Energy Harvesting: introduction

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Summary

▶ Energy harvesting applications and principles

▶ Fundamentals of vibration energy harvesters

▶ Beyond linear systems: linear and nonlinear approaches

▶ Conclusions
Energy harvesting applications

Wireless Sensor Networks

Structural Monitoring

Environmental Monitoring

Transportation

Wearable sensing for health applications
Emergency medical response
Monitoring, pacemaker, defibrillators

Military applications

Energy Harvesting could enable 90% of WSNs applications (IdTechex)
Power sources available from the ambient

- Ultra capacitors
- Rechargeable Batteries
- Wireless Sensor Node
- Piezoelectric
- Electrodynamics
- Photovoltaic
- Hydro Turbine
- Thermal energy
- Solar
- Radioactivity
- VIBRATIONS
- Hydro/wind
- Biochemical
- Wasted thermal energy
- Electronic device
- RF

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Examples of energy harvesting systems

Tree - vegetation

Sailing ship (XVI-XVII century)

Crystal radio - 1906

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

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

Self-charging Seiko wristwatch
Vibration energy harvesting versus power requirements

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Inertial generators are more flexible than direct-force devices because they require only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

Vibration Energy Harvesters (VEHs): basics

- Zinc oxide (ZnO) nanowires
  - Wang et al. 2008

- Moth vibrations
  - Chang, MIT 2013

- Dancing
  - Energy harvesting from dancing

- AC/DC converter
  - Bridge Diodes
  - Rectifier
  - Load (ULP sensors, MEMS actuators)

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Vibration Energy Harvesters (VEHs): basics

Electromagnetic

Magnetostriuctive

Piezoelectric

Electrostatic/Capacitive
Piezoelectric conversion

Pioneering work on the direct piezoelectric effect (stress-charge) in this material was presented by Jacques and Pierre Curie in 1880.

In 1903 Pierre received the Nobel Prize in Physics with his wife, Marie Skłodowska-Curie and Henri Becquerel, for the research on the radiation phenomena discovered by Professor Henri Becquerel.

After poling the zirconate-titanate atoms are off center. The molecule becomes elongated and polarized.
Piezoelectric conversion

Stress-to-charge conversion

Naturally-occurring crystals

- **Berlite** (AlPO₄), a rare **phosphate mineral** that is structurally identical to quartz
- **Cane sugar**
- **Quartz** (SiO₂)
- **Rochelle salt**

Man-made ceramics

- **Barium titanate** (BaTiO₃)—Barium titanate was the first piezoelectric ceramic discovered.
- **Lead titanate** (PbTiO₃)
- **Lead zirconate titanate** (Pb[ZrₓTi₁₋ₓ]O₃ 0≤x≤1)—more commonly known as **PZT**, lead zirconate titanate is the most common piezoelectric ceramic in use today.
- **Lithium niobate** (LiNbO₃)

Polymers

- **Polyvinylidene fluoride** (PVDF): exhibits piezoelectricity several times greater than quartz. Unlike ceramics, long-chain molecules attract and repel each other when an electric field is applied.

Biological

- Bones
- DNA

Direct piezoelectric effect
**Piezoelectric conversion**

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

**Strain-charge**

\[ T = \left[ c^E \right] S - \left[ e^T \right] E \]  
\[ D = \left[ e \right] S + \left[ \varepsilon^S \right] E \]  

- \( S \) = strain vector (6x1) \textit{in Voigt notation}
- \( T \) = stress vector (6x1) \([N/m^2]\)
- \( s_E \) = compliance matrix (6x6) \([m^2/N]\)
- \( c^E \) = stiffness matrix (6x6) \([N/m^2]\)
- \( d \) = piezoelectric coupling matrix (3x6) in Strain-Charge \([C/N]\)
- \( D \) = electrical displacement (3x1) \([C/m^2]\)
- \( e \) = piezoelectric coupling matrix (3x6) in Stress-Charge \([C/m^2]\)
- \( \varepsilon \) = electric permittivity (3x3) \([F/m]\)
- \( E \) = electric field vector (3x1) \([N/C]\) or \([V/m]\)
## Conversion techniques comparison

