Introduction to Vibration Energy Harvesting

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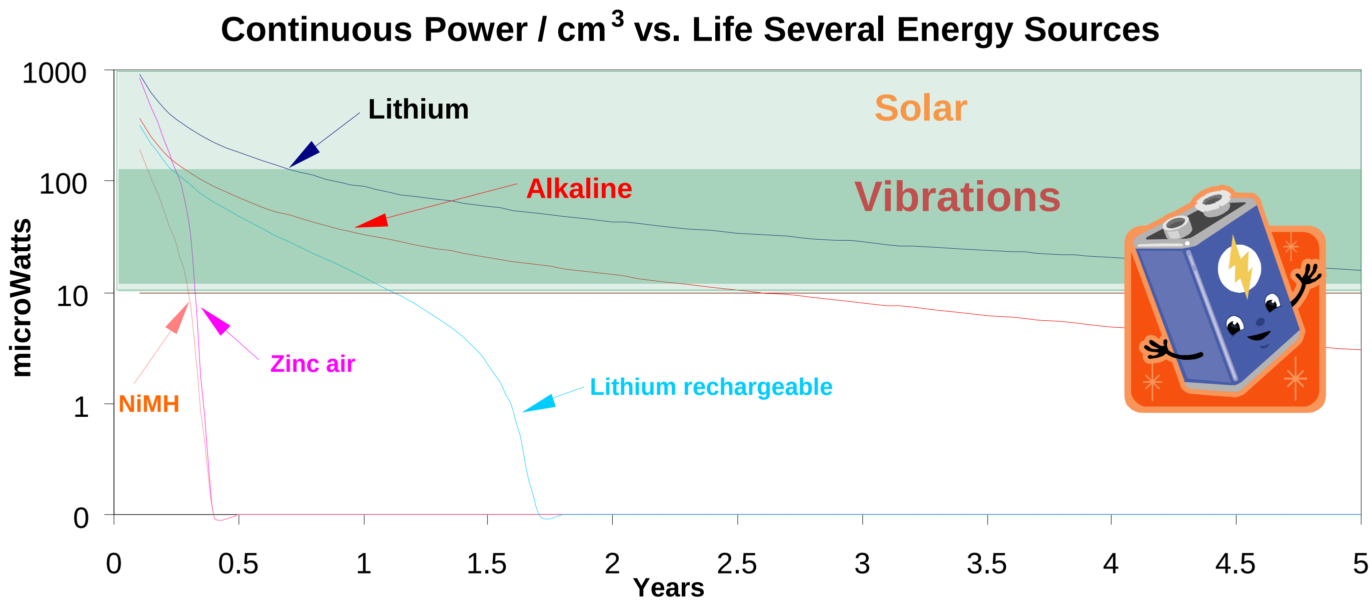
Francesco Cottone

Physics Dep., Università di Perugia
francesco.cottone@pg.infn.it

Summary

- Why vibration energy harvesting ?
- Potential applications
- Vibration-to-electricity conversion principles
- Performance metrics
- Technical challenges and limits
- Conclusions

Energy harvesting: an alternative to batteries?



S. Roundy, 2005. Berkley University

Batteries power density and lifespan are not unlimited !

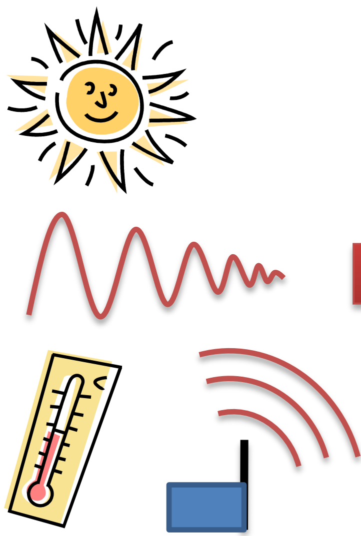
Can we replace or extend battery life?

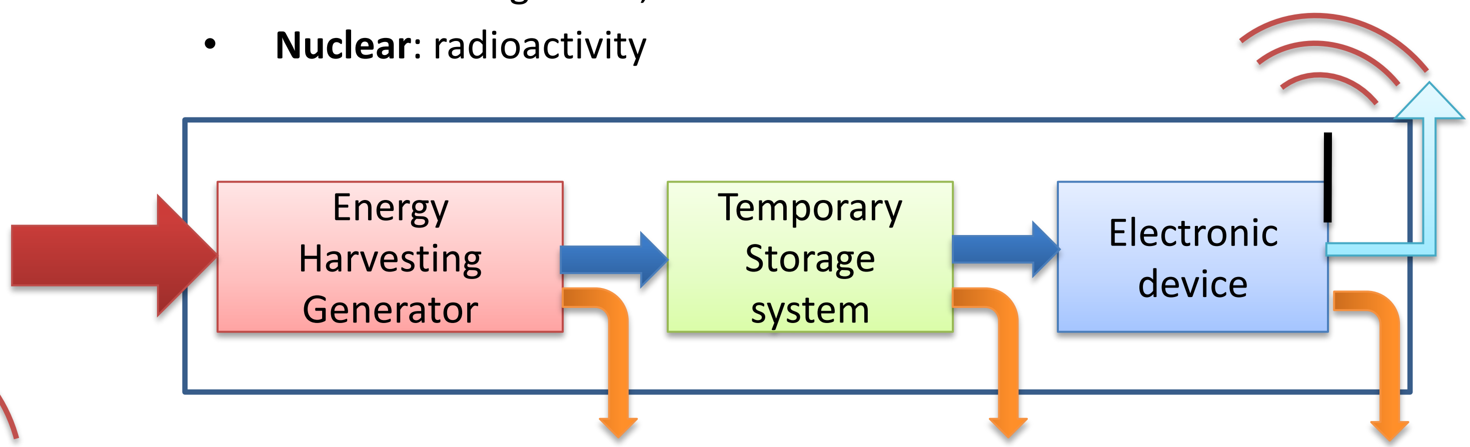
What about disposal problem?

Energy harvesting: an alternative to batteries?

Power sources available from the ambient

- **Electromagnetic**: Light , Infrared, Radio Frequencies
- **Kinetic**: vibrations, machinery vibrations, human motion, wind, hydro
- **Thermal**: temperature gradients
- **Biochemical**: glucose, metabolic reactions
- **Nuclear**: radioactivity





- **Piezoelectric**
- **Electrodynamics**
- Photovoltaic
- Thermoelectric

- Ultra capacitors
- Rechargeable Batteries

- Low power devices
- Wireless Sensors
- MEMS actuators
- Consumer electronics

Available power from various sources

Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	100 mW/cm^2 100 μW/cm^2
Thermal	Human Industrial	~0.1% ~3%	60 μW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 μW/cm^3 ~800 μW/cm^3
RF	GSM 900 MHz WiFi	~50%	0.1 μW/cm^2 0.001 μW/cm^2

Texas Instruments, Energy Harvesting – White paper 2009

An average human walking up a mountain expends around 200 Watts of power.

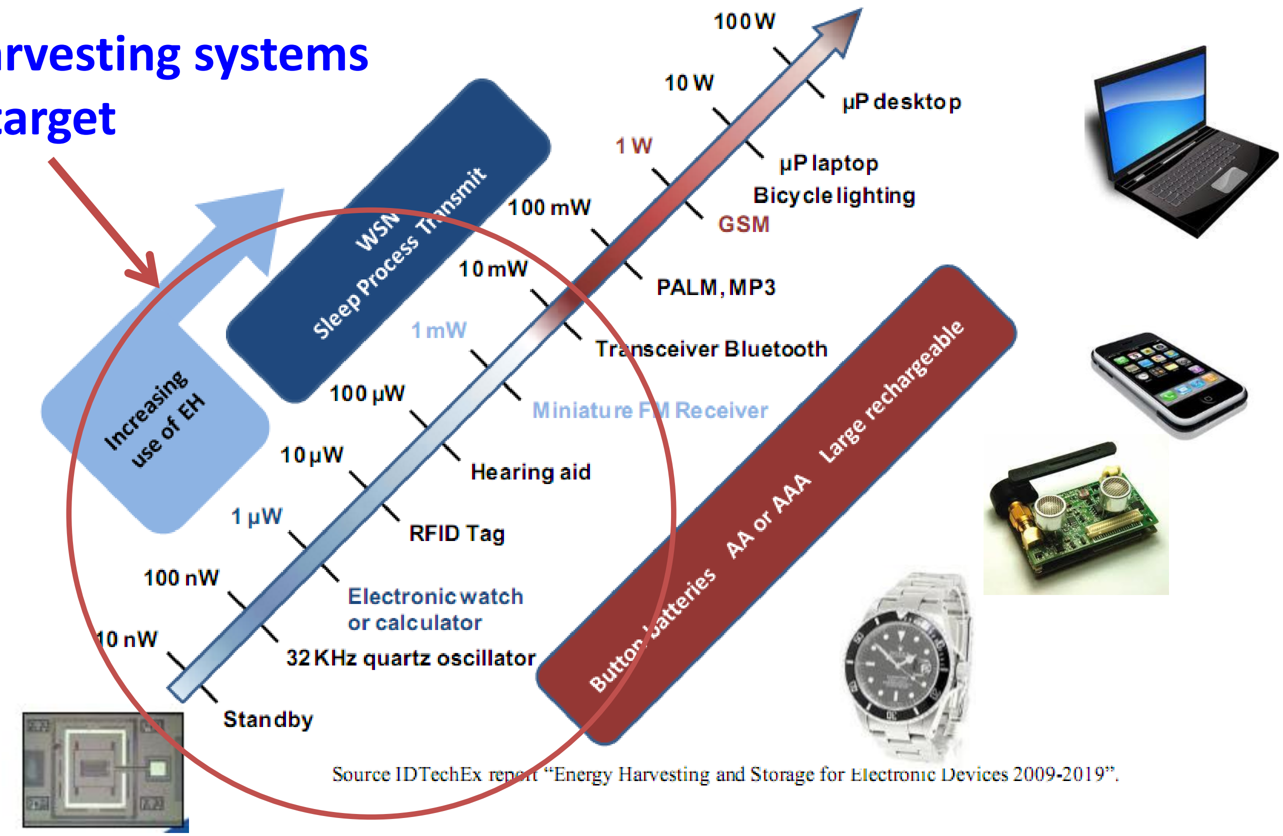
The most amount of power your iPhone accepts when charging is 2.5 Watts.

Energy harvester as partner of batteries to extend their lifespan !!

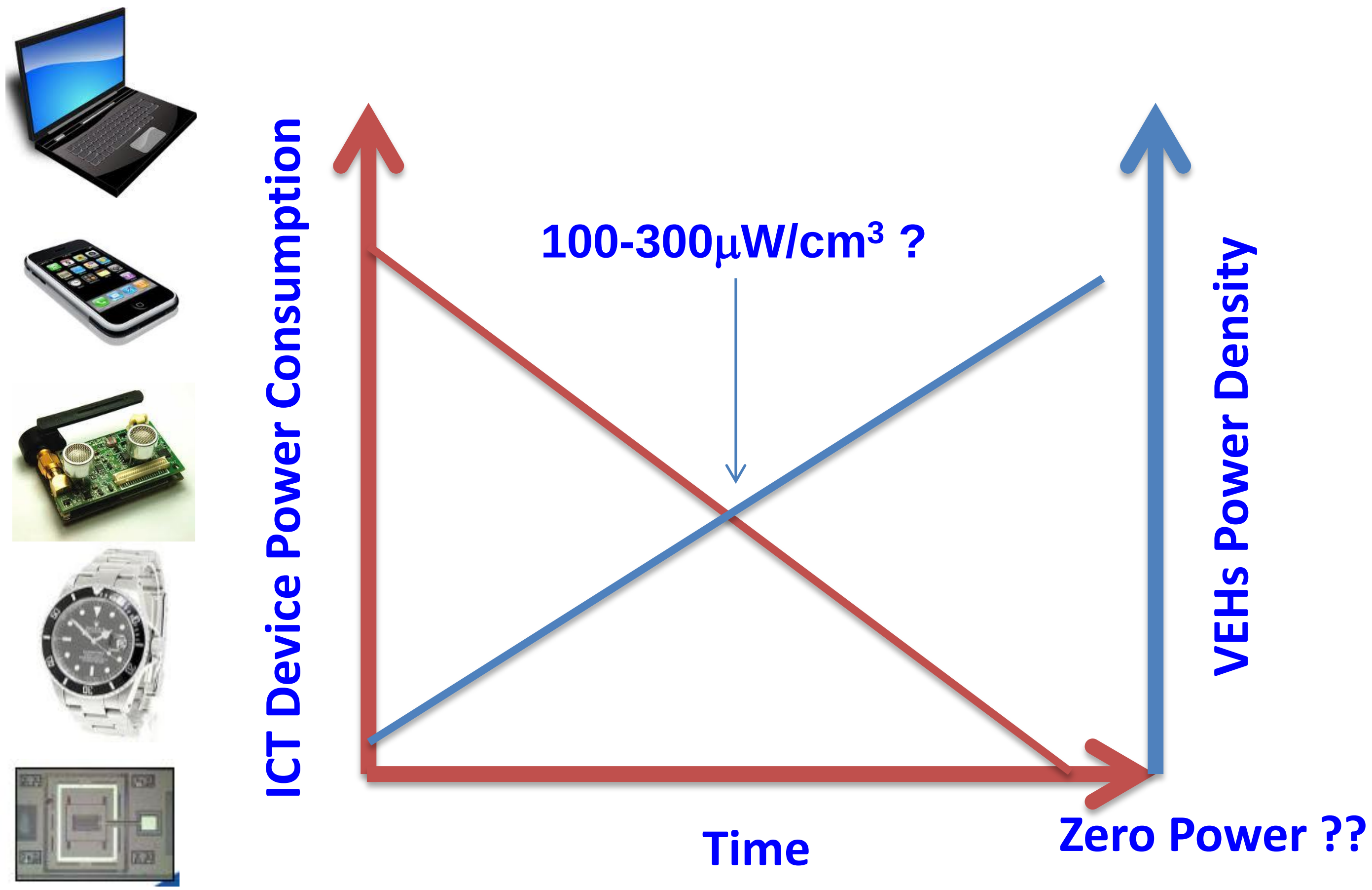
Brother Industries 2010

Vibration energy harvesting versus power requirements

Vibration harvesting systems target



Vibration energy harvesting versus power requirements



Applications of energy harvesting

Wireless Sensor Networks

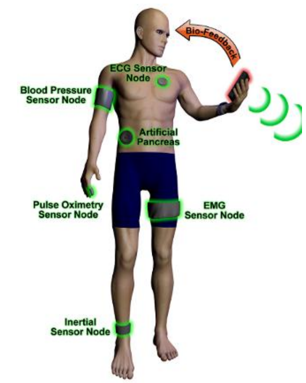
Environmental Monitoring

Habitat Monitoring (light, temperature, humidity)
Integrated Biology

Structural Monitoring

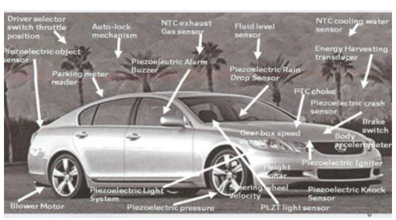
Medical remote sensing

Emergency medical response
Monitoring, pacemaker, defibrillators



Interactive and Control

RFID, Real Time Locator, TAGS
Building, Automation
Transport Tracking, Cars sensors



Military applications and Aerospace

Surveillance

Pursuer-Evader
Intrusion Detection
Interactive museum

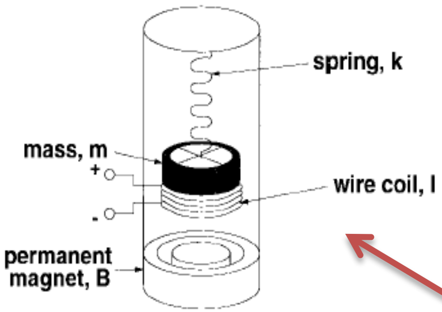
Almost 90% of WSNs applications cannot be enabled without Energy Harvesting technologies that allow self-powering features

What advantages with EH systems ?

