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Piezoelectric Vibration Energy Harvester

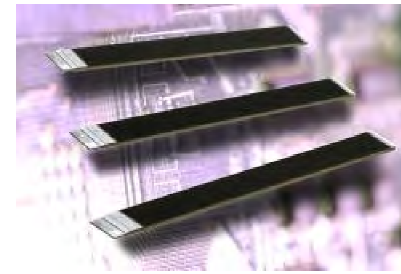
Thomas Daue, Jan Kunzmann, Smart Material Corp.

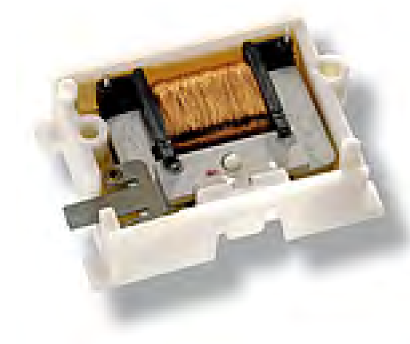
Outline

- Introduction
- Vibration Energy Harvester – why is it so complex?
- Piezoelectric vibration harvester design overview
- Energy Harvesting Application Examples
- Economics of using Piezoelectric composites as vibration harvester
- Summary

Typical Vibration Harvester

- The majority of vibration harvester currently in use are based on the piezo electric or the electro magnetic principle.
- Piezo bulk ceramic **PEG**s (Piezo Electric Generator) in form of Bi- or Trimorphs as well as Electro Magnetic Generators, or **EMG**s are used for more than 40 years as vibration harvester.
- Piezo bulk ceramic PEGs are mostly used in resonance mode applications, advantages over EMGs are lower dielectric losses and no moving parts
- Electromagnetic harvester, EMGs are often the choice over PEGs, due to low price, low impedance in non-resonant or low frequency applications and availability





Photos courtesy Morgan Electro, EnOcean

New Materials for Vibration Harvester

- During the past 20 years new and improved materials became commercially available which can be used for vibration harvester as well:
  – Piezo ceramic composites in form of Advanced Low Profile Actuators (ALPA)
  – MEMs, also electrostatic
  – Magneto strictive devices
  – Thin film piezo ceramic devices

- ALPAs used as PEGs overcome some of the application disadvantages of bulk ceramic material bi- and tri-morphs PEGs for vibration harvester
- <u>Focus in this presentation is on ALPAs used in PEGs</u>

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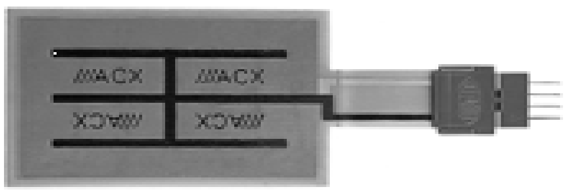
ALPA Types and Development History

