Introduction to Vibration Energy Harvesting

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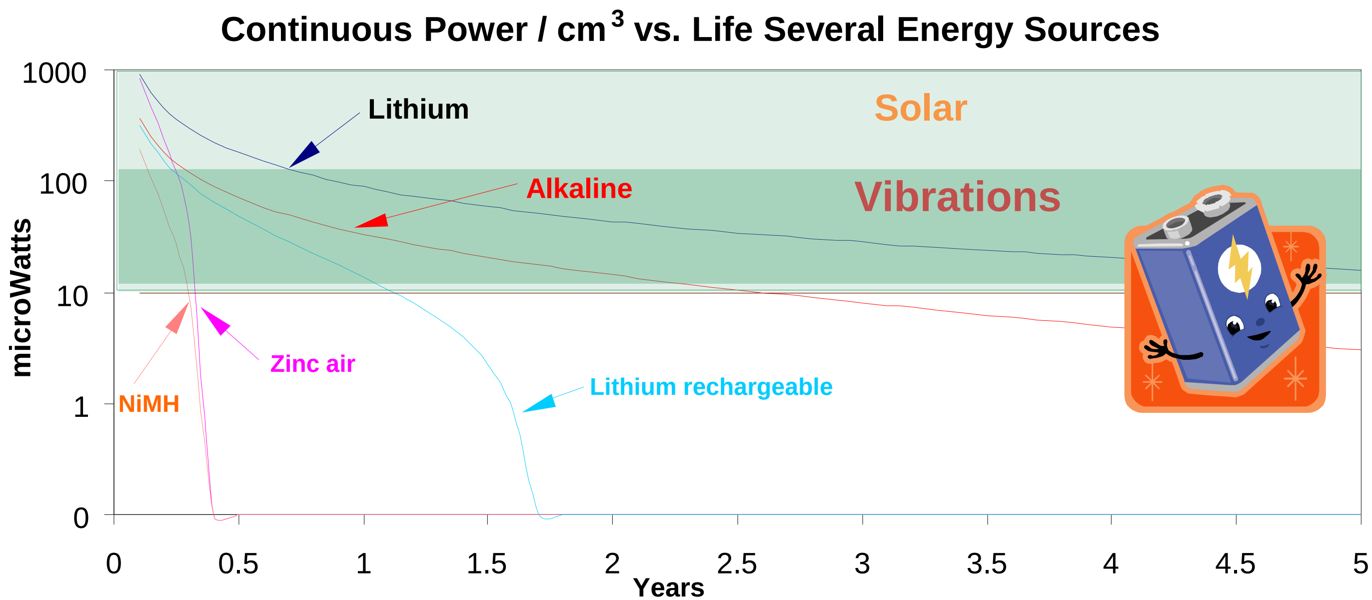
Summary

- 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 !

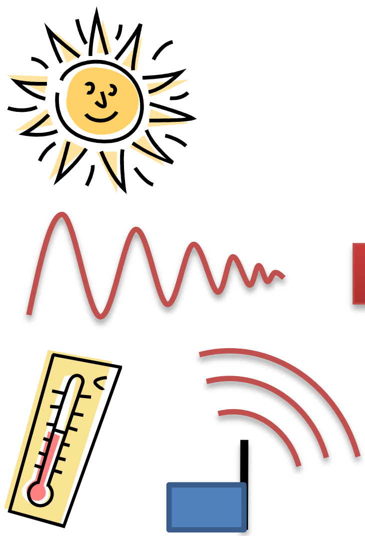
Can we replace or extend battery life?

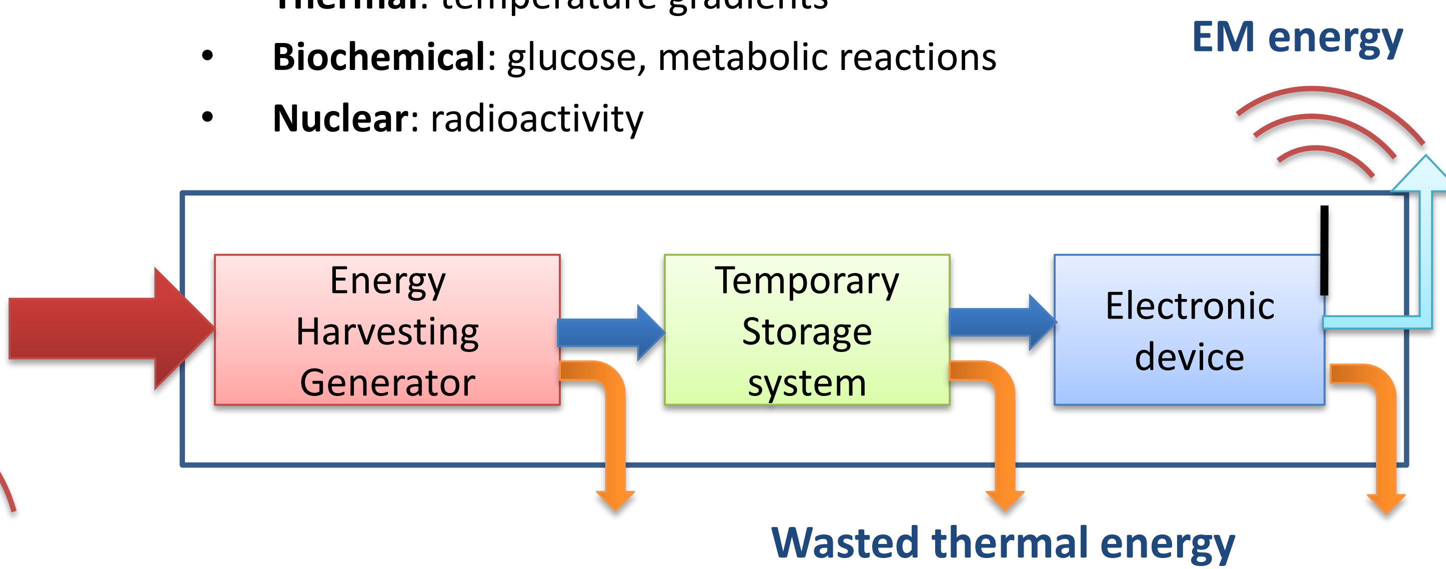
What about disposal problem?

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.

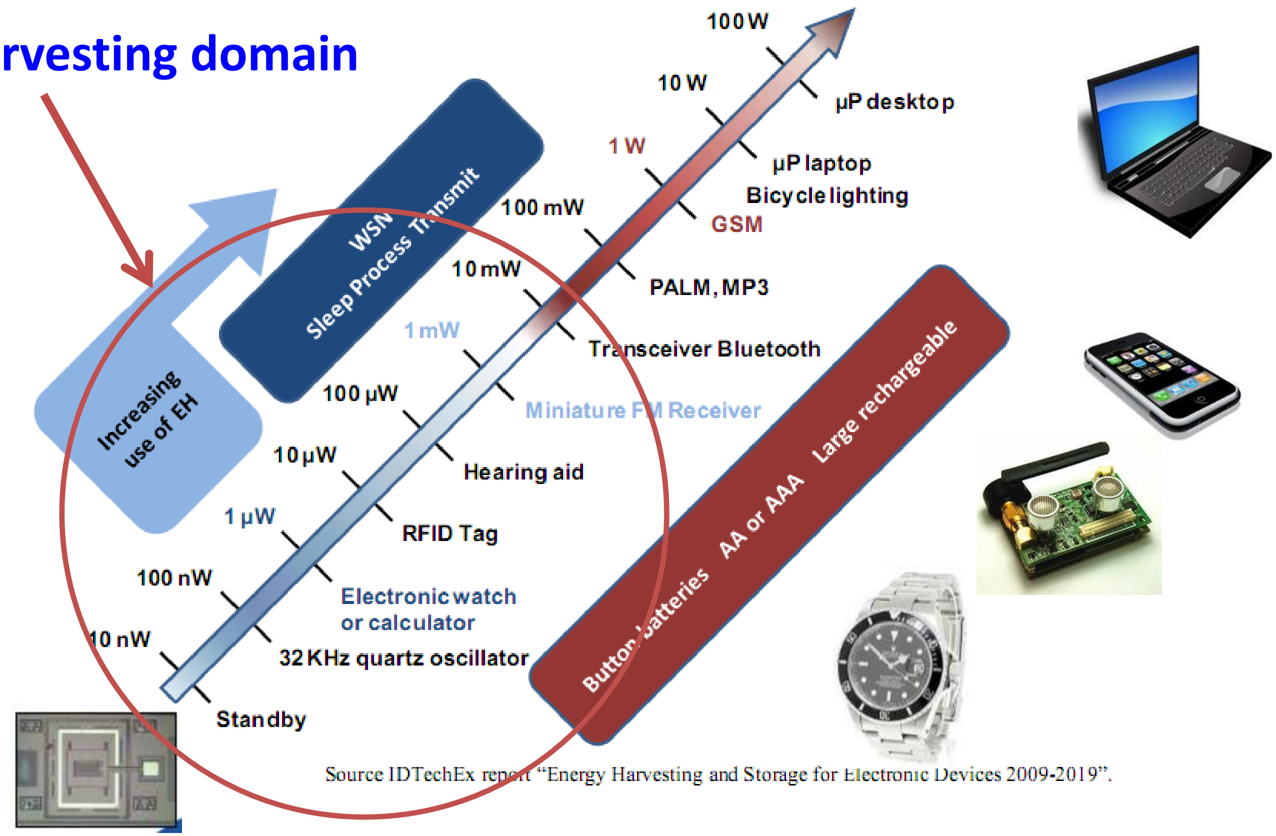
The most amount of power your iPhone accepts when charging is 2.5 Watts.

