Piezoelectric Generators: Modeling, Design and Applications

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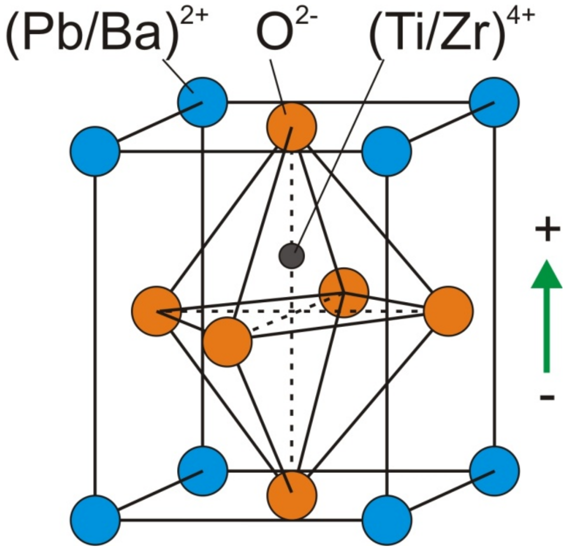
Piezoelectric generators

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)

mechanical energy

mechanical deformation

charge displacement

electrical energy

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
- …..

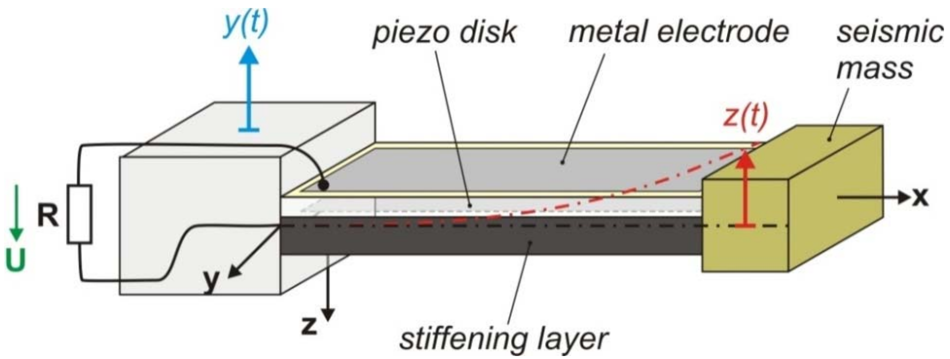
Resume:

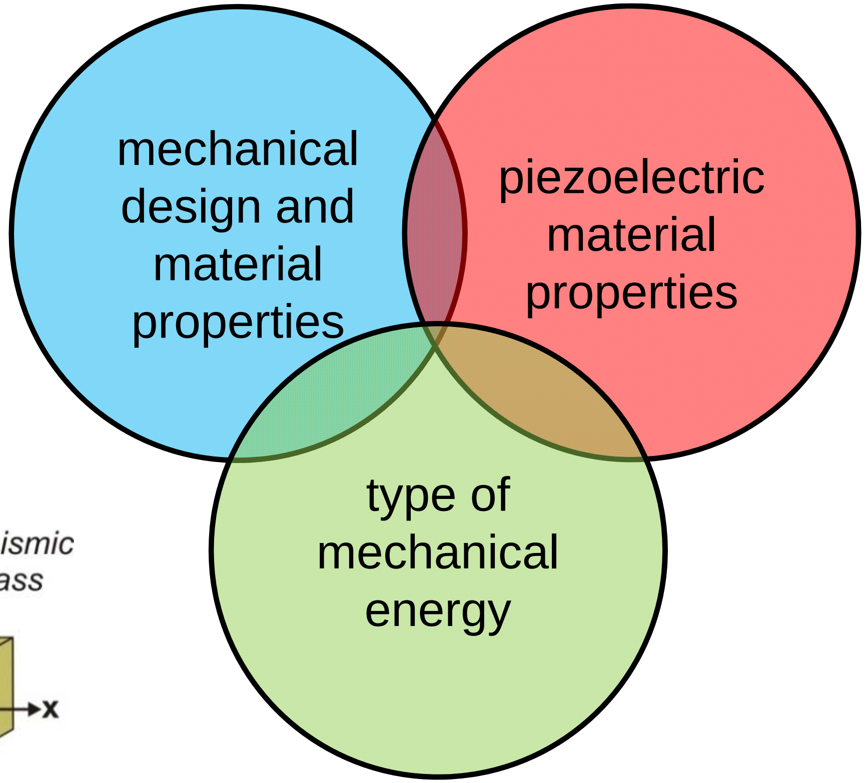
a lot of different (design) parameters for
a lot of different piezomaterials and
a lot of different generator types

