ENERGY HARVESTING TRANSDUCERS - ELECTROMAGNETIC

(ICT-ENERGY SUMMER SCHOOL 2015)

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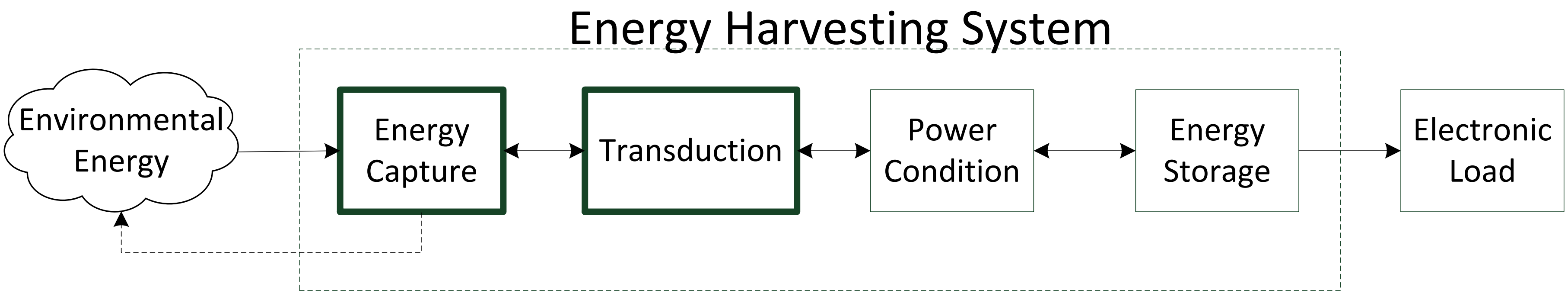
Energy Harvesting System Overview



Briand, et. al. 2015

- An energy harvesting system consists of an energy capture mechanism (e.g. a cantilever beam, wind turbine), an electromechanical transducer (e.g. piezoelectric material), power conditioning circuitry, and usually temporary energy storage all of which delivers electrical power to a some electronic load.
- Each subsystem influences the behavior of the subsystem both immediately upstream and downstream in the overall system. The energy capture mechanism even affects the environment in which it operates, although this effect may be small.
- **This lecture will discuss the transduction block**

Three Types of Electromechanical Lossless Transduction

1. **Electrodynamic** (also called **electromagnetic** or inductive): motor/generator action is produced by the current in, or the motion of an electric conductor located in a fixed transverse magnetic field (e.g. voice coil speaker)

2. **Piezoeletric**: motor/generator action is produced by the direct and converse piezoelectric effect – dielectric polarization gives rise to elastic strain and vice versa (e.g. tweeter speaker)

3. **Electrostatic**: motor/generator action is produced by variations of the mechanical stress by maintaining a potential difference between two or more electrodes, one of which moves (e.g. condenser microphone)

Credit: This classification and much of the flow from Electromagnetic section is based on the 2013 PowerMEMS presentation by Prof. David Arnold at the University of Florida

Outline for Short Course

- Introduction and Linear Energy Harvesting
- **Energy Harvesting Transducers**
  - **Electromagnetic**
  - Piezoelectric
  - Electrostatic
- Wideband and Nonlinear Energy Harvesting
- Applications

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FUNDAMENTALS OF ELECTROMAGNETIC TRANSDUCTION

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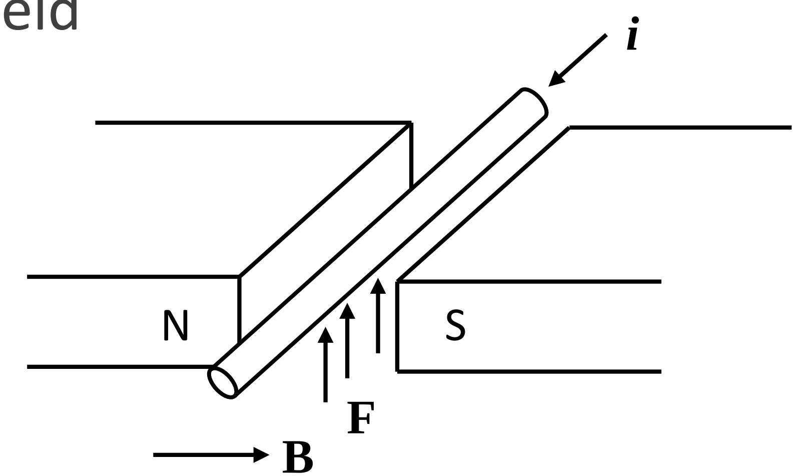
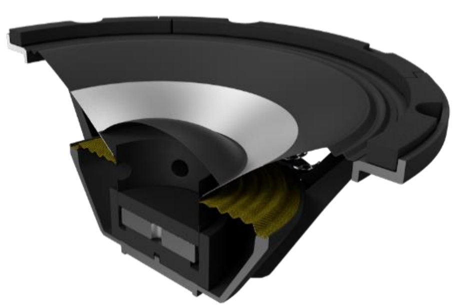
Electromagnetic Transduction

