Micro scale
Energy Harvesting Systems

ERASMUS + IESRES
INNOVATIVE EUROPEAN STUDIES on RENEWABLE ENERGY SYSTEMS

Teaching Activity
8th – 13th May 2017 - Klaipeda, Lithuania

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Outline

• Energy harvesting fundamentals

• Micro- to nano-scale vibrational energy harvesters

• Piezoelectric micro-structures for EH

• MEMS electrostatic systems for EH

• Final considerations
What is an energy harvester?

- Thermal energy
- Radioactivity
- Transmitted EM energy
- Solar
- Vibrations
- RF
- Hydro/wind
- Traffic
- Biochemical

Energy Harvester:

- Generator
- Power Management Unit
- Energy Storage system

Electronic end-user device

Wasted thermal energy
Historical human-made energy harvesters

Wind mill (Origin: Persia, 3000 years BC)

Sailing ship (XVI-XVII century)

Crystal radio - 1906

SELF-powered by Radio Frequencies !!

First automatic wristwatch, Harwood, c. 1929 (Deutsches Uhrenmuseum, Inv. 47-3543)

First automatic watch. Abraham-Louis Perrelet, Le Locle. 1776

Self-charging Seiko wristwatch
Energy harvesting applications

Structural Monitoring

Environmental Monitoring

Healthcare sensors
- Emergency medical response
- Monitoring, pacemaker, defibrillators

Military applications

Nanomedicine

02/07/2014 - Belo Horizonte (Brazil)
(birdge collapse at FIAT factory)
Energy Harvesting research

- Devices
- Energy Harvesting
- Materials
- Energy Conversion Techniques
Vibration Energy Harvesting research

Macro
- Vibrational EM devices
  * Vibrational Piezo Cantilevers
    * Vibrational Structures with Magnetic Shape Memory Alloy (NiMnGa)

Micro
- Electrostatic Generators
  * Piezo Micro beams of stripes
    * ZnO, BaTiO3
  * Electrets SiO2, Parylene, Teflon base

Nano
- Piezoelectric nanopillars, nanoribbons etc.
  * Triboelectric generators
  * Electrets nano-spheres
Vibration energy harvesting

**Electromagnetic**
- Moving magnet
- Spring
- Coil

**Magnetostrictive**

**Electrostatic/Capacitive**
- Spring mass

**Piezoelectric**

**Vibration to electricity energy conversion techniques**

F. Cottone - IESRES Erasmus+ Teaching Activity 8-13 May 2017 - Klaipeda, Lithuania
Piezoelectric conversion

<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>

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

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.
Dynamical model of VEH

At micro/nano scale direct force generators are much more efficient because not limited by the inertial mass!!

\[
\begin{align*}
    m\ddot{z} + \dot{d}\ddot{z} + \frac{dU(z)}{dz} + \alpha V_L &= F(t) \\
    \dot{V}_L + (\omega_c + \omega_i)V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]

\[
\begin{align*}
    m\ddot{\dot{y}} + \dot{d}\ddot{y} + \frac{dU(z)}{dz} + \alpha V_L &= -m\ddot{y} \\
    \dot{V}_L + (\omega_c + \omega_i)V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]

Inertial generators requires only one point of attachment to a moving structure, allowing a greater degree of miniaturization.
Dynamical model of VEH

Inertial generators requires only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

Power fluxes

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

\[ P_m(t) = F(t) \cdot \dot{z}(t) \quad \quad P_m(t) = -m\ddot{y} \cdot \dot{z} = -\rho l^3 \cdot \dot{z} \]
Dynamical model of VEH

\[
\begin{aligned}
\ddot{m} \ddot{z} + d \dot{z} + \frac{dU(z)}{dz} + \alpha V_L &= -m \ddot{y} \\
\dot{V}_L + (\omega_c + \omega_i)V_L &= \lambda \omega_c \dot{z}
\end{aligned}
\]

Parameters that depend only on the transduction technique!

For LINEAR mechanical oscillators with elastic potential well

Laplace transform

\[
\ddot{y} = Y_0 e^{j\omega t} \quad \Rightarrow \quad \left( \begin{array}{c}
ms^2 + ds + k \\
-\lambda \omega_c s
\end{array} \right) \begin{pmatrix} Z \\ V \end{pmatrix} = \begin{pmatrix} -mY \\ 0 \end{pmatrix}
\]

\[
Z = \frac{-mY}{\det A} (s + \omega_c) = \frac{-mY \cdot (s + \omega_c)}{ms^3 + (m\omega_c + d)s^2 + (k + \alpha \lambda \omega_c + d\omega_c)s + k\omega_c},
\]

\[
V = \frac{-mY}{\det A} \lambda \omega_c s = \frac{-mY \cdot \lambda \omega_c s}{ms^3 + (m\omega_c + d)s^2 + (k + \alpha \lambda \omega_c + d\omega_c)s + k\omega_c}.
\]
Dynamical model of VEH

For LINEAR mechanical oscillators

By substituting $s=j\omega$, we can calculate the electrical power dissipated across the resistive load

$$P_e(\omega) = \left| \frac{V}{R_L} \right|^2 = \frac{Y_0^2}{2R_L} \left| \frac{m\lambda\omega_c j\omega}{(\omega_c + j\omega)(-m\omega^2 + dj\omega + k) + \alpha\lambda\omega_c j\omega} \right|^2$$

In approximate version, at resonance $\omega=\omega_n$, (William et al.)