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

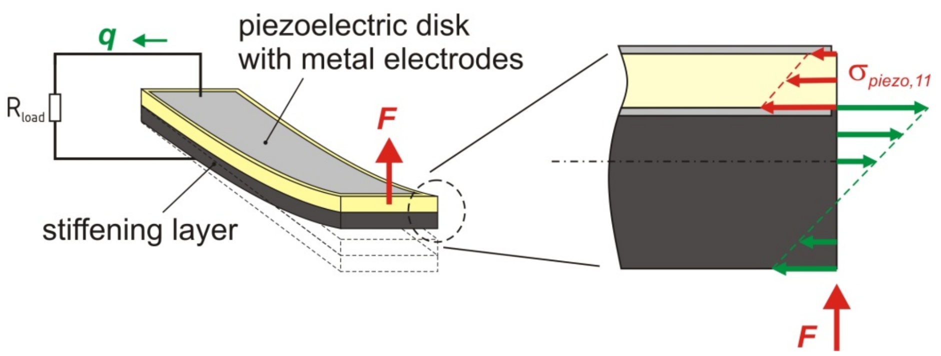


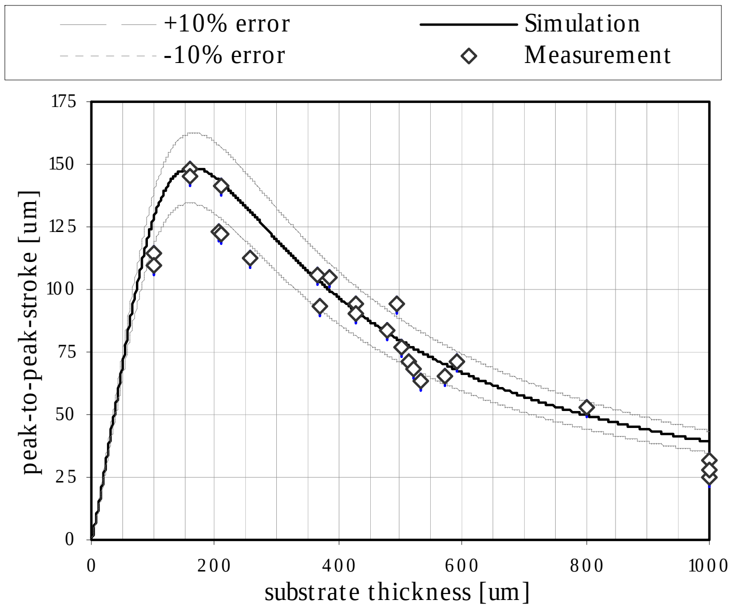


Mechanical design

Design

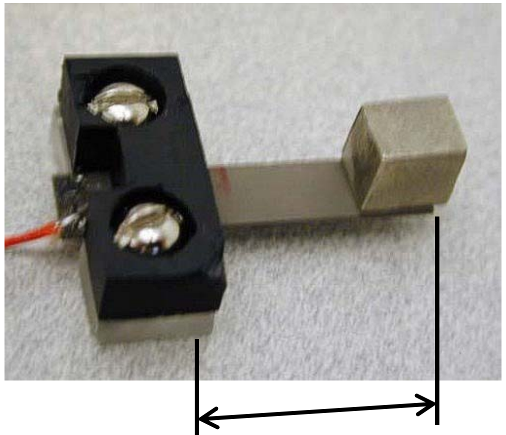
- stiffening layer required to generate unidirectional stress in the piezo layer
- optimal **height** of both layers for a fitting stress load in the piezo layer, both for generators and actuators