1. <u>Electromagnetic Transduction</u>: motor action produced by the current in an electric conductor located in a fixed transverse magnetic field



$$F = Bli$$



Voice coil speaker

Permanent magnet motor

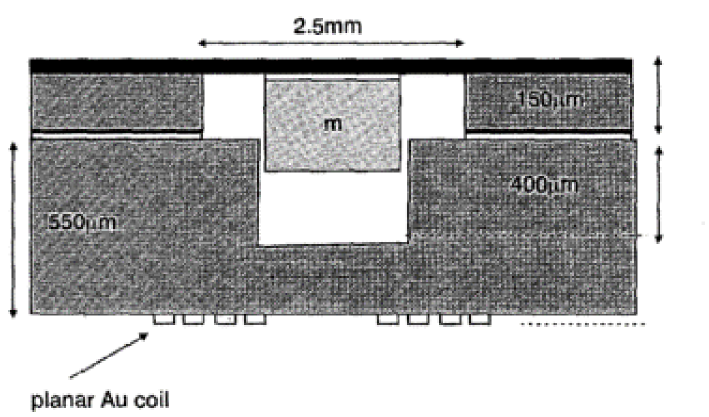
Electromagnetic Vibration Energy Harvesting

- Generally uses permanent magnet and coil
- Voltage induced by time rate of change of flux

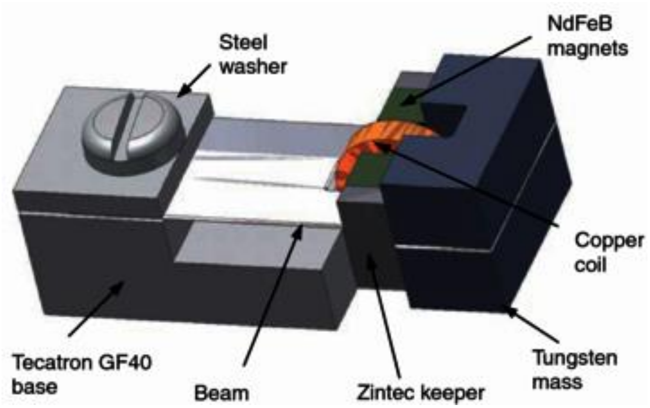
Faraday's Law

$$V = -N\frac{d\Phi}{dt}$$

where N is the number of coil turns and Φ is the magnetic flux



Williams et. al, IEEE Proc. Circuits Devices Syst., 2001



Beeby et. al, JMM, 2007

Common Electromagnetic VEH Architecture

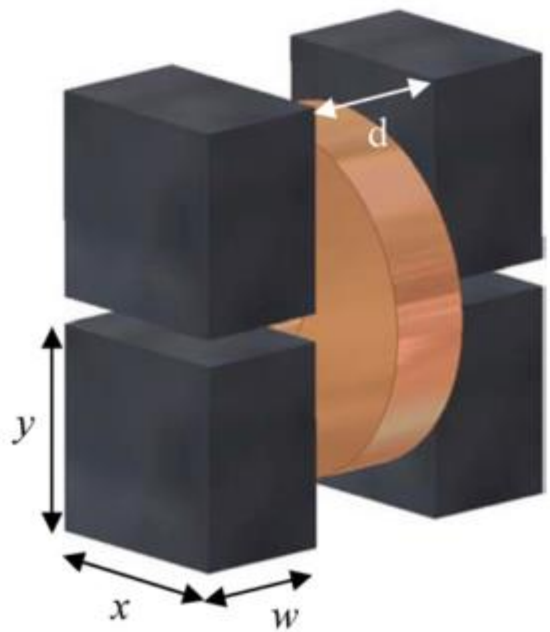


Figure 6. Magnet dimensions for simulation results.

