Ultra-High Power Density Piezoelectric Energy Harvesters

Tian-Bing Xu and Jin Ho Kang
National Institute of Aerospace, Hampton, VA 23666

Emilie J. Siochi
NASA Langley Research Center, Hampton, VA 23681

Lei Zuo and Wanlu Zhou
Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061

Xiaoning Jiang
Department of MAE, North Carolina State University, Raleigh, NC 27695

Energy Harvesting & Storage USA 2015
Santa Clara, CA
November 18~19, 2015
Outline

- Introduction: Background and motivation
- Methodologies for harvesting more electrical energy
  - Enhanced mechanical energy capture
  - Increased mechanical to electrical energy conversion efficiency
  - Increased energy storage efficiency
- Experimental results and validation
- Low cost piezoelectric harvester
- Conclusions
Piezoelectric Energy Harvesting Applications

Structural health monitoring

- Bridge
- Aircraft
- Machine
- Web Server
- Database Server
- Central Server
- Local Monitor

Power for portable devices

- A soldier with portable electronics
- Smartphone
- Automobile
- Building
- Ship
## Vibration Sources

<table>
<thead>
<tr>
<th>Vibration source</th>
<th>Acceleration (m/s²)</th>
<th>G (9.8 m/s²)</th>
<th>Frequency peak (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car engine compartment</td>
<td>12</td>
<td>1.22</td>
<td>200</td>
</tr>
<tr>
<td>Base of 3-axis machine tool</td>
<td>10</td>
<td>1.0</td>
<td>70</td>
</tr>
<tr>
<td>Blender casing</td>
<td>6.4</td>
<td>0.65</td>
<td>121</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>3.5</td>
<td>0.36</td>
<td>121</td>
</tr>
<tr>
<td>Person tapping their heel</td>
<td>3</td>
<td>0.31</td>
<td>1</td>
</tr>
<tr>
<td>Car instrument panel</td>
<td>3</td>
<td>0.31</td>
<td>13</td>
</tr>
<tr>
<td>Door frame just after door closes</td>
<td>3</td>
<td>0.31</td>
<td>125</td>
</tr>
<tr>
<td>Small microwave oven</td>
<td>2.5</td>
<td>0.26</td>
<td>121</td>
</tr>
<tr>
<td>HVAC vents in office building</td>
<td>0.2 - 1.5</td>
<td>0.02 - 0.15</td>
<td>60</td>
</tr>
<tr>
<td>Windows next to a busy road</td>
<td>0.7</td>
<td>0.07</td>
<td>100</td>
</tr>
<tr>
<td>CD on notebook computer</td>
<td>0.6</td>
<td>0.06</td>
<td>75</td>
</tr>
<tr>
<td>Second story floor of busy office</td>
<td>0.2</td>
<td>0.02</td>
<td>100</td>
</tr>
<tr>
<td>Railway</td>
<td>1.078 - 1.568</td>
<td>0.11 - 0.16</td>
<td>12 - 16</td>
</tr>
<tr>
<td>Truck</td>
<td>1.96 - 3.43</td>
<td>0.2 - 0.35</td>
<td>8 - 15</td>
</tr>
<tr>
<td>Ship</td>
<td>0.98 - 2.45</td>
<td>0.1 - 0.25</td>
<td>12 - 13</td>
</tr>
</tbody>
</table>
Wireless sensors need power sources on the order of 100 mW
State-of-the-Art
Piezoelectric Energy Harvesters

Cantilever Beam-based Harvesters


- 0.2μW ~4 mW
- Resonance mode operation
- >1000 papers

Edge Clamped Circular Diaphragm Harvesters


- 1~20 mW
- High resonance frequency > 1000 Hz
- Suitable for acoustic pressure

Flextensional Harvesters - Cymbal


- 52 mW of electrical power to a 400 kΩ matched resistive load under 70 N_{rms} force at 100 Hz
- Energy conversion efficiency: 7.8%

Flextensional Harvesters - Multilayer stack

Sosnicki, O., N. Lhermet, F. Claeyssen, ACTUATOR 2006, 14 – 16 June 2006, Bremen, Germany

- 50 mW electrical power at the resonance frequency of 110 Hz with 0.85g acceleration
Multidisciplinary Challenge

