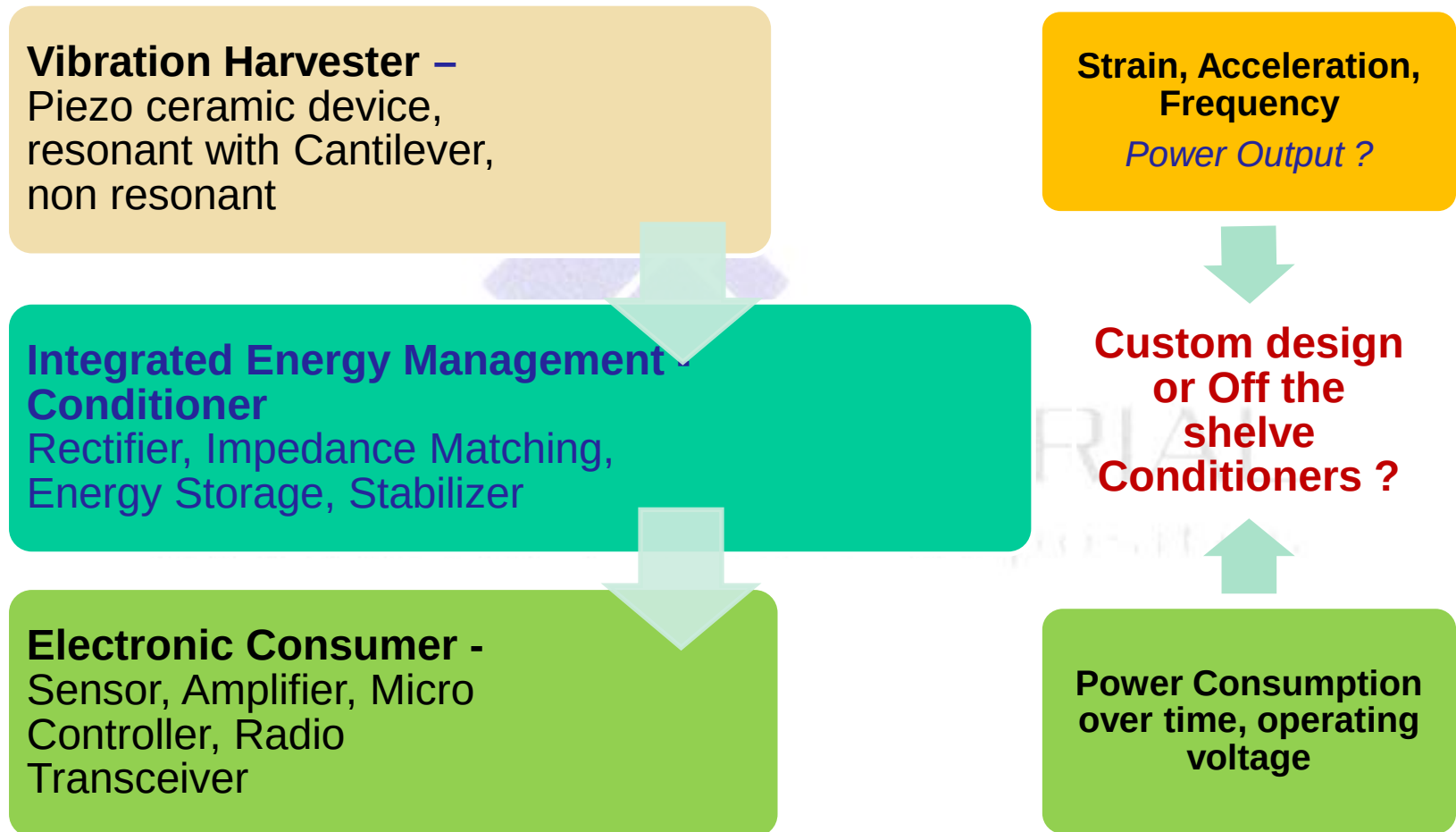

Piezoelectric Vibration Energy Harvester

***State of the Art
System Implementations and Economics***

Outline

- ◆ **Science behind PZT vibration harvester – why is it so complex?**
- ◆ **Are there possible ways to make it better?**
- ◆ **Case studies – applications & economics**
- ◆ **Summery**

Vibration Harvester –Typical Design & Challenge



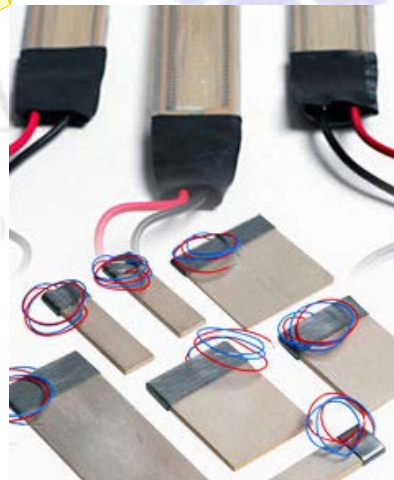
Fact 1: Are we using optimal Structures & Materials?

