Low frequency, non resonant energy harvesting using piezo ceramic Macro Fiber Composites

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Outline

• Introduction
  – Vibration energy Harvesting with low profile piezo ceramic actuators
  – ALPA family
  – Typical EH operational modes
• Motivation for Low Frequency Vibration Harvesting with ALPAs
• Design considerations using ALPAs in Low Frequency Applications
• Conclusion
Piezo Ceramic Vibration Harvester

- Piezo bulk ceramic Bi- and Tri-morphs used for more than 25 years in vibration harvester
- Bi- and Tri-morphs mostly used in resonance mode applications
- Electromagnetic harvester are normally outperforming bi- and tri-morph bulk ceramic harvester, especially in low frequency applications due to
  - price
  - reliability, lifetime
  - low impedance in non-resonant or low frequency applications, yielding higher output
  - availability

Photos courtesy Morgan Electro, EnOcean
New Piezo Vibration Harvester

• Starting by the end of 1999 new piezo ceramic based products and technologies became commercially available which were quickly used for vibration harvester as well:
  – *Piezo ceramic composites in form of an Advanced Low Profile Actuator (ALPA)*
  – MEMs
  – Magnetostrictive devices
  – Thin film piezo ceramic devices

• Focus on Macro Fiber Composite as a member of the ALPA family which are improving the application envelope compared with bulk bi- and tri-morphs in vibration harvester
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**, $> 10^9$ 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
ALPAs overcome many problems - but not all

• Improvements for Vibration Harvester over existing bulk ceramic Bi-, Tri-morphs
  – flexibility,
  – allow for easy non-resonant applications
  – durability, lifetime extended for up to $10^{10}$ cycles, critical to advance over batteries or electro magnetic
  – low profile, easy integration

• Remaining disadvantages
  – price (getting better though)
  – high electric impedance, especially at $< 5$ Hz
Resonant vs. Non-resonant Vibration Harvesting

**Resonant** – mechanical transfer of vibration by Cantilever
- Acceleration (G’s) and frequency main design input
- Use of mechanical structure for energy transfer allows to adapt operation for prevalent vibration frequency
- Optimum energy harvesting at discrete frequencies only
- 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
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Low Frequency = Electromagnetic harvester?

- Low frequency < 5 Hz
- Most of the low frequency vibration harvesting applications are using electromagnetic systems.
- What advantages over electromagnetic systems do ALPAs have?
  - dimensions, low profile
  - easy mechanical integration, flexible, can be directly attached to a node of vibration
  - higher stiffness, requires lower deflection
  - typical lower deflection rates sufficient
  - weight
  - no mechanical moving parts, can be made fully solid state
Low Frequency Application for ALPAs

• Insole for shoes
  – requiring small profile
  – encapsulation, waterproof
  – long lifetime

• Chest band/Shirt
  – translating breathing motions
    in bending of a structure for harvesting
Smart Tile from POWERleap

- Rigid Surface
- Foam Sealing Joints
- Bending Piezoelectric Shim
- Rugged Frame

Detail A
Detail B
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Vibration Harvester – Typical Design & Challenge

**Vibration Harvester** – ALPA, non-resonant integrated in structure, low frequency, 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
Design Challenges to meet

Low frequency < 5Hz and intermittent (not periodic) charge generation have specific design challenges for maximum charge extraction

• High internal impedance, paired with intermittent events require a charge coupled design for best and cost effective charge extraction

• In a clamped condition, strain distribution needs to be addressed with triangle shaped designs to prevent asymmetric charge distribution

• Maximum strain and dependant depolarization limits have to be considered
Basics of power transfer in active dipoles - Compromise

Efficiency

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

Energy Transfer

\[ P_{out} = U_q^2 \cdot \frac{R_{out}}{(R_{in} + R_{out})^2} \]

\[ R_{out} = R_{in} \]
Dynamic impedance behavior for MFC M2814P2

- **PZT 5A1:**
  
  26 nF → 600 kΩ @ 10 Hz

- **PZT SP4:**
  
  14 nF → 1.1 MΩ @ 10 Hz

Low Frequency impedance

- 10 Hz impedance value
Cap to Cap Energy Transfer Loss Problem

With $Q = CU$ and $E = \frac{1}{2} C*U^2 \Rightarrow U_{C1+C2} = \frac{1}{2} U_{C1}$

Energy in C1 and C2 after closing switch = 25% each, 25% is maximum energy extraction!

