Piezoelectric Devices for Vibration Energy Harvesting

Vittorio Ferrari
Dip. Ingegneria dell'Informazione
Università di Brescia - ITALY

Sensors and Electronic Instrumentation Laboratory

Activity:
- Sensors and instrumentation systems
- Analog and digital electronic circuits and systems for:
  - sensor interfacing
  - sensor communication and networking
  - measurement applications

Sensors, MicroSystems and Electronic Interfaces:
- Piezoelectric transducers, acoustic-wave and resonant microsensors
- MEMS sensors and systems
- Contactless sensors
- Electronic interfaces for sensor signals
- Energy harvesting for autonomous sensors
Contents

- Introduction
- Piezoelectric effect for energy harvesting
- Examples of piezoelectric energy harvesters
- From “raw” harvested energy to “usable” power supply
- Prototypes of battery-less autonomous sensor modules
- Conclusions
Sensor Systems

Sensor elements
... into microsystems/MEMS
... into packaged electronic modules
... with wireless communication capability
... and network connectivity

Systems of Systems

- “Pervasive sensing and computing”
- “Ambient intelligence”
- “The internet of things”
Information flow requires exchange of energy
Assuming the external readout unit is energetically self-sufficient ...

the sensor needs power supply

Power supply internal to the sensor (on-board):
- Batteries
- Fuel cells
- ...

Power Supply Options: #2

- Power supplied by the external readout unit:
  - “Passive” RFID devices (class 1 and 2)
  - Passive telemetric sensors
  - Chipless RFID sensors

Power Supply Options: #3

- Power extracted (harvested) from the surrounding ambient
Energy from Ambient: *the idea is not new*

![Images of water and windmills, 1770 A.L. Perrelet self-winding watch, 1920 Jaeger-LeCoultre Atmos clock powered by thermal fluctuations, 1956 Zenith battery-less ultrasound remote, present Eolic generators, present FreePlay wind-up radio, present Motorola PVOT hand-crank phone.]

**Energy from Ambient:**

The idea is not new.

- Water- and windmills.
- 1770, A.L. Perrelet, self-winding watch.
- 1920, Jaeger-LeCoultre, Atmos clock powered by thermal fluctuations.
- 1956, Zenith, battery-less ultrasound remote.
- Present, Eolic generators.
- Present, FreePlay, wind-up radio.
- Present, Motorola PVOT hand-crank phone.

**Energy Harvesting (Scavenging)**

- **Principle:** Energy is extracted from the surroundings

**Surroundings** $\rightarrow$ **Energy** $\rightarrow$ **Conversion** $\rightarrow$ **Conditioning** $\rightarrow$ **Load**

- Environment
- Human body
- Radiant
- Kinetic
- Thermal

**The load can be:**

- Electronic circuits and devices
- Sensors with wireless communication $\rightarrow$ **Autonomous Sensors**
- …
Radiant Energy Harvesting

- **Principle**: Energy is extracted from the surroundings

![Radiant Energy Diagram]

- **Radiant Energy**
  - Solar
  - Radio Frequency

Thermal Harvesting

- **Principle**: Energy is extracted from the surroundings

![Thermal Energy Diagram]

- **Thermal Energy**
  - Thermoelectric effect
  - Pyroelectric effect
Mechanical Energy Harvesting

- Principle: Energy is extracted from the surroundings

Mechanical Energy

MechanoElectrical Conversion

Magnetic induction conversion

Electrostatic conversion

Piezoelectric conversion
MechanoElectrical Conversion

- Magnetic induction conversion:

Magnetic induction conversion:

Electrostatic conversion:

Piezoelectric conversion:

NightStar flashlamp

MechanoElectrical Conversion

- Magnetic induction conversion:

Magnetic induction conversion:

Electrostatic conversion:

Piezoelectric conversion:

NightStar flashlamp

MechanoElectrical Conversion

- Magnetic induction conversion:

Magnetic induction conversion:

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NightStar flashlamp
MechanoElectrical Conversion

- Magnetic induction conversion:
  - Magnetic induction conversion: 
  - Magnetic induction conversion: 
  - Magnetic induction conversion: 