THUNDER

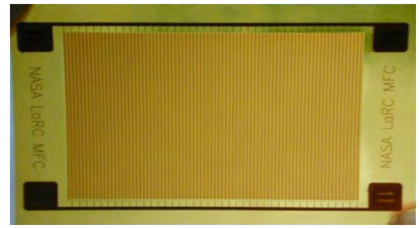
THin layer **UN**imorph **Driv**ER



AFC

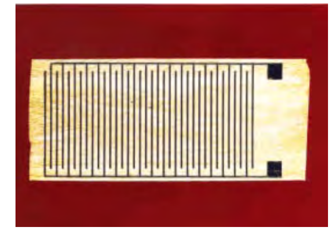
Active **F**iber **C**omposite

MFC

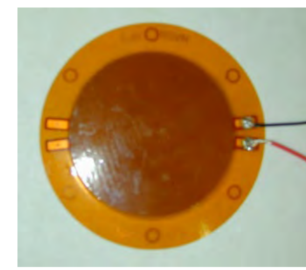


Macro**F**iber **C**omposite

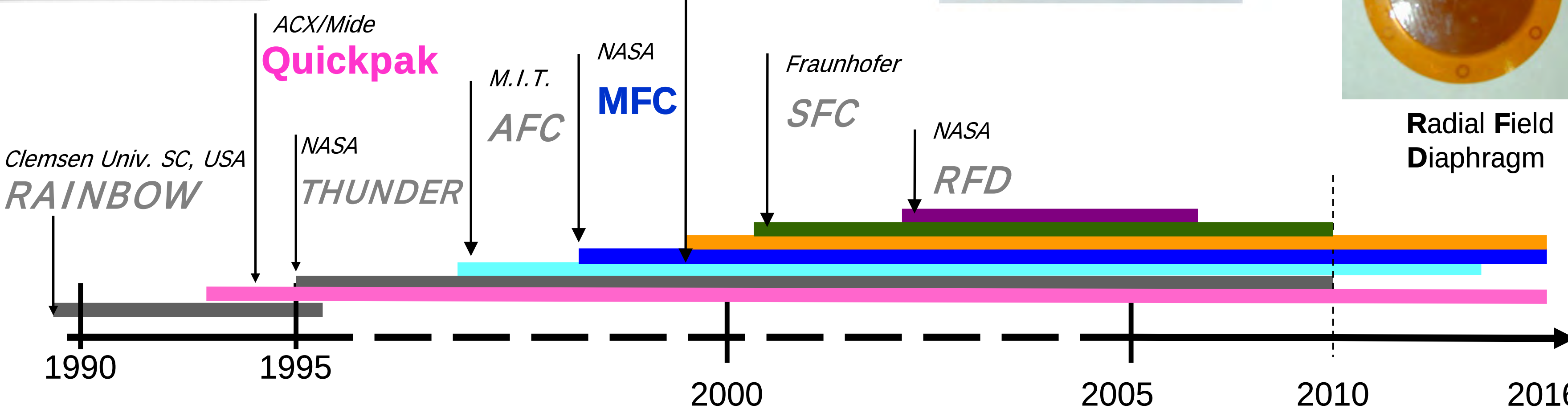
SFC



RFD



Radial **F**ield **D**iaphragm



Photos courtesy NASA, CCC, ACX, DLR, Fraunhofer

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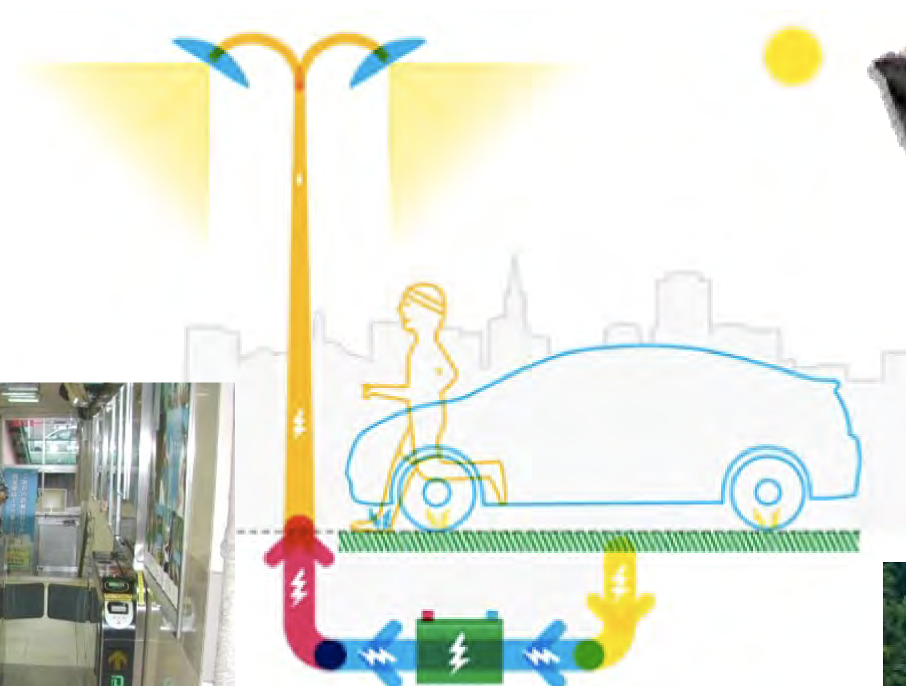
Vibrations are Everywhere and in Abundance!?

Where is the energy really coming from?



People walking in public places, train station, airports, etc

Traffic on streets, highways, bridges

Railways

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Fact 1: The laws of Thermodynamic apply!

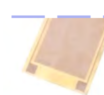
The first law states that energy can be converted from one form to another with the interaction of heat, work and internal energy, but it cannot be created nor destroyed, under any circumstances.

Often heard assumptions like

- "Waste vibration energy is unlimited"
- "We can harvest all or most of the available vibration energy"

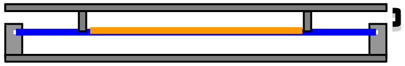
are plain wrong.

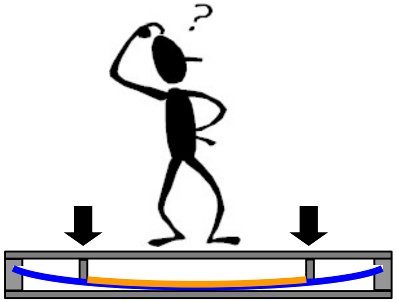
The energy has to come from somewhere, is limited and normally or a fraction can be harvested without impeding the system itself.



Quick energy check: Foot Steps at Grand Central

- 750,000 visitors per day, 31,250 per hour
- *Assumptions*:
    - o **<u>Potential Energy</u>** of a person of 75kg (165lbs) stepping on a tile which gives in about 10mm to convert into a bending/strain motion ~ 7.4J per step
    - o Tile is 50cm by 50cm
    - o Person does on average 500 steps in one hour in the station, one step per tile all tiles are built the same



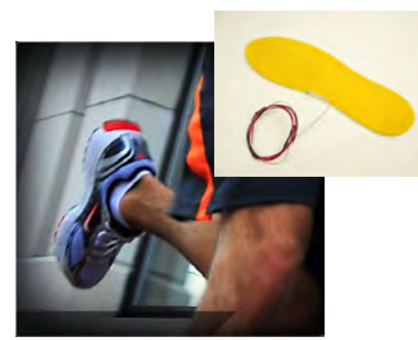


- This converts to about 19.2 kWh **raw potential energy!**
- Typical efficiency of harvester, minus energy being stored in the tile spring to bend back the tile, about 2% (actually measured)
- Total harvested **energy ~ 384 Wh,** it would power just 4 bulbs of the ~4,000 bulbs at Grand Station but at what costs!

Photos courtesy PowerLeap

Cont'd: Figure of Merit, Highways and Sneakers

- Often used example: 600 Semi trucks per hour on a stretch of 1 mile (1.6 km) highway.
  - Each truck is 80,000 lbs (36.2t) and 50ft (15m) long
  - Assumptions: Compresses the highway down 2mm each 15m equals 712J of potential energy
  - Compressing each 15m over 1.6km would equal ~0.02kWh, 600 trucks per hour would generate ~12.7 kWh, potential energy for each length of the truck over 1.6km
  - At assumed 2% efficiency it yields 254 Wh .
  - 600 trucks travelling from LA to San Francisco (362 miles) would yield a total ~92 kWh over a time of 6 hours



- Loading a cell phone with a harvester build into a shoe, generating energy while walking
  - Actual build insole with MFC harvester generates 2mJ or 2mWs per step usable electric energy without discomfort
  - Typical iPhone 6 battery is 1810mAh at 3.82V or 24,890 Ws
  - This would equal **~12 Mill. steps!!**

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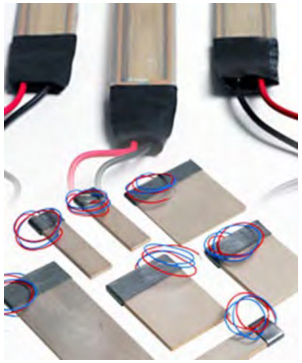
Fact 2 : Using the correct materials and structures

Many vibration harvesting applications are
- low frequency (<5Hz),
- non-resonant excitations like foot steps, traffic, breathing, etc. often coupled with broader bandwidth requirements
- vibrations are often transferred by “soft” materials (low e-modulus) which result in low forces.

- **Elastic Modulus mismatch** between especially PEGs and the source vibration structure are often overlooked and coupling strain from soft materials into PEGs comes often with low yields.
  - Youngs modulus of PEGs using bulk ceramic are in the area of 50 to 80 GPa, The MFC is better at 36GPa. As example textiles, leather and thermoplastics are in the area of 2-8 Gpa.

- Cantilever and other transfer structures are often required to couple vibrations into PEGs, to increase the strain and optimize strain distribution. Disadvantage is frequency selectivity.
- PEGs have at low frequencies a high electrical impedance vs. EMGs, making it more difficult to extract electric energy efficiently



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Fact 3: Piezo Harvester Efficacy – Theory and Practice

Theory of Efficacy of converting Mechanical Energy to Electrical Energy

- PZT coupling coefficient <70%
- Optimum impedance matching, electric charge extraction < 85%
- Storage and output power stabilization (switched step down) < 80 %

