Vibrational Energy Harvesting :

Energy — Life

Source of Conventional Energy is Limited

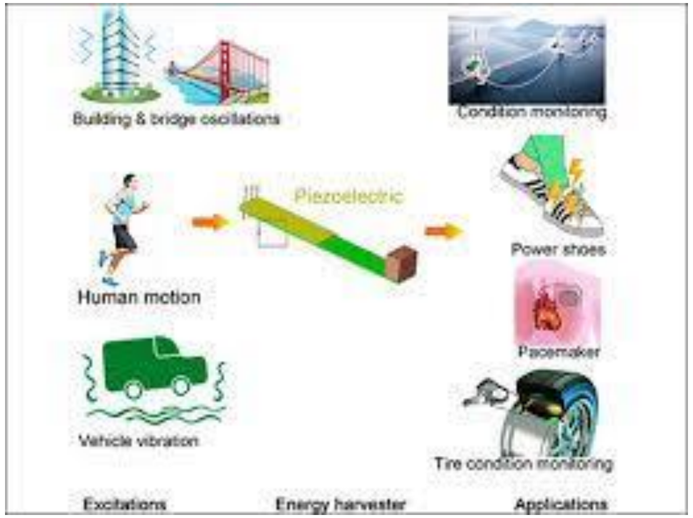
Commonly, Non-conventional Energy sources can not be used in many modern applications

Vibrational Energy Harvesting :

Larger-scale deployments : electrical and thermal power generation the presence of large-scale solar panels, wind turbines, water turbines are evident in many of today's rural and urban environments across the globe.

Energy harvesting generally relates to the process of using ambient energy, which is converted, primarily (but not exclusively) into electrical energy in order to power small and autonomous electronic devices.

Mainly a harvester is to exploit excess or wasted energy within an environment for powering the sensor node. The adopted transduction processes are often inefficient but can, evertheless, produce sufficient electrical energy to take a measurement and sometimes to transmit data via a radio frequency link to a remote base station.

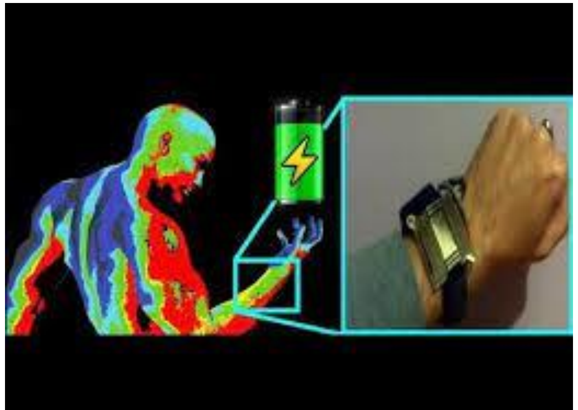


* Small scale solar =>Photodiode

*RF => Electromagnetic

* Vibration => Piezoelectric/electromagnetic

* Thermal => thermoelectric generator (T gradient)



Vibrational Energy Harvesting :

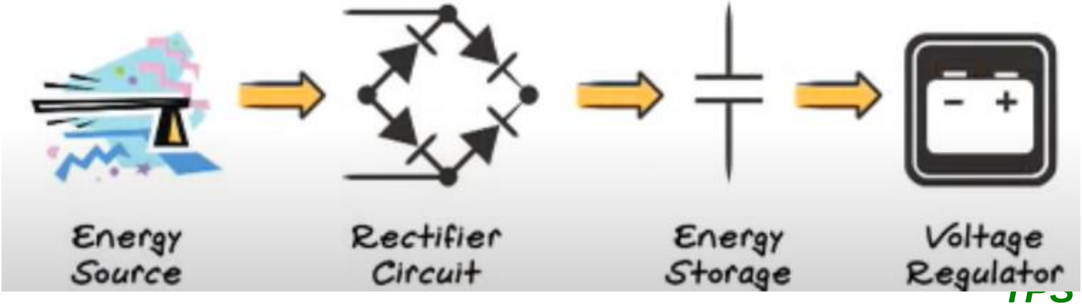
*Thermal=>The thermoelectric energy harvesting technology exploits the Seebeck effect. This effect describes the conversion of temperature gradient into electric power at the junctions of the thermoelectric elements of a thermoelectric generator (TEG) device.

*Small scale solar =>Photodiode+ Photovoltaic

*RF => converting energy from the electromagnetic (EM) field into the electrical domain (i.e., into voltages and currents).-----antennas+diodes

	Conditions	*Power Density*	*Area/volm*	*Energy/Day*
Vibration	$1m/s^2$	$100\ \mu W/cm^3$	$1cm^2$	8.64J (9%) $100\mu W$
Solar	Outdoor (indoor)	$7500(100)\ \mu W/cm^2$	$1cm^2$	324J 100mW (10%-25%)
Solar		$100\mu W/cm^2$	$1cm^2$	4.32J (0.1%-3.0%)
Thermal	$\Delta T = 5^0$	$60\mu W/cm^2$	$1cm^2$	2.59J 10mW
RF	900 MHz	$0.3\mu W/cm^2$	$1cm^2$	$0.1\mu W/cm^2$

A vibration harvester converts vibration energy into electrical energy. The harvester consists of a spring-mass oscillating system, a piezoelectric element, and a load resistor



Vibrational Energy Harvesting :

Harvesting process

Source → transducer → Rectifier → Energy Storage → Voltage Regulator → User

Usually used Sources

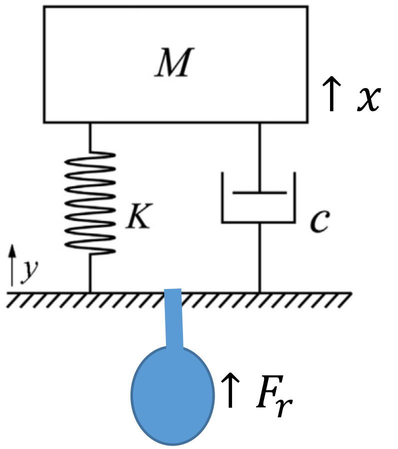
Source of Vibration	Frequency (Hz)
Walking	0.6 – 2.5
Ground vibration (man-made)	0 – 200
Human motion	0.6 – 5
Vehicles bouncing	1 – 10
Golden Gate Bridge	0.262
High-rise buildings	< 1

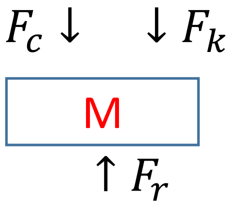
In this case vibrational energy to electrical energy. Mainly 3 types of transducers are used, namely,

1. **Electrostatic**
2. **Electromagnetic**
3. **Piezoelectric**

A **transducer is a device which converts one form of energy to other. In this case vibrational energy to electrical energy:**

Inertial Generators





1. Linear spring stiffness
2. Damping is proportional to velocity
3. Wheels are rigid
4. Mass constant

$$M\ddot{x} + c\dot{x} + kx = F_r$$

$$F_r = F_0 sim\omega t$$

$$\alpha = \frac{F_0}{M}$$
$$\nu = c/2M$$
$$\omega_0^2 = k/M$$

The **transmissibility (TR)**, defined as the ration of the tranmistted force to that of the disturbing force

$$\ddot{x} + \nu\dot{x} + \omega_0^2 x = \alpha sin\omega t$$

$$x(t) = Xsin(\omega t - \delta)$$

$$X = \frac{\alpha}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2}}$$

$$\tan\delta = \frac{2\nu\omega}{\omega_0^2 - \omega^2}$$

At resonance, $X = \frac{\alpha}{2\nu\omega}$ => Max

$$F_0 = Xk\sqrt{(1 - \omega^2/\omega_0^2)^2 + (2\nu\omega/\omega_o)^2}$$

$$F_T = \sqrt{(kX)^2 + (c\omega X)^2} = kX\sqrt{1 + (2\nu\omega/\omega_n)^2}$$

$$TR = \left|\frac{F_T}{F_0}\right| = \sqrt{\frac{1 + (2\nu\omega/\omega_n)^2}{(1 - (\omega/\omega_n)^2)^2 + (2\nu\omega/\omega_n)^2}}$$