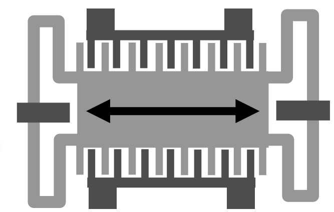
- Long lasting operability
- No chemical disposal
- Cost saving
- Safety
- Maintenance free
- No charging points
- Inaccessible sites operability
- Flexibility
- Applications otherwise impossible

Vibration Energy Harvesters (VEHs): basic principles

Electromagnetic

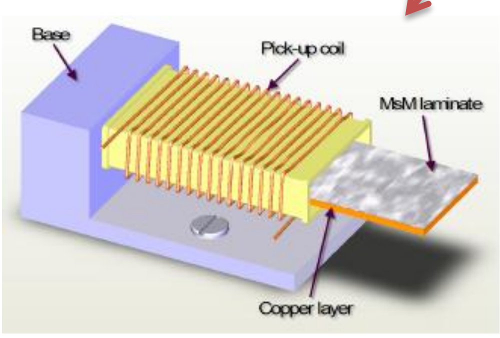


Electrostatic/Capacitive



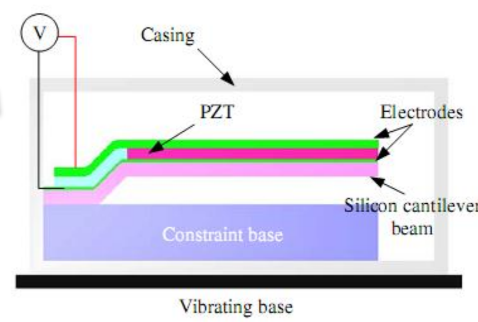
Vibration Harvesting Generator

Magnetostrictive



Ferromagnetic materials: crystalline alloy Terfenol-D amorphous metallic glass Metglas ($Fe_8B_{13.5}Si_{3.5}C_2$).

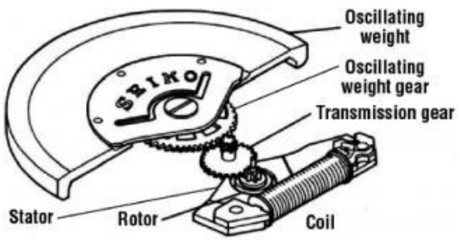
Piezoelectric



Ferroelectric materials: PZT, PVDF, AIN

Motion-driven powering applications

Past → **Present** → **Future**

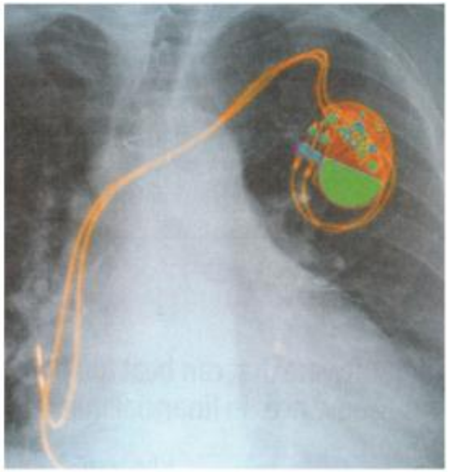


Self-charging Seiko wristwatch

Battery-less wireless sensing (Perpetuum)

- WSN Vibration, Temperature, Air pollution monitoring
- Cargo monitoring and tracking
- Wireless bridge monitoring

Swinburne University, Australia, 2009



University of Southampton
electrodynamic energy harvesting to run pacemaker and defibrillator

- Medical implantations
- Medical remote sensing
- Body Area Network

Emerging commercial applications

http://www.youtube.com/watch?v=CfnyJ0_XarI

STEALING or HARVESTING ENERGY ??

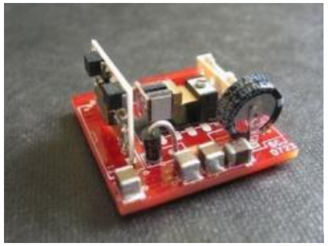
Example of macro-millimetric generators

Electrodynamic

Perpetuum PMG17 (England)

Up to 45mW @ 1g rms (15Hz)

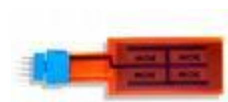
nPower® PEG



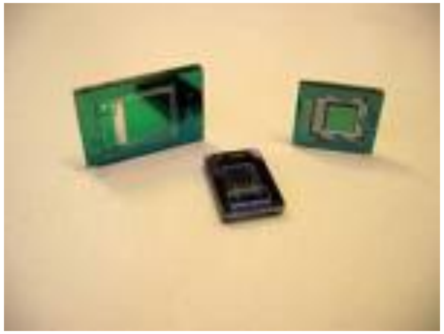
Micro-electromagnetic generator
S. Beeby 2007, (UK)

Piezoelectric

Mide' Volture (USA)
5mW @ 1grms (50Hz)



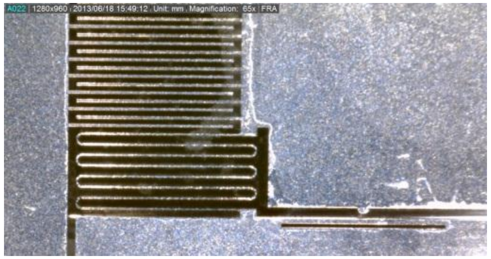
Holst-IMEC (Germany)
Micro PZ generator 500Hz
60uW @ 1g



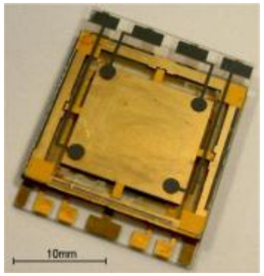
- include tire pressure monitoring systems (TPMS)
- monitoring of industrial equipment

Electrostatic/Capacitive

ESIEE Paris – F. Cottone 2013



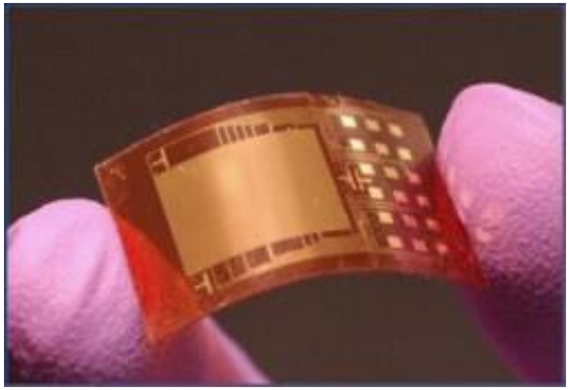
Electrostatic generator 15Hz
1uW @ 0.2g



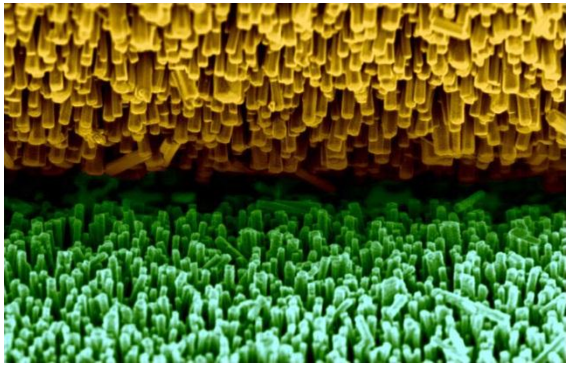
Imperial College,
Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g

State of the art: micro- to nano- generators

zinc oxide (ZnO) nanowires

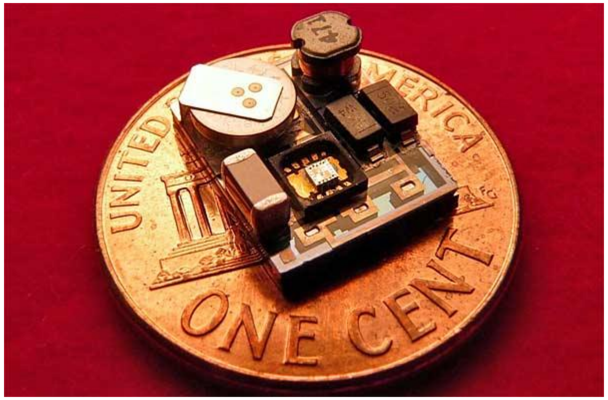


Zhong Lin Wang, Ph.D., Georgia Institute of Technology.



Nanogenerators ZnO nanotubes

200 microwatts at 1.5g vibration @150Hz and charge an ultracapacitor to 1.85 volts.



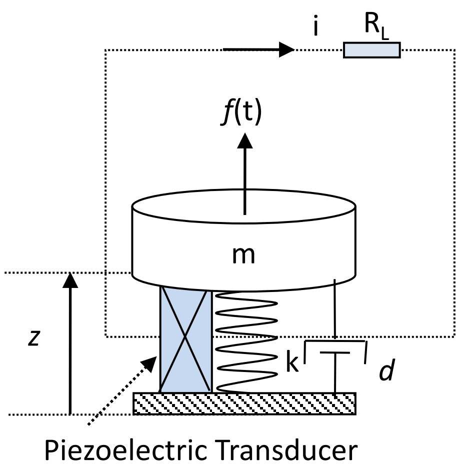
University of Michigan (USA)

energy harvester attached to *Manduca Sexta*.
Courtesy of WM Tsang, MIT.

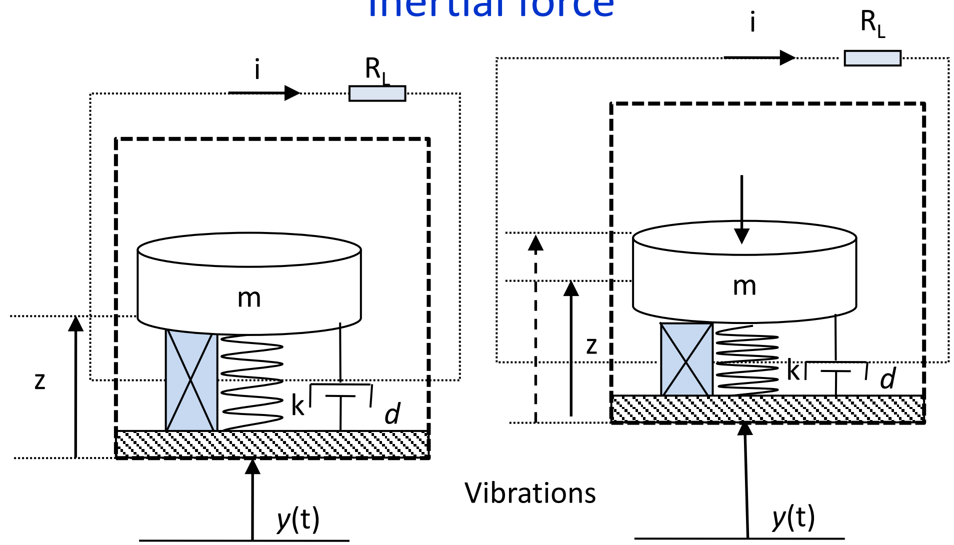
Energy harvesting from moth vibrations
Chang. MIT 2013

Vibration Energy Harvesters (VEHs): basic operating principles

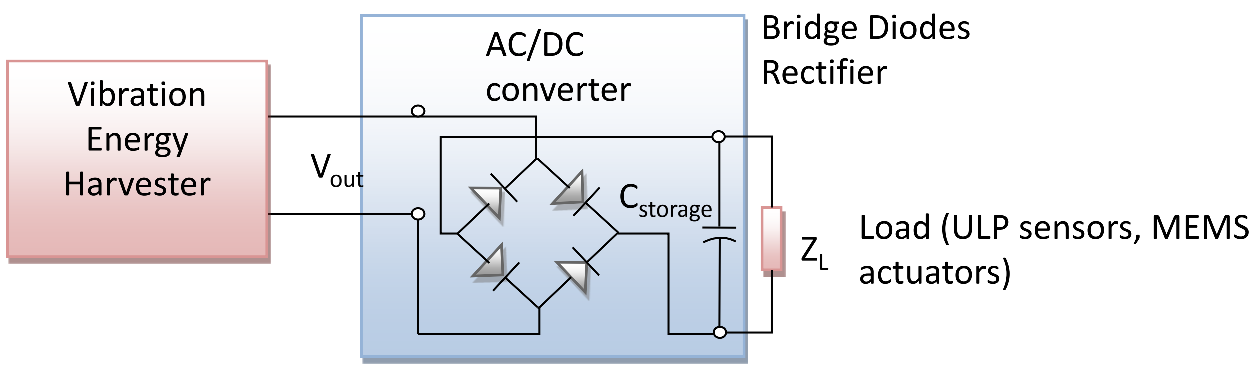
Direct force



Inertial force

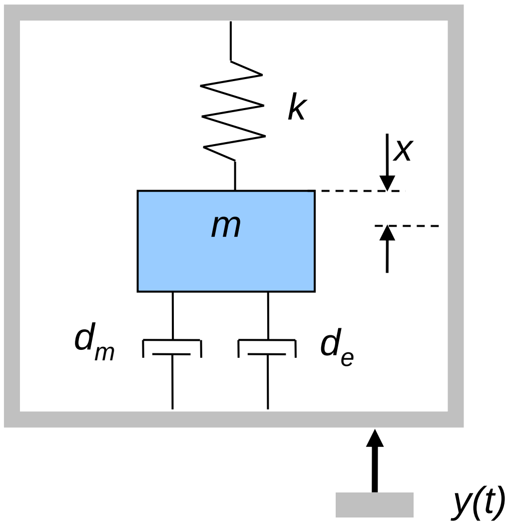


Inertial generators are more flexible than direct-force devices because they require only one point of attachment to a moving structure, allowing a greater degree of miniaturization.



Vibration Energy Harvesters (VEHs): basic operating principles

1-DOF generic mechanical-to-electrical conversion model [William & Yates]



Motion equation

$$m\ddot{x}(t)+(d_m+d_e)\dot{x}(t)+kx(t)=-m\ddot{y}(t)$$

Inertial force

$$f(t)=-m\ddot{y}=Y_0\sin(\omega t)$$

setting $d_T=d_m+d_e$ the total damping coefficient and taking the Laplace transformation of the motion equation

$$(ms^2+d_Ts+k)X(s)=-ms^2Y_0(s)$$

Rearranging yields the transfer function with $s=j\omega$

$$H_{xf}(\omega)=\frac{X(\omega)}{Y(\omega)}=\frac{-ms^2}{ms^2+d_Ts+k}=\frac{\omega^2}{\left(\omega_n^2-\omega^2\right)+2(\zeta_e+\zeta_m)\omega_n\omega j}$$

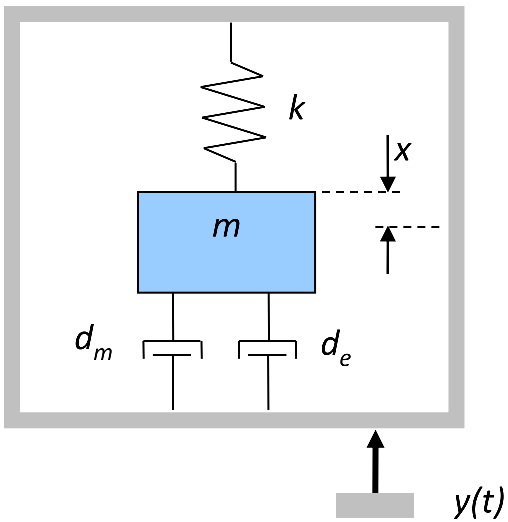
with the natural frequency $\omega_n=\sqrt{k/m}$ and the normalized damping factor $\zeta_T=d_T/2m\omega_n$

By introducing the frequency ratio $r=\omega/\omega_n$ the transfer function becomes

$$H_{xf}(r,\zeta)=\frac{r^2}{(1-r^2)+2\zeta rj}$$

Vibration Energy Harvesters (VEHs): basic operating principles

1-DOF generic mechanical-to-electrical conversion model [William & Yates]



For harmonic Inertial force $f(t) = -m\ddot{y} = Y_0 \sin(\omega t)$

The steady state solution in frequency domain results

$$X = \frac{m\omega^2 Y}{\sqrt{\left(k - m\omega^2\right)^2 + \left(d_e + d_m\right)^2 \omega^2}} = \frac{r^2 Y}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}},$$

The steady state solution in time domain is

$$x(t) = \frac{\omega^2}{\sqrt{\left(\omega_n^2 - \omega^2\right)^2 + \left(\frac{(d_e + d_m)\omega}{m}\right)^2}} Y_0 \sin(\omega t - \phi)$$

the phase angle ϕ is given by $\phi = \tan^{-1}\left(\frac{d_T \omega}{k - m\omega^2}\right)$

In case the input vibration is not harmonic the same solution can be applied as long as the excitation function can be represented as a Fourier series of harmonic functions.