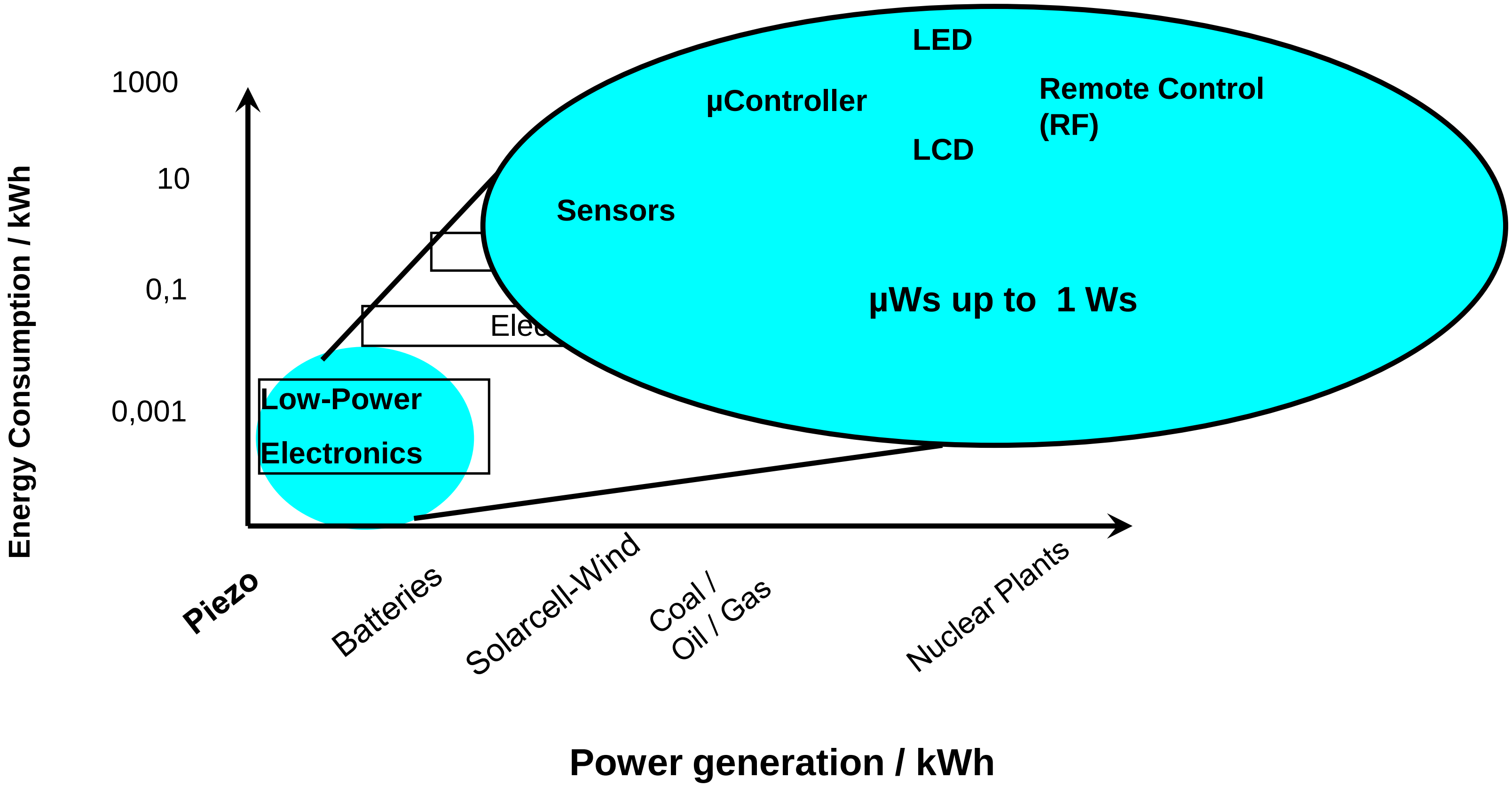
Total ~ 47% in a perfect world, much better than solar panels!

Reality of Efficacy of converting Mechanical Energy to Electrical Energy as of 2016

- PZT coupling coefficient and losses in interface between mechanical systems < *30%*
- Impedance matching, electric charge extraction < 85% BUT this requires inductivities of many Henry (bulky and not practical). Todays devices use mostly charge coupling < *25 %*
- Storage and output power stabilization (step down) < 80 % but to safe power this are often linear circuits < *60%*

Total < 4% today for non-resonant systems, not better than solar panels!

Piezo ceramic energy harvesting = LOW POWER



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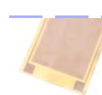
MFC for Vibration Energy Harvesting

- **MFC** – Macro Fiber Composites developed at NASA Langley Research Center
- **Also used as**
  - **Actuator** (1Hz to 10kHz)
  - **Sensor** (0.5 Hz up to 500kHz)
- **Flexible** and **robust**, ready to use package
- **Reliable**, > **10^9** cycles as actuator and > **10^{11}** cycles for energy harvesting*
- Broadband, allows for easy **non-resonant** and **resonant** energy harvesting applications
- Encapsulated and fault tolerant
- Integration of electronic components possible

iF design award 2005



* Fraunhofer reliability test, 2007, 2011

Vibration Harvester – Typical Design & Challenge

Vibration Harvester – Piezoelectric device, (non-) resonant, integrated into a structure, frequency, periodic and/or intermittent use

Conditioner - Integrated Energy Management Rectifier, Impedance Matching, Energy Storage, Stabilizer

Electronic Consumer - Sensor, Amplifier, Micro Controller, Radio Transceiver

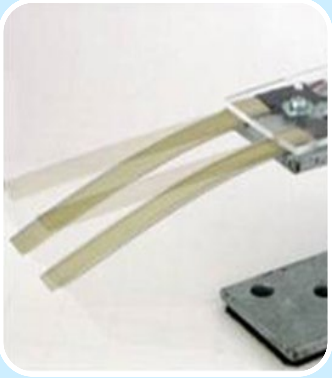
E-module match, Strain optimization (neutral fiber, frequency, distribution), size

Charge Output

Custom designed Conditioner for low frequency mandatory, due to high electric impedance mismatch

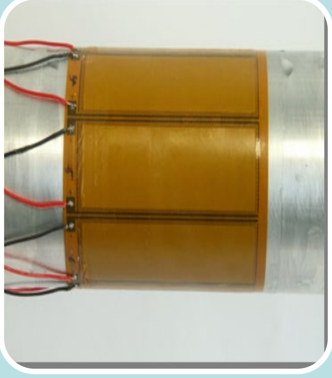
Power Consumption over time, operating voltage

Resonant vs. non-resonant harvesters



Resonant – mechanical transfer of vibration, typical Cantilever

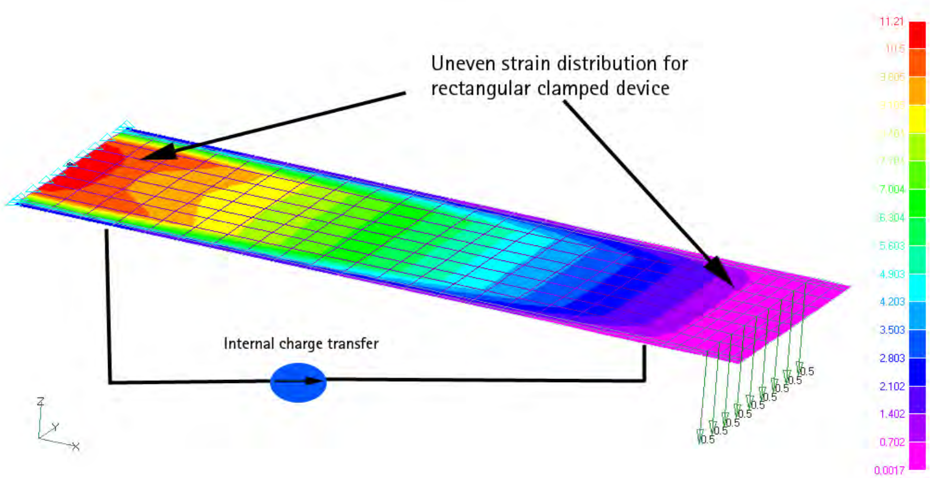
- Acceleration (G's) and frequency main design input
- Mechanical transfer allows to adapt operation based on prevalent vibration frequency
- Optimum energy harvesting at discrete frequencies
- Often bulky device, not suitable for large frequency range