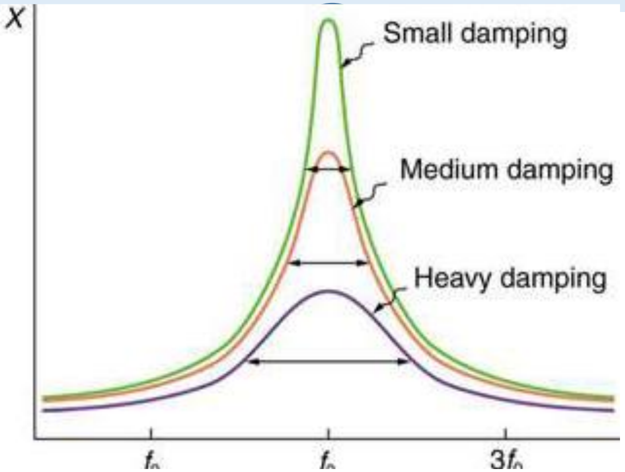
$$x(t) = \frac{F_0/M}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2}}\sin(\omega t + \tan^{-1}\left\{\frac{2\nu\omega}{\omega_0^2 - \omega^2}\right\})$$

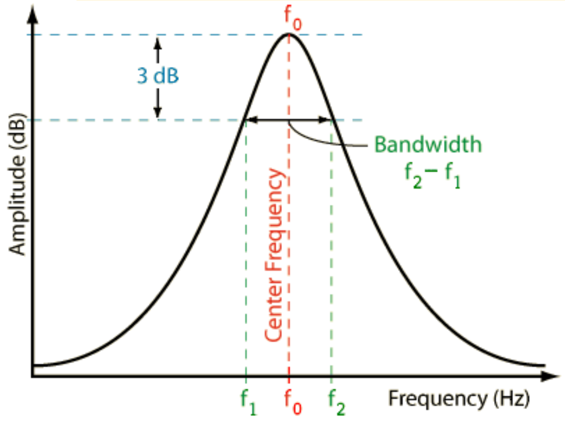
$$W = F.x$$

$$P = \frac{dW}{dt} = F.v$$

$$P = F_0 sim\omega t.X\omega cos(\omega t - \delta)$$

Vibrational Energy Harvesting : $x(t)=\frac{\alpha}{\sqrt{(\omega_0^2-\omega^2)^2+(2\nu\omega)^2}}\sin(\omega t+\tan^{-1}\left\{\frac{2\nu\omega}{\omega_0^2-\omega^2}\right\})$





$$P=\frac{dW}{dt}=F.v$$

$$P=F_0sim\omega t.X\omega cos(\omega t-\delta)$$

$$P=X\omega F_0 sim\omega t\,[\,cos\omega t cos\delta+sin\omega t sin\delta]$$

$$<P>_t=X\omega F_0[<sim\omega t cos\omega t>cos\delta+<\sin^2\omega t>sin\delta]$$

$$<P>=\frac{1}{2}\omega F_0 X sin\delta$$

$$<P>=\frac{1}{2}\omega F_0 X sin\delta$$

$$=\frac{1}{2}\omega F_0\frac{F_0}{M\sqrt{(\omega_0^2-\omega^2)^2+(2\nu\omega)^2}}\frac{2\nu\omega}{\sqrt{(\omega_0^2-\omega^2)^2+(2\nu\omega)^2}}$$

The **wider** the **bandwidth** the **more energy** you can harvest. The **lower resonance** frequency the **more** kinetic **energy** you can harvest.

The harvesting bandwidth is defined as the range of frequencies where output power is **higher than or equal** half of the maximum power achieved at resonance.

$$\boxed{<P>=\frac{F_0^2\nu\omega^2}{M\omega_0^2\left[\left(1-\frac{\omega^2}{\omega_0^2}\right)^2+\left(2\nu\frac{\omega}{\omega_0}\right)^2\right]}}\quad <P>_{max}=\frac{F_0^2}{4\nu^2M}$$

$$\boxed{<P>_{1/2}=\frac{1}{2}<P>_{max}\Rightarrow\frac{F_0^2\nu\omega^2}{M\omega_0^2\left[\left(1-\frac{\omega^2}{\omega_0^2}\right)^2+\left(2\nu\frac{\omega}{\omega_0}\right)^2\right]}=\frac{F_0^2}{8\nu^2M}}$$

Two values of frequency, $\omega_1=\omega_0-\nu,\quad \omega_2=\omega_0+\nu$

Half band width, $\Delta\omega=\omega_2-\omega_1=2\nu.$

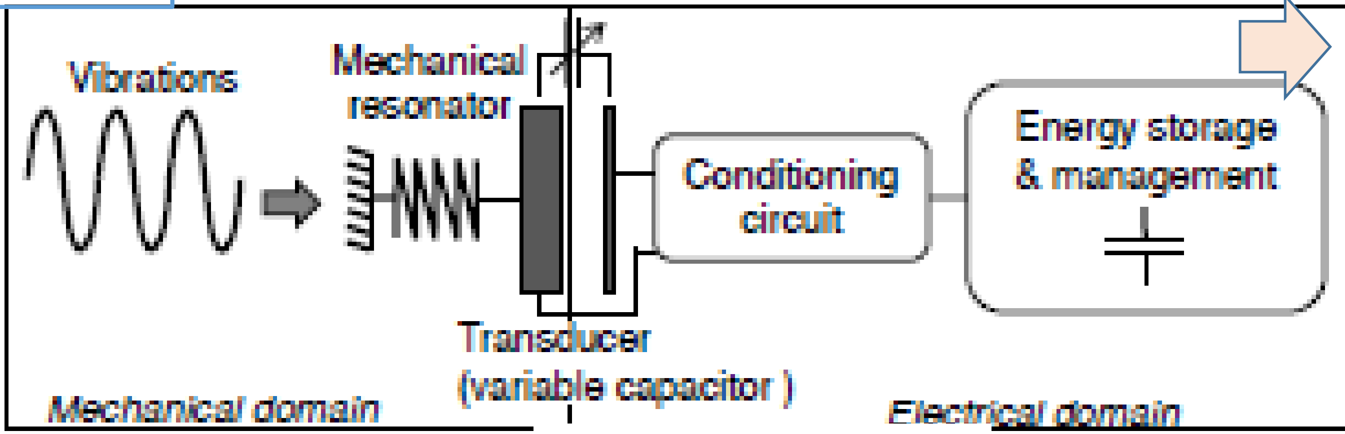
To Choose a VEH:

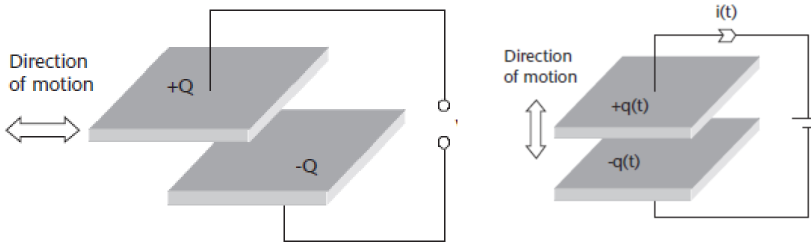
- frequency Resonance position.
- Harvesting Bandwidth (3dB bandwidth).
- Amplitude.
- Output power.
- Physical profile

These types of transducer consist of a variable capacitor.

External mechanical vibrations cause the gap between the plates to vary and hence the capacitance changes

In order to extract energy, the plates must be charged and the mechanical vibrations work against the electrostatic forces present in the device.