Vibration source
- Coupling to active element

Piezoelectric element
- Energy conversion efficiency and its measurement

Energy storage
- Charge transport and delivery to load

Mechanical Engineering

Materials Science

Electrical Engineering
Outline

- Introduction: Background and motivation
- Methodologies for harvesting more electrical energy
  - Enhanced mechanical energy capture
  - Increased mechanical to electrical energy conversion efficiency
  - Increased energy storage efficiency
- Experimental results and validation
- Low cost piezoelectric harvester
- Conclusions
Approach I: Capture More Mechanical Energy

Two-stage Force Amplification Piezoelectric Energy Harvester (TS-FAPEH)

If $\theta_1 = \theta_2 = 11^\circ$, then **625 times** more mechanical energy can be captured/transferred into each piezoelectric element

$$F_{CC} = \cot(\theta_1)\cot(\theta_2)F_{AA}$$
$$E \propto F_{CC}^2$$

Approach II: Increase Energy Conversion Efficiency
Piezoelectric Material Selection and Mode

<table>
<thead>
<tr>
<th>Property</th>
<th>High K HK1-HD</th>
<th>Type II 200-HD</th>
<th>Type III 300-HD</th>
<th>SC-PMN-32% PT*</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;31&quot; energy conversion efficiency ((k^2_{31}))</td>
<td>0.15</td>
<td>0.14</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>&quot;33&quot; energy conversion efficiency ((k^2_{33}))</td>
<td>0.55</td>
<td>0.53</td>
<td>0.46</td>
<td>0.83</td>
</tr>
</tbody>
</table>

\[ k^2_{33} \approx (3 - 5) k^2_{31} \]

"33" mode

"31" mode

poling direction

SC-PMN-32% PT = Single crystals of lead magnesium niobate-lead titanate

*TRS: http://www.trstechnologies.com*
Approach III: Increase Energy Storage Efficiency
Optimization of Multilayer Stacks

Optimize number of layers, \( n \), for charge generation and collection

Stored energy

\[
\Delta E = \frac{2Q_0 \Delta Q + (\Delta Q)^2}{2C_S} = \frac{(\Delta Q)^2}{2C_S} \quad \text{(if \quad } Q_0 = 0)\
\]

where \( Q_0 \) initial electric charge in the super-capacitor
Multidisciplinary Integration and Design Optimization

- **Design**
- **Fabrication**
  - Parameters of PMN-PT
  - Single Crystal Multilayer Stack
  - 62 piezoelectric layers
  - 22 mm x 5 mm x 5 mm
  - 4.5 gram
- **Integration**

➢ Frame geometry and parameters design is critical
Outline

- Introduction: Background and motivation
- Methodologies for harvesting more electrical energy
  - Enhanced mechanical energy capture
  - Increased mechanical to electrical energy conversion efficiency
  - Increased energy storage efficiency
- Experimental results and validation
  - Low cost piezoelectric harvester
- Conclusions
Two finger compression can directly power 50 LEDs.
The generated electrical power is proportional to
- frequency
- the square of the applied force.
Resonance Mode Operation Without Proof Mass
34 gram TS-FAPEH

Frequency spectra

Charging a 6,600 μF Super-capacitor at 213 Hz with 1 g acceleration

It only took 1.4 seconds to charge a 6,600 μF super-capacitor from 0 to 6.8 V (full) for 1 g<sub>rms</sub> acceleration
## Comparison With the State-of-the-Art
**Piezoelectric Energy Harvesters**

### Off-resonance mode operation

<table>
<thead>
<tr>
<th>Harvesters</th>
<th>Weight (gram)</th>
<th>Applied force</th>
<th>Generated electrical power (mW)</th>
<th>Power density normalized by weight, force², and frequency {μW/[kg.(N_{rms})².Hz]}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Force (N_{rms})</td>
<td>Frequency (Hz)</td>
<td></td>
</tr>
<tr>
<td>Cymbal (K. Uchino and T. Ishii, Ferroelectrics, 400, 305 (2010))</td>
<td>10.5</td>
<td>49.5</td>
<td>100</td>
<td>52</td>
</tr>
<tr>
<td>This TS-FAPEH</td>
<td>34</td>
<td>15</td>
<td>128</td>
<td>248</td>
</tr>
</tbody>
</table>