Vibration Energy Harvesters (VEHs): basic operating principles

First order power calculus

The instantaneous dissipated power by electrical damping is given by

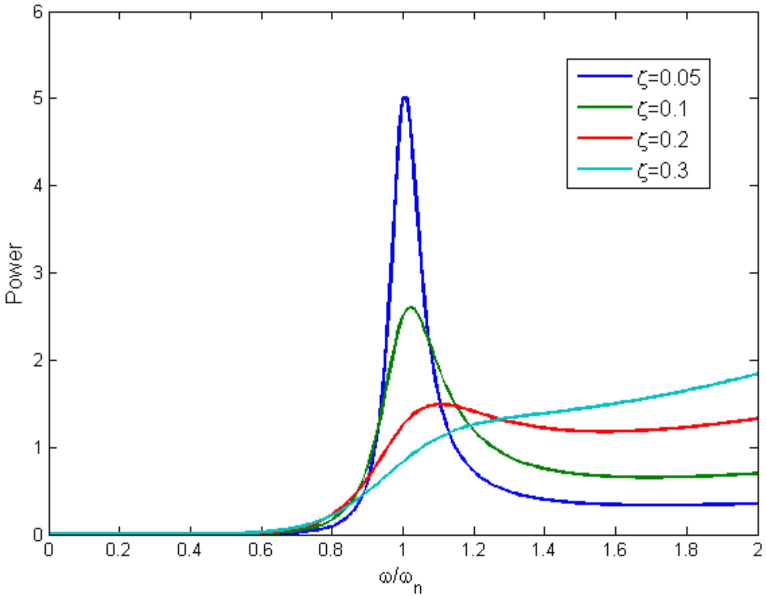
$$P(t) = \frac{d}{dt}\int_0^x F(t)dx = \frac{1}{2} d_T \dot{x}^2$$

The velocity is obtained by the first derivative of steady state amplitude

$$\dot{X} = \frac{\omega r^2 Y}{\sqrt{(1-r^2)^2 + (2(\zeta_e + \zeta_m)r)^2}},$$

that is

$$P_e = \frac{m\zeta_e \left(\frac{\omega}{\omega_n}\right)^3 \omega^3 Y_0^{\ 2}}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2(\zeta_e + \zeta_m)\frac{\omega}{\omega_n}\right]^2}$$



At resonance, that is $\omega = \omega_n$, the maximum power is given by

$$P_e = \frac{m\zeta_e \omega_n^3 Y_0^{\ 2}}{4(\zeta_e + \zeta_m)^2} = \frac{m^2 d_e \omega_n^4 Y^2}{2(d_e + d_m)^2}$$

or with acceleration amplitude $A_0 = \omega_n^{\ 2} Y_0$.

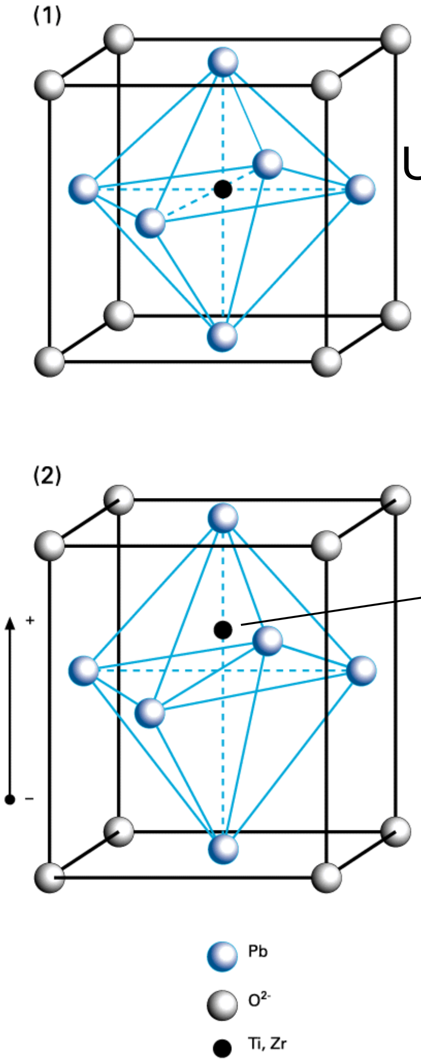
for a particular transduction mechanism forced at natural frequency ω_n, the power can be maximized from the equation

$$P_{el} = \frac{m\zeta_e A^2}{4\omega_n(\zeta_m + \zeta_e)^2}$$

Max power when the condition $\zeta_e = \zeta_m$ is verified

Piezoelectric conversion

Piezoelectric materials

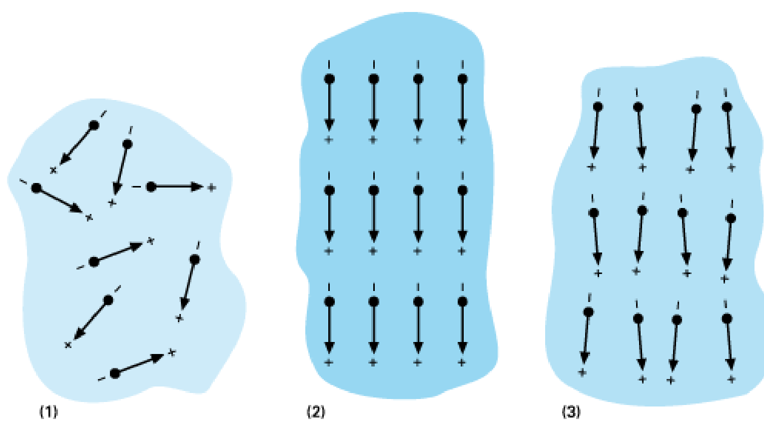


Unpolarized Crystal

Polarized Crystal

Pioneering work on the direct piezoelectric effect (stress-charge) in this material was presented by Jacques and Pierre Curie in 1880

In 1903 Pierre received the Nobel Prize in Physics with his wife, Marie Skłodowska-Curieand and Henri Becquerel, for the research on the radiation phenomena discovered by Professor Henri Becquerel.

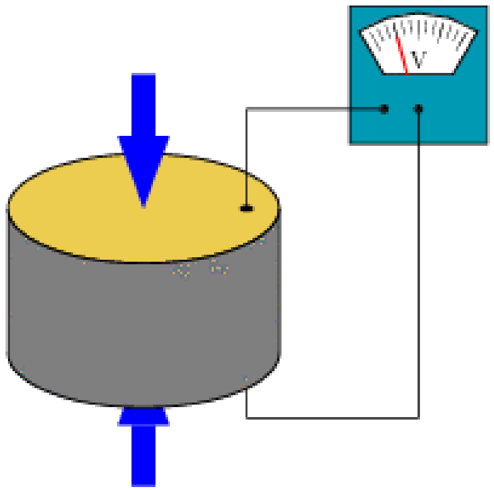


After poling the zirconate-titanate atoms are off center. The molecule becomes elongated and polarized

Piezoelectric conversion

Piezoelectric materials

Stress-to-charge conversion



direct piezoelectric effect

Biological

- Bones
- DNA !!!

Naturally-occurring crystals

- Berlinite ($AlPO_4$), a rare phosphate mineral that is structurally identical to quartz
- Cane sugar
- Quartz (SiO_2)
- Rochelle salt

Man-made ceramics

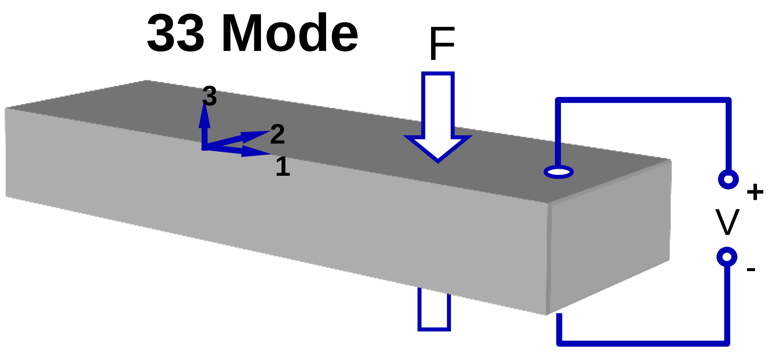
- Barium titanate ($BaTiO_3$)—Barium titanate was the first piezoelectric ceramic discovered.
- Lead titanate ($PbTiO_3$)
- Lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$ $0 \leq x \leq 1$)—more commonly known as ***PZT***, lead zirconate titanate is the most common piezoelectric ceramic in use today.
- Lithium niobate ($LiNbO_3$)

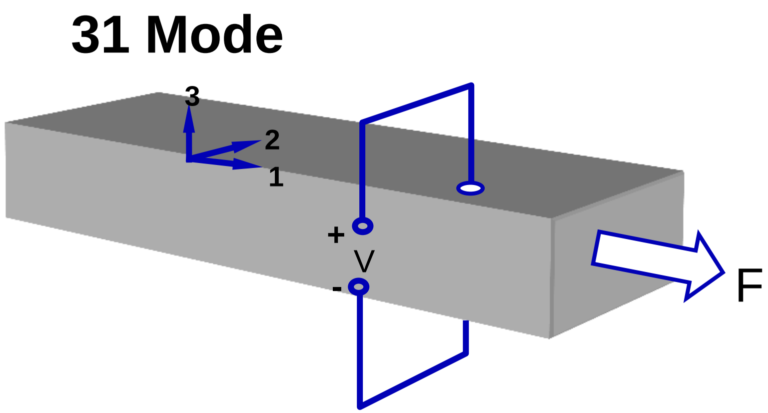
Polymers

- Polyvinylidene fluoride (PVDF): exhibits piezoelectricity several times greater than quartz. Unlike ceramics, long-chain molecules attract and repel each other when an electric field is applied.

Piezoelectric conversion

Costitutive equations





$$S = [s_E]T + [d^t]E$$
$$D = [d]T + [\varepsilon_T]E$$

Strain-charge

$$T = [c^E]S - [e^t]E$$
$$D = [e]S + [\varepsilon^S]E$$

Stress-charge

- S = strain vector (6x1) in Voigt notation
- T = stress vector (6x1) [N/m^2]
- s_E = compliance matrix (6x6) [m^2/N]
- c^E = stifness matrix (6x6) [N/m^2]
- d = piezoelectric coupling matrix (3x6) in Strain-Charge [C/N]
- D = electrical displacement (3x1) [C/m^2]
- e = piezoelectric coupling matrix (3x6) in Stress-Charge [C/m^2]
- ε = electric permittivity (3x3) [F/m]
- E = electric field vector (3x1) [N/C] or [V/m]

Piezoelectric conversion

Costitutive equations

converse piezoelectric effect

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

direct piezoelectric effect

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Depending on the independent variable choice 4 piezoelectric coefficients are defined:

$$d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)^E = \left(\frac{\partial S_j}{\partial E_i}\right)^T$$

$$e_{ij} = \left(\frac{\partial D_i}{\partial S_j}\right)^E = -\left(\frac{\partial T_j}{\partial E_i}\right)^S$$

$$g_{ij} = -\left(\frac{\partial E_i}{\partial T_j}\right)^D = \left(\frac{\partial S_j}{\partial D_i}\right)^T$$

$$h_{ij} = -\left(\frac{\partial E_i}{\partial S_j}\right)^D = -\left(\frac{\partial T_j}{\partial D_i}\right)^S$$

Voigt notation is used to represent a symmetric tensor by reducing its order.
Due to the symmetry of the stress tensor, strain tensor, and stiffness tensor, only 21 elastic coefficients are independent. *S* and *T* appear to have the "vector form" of 6 components. Consequently, *s* appears to be a 6 by 6 matrix instead of rank-4 tensor.

Piezoelectric conversion

Material properties example

Property	PZT-5H	PZT-5A	$BaTiO_3$	PVDF
d_{33} $(10^{-12}\ \mathrm{C\ N^{-1}})$	593	374	149	−33
d_{31} $(10^{-12}\ \mathrm{C\ N^{-1}})$	−274	−171	78	23
g_{33} $(10^{-3}\ \mathrm{V\ m\ N^{-1}})$	19.7	24.8	14.1	330
g_{31} $(10^{-3}\ \mathrm{V\ m\ N^{-1}})$	−9.1	−11.4	5	216
k_{33}	0.75	0.71	0.48	0.15
k_{31}	0.39	0.31	0.21	0.12
Relative permittivity $(\varepsilon/\varepsilon_o)$	3400	1700	1700	12

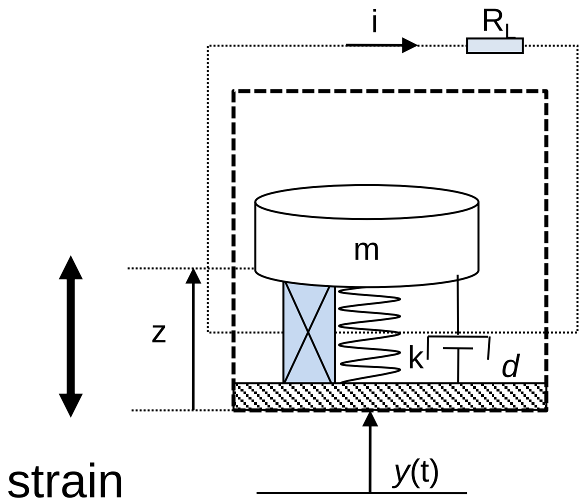
Electromechanical Coupling is a non-dimensional factor defined as the ratio between the mechanical energy converted and the electric energy input or the electric energy converted per mechanical energy input

$$k_{31}^2 = \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}$$

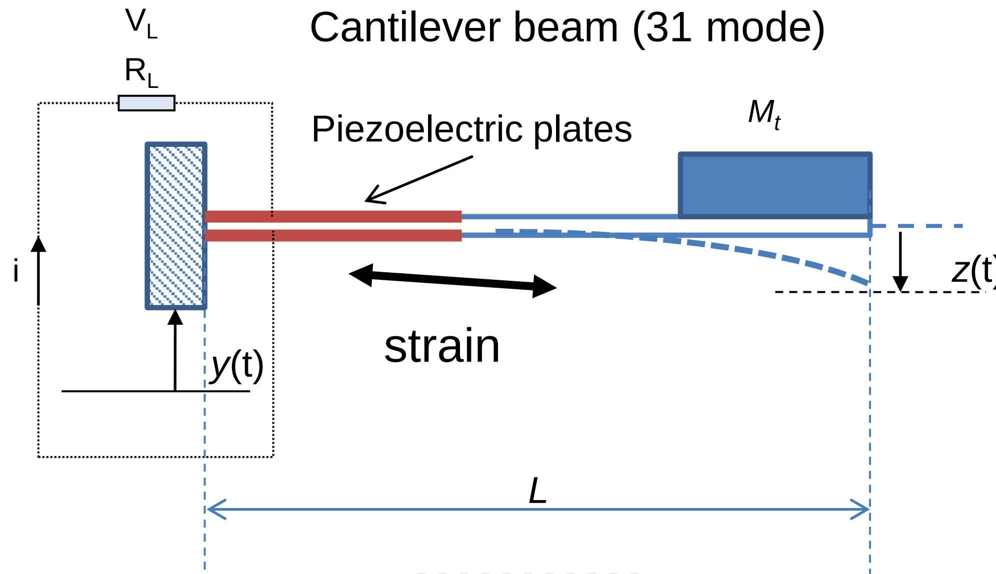
Piezoelectric conversion

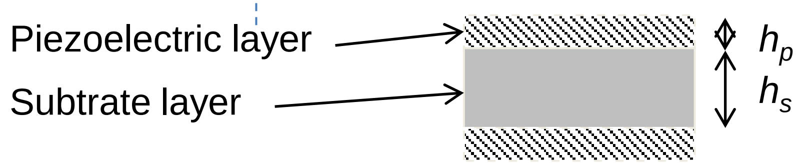
Mechanical-to-electrical conversion models

