MEMS/NEMS scale vibration energy harvesting

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Outline

• MEMS- to NEMS-based energy harvesters and potential applications

• Micro/nanoscale energy harvesters: scaling issues

• Nonlinear and frequency-up conversion approaches

• Conclusions
MEMS- to NEMS-based harvesting devices and potential applications

Medical applications

Nanomedicine

Internet of Things (IoT)

Body powered pacemaker

Structural Monitoring

Military/Aerospace

University of Illinois and University of Arizona.

02/07/2014 - bridge collapse at FIAT factory @ Belo Horizonte (Brazil) (source: Corriere della sera)

source: www.google.com

source: microstrain

https://www.youtube.com/watch?v=F11M7978n7c
MEMS- to NEMS-based harvesting devices and potential applications

**MEMS-based drug delivery systems**

Bohm S. et al. 2000

**Body-powered oximeter**

Leonov, V., & Vullers, R. J. (2009).

**Heart powered pacemaker**

D. Tran, Stanford Univ. 2007

Pacemaker consumption is around **40uW**.

Beating heart could produce **200uW** of power from heat differentials, physiological pressures, and flows and movements, such as blood flow

**Micro-robot for remote monitoring**

A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999

A 1mm-20mg nanorobot flying at 1 m/s requires F ~ 4 microN and P ~ 41 uW.

The input power for a 20mg robotic fly is **10 – 100 uW** depending on many factors: air friction, aerodynamic efficiency etc.
MEMS- to NEMS-based harvesting devices and potential applications

**MEMS-based energy harvesting devices**

- **Jeon et al. 2005**
- **M. Marzencki 2008 – TIMA Lab (France)**
- **Khalil Najafi 2011 Univ. Michigan**
- **Chang. MIT 2013**
- **EM generator, Miao et al. 2006**
- **D. Briand, EPFL 2010**
- **Le, C. P., Halvorsen 2012**
- **Mitcheson 2005 (UK)**
  Electrostatic generator 20Hz
  2.5uW @ 1g
- **Cottone F., Basset P. ESIEE Paris 2013-14**

**Time**

2005 — 2015
MEMS- to NEMS-based harvesting devices and potential applications

NEMS-based energy harvesting devices

ZnO nanowires – Xu F. (2010) tensile stress test

ZnO nanowires
Wang, Georgia Tech (2005)


Qi, Yi, 2011 Nano Letters PZT Nanoribbons

Virus-directed BaTiO3 nanogenerator

Time

2005 2015
Objective:
100 µW/cm³ of power density

Temporary storage and conditioning electronics:
- Ultra capacitors
- Rechargeable Batteries

Energy harvesting system:
- piezoelectric,
- electromagentic,
- electrostatic,
- magnetostrictive

Mechanical vibrations
Sensor node and transceiver
Who’s the best for MEMS/NEMS?

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric</td>
<td>• high output voltages</td>
<td>• expensive</td>
</tr>
<tr>
<td></td>
<td>• well adapted for miniaturization</td>
<td>• small coupling for piezoelectric thin films</td>
</tr>
<tr>
<td></td>
<td>• high coupling in single crystal</td>
<td>• large load optimal impedance required (MΩ)</td>
</tr>
<tr>
<td></td>
<td>• no external voltage source needed</td>
<td>• Fatigue effect</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>• suited for MEMS integration</td>
<td>• need of external bias voltage</td>
</tr>
<tr>
<td></td>
<td>• good output voltage (2-10V)</td>
<td>• relatively low power density at small scale</td>
</tr>
<tr>
<td></td>
<td>• possiblity of tuning electromechanical coupling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Long-lasting</td>
<td></td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>• good for low frequencies (5-100Hz)</td>
<td>• inefficient at MEMS scales: low magnetic field, micro-magnets manufacturing issues</td>
</tr>
<tr>
<td></td>
<td>• no external voltage source needed</td>
<td>• large mass displacement required.</td>
</tr>
<tr>
<td></td>
<td>• suitable to drive low impedances</td>
<td></td>
</tr>
</tbody>
</table>
First order power calculus with William and Yates model

\[ F(t) = -m \ddot{y} \]

Motion equation

\[ m \ddot{x}(t) + (d_m + d_e) \dot{x}(t) + kx(t) = -m \ddot{y}(t) \]

Inertial force

\[ f(t) = -m \ddot{y} = Y_0 \sin(\omega t) \]

motion equation

\[
x(t) = \frac{\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{(d_e + d_m)\omega}{m}\right)^2}} Y_0 \sin(\omega t - \phi)
\]

Steady state solution

setting \( d_T = d_m + d_e \) the total damping coefficient, the phase angle \( \phi \) is given by

\[
\phi = \tan^{-1} \left( \frac{d_T \omega}{k - \omega^2 m} \right)
\]

and the natural frequency \( \omega_n = \sqrt{\frac{k}{m}} \)