Interesting energy sources:

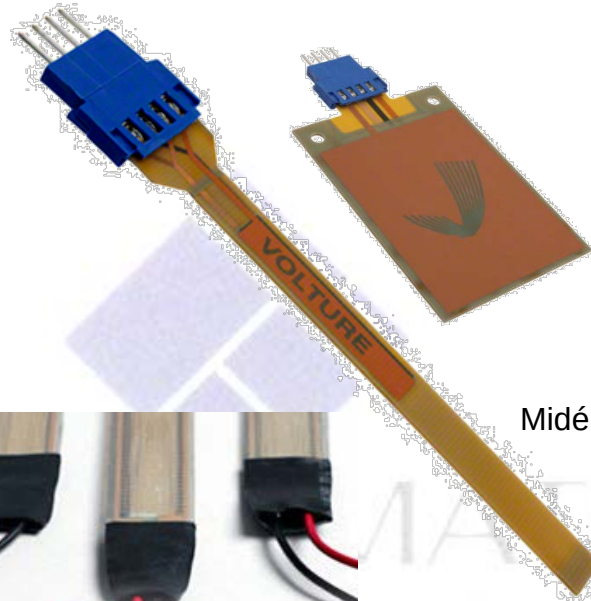
- human footsteps
- breathing
- ocean waves
- traffic vibrations



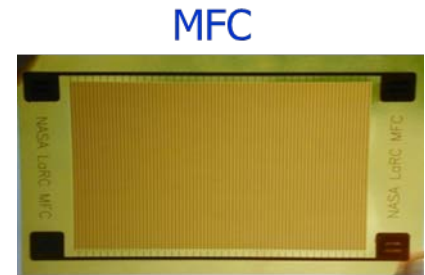
Advanced Cerametrics



But cantilever beams are everywhere



Midé



MacroFiber Composite

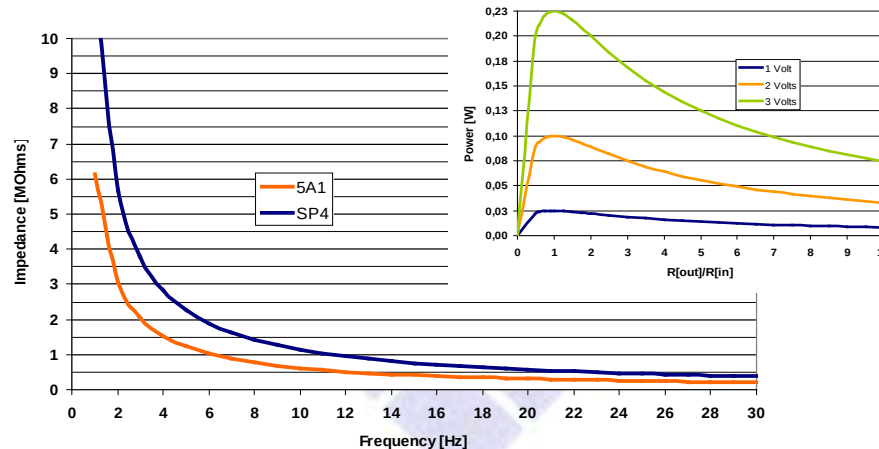
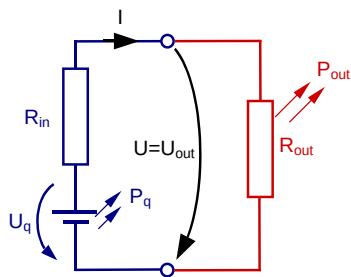
Nature of typical excitations:

- around 1-3 Hz
- unevenly
- small forces



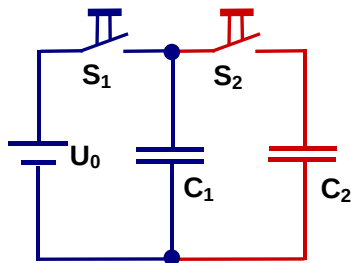
Fact 2: How efficiently do we transfer the energy?

AC excitation



Is an impedance matching in the MΩ range really realistic?