Electrostatic conversion

Piezoelectric conversion

Magnetic induction conversion

Electrostatic conversion

Piezoelectric conversion

- Electrostastic conversion:
  - Electrostastic conversion:
  - Electrostastic conversion:

www.enocean.com

UCB, Berkeley, USA

UCB, Berkeley, USA

UCB, Berkeley, USA

MIT, Boston, USA

V.Ferrari

Summer School: Energy Harvesting at micro and nanoscale, Aug. 1-6, 2010
MechanoElectrical Conversion

- Magnetic induction conversion
- Electrostatic conversion
- Piezoelectric conversion

Mechanical Energy Harvesting

- Direct deformation (strain)
  - E.g. piezoelectric fiber composites

- Impact & transient loads
  - E.g. piezoelectric thin plates

- Vibrations
  - Seismic-mass inertial system

\[ P_d = \frac{m \zeta T Y^2 \left( \frac{\omega_T}{\omega_b} \right)^3}{1 - \left( \frac{\omega_T}{\omega_b} \right)^2 + 2 \zeta T \left( \frac{\omega_T}{\omega_b} \right)} \]

(approximated for piezoelectric converters)


- Unfavorable scaling with reducing dimensions
The Piezoelectric Effect

- Discovered in 1880-81 by the Curie brothers
- Property of certain materials in which:
  - a mechanical stress induces an electric charge
    (direct effect)
  - an electric field develops a mechanical strain
    (converse effect)

- The effect is linear, as opposed to electrostriction
Applications of Piezoelectricity

- Sonic and ultrasonic wave generation and detection:
  - Sensors and transducers
  - Filters and resonators

- ElectroMechanical & MechanoElectrical conversion:
  - Actuators
  - Transformers
  - Gas igniters
  - Motors and machining tools
  - Nebulizers and humidifiers
  - Energy harvesters

Crystal Structure and Properties

- The degree of structural symmetry affects the piezo and pyro properties of the material

- 32 classes (point groups)
- 21 non centrosymmetrical
- 11 centrosymmetrical
The degree of structural symmetry affects the piezo and pyro properties of the material.

- 32 classes (point groups)
- 21 non-centrosymmetrical
- 11 centrosymmetrical

Piezoelectricity in Quartz

- X axis: electrical axis
- Y axis: mechanical axis
- Z axis: optical axis
Crystal Structure and Properties

- The degree of structural symmetry affects the piezo and pyro properties of the material

11 centrosymmetrical

21 non-centrosymmetrical

32 classes (point groups)

- 20 piezoelectric (stress-induced polarization)
- 10 pyroelectric (polar with spontaneous polarization)

- Quartz
- Turmaline
- AlN
- ZnO
- BaTiO₃
- Pb(Zr,Ti)O₃ (PZT)

32 classes (point groups)
Ferroelectrics

- Materials in this class exhibit the strongest piezo and pyro effects.
- Monocrystals (e.g. Rochelle salt) or Polycrystals (e.g. PZT ceramics).
- Dipoles are arranged in domains.
- Above $T_{\text{Curie}}$ the domains are randomly oriented.
- Poling:
  - an electric field is applied to orient the domains and set up a permanent polarization.

Lead Zirconate Titanate (PZT)

- Ferroelectric polycrystalline ceramic made by a solid solution of two perovskite type oxides ($\text{ABO}_3$):
  - $\text{PbZrO}_3$
  - $\text{PbTiO}_3$
- Above Curie temperature:
  - cubic, nonpolar
- Below Curie temperature:
  - rhombohedral/tetragonal, polar
- Large piezoelectric and pyroelectric effects.
- High coupling coefficient.
- Various compositions (PZT-4, PZT-5, PZT-5H Navy, ...)
- Other commercial name: PXE.
**Basics of Piezoelectricity (1)**

- Interaction between Electrical and Mechanical domains described by linear piezoelectric constitutive equations
- Several options depending on the chosen EM variables
- In the monodimensional simplified hypothesis:

\[
\begin{align*}
S &= s^E T + d E \\
D &= d T + e^T E \\
S &= s^D T + g D \\
E &= -g T + D/e^T
\end{align*}
\]

\[T = \text{stress [N/m²]}\]
\[D = \text{dielectric displacement [C/m²]}\]
\[E = \text{electric field [V/m]}\]
\[s^I = \text{elastic compliance [m²/N]}\]
\[\varepsilon^I = \text{dielectric permittivity [F/m]}\]
\[d, e, g, h = \text{piezoelectric constants}\]

\[
\begin{align*}
\varepsilon^+ &= \varepsilon^+ \Delta \varepsilon^+ = E d T S \\
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Examples of Piezoelectric Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie point (°C)</th>
<th>First direction</th>
<th>Piezo coefficient</th>
<th>Piezoelectric constant (d)</th>
<th>Young's modulus (GPa)</th>
<th>Dielectric constant (%)</th>
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TP 238, Matroc E electroceramics.

