Piezoelectric Generators: 
Modeling, Design and Applications

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Piezoelectric generators

**Principle: Direct piezoelectric effect**

*charge displacement in a nonsymmetric crystal lattice, obtained via a mechanical deformation of the piezoelectric material*

Perovskite crystal structure of standard piezoceramic material (here PbZrTi or PZT and BaZrTi)
Piezoelectric energy harvesting from „mechanical energy“

Types of „mechanical energy“
- vibration (at/from solid bodies)
- sound (transmitted through air)
- impact
- deformation
- rotation
- change of position
- ….

Corresponding parameters
- natural frequencies
- frequency spectra or broadband
- amplitudes
- acoustic or mechanical coupling
- forces and bending moments
- rotation speed
- speed of movement
- ….

Resume:
*a lot of different (design) parameters for a lot of different piezomaterials and a lot of different generator types*
Piezoelectric bending generators as exemplary case

Design

- generator as double layer or triple layer beam (1..2 piezo + 1 stiffening layer)
- „double nature“: generator is also the spring of the seismic mass of a mechanical oscillator
Mechanical design

Design

- stiffening layer required to generate unidirectional stress in the piezo layer
- optimal **height** of both layers for a fitting stress load in the piezo layer, both for generators and actuators

C. Friese, P. Woias, F. Goldschmidtboeing
Examples of beam-type generators

$P_{\text{max}} = 0.08 \text{ mW} @ 0.23 \text{ g and 120 Hz}$

S. Roundy et al.,
UC Berkeley, 2004

$P = 0.45 \text{ mW} @ 1\text{g and 60 Hz}$

„Joule Thief“
© AdaptivEnergy, 2009
Piezo-Polymer-Composite (PPC) technology

Advantages

- Fabrication and microintegration on one step
- low-cost-perspective via insert inject molding
- extremely high design flexibility
- generators and actuators from one fabrication technology
Examples of PPC microdevices

- nanojet dispenser
- various piezogenerators
- 2D tilting mirror
- microvalve
Piezoelectric materials: constitutive equations

Material parameters

\[ d : \ \text{piezoelectric strain coefficient} \quad \left[ \frac{m}{V} \right] \]

\[ e : \ \text{dielectric constant} \quad \left[ \frac{As}{Vm} \right] \]

\[ Y : \ \text{Young's modulus} \quad \left[ \frac{N}{m^2} \right] \]

Variables

\[ \sigma : \ \text{mechanical stress} \quad \left[ \frac{N}{m^2} \right] \]

\[ \varepsilon : \ \text{mechanical strain} \]

\[ E : \ \text{electrical field strength} \quad \left[ \frac{V}{m} \right] \]

\[ D : \ \text{electrical displacement} \quad \left[ \frac{As}{m^2} \right] \]

\[ \varepsilon = \frac{\sigma}{Y} + d \cdot E \]

\[ D = e \cdot E + d \cdot \sigma \]
Typical piezoelectric material parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>units</th>
<th>„hard“ PZT PIC 181</th>
<th>„soft“ PZT PIC 255</th>
<th>biaxial PVDF</th>
<th>PZN-PT 001P-33(31)T</th>
</tr>
</thead>
<tbody>
<tr>
<td>strain coefficient $d_{31}$</td>
<td>$10^{-12}$ As/N</td>
<td>-120</td>
<td>-180</td>
<td>6...10</td>
<td>-1400</td>
</tr>
<tr>
<td>strain coefficient $d_{33}$</td>
<td>$10^{-12}$ As/N</td>
<td>+265</td>
<td>+400</td>
<td>13...22</td>
<td>+2400</td>
</tr>
<tr>
<td>relative permittivity $e_{r,11}$</td>
<td>---</td>
<td>1500</td>
<td>1650</td>
<td>10...12</td>
<td>---</td>
</tr>
<tr>
<td>relative permittivity $e_{r,33}$</td>
<td>---</td>
<td>1250</td>
<td>1750</td>
<td>10...12</td>
<td>6500</td>
</tr>
<tr>
<td>Young’s modulus $Y_{33}$</td>
<td>$10^{10}$ N/m²</td>
<td>16.6</td>
<td>---</td>
<td>0.16...0.22</td>
<td>---</td>
</tr>
</tbody>
</table>

One could think: „Soft is better“

PI Ceramics, Germany
Piezotech, France
Microfine Materials, Singapore
Piezoelectric energy harvesting: Coupling, quality factor, Figure of Merit