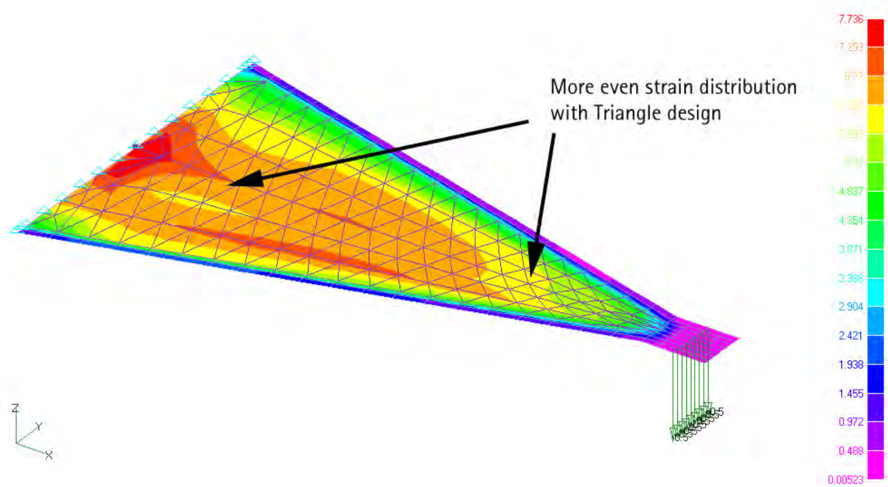


Non Resonant - directly attached to strain area

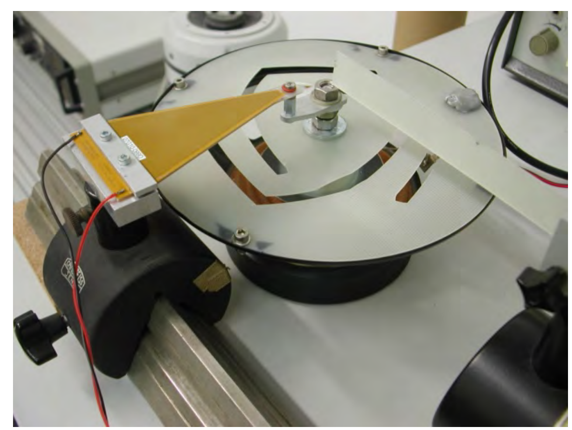
- Strain and frequency is main design input
- Piezo harvester is attached directly to maximum strain – area, very small mechanical harvester possible
- Normally not operating at resonance – lower yield
- Capable of harvesting from broad frequency spectrum

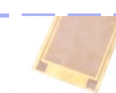
Charge transfer in clamped device – shape counts



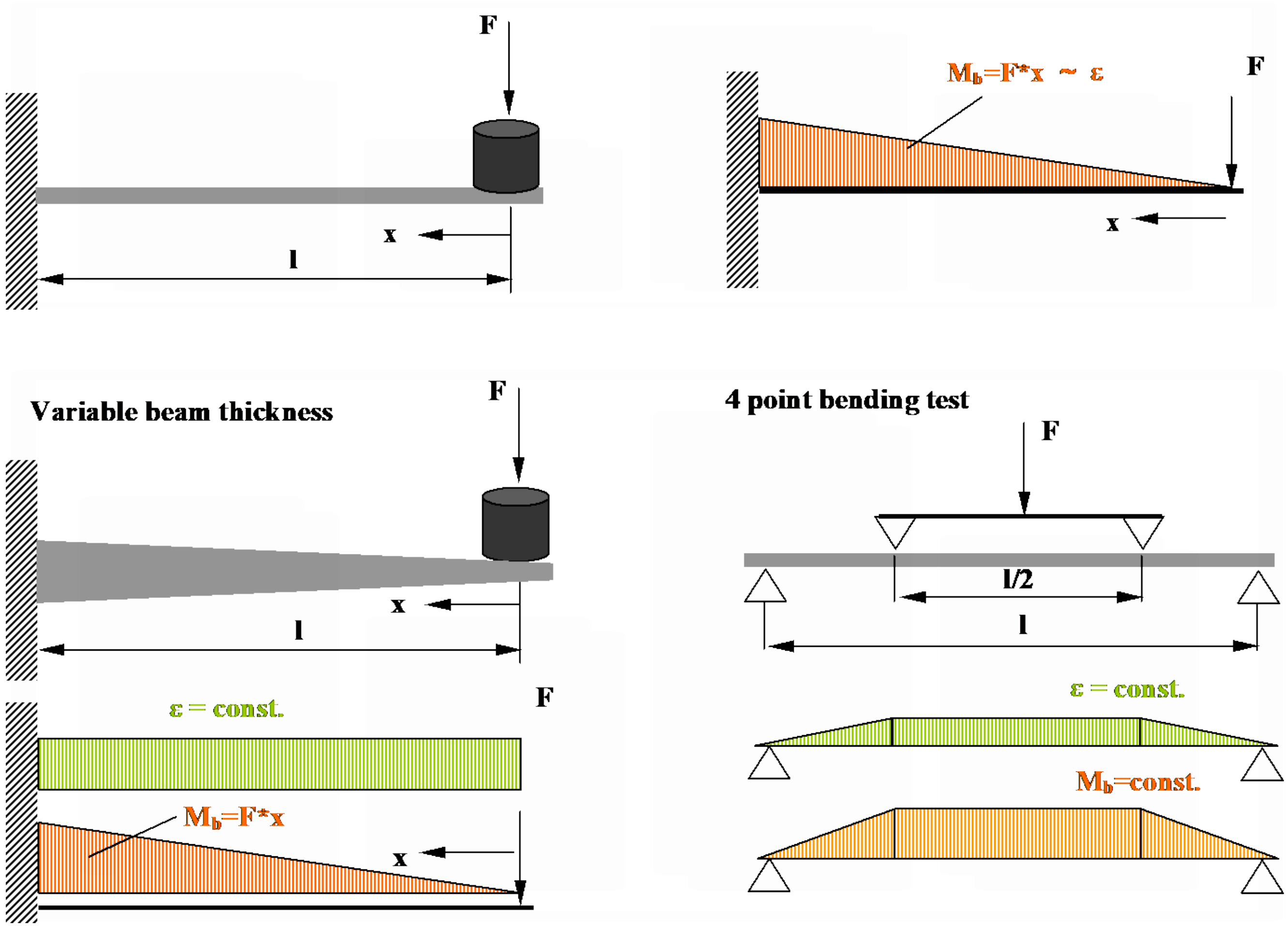


- Rectangular mechanically clamped PZT harvester result in uneven strain distribution over length
- this might cause device internal charge transfer between different areas of strain and lower the overall charge extraction
- triangle shaped PZT harvester are improving the strain distribution and overall charge extraction



