Reduced Order Modeling Enables System Level Simulation of a MEMS Piezoelectric Energy Harvester with a Self-Supplied SSHI-Scheme

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Outline

- Introduction

- MEMS Piezoelectric Energy Harvester
  - Finite Element Model
  - Reduced Order Model

- Power Extraction Techniques

- Results and Discussion

- Conclusion and Future Work
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How to supply all these sensors with energy?
Just wire them ...?

- You need to install power plugs
  → wiring retrofit cost 100 $ / meter
- Wiring complexity

© Porsche AG

3 km cables

500+ km cables

© FlightCommander
Use batteries, but ...

- Limited lifetime
- Maintenance costs
  - Replacement, recharging, recycling
- Environmental effects

remaining 70 % get dumped or burned

© Prof. Woiás
Wireless Autonomous Transducer Solution (WATS)

Sensor frontend (ASIC) 20 µW
Sensor 20 µW
µ-Contr. 20 µW
DSP 20 µW
Radio 20 µW
Micropower module -100 µW

thermal, RF, vibrational, light harvesting
Vision: use MEMS to provide 100 µW / cm² to power wireless autonomous systems

- Piezoelectric
- Electrostatic
- Electromagnetic
- Vibration
Piezoelectric Material

Coupling modes

Asymmetrical form
Low piezo effect (Quartz)

Symmetrical form
No piezo effect (NaCl)

Transversal
Piezoelectric Energy Harvester

Transformer represent mechanical and electrical coupling

\[
\begin{align*}
\sigma & \quad \text{vibration acceleration} \\
L & \quad \text{internal mass} \\
C & \quad \text{mechanical stiffness} \\
R & \quad \text{the energy lost}
\end{align*}
\]
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- Introduction

- MEMS Piezoelectric Energy Harvester
  - 1\textsuperscript{st} and 2\textsuperscript{nd} generation designs
  - Finite Element Model
  - Reduced Order Model

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- Conclusion and Future Work
Outline

- Energy harvesting context - The vision

- Piezoelectric harvesting
  - Fabrication, results, application
  - Modeling

- Multifrequency harvesting
  - Motivation for frequency agility
  - Design implementations
Piezoelectric energy harvester
1st generation design (single mode)

- harvester fabrication on silicon wafer with glass capping
  - Micromechanical resonator
  - DRIE-based structuring of SOI substrates
  - AlN and PZT as piezoelectric material

![Diagram of piezoelectric energy harvester](image)
Power delivery results
1st generation design (non-packaged)

2005
- PZT (lead circonate titanate)
- fabricated by sol-gel

2008
- AlN (aluminum nitride)
- sputtered

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beam width: 5 mm, device length: 6 mm, mass: 34 mg, load ~ 400 kΩ, Q ~ 150

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JMM 19(9), (2009)
Wafer-scale fabrication and packaging

- 150 mm SOI substrates
- Wafer-scale encapsulation between glass substrates
  → Hermeticity to be improved
Power delivery results
1\textsuperscript{st} generation design (packaged)

- Vacuum packaged
- Max. excitation 1.8 g (mass impact on cap)

140 µW @ 572 Hz

year 2011:
record power of 489 µW

device width: 7 mm, mass length: 7 mm, mass: 75 mg,
load ~ 500 kΩ, Q ~ 400, max. displ. 600 um @ 1.8 g

Proc. IEDM (2011)
Autonomous operation of wireless system

- vibration powered at 300 Hz & fully autonomous
- 15 s duty-cycle for radio transmissions of temperature reading

- Energy harvester
- TI MSP430 µC
- Nordic nRF2401
Lumped element modeling
1st generation design