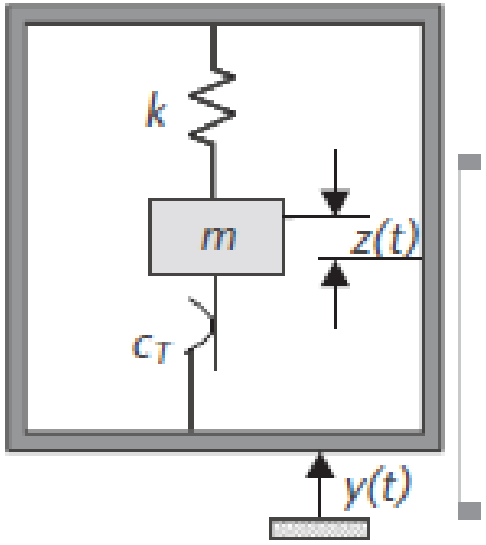


$C = Q/V$ $C = \epsilon A/d$ $V = \dfrac{Qd}{\epsilon A}$ Energy, $E = \frac{1}{2}CV^2 = \frac{1}{2}Q^2/C = \frac{1}{2}QV$

Electrostatic generators can be either voltage- or charge-constrained. Voltage constrained devices have a constant voltage applied to the plates, and therefore the charge stored on the plates varies with changing capacitance. This typically involves an operating cycle that starts with the capacitance being at a maximum value (C_{max})

At this stage, the capacitor is charged up to a specified voltage (V) from a reservoir while the C remains constant. The voltage is held constant while the plates move apart until the capacitance is minimized (C_{min}). The excess charge flows back to the reservoir as the plates move apart and the net energy gained is given by

Energy gain , $E = \frac{1}{2}(C_{max} - C_{min})V^2$



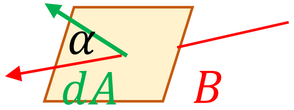
Vibrational Energy Harvesting :

Electromagnetic Transducer

Faraday's Law: $V = -\frac{d\phi}{dt}$

For a coil of N number of turns: $V = -\frac{d\Phi}{dt} = -N\frac{d\phi}{dt}$

$\Phi = \sum_{i,=1,N} \int_{A_i} B.dA\,,$



$\Phi = NBAsin\alpha$

For a coil of N number of turns:

$V = -N\frac{dB}{dt}Asin\alpha$

$V = -\frac{d\Phi}{dx}\frac{dx}{dt} = -NA\frac{dB}{dx}\frac{dx}{dt}$

$F_{EM} = D_{EM}\frac{dx}{dt}$

$P(t) = F_{EM}\frac{dx}{dt} = D_{EM}\left(\frac{dx}{dt}\right)^2$

$P(t) = \frac{V^2}{R_L+R_e+j\omega L_e}$

$D_{EM}\left(\frac{dx}{dt}\right)^2 = \frac{V^2}{R_L+R_e+j\omega L_e} = \frac{1}{R_L+R_e+j\omega L_e}\left(-\frac{d\Phi}{dx}\frac{dx}{dt}\right)^2$

In most linear vibration-generators, the motion between the coil and the magnet is in a single direction (x-direction, say) and B, is produced by a permanent magnet is constant of t.

Power is extracted from the generator by connecting the coil terminals to a load resistance, $\boldsymbol{R_L}$, and allowing a current to flow in the coil. This current creates its own magnetic field which acts to oppose the field giving rise to it. The interaction between the fields gives rise to a force which opposes the motion. It is by acting against this electromagnetic force, $\boldsymbol{F_{EM}}$, that the mechanical energy is transformed into electrical energy. The EM force is proportional to the current ($\boldsymbol{i}$) and hence the velocity (v) and is expressed as the product of an EM damping, D_{EM} and v.

The instantaneous power extracted by the electromagnetic force

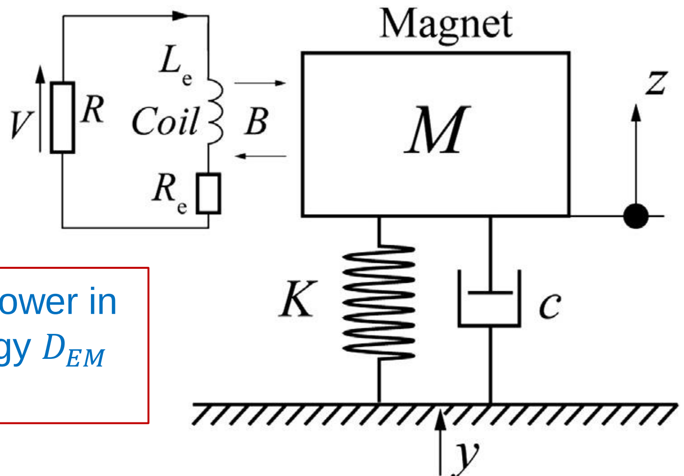
This power is dissipated in the coil and load impedance. Equating the power dissipation in the coil and load to that obtained from the electromagnetic force

where R_L and R_e are load and coil resistances, respectively, and L_e is the coil inductance.

$$D_{EM} = \frac{1}{R_L+R_e+j\omega L_e}\left(\frac{d\Phi}{dx}\right)^2$$

D_{EM} increases with the flux linkage gradient, and decreases with the coil impedance.

To extract the maximum power in the form of electrical energy D_{EM} should be Maximized.



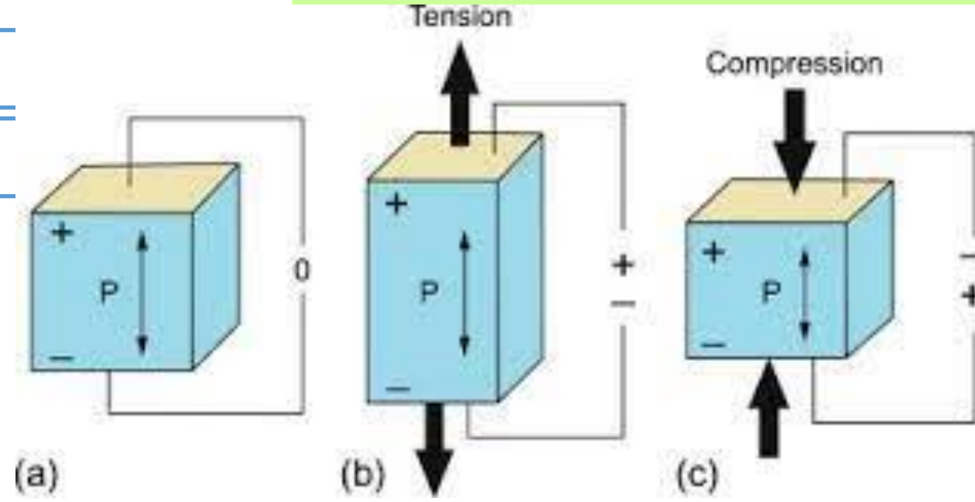
Vibrational Energy Harvesting : Piezoelectric Transducer

Waves and Vibrations (PH2001)

Piezoelectricity: Pierre Curie and Jacques Curie (1880)

Piezoelectricity Ceramics (1940) --

Piezoelectric materials, a subset of ferroelectric materials, exhibit the formation of a local charge separation (electrical dipoles) under mechanical stress due to their non-centrosymmetric crystal structure.