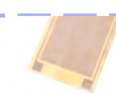


Coupling vibrations as strain into a harvester



State of the art

Increased performance



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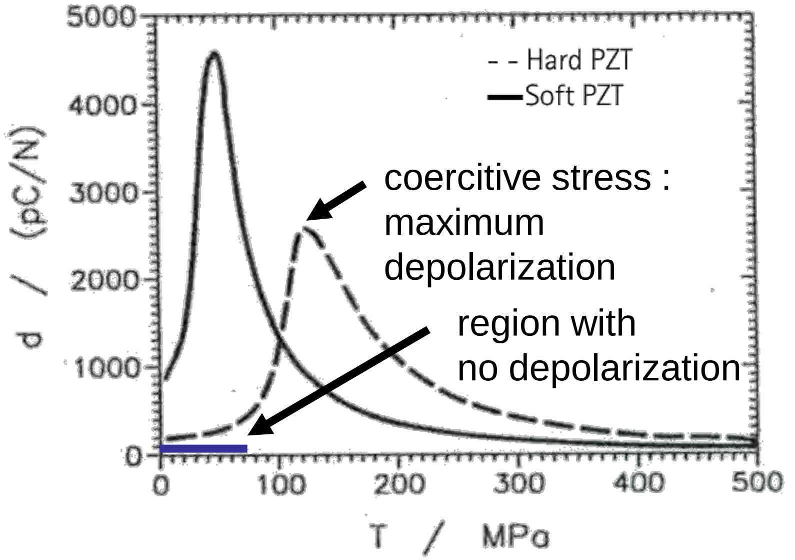
Basic of PZT Materials – Depolarization as Design factor

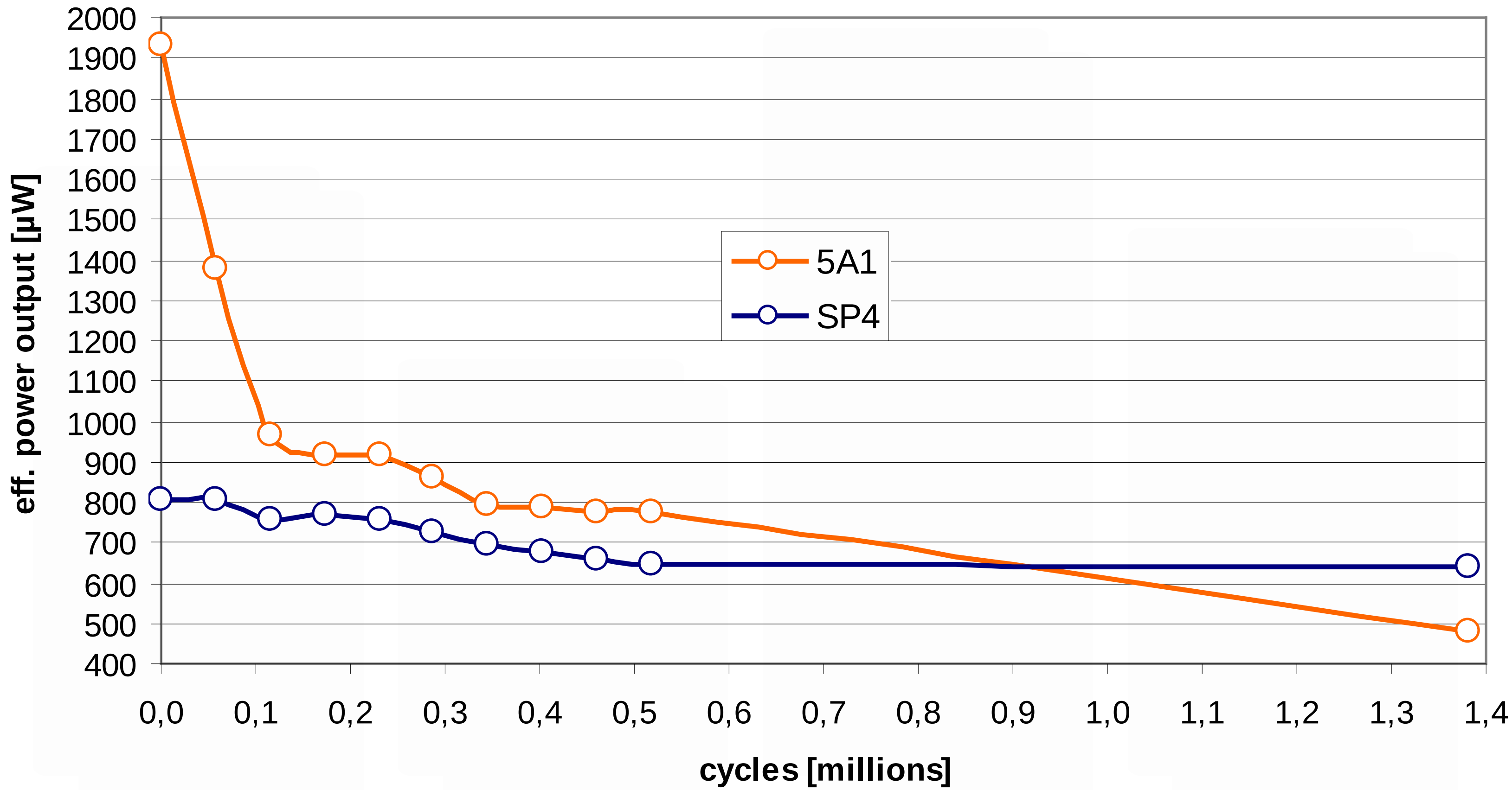
standard MFC material – actuator type

Specifications	SONOX P4	SONOX 505	PZT 5H	PZT 8
Pr [µC/cm2]	30	38	33	25
d33 [10^{-12}m/N]	289	374	593	225
d31 [10^{-12}m/N]	-123	-171	-274	-37
Max. Pressure in poling direction, constant [MPa]	68,90	20,67	10,33	82,68
Max. Pressure in poling direction cyclic [MPa]	82,68	20,67	17,22	na
Max. Pressure perpendicular to poling direction, constant [MPa]	55,12	13,78	10,33	55,12



energy harvester material – hard type

Power output @ 0.2 % compression



Restriction to about **0.1% compression** for longevity of softer and higher charge yielding PZT material is important!