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TP 238, Matroc E electroceramics.
Piezoelectricity Modeling

- Making reference, for instance, to the formulation:
  \[
  T = c^E S - eE \\
  D = eS + e^E E
  \]

- ... passing to global variables force \( F \), displacement \( X \), voltage \( V \), and current \( I \), an equivalent-circuit representation can be drawn:

\[
  F = \frac{eA}{l} X - \frac{eA}{l} V \\
  Q = \frac{eA}{l} X + \frac{e^S A}{l} V \\
  I = \frac{eA}{l} j\omega X + j\omega C^S V
  \]

\[
  F = \frac{k E}{l} X - \frac{eA}{l} V \\
  I = \frac{eA}{l} j\omega X + j\omega C^S V
  \]

- Spring constant \( k \) (capacitance \( C \)) depends on electrical (mechanical) boundary conditions

- Spring constant:
  - Electrically shorted: \( \frac{F}{X} = k^E \)
  - Electrically opened: \( \frac{F}{X} = k^E + \frac{A}{l} eh = k^D > k^E \)

- Capacitance:
  - Mechanically clamped: \( \frac{I}{j\omega V} = C^S \)
  - Mechanically free: \( \frac{I}{j\omega V} = C^S + \frac{A}{l} ed = C^T > C^S \)

* DC-responding ideal transformer

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Electro-Mechanical Coupling

- The energy transfer between the EM domains can be expressed by the electromechanical coupling factor $\kappa$:

$$\kappa^2 = \frac{(\text{stored energy})_E}{(\text{supplied energy})_M} = \frac{(\text{stored energy})_M}{(\text{supplied energy})_E}$$

- By reflecting the corresponding impedance through the transformer ports it results:

$$\kappa^2 = \frac{\alpha^2}{\alpha^2 + k\varepsilon C_s} = \frac{\varepsilon^2}{c\varepsilon s^2} = \frac{d^2}{s^2\varepsilon^4}$$

Power Conversion from Vibrations

- A vibrating structure is assumed to move with dynamic displacement $x(t)$ with respect to a fixed reference.

- A seismic equipment is used to convert the displacement $x$ into an inertia force acting on the proof mass $m$.

- This in turn causes a relative displacement $y(t)$ between the structure and the proof mass generating a stress in the piezo.

- A lumped-element model can be used to describe the system around resonance.
In general, a maximum exists to the power that can be extracted by an ideal converter.

This power limit occurs at resonance and for a converter with a purely resistive mechanical impedance adapted to $r$:

$$P_{\text{lim}} = \frac{m^2 \ddot{X}^2}{8r} = \frac{m^2 a_x^2}{8r}$$

Same results as in:

Piezoelectric Power Conversion

- Assuming $Z_L = R$, the transfer function between $F_y$ and $Y$ is:
  \[
  Y = \frac{1 + j\omega RC}{j\omega \alpha^2 + (1 + j\omega RC)[-\omega^2 m + j\omega r + k + k^E]}
  \]

- The transfer function between $F_y$ and $I$ is then:
  \[
  I = \frac{Y I}{F_y} = \frac{j\omega \alpha}{j\omega \alpha^2 + (1 + j\omega RC)[-\omega^2 m + j\omega r + k + k^E]}
  \]

The electrical power $P_E$ on a resistive load $R$ is:

\[
P_E = \frac{R|I|^2}{2} = \frac{R|F_y|^2}{2} \left| \frac{j\omega \alpha}{j\omega \alpha^2 + (1 + j\omega RC)[-\omega^2 m + j\omega r + k + k^E]} \right|^2
\]

- $P_E$ is a function of $R$ that maximizes to $P_{opt}$ at the optimal resistive load $R_{opt}$

- $P_{opt}$ is a function of frequency that maximizes at about the "short-circuit" natural frequency:
  \[
  \omega_{sc} = \sqrt{\frac{k + k^E}{m}}
  \]

- $P_{opt}$ tends to $P_{lim}$ with increasing the electromechanical coupling factor $\kappa$

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Piezoelectric Power Conversion

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Fig. 4. Harvested power dissipated in the optimal resistive load versus operating frequency and squared coupling factor $\kappa$. $m = 1.1 \text{ g}, k = 30700 \text{ N/m}, C_0 = 750 \mu\text{F}, d = 0.072 \text{ N\cdot s/m}, \alpha = 5 \text{ m/s}^2$.


