High efficient energy harvesting using piezo macro fiber composites on vibrators with optimized energy transfer

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Outline

• Introduction
• Basics of using MFCs for Energy harvesting
• Test Setup and Components
• Results and Measured Data
• Recommendations and Conclusion
Piezo ceramic energy harvesting = LOW POWER

Introduction
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 shelve Conditioners?

Power Consumption over time, operating voltage

Introduction
Power requirement and Vibration Modes

Vibration Synchronous
- Power requirements are synchronous with Vibration and maximum power needed is always less than harvested energy
- Simple sensors, RFIDs, Visual feedback applications

Vibration Synchronous & Burst
- Power requirements are synchronous with Vibration but power intermittent powers bursts 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

Introduction
Resonant vs. Non-resonant Vibration Harvesting

**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
Outline

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MFC - good 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
Typical Applications for MFCs

• Vibration and Noise Control
• Strain gauge
• Health Monitoring Systems
  – Passive and active acoustic emission spectroscopy
  – Resonance shift detection
• Adaptive Structures
  – Morphing and Shaping of structures
• Energy Harvesting from Environmental Vibrations
MFC – available in d33 and d31 operational mode

**P1-Type MFC (d33)**

<table>
<thead>
<tr>
<th>Device</th>
<th>Operation voltage</th>
<th>Capacity</th>
<th>Sensor characteristic</th>
<th>Actuator characteristic</th>
<th>Generator characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-3 MFC</td>
<td>$V_{op^+}$ [V]</td>
<td>$V_{op^-}$ [V]</td>
<td>$C_{pol}$ [nF/cm$^2$]</td>
<td>$d_{33}^{eff}$ [pC/N]</td>
<td>$d_{31}^{eff}$ [pC/N]</td>
</tr>
<tr>
<td>3-3 MFC</td>
<td>1500</td>
<td>-500</td>
<td>0.42</td>
<td>460</td>
<td>-</td>
</tr>
</tbody>
</table>

**P2-Type MFC (d31)**

<table>
<thead>
<tr>
<th>Device</th>
<th>Operation voltage</th>
<th>Capacity</th>
<th>Sensor characteristic</th>
<th>Actuator characteristic</th>
<th>Generator characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1 MFC</td>
<td>360</td>
<td>-60</td>
<td>4.5</td>
<td>-</td>
<td>-370</td>
</tr>
</tbody>
</table>

Basics of using the MFC
Basics of power transfer in active dipoles - Compromise

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

\( R_{\text{out}} \gg R_{\text{in}} \)

Energy Transfer

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

\( R_{\text{out}} = R_{\text{in}} \)
Dynamic impedance behavior for the M2814P2 (4 cm²)

![Graph showing impedance behavior](image)

**Basics of using the MFC**
Outline

• Introduction
• Basics of using MFCs for Energy harvesting
• **Test Setup and Components**
• Results and Measured Data, Comparison
• Recommendations and Conclusion
Setup for Strain measurements – non resonant

- Actuator MFC (M8557-P1)
- CFC Host Structure (0.2 mm)
- SP4 Generator Bank (M2814-P2)
- 5A1 Generator Bank (M2814-P2)
- Bothsided Support
- Laser
- Actuator MFC (M8557-P1)
Setup for acceleration – resonant with cantilever

- tuning tip mass
- acceleration sensor
- generator sample
- shaker
- oscilloscope
- conditioner circuit

Test Setup
Conditioner – critical for optimized energy transfer

Simple circuit but good for basic measurements

dynamic input impedance for good power matching

Schottky rectifier / 609 μF

EH 300

excellent leakage-free battery cell

Special input impedance matching for MFC generators

MPM101-7A

Smart EH Module

Test Setup

Photos courtesy Infinite Power Solutions, Advanced Linear Devices
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Generator characterization – resonant mode

$d_{33}$ generators (P1; interdigitated electrodes) vs. $d_{31}$ generators (P2; surface electrodes)

- P2 type MFCs ($d_{31}$ effect) about 7 times better generators due to larger surface and lower source impedance
- Output energy is a function of:
  - frequency
  - source impedance matching
  - Deflection as a function of acceleration/frequency

<table>
<thead>
<tr>
<th>Source Energy [mJ]</th>
<th>Frequency [Hz]</th>
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<tbody>
<tr>
<td>0.25 G</td>
<td></td>
</tr>
<tr>
<td>0.5 G</td>
<td></td>
</tr>
<tr>
<td>1.0 G</td>
<td></td>
</tr>
</tbody>
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Results
Different sized Generators – Size matters