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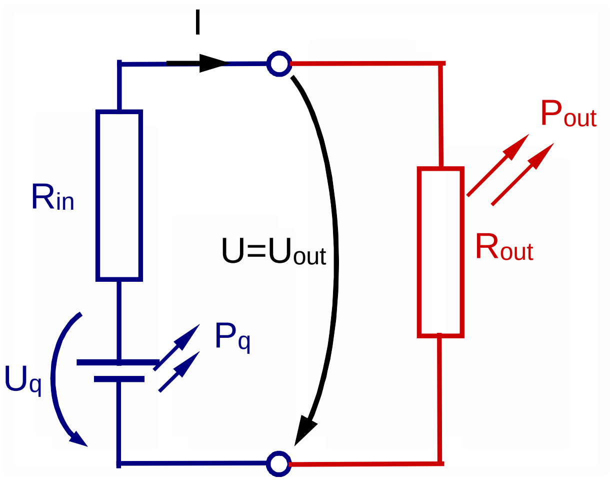
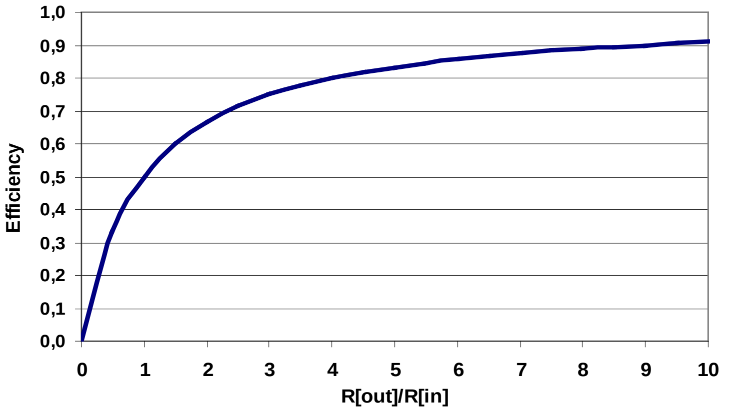
Basics of power transfer - Compromise