C. Friese, P. Woias, F. Goldschmidtböing
IEEE Transducers ´03, Dig. Techn. Papers, Vol. 2, 2003, 1007-1010.

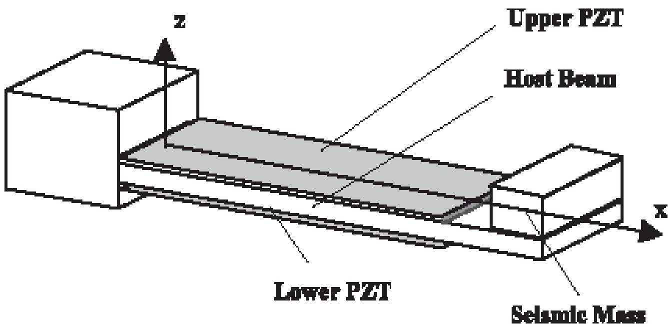
Examples of beam-type generators

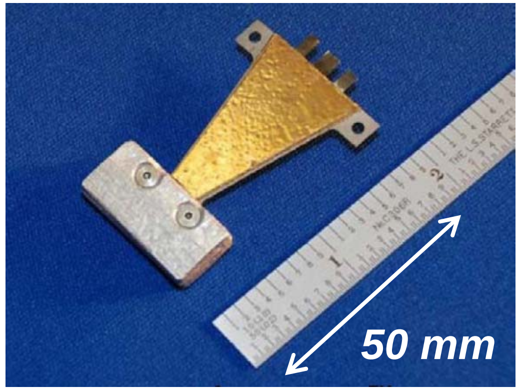


17,5 mm

P_{max} = 0,08 mW @ 0,23 g and 120 Hz

S. Roundy et al.,
UC Berkeley, 2004

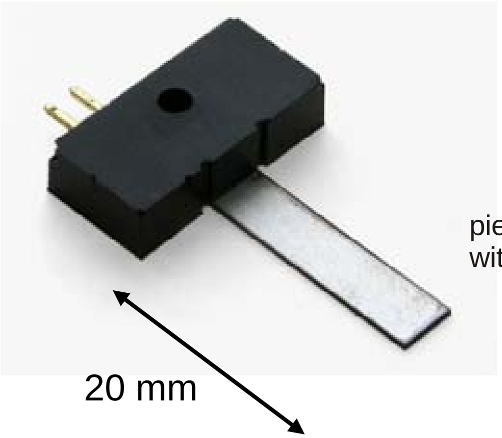


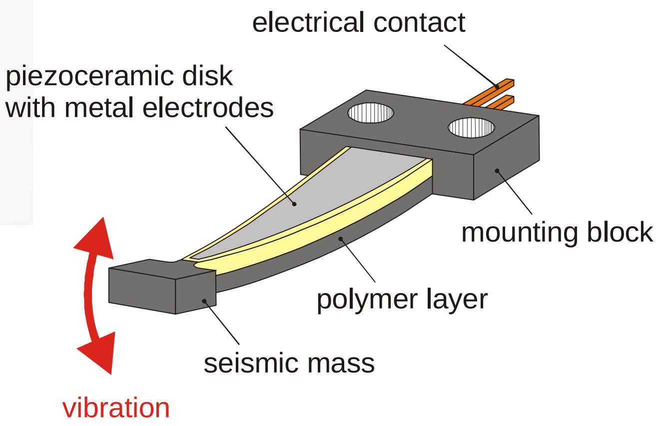


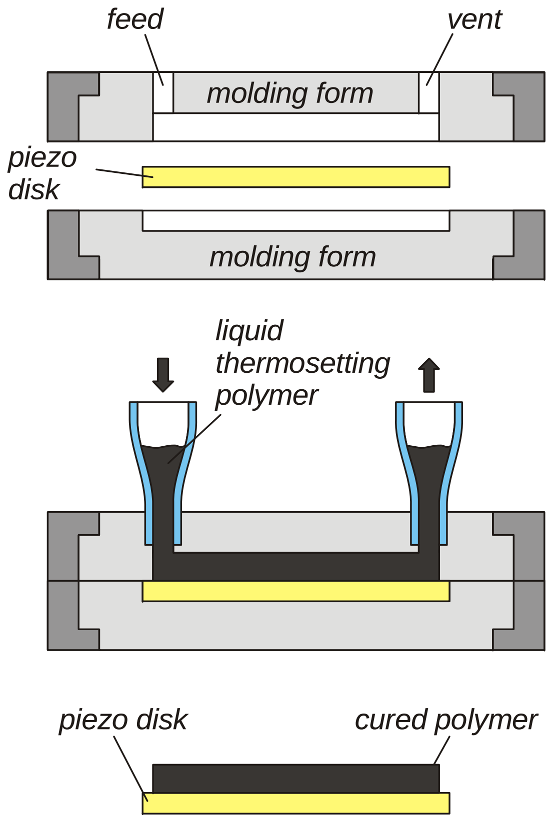