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Piezoelectric</strong></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 ($M\Omega$)</td>
</tr>
<tr>
<td></td>
<td>• no external voltage source needed</td>
<td>• Fatigue effect</td>
</tr>
<tr>
<td><strong>Electrostatic</strong></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>• possibility of tuning electromechanical coupling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Long-lasting</td>
<td></td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></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>
Example of vibration sources

Human activity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taking a book off a shelf</td>
<td>&lt;10 $\mu W$</td>
</tr>
<tr>
<td>Putting on reading glasses</td>
<td>&lt;10 $\mu W$</td>
</tr>
<tr>
<td>Reading a book</td>
<td>&lt;10 $\mu W$</td>
</tr>
<tr>
<td>Writing with a pencil</td>
<td>10–15 $\mu W$</td>
</tr>
<tr>
<td>Opening a drawer</td>
<td>10–30 $\mu W$</td>
</tr>
<tr>
<td>Spinning in a swivel chair</td>
<td>&lt;10 $\mu W$</td>
</tr>
<tr>
<td>Opening a building door</td>
<td>&lt;1 $\mu W$</td>
</tr>
<tr>
<td>Shaking an object</td>
<td>&gt;3,000 $\mu W$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activity</th>
<th>Sensing unit placement</th>
<th># subjects</th>
<th>Median $f_m$ (Hz)</th>
<th>Median $P$ ($\mu W$)</th>
<th>Median $r$ (Kb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relaxing</td>
<td>Trouser pocket</td>
<td>42</td>
<td>N/A</td>
<td>1.9</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Waist belt</td>
<td>42</td>
<td>N/A</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Trouser pocket</td>
<td>42</td>
<td>N/A</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Walking</td>
<td>Shirt pocket</td>
<td>42</td>
<td>1.9</td>
<td>2.0</td>
<td>155.2</td>
</tr>
<tr>
<td></td>
<td>Waist belt</td>
<td>42</td>
<td>2.0</td>
<td>2.0</td>
<td>180.3</td>
</tr>
<tr>
<td></td>
<td>Trouser pocket</td>
<td>42</td>
<td>2.0</td>
<td>2.0</td>
<td>202.4</td>
</tr>
<tr>
<td>Running</td>
<td>Shirt pocket</td>
<td>42</td>
<td>2.8</td>
<td>2.8</td>
<td>813.3</td>
</tr>
<tr>
<td></td>
<td>Waist belt</td>
<td>41</td>
<td>2.8</td>
<td>2.8</td>
<td>678.3</td>
</tr>
<tr>
<td></td>
<td>Trouser pocket</td>
<td>42</td>
<td>2.8</td>
<td>2.8</td>
<td>612.7</td>
</tr>
<tr>
<td>Cycling</td>
<td>Shirt pocket</td>
<td>30</td>
<td>3.5</td>
<td>2.8</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>Waist belt</td>
<td>29</td>
<td>3.8</td>
<td>2.8</td>
<td>45.4</td>
</tr>
<tr>
<td></td>
<td>Trouser pocket</td>
<td>30</td>
<td>1.1</td>
<td>2.8</td>
<td>41.3</td>
</tr>
</tbody>
</table>

Example of vibration sources

- Train
- Microwave oven
- Walking person
- Chicago North Bridge
- Car in highway

[Graphs showing power spectral density for each source]

[Link to website: http://realvibration.nipslab.org]
A general model for VEHs

Electromagnetic transduction

\[ m \ddot{z} + d \dot{z} + \frac{dU(z)}{dz} + \alpha V_L = -m \ddot{y} \]

\[ \dot{V}_L + (\omega_c + \omega_i) V_L = \lambda \omega_c \dot{z} \]

Piezoelectric transduction

Piezo bar or cantilever beam

Seismic mass
A general model for VEHS

LINEAR mechanical oscillator

\[ U(z) = \frac{1}{2}kz^2 \]

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

\[
\begin{align*}
\ddot{y} &= Y_0 e^{j\omega t} \\
Y(s) &= \left( \begin{array}{cc} ms^2 + ds + k & \alpha \\ -\lambda \omega_c s & s + \omega_c \end{array} \right) Y(s) = \left( \begin{array}{c} -mY \\ 0 \end{array} \right)
\end{align*}
\]

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

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

Hence, the transfer functions between displacement and voltage over input acceleration are given by

\[ H_{ZY}(s) = \frac{Z}{Y}, \quad (a) \quad H_{VY}(s) = \frac{V}{Y}. \quad (b) \]