DC excitation



before closing S2

$$Q = C_1 * U_0$$

$$E = \frac{1}{2} * C_1 * U_0^2$$

after closing S2

$$Q = C_1 * \frac{1}{2} * U_0 + C_2 * \frac{1}{2} * U_0$$

$$E = \frac{1}{2} * C_1 * \left(\frac{U_0}{2} \right)^2 + \frac{1}{2} * C_2 * \left(\frac{U_0}{2} \right)^2$$

$$E = \frac{1}{2} * \left[\frac{1}{2} * C_1 * U_0^2 \right]$$



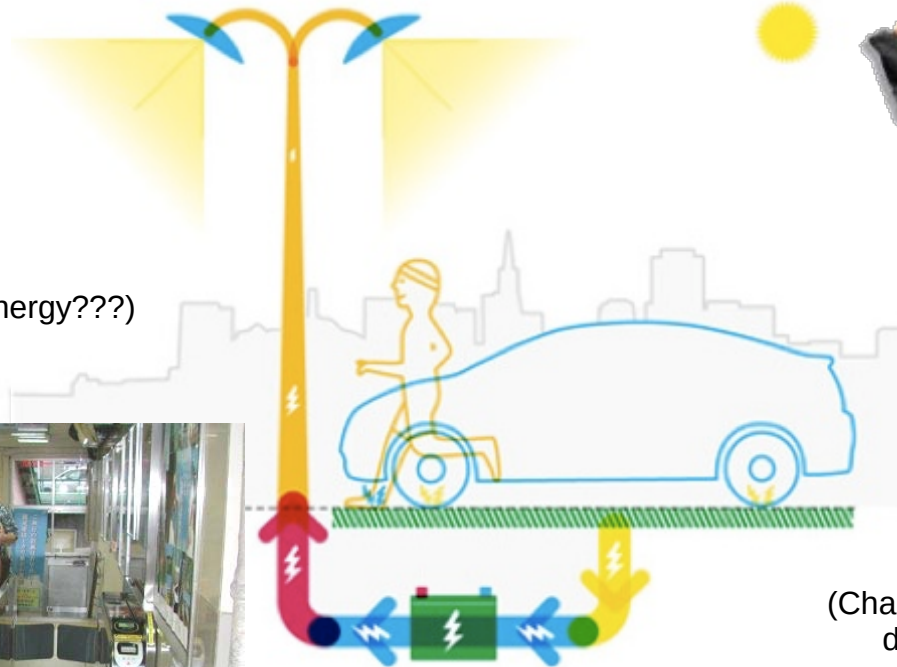
Where are the other 50% going
Only 25% are being transferred

Fact 3: Energy management and power hungry apps



Where is the energy really coming from?

(Law of conservation of energy???)



Example:
(Charging cell phone battery due to human footsteps)



typical cell phone battery
 $3.7V \cdot 1600mAh = 355Ws$

Typical piezo generator:
2mWs / step

177'500 steps = 90km = 2x Marathon distance

Piezo Ceramic 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 2012

- 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), today's devices use mostly charge coupling < **20 %**
- Storage and output power stabilization (step down) < 80 % but to safe power this are often linear circuits < **60%**

**Total ~ 3-4% today, not better than solar
panels!**

Outline



Science behind PZT vibration harvester – why is it so complex?



Are there possible ways to make it better?

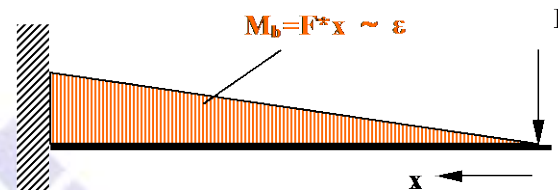
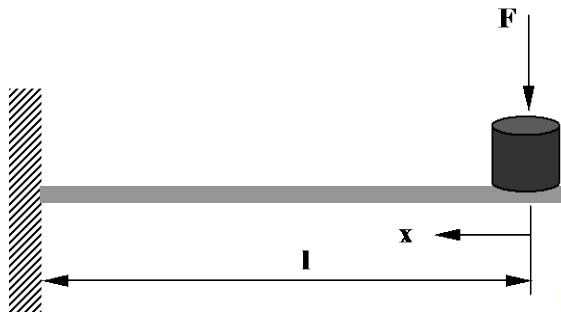