Piezoelectric coupling coefficient $k$

... defines the ability of a piezoelectric material to convert mechanical into electrical energy, here:

$$ k = d \cdot \sqrt{\frac{Y}{e}} $$

Quality factor $Q$

... defines, for a resonant harvester, its "aptitude for resonance". $Q$ is, as for any oscillator, inversely proportional to damping $\delta$:

$$ Q \approx \frac{1}{\delta} $$

Figure of Merit $F$

... defines the power output of a piezoelectric generator:

$$ P_{out} \approx k^2 \cdot Q^2 $$

$$ F = k^2 \cdot Q^2 $$

Example for nonlinearities: Young‘s modulus Y

Linear model (essentially Hooke‘s law)

\[ \sigma(t) = Y_1 \cdot \epsilon(t) + \ldots \]

with sinusoidal excitation: \( \epsilon(t) = \epsilon_0 \cdot \sin(\omega t) \)

Modeling results

- **symmetric** behaviour at resonance
- **constant resonance frequency** at variable excitation amplitudes

Example for nonlinearities: Young’s modulus $Y$

Cubic model

$$
\sigma(t) = Y_1 \cdot \varepsilon(t) + \frac{1}{2} Y_2 \cdot \varepsilon(t)^2 + \frac{1}{6} Y_3 \cdot \varepsilon(t)^3 + \ldots
$$

cancels out for bending

with sinusoidal excitation:

$$
\varepsilon(t) = \varepsilon_0 \cdot \sin(\omega t)
$$

$$
\varepsilon(t)^3 = \varepsilon_0^3 \cdot \sin^3(\omega t)
$$

Modeling results

- Resonance curves tilted to lower frequencies
- Tilting increases severely with excitation amplitude (in contrast to experimental observations)

Example for nonlinearities: Young’s modulus Y

Experimental results

Results from a cubic model

Example for nonlinearities: Young’s modulus $Y$

Adapted model with „amplitude nonlinearity“

$$\sigma(t) = Y_1 \cdot \varepsilon(t) + \frac{1}{2} Y_2 \cdot \varepsilon(t)^2 + \frac{1}{6} Y_3 \cdot \varepsilon(t)^3 + ...$$

With usual „full nonlinearity“:

- $\varepsilon(t) = \varepsilon_0 \cdot \sin(\omega t)$
- $\varepsilon(t)^2 = \varepsilon_0^2 \cdot \sin^2(\omega t)$
- $\varepsilon(t)^3 = \varepsilon_0^3 \cdot \sin^3(\omega t)$

Using „amplitude nonlinearity“ caused by the ferroelectric hysteresis and taking only the second order terms:

- $\varepsilon(t) = \varepsilon_0 \cdot \sin(\omega t)$
- $\varepsilon(t)^2 \rightarrow \varepsilon_0 \cdot \varepsilon_0 \cdot \sin(\omega t) = \varepsilon_0^2 \cdot \sin(\omega t)$

$$\sigma(t) = Y_1 \cdot \varepsilon(t) + \frac{1}{2} Y_2 \cdot \varepsilon_0 \cdot \varepsilon(t)$$
Comparison to measurements: Adapted nonlinear model

\[ \sigma(t) = Y_1 \cdot \varepsilon(t) + \frac{1}{2} \cdot Y_2 \cdot \varepsilon_0 \cdot \varepsilon(t) \]

With sinusoidal excitation: \( \varepsilon(t) = \varepsilon_0 \cdot \sin(\omega t) \)

Modeling and experimental results

- good fit for small and large excitations
- good prediction of …
  - resonance frequency shift
  - amplitude shift
- some consequences for material choice


Quality and power factor with the adapted nonlinear model

„Hard“ vs. „soft“ PZT: Theoretical and experimental observations

<table>
<thead>
<tr>
<th>Material property</th>
<th>Charge coeff. $d_{31}$</th>
<th>„Hard“</th>
<th>„Soft“</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator property</td>
<td>Quality factor $Q$</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Figure of Merit $F$</td>
<td>+ +</td>
<td>+ +</td>
</tr>
<tr>
<td>Power bandwidth</td>
<td>lower</td>
<td>higher</td>
<td></td>
</tr>
</tbody>
</table>

„Hard“ PZT shows a larger $Q$ and $F$, hence a higher output power, despite its lower charge coefficient $d_{31}$.

