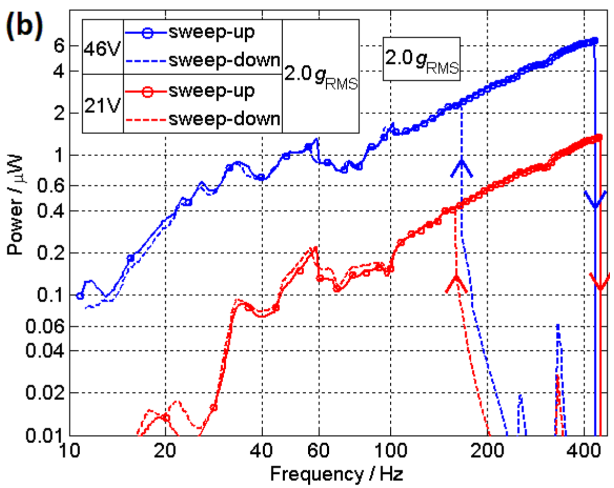
$$v_{sf} = \frac{(e+1)m_b v_{bi} + (m_b - e m_b) v_{si}}{m_b + m_s}$$

Velocity Amplified Energy Harvester
At Stoke Institute, University of Limerick, Ireland

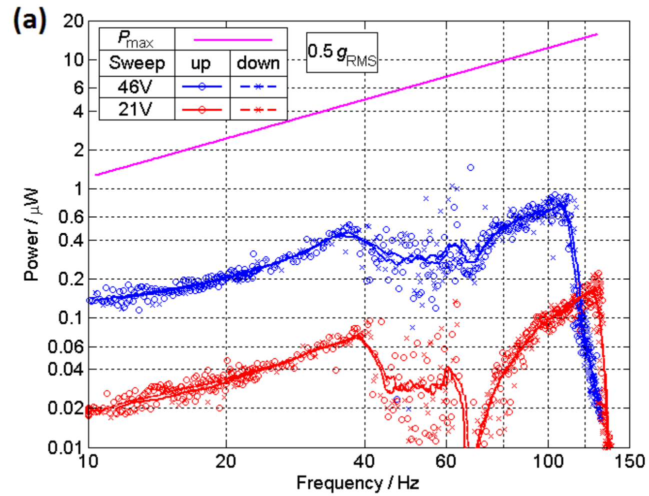
Low-frequency MEMS electrostatic VEH

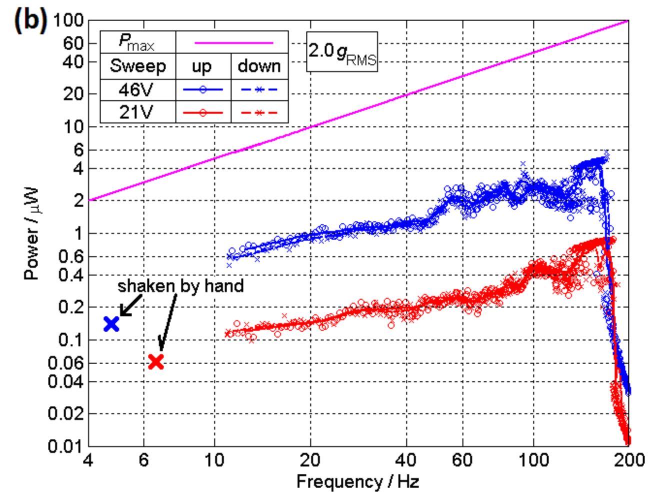
without micro-ball





with micro-ball





Y. Lu, F. Cottone, S. Boisseau, F. Marty, D. Galayko, and P. Basset, Appl. Phys. Lett. 2015.

Performance comparison

Vibration type	MEMS Direction	Accel. (gRMS)	Main input Freq. (Hz)	Vbias (V)	Power (uW)	Power Density (uW/cm3)
Man walking	X	0.39	4.15	20	1.34	13.40
Man walking	Y	0.27	2.1	20	0.793	7.93
Man walking	Z	0.41	2.44	20	1.15	11.50
Man running	Z	1.20	3.3	20	14.9	142.00

Table 2 Comparison of Effectiveness of Published Electrostatic Motion Harvesters

Author	Reference	Generator Volume [cm^3]	Proof Mass [g]	Input Amplitude [μm]	Input Frequency [Hz]	Z_l [μm]	Power (unprocessed) [μW]	Power (processed) [μW]	Power Density [$\mu W/cm^3$]	Harvester Effectiveness [%]	Volume Figure of Merit [%]
Tashiro	[104]		640	380	4.76	19000		58		0.09	
Tashiro	[142]	15	780	9000	6		36		2.42		0.02
Mizuno	[108]	0.6	0.7	0.64	743	4.9	7.4×10^{-6}		1.23×10^{-3}	6.6×10^{-6}	1.86×10^{-9}
Miyazaki	[143]		5	1	45	30		0.21		12.4	
Arakawa	[144]	0.4	0.65	1000	10	1000	6		15	7.42	0.68
Despesse	[145]	18	104	90	50	90	1760	1000	56	7.66	0.06
Yen	[146]				1500			1.8			
Tsutsumino	[147]			600	20	600	278				
Tsutsumino	[148]			1000	20	1000	6.4				
Mitcheson	[109]	0.6	0.12	1130	20	100	2.4		4	17.9	0.02