By introducing the damping ratio, namely \( \zeta_T = (\zeta_e + \zeta_m) = d_T / 2m \omega_n \), the position transfer function is expressed by

\[
H_{xy}(\omega) = \frac{X(\omega)}{Y(\omega)} = \frac{\omega^2}{-\omega^2 + 2i \omega (\zeta_e + \zeta_m) \omega_n + \omega_n^2}
\]
First order power calculus with William and Yates model

The instantaneous dissipated power by electrical damping is given by

$$P(t) = \frac{d}{dt} \int_0^x F(t) dx = \frac{1}{2} d_T \dot{x}^2$$

The velocity is obtained by the first derivative of steady state amplitude

$$\dot{x} = \frac{\omega r^2 Y_0}{\sqrt{(1-r^2)^2 + (2(\zeta_e + \zeta_m)r)^2}},$$

that is

$$P_e = \frac{m \zeta_e \left( \frac{\omega}{\omega_n} \right)^3 \omega^3 Y_0^2}{\left[ 1 - \left( \frac{\omega}{\omega_n} \right)^2 \right]^2 + \left[ 2(\zeta_e + \zeta_m) \frac{\omega}{\omega_n} \right]^2}$$

At resonance, that is $\omega = \omega_n$, the maximum power is given by

$$P_e = \frac{m \zeta_e \omega_n^3 Y_0^2}{4(\zeta_e + \zeta_m)^2} = \frac{m^2 d_e \omega_n^4 Y^2}{2(d_e + d_m)^2}$$

or with acceleration amplitude $A_0 = \omega_n^2 Y_0$.

for a particular transduction mechanism forced at natural frequency $\omega_n$, the power can be maximized from the equation

$$P_{el} = \frac{m \zeta_e A^2}{4 \omega_n (\zeta_m + \zeta_e)^2}$$

Max power when the condition $\zeta_e = \zeta_m$ is verified
Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC MATERIALS COMPARISON

\[ \omega_n = 2\pi C_n \sqrt{\frac{E}{\rho}} \frac{h}{l^2} \]

\[ k = \xi E w \frac{h^3}{l^3} \]

\[ m_{\text{eff}} = m_{\text{beam}} + 0.32m_{\text{tip}} = lwh\rho_{si} + 0.32(l/4)^3\rho_{si} \]

\[ P_{el} = \frac{m\xi_e A^2}{4\omega_n (\xi_m + \xi_e)^2} = \left( lwh\rho_{si} + 0.32(l/4)^3\rho_{mo} \right) \frac{A^2}{8\omega_n \xi_m} = \left( lwh\rho_{si} + 0.32(l/4)^3\rho_{mo} \right) A^2 \]

At max power condition \( \xi_e = \xi_m \)

By assuming

\[ A = 1g \]
\[ \xi_m = 0.01 \]
\[ h = l/200 \]
\[ w = l/4 \]

\[ P_{el} = \rho_{si} \frac{1}{800 + 0.32 \cdot 64\rho_{mo}} \frac{16}{200} \pi C_n \sqrt{\frac{E}{\rho_{si}} \xi_m} A^2 l^4 \]
Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC MATERIALS COMPARISON

By assuming:

\[ A = 1g \]
\[ \zeta_m = 0.01 \]
\[ h = \frac{l}{200} \]
\[ w = \frac{l}{4} \]
Microscale kinetic harvesters: scaling issues

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PIEZOELECTRIC MATERIALS COMPARISON

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\[ \zeta_m = 0.01 \]

\[ h = l / 200 \]

\[ w = l / 4 \]
Piezoelectric conversion

Material properties example

Strain-charge
\[ S = s_E \cdot T + d^{\dagger} \cdot E \]
\[ D = d \cdot T + \varepsilon_T \cdot E \]

Stress-charge
\[ T = c_E \cdot S - e^{\dagger} \cdot E \]
\[ D = e \cdot S + \varepsilon_S \cdot E \]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PZT-5H</th>
<th>BaTiO3</th>
<th>PVDF</th>
<th>AlN (thin film)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{33} ) (10^{-10} C/N)</td>
<td>593</td>
<td>149</td>
<td>-33</td>
<td>5,1</td>
</tr>
<tr>
<td>( d_{31} ) (10^{-10} C/N)</td>
<td>-274</td>
<td>78</td>
<td>23</td>
<td>-3,41</td>
</tr>
<tr>
<td>( k_{33} )</td>
<td>0,75</td>
<td>0,48</td>
<td>0,15</td>
<td>0,3</td>
</tr>
<tr>
<td>( k_{31} )</td>
<td>0,39</td>
<td>0,21</td>
<td>0,12</td>
<td>0,23</td>
</tr>
<tr>
<td>( \varepsilon_r )</td>
<td>3400</td>
<td>1700</td>
<td>12</td>
<td>10,5</td>
</tr>
</tbody>
</table>

\[ k_{31}^2 = \frac{El.\text{energy}}{Mech.\text{energy}} = \frac{d_{31}^2}{s_{11}^{\text{E}} \varepsilon_{33}^{\text{T}}} \]