Brother Industries 2010

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

Vibration energy harvesting versus power requirements

Vibration harvesting domain

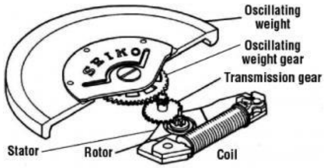


An energy harvesting generator
must provide at least **100-300µW per cm^3 of device volume**

Applications of energy harvesting

Past → **Present** → **Future**

Past



Self-charging Seiko wristwatch

Wind-up electrodynamic EH Torch, Dynamo

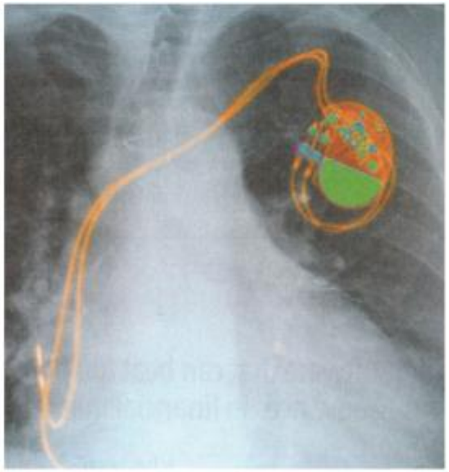
Present

Battery-less wireless sensing (Perpetuum)

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

Swinburne University, Australia, 2009

Future



University of Southampton
electrodynamic energy harvesting to run pacemaker and defibrillator

- Medical implantations
- Medical remote sensing
- Body Area Network

Applications of energy harvesting

Wireless Sensor Networks

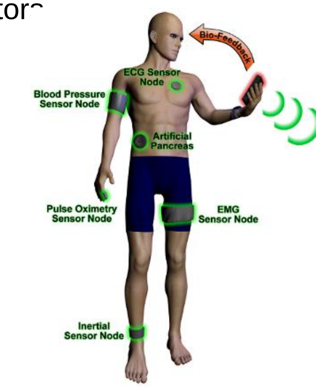
Environmental Monitoring

Habitat Monitoring (light, temperature, humidity)
Integrated Biology

Structural Monitoring

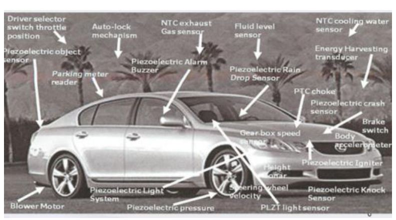
Medical remote sensing

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

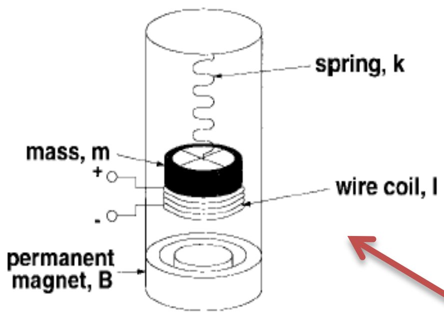
Applications of energy harvesting

Possible future?

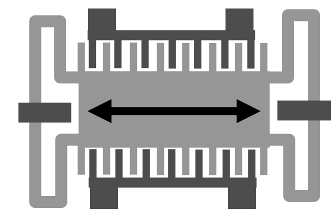
http://www.youtube.com/watch?v=ZQRbz7z3xcg

Vibration Energy Harvesters (VEHs): basic principles

Electromagnetic

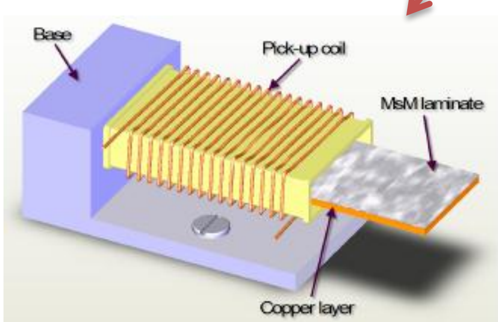


Electrostatic/Capacitive



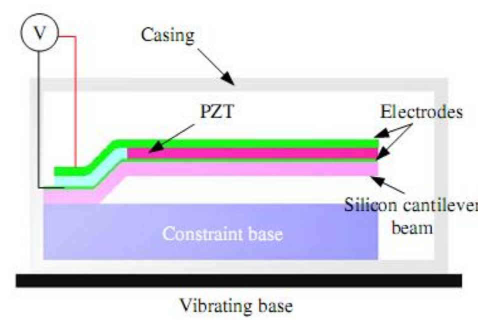
Vibration Harvesting Generator

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

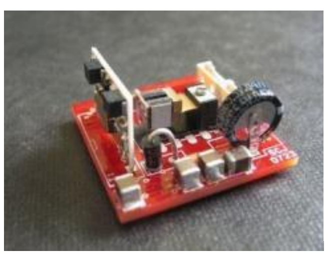
Example of macro-millimetric generators

Electrodynamic

Perpetuum PMG17 (England)

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

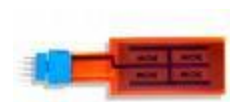
nPower® PEG



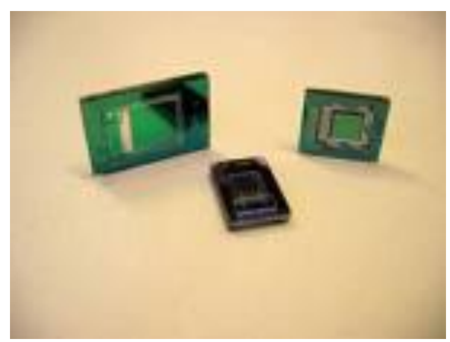
Micro-electromagnetic generator S. Beeby 2007, (UK)

Piezoelectric

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

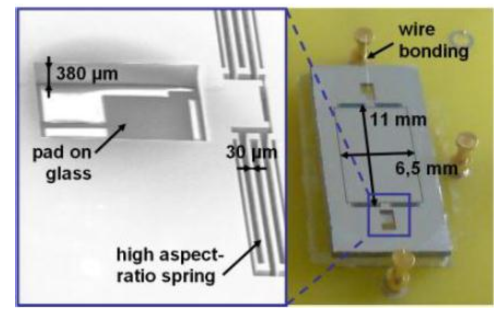


Holst-IMEC (Germany)
Micro PZ generator 500Hz
60uW @ 1g

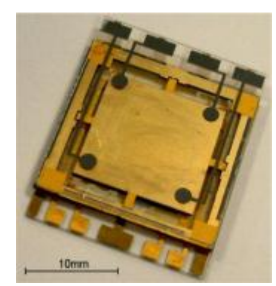


Electrostatic/Capacitive

ESIEE Paris – A. Mahmood Parracha



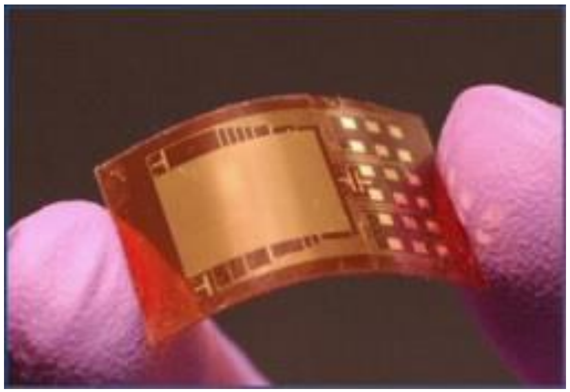
Imperial College, Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