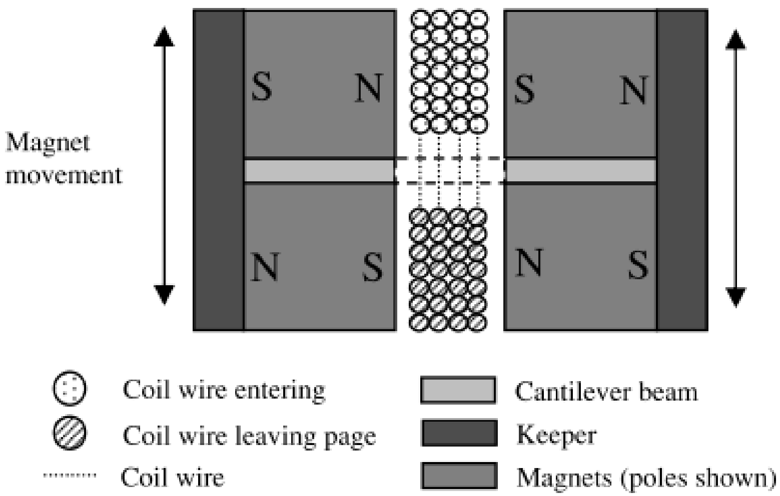


Figure 3. Cross section through the four-magnet arrangement.

Beeby et. al, JMM, 2007

Electromagnetic VEH Theory

Faraday's Law

$$V = -\frac{d\Phi}{dt}$$

Φ is the total flux through a surface

We can get to the get to the voltage in one of two ways

$$V_{tr} = -\int_S \frac{\partial \boldsymbol{B}}{\partial t} \cdot d\vec{\boldsymbol{s}}$$

which is from the perspective of the coil and assumes the flux is changing

$$V_m = \oint_C (\vec{v} \times \boldsymbol{B}) \cdot d\vec{l}$$

which is from the perspective of the B-field and assume the coil is moving

Either of these methods should give the same answer

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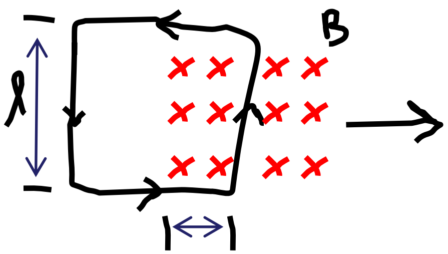
A Simple Example

A square coil moves relative to an orthogonal B-field

(or the magnet moves relative to the coil, it doesn't matter):



l is the length of the side of the coil

z is the distance of the length of the coil in the B-field

$$V_m = V = \oint_C (\vec{v} \times \boldsymbol{B}) \cdot d\vec{l} = \dot{z}Bl$$

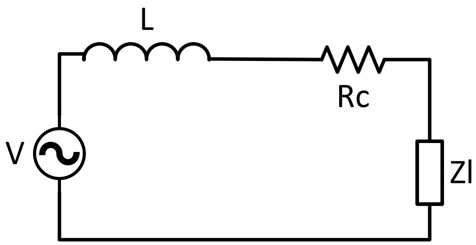
Or for N coils:

$$V(t) = NBl\dot{z}(t)$$

NBl is often referred to as the "transformation factor"

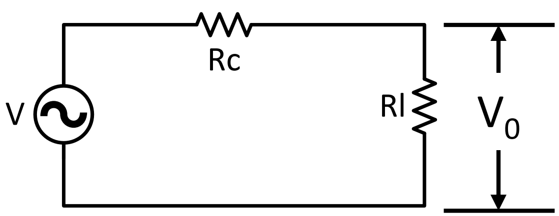
Power Output from a EM Harvester

Electric circuit



V is the voltage generated by the coil
L is coil inductance
Rc is coil resistance
Zl is load impedance

But usually, frequencies are low so inductance can be ignored, and power output is calculated through a resistor



$$P_{rms} = \frac{1}{2}\frac{|V_0|^2}{R_l}$$

$$|V_0| = |V|\frac{R_l}{R_c + R_l}$$

$$P_{rms} = \frac{1}{2}\frac{|V|^2 R_l}{(R_c + R_l)^2}$$

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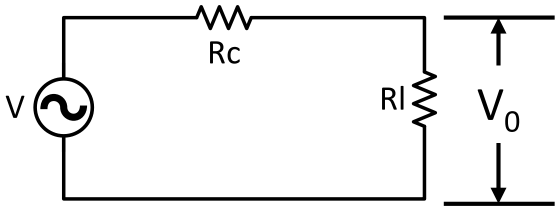
Power Output from a EM Harvester



From the previous simple example

$$V(t) = NBl\dot{z}(t)$$

So:

$$P_{rms} = \frac{1}{2}\frac{(NBl)^2 R_l}{(R_c + R_l)^2}\,|\dot{z}|^2 = \frac{1}{2}\frac{(NBl)^2 R_l}{(R_c + R_l)^2}\,\omega^2 Z_0^2$$

where Z_0 is the relative displacement magnitude

For reasons that will become apparent, we will write this as:

$$P_{rms} = \frac{1}{2}\frac{(NBl)^2}{R_c + R_l}\frac{R_l}{R_c + R_l}\,\omega^2 Z_0^2$$