### Resonance mode operation

<table>
<thead>
<tr>
<th>Type of PEH</th>
<th>Weight (gram)</th>
<th>Excitation</th>
<th>Generated electrical power (mW)</th>
<th>Power density normalized by weight and accel.² [W/(kg.g²)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Acceleration (g_{rms})</td>
<td>Frequency (Hz)</td>
<td></td>
</tr>
<tr>
<td>One-stage Flex tensional (O. Sosnicki, N. Lhernet, and F. Ciaeyssen, ACTUATOR 2006)</td>
<td>269</td>
<td>0.9</td>
<td>110</td>
<td>50</td>
</tr>
<tr>
<td>This TS-FAPEH</td>
<td>34</td>
<td>0.7</td>
<td>213</td>
<td>366</td>
</tr>
</tbody>
</table>

> Power density is more one order of magnitude higher than others
Outline

➤ Introduction: Background and motivation

➤ Methodologies for harvesting more electrical energy
  ➤ Enhanced mechanical energy capture
  ➤ Increased mechanical to electrical energy conversion efficiency
  ➤ Increased energy storage efficiency

➤ Experimental results and validation

➤ Low cost piezoelectric harvester

➤ Conclusions
Low Cost PZT Polycrystalline Ceramic Stack-Based TS-FAPEH

Overall:
70 mm x 38 mm x 31 mm
Weight = 88 grams

PZT ceramic stack:
7 mm x 7 mm x 32.4 mm,
Weight = 9 grams
Capacitance = 2.5 μF

- Generated 3.5 mW electrical power from low frequency manual compression
- PZT polycrystalline material cost is 10 times lower than PMN-PT single crystal material
Resonance Mode Operation
PZT MS-FAPEH without Proof Mass

Frequency spectra

Charging a 6,600 μF Super-capacitor

- a = 0.5 g<sub>rms</sub>, 108 Hz
- a = 1 g<sub>rms</sub>, 108 Hz

- It took 8 seconds to charge a 6,600 μF super-capacitor from 0 to 6.8 V (full) for 0.5 g<sub>rms</sub> acceleration and 2 seconds for 1 g<sub>rms</sub> acceleration.
Resonance Mode Operation
PZT TS-FAPEH with Proof Masses

- Adding proof mass
  - Lowered the resonance frequency
  - Significantly increased the generated electrical power
Resonance Mode Operation at 0.25 g_{rms} Acceleration
PZT TS-FAPEH with 50 gram Proof Mass

Power delivered to resistive loads

Charging a 6,600 μF Super-capacitor
At 0.25 g_{rms} with 50 gram proof mass
Outline

- Introduction: Background and motivation
- Methodologies for harvesting more electrical energy
  - Enhanced mechanical energy capture
  - Increased mechanical to electrical energy conversion efficiency
  - Increased energy storage efficiency
- Experimental results and validation
- Low cost piezoelectric harvester
- Conclusions
Comparison of Two-Stage and Single-Stage Flextensional Harvesters

Two-stage At 0.5 $g_{\text{rms}}$ acceleration

One-stage

- The power density of the two-stage is more than one order of magnitude higher than the same-stacked one-stage
- The operational frequency of the TS-FAPEH is in the range of practical applications
Conclusions

- TS-FAPEH energy harvesters gave high energy (>10 times) density via three approaches:
  - **Two-stage structures** that capture orders of magnitude more mechanical energy
  - "33" mode piezos that increase energy conversion efficiency
  - **Optimized multilayer stacks** that increase energy storage efficiency many times
- The TS-FAPEH generated significantly higher electrical power both off-resonance and at resonance -- with and without proof masses
- A lower-cost PZT-multilayer TS-FAPEH also exhibits excellent performance
- The resonance frequency of the TS-FAPEH is in the range of many practical applications.
Contact Information

For licensing/other business POC

- Dr. Rhea P. Turcotte
- NASA Langley Research Center
- Email: rheal.p.turcotte@nasa.gov
  Phone: 757-864-8881

Questions?