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

\[ P_e(\omega) = \frac{Y_0^2}{2R_L} \left| \frac{m_2 \lambda \omega_c j\omega}{(\omega_c + j\omega)(-m_2 \omega^2 + d_2 j\omega + k_2) + \alpha \lambda \omega_c j\omega} \right|^2 \]

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Piezoelectric conversion

**Strain-charge**
\[ S = s_E \cdot T + d^t \cdot E \]
\[ D = d \cdot T + \varepsilon_T \cdot E \]

**Stress-charge**
\[ T = c_E \cdot S - e^t \cdot E \]
\[ D = e \cdot S + \varepsilon_S \cdot E \]

<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>

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

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.
Piezoelectric conversion

\[
\begin{align*}
\alpha &= kd_{31}/h_p k_2, \\
\omega_c &= 1/R_L C_p, \\
\omega_i &= 1/R_i C_p, \\
\lambda &= \alpha R_L, \\
k &= k_i k_2 E_p, \\
k_1 &= \frac{2I}{b(2l_b + l_m - l_c)}, \\
k_2 &= \frac{3b(2l_b + l_m - l_c)}{l_b^2 \left(2l_b + \frac{3}{2}l_m\right)}, \\
b &= \frac{h_s + h_p}{2}, \\
I &= 2 \left[ \frac{w_b h_p^3}{12} + \frac{w_b h_p b^2}{12} \right] + \frac{E_s / E_p w_b h_s^3}{12}, \\
\end{align*}
\]

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

$\mathbf{E}$

$m \ddot{z} + d \dot{z} + k z + \alpha V_L = -m \ddot{y}$

$\dot{V}_L + (\omega_c + \omega_i)V_L = \lambda \omega_c \dot{z}$

$\alpha = Bl / R_L,$
$\lambda = Bl = \alpha R_L,$
$\omega_c = R_L / L_c,$
$\omega_i = R_i / L_c,$
Mathematical modeling

Governing equations

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

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

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

- narrow bandwidth that implies constrained resonant frequency-tuned applications
- Non-adaptation to variable vibration sources
- small inertial mass and high resonant frequency at micro/nano-scale -> most of vibration sources are below 100 Hz

At 20% off the resonance the power falls by 80-90%
Beyond linear harvesting systems

Frequency tuning

Piezoelectric cantilever with a movable mass

Wu et al. 2008

Piezoelectric cantilever with magnetic tuning

Challa et al. 2008

Piezoelectric beam with a scavenging and a tuning part

Roundy and Zhang 2004

## Beyond linear harvesting systems

### Frequency tuning

<table>
<thead>
<tr>
<th>Author</th>
<th>Methods</th>
<th>Tuning range (Hz)</th>
<th>Tunability, (\frac{\text{frequency change}}{\text{average frequency}}) (%)</th>
<th>Tuning load (force, distance, and voltage)</th>
<th>Energy or power for tuning</th>
<th>Automatic controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leland and Wright (2006)</td>
<td>Mechanical (passive)</td>
<td>200–250</td>
<td>22.22</td>
<td>Up to 65 N</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Eichhorn et al. (2008)</td>
<td>Mechanical (passive)</td>
<td>292–380</td>
<td>26.19</td>
<td>Up to 22.75 N</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Hu et al. (2007)</td>
<td>Mechanical (passive)</td>
<td>58.1–169.4</td>
<td>97.85</td>
<td>−50–50 N</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Morris et al. (2008)</td>
<td>Mechanical (passive)</td>
<td>80–235</td>
<td>≥98.41</td>
<td>≈1.25 mm</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Loverich et al. (2008)</td>
<td>Mechanical (passive)</td>
<td>56–62</td>
<td>10.17</td>
<td>0.5 mm</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Wu et al. (2008)</td>
<td>Mechanical (passive)</td>
<td>130–180</td>
<td>32.26</td>
<td>21 mm</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Challa et al. (2008)</td>
<td>Magnetic (passive)</td>
<td>22–32</td>
<td>37.04</td>
<td>3 cm</td>
<td>85 mJ</td>
<td>×</td>
</tr>
<tr>
<td>Reissman et al. (2009)</td>
<td>Magnetic (passive)</td>
<td>88–99.38</td>
<td>12.15</td>
<td>1.5 cm</td>
<td>−</td>
<td>×</td>
</tr>
<tr>
<td>Zhu et al. (2008)</td>
<td>Magnetic (passive)</td>
<td>67.6–98</td>
<td>36.71</td>
<td>3.8 mm</td>
<td>2.04 mJ/mm</td>
<td>√</td>
</tr>
<tr>
<td>Wu et al. (2006)</td>
<td>Piezoelectric (active)</td>
<td>91.5–94.5</td>
<td>3.23</td>
<td>−</td>
<td>µW level</td>
<td>√</td>
</tr>
<tr>
<td>Peters et al. (2009)</td>
<td>Piezoelectric (active)</td>
<td>66–89</td>
<td>29.68</td>
<td>±5 V</td>
<td>150 mW</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(actuator PL140)</td>
<td></td>
<td>(discrete control circuit)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roundy and Zhang (2005)</td>
<td>Piezoelectric (active)</td>
<td>64.5–67</td>
<td>3.80</td>
<td>5 V</td>
<td>440 µW</td>
<td>×</td>
</tr>
<tr>
<td>Wischke et al. (2010)</td>
<td>Piezoelectric (semi-passive)</td>
<td>20</td>
<td>6.70</td>
<td>−65 to +130 V</td>
<td>200 µJ</td>
<td>×</td>
</tr>
</tbody>
</table>