EM Harvester Mechanics

Lorentz Force:

$$F = \boldsymbol{I} \oint_C d\boldsymbol{l} \times \boldsymbol{B}$$

For our simple example, this reduces to

$$F(t) = NBli(t)$$

$$i(t) = \frac{V(t)}{R_c + R_l} = \frac{NBl}{R_c + R_l}\dot{z}(t)$$

$$F(t) = \frac{(NBl)^2}{R_c + R_l}\dot{z}(t)$$

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EM Harvester Mechanics

Remember from Linear VEH theory

$$m\ddot{z} + (b_m + b_e)\dot{z} + kz = -m\ddot{y}$$

where $b_e\dot{z}$ is the electrically induced force. Substituting:

$$m\ddot{z} + b_m\dot{z} + \frac{(NBl)^2}{R_c + R_l}\dot{z} + kz = -m\ddot{y}$$

And we can say:

$$b_e = \frac{(NBl)^2}{R_c + R_l}$$

Governing Equations and System Models

The governing equations for the Electromagnetic VEH are:

$$m\ddot{z} + b_m\dot{z} + \frac{(NBl)^2}{R_c + R_l}\dot{z}(t) + kz = -m\ddot{y}$$

$$V_0(t) = NBl\,\frac{R_l}{R_c + R_l}\,\dot{z}(t)$$

where the independent states of the system are: z and $\dot{z}$ or V_o

and the power is given by:

$$P_{rms} = \frac{1}{2}\frac{(NBl)^2}{R_c + R_l}\frac{R_l}{R_c + R_l}\omega^2 Z_0^2 = \frac{1}{2}b_e\frac{R_l}{R_c + R_l}\omega^2 Z_0^2$$

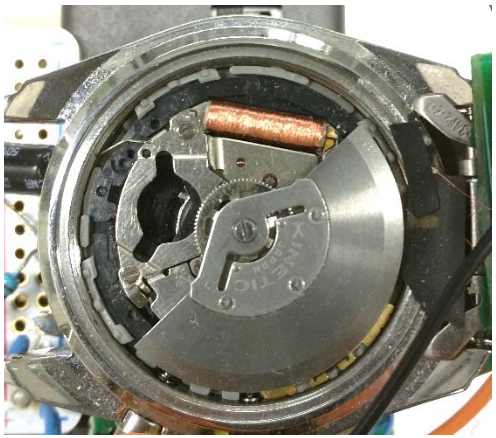
Interesting Points

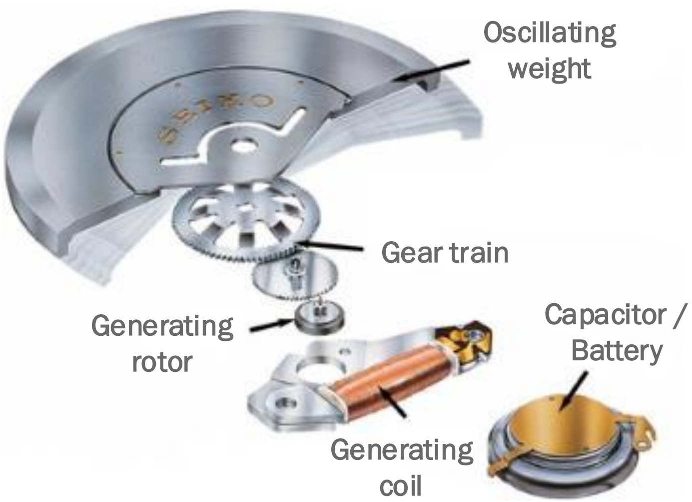
- The electromechanical force is actually in phase with velocity (disregarding coil inductance) and so the VDRG model matches electromagnetic harvesters well
- If coil resistance were zero, power output would exactly match the maximum possible power predicted by the VDRG model
- For a fixed coil resistance, power output is maximized for $R_l = R_c$
  - But this is not max “efficiency”. So, max power and max efficiency are not the same operating point.
- The simplified algebraic relationships don’t hold exactly for more complex geometry, but the basic principles do

DEVICE EXAMPLES

Self-powered Watches

Seiko





Kinetron

3D drawing of the MGS Watch

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A Way to Get Rid of the Gears