Piezoelctric bulk (33 mode)

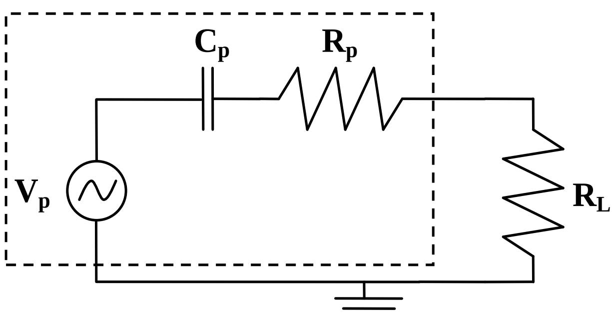


Cantilever beam (31 mode)





Piezoelectric generator



At open circuit $$V_{oc} = -\frac{d_{31} \cdot h}{\varepsilon^S} T_1$$

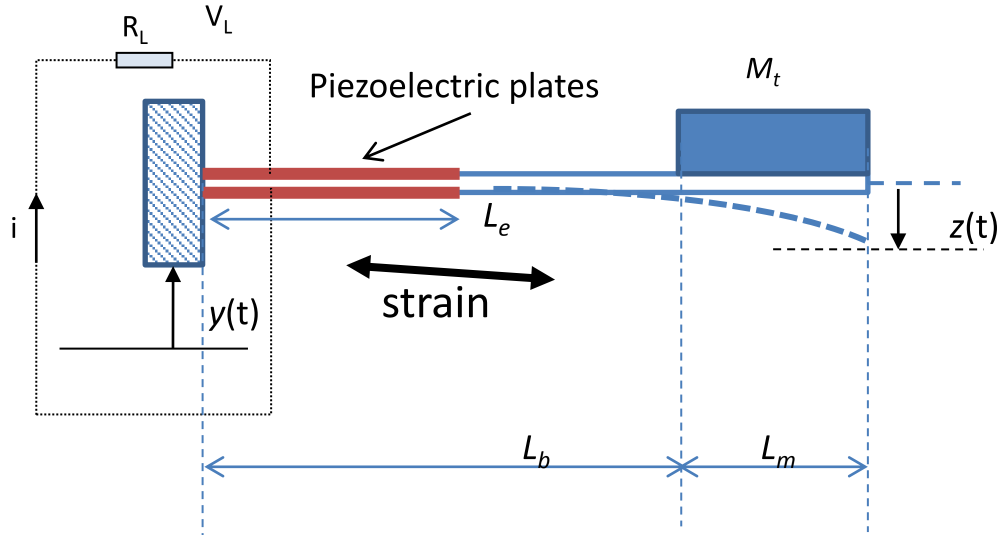
The instantaneous power delivered to the load is simply $$P = \frac{V_{rms}^2}{R_L}$$

S. Roundy, Energy scavenging for wireless sensor networks, Kluwer

Piezoelectric conversion

Mechanical-to-electrical conversion models

Cantilever beam (31 mode)



$$T_1 = c_{11}^E S_1 - e_{31} E_3,$$

$$D_3 = e_{31} S_1 + \varepsilon_{33}^S E_3,$$

$$\begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + \omega_c V_L = \delta_c \dot{z} \end{cases}$$

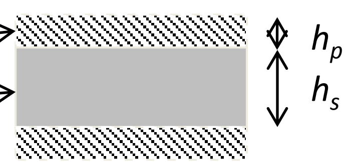
$$\alpha = K_{eff} d_{31} a / 2 h_p k_2$$

$$\delta_c = \left(h_p d_{31} E_p k_2 / \varepsilon_0 \varepsilon_r \right) R_L = \alpha R_L$$

$$\omega_c = 1 / R_L C_p$$

Piezoelectric layer

Subtrate layer



Ep and Es are the Young's modulus of piezo layer and steel substrate respectively

$$k_1 = \frac{2I}{b(2l_b + l_m - l_e)}$$

Average strain to vertical displacement

$$k_2 = \frac{3b(2l_b + l_m - l_e)}{l_b^2 \left(2l_b + \frac{3}{2} l_m \right)}$$

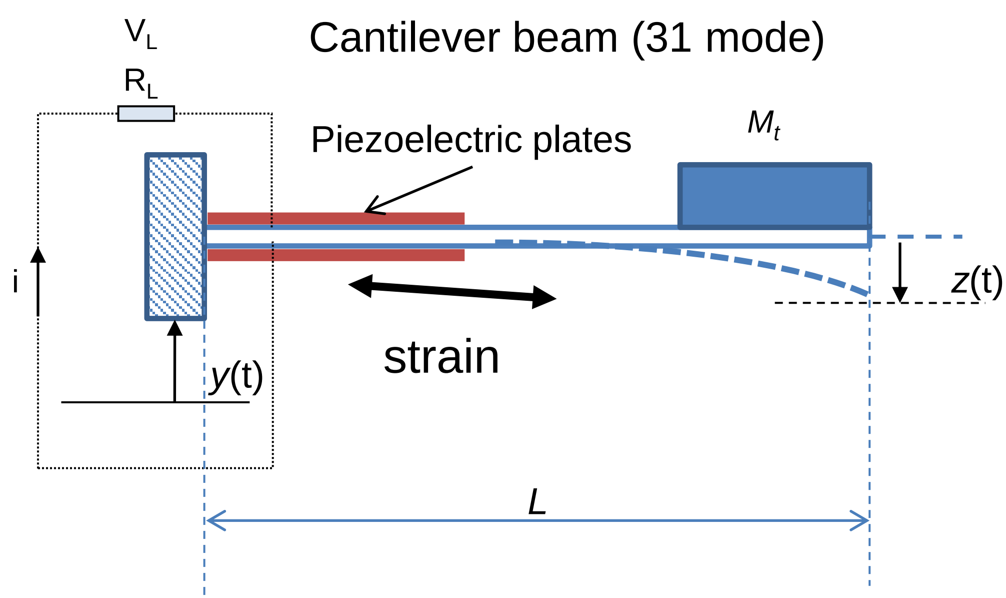
Input force to average induced stress

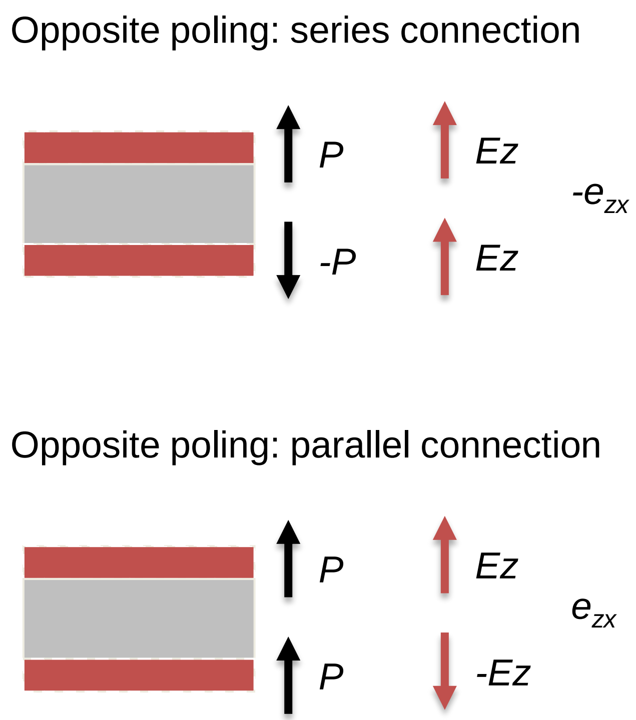
$$b = \frac{h_s}{2} + \frac{h_p}{2}$$

$$I = 2\left[\frac{w_b h_p^3}{12} + w_b h_p b^2 \right] + \frac{E_s / E_p w_b h_s^3}{12}$$

Piezoelectric conversion

Mechanical-to-electrical conversion models





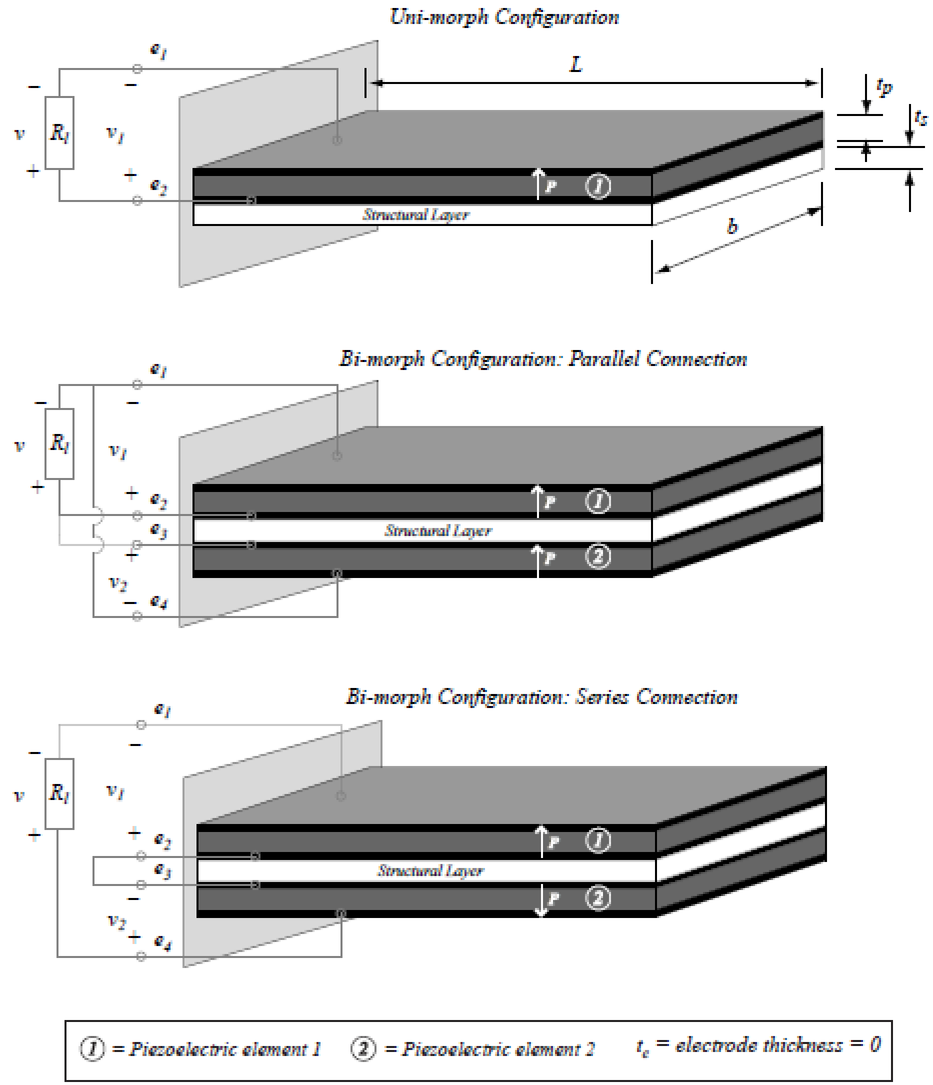


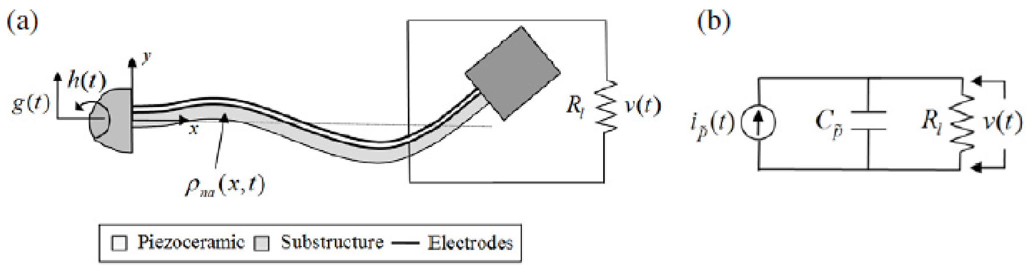
Figure C-1: Series and parallel connections for {3-1} cantilevered harvesters: (*top*) uni-morph configuration, (*middle*) bi-morph configuration with parallel connection, and (*bottom*) bi-morph configuration with series connection.

Du Toit MS thesis

Piezoelectric conversion

Coupled distributed parameter model for cantilever beam VEH

[Erturk and Inmann (2008)]



$$T_1 = c_{11}^E S_1 - e_{31} E_3,$$

$$D_3 = e_{31} S_1 + \varepsilon_{33}^S E_3,$$

Free vibration of the cantilever beam is governed by

$$\frac{\partial^2 M(x,t)}{\partial x^2} + c_s I \frac{\partial^5 w_{rel}(x,t)}{\partial x^4 \partial t} + c_a \frac{\partial w_{rel}(x,t)}{\partial t} + m \frac{\partial^2 w_{rel}(x,t)}{\partial t^2} = -[m + M_t \delta(x - L)] \frac{\partial^2 w_b(x,t)}{\partial t^2}$$

Internal strain rate (Kelvin Voigt) damping term

Air viscous damping

The absolute transverse motion of the beam at any point *x* and time *t* can be written as

$$w(x,t) = w_b(x,t) + w_{rel}(x,t)$$

$$w_b(x,t) = g(t) + x h(t)$$

The internal bending is

$$M(x,t) = -b\left(\int_{-h_{\bar{p}}-h_{\bar{s}}/2}^{-h_{\bar{s}}/2} T_1^{\bar{p}} y \, dy + \int_{-h_{\bar{s}}/2}^{h_{\bar{s}}/2} T_1^{\bar{s}} y \, dy + \int_{h_{\bar{s}}/2}^{h_{\bar{p}}+h_{\bar{s}}/2} T_1^{\bar{p}} y \, dy\right)$$

The axial strain at a certain is simply proportional to the curvature of the beam at that position (x):

$$S_1(x,y,t) = -y \frac{\partial^2 w_{rel}(x,t)}{\partial x^2}.$$

Erturk, A. and D. J. Inman (2008). "A distributed parameter electromechanical model for cantilevered piezoelectric energy harvesters." Journal of vibration and acoustics **130**