Microlab at UC Berkeley (Mitcheson)

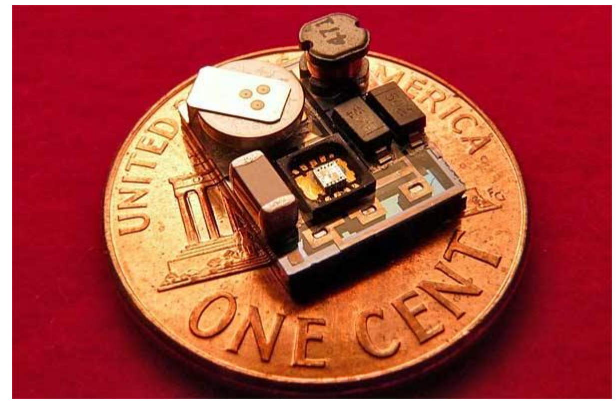
State of the art: micro- to nano- generators

zinc oxide (ZnO) nanowires

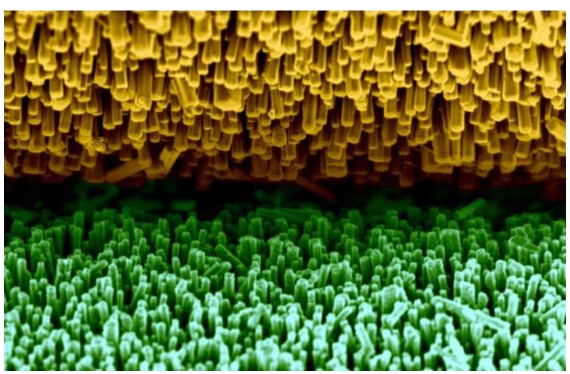


Zhong Lin Wang, Ph.D., Georgia Institute of Technology.

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



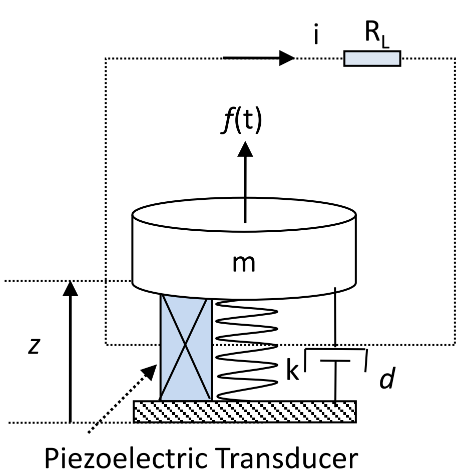
University of Michigan (USA)



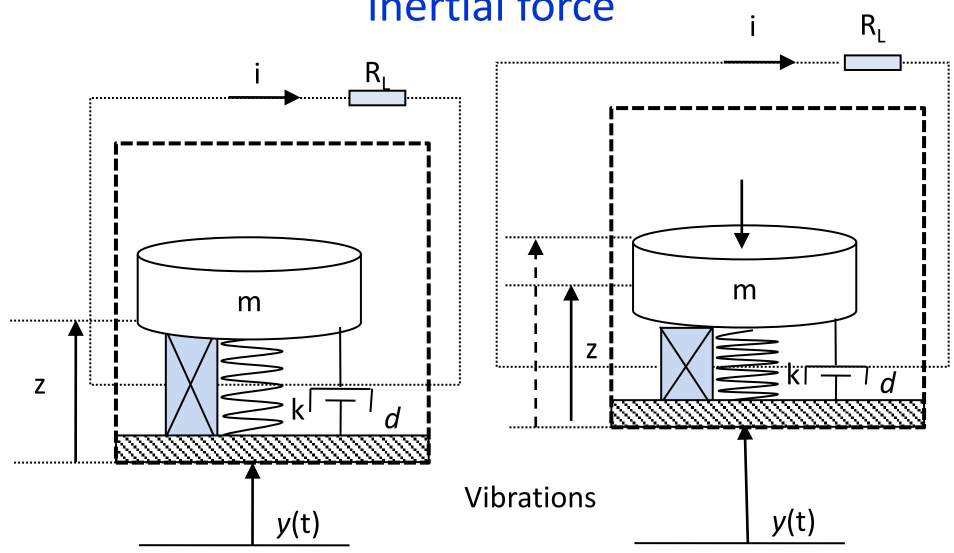
Nanogenerators produce electricity from running rodents

Vibration Energy Harvesters (VEHs): basic principles

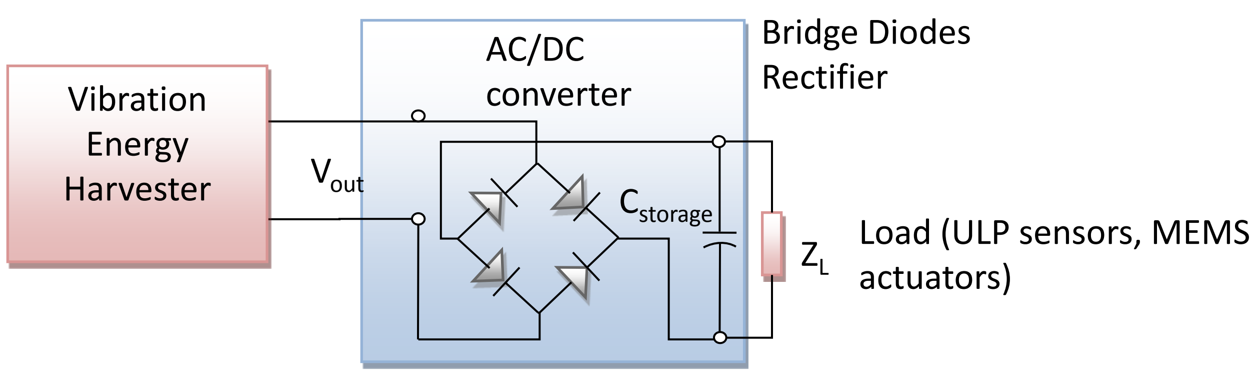
Direct force



Inertial force

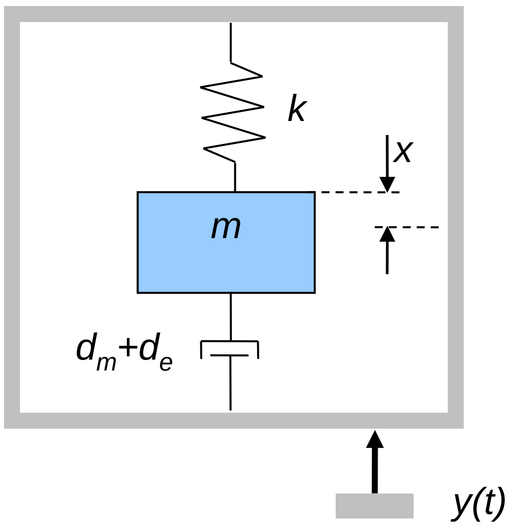


Inertial generators are more flexible than direct-force devices because they require only one point of attachment to a moving structure, allowing a greater degree of miniaturization.