C1 = C2 optimum energy transfer

<table>
<thead>
<tr>
<th>Voltage</th>
<th>20 V</th>
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<tr>
<td>C1</td>
<td>170 nF</td>
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### Table

<table>
<thead>
<tr>
<th>C1-C2 ratio</th>
<th>0.01</th>
<th>0.02</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
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<tr>
<td>C2 nF</td>
<td>1.7</td>
<td>3.4</td>
<td>8.5</td>
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<td>34</td>
<td>170</td>
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<td>0.03268</td>
<td>0.03084</td>
<td>0.0281</td>
<td>0.02361</td>
<td>0.0085</td>
<td>0.00756</td>
<td>0.00472</td>
<td>0.00281</td>
<td>0.00154</td>
<td>0.00065</td>
<td>0.00033</td>
</tr>
<tr>
<td>Initial charge in C1</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
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<td>0.00281</td>
<td>0.00154</td>
<td>0.00065</td>
<td>0.00033</td>
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<td>Voltage after switching</td>
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<td>19.61</td>
<td>19.05</td>
<td>18.18</td>
<td>16.67</td>
<td>10.00</td>
<td>6.67</td>
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<td>Charge in C2</td>
<td>3.4E-08</td>
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<td>0.00154</td>
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<td>0.00281</td>
<td>0.00154</td>
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<td>0.00033</td>
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<tr>
<td>Energy C2 % of initial</td>
<td>1.0</td>
<td>1.9</td>
<td>4.5</td>
<td>8.3</td>
<td>13.9</td>
<td>25.0</td>
<td>22.2</td>
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<tr>
<td>Energy in C1 after switch</td>
<td>0.03333</td>
<td>0.03268</td>
<td>0.03084</td>
<td>0.0281</td>
<td>0.02361</td>
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<td>0.00281</td>
<td>0.00154</td>
<td>0.00065</td>
<td>0.00033</td>
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<tr>
<td>Total Energy after switch</td>
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<td>Total Energy as % of initial</td>
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<td>50.00</td>
<td>33.33</td>
<td>16.67</td>
<td>9.09</td>
<td>4.76</td>
<td>1.96</td>
<td>0.99</td>
</tr>
</tbody>
</table>
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
Low Frequency Conditioner EH-CL50

- Standard PZT Conditioners now available as chipsets or standard circuit DO NOT imply good performance for low frequency/intermittent harvester applications!
- EH-CL50 special developed piezo ceramic conditioner for P2-type MFCs for low frequency/intermittent harvesting applications
- Based on capacitive energy extraction
- automatic capacitance switching and impedance matching
Conclusions

• Low profile piezo composite actuators (ALPA) are significant improvement over standard PZT bi- and tri-morphs in vibration energy harvesting applications.
• ALPA have advantages for non-resonant energy harvesting by applying them directly to vibration nodes.
• In low frequency, intermittent modes ALPAs have advantages over normally used electromagnetic systems, especially if weight, dimensions are critical and a non-moving parts design is important.
• Intrinsic high impedance of piezo ceramic harvester at low frequencies require special designed Conditioner circuits, normally charge coupled designs (cap to cap) for size and cost reasons.
• Off-the-shelf conditioners and harvester chipsets are not implicitly efficient in low frequency harvesting applications.
• Cap-to-cap designs limit maximum energy extraction to 25%, in general total system performance is more near 10-15% of initial PZT generated energy compared with 25-35% for resonant, periodic systems.
• Due to the lower efficacy of low frequency ALPA systems, an even strain distribution in the harvester for optimum charge generation is mandatory (triangle design)