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

Where $\omega_c$, $\lambda$ and $\alpha$ are included in the electrical damping factor $d_e$
Piezoelectric conversion

\[
\begin{align*}
\alpha &= \frac{k d_{31}}{h_p k_2}, \\
\lambda &= \alpha R_L, \\
\omega_c &= 1 / R_L C_p, \\
\omega_i &= 1 / R_i C_p,
\end{align*}
\]

Inertia area moment of the beam

\[
I = 2 \left[ \frac{w_b h_p^3}{12} + w_b h_p b^2 \right] + \frac{E_s / E_p w_b h_p^3}{12},
\]

\[
E_p \text{ and } E_s \text{ are the Young’s modulus of piezo layer and steel substrate respectively.}
\]
Electromagnetic conversion

Governing equations

\[
\begin{align*}
\dot{m}\ddot{z} + d\dot{z} + kz + \alpha V_L &= -m\ddot{y} \\
\dot{V}_L + (\omega_c + \omega_i)V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]

\[
\begin{align*}
\alpha &= Bl / R_L, & \lambda &= Bl = \alpha R_L, \\
\omega_c &= R_L / L_c, & \omega_i &= R_i / L_c,
\end{align*}
\]
Electrostatic conversion

**Governing equations**

\[
\begin{align*}
    m \frac{d^2 x}{dt^2} + \left( c_a + c_i \right) \frac{dx}{dt} + \frac{dU(x)}{dx} &= -m \frac{d^2 y}{dt^2}, \\
    R_L \frac{d}{dt} (C \cdot V) + V &= U_0,
\end{align*}
\]

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

\[ FoM_V = \frac{\text{Useful Power Output}}{\frac{1}{10} Y_0 \rho_{Au} V_0^3 \omega^3} \]

Bandwidth figure of merit

\[ FoM_{BW} = FoM_V \times \frac{\delta \omega_{1 \, dB}}{\omega} \]

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

Galchev et al. (2011)

**Figure of merit**

\[
F_{oM_v} = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{Au} V_0^{\frac{3}{2}} \omega^3}
\]

**Bandwidth figure of merit**

\[
F_{oM_{BW}} = F_{oM_v} \times \frac{\delta \omega_{1 \text{ dB}}}{\omega}
\]

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

Galchev et al. (2011)

## Comparison of conversion techniques

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

MEMS-based drug delivery systems

Bohm S. et al. 2000

Body-powered oximeter

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

Heart powered pacemaker

Pacemaker consumption is 40uW.

Beating heart could produce 200uW of power

D. Tran, Stanford Univ. 2007

Micro-robot for remote monitoring

The input power a 20 mg robotic fly is 10 – 100 uW

A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999
Microscale energy harvesters

Piezoelectric

Jeon et al. 2005

ZnO nanowires
Wang, Georgia Tech (2005)

Chang. MIT 2013

piezoelectric
AlN thin layer
Aluminium electrode
seismic mass

M. Marzencki 2008 – TIMA Lab (France)

PZT/Si cantilever
Si proof mass

1 mm

D. Briand, EPFL 2010
Microscale energy harvesters

Electrostatic and electromagnetic

Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g

EM generator, Miao et al. 2006

Le and Halvorsen, 2012

Cottone F., Basset P. ESIEE Paris 2013
Microscale energy harvesters: scaling issues

First order power calculus with William and Yates model

- Low efficiency off resonance
- High resonant frequency at miniature scales
- Power $\rightarrow A^2/l^4$ where $A$ is the acceleration and $l$ the linear dimension

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

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>doubly clamped</td>
<td>1.03</td>
</tr>
<tr>
<td>cantilever</td>
<td>0.162</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Uniform load $\xi$</th>
<th>Point load $\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>doubly clamped</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>cantilever</td>
<td>0.67</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Microscale energy harvesters: scaling issues

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 $A_0 = \omega_n^2 Y_0$

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

Max power when the condition $\zeta_e = \zeta_m$ is verified

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

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

that is

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

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

First order power calculus with William and Yates model

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

\[ k = \frac{\xi Ewh^3}{l^3} \]

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

\[ P_{\text{el}} = \frac{m\xi_e A^2}{4\omega_n (\xi_m + \xi_e)^2} = \frac{(lwh\rho_{\text{si}} + 0.32(l/4)^3\rho_{\text{mo}})}{8\omega_n \xi_m} A^2 = \frac{(lwh\rho_{\text{si}} + 0.32(l/4)^3\rho_{\text{mo}})}{16\pi C_n \sqrt{\frac{E}{\rho_{\text{si}} l^2 \xi_m}}} A^2 \]

