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

Vibration Harvester – Piezo ceramic device, resonant with Cantilever, non resonant

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

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

Strain, Acceleration, Frequency
Power Output?

Custom design or Off the shelf Conditioners?

Power Consumption over time, operating voltage
Fact 1: Are we using optimal Structures & Materials?

Interesting energy sources:
- human footsteps
- breathing
- ocean waves
- traffic vibrations

But cantilever beams are everywhere

Nature of typical excitations:
- around 1-3 Hz
- unevenly
- small forces

Thomas P. Daue; Dr. Jan Kunzmann  Smart Material Corp.
Fact 2: How efficiently do we transfer the energy?

Is an impedance matching in the MΩ range really realistic?

Before closing S2

After closing S2

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 conversation of energy???)

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

typical cell phone battery
3.7V*1600mAh=355Ws

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

Typical piezo generator:
2mWs / step
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%

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

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

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Smart Material Corp.
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Design rules for vibration harvesters

State of the art

Increased performance

Variable beam thickness

4 point bending test

$F$

$x$

$l$

$M_b = F \cdot x \sim \varepsilon$

$F$

$\varepsilon = \text{const.}$

$M_b = \text{const.}$

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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

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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

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 ¾ year

Solid State Batteries

High efficient energy harvesting and
storage due to Peak Power Tracking
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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 µW

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

Clock spring energy harvester

Thomas P. Daue; Dr. Jan Kunzmann
Smart Material Corp.
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 (photos & data courtesy microstrain inc., St. Arms)
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

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

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

<table>
<thead>
<tr>
<th>100μWs, 3V output</th>
<th>M2814P2 MFC + EH300</th>
<th>CR123</th>
<th>CR2032</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Hz, 0.05ppm</td>
<td>1500mA/h</td>
<td>230mA/h</td>
<td></td>
</tr>
<tr>
<td>Acquisition Cost (&gt; 1Mill. units)</td>
<td>$19.00</td>
<td>$2.00</td>
<td>$1.50</td>
</tr>
<tr>
<td>Lifetime years, calculated cost per year</td>
<td>30</td>
<td>5</td>
<td>0.79</td>
</tr>
<tr>
<td>Energy Harvesting is economical</td>
<td>-</td>
<td>&gt; 5 years</td>
<td>&gt; 1 years</td>
</tr>
<tr>
<td>10 years with change of battery(^1), cost per year</td>
<td>$1.90</td>
<td>$1.40</td>
<td>$14.56</td>
</tr>
</tbody>
</table>

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