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The energy balance gives:
\[
\int F_y \dot{y} dt = \frac{1}{2} m \dot{y}^2 + \frac{1}{2} (k + k^E) y^2 + \int r \dot{y}^2 dt + \int \alpha V \dot{y} dt
\]

The transferred energy is in turn:
\[
\int \alpha V \dot{y} dt = \frac{1}{2} C_s V^2 + \int V I dt
\]
Mechanical Energy from Vibrations

<table>
<thead>
<tr>
<th>Vibration Source</th>
<th>Peak Acc. (m/s²)</th>
<th>Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base of 3-axis machine tool</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>Kitchen blender casing</td>
<td>6.4</td>
<td>121</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>3.5</td>
<td>121</td>
</tr>
<tr>
<td>Door frame just as door closes</td>
<td>3</td>
<td>125</td>
</tr>
<tr>
<td>Small microwave oven</td>
<td>2.25</td>
<td>121</td>
</tr>
<tr>
<td>HVAC vents in office building</td>
<td>0.2 – 1.5</td>
<td>60</td>
</tr>
<tr>
<td>Wooden deck with foot traffic</td>
<td>1.3</td>
<td>385</td>
</tr>
<tr>
<td>Breadmaker</td>
<td>1.03</td>
<td>121</td>
</tr>
<tr>
<td>External windows (size 2 ft X 3 ft)</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>Notebook computer while CD is being</td>
<td>0.6</td>
<td>75</td>
</tr>
<tr>
<td>Washing machine</td>
<td>0.5</td>
<td>109</td>
</tr>
<tr>
<td>Second story floor of a wood frame</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>0.1</td>
<td>240</td>
</tr>
</tbody>
</table>

Nanoscale Energy Converters

- A single piezoelectric nanowire of BaTiO₃ excited by vibrations generates current

Nanoscale Energy Converters

- Piezoelectric nanowires of ZnO deflected by an AFM tip or excited by ultrasound waves generate current

Self-powered nanowire devices

Sheng Xu, Yiqi Qin, Chen Xu, Yaguang Wei, Runen Yang and Zhong Lin Wang*

Microscale Energy Converters

- Piezoelectric MEMS under typical excitations generate in the order of 1 µW

Application to TPMS

- Next generation Tire-Pressure Monitor Systems (TPMS) will dismiss batteries and rely on energy harvesting
- MEMS converters can find their way in the field

First embedded tire in 2007: Siemens / Goodyear Tire IQ

Macroscale Energy Converters: commercial devices

Joule-Thief™

Perpetuum
Macroscale Energy Converter

W = 15mm
L = 40mm
T = 500μm

PZT: Piezokeramika 856
δ33 = 590pC/N
δ31 = -260pC/N
εr = 4000

C = 151pF
R = 363MΩ
(A = 13.6V)

Resistive load R_L
Capacitive load C_L

Computed
Experimental

Film Properties

Alumina substrate
W = 18 mm
L = 31 mm
Film Thickness = 125 μm

Harmonic steel substrate
W = 5 mm
L = 35 mm
L_p = 30 mm

Parameter
BULK CERAMIC
THICK FILM
rel. dielectric const. ε/ε_0
4100
100 ± 10

density ρ [g/km³]
7.5
4 ± 0.1

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Limitations with Resonant Converters

- Best harvesting effectiveness is when the converter operates at mechanical resonance
- This is problematic to guarantee with frequency-varying vibrations and is considerably sub-optimal for wideband noise
- Lowering the converter quality factor increases the bandwidth, but worsens the peak response

Frequency Up-Conversion

- Mechanical methods have been proposed to up-shift the vibration frequency where the converter is more responsive

Fig. 1. Proof mass approach vs novel frequency up conversion (or rectification) approach.

Fig. 2. Schematic concept of micro energy harvesting device using frequency up conversion.