Piezoelectric conversion

Coupled distribuited parameter model for cantilever beam VEH

[Erturk and Inmann (2008)]

the coupled beam equation can be obtained for the series connection

$$YI\frac{\partial^4 w_{\mathrm{rel}}^{\mathrm{s}}(x,t)}{\partial x^4} + c_{\mathrm{s}}I\frac{\partial^5 w_{\mathrm{rel}}^{\mathrm{s}}(x,t)}{\partial x^4 \partial t} + c_{\mathrm{a}}\frac{\partial w_{\mathrm{rel}}^{\mathrm{s}}(x,t)}{\partial t} + m\frac{\partial^2 w_{\mathrm{rel}}^{\mathrm{s}}(x,t)}{\partial t^2} + \vartheta_{\mathrm{s}} v_{\mathrm{s}}(t)\left[\frac{\mathrm{d}\delta(x)}{\mathrm{d}x} - \frac{\mathrm{d}\delta(x-L)}{\mathrm{d}x}\right]$$
$$= -[m + M_{\mathrm{t}}\delta(x-L)]\frac{\partial^2 w_{\mathrm{b}}(x,t)}{\partial t^2}$$

vibration response relative to the base can be expressed by using the modal expansion theorem

$$w_{\mathrm{rel}}^{\mathrm{s}}(x,t) = \sum_{r=1}^{\infty}\phi_r(x)\eta_r^{\mathrm{s}}(t),$$

With mass normalized eigenfunctions $\phi_r(x) = C_r\left[\cos\frac{\lambda_r}{L}x - \cosh\frac{\lambda_r}{L}x + \varsigma_r\left(\sin\frac{\lambda_r}{L}x - \sinh\frac{\lambda_r}{L}x\right)\right]$ with eigenvalues λ_r

modal amplitude Cr and eigenvalues λ_r
are evaluated by normalizing the eigenfunctions according to the orthogonality and bonduary conditions

the undamped natural frequency of the *r* th vibration mode in short circuit

$$\omega_r = \lambda_r^2\sqrt{\frac{YI}{mL^4}}$$

the electric current output is then obtained from the Gauss law

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\int_A \mathbf{D}\cdot\mathbf{n}\,\mathrm{d}A\right) = \frac{v(t)}{R_{\mathrm{l}}} \quad\Rightarrow\quad \frac{\bar{\varepsilon}_{33}^S bL}{h_{\tilde{\mathrm{p}}}}\frac{\mathrm{d}v(t)}{\mathrm{d}t} + \frac{v(t)}{R_{\mathrm{l}}} = -\bar{e}_{31}h_{\tilde{\mathrm{p}}\mathrm{c}}b\int_0^L \frac{\partial^3 w_{\mathrm{rel}}(x,t)}{\partial x^2 \partial t}\mathrm{d}x$$

By substituing the modal expansion

$$\Rightarrow\quad \frac{\bar{\varepsilon}_{33}^S bL}{h_{\tilde{\mathrm{p}}}}\frac{\mathrm{d}v(t)}{\mathrm{d}t} + \frac{v(t)}{R_{\mathrm{l}}} = \sum_{r=1}^{\infty}\kappa_r\frac{\mathrm{d}\eta_r(t)}{\mathrm{d}t}$$

Where the modal coupling term in the electrical circuit is

$$\kappa_r = -\bar{e}_{31}h_{\tilde{\mathrm{p}}\mathrm{c}}b\int_0^L \frac{\mathrm{d}^2\phi_r(x)}{\mathrm{d}x^2}\mathrm{d}x = -\bar{e}_{31}h_{\tilde{\mathrm{p}}\mathrm{c}}b\left.\frac{\mathrm{d}\phi_r(x)}{\mathrm{d}x}\right|_{x=L}$$

segmented electrodes can be used in harvesting energy from the modes higher than the fundamental mode in order to avoid self cancellations effects

Piezoelectric conversion

Coupled distribuited parameter model for cantilever beam VEH
[Erturk and Inmann (2008)]

Coupled electro-mechanical beam equations in modal coordinates

$$\frac{\mathrm{d}^2\eta_r^{\mathrm{s}}(t)}{\mathrm{d}t^2} + 2\zeta_r\omega_r\frac{\mathrm{d}\eta_r^{\mathrm{s}}(t)}{\mathrm{d}t} + \omega_r^2\eta_r^{\mathrm{s}}(t) + \chi_r^s v_{\mathrm{s}}(t) = f_r(t)$$

With the modal electromechanical coupling term $\chi_r^s = \vartheta_{\mathrm{s}} \left.\frac{\mathrm{d}\phi_r(x)}{\mathrm{d}x}\right|_{x=L}$

and the modal mechanical forcing

$$f_r(t) = -m\left(\frac{\mathrm{d}^2 g(t)}{\mathrm{d}t^2}\int_0^L \phi_r(x)\,\mathrm{d}x + \frac{\mathrm{d}^2 h(t)}{\mathrm{d}t^2}\int_0^L x\phi_r(x)\,\mathrm{d}x\right) - M_{\mathrm{t}}\phi_r(L)\left(\frac{\mathrm{d}^2 g(t)}{\mathrm{d}t^2} + L\frac{\mathrm{d}^2 h(t)}{\mathrm{d}t^2}\right).$$

the Kirchhoff laws applied to the equivalent electrical circuit gives

$$C_{\tilde{\mathrm{p}}}\frac{\mathrm{d}v(t)}{\mathrm{d}t} + \frac{v(t)}{R_{\mathrm{l}}} = i_{\tilde{\mathrm{p}}}(t)$$

with $C_{\tilde{\mathrm{p}}} = \frac{\bar{\varepsilon}_{33}^S bL}{h_{\tilde{\mathrm{p}}}}$, $i_{\tilde{\mathrm{p}}}(t) = \sum_{r=1}^{\infty}\kappa_r\frac{\mathrm{d}\eta_r(t)}{\mathrm{d}t}$

Piezoelectric conversion

Coupled distribuited parameter model for cantilever beam VEH

[Erturk and Inmann (2008)]

If the translational and rotational components of the base displacement are harmonic

$$g(t) = Y_0 e^{j\omega t},$$

$$h(t) = \vartheta_0 e^{j\omega t}$$

The modal forcing can be expressed

$$f_r(t) = F_r e^{j\omega t}$$

The resulting voltage amplitude

$$v_s(t) = \frac{\sum_{r=1}^{\infty} \frac{j\omega\kappa_r F_r}{\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega}}{\frac{1}{R_l} + j\omega\frac{C_{\tilde{p}}}{2} + \sum_{r=1}^{\infty} \frac{j\omega\kappa_r \chi_r^s}{\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega}} e^{j\omega t}$$

the steady state modal mechanical response

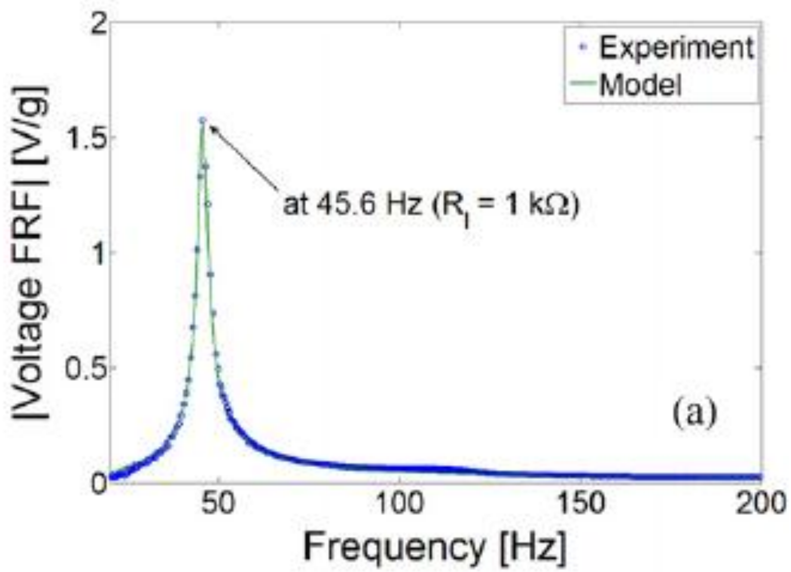
$$\eta_r^s(t) = \left(F_r - \chi_r^s \frac{\sum_{r=1}^{\infty} \frac{j\omega\kappa_r F_r}{\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega}}{\frac{1}{R_l} + j\omega\frac{C_{\tilde{p}}}{2} + \sum_{r=1}^{\infty} \frac{j\omega\kappa_r \chi_r^s}{\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega}} \right) \times \frac{e^{j\omega t}}{\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega}.$$

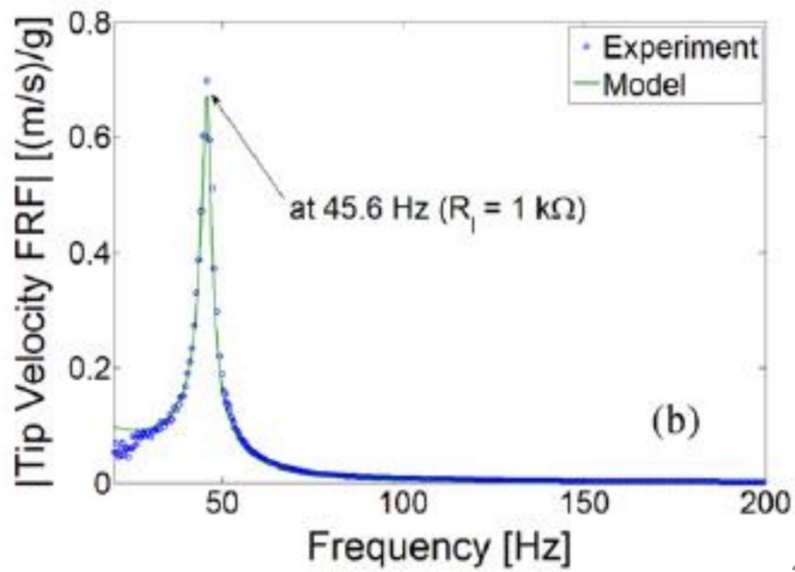
Piezoelectric conversion

Coupled distribuited parameter model for cantilever beam VEH
[Erturk and Inmann (2008)]

Electrical peak power for sinusoidal vibration input at $\omega \simeq \omega_r$

$$\left|\hat{P}(t)\right| = \frac{R_l(\omega\varphi_r F_r)^2}{\left[\omega_r^2 - \omega^2(1+2\zeta_r\omega_r R_l C_p)\right]^2 + \left[2\zeta_r\omega_r\omega + \omega R_l\left[C_p\left(\omega_r^2-\omega^2\right)+\varphi_r\chi_r\right]\right]^2}$$

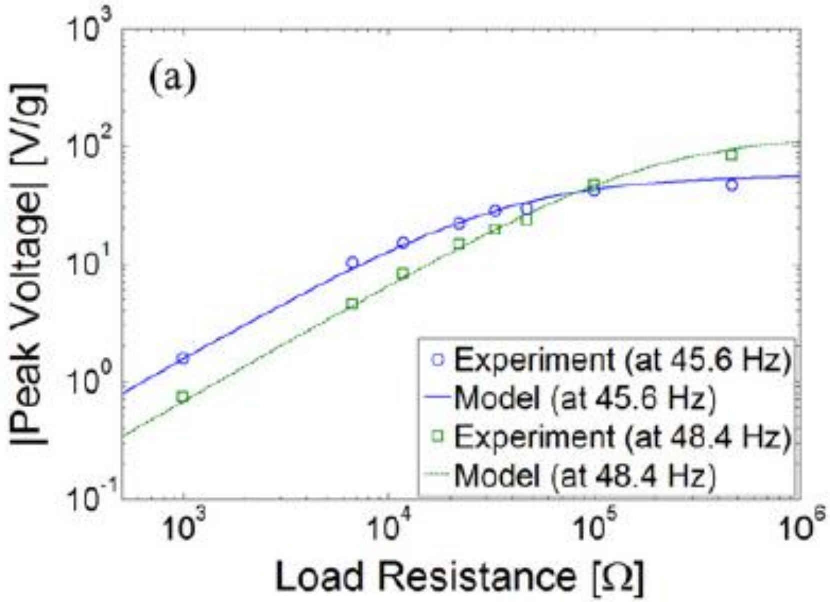


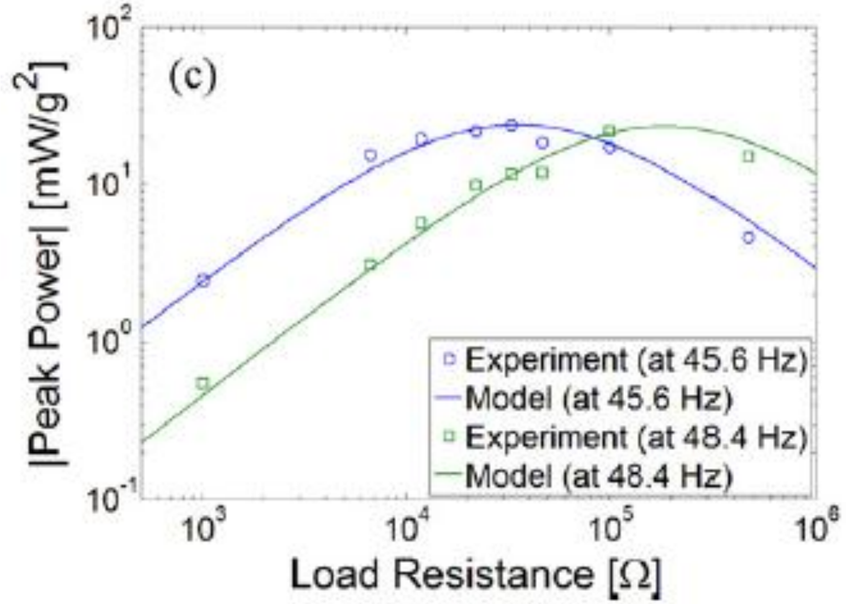


Piezoelectric conversion

Coupled distribuited parameter model for cantilever beam VEH

[Erturk and Inmann (2008)]

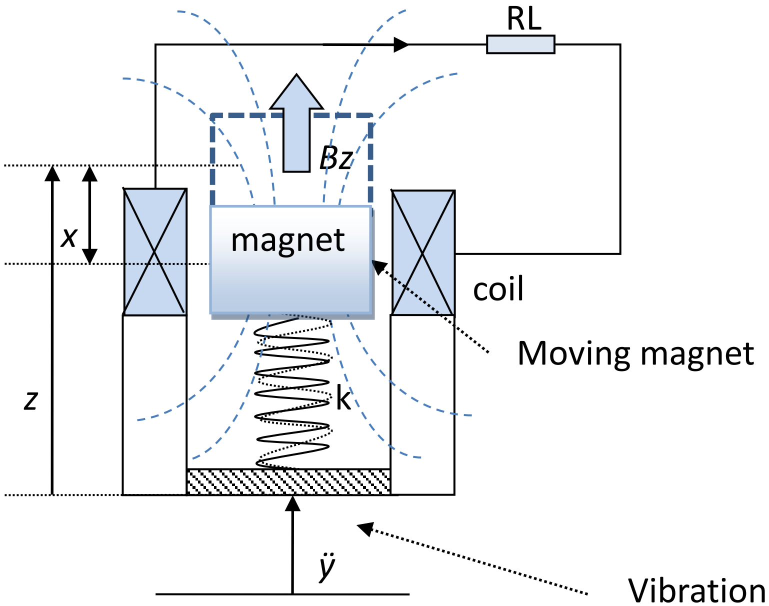


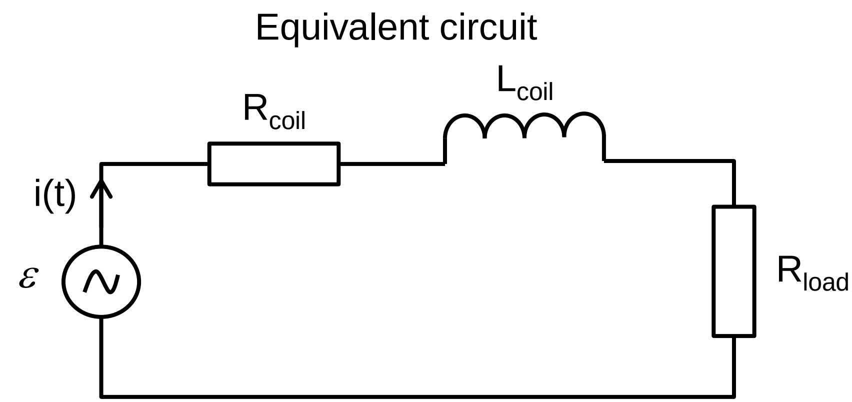


Erturk, A. and D. J. Inman (2009). "An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations." Smart materials and structures **18**: 025009.

