Thickness Optimization of a Piezoelectric Converter for Energy Harvesting

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Introduction

Extensive diffusion of sensing nodes and sensing networks (automotive, factory automation, entertainment, environment monitoring, security systems, …)

Main issue: **power supply**

- Batteries
  - limited lifetime
  - recharging/replacement/disposal
  - cost

- Power harvesting
  - in principle unlimited lifetime
  - unattended operation
  - sometimes limited output power

- Solar energy
- Mechanical vibrations
- Temperature gradients
- …

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Mechanoelectrical energy conversion

- Conversion techniques
  - electromagnetic (inductive)
  - electrostatic (capacitive)
  - piezoelectric

Direct piezoelectric effect: surface charge induced by a mechanical stress

- Piezoelectric energy converter
  - unimorph cantilever shape (thick-film, MEMS technologies)
Use of COMSOL

- Improvement of the converted energy
  - Optimization of the dimensions
    - piezoelectric layer thickness

- Application modes
  - piezoelectric: mechanical / electrical behaviour
    - sinusoidal vertical acceleration application
    - generated charge / voltage
  - moving mesh: thickness change
Geometry

- 3D cantilever
  - length $L = 27$ mm;
  - width $w = 3$ mm;
  - steel thickness $t_{\text{steel}} = 200$ $\mu$m;
  - piezoelectric layer thickness $t_{\text{PZT}} = 60$ $\mu$m (poled along thickness)
Mesh

- Mapped mesh
  - 320 quad elements; 11808 degrees of freedom

2 elements linearly spaced

4 elements linearly spaced

20 elements exponentially spaced
Governing equations

- **Piezoelectric layer**
  - **strain-charge form**

\[
S = s^E T + dE
\]

\[
D = \varepsilon^T E + dT
\]

- \( S = \) mechanical strain
- \( T = \) mechanical stress [N/m²]
- \( s^E = \) elastic compliance [Pa⁻¹]
- \( d = \) piezoelectric coefficient [C/N]
- \( D = \) electric displacement [C/m²]
- \( E = \) electric field [V/m]
- \( \varepsilon^T = \) dielectric permittivity [F/m]

- **Steel layer**

\[
S = sT
\]

\[
\begin{bmatrix}
50 & -20 & -20 & 0 & 0 & 0 \\
-20 & 50 & -20 & 0 & 0 & 0 \\
-20 & -20 & 50 & 0 & 0 & 0 \\
0 & 0 & 0 & 70 & 0 & 0 \\
0 & 0 & 0 & 0 & 70 & 0 \\
0 & 0 & 0 & 0 & 0 & 70
\end{bmatrix} \times 10^{-12} \text{Pa}^{-1}
\]

\[
d = \begin{bmatrix}
0 & 0 & 0 & 0 & 11 & 0 \\
0 & 0 & 0 & 11 & 0 & 0 \\
-2.5 & -2.5 & 5 & 0 & 0 & 0
\end{bmatrix} \times 10^{-12} \text{C/N}^{-1}
\]

\[
\varepsilon^T = \begin{bmatrix}
50 & 0 & 0 \\
0 & 50 & 0 \\
0 & 0 & 50
\end{bmatrix} \times \varepsilon_0
\]

\( \rho = 3000 \text{ kg} \cdot \text{m}^{-3} \)

\[
s = 5 \times 10^{-12} \text{ Pa}^{-1}
\]
Subdomain and boundary conditions

- **Vertical acceleration**
  - Body load \( F_z = a \rho \)
  - \( a = 0.1 \text{ g} \)
  - \( \rho = \text{material density} \)

- **Mechanical boundary conditions**
  - clamped end

- **Electrostatic boundary conditions**
  - bottom surface: grounded
  - upper surface: floating potential
  - other surfaces: zero charge

- **Mesh boundary conditions**
  - bottom surface: clamped
  - vertical surfaces: normally clamped
  - upper surface: tangentially clamped, normally displaced (deltaThick)

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Thickness Optimization of a Piezoelectric Converter for Energy Harvesting 7/12
Solver parameters

- **Parametric segregated solver**
  - group 1: moving mesh, static analysis
    - \( \text{deltaThick} \): \(-50 \ \mu \text{m} \rightarrow 340 \ \mu \text{m}\)
  - group 2: piezoelectric variables, frequency response
    - frequency = \(10 \ \text{Hz}\)
Results – tip displacement

PZT rigidity $\ll$ steel rigidity
$\text{tip displacement} \approx \text{const}$

PZT rigidity $\gg$ steel rigidity
$\text{tip displacement} \approx \frac{1}{t_{\text{PZT}}}$

$t_{\text{PZT}} = 60 \ \mu\text{m}$

$t_{\text{PZT}} = 400 \ \mu\text{m}$
Results – electrical output

- Stored electrical energy

\[ E = \frac{1}{2} QV \]

PZT rigidity << steel rigidity
charge: maximum
voltage: increases

PZT rigidity >> steel rigidity
charge: decreases
voltage ≈ const

- Thickness Optimization of a Piezoelectric Converter for Energy Harvesting
Results – influence of the geometry

- Different geometries

<table>
<thead>
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<th>Substrate thickness [µm]</th>
<th>Width [mm]</th>
<th>Length [mm]</th>
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<td>10</td>
</tr>
</tbody>
</table>

Graph showing stored electrical energy [fJ] and $\tau_{PZT} / \tau_{substrate}$ for different geometries.
Conclusions

- FEM simulations used for optimizing the geometrical dimensions of a piezoelectric energy converter
- Geometry with parametrized thickness
  - piezoelectric application mode
  - moving mesh application mode
- The optimal $t_{\text{PZT}}/t_{\text{substrate}}$ was found for maximizing the electrical energy
- The optimal $t_{\text{PZT}}/t_{\text{substrate}}$ value is independent from the converter dimensions
- This model is a specific example of using moving mesh for device geometry optimization