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

By assuming

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

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

By assuming

\[ A = 1g \]
\[ \zeta_m = 0.01 \]
\[ h = l / 200 \]
\[ w = l / 4 \]
Piezoelectric micro-pillars

Why ZnO

• Non-toxic → bio-compatible
• Wurzite structure
• Easy to fabricate
• Vast morphology
Piezoelectric micro-pillars

ZnO forest

ZnO Pillar
Piezoelectric micro-pillars

Hydrotermal synthesis
Length: 15 µm
Thickness: 4 – 6 µm
Piezoelectric micro-pillars

Stress-strain equations

\[
S = \left[ s_E \right] T + \left[ d^T \right] E
\]
\[
D = \left[ d \right] T + \left[ \varepsilon_T \right] E
\]

Strain-charge form

\[
\omega_1 = \beta_1^2 \sqrt{\frac{EI}{\mu}} = \frac{3.515}{L^2} \sqrt{\frac{EI}{\mu}}
\]

Length: 17 µm
Thickness: 5um
First mode: 10.9 Mhz
Piezoelectric micro-pillars

- SEM with metal probes (100nm) on a single ZnO crystal for frequency mode investigation
Piezoelectric micro-pillars: future development

- Implementation of vertically-aligned ZnO micropillars on IDE and other geometry (e.g. horizontal)
- Use of the device as VEH and vibration sensor
- Fabrication of same device with BaTiO3
- Use of the piezo pillars as micro electro-mechanical antenna

Microfibre-Nanowire:

Piezoelectric ribbon:

Microantenna

Wang(2008)

Yang(2009)
Low-frequency MEMS electrostatic VEH

Prototype fabrication process

(a) Interdigitated fingers
Fixed electrode
Spring
Protrusion
Elastic beam
Movable electrode
Miniature ball
Fixed end

(b) Cap
Cavity
Movable electrode
Fixed end
Miniature ball
Handle wafer

(c) Image of fabricated component

(d) Close-up of fabricated component
Low-frequency MEMS electrostatic VEH

Experimental test

Working principle

Impact time

\[ v_{sf} = \frac{(e + 1) m_b v_{bi} + (m_b - em_b) v_{si}}{m_b + m_s} \]

Velocity Amplified Energy Harvester
At Stoke Institute, University of Limerick, Ireland
Low-frequency MEMS electrostatic VEH

Low-frequency MEMS electrostatic VEH

TEST with hand shaking of the transient output voltage and extracted energy.

(a) $V_{bias}=21$ V, $a=2.0$ grms, $f=6.5$ Hz
(b) $V_{bias}=46$ V, $a=2.0$ grms, $f=4.7$ Hz

A 47-$\mu$F capacitor has been also charged through a bridge diode rectifier to 3.5 V to supply a wireless temperature sensor node.

## Performance comparison

<table>
<thead>
<tr>
<th>Vibration type</th>
<th>MEMS Direction</th>
<th>Accel. (gRMS)</th>
<th>Main input Freq. (Hz)</th>
<th>Vbias (V)</th>
<th>Power (uW)</th>
<th>Power Density (uW/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man walking X</td>
<td>0.39</td>
<td>4.15</td>
<td>20</td>
<td>1.34</td>
<td>13.40</td>
<td></td>
</tr>
<tr>
<td>Man walking Y</td>
<td>0.27</td>
<td>2.1</td>
<td>20</td>
<td>0.793</td>
<td>7.93</td>
<td></td>
</tr>
<tr>
<td>Man walking Z</td>
<td>0.41</td>
<td>2.44</td>
<td>20</td>
<td>1.15</td>
<td>11.50</td>
<td></td>
</tr>
<tr>
<td>Man running Z</td>
<td>1.20</td>
<td>3.3</td>
<td>20</td>
<td>14.9</td>
<td><strong>142.00</strong></td>
<td></td>
</tr>
</tbody>
</table>

Almost 1 order of magnitude higher than average power density of previous works

---

Modeling of e-VEH

With Homotopy Perturbation Method

Dr. Riccardo Marcaccioli - unpublished
Final considerations

- **MEMS/NEMS Energy harvesting systems** are becoming a promising technology to enable autonomous low-power wireless devices.

- **Inertial vibration energy harvesters** are very limited at small scale $P \sim I^3 \rightarrow$ direct force piezoelectric/electrostatic devices are more efficient at nanoscale.

- **Power efficiency** can be improved by:
  - Innovative **electro-active materials** (electrets, lead-free piezo)
  - Innovative **micro and nanostructures**
  - **Nonlinear dynamical approach**: bistable systems, frequency-up converters, impacting masses, electrostatic softening.

- Specific **application** decides if one or many micro-VEH are the best choice with respect to one macro-scale VEH.

- Micro- to nano-structures of piezoelectric materials have wide applications as **sensors**.