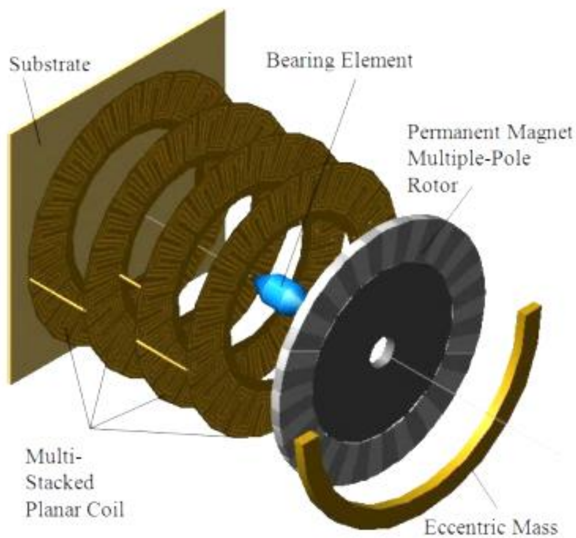


Figure 2: Schematic of the energy-harvesting generator with a single rotor disk.

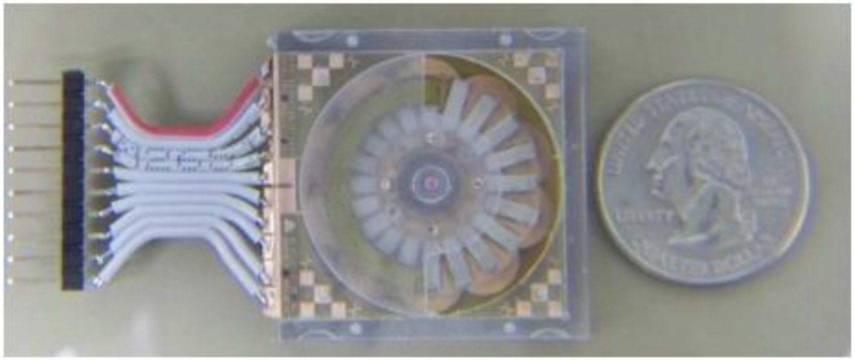


Figure 6: Prototype photo. The added eccentric weight is partially covering the permanent magnets. A US quarter coin was added for size comparison purposes.

Romero et. al., IEEE MEMS, 2011

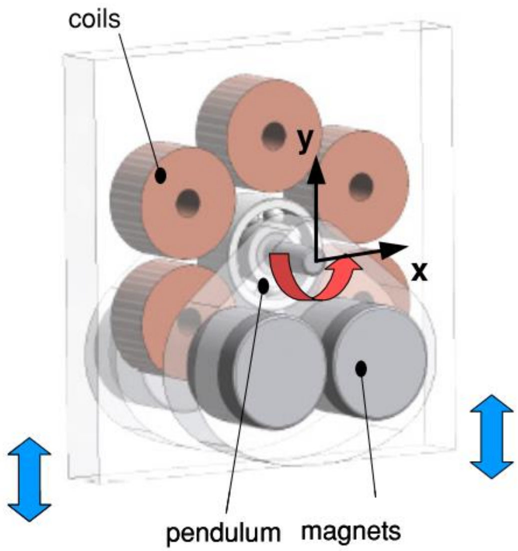
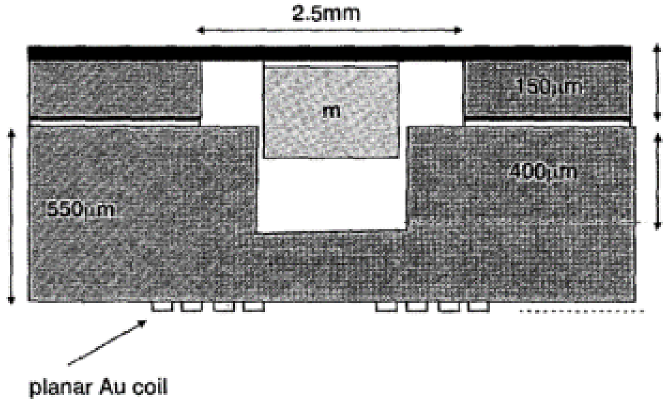


Figure 1. Under certain conditions linear vibration causes movement of the pendulum.

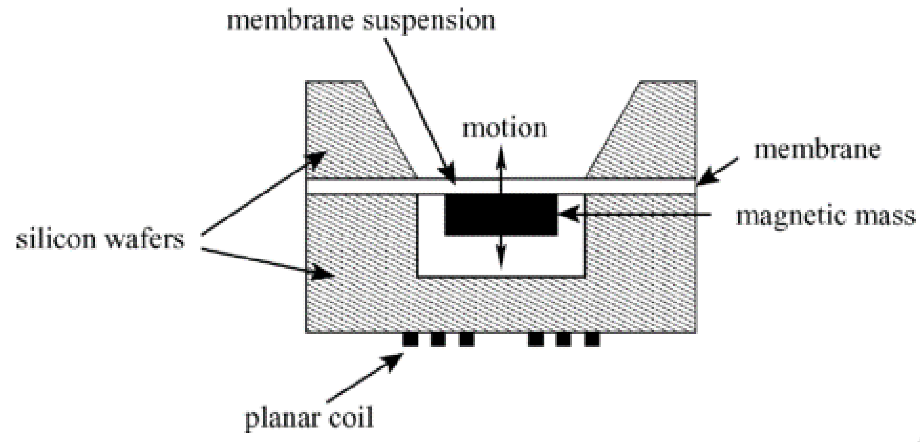
Figure 7. Prototype of an inductive non-resonant vibration transducer.