P = 0,45 mW @ 1g and 60 Hz

„Joule Thief“
© AdaptivEnergy, 2009

Piezo-Polymer-Composite (PPC) technology





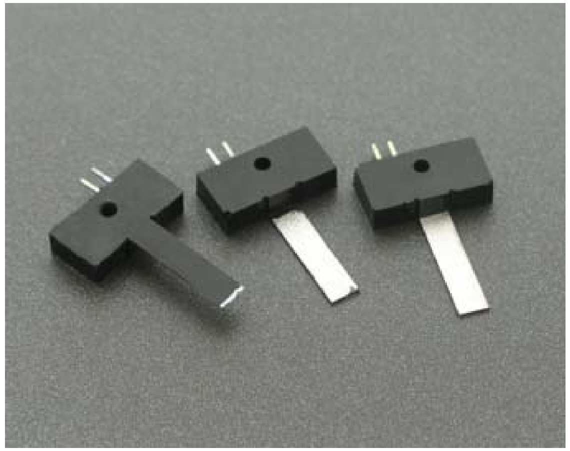


Advantages

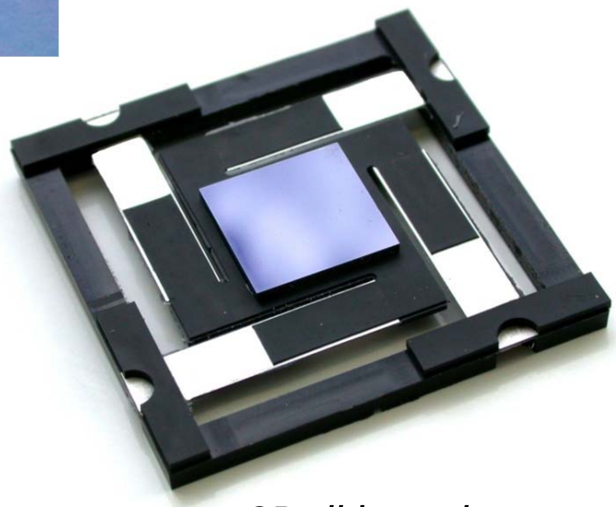
- Fabrication and microintegration on one step
- low-cost-perspective via insert inject molding
- extremely high design flexibility
- generators and actuators from one fabrication technology