- Equivalent circuit models electro-mechanical behavior
- Coupling factor $\mathcal{F}$ describes energy conversion

\[
L_m = \frac{m}{I^2} \quad k \cdot R_m = \frac{d}{l^2}
\]

\[
C_m = \frac{l^2}{k}
\]

\[
\begin{align*}
R_{load, opt.} &= \frac{R_m}{\sqrt{1 + \omega_m^2 R_m^2 C_{piezo}^2}} \\
P_{load, max.} &= \left(\frac{\mathcal{F}}{1}\right)^2 \frac{1}{2R_m} \frac{1}{1 + \sqrt{1 + \omega_m^2 R_m^2 C_{piezo}^2}}
\end{align*}
\]
Lumped element modeling
1st generation design

- Equivalent circuit models electro-mechanical behavior
- Coupling factor $\mathcal{F}$ describes energy conversion

\[
\begin{align*}
L_m &= \frac{m}{l^2} \\
R_m &= \frac{d}{l^2} \\
C_m &= \frac{l^2}{k}
\end{align*}
\]

at resonance

\[
R_{\text{load, opt.}} = \frac{R_m}{\sqrt{1 + \omega_m^2 R_m^2 C_{\text{piezo}}^2}}
\]

\[
P_{\text{load, max.}} = \left(\frac{F}{I}\right)^2 \frac{1}{2R_m} \frac{1}{1 + \sqrt{1 + \omega_m^2 R_m^2 C_{\text{piezo}}^2}}
\]

under vacuum

\[F / I^*\]

\[C_{\text{piezo}} - R_{\text{load}}\]

Lumped element modeling
1st generation design

- Equivalent circuit models electro-mechanical behavior
- Coupling factor $\Gamma$ describes energy conversion

\[
L_m = \frac{m}{l^2}, \quad R_m = \frac{d}{l^2}, \quad C_m = \frac{l^2}{k}
\]

\[ R_{\text{load, opt.}} = \frac{R_m}{\sqrt{1 + \omega_m^2 R_m^2 C_{\text{piezo}}^2}} R_{\text{load, opt.}} \]

\[ P_{\text{load max.}} = \frac{1}{\omega_m C_{\text{piezo}}} \left( \frac{F}{l} \right)^2 \frac{1}{2R_m} \frac{1}{1 + \sqrt{1 + \omega_m^2 R_m^2 C_{\text{piezo}}^2}} \]

Numerical (finite element) modeling
1st generation design

- Model is based on actual geometry
- Includes circuit elements
- Yields resonance frequency, displacements, strain, power, ...
Model verification: results & experiments
Piezoelectric energy harvester
2nd generation design (multi-mode)

- Two coupled resonators
- Closely spaced resonance frequencies
- Subject to design optimization

Piezoelectric energy harvester 2nd generation design (multi-mode)

- Harvested power of 20µW with 1.2g @ 694Hz
- Tuning range of 3Hz by varying DC voltage between ± 30V

Two sets of capacitors denoted by (+) and (-)

Top view of the fabricated harvester using MEMS process with multiple masses and beams (Pt, AlN and Al layers)

Finite Element Model of the Harvester

- Geometry and mesh view of the piezoelectric energy harvester with 47,800 nodes (145,000 DOF) implemented in ANSYS V.14.5

1\textsuperscript{st} resonance 1.966.2 Hz

2\textsuperscript{nd} resonance 3.755.6 Hz
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Model Order Reduction (1)

- Goal: consider interaction between device and electrical circuit,

- MOR: algorithms that transform large (sparse) ODE systems into much smaller (full) systems
Model Order Reduction (2)

- system matrices are reduced using a Krylov subspace-based Arnoldi algorithm (MIMO setup, expansion around $f = 0$ Hz).