Tang et al. 2010
Beyond linear harvesting systems

Multimodal Energy Harvesting

Tadesse et al. 2009

Hybrid harvester with piezoelectric and electromagnetic transduction mechanisms


Piezoelectric cantilever arrays with various lengths and tip masses

Shahruz 2006
Beyond linear harvesting systems

Frequency-up conversion


D.G. Lee et al. IEEE porc. (2007)

Impact electrostatic MEMS generator


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Beyond linear harvesting systems

Nonlinear systems


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Beyond linear harvesting systems

Nonlinear systems for vibration energy harvesting

Magneto-elastic potential

Governing equations of a single-DOF piezo-magnetoelastic model

\[ U(x, \Delta) = \frac{1}{2} K_{\text{eff}} x^2 + \frac{\mu_0}{2\pi} \frac{M_1 M_2}{(x^2 + \Delta^2)^{3/2}} \]

\[
\begin{cases}
  m\ddot{x}(t) + \delta \dot{x}(t) + K_{\text{eff}} x(t) + \frac{\partial U(x, \Delta)}{\partial x} + K_v V(t) = -m\ddot{y}(t) \\
  \dot{V}(t) + \frac{1}{\tau} V(t) = K_c \dot{x}(t); \quad \tau = R_L C_p
\end{cases}
\]


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Bistable oscillators for vibration energy harvesting

**Bistable: inter-well and intra-well oscillations**

**U(x,Δ)**

**Resonant monostable**

Δ=25mm

**Bifurcation point**

**Cottone, F., H. Vocca & L. Gammaitoni, Nonlinear Energy Harvesting. PRL, 102 (2009).**
Bistable oscillators for vibration energy harvesting

Bistable: inter-well and intra-well oscillations

Resonant monostable

$\Delta = 25\text{mm}$

$U(x, \Delta)$

Bandwidth enhancement when interwell jumps occur

$U(x, \Delta)$

$P(10^{-7}\text{Watt})$ vs $\Delta (\text{mm})$

- $\sigma = 1.2 \text{ (mN)}$
- $\sigma = 0.8 \text{ (mN)}$
- $\sigma = 0.3 \text{ (mN)}$
Bistable oscillators for vibration energy harvesting

Buckled beam piezoelectric harvesters


Snapping between buckled states

![Diagram showing buckled states and stretching and bending](image)

Load Resistance = 1MΩ (a) Load Resistance = 25kΩ (b)

![Graphs showing load resistance and deflection](image)

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Bistable oscillators for vibration energy harvesting