Electromagnetic generators

Model with coupled governing equations





The coupled governing equations for only 1-DOF model of a EM VEH can be written in a general form

$$\begin{cases} m\ddot{z} + d\dot{z} + kz = -\alpha V_L - m\ddot{y} \\ \dot{V}_L + \omega_c V_L = \delta_c \omega_c \dot{z} \end{cases}$$

where

$\alpha = NB_z l / (R_L + R_c)$ Electrical coupling force factor

$\delta_c = NB_z l$ Conversion factor

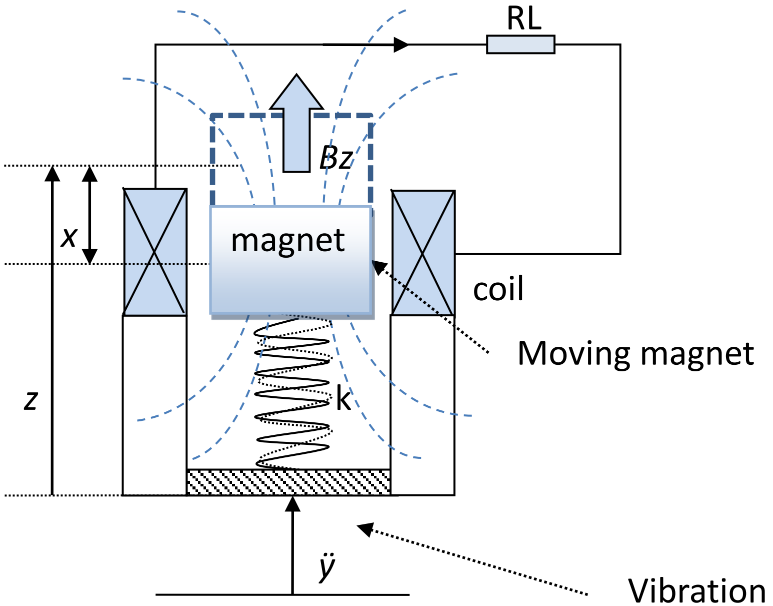
$\omega_c = R_L / L_e$ Characteristic cut-off frequency

$L_e = \mu_0 N^2 \pi R^2 / h_b$ Coil self-inductance

Joon Kim, K., **F. Cottone**, et al. (2010). "Energy scavenging for energy efficiency in networks and applications." Bell Labs Technical Journal **15**(2): 7-29.

Electromagnetic generators

Transfer functions and power calculus



By transforming the motion equations and into Laplace domain with ***s*** as Laplace variable, considering only the forced solution, the acceleration of the base being *Y(s)*

$$\begin{pmatrix} ms^2+ds+k & \alpha \\ -\delta_c\omega_c s & s+\omega_c \end{pmatrix}\begin{pmatrix} Z \\ V \end{pmatrix}=\begin{pmatrix} -mY \\ 0 \end{pmatrix}$$

The left-side matrix A represents the generalized impedance of the oscillating system. So the solution is given by

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

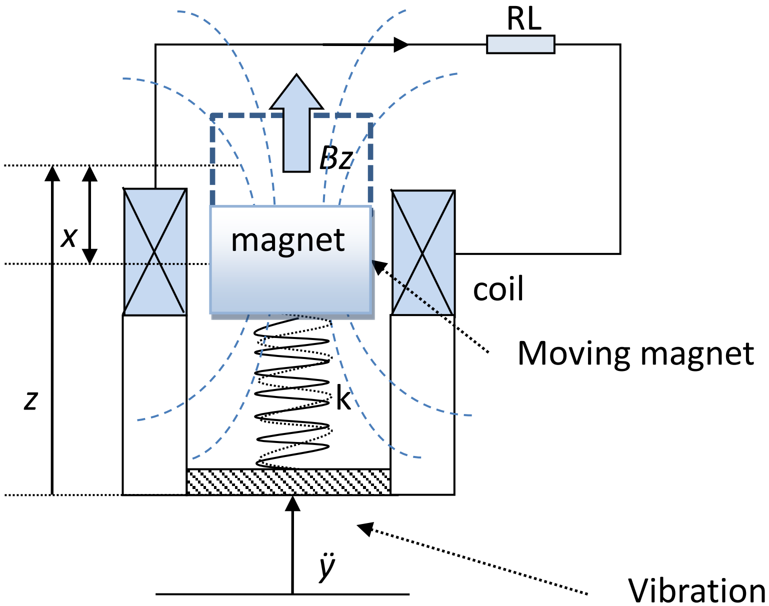
$$V=\frac{-mY}{\det A}\delta_c\omega_c s=\frac{-mY\delta_c\omega_c s}{ms^3+(m\omega_c+d)s^2+(k+\alpha\delta_c\omega_c+d\omega_c)s+k\omega_c}$$

the transfer functions between displacement *Z,* voltage *V* over acceleration input *Y* are defined as

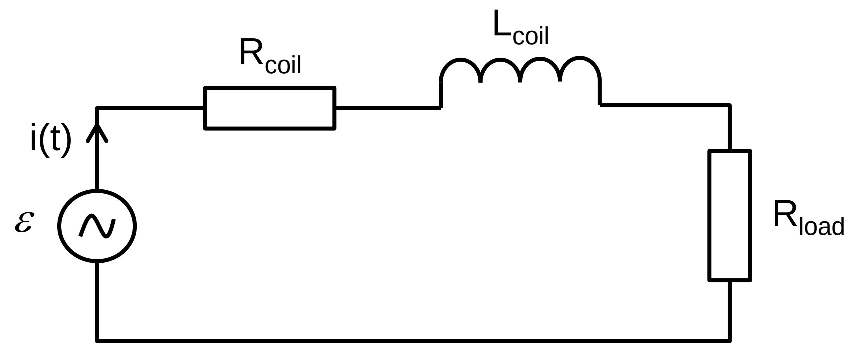
$$H_{ZY}(s)=\frac{Z}{Y};\qquad H_{VY}(s)=\frac{V}{Y}$$

with the Laplace variable $s=j\omega$

Electromagnetic generators



Equivalent circuit



The electrical power P_e across the resistive load R_L in frequency domain with harmonic input is

$$\ddot{y} = Y_0 e^{j\omega t}$$

$$P_e(\omega) = p_e(\omega)|Y(j\omega)|^2 = \frac{|V(j\omega)|^2}{2R_L} = \frac{|H_{VY}(j\omega)|^2 |Y(j\omega)|^2}{2R_L}$$

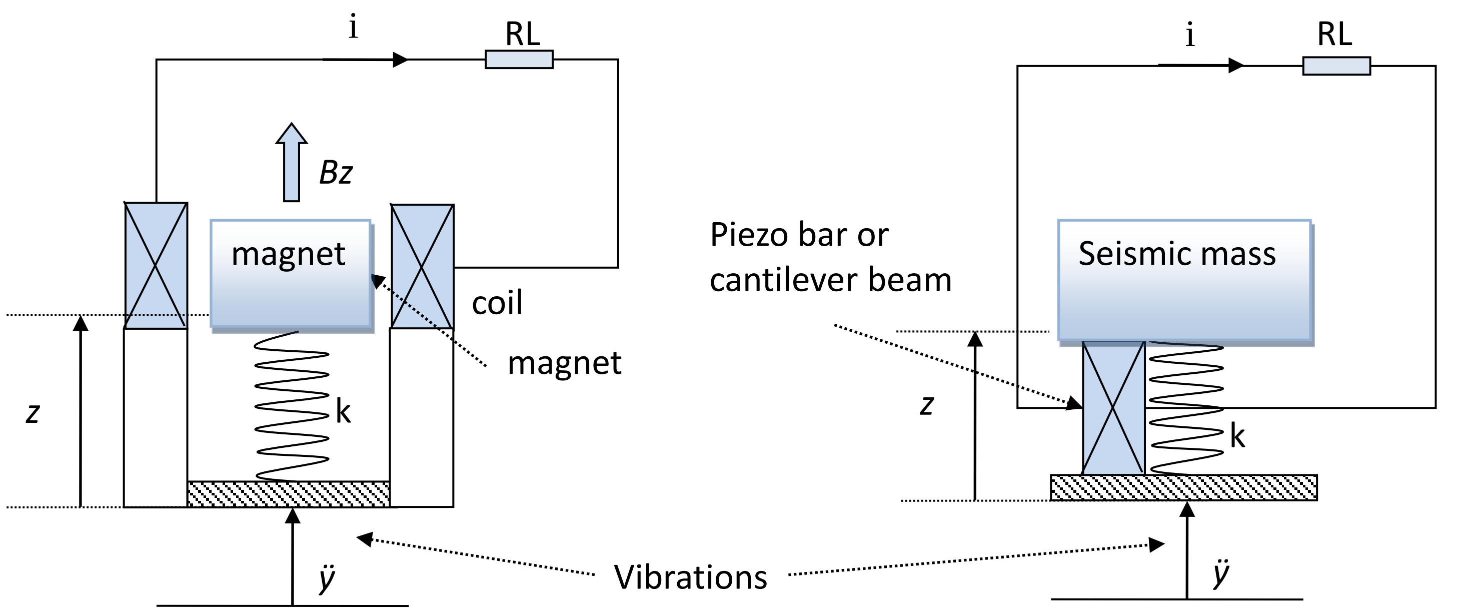
$$P_e(\omega) = \frac{Y_0^2}{2R_L}\left|\frac{m\delta_c\omega_c j\omega}{(\omega_c + j\omega)(-m\omega^2 + dj\omega + k) + \alpha\delta\omega_c j\omega}\right|^2$$

Considering electrical domain analog matching we can find the optimal impedance

$$R_{load,opt} = R_{coil} + \frac{\delta_c^2}{d_m}$$ with $$\delta_c = NB_z l$$

A general modeling approach for VEHs

Electromagnetic transduction **Piezoelectric transduction**



$$\begin{cases} m\ddot{z} + d\dot{z} + kz = -\alpha V_L - m\ddot{y} \\ \dot{V}_L + \omega_c V_L = \delta\omega_c \dot{z} \end{cases}$$

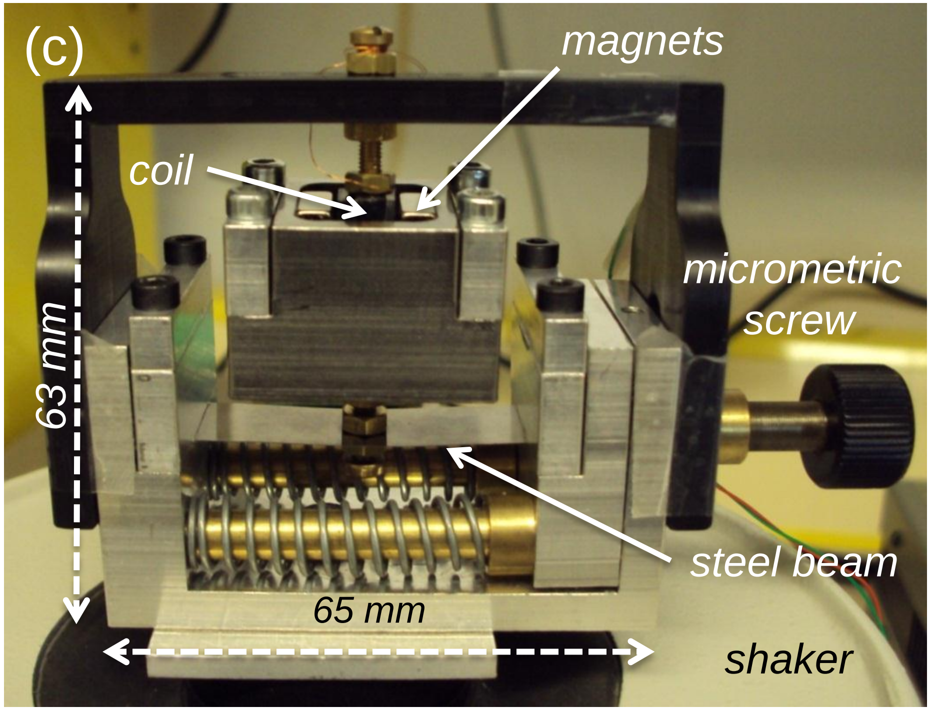
Parameters	Electromagnetic	Piezoelectric	Description
α	$B_z l / R_L$	$h_{33}C_0$	Electrical restoring force factor
δ_c	$B_z l$	αR_L	Conversion coefficient
ω_c	$\frac{R_L}{L_e}$	$\frac{1}{R_L C_0}$	Characteristic cut-off frequency

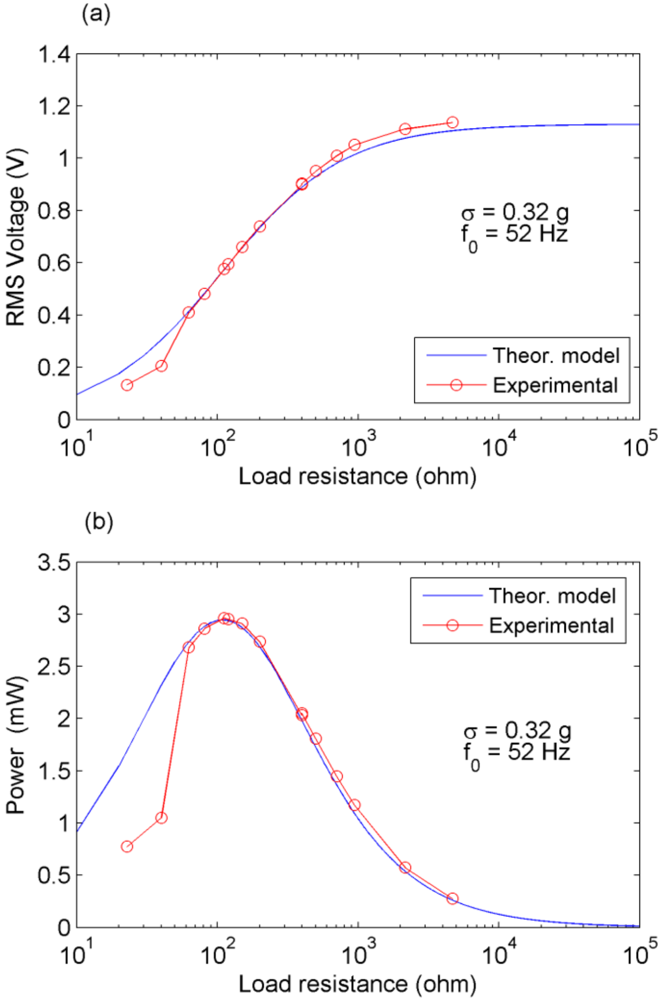
$$\ddot{y} = Y_0 e^{j\omega t}$$

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

Electromagnetic buckled-beam generator

Experimental test



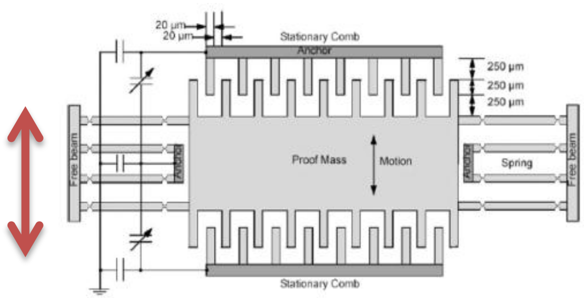


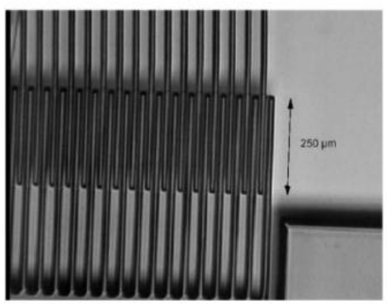
Cottone, F., Basset, P., Gammaitoni, L., Vocca H., (2012)
Electromagnetic buckled beam oscillator for enhanced vibration energy harvesting.
Submitted for publication.