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

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

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

Steady state solution

setting $d_T=d_m+d_e$ the total damping coefficient, the phase angle ϕ is given by

$$\phi=\tan^{-1}\left(\frac{d_T\omega}{k-\omega^2 m}\right)$$

and the natural frequency $\omega_n=\sqrt{k/m}$

The instantaneous kinetic power $p(t)=-m\ddot{y}(t)[\dot{y}(t)+\dot{x}(t)]$ taking the Laplace transform of motion equation

$$H_{xf}(\omega)=\frac{X(\omega)}{Y(\omega)}=\frac{\omega^2}{-\omega^2+2i\omega(\zeta_e+\zeta_m)\omega_n+\omega_n^2}$$

Vibration Energy Harvesters (VEHs): basic operating principles

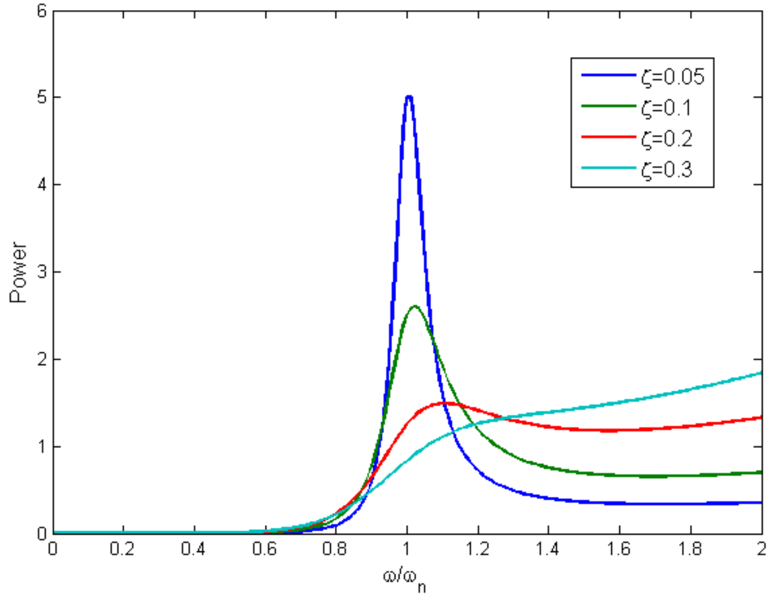
1-DOF generic mechanical-to-electrical conversion model [William & Yates]

the power dissipated by total electro-mechanical damping ratio, namely $\zeta_T=(\zeta_e+\zeta_m)=d_T/2m\omega_n$, is expressed by

$$P_{diss}(\omega) = m\zeta_T\omega_n \left|\dot{X}\right|^2 = m\zeta_T\omega_n\omega^2\left|f\cdot H_{xf}\right|^2$$

that is

$$P_{diss} = \frac{m\zeta_T Y_0^{\,2}\left(\frac{\omega}{\omega_n}\right)^3\omega^3}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\left[2\zeta_T\left(\frac{\omega}{\omega_n}\right)\right]^2}$$



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

$$P_{diss} = \frac{mY_0^{\,2}\omega_n^3}{4\zeta_T}$$

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

$$P_{diss} = \frac{mA_0^2}{4\omega_n\zeta_T}$$

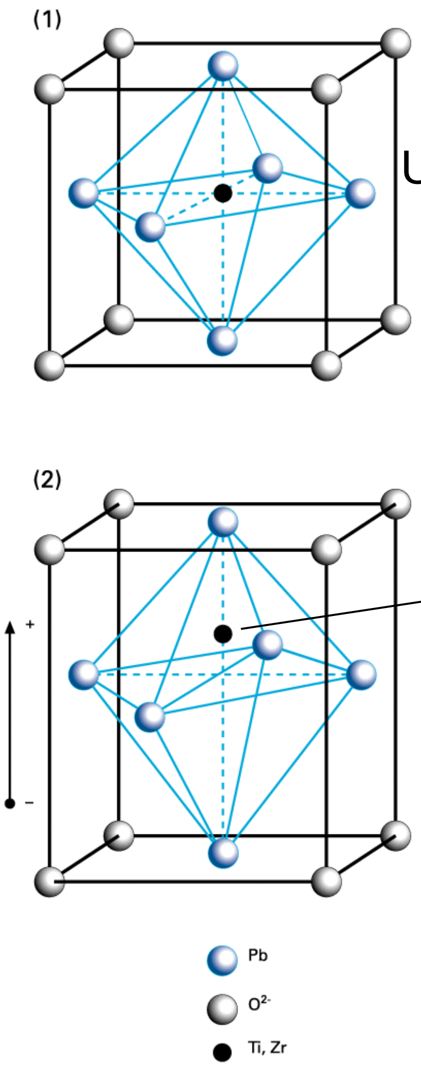
Separating parasitic damping ζ_m and transducer damping ζ_e for a particular transduction mechanism forced at natural frequency ω_n, the power can be maximized from the equation

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

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

Piezoelectric conversion

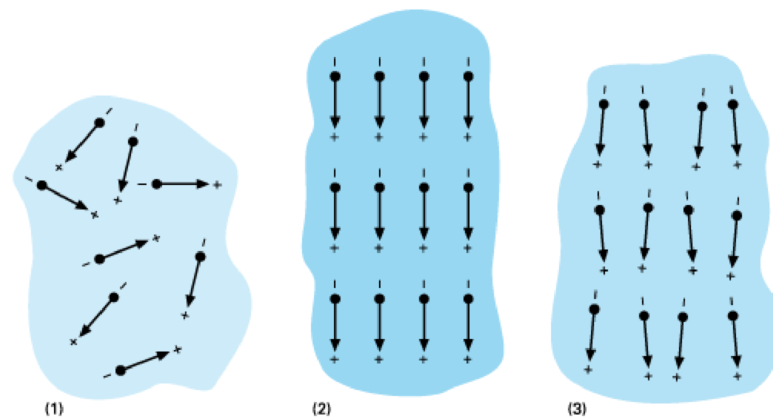
Piezoelectric materials



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

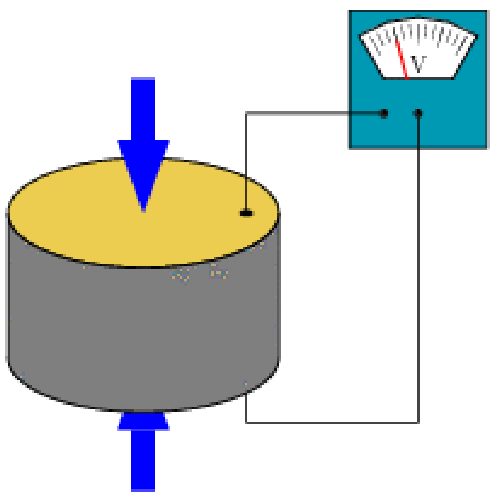


After poling the zirconate-titanate atoms are off center. The molecule becomes elongated and polarized

Piezoelectric conversion

Piezoelectric materials

Stress-to-charge conversion



direct piezoelectric effect

Naturally-occurring crystals

- Berlinite ($AlPO_4$), a rare phosphate mineral that is structurally identical to quartz
- Cane sugar
- Quartz
- 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 ($LiNbO_3$)

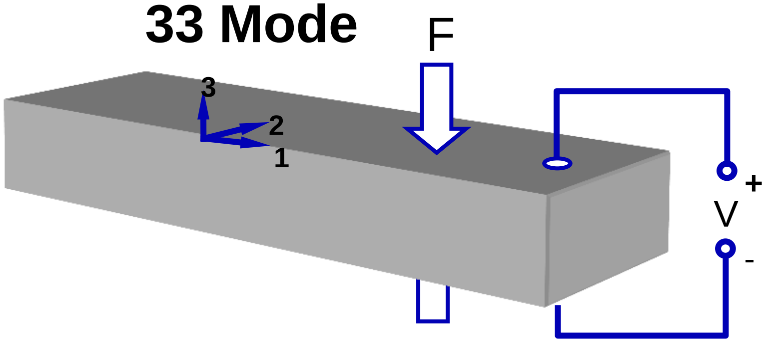
Polymers

- 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.