Piezoelectric materials:

Naturally occurring biological: human bone, cellulose, deoxyribonucleic acid, tendon, collagen,

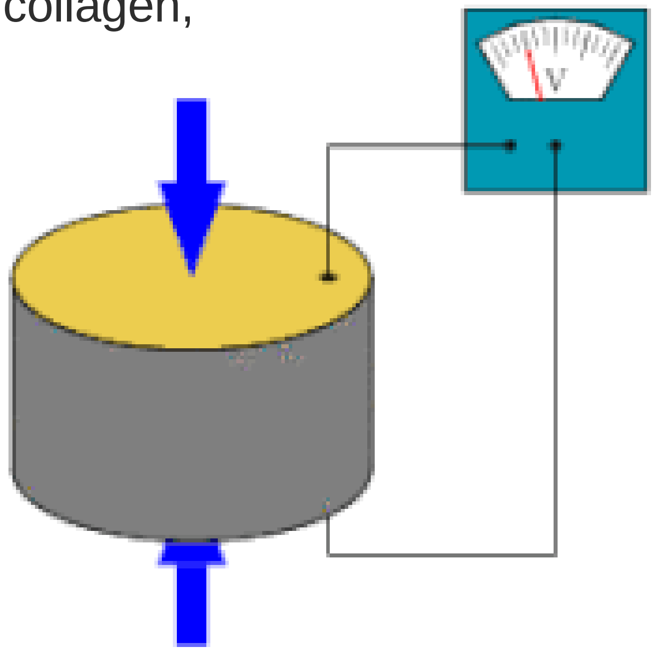
Natural crystals: quartz (SiO_2), Rochelle's salt, topaz, tourmaline group minerals, etc.

Synthetic ceramics: lead zirconium titanate, PZT($Pb[Zr_xTi_{1-x}]O_3$ $0 \le x \le 1$), barium titanate ($BaTiO_3$), potassium niobate ($KNbO_3$), bismuth ferrite ($BiFeO_3$), ZnO, etc.

brittleness, low strain capabilities, and the toxicity of Pb containing materials

Synthetic piezoelectric polymers: poly(vinylidene fluoride) ($(CH_2\text{-}CF_2)_n$), co-polymers of PVDF such as poly(vinylidenefluoride-*co*-trifluoroethylene) P(VDF-TrFE), polyimide, odd numbered polyamides, cellular polypropylene, etc.

Low material density, flexibility, biocompatibility, and lower costs.

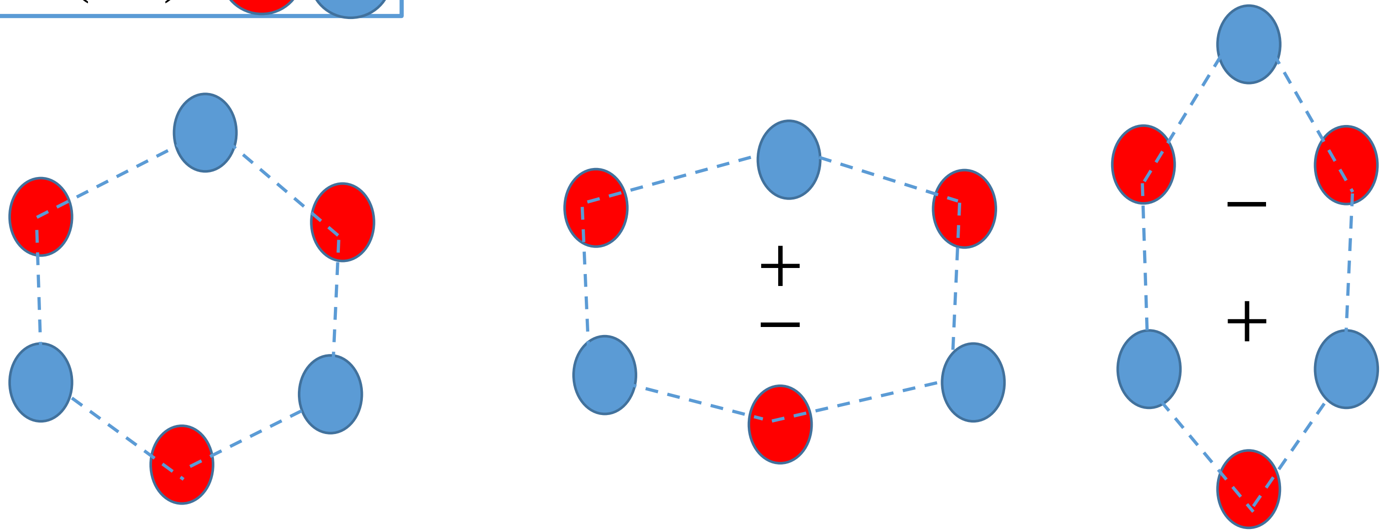


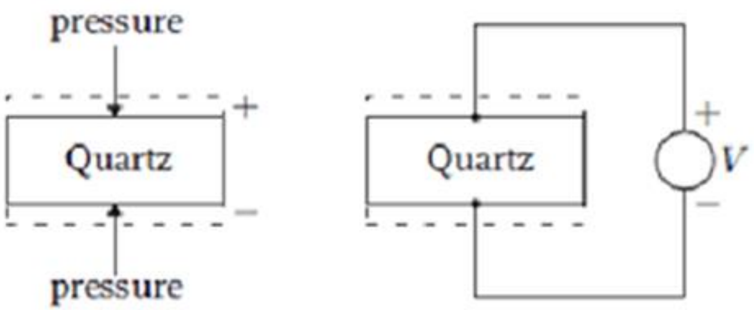
Vibrational Energy Harvesting :

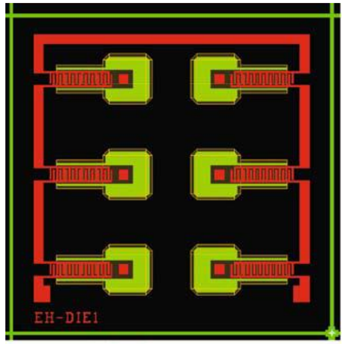
Piezoelectric Transducer

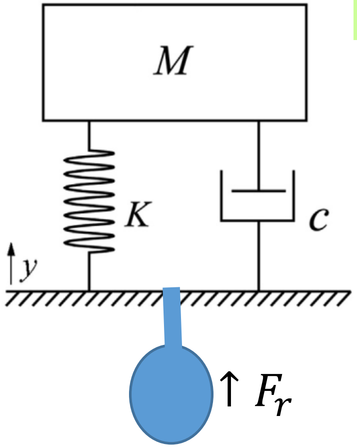
Waves and Vibrations (PH2001)