Electromechanical Coupling is an adimensional factor that provides the effectiveness of a piezoelectric material. It’s defined as the ratio between the mechanical energy converted and the electric energy input or the electric energy converted per mechanical energy input.
Bandwidth figure of merit

\[
\text{FoM}_{\text{BW}} = \text{FoM}_V \times \frac{\delta \omega_{1 \text{ dB}}}{\omega}
\]

Frequency range within which the output power is less than 1 dB below its maximum value

\[
\text{FoM}_V = \frac{\text{Useful Power Output}}{\frac{1}{10} Y_0 \rho_A V_0 \frac{1}{3} \omega^3}
\]

Galchev et al. (2011)

Microscale kinetic harvesters: scaling issues

\[ \text{FoM}_V = \frac{\text{Useful Power Output}}{\frac{1}{10} Y_0 \rho_A u V_0 \beta^3 \omega^3} \]

Bandwidth figure of merit

\[ \text{FoM}_{BW} = \text{FoM}_V \times \frac{\delta \omega_{1\text{ dB}}}{\omega} \]

Frequency range within which the output power is less than 1 dB below its maximum value


Galchev et al. (2011)
At micro/nano scale direct force generators are much more efficient because not limited by the inertial mass!!!
Microscale kinetic harvesters: scaling issues

Power fluxes

\[ m \ddot{z} \ddot{z} + d \dot{z}^2 + \frac{dU(z)}{dz} \dot{z} + \alpha V_L \dot{z} = F(t) \dot{z} \]

\[ P_m(t) = F(t) \cdot \dot{z}(t) \]

\[ P_m(t) = -m \ddot{y} \cdot \dot{z} = -\rho l^3 \cdot \dot{z} \]
Main limits of inertial resonant VEHs

Problems at micro- to nano-scale

• Narrow bandwidth

• Non-adaptation to variable vibration sources

• High resonant frequency at micro/nano-scale

• Poor piezoelectric coefficient

At 20% off the resonance the power falls by 80-90%
Nonlinear MEMS electrostatic kinetic energy harvester


Nonlinear MEMS electrostatic kinetic energy harvester

Mathematical modeling

Governing equations

\[ m \frac{d^2 x}{dt^2} + (c_a + c_i) \frac{dx}{dt} + \frac{dU(x)}{dx} = -m \frac{d^2 y}{dt^2}, \]

\[ R_L \frac{d}{dt} (C \cdot V) + V = U_0, \]

\[ U(x) = \begin{cases} 
\frac{1}{2} k_{sp} x^2 - \frac{1}{2} C(x) U_0^2, & \text{for } |x| < x_{lim} \\
\frac{1}{2} (k_{sp} + k_{st}) x^2 - \frac{1}{2} C(x) U_0^2, & \text{for } |x| \geq x_{lim}
\end{cases} \]

\[ C(x) = C_{par} + \varepsilon N_f l_f \frac{1}{2r} \left[ \ln \left( \frac{d_0 - x + 2hr}{d_0 - x} \right) + \ln \left( \frac{d_0 + x + 2hr}{d_0 + x} \right) \right], \]
Nonlinear MEMS electrostatic kinetic energy harvester

Mathematical modeling

\[ U(x) = \begin{cases} \frac{1}{2} k_{sp} x^2 - \frac{1}{2} C(x) U_0^2, & \text{for } |x| < x_{\text{lim}} \\ \frac{1}{2} (k_{sp} + k_{st}) x^2 - \frac{1}{2} C(x) U_0^2, & \text{for } |x| \geq x_{\text{lim}} \end{cases} \]
Electrostatic generators

F. Cottone, P. Basset Université Paris-Est, ESIEE Paris,
Silicon MEMS-based electrostatic harvesters.
Nonlinear MEMS electrostatic kinetic energy harvester


Conclusions

- Many potential applications are waiting for powerful MEMS/NEMS harvesting system to enable self-powering features

- Inertial vibration energy harvesters are very limited at small scale -> direct force piezoelectric/electrostatic devices are more efficient at nanoscale

- Design challenges
  - Materials with high electromechanical coupling,
  - Cheap miniaturization/fabrication processes
  - Very efficient conditioning electronics

- In general the specific application decides if one or many micro-VEH are the best choice with respect to one macro-scale VEH
Research activities done in collaboration with

Thank you

2008
2011
2010
2013