- harvested energy ~ to size
- select width over length
- position at max. strain position

Results
M2814P2 power matching results at Nominal Strain

5A1 @ 0.05% compression, 10Hz

0.107 mW (600 kΩ)

SP4 @ 0.05% compression, 10 Hz

0.047 mW (1.1 MΩ)
Power output @ 0.15% compression and 10Hz

M2814 P2 - 5A1

M2814 P2 - SP4

Results
Conditioner at 10Hz – good performance for all

- At 10Hz, 1G the M8528P2 is providing approx. 4mWs
- All managed circuits have discrete “on” voltage threshold
- Time between beginning of harvesting and first “switch on” difficult to determine for battery based systems => unknown charge status
- Better impedance matching of the Smart Module allows for highest power transfer

Results
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Basic Design Rules for harvesting from environmental vibration

1. **Non resonant approach:** Check for typical strain and frequency using strain gauge and/or laser vibrometer, locate nodes of high strain best suited to attach MFCs.

2. **Resonant approach:** Check for acceleration at single frequency using accelerometer, clamp cantilevered MFC at point of highest acceleration.

3. For long life (> 10 years) best strain range for P2 MFC is 100 to 500 ppm. Strain up to 1500 ppm is permissible at reduced life expectancy. Maximum tensile strength is 4000 ppm.

4. Best frequency range for low dynamic impedance ($R_{in}$) and life time is 10 Hz to 500 Hz.

5. Adjust MFC size and PZT material according to required charge generation, complex relation but ballpark estimate:
   - At 500 ppm, 10 Hz, approx. 30 μWs/cm² (5A1 PZT)
   - At 1G, 10 Hz resonant mode approx. 200 μWs/cm² (5A1 PZT)

6. **Adjust rectifier/load balancing electronic, i.e. Conditioner** for optimal load impedance, typical use of harvested energy to select available intelligent rectifier electronics.

Recommendations
### Storage retention, energy density => Battery

<table>
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<th>Type</th>
<th>Characteristics</th>
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| Thin film Batteries         | • < 8% self discharge p.a.  
• highest energy density, size                                                  |
| Super Caps, Multi Layer Tantals | • Self discharge to 60% in 30 days  
• ¼ energy density of battery                                                  |
| Standard electrolytic capacitors | • Self discharge to 60% < 3 hours  
• 1/8 energy density of battery, inexpensive                                  |

Conclusions
### Best (cost, efficacy) Conditioner applied

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**Schottky Bridge with Cap**

**Schottky Bridge, EH300 device with Super Cap**

**Infinite Power, Battery Technology**
Conclusions

- **Design of Piezo Harvester** requires specific and careful adaptation to each targeted vibration source for maximum efficacy and energy transfer.
- **Correct impedance matching of Piezo Harvester** is the single most important design input for optimized energy transfer.
- Many standard available Conditioners are designed to accommodate a variety of energy harvesting components (i.e. solar, electromagnetic, etc) => **sensitive impedance matching** for piezo ceramic devices is often not optimized (yet).
- **Thin film battery solutions** appear to be the best approach for long term managed energy storage especially in asynchronous energy harvesting applications.
- Non-resonant applications still require system design for the Conditioner for optimum efficacy.
- **A simple and well designed Schottky bridge** with capacitor can still be the best solution for synchronous applications!
- A good Conditioner for a piezo ceramic harvester will **require adaptive or adjustable impedance matching** and a combination of cap and battery storage with a smart charging management.
Supporting Slides
Testing the Conditioners - parameters

- Acceleration constant 1G
- Frequency 5Hz, 10Hz, 15Hz based on power distribution for energy harvester

**Energy Harvester**
- M8528P2
- mounted on glass fiber cantilever
- Optimum energy output at about 10Hz@1G

**Conditioner**
- output voltage between 3V – 6V

**Consumer**
- resistive 15kOhm load
- at 3-6V simulates 650µW to 1.6mW consumer
Emerging Applications using PZT Harvester

- Telemetry and Condition (Health) Monitoring, typical 100-400µWs
  - airplanes, helicopters
  - automotive crash sensors
  - wind generator blades
  - bridges and other high rise structure with “vibrations”
  - medical devices used by patients

Photos courtesy Microstrain, Inc., COR Insulin Wristwatch,
Applications cont’d

• Backup chargers for applications using rechargeable batteries, typical 500µWs
  – Buoys
  – Active RFIDs

• “wake-up” circuits for dormant electronic circuits, typical < 100 µWs
  – Sealed and/or submersed Alarm systems
  – Door entries