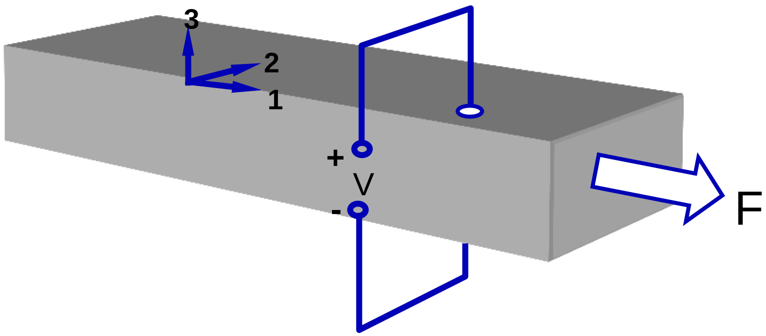
Piezoelectric conversion

Costitutive equations

33 Mode



31 Mode



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

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

Material properties example

Property	PZT-5H	PZT-5A	$BaTiO_3$	PVDF
d_{33} (10^{-12} C N^{-1})	593	374	149	−33
d_{31} (10^{-12} C N^{-1})	−274	−171	78	23
g_{33} (10^{-3} V m N^{-1})	19.7	24.8	14.1	330
g_{31} (10^{-3} 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 an adimensional factor defined as

the ratio between the mechanical energy converted and the electric energy input or

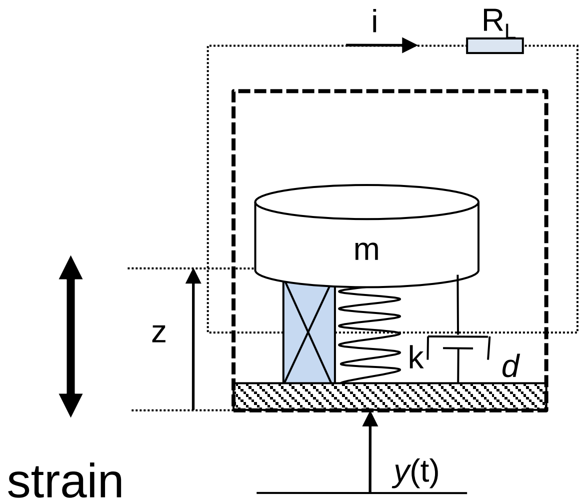
$$k_{31}^2 = \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}$$

the electric energy converted per mechanical energy input

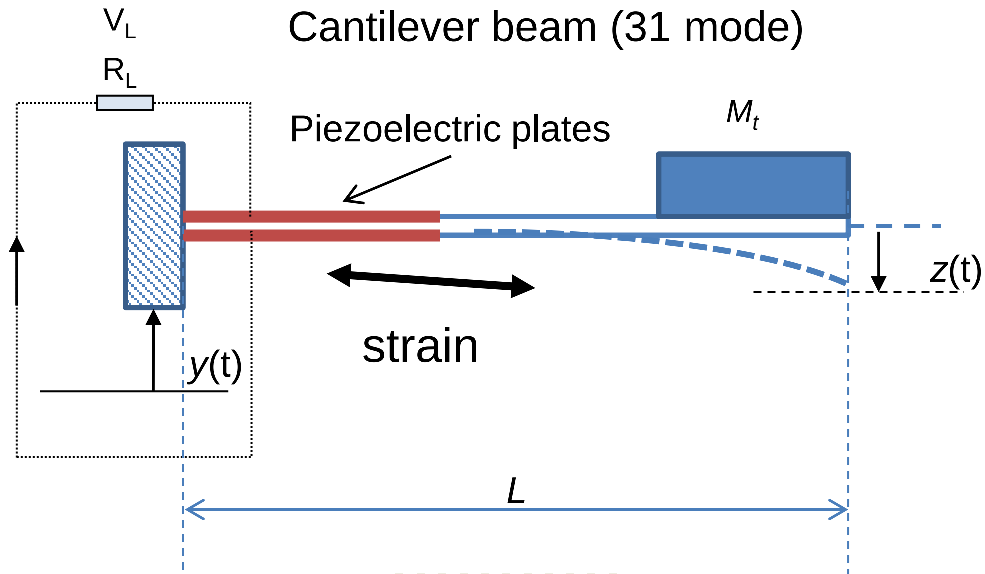
Piezoelectric conversion

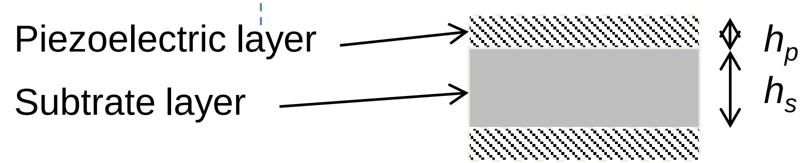
Mechanical-to-electrical conversion models

Piezoelctric bulk (33 mode)

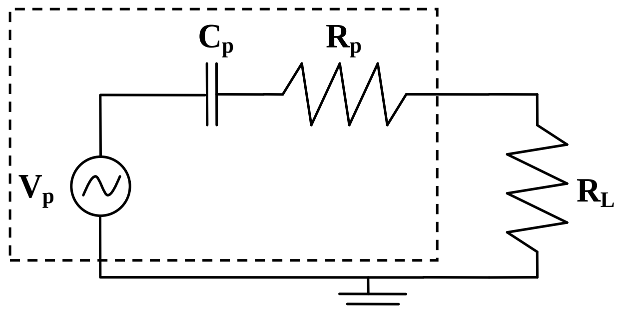


Cantilever beam (31 mode)





Piezoelectric generator



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

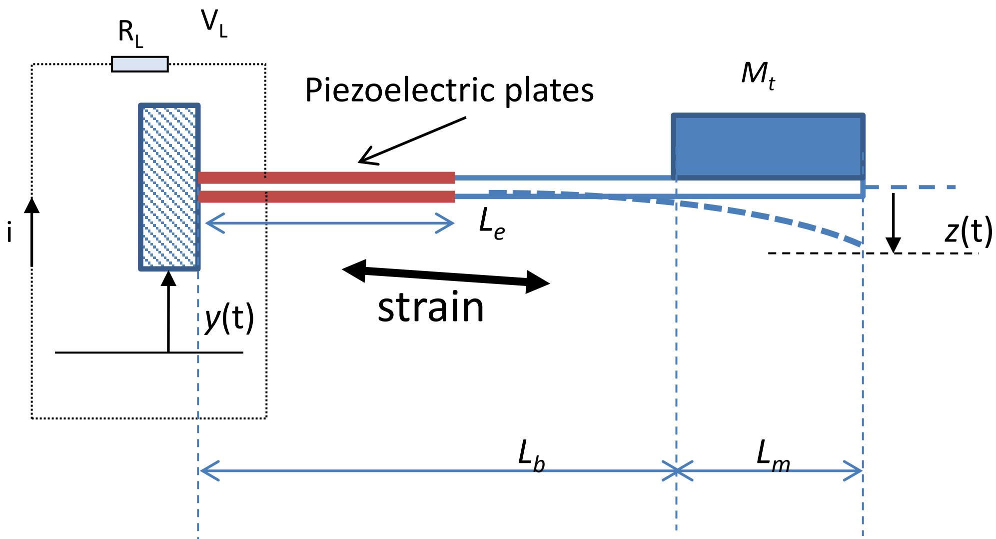
The instantaneous power delivered to the load is simply $P = \frac{V_{rms}^2}{R_L}$

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

Piezoelectric conversion

Mechanical-to-electrical conversion models

Cantilever beam (31 mode)



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

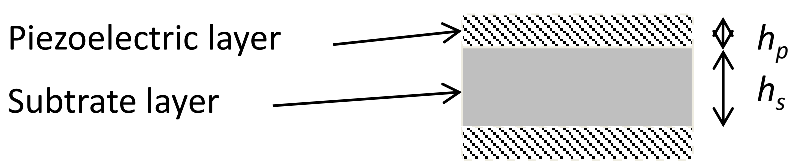
$$D_3 = e_{31} S_1 + \varepsilon_{33}^S E_3,$$