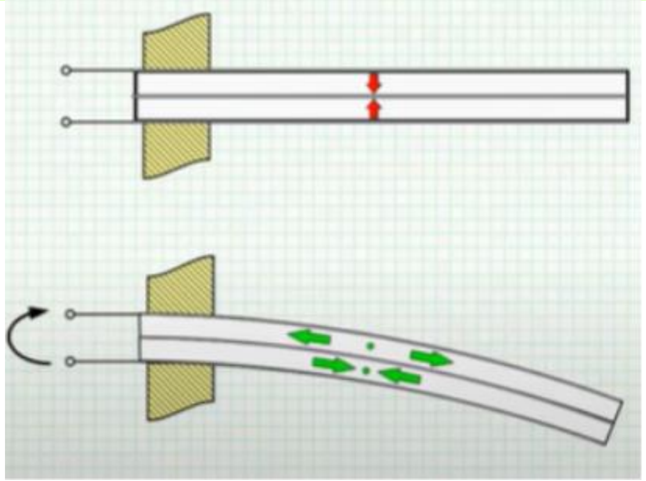
Qurtz (SiO)-- Si O

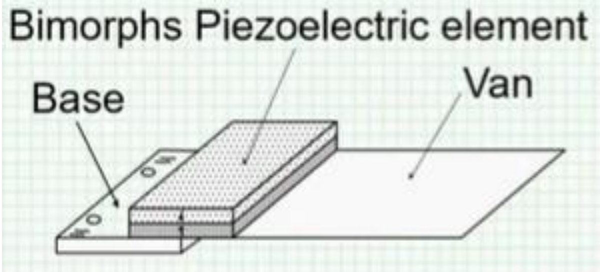








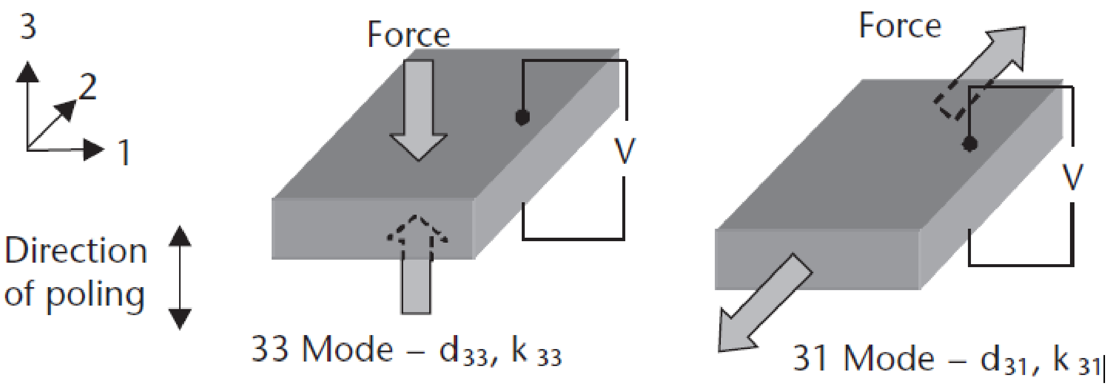




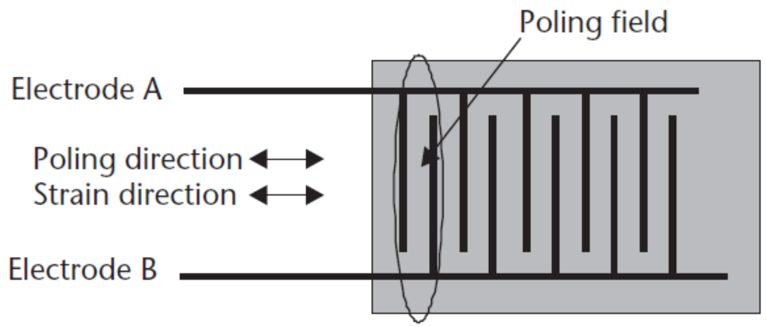
Electromechanical coupling coefficient (k) → $K^2 = \frac{converted\ energy}{input\ energy}$, $0 < \mathrm{K}^2 < 1$

$$K^2 = \frac{converted\ energy}{input\ energy}\ , \qquad 0 < K^2 < 1$$

Electromechanical coupling factor, K_{ij}, is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy, or converts mechanical energy into electrical energy.
The first subscript i to K denotes the direction along which the electrodes are applied; the second j denotes the direction along which the mechanical energy is applied,



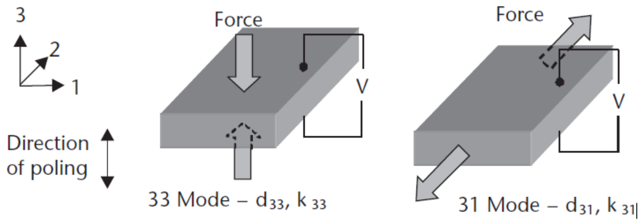
Piezoelectric charge constant, d_{ij}: Induced polarization in direction i per unit stress applied in direction j; or Induced strain



Property	*Quartz*	*PZT-5H*	*PZT-5A*	*$BaTiO_3$*	*PVDF*
Material type	Single crystal	Piezoceramic	Piezoceramic	Piezoceramic	Polymer
d_{33} (10^{12} C/N)	–2.3 (d_{11})	593	374	149	–33
d_{31} (10^{12} C/N)	–0.93 (d_{12})	–274	–171	78	23
k_{33}	0.07	0.75	0.71	0.48	0.15
k_{31}	—	0.39	0.31	0.21	0.12
Relative permittivity ($\varepsilon/\varepsilon_o$)	4.4	3,400	1,700	1,700	12
Curie temperature (C)	573	195	365	120	~150

Vibrational Energy Harvesting : Piezoelectric Transducer

$$K^2 = \frac{converted\ energy}{input\ energy}, \qquad 0 < K^2 < 1$$



when an electric field E is applied to a piezoelectric material. Since the input electrical energy density is $U_{elec}(\text{in}) = \frac{1}{2}\epsilon_0\epsilon^x E^2$, ($\epsilon^x$: permittivity under stress free condition) and the stored mechanical energy density under zero external stress is given by $U_{mech}(\text{stored}) = \frac{1}{2} \times stiffness \times x^2 = \frac{1}{2}(Ed)^2/S^E$ (s^E: elastic compliance under short-circuit condition (constant E), d: piezoelectric coefficient polarization for unit applied stress (pC/N or m/V), the inverse of Young's modulus), k^2 can be calculated as the following:

$$K^2 = \frac{\frac{1}{2}(dE)^2/S^E}{\frac{1}{2}\epsilon_0\epsilon^x E^2} = \frac{d^2}{\epsilon_0\epsilon^x S^E},$$

In some dielectric materials (crystals, ceramics, polymers) without center symmetry, an electric polarization can be generated by the application of mechanical stresses

P = d σ, direct effect **e= d E** , converse effect

P: polarization (pC/m2) σ : stress (N/m2) e :strain

d: piezoelectric coefficient (pC/N or m/V)

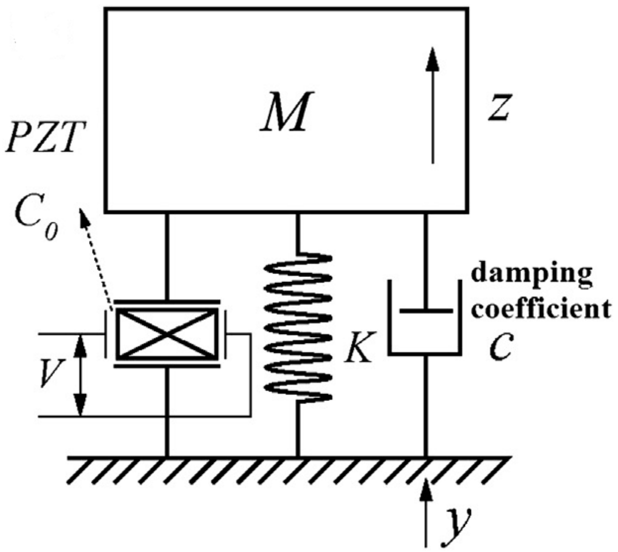
The generalized Hooke's law relating stresses σ_{ij} to strains ϵ_{ij} for anisotropic elastic materials via compliance Matrix S,

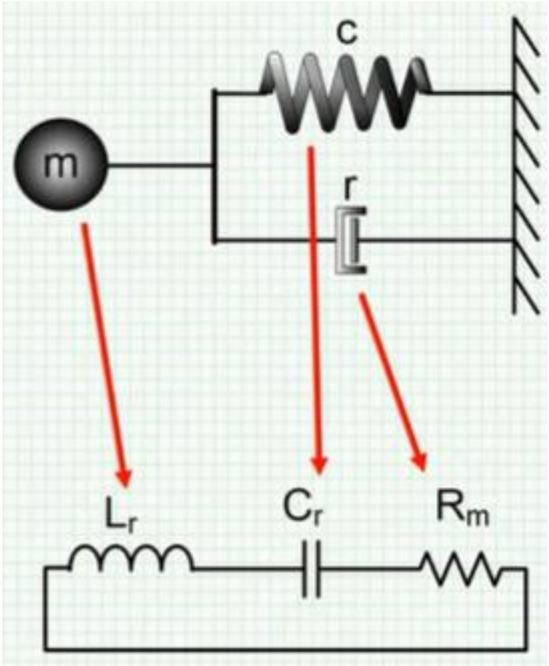
$\epsilon_{ij} = S\sigma_{ij}$

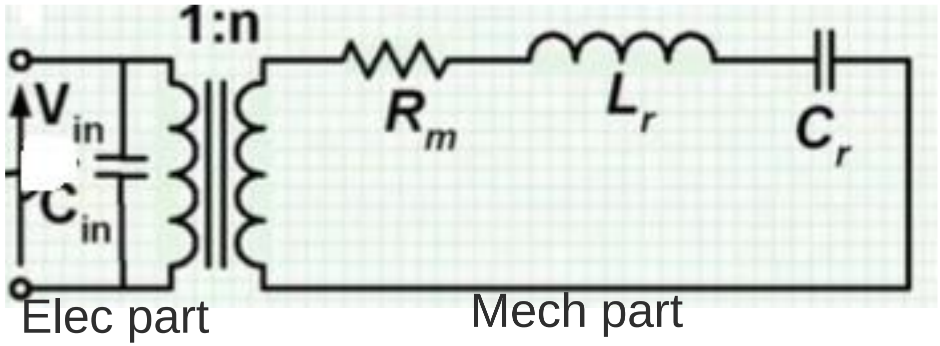
$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$