Spreemann et. al., JM&M, 2006

Earliest Linear EM VEHs



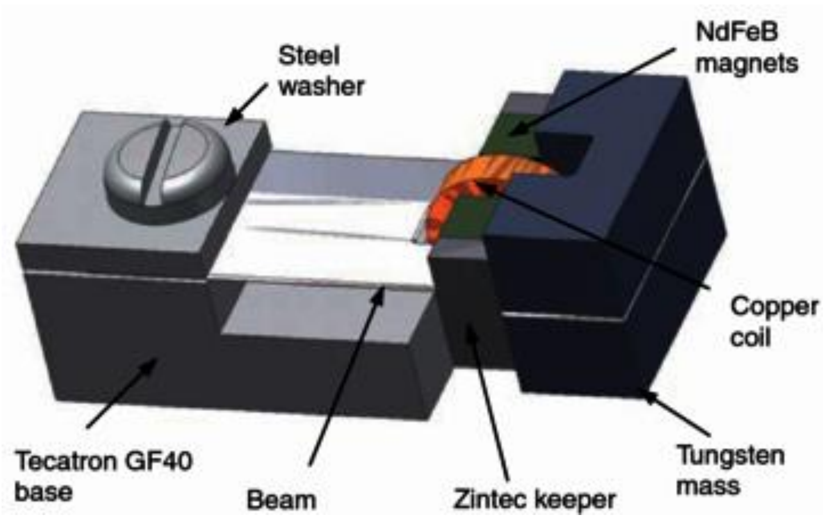
Shearwood and Yates, Electronics Letters., 1997