Efficiency

$$\eta = \frac{P_{out}}{P_q} = \frac{R_{out}}{R_{in} + R_{out}}$$

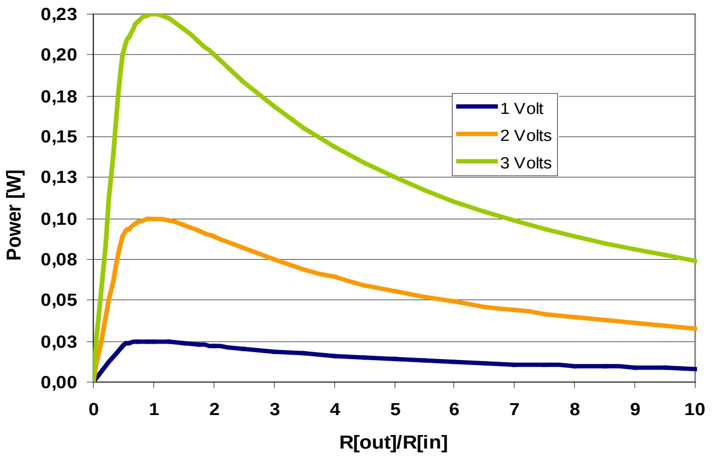
$R_{out} >> R_{in}$



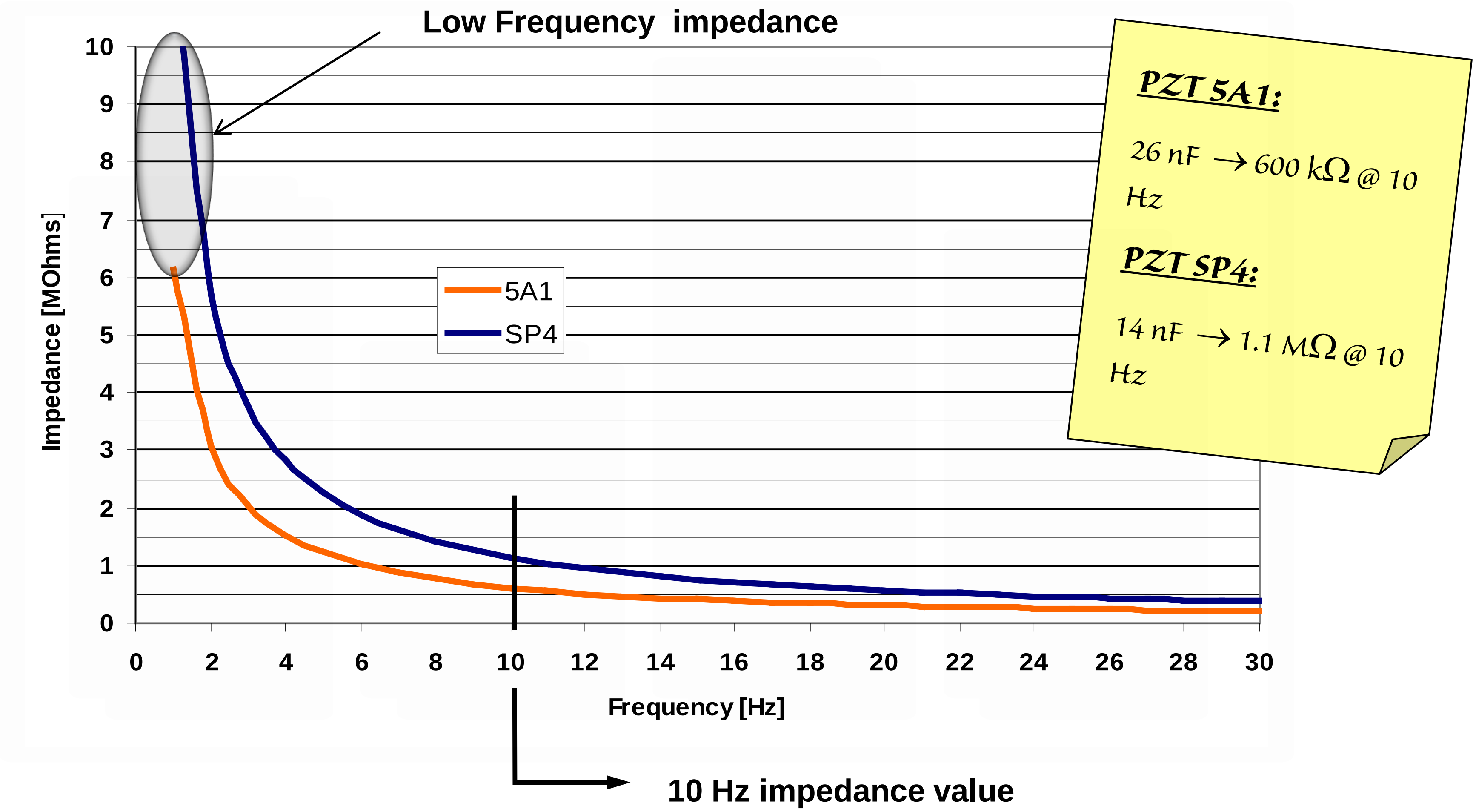
Energy Transfer

$$P_{out} = U_q^2 * \frac{R_{out}}{(R_{in} + R_{out})^2}$$

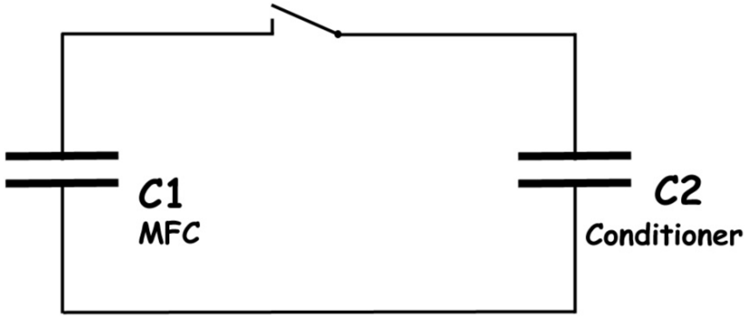
$R_{out} = R_{in}$



Dynamic impedance behavior for MFC M2814P2



C-to-C Energy Extraction Loss Problem



With **Q = CU** and **E = ½ C*U² =>**

$\mathbf{U_{C1+C2} = \frac{1}{2} U_{C1}}$

Energy in C1 and C2 after closing switch = 25% each,

25% is maximum energy extraction!

C1 = C2 optimum energy transfer

Extracting the generated electric charge from the PEG is one of the most important design steps to optimize efficacy:

- Correct impedance matching, especially < 10Hz
- Wideband harvesting requires adaptive impedance matching
- Capacitive vs. inductive charge extraction

A good electronic design can make all the difference between a mediocre efficacy for a Conditioner of < 10% to a well adapted design with more than 70% (inductivity based).

Operational modes and energy requirements

Vibration Synchronous

Power requirements are synchronous with vibration and maximum power needed is always **< harvested energy**

simple sensors, RFIDs, Visual feedback applications

Vibration Synchronous & Burst

Power requirements are synchronous with vibration, intermittent powers bursts are **>** harvested energy requiring **energy storage**

Intermittent Radio transmitter "telemetry" devices, SHM

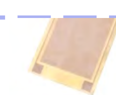
Vibration Asynchronous

Power requirements continuously, Vibration is intermittent and/or varies over time, **long term energy storage and management**

Complex Structural Health Monitoring Devices, Storing RFIDs, Event Monitoring Devices

Summary of Design Challenges using a PEG

- High internal impedance, especially at low frequencies < 10Hz require good or adaptive impedance matching.
- Extraction electronics, often called Conditioners need to be cost effective and of small form factor, often leading to a charge coupled design (inductivities to bulky), which in return lowers efficacy.
- In a clamped condition, strain distribution needs to be addressed with for example triangle shaped PEG designs or special mechanical fixtures to prevent asymmetric strain/charge distribution.
- Maximum strain and material dependent depolarization limits have to be considered.
- Harvesting energy from intermittent vibration sources or to allow burst consumer events require additional energy storage (super cap, battery).



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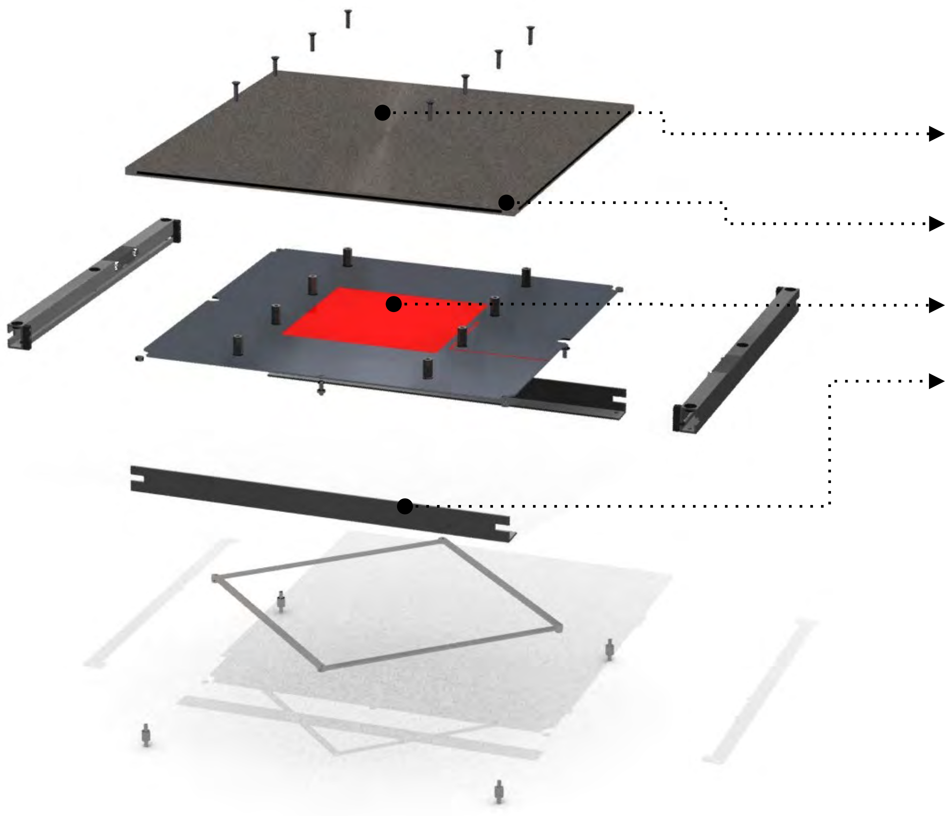
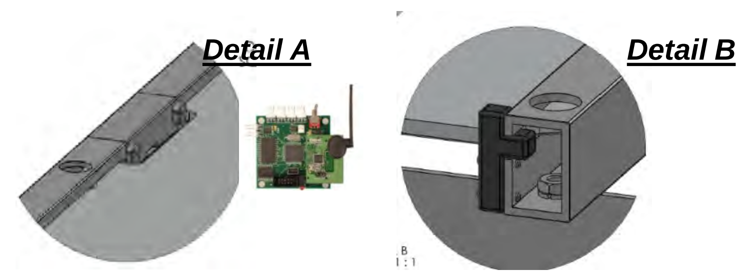
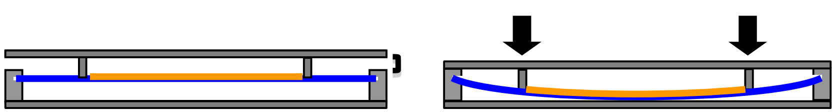
Smart Tile from POWERleap







Harvests 6mJ per step with two M8585P2

Bell Helicopter Pitch Link Harvester

- Bell M412 pitch link, harvesting energy during flight from small vibration of the link
- Harvested energy used for MicroStrain structural health monitoring data system transmitting critical rotor data to cockpit
- Cantilever PEGs or EMGs not feasible due to
    - High rotational forces of > 500G,
    - weight
    - low profile required
- Customized MFC Array for easy adaptation to pitch link

- Harvested energy from broad bandwidth excitation about 410µWs during flight
- Harvested energy sufficient for structural health monitoring
- This enables an on-board wireless load sensor to operate perpetually without battery maintenance.