Vibrational Energy Harvesting :

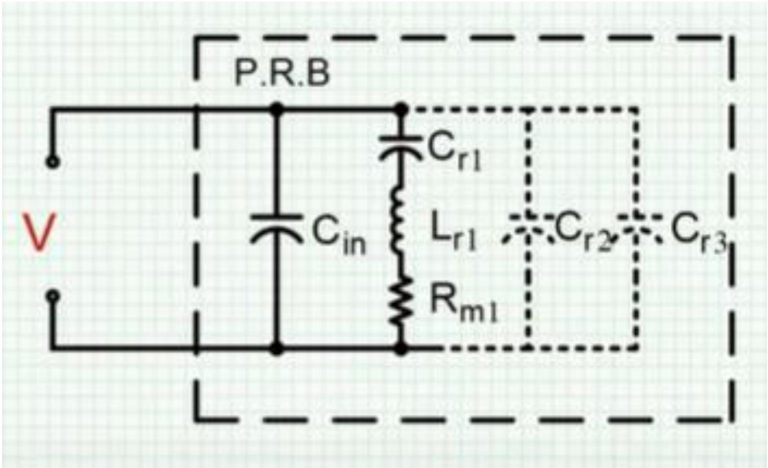
Piezoelectric Transducer





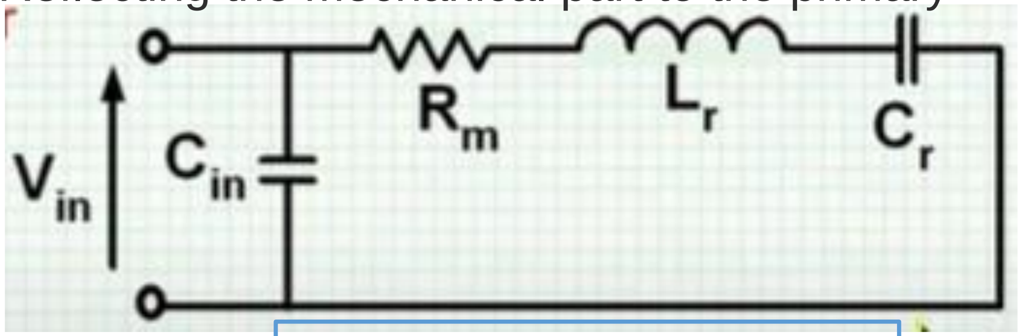


Transformer couples the electrical and mechanical variables



Mechanical System	Electronic system
m-mass	L
r-losses	R
c=1/stiffness	C
v-velocity	i
F-force	V

Reflecting the mechanical part to the primary



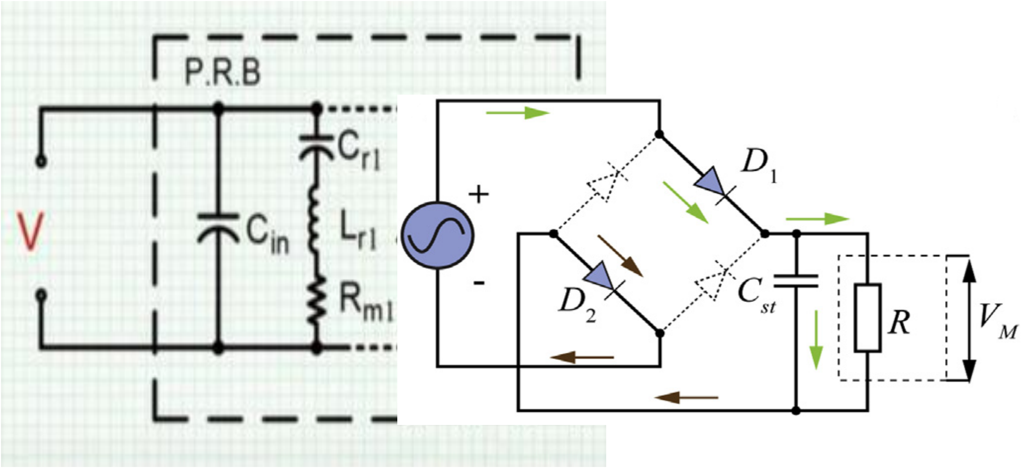
Piezoelectric Transducer

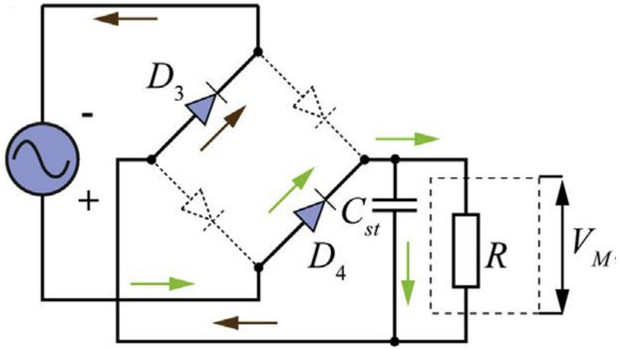
Vibrational Energy Harvesting :

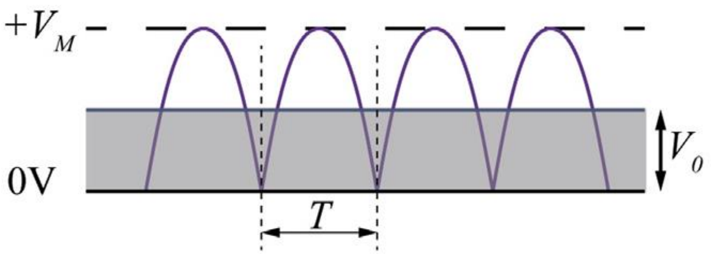
Piezoelectric Transducer

Waves and Vibrations (PH2001)

AC power supply (**PS**) → **AC-DC converter** → AC **PS**





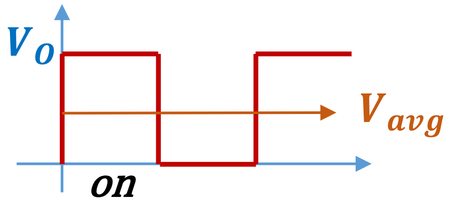


Switching (Chopper)

Fixed (**PS**) → **DC-DC converter** → **adjustable/controlled PS**

On/closed➔ V=0, P=VI=0

Buck↓ Boost↑ Boost Buck



Linear regulator: Transistor (drop of voltage across it controlling base bias)