Mitcheson et. al., JMEMS, 2004

Southampton and Perpetuum

Perpetuum



Beeby et. al, JMM, 2007

Multi-pole Magnet Generators

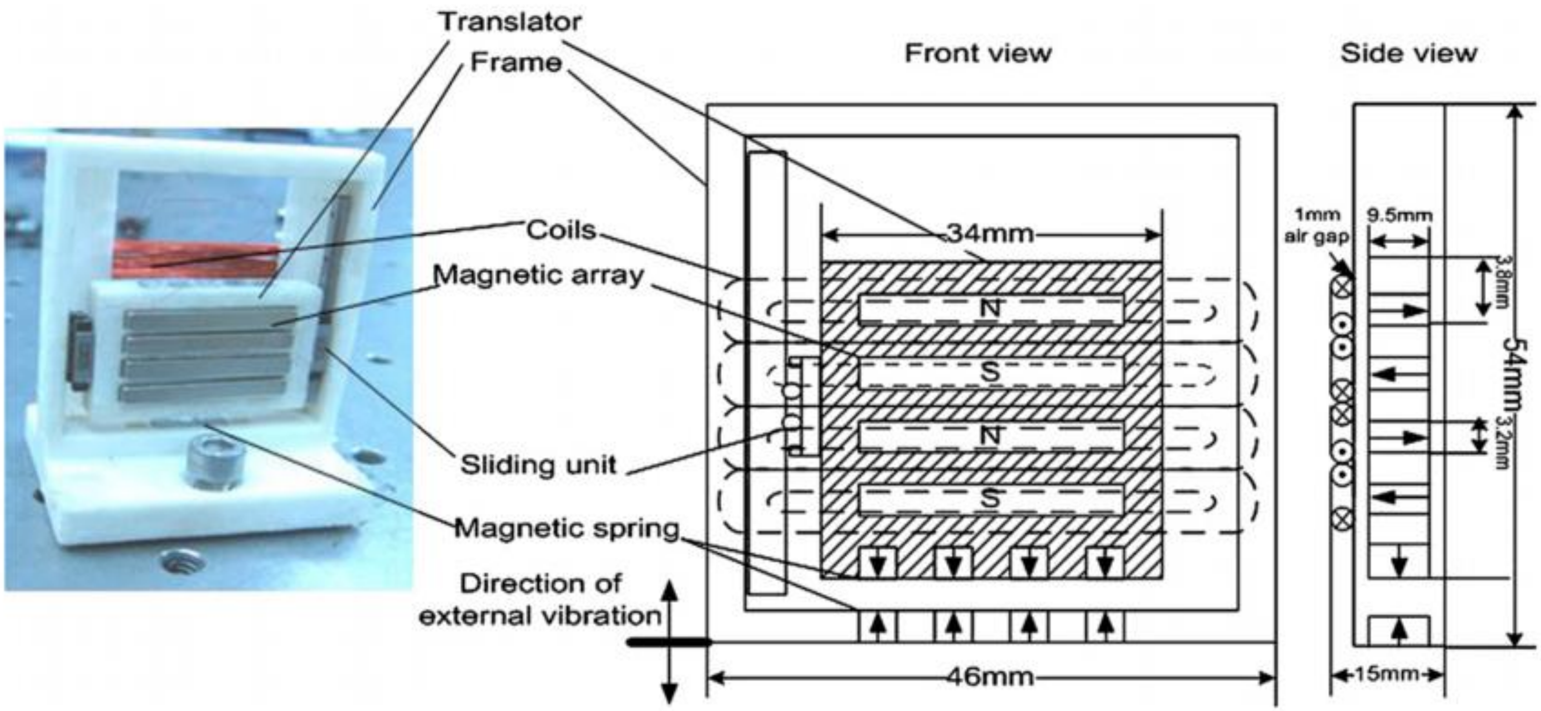


Figure 4. Picture and schematic of the prototype four-pole energy harvester.

Cheng and Arnold, JMM, 2010

Multi-pole Magnet Generators

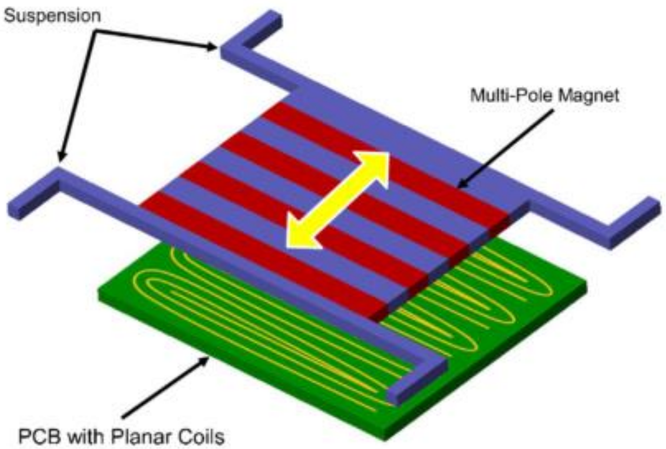
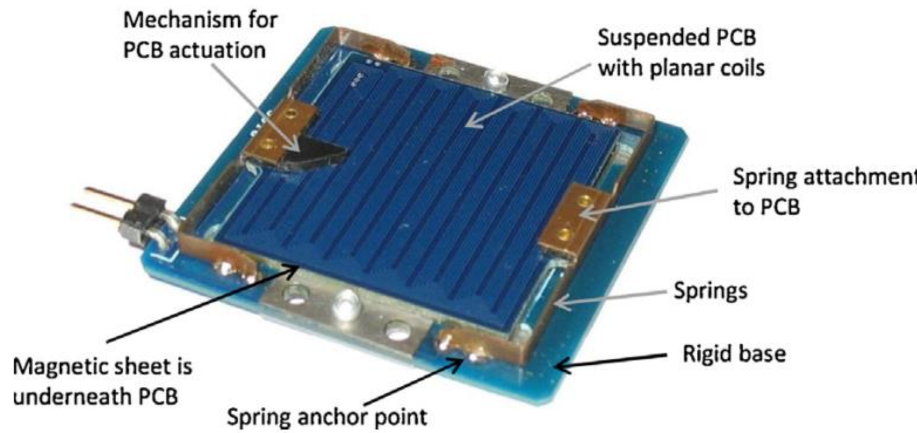


Fig. 1. Schematic of basic transducer concept. A multi-pole magnet is suspended over the PCB with planar coils. As the magnet moves over the top of the PCB, voltage is generated in the planar coils.