**Frequency Tuning**

- An adjustable axial tension changes the beam resonant frequency

The method is not self adaptive

Electrical automatic tuning can be used, but this requires extra energy

---

**MultiFrequency Converter Array**

- Multiple converters combined to obtain a wider equivalent bandwidth:

Silicon MEMS with PZT films:
  Design: University of Brescia
  Fabrication: CNM, Barcelona, Spain
  In collaboration with:


---

Multi-Frequency Converter Array MEMS Implementation

- PZT low-curing-temperature film
- IDT electrodes (d$_{33}$ mode)
- Embedded piezoresistors

Multiple-Converter System

- Multiple converters are coupled into a single structure
Nonlinear Approach: Theory

- **Bistability** is exploited to amplify displacement induced by random vibrations due to stochastic resonance.
- For decreasing values of $d$:
  - Quasi linearity
  - Nonlinearity
  - Bistability

\[ mx + (k - k_{NL})x = 0 \]
\[ k_{NL}(d) = \alpha - \beta x^2 \]
\[ F_{NL}(d) = \alpha x - \beta x^3 \]

Nonlinear Approach: Experiment

- Bimorph cantilever beam fabricated with:
  - Stainless steel
  - Low-curing-temperature PZT films

\[ t_{PZT} = 75 \text{ nm} \]
\[ 40 \text{ mm} \]

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Nonlinear Approach: Results

- Behaviour in agreement with theory:

\[ V_{d=25.0\,\text{mm}} = 0.78\,\text{V}, \quad V_{d=12.0\,\text{mm}} = 1.68\,\text{V}, \quad V_{d=10.5\,\text{mm}} = 3.33\,\text{V} \]

Nonlinear Single-Magnet Converter

- A ferromagnetic substrate is coupled to a fixed magnet
Contents

- Introduction
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Energy Harvesting at micro and nanoscale

Power Supplied to a Resistive Load

- Average power into a resistive load $R_L$:
  - Sinusoidal regime at $f_0$
  \[ P = \frac{j2\pi f_0 C_p R_L}{1 + j2\pi f_0 C_p R_L} \left( \frac{V_p^2}{R_L} \right) \rightarrow P_{\text{opt}} = \frac{V_p^2}{4R_L} \]

- Broadband between $f_1$ and $f_2$
  \[ P = \int_{f_1}^{f_2} S_{V_r}(f) \left| \frac{j2\pi f C_p R_L}{1 + j2\pi f C_p R_L} \right|^2 \frac{1}{R_L} df = \int_{f_1}^{f_2} S_{V_r}(f) |H(f)|^2 \frac{1}{R_L} df \]

- The power spectral density $S_{V_r}(f)$, commonly used as an indicator of signal power, is not sufficient to describe $P$
- The weighting function $H(f)$ should be also considered
**“Usable” Power in Electronics**

- A large power into a resistive load does not necessarily mean a correspondingly high usable power.
- This is because power into a resistive load is associated to AC voltage (current).
- Electronic circuits and microsystems usually need DC power supply.

- **AC/DC converters**, i.e. rectifier circuits, are required.
- They in turn introduce nonidealities and losses, and pose requirements on the voltage levels to operate properly.

**AC/DC Circuits in Sinusoidal State**

- AC and DC driving of a resistive load:

  - **Synchronized Switch Harvesting on Inductor (SSH) technique**:

  - **Voltage has the same sign of velocity**

---


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AC/DC Circuits in Sinusoidal State

- S S H I for AC load driving:

![AC Circuit Diagram]

Fig. 7. Nonlinear AC device and associated voltage and displacement.

- S S H I for DC load driving:

![DC Circuit Diagram]

Fig. 8. Nonlinear DC device.

Fig. 9. Typical voltage and displacement waveforms for the nonlinear DC device.

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AC/DC Circuits in Sinusoidal State

- Power comparison under weak EM coupling:

![Power Comparison Graph]

Fig. 10. Harvested power versus the load R for the same displacement amplitude (α = 0.0008 N/m, f_p = 2000 Hz). M = 48 g, C_l = 55.8 nF, C_0 = 2.6, w_o = 0.6 Hz.

- Power comparison versus the EM coupling:

![Power Comparison Graph]

Fig. 14. Maximum harvested power for each technique versus the squared coupling coefficient (α = 0.0005 N/m, f_p = 2000 Hz). M = 48 g, C_l = 55.8 nF, C_0 = 0.223 Ns/m, C_0 = 2.6, F_o = 0.1 Hz.