F. Goldschmidtboing, S. Neiss, M. Kröner, P. Woias, Proc. MST-Kongress 2013, 532-535. (in German)
Typical (non-adaptive) power output

Characteristics of resonant operation

- highest output power $P_{\text{max}}$ at resonance only
- small power bandwidth $\Delta f$ at high Q factor and conversion efficiency
- not adapted to variable input frequencies
Frequency-tunable piezo generators?

Principle and inspiration

- continuous re-tuning of a mechanical oscillator
- similar to the tuning of a musical string instrument

Frequency tuning via change of...

- mechanical stress
- size (length)
- seismic mass

[koto player, (postcard, around 1900)]

[robot violinist] © Toyota, 2010

Peter Woias, E-MRS Spring Meeting, Lille, France, 06.05.2016
Frequency-tunable piezo generator

Principle of „stress tuning“
- Actuation force in the „arms“ will stiffen the resonating beam and thus change its resonance frequency
  ➤ high tuning range (22%)
  ➤ loss of Q factor with increasing force

Frequency-tunable generator system

Fundamental questions

- How often will a „re-tuning“ be required?
- Will the tuning operation itself „eat“ all the harvested power?
- If so, how to avoid this?

Quasi-static tuning of piezoactuators

1. untuned

2. fast tuning

3. slow relaxation

Advantages

- piezoactuator stores charge and position
- only slow relaxation due to leakage currents
System characteristics

- fully self-powered system
- 3.5-fold increase of power bandwidth $\Delta f$
- low tuning power (5…25 µW)
- microcontroller already „on board“, can be used for other purposes as well

untuned: $\Delta f = 12$ Hz

tuned: $\Delta f = 42$ Hz

output power in tuned and un-tuned operation (tuning intervals: 20 s, acceleration: 0.6 G)

Plucking-type piezogenerators

Example: Knee-joint harvester

- central hub with piezo bimorphs
- plucking via a ring of plectrums during angular movements of the knee joint

Plucking-type piezogenerators

Knee-joint harvester: output voltage and output power

Calculated output power during one plucking event (averaged values)


Simulated and measured tip displacement and output voltage

Energy-autonomous pedometers

Battery-powered pedometer: example Nike+

- battery-powered pedometer and wireless transmitter in the sole of a sports shoe
- wireless receiver at the Apple iPod™

Drawbacks

- completely encapsulated sensor
- no battery exchange is possible
  ➔ limited lifetime
  ➔ sensor with empty battery = waste
  ➔ energy-autonomous alternative?
Energy-autonomous pedometer

Concept

- impact-type piezogenerator in a small „add-on package“ mounted at a sports shoe
  
  *typical output power: 80 µW*

- pedometer and wireless transmitter at/in the shoe

- wireless receiver in a sports watch
Autonomous sensors in tunnel buildings

- environmental monitoring (temperature, humidity, ventilation, ...)
- detection of fire, explosions, earthquake, ...
- monitoring of the building's structural health
Harvesting from vibrations at the rail

Application: train monitoring
- detection of train passage
- measurement of train velocity
- detection of train stops

But first: measurement of the available vibrations
- wide frequency spectrum
- different levels at different locations
- severe influence of train (passenger train, freight train)

vertical acceleration spectrum from 57 trains at a modern concrete rail sleeper, measured in the Arlberg tunnel, Austria
Harvesting from vibrations at the rail

Generator and power management

- array of four piezogenerators with different resonance frequencies
- low power start-up electronics
- on-site test under real conditions (Loetschberg basis tunnel, Switzerland)
Harvesting from vibrations at the rail

System integration and test

- integration of harvester, storage capacitor, power management and wireless module (Enocean STM 300)
- test on a shaker with real-life vibration pattern

transmission of radio telegrams

system operation during the simulated passage of a freight train in the Loetschberg basis tunnel
Summary and conclusions

The design of a piezoelectric generator is a complex and “multidimensional” approach, taking into account the …

- nature of the mechanical energy to be harvested from,
- the design of appropriate piezo generators
- the appropriate choice of piezoelectric materials
- the establishment of system concepts, including active generator control,
- the development of suitable fabrication processes, and
- many application-specific requirements.

However, if done well, we are capable **today** to provide generators for …

- high-efficiency mono-resonant energy harvesting,
- broadband energy harvesting,
- frequency-adapted harvesting systems, or
- harvesting from stochastic or regular low-frequency signals.
Thank you very much for your attention!

Up-coming one-day seminar on Energy Harvesting:

„Energy Harvesting“, late autumn 2016, Zuerich, Switzerland

details on: www.fsrm.ch