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

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

$$\delta_c = h_p \mathrm{d}_{31} E_p k_2 / \varepsilon_0 \varepsilon_r$$

$$\omega_c = 1 / R_L C_p$$



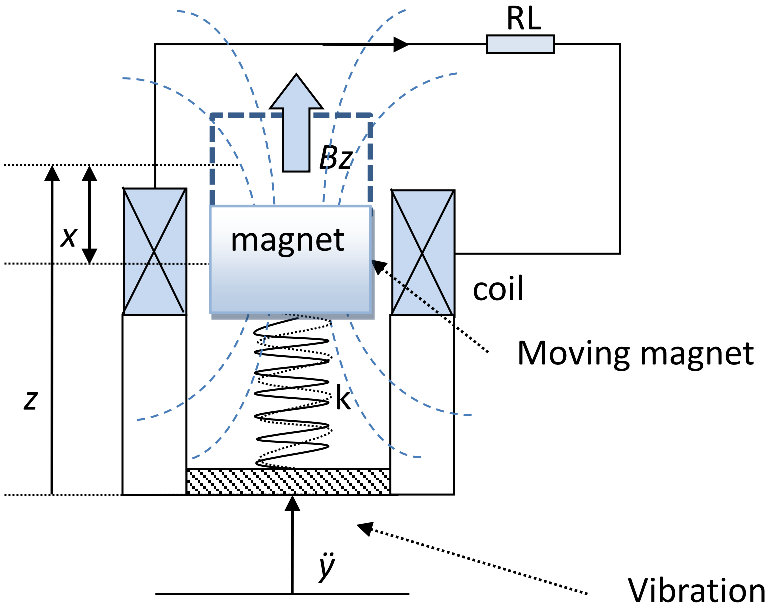
$$k_1 = \frac{2I}{b(2l_b + l_m - l_e)}$$ Av strain to vertical displacement

$$k_2 = \frac{3b(2l_b + l_m - l_e)}{l_b^2 \left(2l_b + \frac{3}{2} l_m\right)}$$ Input force to avg induced stress

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

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

Electromagnetic generators



The Faraday's law states that

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

for a coil moving through a perpendicular constant magnetic field, the maximum open circuit voltage across the coil is

$$V_{oc} = NBl\frac{dx}{dt}$$

N is the number of turns in the coil, *B* is the strength of the magnetic field, *l* is length of a winding and *x* is the relative displacement distance between the coil and magnet

The governing equations for only one-DOF model of a EM VEH can be written in a more 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

$\alpha = B_z l / R_L$ Electrical coupling force factor

$\delta_c = B_z l$ Conversion factor

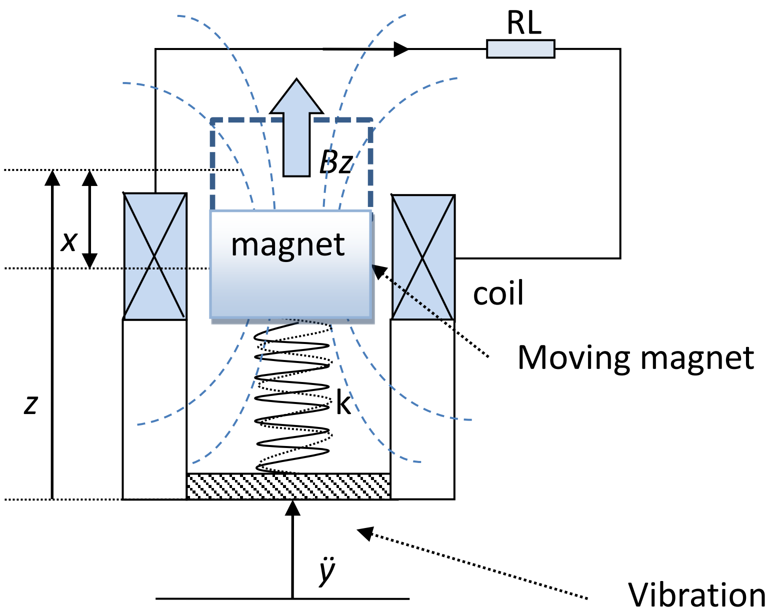
$\omega_c = R_L / L_e$ Characteristic cut-off frequency

$L_e = \mu_0 N^2 \pi R^2 / h_b$ 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



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

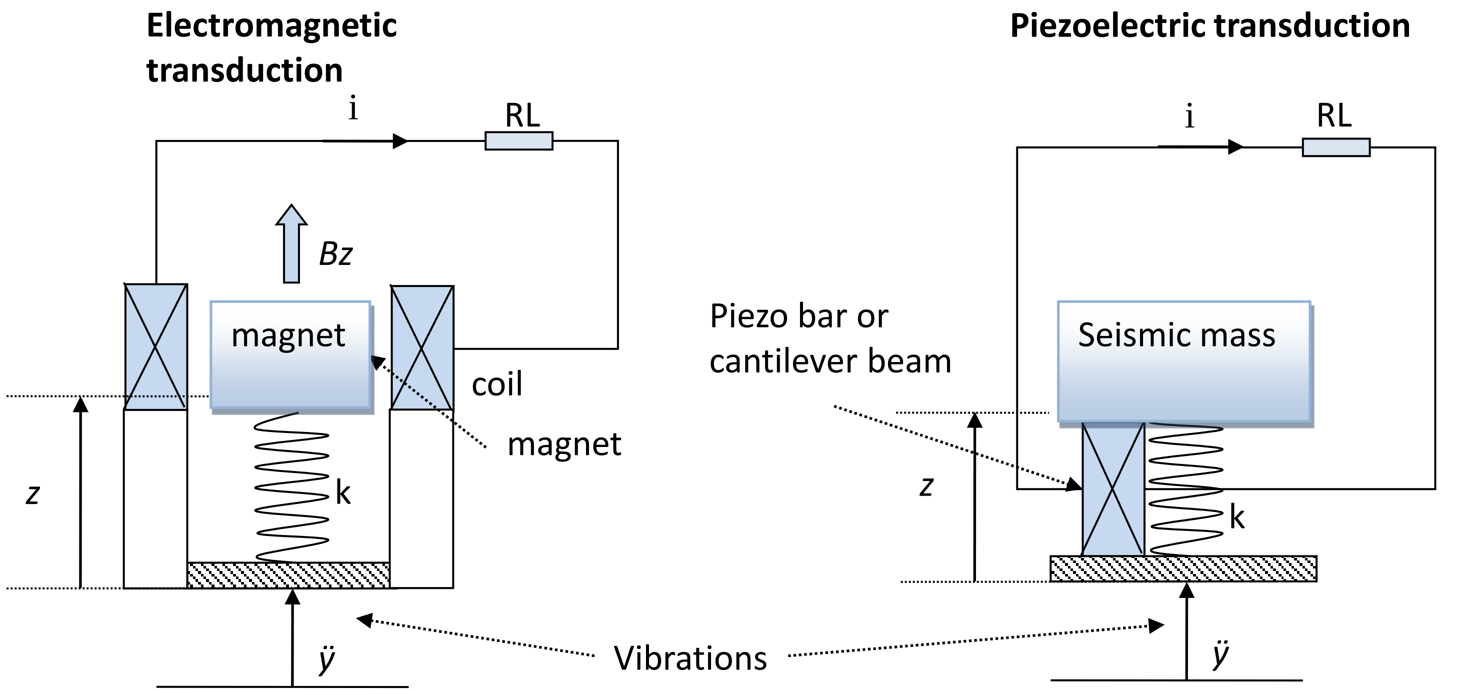
$$H_{ZY}(s) = \frac{Z}{Y}; \qquad H_{VY}(s) = \frac{V}{Y}$$

with the Laplace variable $s = j\omega$

let us calculate the electrical power P_e across the resistive load R_L in frequency domain with harmonic input $\ddot{y} = Y_0 e^{j\omega t}$

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

A general modeling approach



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

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	$\dfrac{R_L}{L_e}$	$\dfrac{1}{R_L C_0}$	Characteristic cut-off frequency

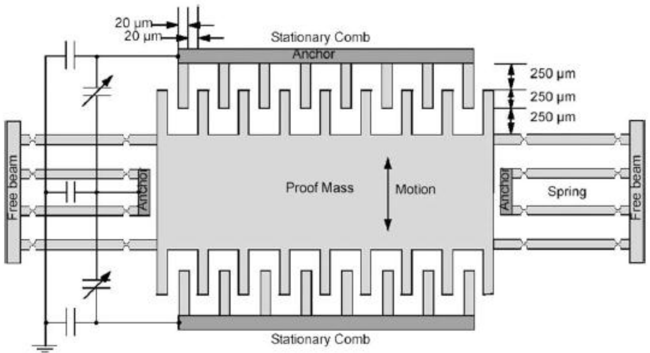
$$\ddot{y} = Y_0 e^{j\omega t}$$

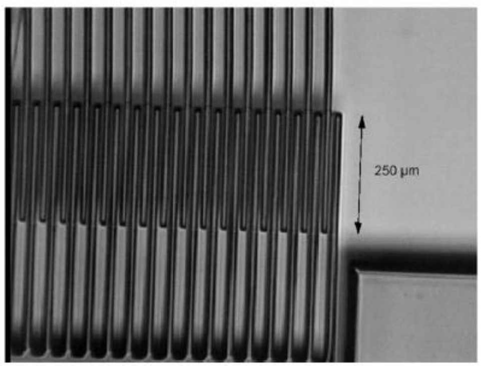
$$P_e(\omega) = \frac{Y_0^2}{2R_L}\left|\frac{m_2 \delta_c \omega_c j\omega}{(\omega_c + j\omega)(-m_2\omega^2 + d_2 j\omega + k_2) + \alpha\delta\omega_c j\omega}\right|^2$$