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**Intermittent Operation**

- Differences with respect to load driven under sinusoidal steady state arise when energy must be accumulated.

- If available power is insufficient for continuous supply of the system.

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- Conclusions
Autonomous Module with RF Link

- The converted energy is stored and intermittently used to trigger a radio-frequency (RF) transmitter

! No battery, no internal power sources!

- How a sensor can be inserted into the system?
  ...considering that:
  - the power budget is quite restrictive
  - voltage and current levels are poorly defined
  - suitable resolution should be granted

Autonomous Sensor Module

- The converted energy is stored and intermittently used to trigger a radio-frequency (RF) transmitter

- The sensor (R or C) is inserted into an oscillator
- The oscillator frequency modulates the envelope of the RF carrier
- The measurement information is carried in the time domain
Autonomous Temperature Sensor

- Sensitivity: $S_f \approx 1.3 \text{kHz/}^\circ C$
- Standard deviation (30 repetitions): $\sigma \approx 10 \text{Hz}$
- Resolution: $R_c = \frac{3\sigma}{S_f} = \frac{30 \text{Hz}}{1.3 \text{kHz/}^\circ C} = 0.023 \text{ }^\circ C$

Thermistor response curve

NTC Epcos K164/10k

Frequence vs. Temperature [

Resolution:

Sensitivity:

Standard deviation (30 repetitions): 

Resolution: 

NTC Epcos K164/10k

- Piezoelectric vibration-powered module for temperature sensing and transmission of the reading over a RF link

Energy conditioning and storage

Signal conditioning and RF transmission

Piezo bimorph
Autonomous Multi-Sensor Module

- The piezo harvester powers a module comprising 2 sensors
- Energy is sequentially switched between the sensors
- Signals are transmitted in time multiplexing

A digital ID-code can also be transmitted for module tagging and tracking

Multi-Frequency Converter Array

- Multiple differently-tuned converters combined to obtain a wider equivalent bandwidth:

\[ V_1, V_2, V_3, V_4, V_5 \]

\[ C_{p1}, C_{p2}, C_{p3}, C_b \]

\[ R_{p1}, R_{p2}, R_{p3} \]

- Multi-Frequency Converter Array: experimental results

- Wideband excitation:

\[ V(t) \]

\[ 0, 1, 2, 3, 4 \]

\[ 0, 5, 10, 15, 20 \]

Measured frequency response.


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Measured open circuit voltages of the three converters.

Measured voltage across the storage capacitor.


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Multi-Frequency Converter Array: experimental results

- Wideband excitation:

\[ \text{Measured voltage across the storage capacitor.} \]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Cantilever 1</th>
<th>Cantilever 2</th>
<th>Cantilever 3</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>113 Hz</td>
<td>17.8 s</td>
<td>X</td>
<td>X</td>
<td>14 s</td>
</tr>
<tr>
<td>183 Hz</td>
<td>X</td>
<td>27.8 s</td>
<td>X</td>
<td>14.3 s</td>
</tr>
<tr>
<td>281 Hz</td>
<td>X</td>
<td>X</td>
<td>12.2 s</td>
<td>6.6 s</td>
</tr>
<tr>
<td>145 Hz</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>21 s</td>
</tr>
</tbody>
</table>

Output Combinations in a MFCA

- Parallel-like combination:
  - Rectified currents are fed to a single capacitor
Output Combinations in a MFCA

- **Series-like combination:**
  - Rectified voltages on different capacitors are summed

\[ V_1 + V_2 + V_3 \]

- **Parallel-like configuration**

\[ V_{Cb1} + V_{Cb2} + V_{Cb3} \]


Experimental results:
- The series-like configuration reaches the threshold to trigger the RF transmission
- It is especially suitable for arrays of low-voltage MEMS converters

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Final Comments

- Energy harvesting for sensors is a fast-growing area evolving from gadgets to enabling technology in such fields as:
  - Industrial control and automation
  - Transport, automotive, avionics
  - Power plants & distribution
  - Structural monitoring
  - Medical and healthcare
  - Security and military

- University of Brescia is active in the field with:
  - Applied research programs
  - Projects in cooperation with industrial Partners

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  - Marco Ferrari
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  - Emanuele Tonoli
  - Stefano Zaiba