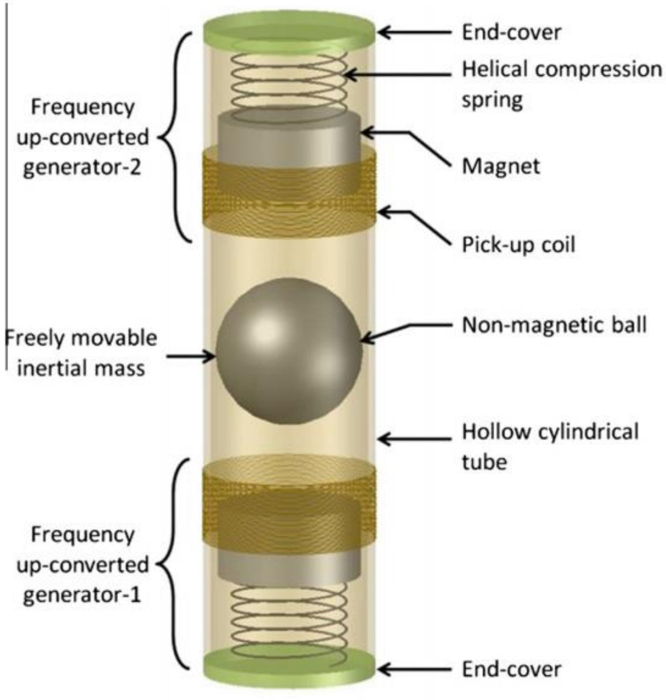


Roundy and Takahashi, Sensors & Actuators, 2013

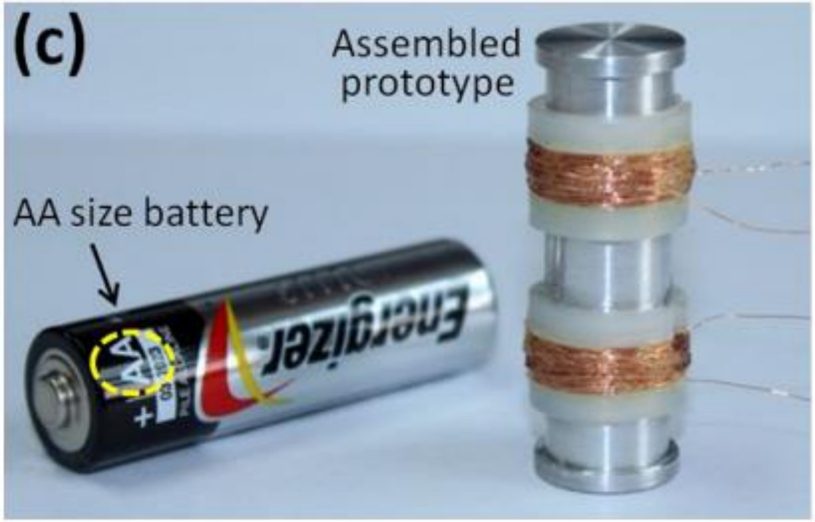
EnOcean Light Switch

EnOcean, www.enocean.com

Impact Based



(a)



Miah and Park, Energy Conversion & Management, 2015

Wearable

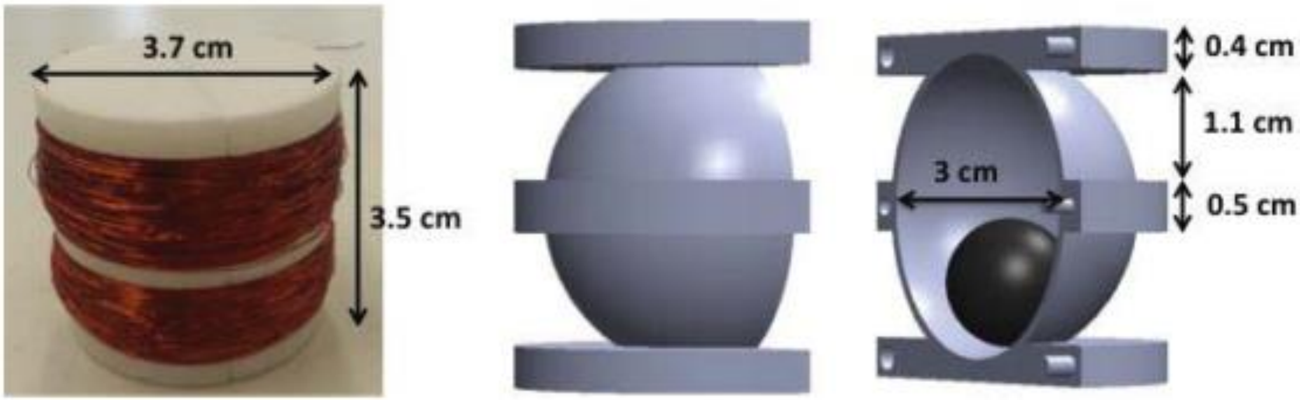


Figure 1. Photograph (left) and 3-D schematic (right) of the energy harvester.

Rao et. al., PowerMEMS, 2013

Summary

- First commercially successful energy harvesters have been electromagnetic
  - Watches
  - Perpetuum
- High coupling is achievable at sizes cm^3 and above
- Voltages (and source impedance) tend to be low
- Few micro-scale implementations