Buckled piezoelectric beams

\[ w(x,t) = w_1(x) + v(x,t) \]

the initial buckling shape function is

\[ \psi(x) = h_0(1 - \cos(2\pi x / L)) / 2 \]

by applying Euler-Lagrange equations

\[
\frac{d}{dt} \left( \frac{\partial \mathcal{G}}{\partial \dot{q}} \right) - \frac{\partial \mathcal{G}}{\partial q} = F(t), \quad \frac{d}{dt} \left( \frac{\partial \mathcal{G}}{\partial \dot{\lambda}} \right) - \frac{\partial \mathcal{G}}{\partial \lambda} = I(t)
\]

\[
\begin{cases}
    m\ddot{q} + c\dot{q} + k_3q^3 + (k_2 - k_1V)q + k_0V = -\eta \ddot{z}, \\
    \ddot{V} + \frac{2}{R_L C_p}V = 2 \frac{k_0}{C_p} \dot{q} - 2 \frac{k_1}{C_p} q\dot{q}.
\end{cases}
\]

gives two coupled second order nonlinear differential equations governing the motion of the piezoelectric buckled beam

Where the output voltage is related to the flux linkage \( V = -\dot{\lambda} \)
Bistable oscillators for vibration energy harvesting

Experimental and numerical results

Nonlinear electromagnetic generators for wide band vibrational energy harvesting

\[ \frac{d^2 \ddot{q}(\tau)}{d\tau^2} + \frac{1}{Q} \frac{d\ddot{q}(\tau)}{d\tau} + \ddot{q}(\tau) + \dddot{q}(\tau) + \dot{V}(\tau) = -\frac{d^2 \dddot{y}(\tau)}{d\tau^2}, \]

\[ \frac{d\dot{V}(\tau)}{d\tau} + \frac{1}{\gamma} \dot{V}(\tau) = k_{em}^2 \frac{d\ddot{q}}{d\tau}, \]

\[ \gamma = \omega_0 / (\omega_R + \omega_L) \quad k_{em}^2 = \frac{\lambda^2}{k_1 L_c} = \frac{(Bl)^2}{k_1 L_c}, \quad k_{pc}^2 = \frac{\alpha^2}{k_1 C_0}. \]
Nonlinear electromagnetic generators for wide band vibrational energy harvesting

Bandwidth enhancement of 2.5x with bistability at 0.2 grms

Figure 6. Experimental comparison of unbuckled- and buckled-beam ($h_0 = 0.3$ mm) generators for up (left column) and down (right column) frequency sweeps with acceleration amplitudes of 0.1, 0.2, and 0.5 g$_{rms}$. (a and b) $rms$ voltage and (c and d) the corresponding power dissipated across the optimal load resistance $R_L = 112$ Ω. $rms$: root mean square.
MEMS electrostatic kinetic energy harvester

Université Paris-Est, ESIEE Paris, Silicon MEMS electrostatic harvesters.

MEMS electrostatic kinetic energy harvester


MEMS electrostatic kinetic energy harvester

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


Electromagnetic generators

Velocity-amplified multiplet-mass EM VEH

\[
v_{2f} = \frac{(e + 1)m_1v_{1i} + (m_2 - em_1)v_{2i}}{m_1 + m_2}
\]

if \( e = 1 \) and in the limit of \( m_1 / m_2 \to \infty \),

the final velocity of the smaller mass is

\[
v_{2f} = 2v_{1f} - v_{2i}.
\]

In the case of equal but opposite initial velocities

\[
v_{2f} = -3v_{2i},
\]

which represents a gain factor of 3x in velocity.
Electromagnetic generators

Velocity-amplified multiple-mass EM VEH

For a series of \( n \)-bodies of progressively smaller mass that impact sequentially, the velocity gain is proportional to \( n \).

(Rodgers et al., 2008)

\[
G_n = (1 + e_{1,0}) \prod_{k=2}^{n} \left( \frac{1 + e_{k,k-1}}{1 + r_{k,k-1}} \right) - 1
\]
Electromagnetic generators

Velocity-amplified multiple-mass EM VEH
Electromagnetic generators

Velocity-amplified multiple-mass EM VEH

(a) NdFeB magnet, coil, high $C_R$ springs, heavy mass, shaft, vibrations

(b) $V_{emf}$

(c) magnet, spring stoppers, 60 mm

(d) magnet, 40 mm

(a) VAEG Double-mass

(b) Single-mass ($m_0 = m_1 + m_2$)

(c) VAEG Triple-mass

(d) Single-mass ($m_0 = m_1 + m_2 + m_3$)
Velocity-amplified multiple-mass EM VEH

Electromagnetic generators
Electromagnetic generators

Velocity-amplified multiple-mass EM VEH

Prototype 2 with transversal magnetic flux

Top cap
High Q-factor springs
Gap magnet expansions (iron)
Moving coil
Linear low friction guides
Base for clamping

NdFeB Magnets

University of Limerick (Ireland) and Bell-Labs Alcatel (USA).