Chopper: step up /step down

Power loss

DC+AC

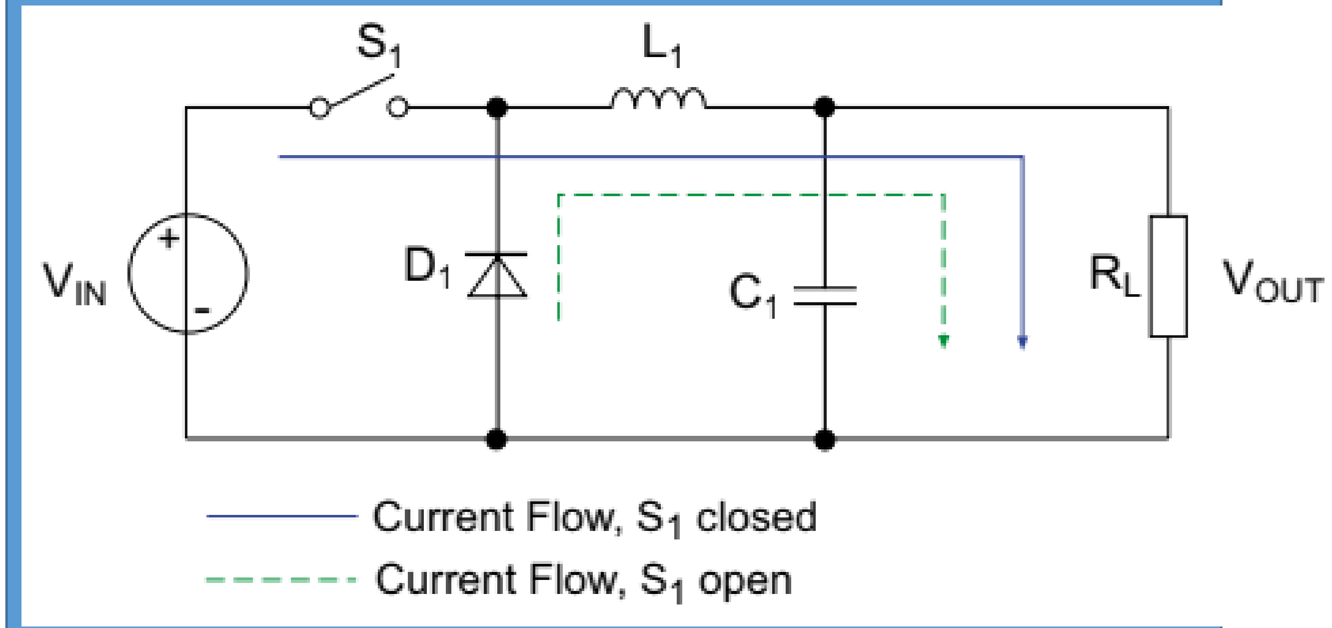
TPS

Vibrational Energy Harvesting :

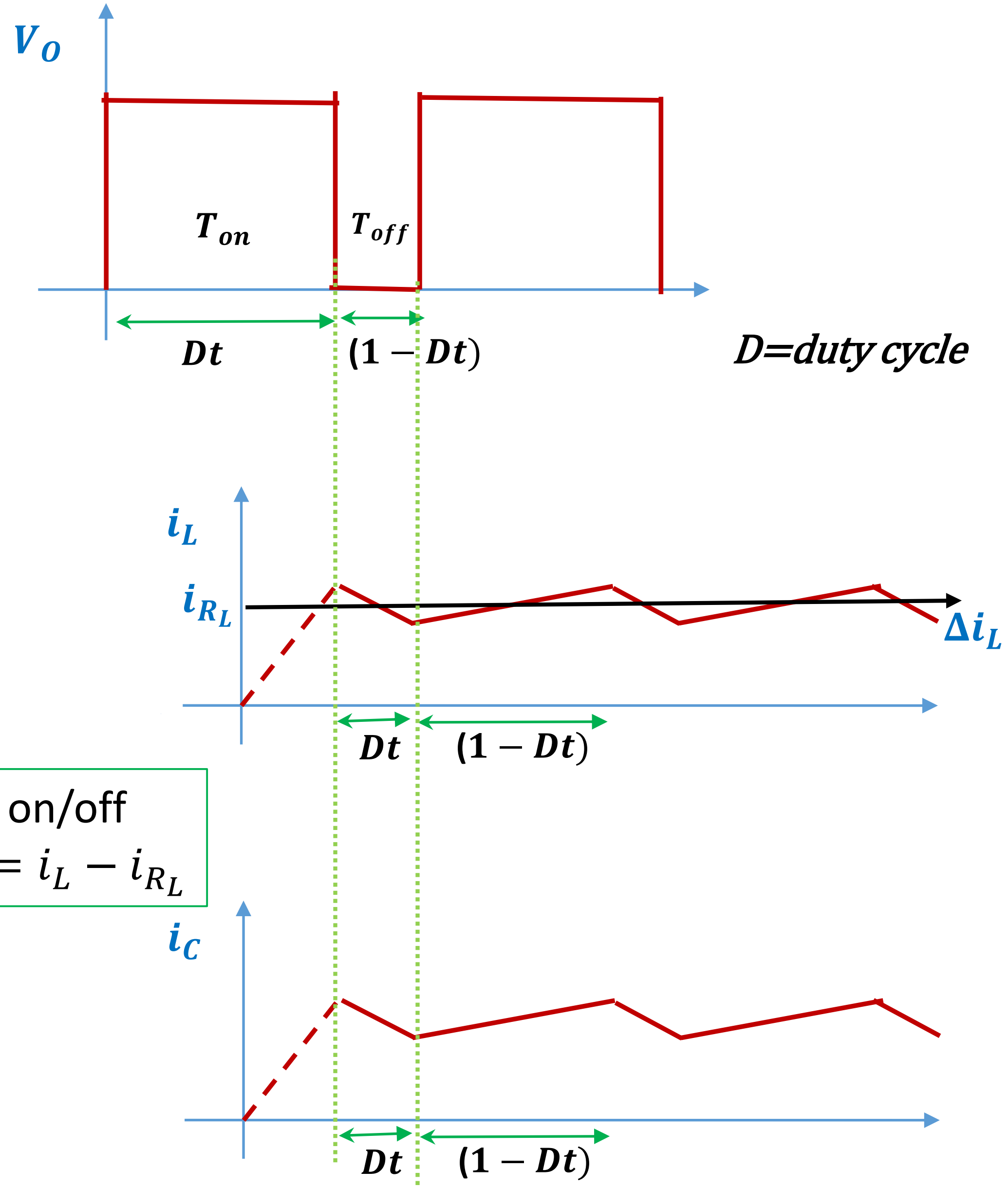
Switching

Chopper+Filter

Low pass: passes DC and blocks AC



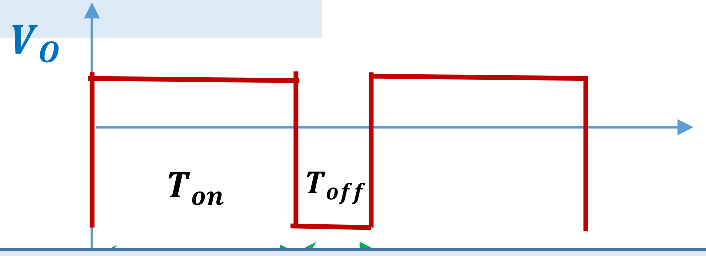
D1 helps L1 to discharge when S1 is open



For on/off
$i_C = i_L - i_{R_L}$

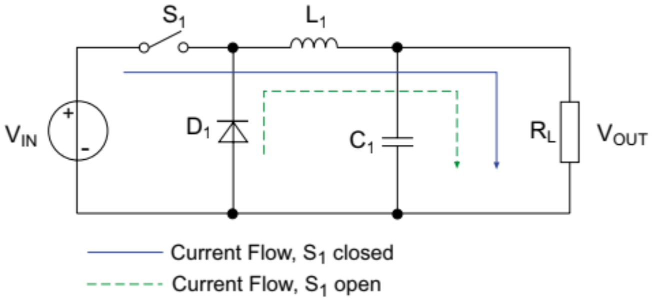
Vibrational Energy Harvesting :