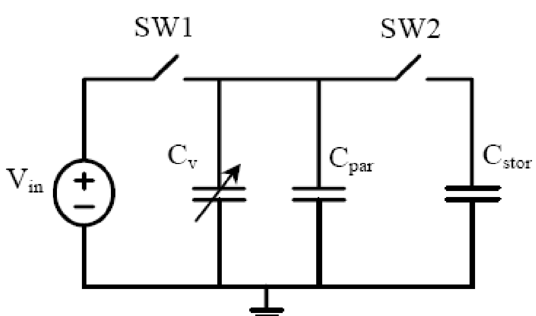
Joon Kim, K., F. Cottone, et al. (2010). "Energy scavenging for energy efficiency in networks and applications." Bell Labs Technical Journal **15**(2): 7-29.

Electrostatic generators

Operating principle [Roundy model]







Variation in capacitance causes either voltage or charge increase.

The electrostatic energy stored within capacitor is given by

$$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}Q^2C \qquad \text{with} \qquad C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

for a parallel plates capacitor

At constant voltage, in order to vary the energy it's needed to counteract the electrostatic force between the mobile plates

$$F_e = \frac{1}{2}\varepsilon \frac{AV^2}{d^2}$$

while at constant charge

$$F_e = \frac{1}{2}Q\frac{2d}{\varepsilon A}$$

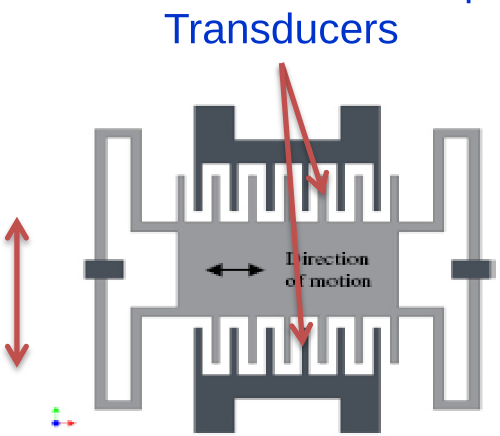
The maximum potential energy per cycle that can be harvested

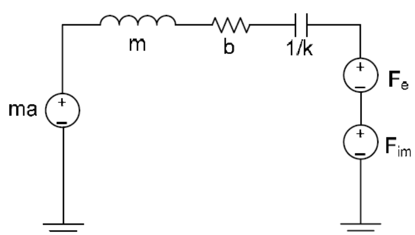
$$E = \frac{1}{2}V_{in}^2 \Delta C \left(\frac{C_{\max} + C_{par}}{C_{\min} + C_{par}} \right) \Rightarrow E = \frac{1}{2}V_{\max}V_{in}\Delta C$$

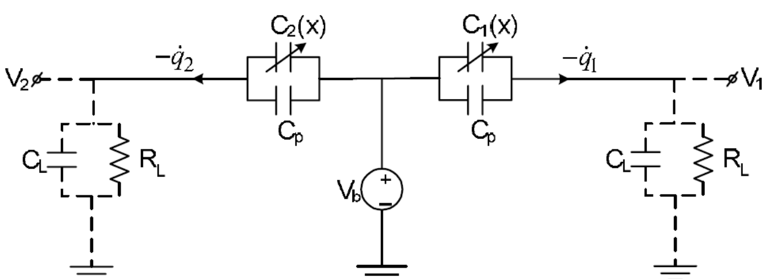
with $\Delta C = C_{max} - C_{min}$ and V_{max} which represents the maximum allowable voltage across a switch.

Electrostatic generators

Operating principle (E. Halvorsen, JMM 2012)







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

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

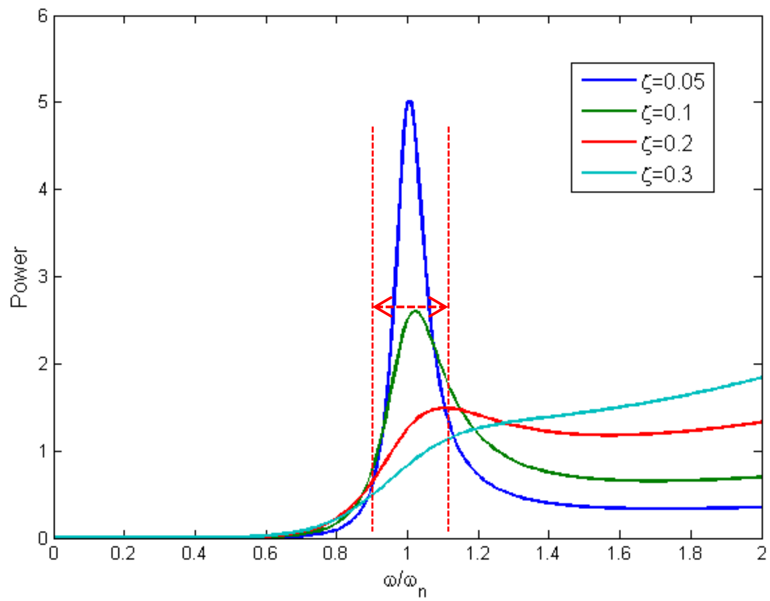
where

$$C_{1/2}(x)=C_0\left(1\pm\frac{x}{x_0}\right)=2N_f\varepsilon_0\frac{x_0t}{g_0}\left(1\pm\frac{x}{x_0}\right)$$

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.

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
  - provide suitable output voltages and are well adapted for miniaturization, e.g. in MEMS applications,
  - the electromechanical coupling coefficients for piezoelectric thin films are relatively small
  - relatively large load impedances are typically required for the piezoelectric transducer to reach it optimum working point.

- Electrostatic transducers
  - well suited for MEMS applications
  - but they have relatively low power density, and they need to be charged to a reference voltage by an external electrical source such as a battery.

- Electromagnetic transducers
  - very good for operation at relatively low frequencies in devices of medium size
  - suitable to drive loads of low impedance
  - expensive to integrate in microsystems: micro-magnets are complex to manufacture, and relatively large mass displacement is required.

Transduction techniques comparison

Type	Advantages	Disadvantages
Electromagnetic	• no need of smart material • no external voltage source	• bulky size: magnets and pick-up coil • difficult to integrate with MEMS • max voltage of 0.1V
Electrostatic	• no need of smart material • compatible with MEMS • voltages of 2~10V	• external voltage (or charge) source • mechanical constraints needed • capacitive
Piezoelectric	• no external voltage source • high voltages of 2~10V • compact configuration • compatible with MEMS • high coupling in single crystals	• depolarization • brittleness in PZT • poor coupling in piezo-film (PVDF) • charge leakage • high output impedance
Magnetostrictive	• ultra-high coupling coefficient >0.9 • no depolarization problem • high flexibility • suited to high frequency vibration	• non-linear effect • pick-up coil • may need bias magnets • difficult to integrate with MEMS

Wang, L. and F. Yuan (2007).
Energy harvesting by magnetostrictive material (MsM) for powering wireless sensors in SHM.
SPIE Smart Structures and Materials