Electromagnetic generators

Velocity-amplified multiple-mass EM VEH

Prototype 2 with transversal flux linkage

University of Limerick (Ireland) and Bell-Labs Alcatel (USA).

## Comparison of various approaches

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical tuning</td>
<td>• High efficiency</td>
<td>• Extra system and energy are required</td>
</tr>
<tr>
<td>• Change dimension</td>
<td>• Does not affect damping</td>
<td>• Responds to only one frequency at a time</td>
</tr>
<tr>
<td>• Change centre of gravity</td>
<td>• Does not affect damping</td>
<td>• Slow response to a change in a vibration frequency</td>
</tr>
<tr>
<td>• Change spring stiffness</td>
<td>• Suitable for <em>in situ</em> tuning</td>
<td>• Difficult to implement</td>
</tr>
<tr>
<td>continuously</td>
<td>• Easy to implement</td>
<td>• Not suitable for tuning <em>in situ</em></td>
</tr>
<tr>
<td>• Apply axial load (change spring</td>
<td>• Suitable for <em>in situ</em> tuning</td>
<td>• Not suitable for tuning <em>in situ</em></td>
</tr>
<tr>
<td>stiffness intermittently)</td>
<td>• No energy is required when generators work at resonance</td>
<td>• Consumes energy when generators work at resonance</td>
</tr>
<tr>
<td></td>
<td>• Damping is not affected when the tensile load is applied</td>
<td>• Increased damping when the compressive load is applied</td>
</tr>
<tr>
<td>Electrical tuning</td>
<td>• Easy to implement</td>
<td>• Low tuning efficiency</td>
</tr>
<tr>
<td>• Widen bandwidth</td>
<td>• No tuning mechanism required</td>
<td>• Complexity in design</td>
</tr>
<tr>
<td></td>
<td>• Respond to different frequencies at the same time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Immediate response to a change in vibration frequency</td>
<td></td>
</tr>
<tr>
<td>• Generator array</td>
<td>• Damping is not affected</td>
<td>• Complexity in design</td>
</tr>
<tr>
<td>• Use mechanical stopper</td>
<td>• Easy to implement</td>
<td>• Low volume efficiency</td>
</tr>
<tr>
<td>• Coupled oscillators</td>
<td>• Easy to implement</td>
<td>• Fatigue problem</td>
</tr>
<tr>
<td>• Nonlinear generators</td>
<td>• Better performance at excitation frequencies higher than resonant</td>
<td>• Decrease in the maximum output power</td>
</tr>
<tr>
<td>• Bi-stable structure</td>
<td>• Better performance at excitation frequencies much lower than resonant frequency</td>
<td>• Decrease in the maximum output power</td>
</tr>
</tbody>
</table>

* Tuning while the generator is mounted on the vibration source and working.

Performance metrics

\[ F_{\text{OM}_V} = \frac{\text{Useful Power Output}}{\frac{1}{10} Y_0 \rho_{A_1} V_0 \delta \omega^3} \]

Bandwidth figure of merit

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

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

Conclusions

- Marriage between Energy harvesting systems and Zero-power Technology will enable autonomous WSN applications

- Energy harvesting systems can be improved by:
  - Nonlinear dynamic: Bistable systems, frequency-up converters, impacting masses, electrostatic softening
  - Innovative electro-active materials (electrets, lead-free piezo)
  - Miniaturization

- Zero-Power Technology has plenty of room for improvement at level of
  - Low-consumption components,
  - Efficient conditioning.
Current technical challenges

- **Miniaturization issues**
  - Improvements of piezoelectric-material properties
  - Improving capacitive design
  - Increasing magnetic filed in micro magnets
  - Research on electrets materials

- **Efficient conditioning electronics**
  - Efficient Integrated design
  - Power-aware operation of the powered device

- **Target applications**
  - Tailoring the WSN technology to specific applications
Acknowledgments

Thank you