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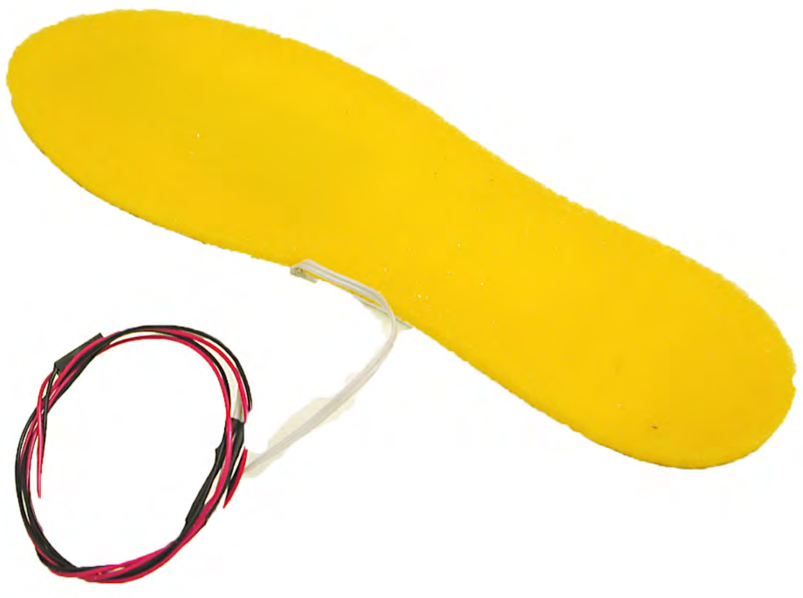
Energy Harvesting Applications



Shoe insole with strain optimized MFC generator

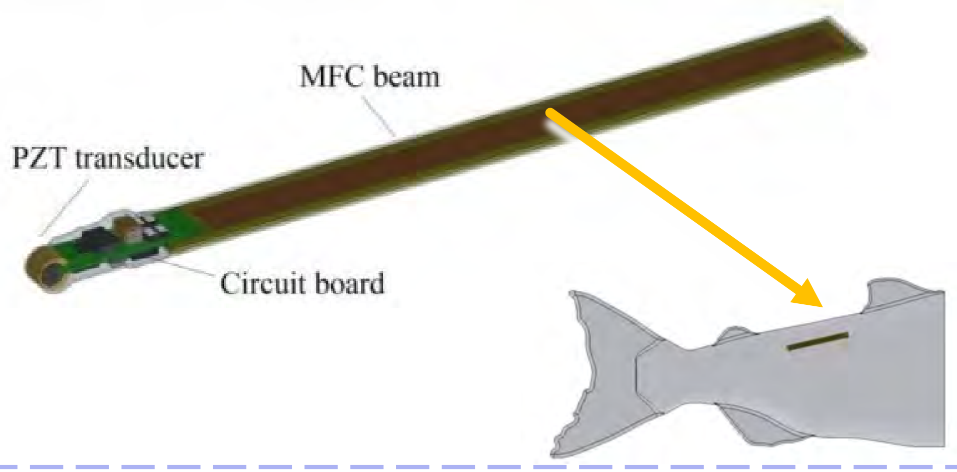
- MFC positioned at bending zone
- Optimized GFC structure for an excellent reliability
- Typical energy generated per step: 1.5mJ
- Energy harvested sufficient for sending ~ 3 datagrams/step

Possible Applications:

- Pedometer
- Foot health monitoring during Expeditions (warning of frost bites, constant wet, …)
- Patient/Person tracking
- Medical controlling

Self-Powered Fish Tags

- Development at Pacific Northwest National Laboratory, USA to study the behaviors and migration patterns of fish for longer periods of time.
- Implantable beam with a MFC and transmitter electronic. Beam is surgically inserted just under skin near each fish's rear dorsal fins.
- MFC harvester powers an Ultrasound transmitter operating completely autonomous and sending ultrasound signals to track movement as long as fish swims.
- Battery powered tags not allowing for enough tracking time.
- Tested on live trouts and sturgeons



PNNL's self-powered fish-tracking tag comes in two lengths to accommodate differently sized fish: 100 and 77 millimeters, or about 11 to 14 grains of long rice placed head-to-head.

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Comparison MFC Energy Harvester vs. Batteries

	MFC P2 type with CL-50	Battery Li-Manganese
Lifetime 5 years	++	++
Lifetime 10 years	++	-
Maintenance Free	++	+
Acquisition cost	-	++
Cost incl. Maintenance (>5 years)	++	-
System integration	-/+	++
Wide temperature range	++	-
Self sufficient	- (requires vibration)	++
Green Product	(+)	-
Weight	++	+

- only batteries no rechargeables considered, due to high discharge ratio
- temperature range for MFC -40 to 100C
- CL-50 energy harvesting conditioner, 3.3V output up to 200mW
- Battery is CR123
- Green product is referencing amount of non-degradable waste, toxicity
- Maintenance references exchange of parts

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Energy Extraction – PEG's, EMG's yields comparable

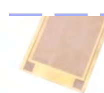
PEGs and EMGs show dual values of parameters for extracting energy from vibrating system:

- PEGs
  - Lower coupling coefficient
  - Higher impedance yielding low resistive losses
  - PEG size (generator volume) can be scaled with little changes in parameters
- EMGs
  - Higher coupling coefficient
  - Higher electric losses due to coil inductivity
  - Decreasing size of EMGs decreases efficiency due to coil design and losses

EMGs and PEGs characteristics indicate two different operational points which can extract theoretically similar energy levels, with PEGs gaining with decreasing generator size*.

EMGs are often the more economic solution!

* E. Arroyoa,∗, A. Badela, F. Formosaa, Y. Wub, J. Qiub



Summary

- The laws of Thermodynamic need to be always considered if designing a piezoelectric harvester.
- Low profile piezo composite actuators (ALPA) are offering improvements over standard PZT bi- and tri-morphs in vibration energy harvesting applications due to increased flexibility, robustness and life time.
- ALPAs have also advantages for non-resonant energy harvesting by applying them directly to vibration nodes, allowing for a complete solid state approach.
- Intrinsic high impedance of piezo ceramic harvester at low frequencies require special designed Conditioner circuits.
- Charge coupled Conditioner or extraction circuits forego 50% of generated electrical energy due to physics.
- Typically EMGs and PEGs have similar energy extraction rates as vibration harvester. EMGs are in many applications the more cost effective solution.
- PEGs, if properly designed, have especially advantages in high G force and hazardous environments.