Case studies – applications & economics



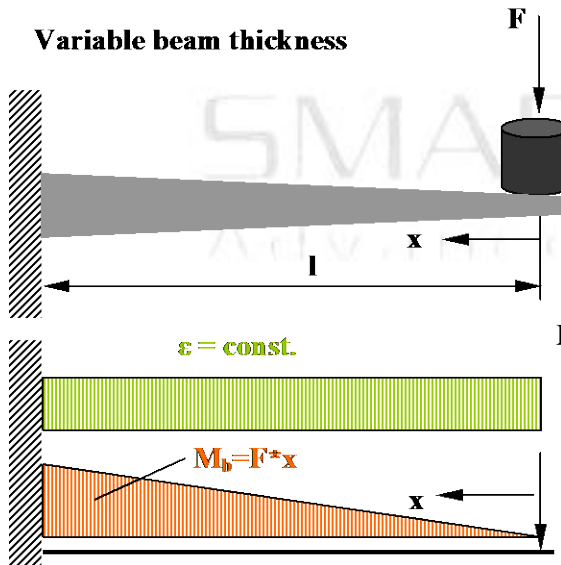
Summery

Design rules for vibration harvesters

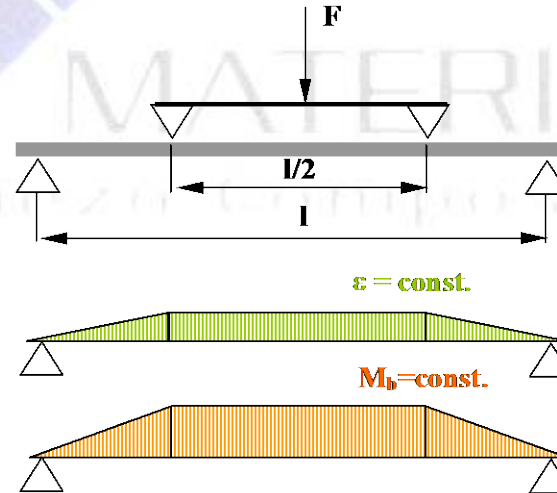


State
of the art

Variable beam thickness

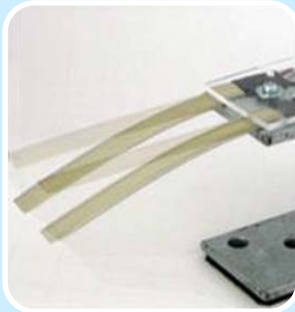


4 point bending test



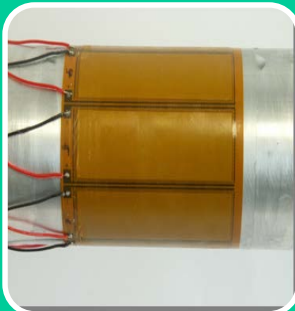
Increased
performance

Design rules for vibration harvesters



Resonant – mechanical transfer of vibration, 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

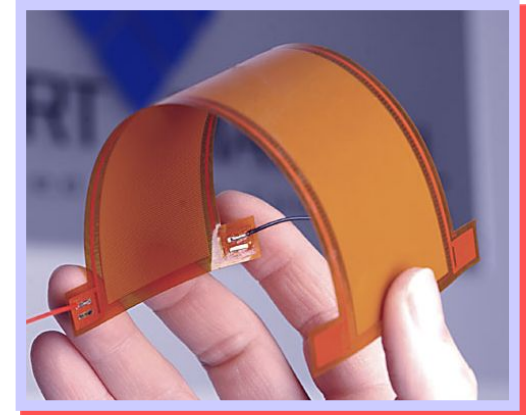


Non Resonant - directly attached to strain area

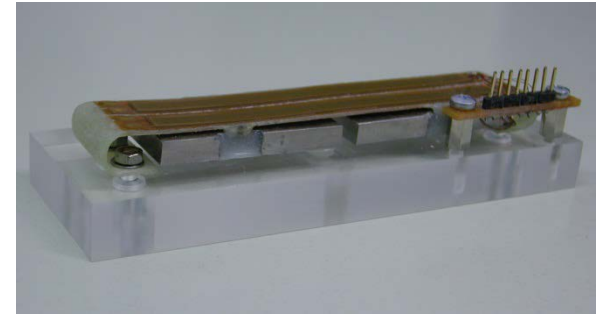
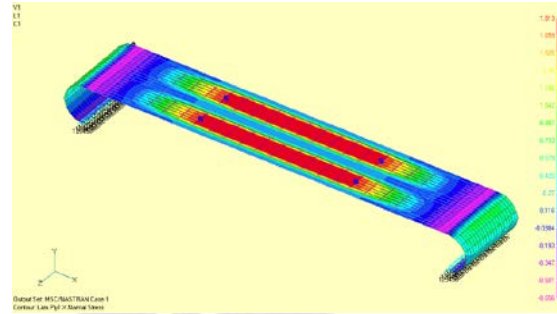
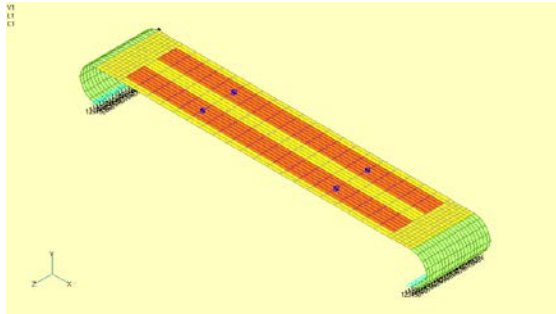
- Strain and frequency is main design input
- Piezo harvester is attached directly to maximum strain – area, very small mechanical harvester possible
- Normally not operating at resonance – lower yield
- Capable of harvesting from broad frequency spectrum