Almost 1 order of magnitude higher than average power density of previous works

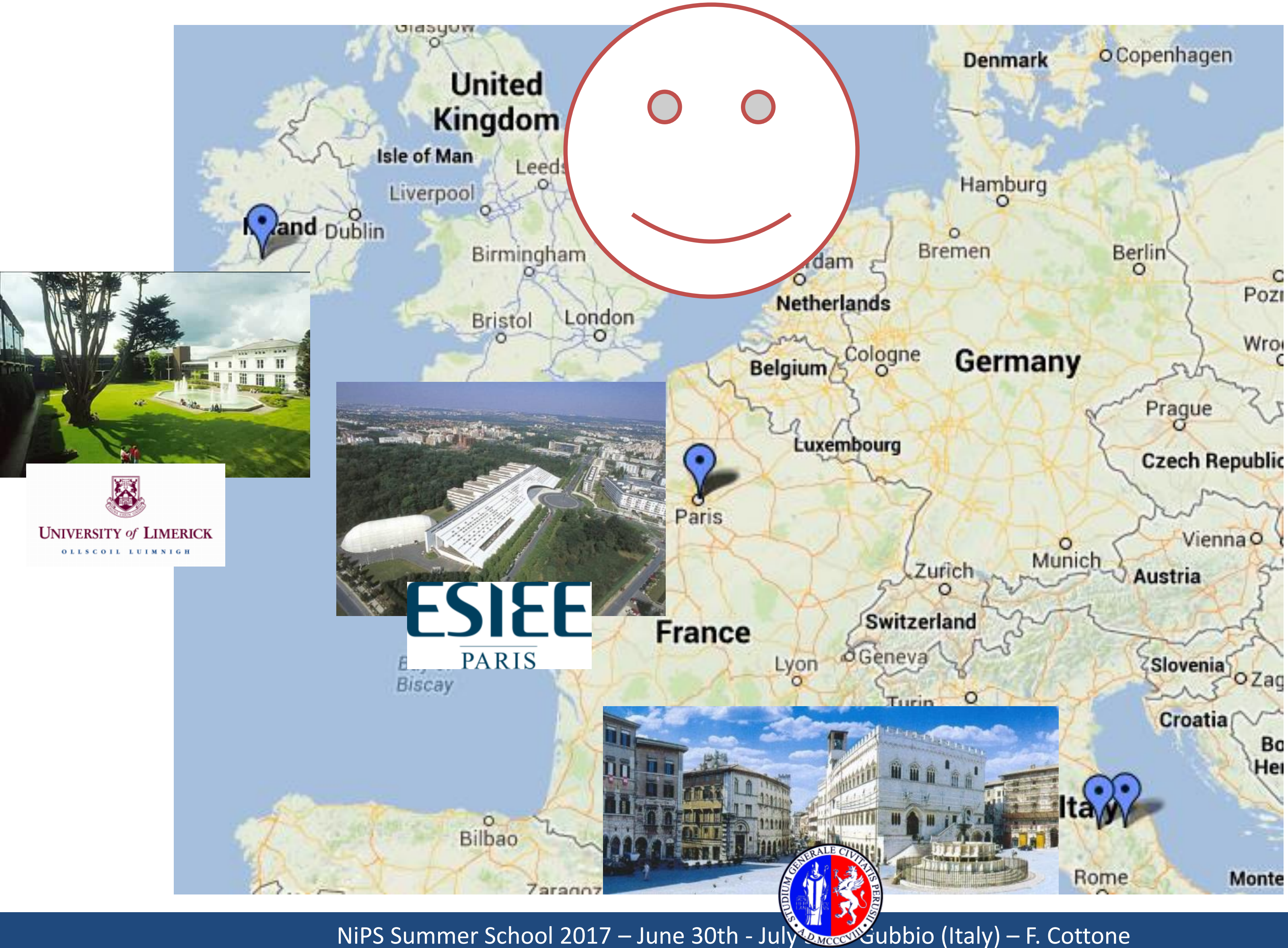
P. D. Mitcheson, et al, *Proceedings of the IEEE,* vol. 96, pp. 1457-1486, 2008.

Final considerations

- **Nonlinear energy vibration energy harvesters** are more efficient to capture energy from random noise or wideband vibrating sources than resonant ones. Many designs and concept have been presented:
  - Frequency up-conversion
  - Array resonators
  - Nonlinear stiffness oscillators
  - Bistable systems
  - Velocity amplification by collisions sequence

- Combination of previous techniques can increase the efficiency of miniature VEHs.
  - Examples of bistabel piezoelectric , velocity amplified and MEMS e-VEH have given.

Thank you!


United Kingdom
Isle of Man
Leeds
Liverpool
Dublin
Birmingham
Bristol
London
Denmark
Copenhagen
Hamburg
Bremen
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Belgium
Cologne
Germany
Prague
Czech Republic
Luxembourg
Paris
France
Vienna
Munich
Zurich
Austria
Switzerland
Geneva
Lyon
Slovenia
Croatia
Biscay
Bilbao
Rome
UNIVERSITY of LIMERICK
OLLSCOIL LUIMNIGH
ESIEE
PARIS