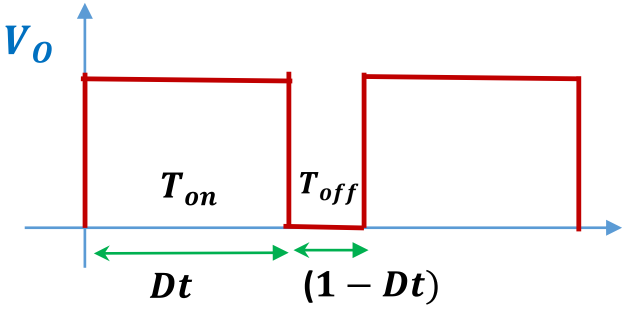
Volt-Sec balance

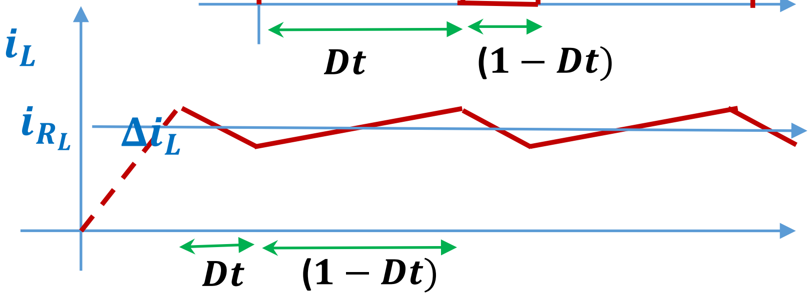


$$\Delta i_L = \frac{V_O}{L}(1-D)t$$

$$L = \frac{V_O}{\Delta i_L}\frac{1-D}{f}$$

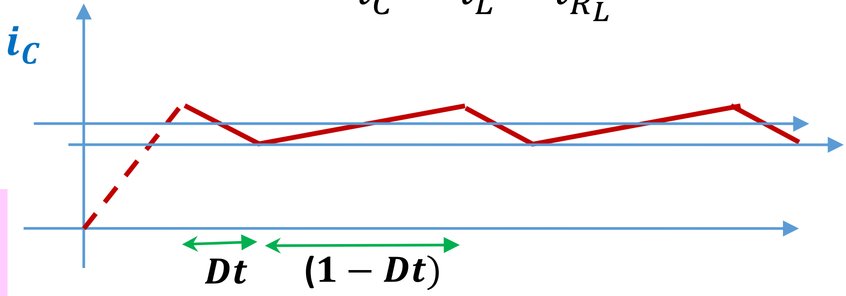






For on/off

$$i_C = i_L - i_{R_L}$$

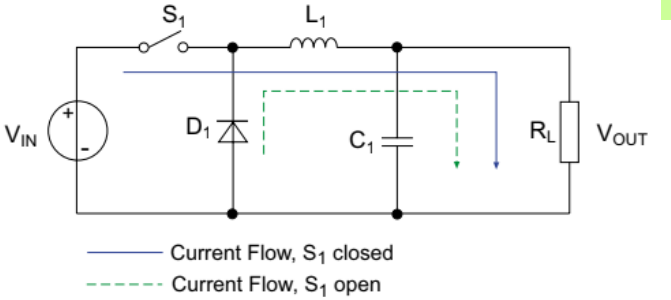


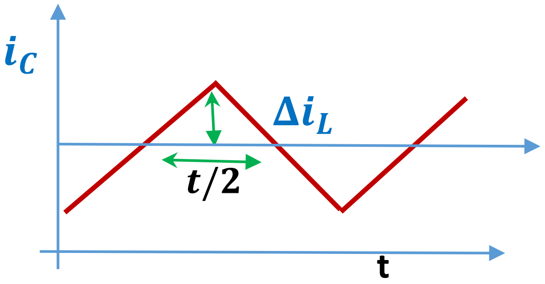
$$L_m = \frac{1-D}{2R_L f}$$

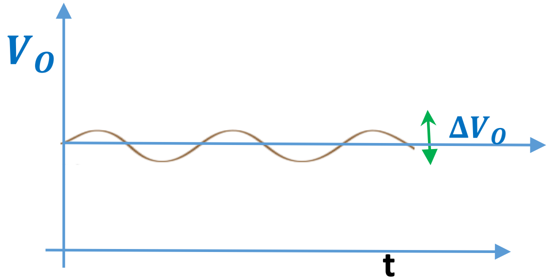
Vibrational Energy Harvesting :

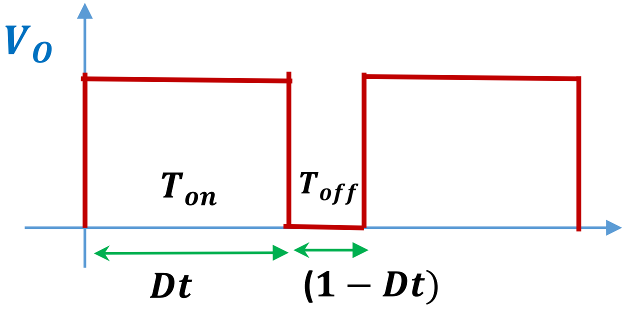
Output voltage ripple

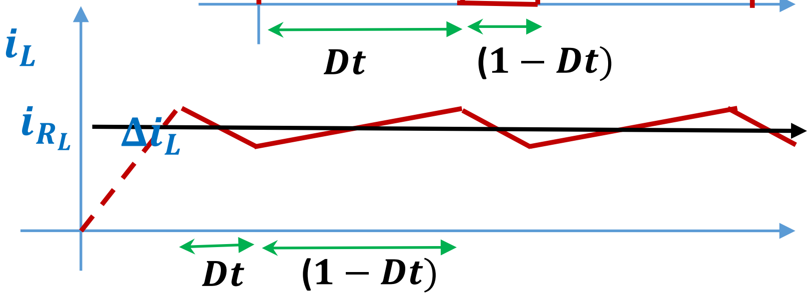
$$\Delta i_L = \frac{V_O}{L}(1-D)t$$







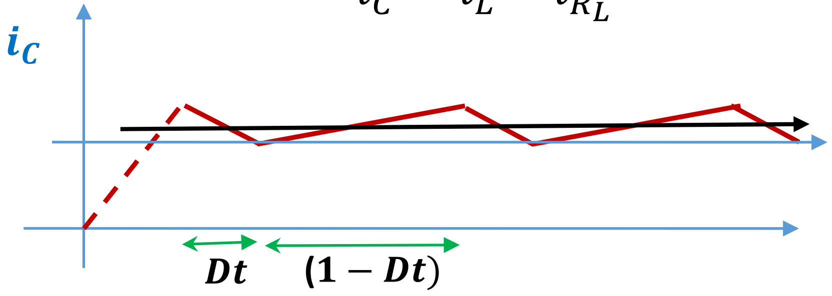


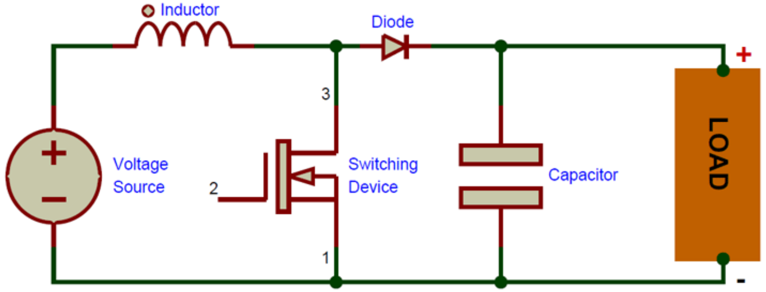


$$C = \frac{\Delta i_L}{4f\Delta V_C}$$

For on/off

$$i_C = i_L - i_{R_L}$$





Vibrational Energy Harvesting :

https://www.youtube.com/watch?v=[illegible]

f

AC
en

u

or
h

turns
which turns it
JM

$\vec{k} \cdot \vec{r} = a,$ constant