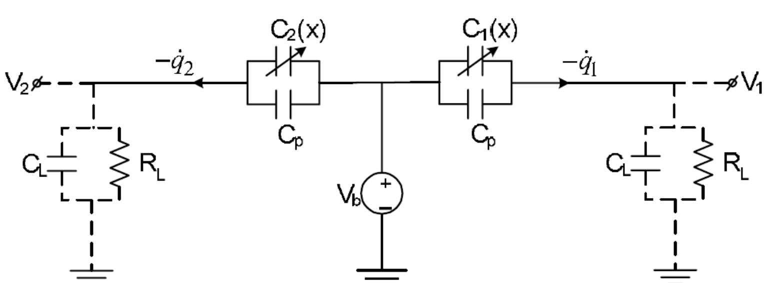
Electrostatic generators

Operating principle (E. Halvorsen, JMM 2012)

Overlap architecture







The coupled governing equations are

$$m\ddot{x}(t) + d\dot{x}(t) + kx(t) + F_e = -m\ddot{y}(t)$$

$$V_b = -\frac{q_{1/2}}{C_{1/2}(x) + C_P} + V_{L1/L2}$$

where q_1 and q_2 are the charges on transducers 1 and 2, respectively.

The electrostatic force is

$$F_e = \frac{1}{2}q_1^2\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{1}{C_1(x)+C_p}\right) + \frac{1}{2}q_2^2\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{1}{C_2(x)+C_p}\right)$$

where

$$C_{1/2}(x) = C_0\left(1 \pm \frac{x}{x_0}\right) = 2N_f\varepsilon_0\frac{x_0 t}{g_0}\left(1 \pm \frac{x}{x_0}\right)$$

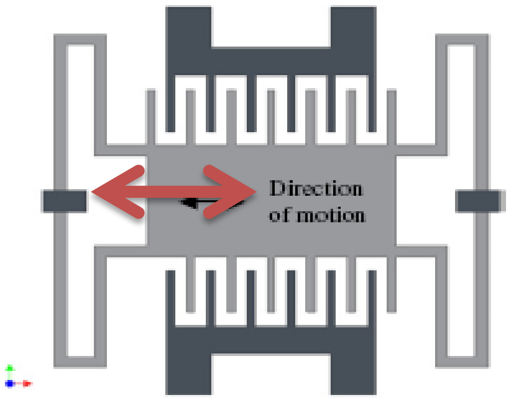
g_0 is a gap between the capacitor, x_0 is an initial capacitor finger overlap and N_f is the number of capacitor fingers on each electrode.

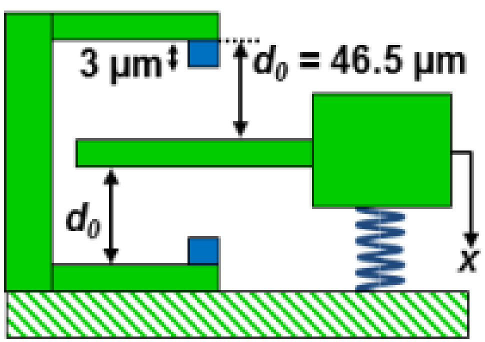
Electrostatic generators

Operating principle (E. Halvorsen, JMM 2012)

Gap-closing

Interdigitated Comb





The coupled governing equations are

$$m\frac{d^2x}{dt^2}+(c_a+c_i)\frac{dx}{dt}+\frac{dE_p(x)}{dx}=-m\frac{d^2y}{dt^2},$$
$$R_L\frac{d}{dt}(C\cdot V)+V=U_0,$$

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

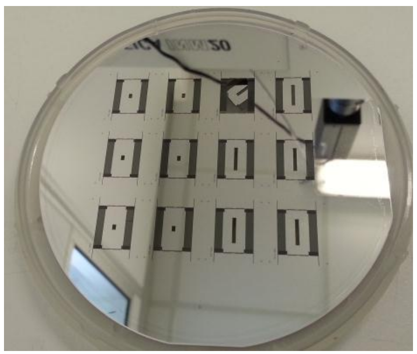
and the capacitance is

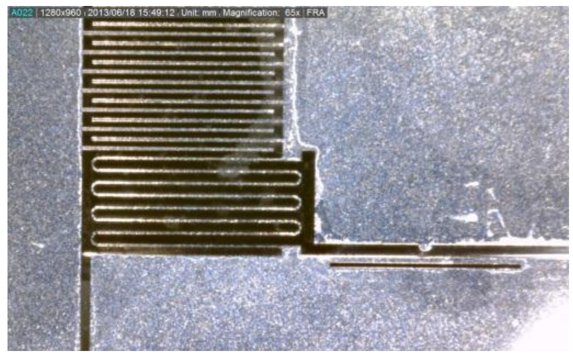
$$C(x)=C_{par}+\varepsilon N_f l_f\frac{1}{2r}\left[\ln\left(\frac{d_0-x+2hr}{d_0-x}\right)+\ln\left(\frac{d_0+x+2hr}{d_0+x}\right)\right],$$

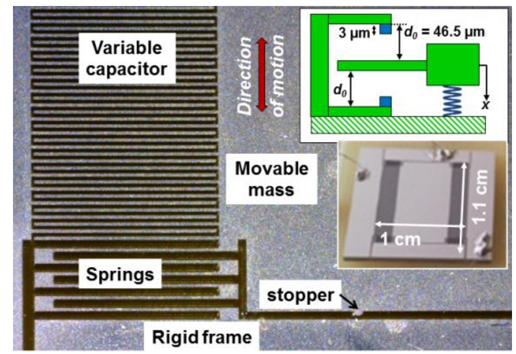
Electrostatic generators

Université Paris-Est, ESIEE Paris,

Silicon MEMS-based electrostatic harvesters.



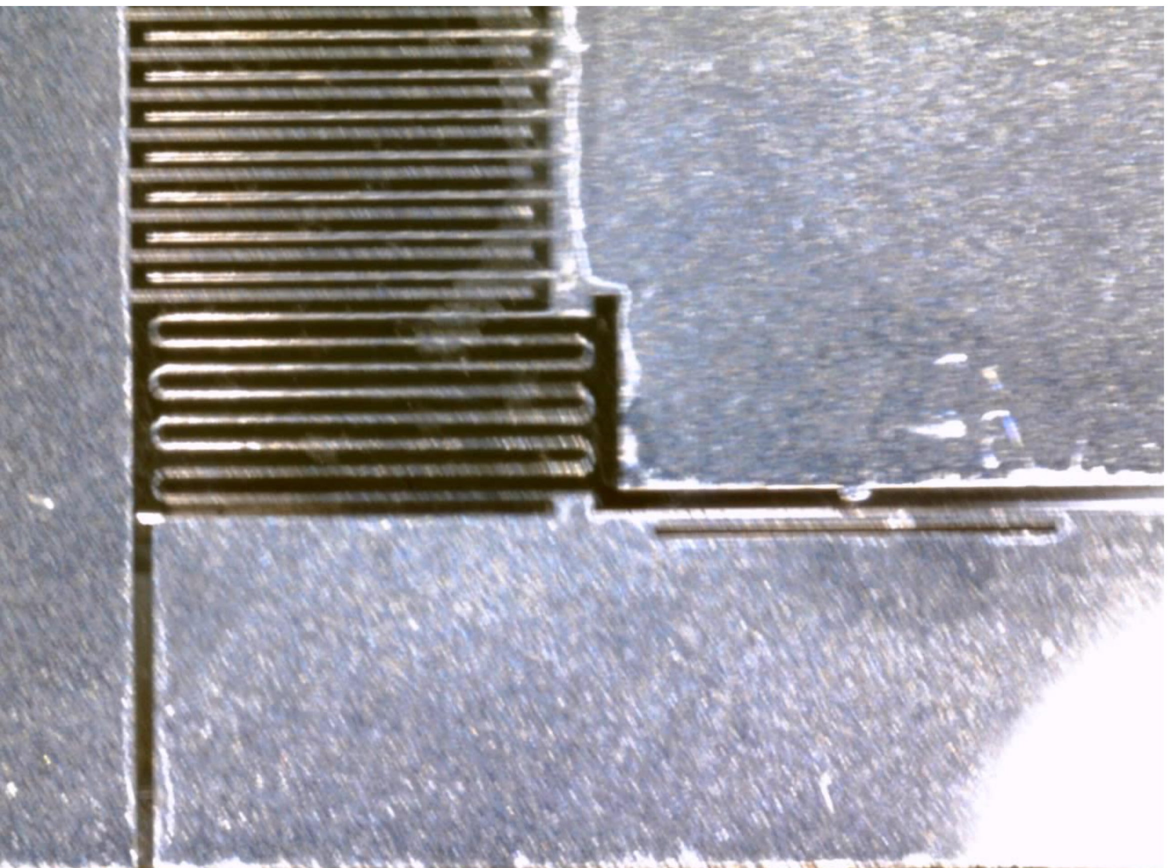


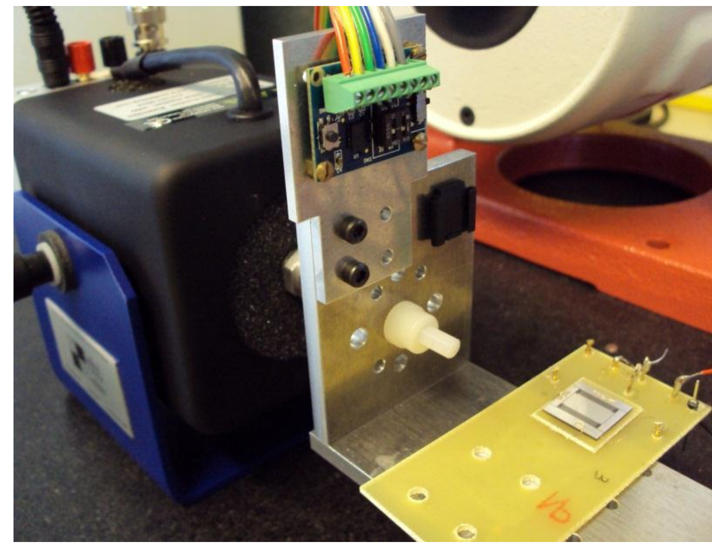


- **Cottone, F.,** Basset, P., Guillemet, R., Galayko, D., Marty, F. and T. Bourouina. Non-linear MEMS electrostatic kinetic energy harvester with a tunable multistable potential for stochastic vibrations, (2013) Conf. Proceeding. IEEE TRANSDUCERS 2013.
- **Cottone, F.,** Basset, P., Guillemet, R., Galayko,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

Electrostatic generators

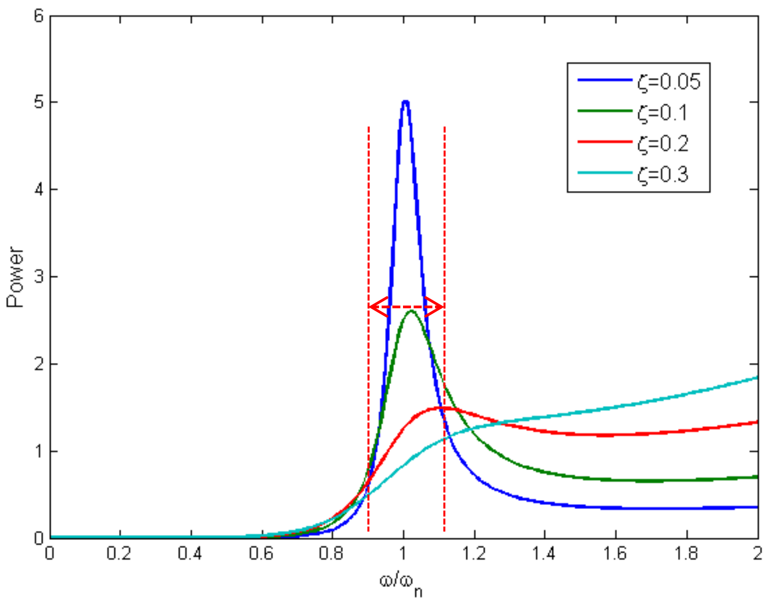
F. Cottone, P. Basset, Université Paris-Est, ESIEE Paris,
Silicon MEMS-based electrostatic harvesters.





Main limits of resonant VEHs

- narrow bandwidth that implies constrained resonant frequency-tuned applications
- small inertial mass and maximum displacement at MEMS scale
- low output voltage (~0,1V) for electromagnetic systems
- limited power density at micro scale (especially for electrostatic converters), not suitable for milliwatt electronics (10-100mW)
- versatility and adaptation to variable vibration sources
- Miniaturization issues (micromagnets, piezo beam)



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

Transduction techniques comparison

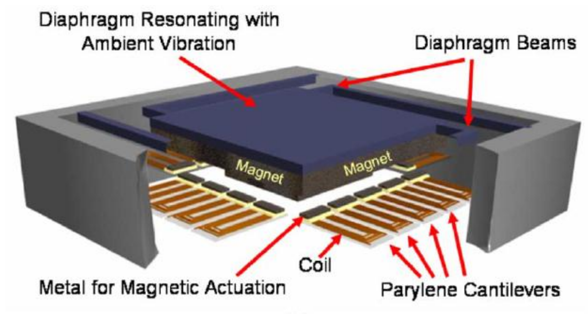
- Piezoelectric transducers
  - 🙂 high output voltages and well adapted for compact miniaturization
  - 🙂 high coupling in single crystal
  - 🙂 no external voltage source needed
  - ☹ small electromechanical coupling for piezoelectric thin films at small scale
  - ☹ large load optimal impedance required (MΩ)

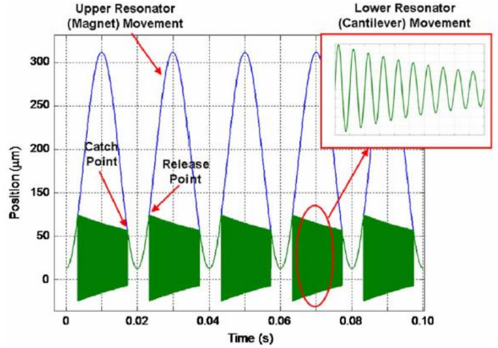
- Electrostatic transducers
  - 🙂 very well suited for MEMS integration
  - 🙂 no need of smart materials
  - 🙂 good output voltage (2-10V)
  - ☹ relatively low power density
  - ☹ need to be pre-charged at a reference voltage by an external source.

- Electromagnetic transducers
  - 🙂 good for relatively low frequencies (5–100Hz)
  - 🙂 no external voltage source needed
  - 🙂 suitable to drive loads of low impedance
  - ☹ low output voltage (usually 0.1-1V) only true at MEMS scales
  - ☹ complex micro-magnets manufacturing at MEMS scales
  - ☹ relatively large mass displacement required (few millimeters to centimeter).