- Advantages:
  - Maintains the accuracy of the original numerical model
  - Reduces the transient simulation time by several orders of magnitude
  - Allows for multi-physical compact modeling (stability issues have to be considered)
Reduced Order Model of the Harvester

Model stabilization [2]

\[
\begin{align*}
\{(x_1^1) + & \begin{bmatrix} [E] & [0] \\ [C] & [0] \end{bmatrix} \cdot \{(x_1^2) \} + \begin{bmatrix} [K_{11}] & [K_{12}] \\ [K_{21}] & [K_{22}] \end{bmatrix} \cdot \{(x_2)\} = \begin{bmatrix} [B_1] \\ [B_2] \end{bmatrix} \cdot (u) \\
\{y\} &= \begin{bmatrix} [C_1] \\ [C_2] \end{bmatrix}
\end{align*}
\]

Schur complement

\[
x_2 = -K_{22}^{-1}K_{21}x_1 + K_{22}^{-1}B_2u
\]

\[
M\ddot{x}_1 + E\dot{x}_1 + (K_{11} - K_{12}K_{22}^{-1}K_{21})x_1 = (B_1 - K_{12}K_{22}^{-1}B_2)u
\]

\[
y - (C_1 - C_2K_{22}^{-1}K_{21})x_1 + (C_2K_{22}^{-1}B_2)u
\]

Reduced Order Model of the Harvester

Comparison between the full and the reduced model

<table>
<thead>
<tr>
<th></th>
<th>full model</th>
<th>reduced model</th>
</tr>
</thead>
<tbody>
<tr>
<td>computation time (s )</td>
<td>6.269,0</td>
<td>4.71</td>
</tr>
<tr>
<td>3.1 GHz with 8 GB RAM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>model dimension</td>
<td>145.517</td>
<td>50</td>
</tr>
</tbody>
</table>


Transfer functions near fundamental resonance frequency

Performance Comparison between Full and Reduced Model

- Model order reduction
  from 145,500 (full) → 50 (reduced)

- Acceleration of computation time for transient simulation
  from 6,300 seconds (full) → 4,7 seconds (reduced)!

- Accuracy is maintained
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Power Extraction Techniques

Bridge Rectifier

- Low power extraction efficiency

- Increasing the conversion ability:
  - Increase the piezoelectric output voltage.
  - Increase the electro-mechanical coupling coefficient.
  - Reduce the time shift between the voltage and the harvester speed.
Power Extraction Techniques

Synchronized switch harvesting on inductor (SSHI)

Synchronous electric charge extraction (SECE)

[Diagrams and graphs related to SSHI and SECE]
SSHI Circuit Implementation

- MOR of a high dimensional FEM (mechanical port (left) and electrical port (right))
- self-supplied comparator
- switchable inductive branch for voltage inversion
- full-bridge rectifier with flattening capacitor and resistive load

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Results and Discussion

→ Transient response

Transient response of system-level simulation (Simplorer 11)

- output voltage at open circuit condition increased from 3.7V to 5.9V
Results and Discussion

\[ \rightarrow \] Parametrization and Optimization

The power dissipation through the circuit.

<table>
<thead>
<tr>
<th>comparator</th>
<th>switch</th>
<th>bridge rectifier</th>
<th>load</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>12%</td>
<td>25%</td>
<td>60%</td>
</tr>
</tbody>
</table>

**Power drops due to:**

- The electrical losses in the harvesting stages.
- The mechanical re-injection losses due to the damping effect.
Results and Discussion

Parametrization and Optimization

Parametrization within system-level simulation (Simplorer 11)

- output peaks at optimum load resistance value
- appr. 70 % power efficiency.
Results and Discussion

→ Experimental verification

Voltage inversion event is observed under attached SSHI circuit

- Sinusoidal excitation (0.3 g) at resonance frequency
- External supply for the comparator
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Conclusion

- A reduced order model of the harvester was successfully used in a co-simulation with electrical power circuitry.
  - Enables **true system-level simulation**
  - Reduces the computation time
  - Preserves **system dynamics / accuracy** of FE model
  - Stability is preserved after the Schur-Complement transformation

- Improve harvested voltage using SSHI-scheme with simple self-supplied control circuit.
Future Work

- Consider other power extraction approaches.
- Extend reduced order model to multiport form (two electrical ports and one mechanical port)
- Stability issues of the reduced order model deserve further research
New Book Published at Wiley-VCH

System-level Modeling of MEMS

Brand, Fedder, Hierold, Korvink, Tabata (Eds.)
Thank you very much for your kind attention!

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