MFC – excellent match for vibration energy harvesting

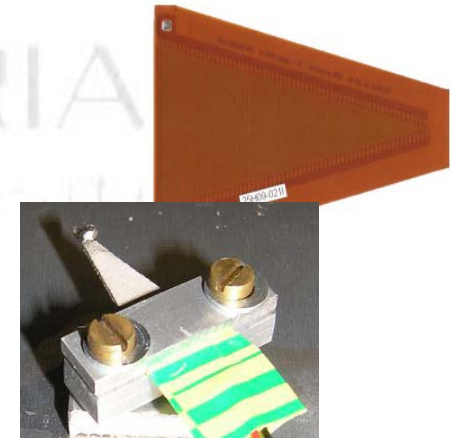
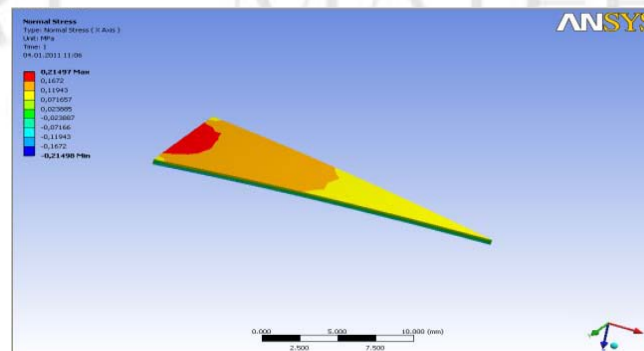
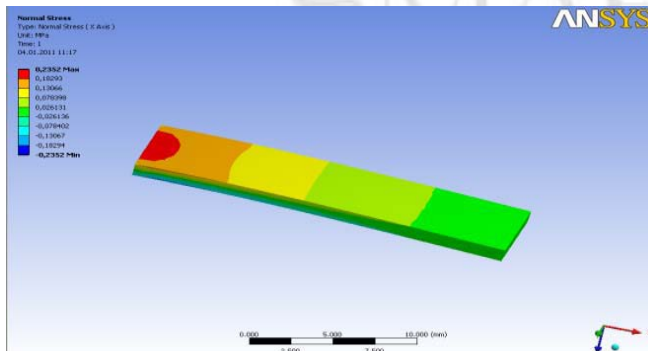
- MFC – Macro Fiber Composites developed at NASA LaRC during the late `90s
- **Actuator** (1Hz to 10kHz)
- **Sensor** (0.5 Hz up to 500kHz)
- **Flexible** and **robust**, ready to use package, overcomes disadvantages of solid PZT plates or patches based on solid wafers
- **Reliable**, > 10^8 cycles as actuator and > 10^{10} cycles for energy harvesting
- Broadband, allows for easy **non-resonant** and **resonant** energy harvesting applications
- Encapsulated and fault tolerant
- Integration of electronic components possible



Design rules for vibration harvesters - examples



Piezo Harvester using the 4Point-Bending approach

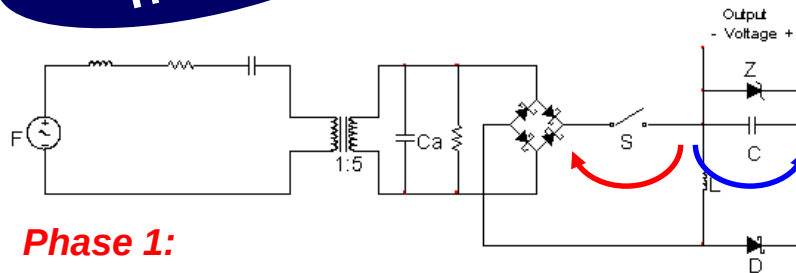


Piezo Harvester with variable geometry for better strain distribution

Photos courtesy Fraunhofer IKTS

New approaches for an efficient energy transfer

Peak Power Tracking



Phase 1:

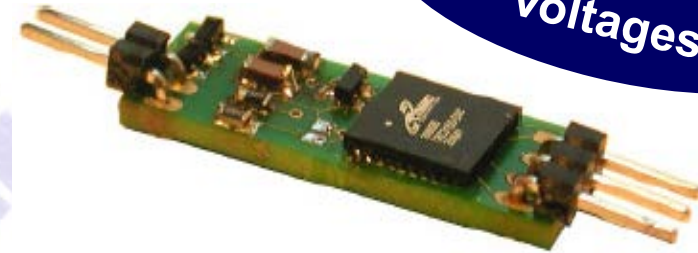
Switch S is closed
Energy flows from Piezo into inductor L

Phase 2:

Switch S is open/
Energy flows from inductor into the capacitor C



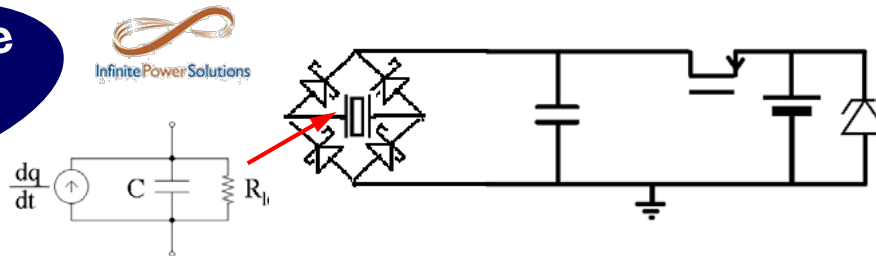
Regulated buffer voltages



Smart Conditioner CL50

energy is being transferred to the output depending on buffer cap voltage status

Current source approach



Schottky diodes for dynamic impedance matching, battery voltage constrains the piezo source voltage and leads to a big driving force for the "Coulombs"

Energy storage and low power applications

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**

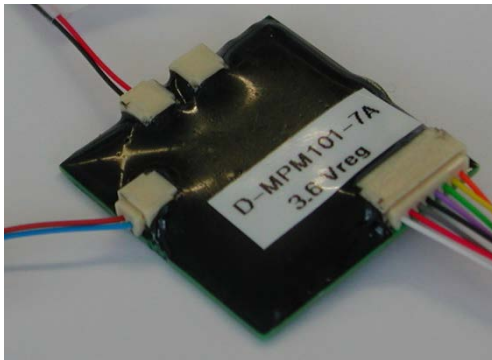
Intermittent Radio transmitter “telemetry” devices, SHM

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

Energy storage and low power applications



Thin Film Batteries



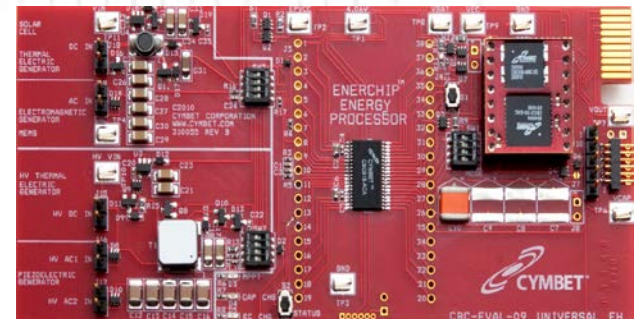
nearly leakage-free battery cells with charge guaranty over $\frac{3}{4}$ year



Solid State Batteries



High efficient energy harvesting and storage due to Peak Power Tracking



Outline



Science behind PZT vibration harvester – why is it so complex?



Are there possible ways to make it better?