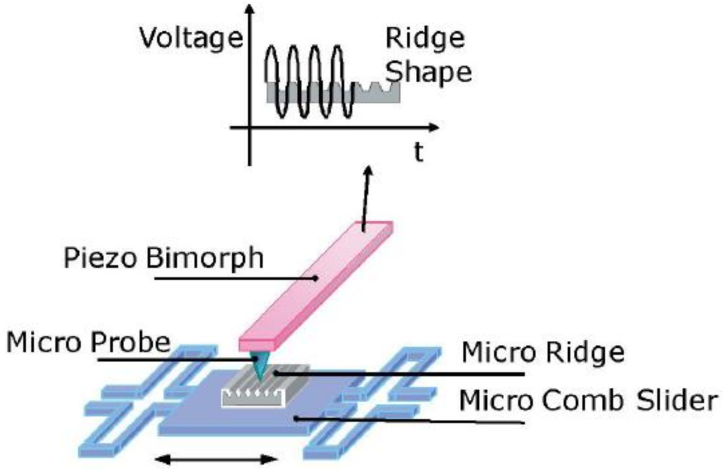
Beyond linear harvesting systems

Frequency up conversion systems

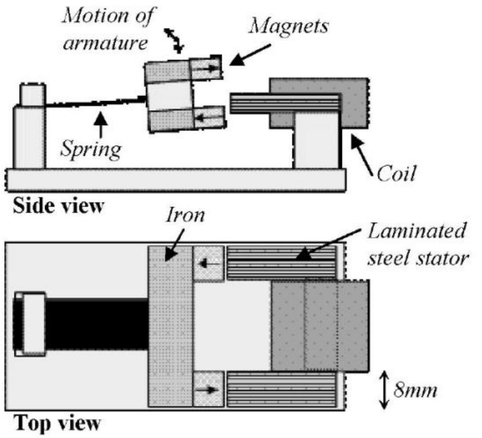




H. Kulah and K. Najafi, IEEE Sensors Journal **8** (3), 261 (2008).



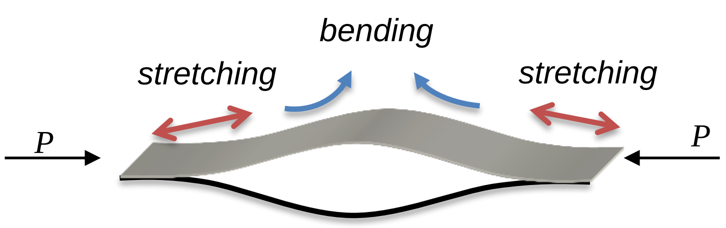
D.G. Lee et al. IEEE porc. (2007)

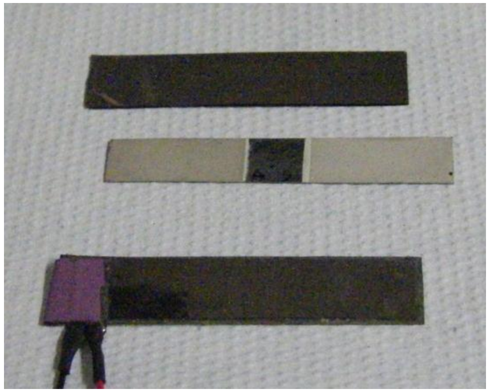


Burrow, S.G and Clare, L.R. IEEE porc. (2007)

Beyond linear harvesting systems

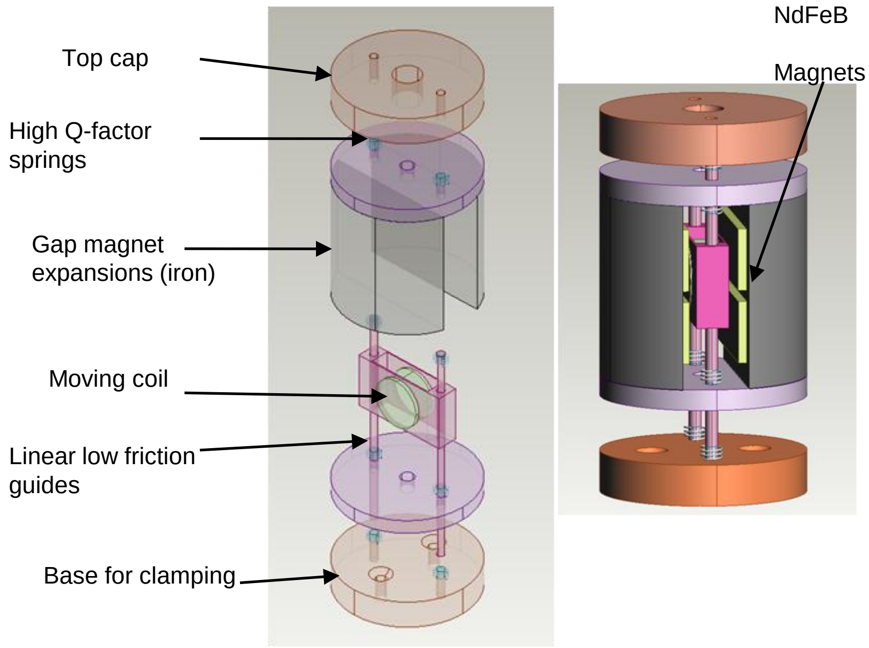
Bistable piezoelectric systems





University of Camerino and University of Perugia (Italy)
Project NANOPOWER (EU-FP7)

Velocity-amplified mulitple-mass with impacts



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

Performance metrics

Possible definition of effectiveness $$E_H = \frac{\text{Useful Power Output}}{\text{Maximum Possible Output}} = \frac{\text{Useful Power Output}}{\frac{1}{2}Y_0 Z_l \omega^3 m}.$$

Power density $$PD = \frac{El.Power}{Volume}$$

Normlized power density $$NPD = \frac{El.Power}{mass \cdot acceleration}$$

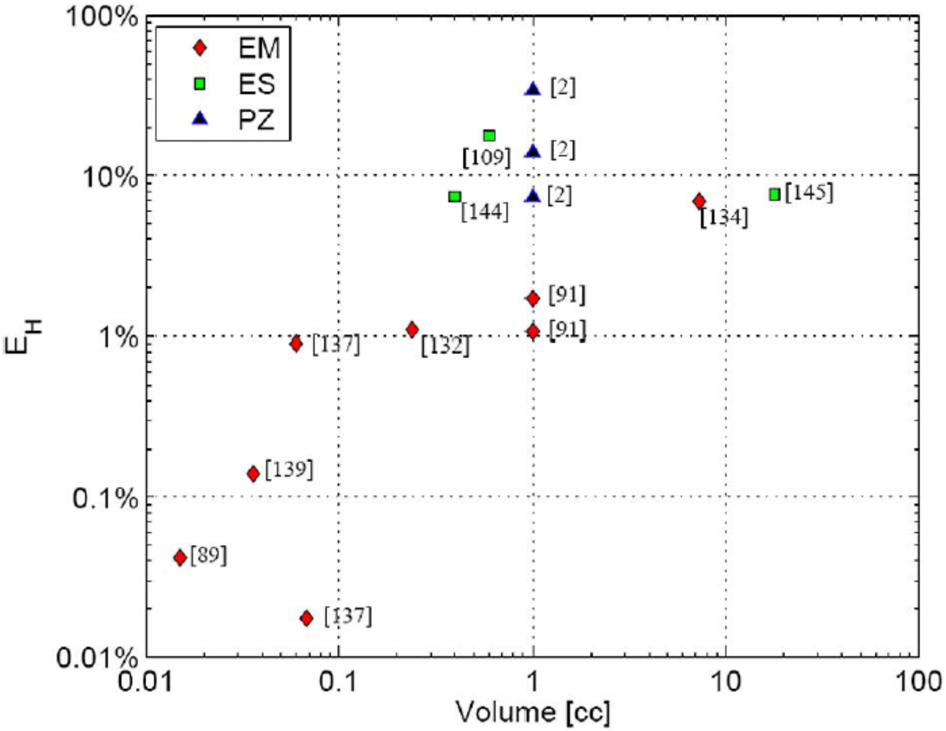
What about frequency bandwidth?

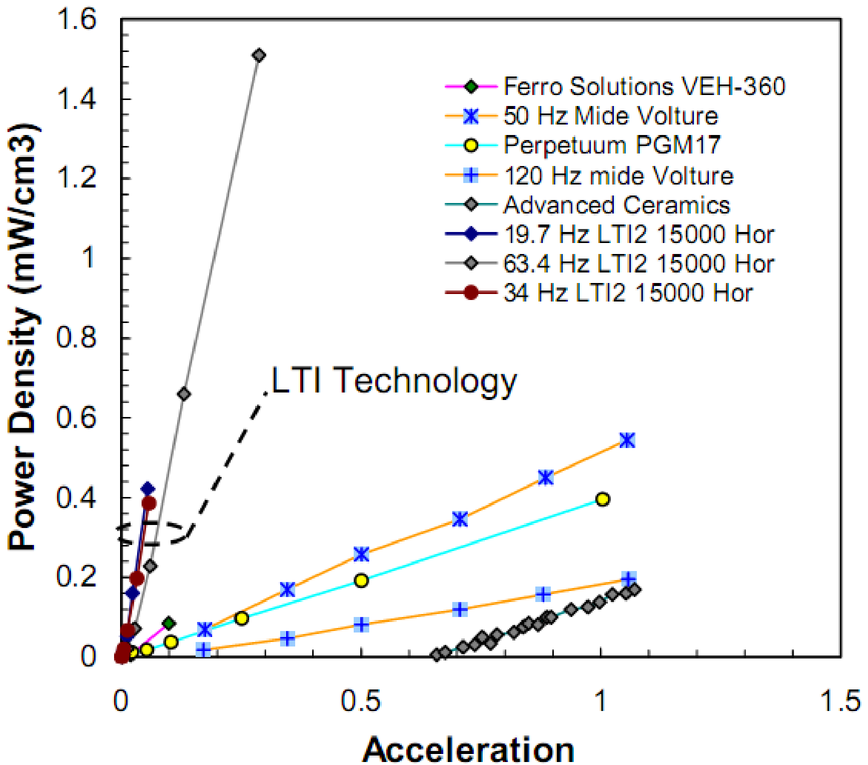
Generator[a]	Freq (Hz)	Acceln (m s^{-2})	Inertial mass (g)	Volume (cm^3)	Power (μW)	NPD (kgs m^{-3})
VIBES Mk2 EM	52	0.589	0.66	0.15	46	883.97
Glynne-Jones [13] EM	99	6.85	2.96	4.08	4990	26.07
Perpetuum [14] EM	100	0.400	50	30	4000	833.33
Ching [15] EM	110	95.5	0.192	1	830	0.09
White [16] PZ	80	2.3	0.8	0.125	2.1	3.18
Roundy [17] PZ	120	2.5	9.15	1	375	60.00
Hong [18] PZ	190	71.3	0.01	0.0012	65	10.67
Jeon [19] PZ	13 900	106.8	2.20×10^{-07}	0.000 027	1	3.25
Mitcheson [20] ES	30	50	0.1	0.75	3.7	0.002
Despesse [21] ES	50	8.8	104	1.8	1052	7.55

[a] Generators are labelled by technology: EM, electromagnetic; PZ, piezoelectric; ES, electrostatic.

Beeby, S., R. Torah, et al. (2007). "A micro electromagnetic generator for vibration energy harvesting." Journal of Micromechanics and Microengineering **17**: 1257.

Performance metrics





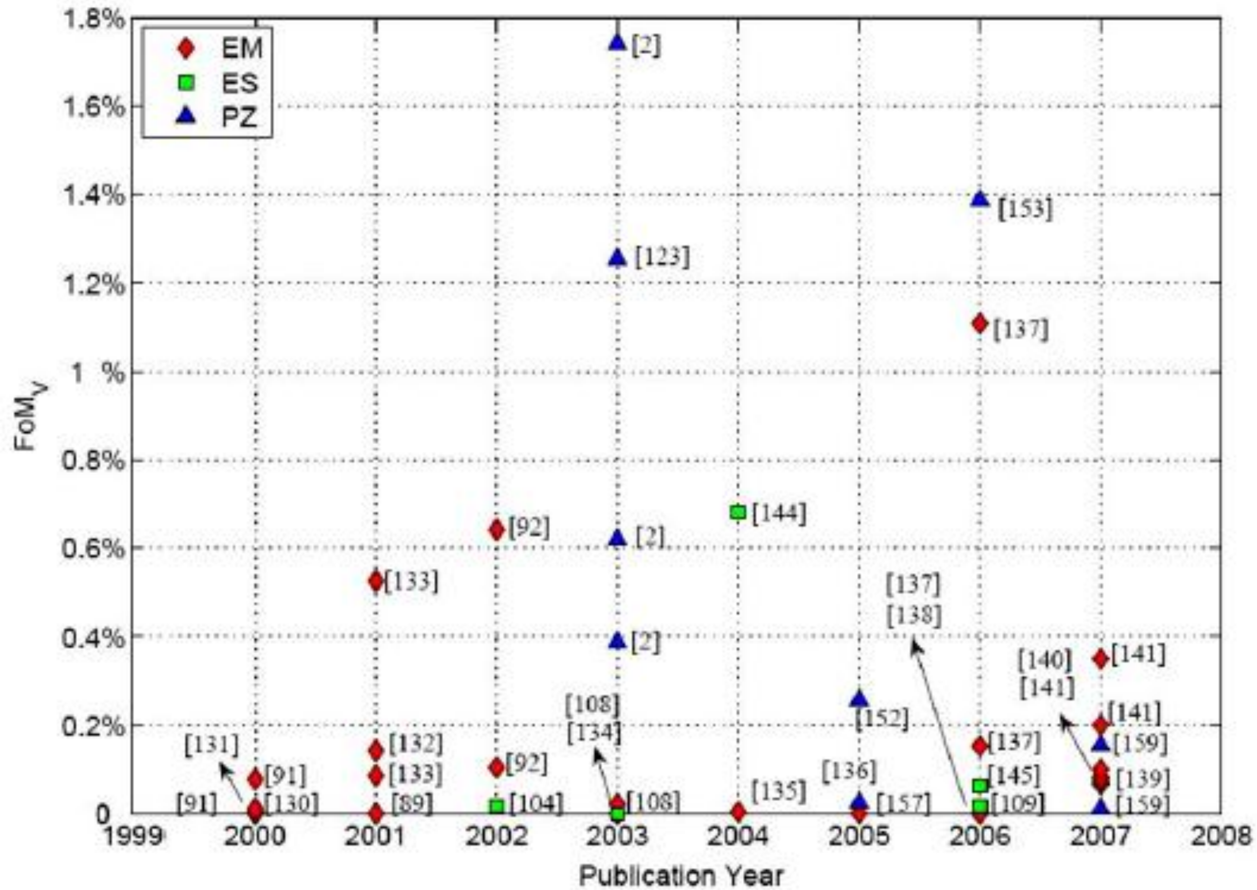
Mitcheson, P. D., E. M. Yeatman, et al. (2008). "Energy harvesting from human and machine motion for wireless electronic devices." Proceedings of the IEEE **96**(9): 1457-1486.

Performance metrics

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

Bandwidth figure of merit

$$\text{FoM}_{\text{BW}} = \text{FoM}_V \times \frac{\delta\omega_{1\ \text{dB}}}{\omega}$$



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.

Technical challenges and room for improvements

- **Maximize the proof mass m**
  - Improve the strain from a given mass

- **Widen frequency response and frequency tuning**
  - Actively and passive tuning resonance frequency of generator
  - Wide bandwidth designs: oscillators array, multiple degree-of freedom systems
  - Frequency up-conversion systems
  - Nonlinear Nonresonant Dynamical Systems

- **Miniaturization issues:** coupling coefficient at small scale and power density
  - Improvements of Thin-film piezoelectric-material properties
  - Improving capacitive design
  - Micro magnets implementation

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

Conclusions

- 90% of WSNs cannot be enabled without Energy Harvesting technologies.
- Vibrations harvesting represents a promising renewable and reliable source for mobile electronics powering.
- Most of vibrational energy sources are inconsistent and have relative low frequency.
- Scaling from millimeter down to micrometer size is important as well as further improvement of conversion efficiency.
- Efficiency improvement of Vibration Energy Harvesting technologies deal with:
  - efficient nonlinear dynamical systems,
  - material properties,
  - miniaturization procedures,
  - efficient harvesting electronics.
- A precise metrics for effectiveness is not yet well defined

Thanks for your attention!

University of Limerick
Ollscoil Luimnigh

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PARIS