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

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

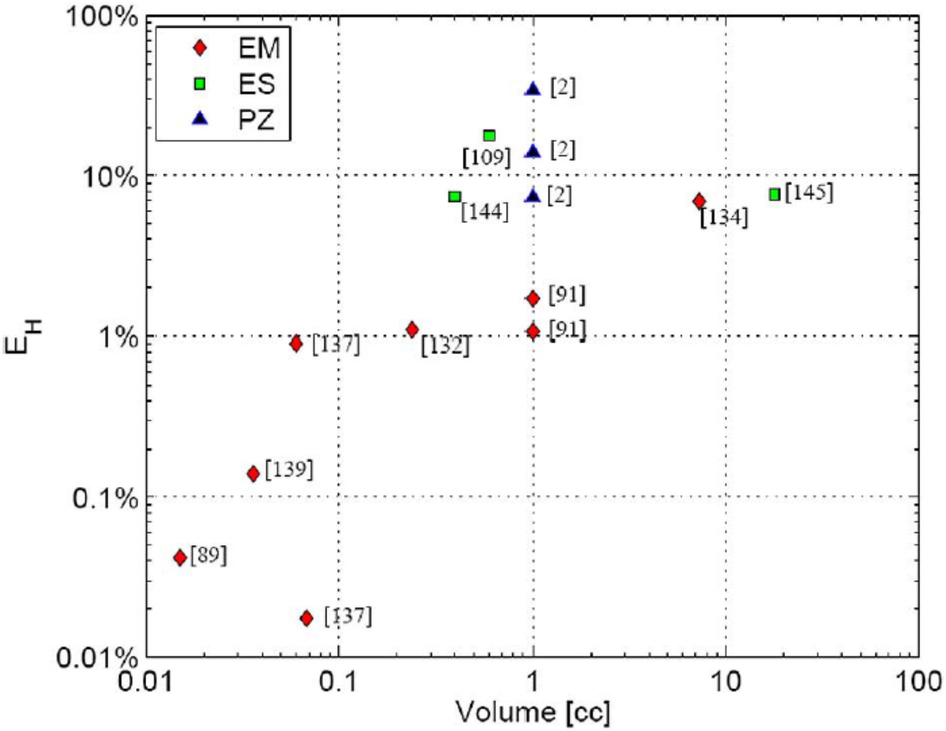
What about frequency bandwidth?

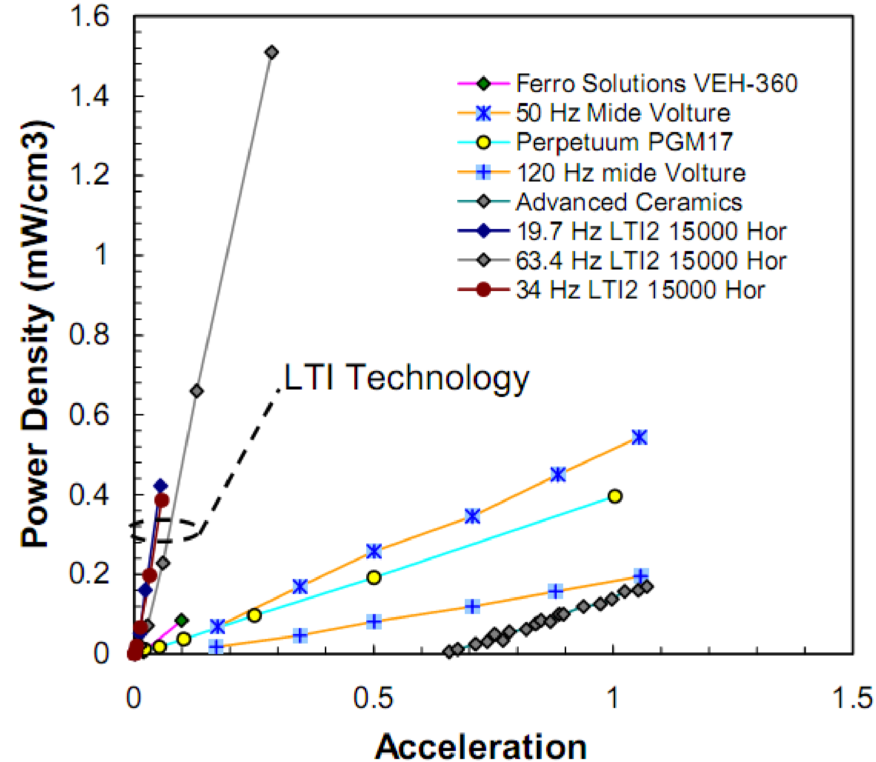
Generator[a]	Freq (Hz)	Acceln (m s^{-2})	Inertial mass (g)	Volume (cm^3)	Power (μW)	NPD (kgs m^{-3})
VIBES Mk2 EM	52	0.589	0.66	0.15	46	883.97
Glynne-Jones [13] EM	99	6.85	2.96	4.08	4990	26.07
Perpetuum [14] EM	100	0.400	50	30	4000	833.33
Ching [15] EM	110	95.5	0.192	1	830	0.09
White [16] PZ	80	2.3	0.8	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

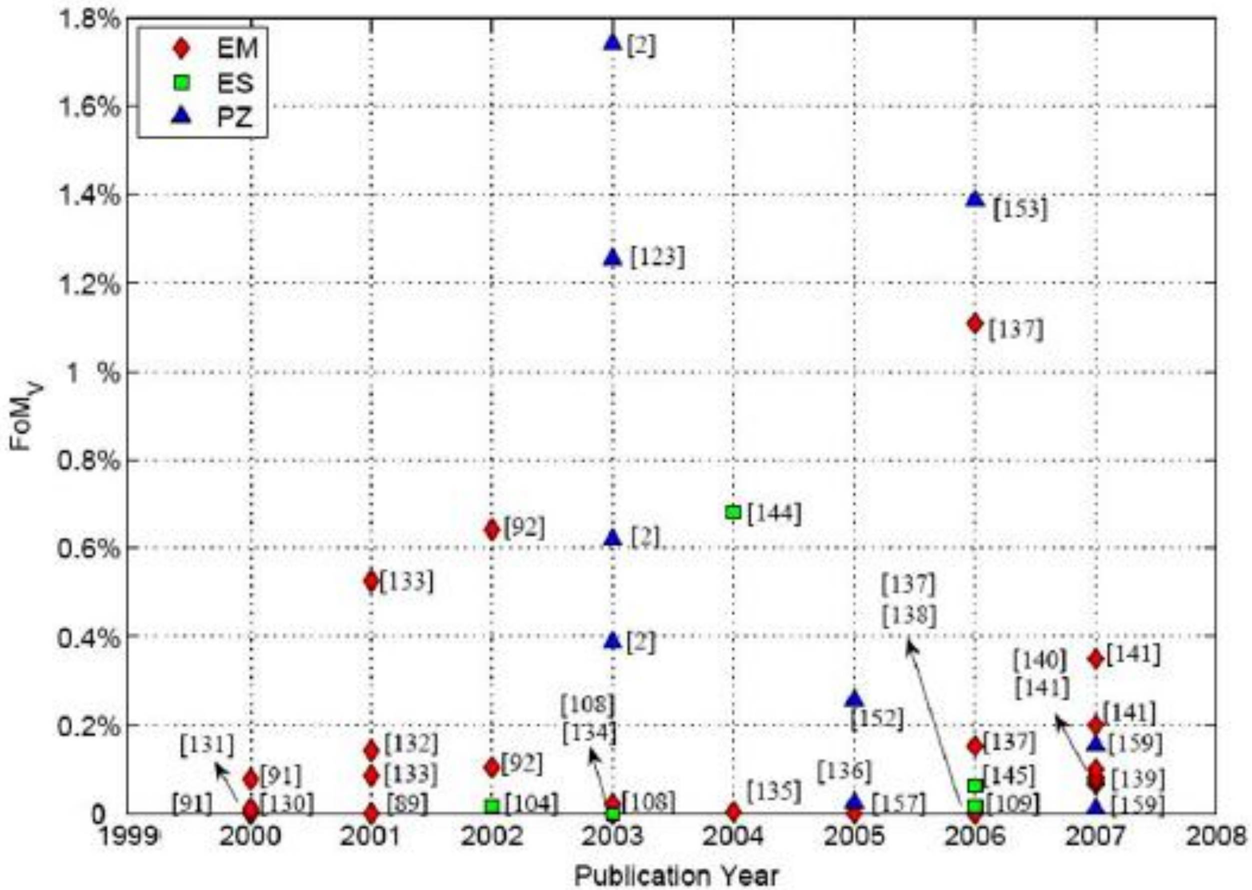




Mitcheson, P. D., E. M. Yeatman, et al. (2008). "Energy harvesting from human and machine motion for wireless electronic devices." Proceedings of the IEEE **96**(9): 1457-1486.

Performance metrics

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



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.

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!

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