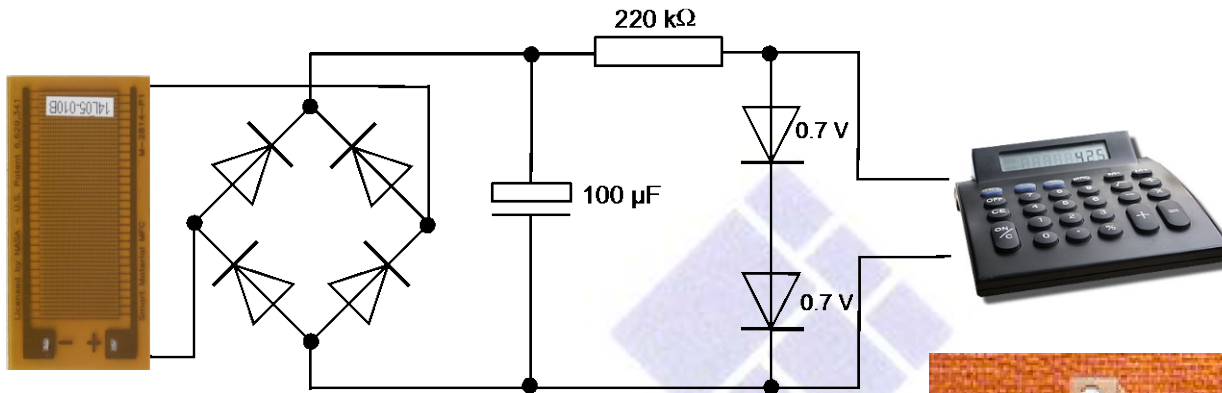


Case studies – applications & economics



Summery

Energy Harvesting Applications



- M8528-P2
- 10 seconds pumping
- 2-3 min duty cycle
- 1,5 μW power consumption

Energy autarchic calculator



Energy Harvesting – SmartFloor™ from POWERleap™

SmartFloor™ is an autonomous floor tile system using the latest P2-type MFC design for energy harvesting, resulting in decreased maintenance, lower energy costs and reduced installation cost in public buildings.

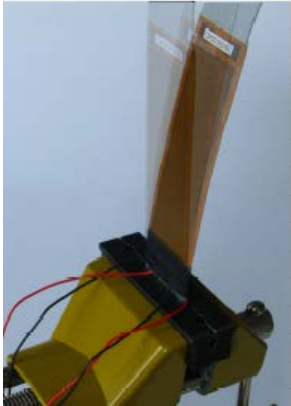
Intelligent Occupancy Sensing allows customers to control & track:

- GREEN BUILDING AUTOMATION
- INTELLIGENT TRAFFIC FLOW
- RETAIL TRAFFIC PATTERNS
- SECURITY
- INTERACTIVE FEATURES



Photos courtesy POWERleap

Energy Harvesting Applications



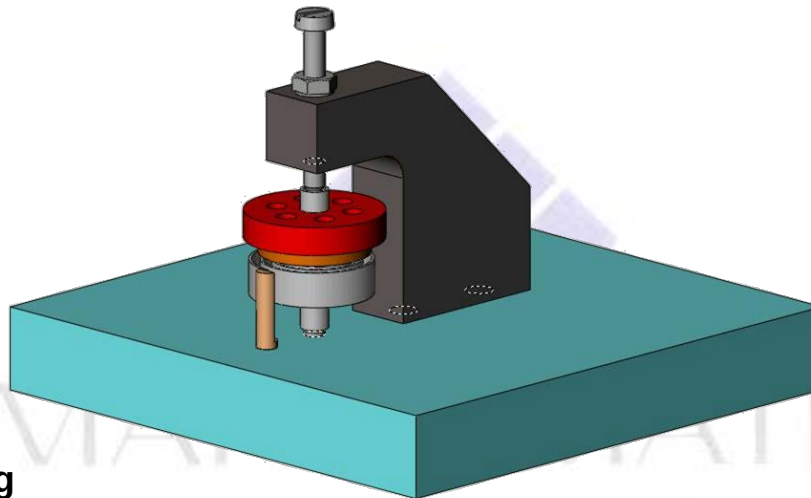
- energy from environmental vibrations
- up to 300 meters outdoors, 60 meters indoors
- reliable connection
- 3 Sensor types available
- Software provides logfile

Applications

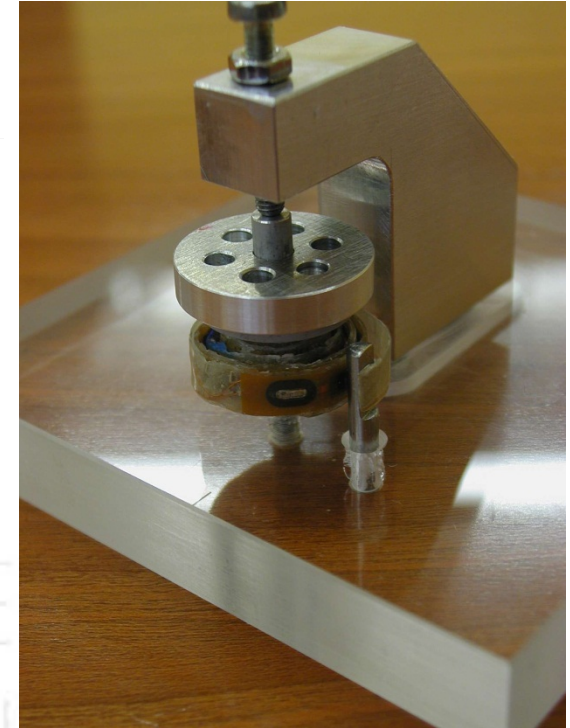
- Maintenance-free telemetry
- Vibration monitoring
- Industrial alarm systems
- Aerospace sector

AmbioMote by AmbioSystems

Energy Harvesting Applications



- 2x M8503-P2
- GFC Clock spring
- Resonance at 8 Hz
- Adjustable by additional masses
- Output about 10 μ W



Proof of concept for a customer
(detailed information covered by a NDA)

Clock spring energy harvester

Energy Harvesting Applications



Bell M412



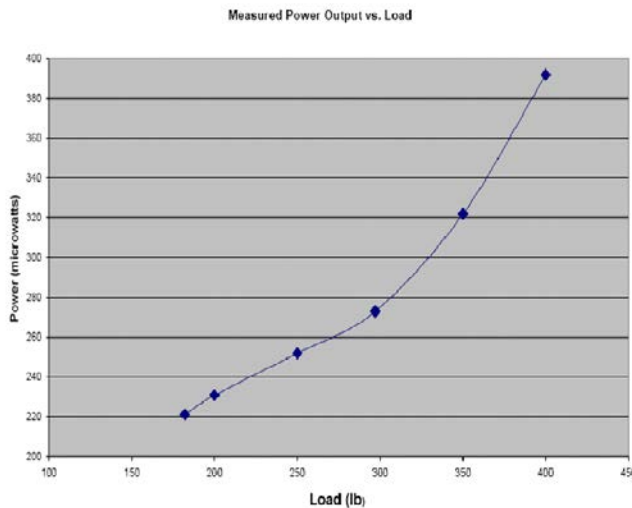
RF antenna

Circuit board module,
microprocessor, and
electrochemical battery

Piezoresistive strain gauge

Electrical insulation, EMI
shielding,
& protective covering
(shown transparent for
illustration purposes)

Piezoelectric energy
harvesting elements



*Energy Harvesting on helicopter pitch links
(potos & data courtesy mircostrain inc., St. Arms)*



Sikorsky H-60 Blackhawk

Energy Harvesting Applications



- MFC positioned at bending zone
- Optimized GFC structure for an excellent reliability
- Energy harvested sufficient for sending ~ 3 datagrams/step

Applications

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

Shoe insole with strain optimized MFC generator

Energy Harvesting - Economics

	MFC P2 type with EH301	Battery Li-Manganese
Lifetime 5 years +	++	+
Lifetime 10 years +	++	-
Maintenance Free	++	+
Acquisition cost	-	++
Cost incl. Maintenance	++	-
System integration	-/+	++
Wide temperature range	++ - (vibration must be present)	-
Self sufficient		++
Green Product	(+)	-
Weight	++	+

- only batteries are considered, not re-chargeable batteries due to their high discharge ratio
- temperature range for MFC -40 to 100C
- EH300 is a energy harvesting electronic, 3V output up to 200mW
- Battery is CR123
- Green product is referencing amount of non-degradable wastewaste, toxicity
- Maintenance references exchange of parts

Energy Harvesting - Economics

100 μ Ws, 3V output 10Hz, 0.05ppm	M2814P2 MFC + EH300	CR123 1500mA/h	CR2032 230mA/h
Acquisition Cost (> 1Mill. units)	\$ 19.00	\$ 2.00	\$ 1.50
Lifetime years, calculated	30	5	0.79
cost per year	\$ 0.63	\$ 0.40	\$ 1.90
<i>Energy Harvesting is economical</i>	-	> 5 years	> 1 years
10 years with change of battery ¹ , cost per year	\$ 1.90	\$ 1.40	\$ 14.56

¹ change cost of \$10.- assumed, calculation based on 2008 costs, not accounting for battery voltage decrease with depletion, room temperature assumed

Outline



Science behind PZT vibration harvester – why is it so complex?



Are there possible ways to make it better?



Case studies – applications & economics



Summary

Summery



In the most cases state-of-the-art harvesters don't match the energy sources and apps pretty well



Some interesting power conversation approaches are present but academic validations are still missing



Vibration harvesters can compete with batteries in hand-picked applications mostly for the background of a maintenance-free usage and life time

Thank you for your attention

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