Examples of PPC microdevices

nanojet dispenser

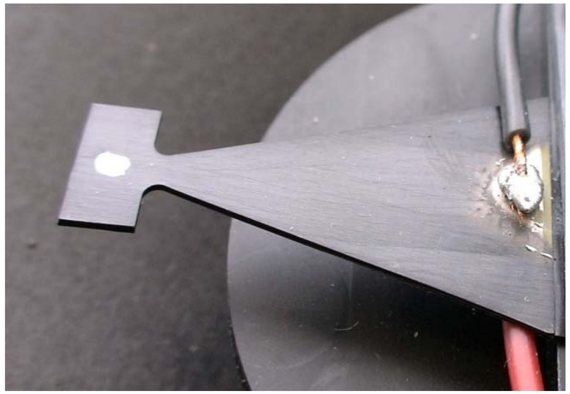


various piezogenerators



2D tilting mirror

microvalve



Piezoelectric materials: constitutive equations

Material parameters

$d:$ *piezoelectric strain coeffizient* $\left[\frac{m}{V}\right]$

$e:$ *dielectric constant* $\left[\frac{As}{Vm}\right]$

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

Variables

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

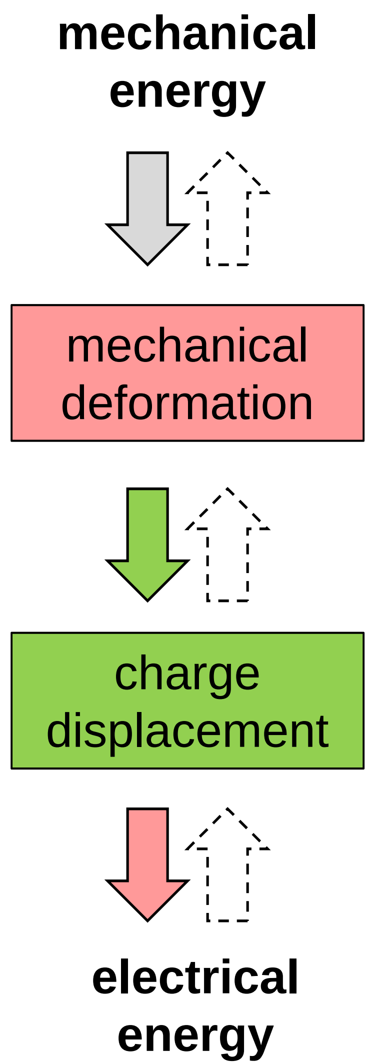
$\varepsilon:$ *mechanical strain*

$E:$ *electrical field strength* $\left[\frac{V}{m}\right]$

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

$$\overbrace{\varepsilon = \frac{\sigma}{Y}}^{\text{Hooke's Law}} + \overbrace{d \cdot E}^{\text{piezoelectric coupling}}$$

$$\underbrace{D = e \cdot E}_{\text{dielectric equation}} + \underbrace{d \cdot \sigma}_{\text{piezoelectric coupling}}$$



Typical piezoelectric material parameters

One could think: „Soft is better"

	units	„hard" PZT *PIC 181*	„soft" PZT *PIC 255*	biaxial PVDF	PZN-PT *001P-33(31)T*
strain coefficient d_{31}	10^{-12} As/N	- 120	- 180	6...10	- 1400
strain coefficient d_{33}	10^{-12} As/N	+ 265	+ 400	13...22	+ 2400
relative permittivity $e_{r,11}$	---	1500	1650	10…12	---
relative permittivity $e_{r,33}$	---	1250	1750	10…12	6500
Young's modulus Y_{33}	10^{10} N/m²	16.6	---	0.16…0.22	---
		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:

$$k = \sqrt{\frac{\text{electrical energy stored}}{\text{mechanical energy applied}}}$$

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

Quality factor Q

… defines, for a resonant harvester, ist „aptitude for resonance“. Q is, as for any oscillator, inversely proportional to damping δ:

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

Figure of Merit F

… defines the power output of a piezoelectric generator:

$$P_{out} \approx \underbrace{k^2 \cdot Q^2}_{\text{Figure of Merit } F}$$

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

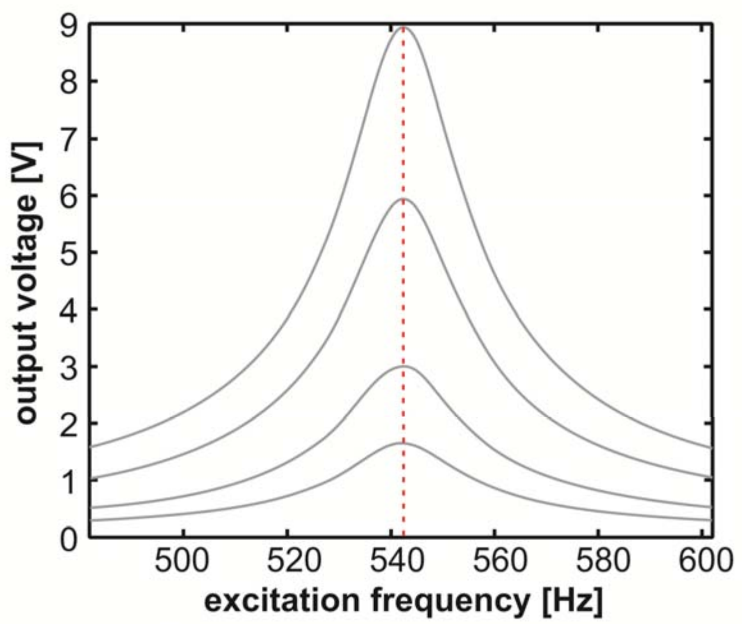
F. Goldschmidtboeing *et al.*, *J. Micromech. Microeng.* 21, 2011, 045006.

Example for nonlinearities: Young‘s modulus Y

Linear model (essentially Hooke‘s law)

$$\sigma(t) = Y_1 \cdot \varepsilon(t) + \ldots$$

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



Modeling results

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

S. C. Stanton et al., *Journal of Intelligent Material Systems and Struct.* 23, 2012, 183.

Example for nonlinearities: Young's modulus Y

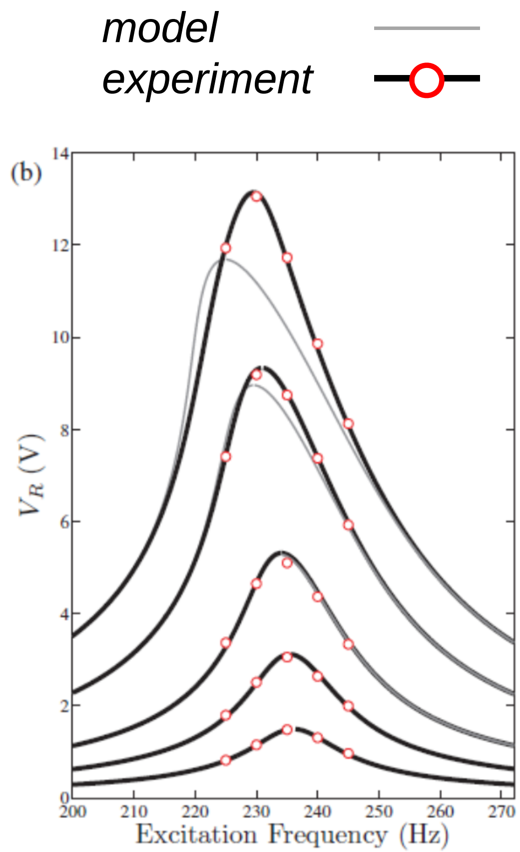
Cubic model

$$\sigma(t) = Y_1 \cdot \varepsilon(t) + \underbrace{\frac{1}{2} \cdot Y_2 \cdot \varepsilon(t)^2}_{\text{cancels out for bending}} + \frac{1}{6} \cdot Y_3 \cdot \varepsilon(t)^3 + \ldots$$

with sinusoidal excitation:

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

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



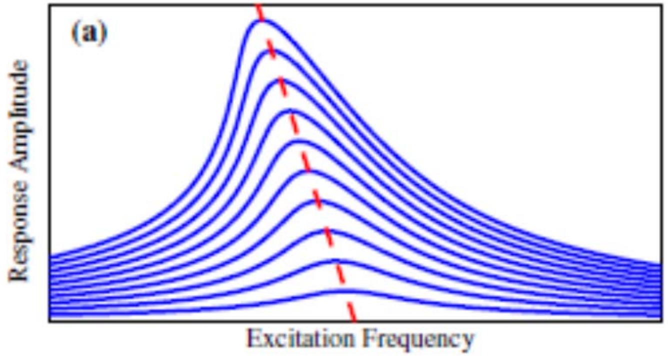
Modeling results

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

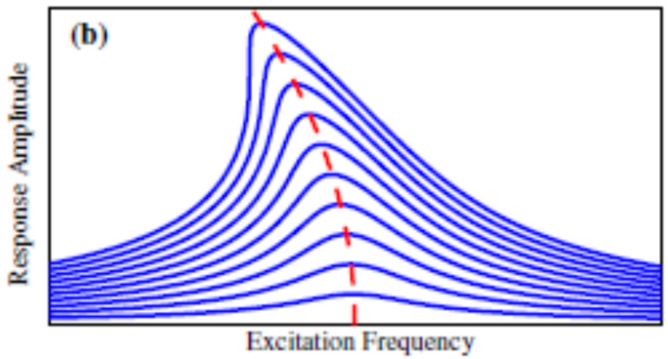
S. C. Stanton et al., *Journal of Intelligent Material Systems and Struct.* 23, 2012, 183.

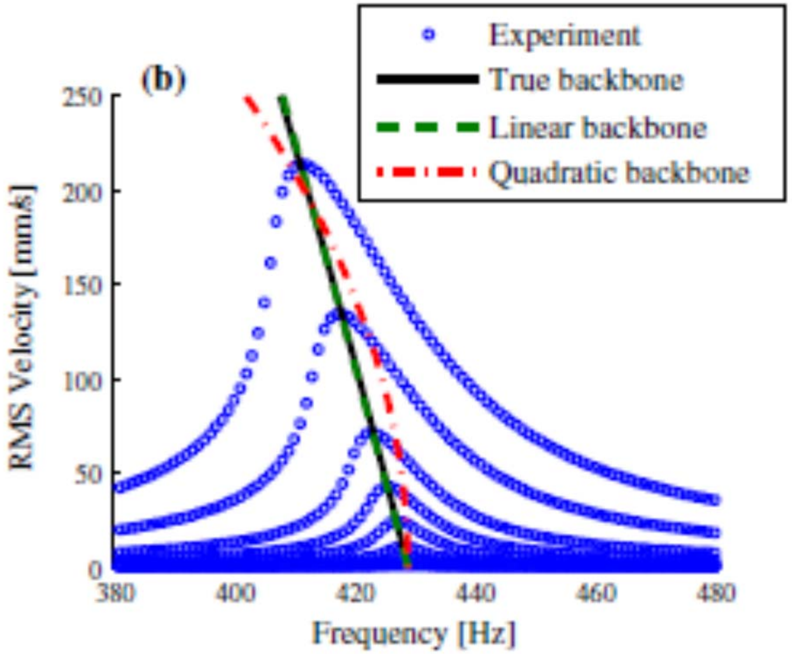
Example for nonlinearities: Young‘s modulus Y

Experimental results



Results from a cubic model





S. Leadenham, A. Erturk,
Nonlinear Dynamics 79, 2015, 1727-1743.

Example for nonlinearities: Young‘s modulus Y

Adapted model with „amplitude nonlinearity“

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

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:

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

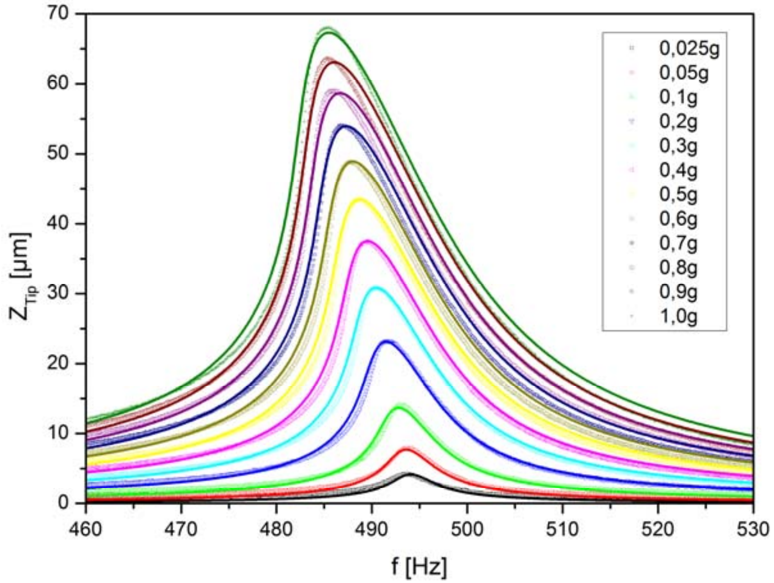
$$\varepsilon(t)^2 \rightarrow \varepsilon_0 \cdot \varepsilon_0 \cdot \sin(\omega t) = \varepsilon_0^2 \cdot \sin(\omega t)$$

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

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

F. Goldschmidtböing, S. Neiss, M. Kröner, P. Woias, *Proc. MST-Kongress 2013*, 532-535. (in German)

F. Goldschmidtboeing, C. Eichhorn, M. Wischke, M. Kroener, P. Woias, *Proc. PowerMEMS 2011,* 114-117.

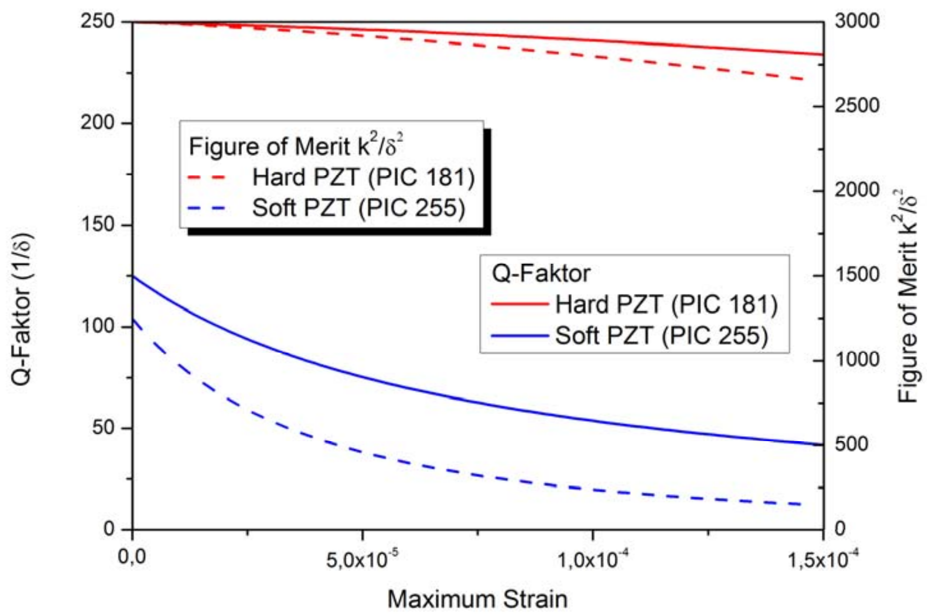
Quality and power factor with the adapted nonlinear model

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

		„Hard“	**„Soft“**
Material property	Charge coeff. d_{31}		+
Generator property	Quality factor Q	+ + +	
	Figure of Merit F	+ + +	
	Power bandwidth	lower	higher

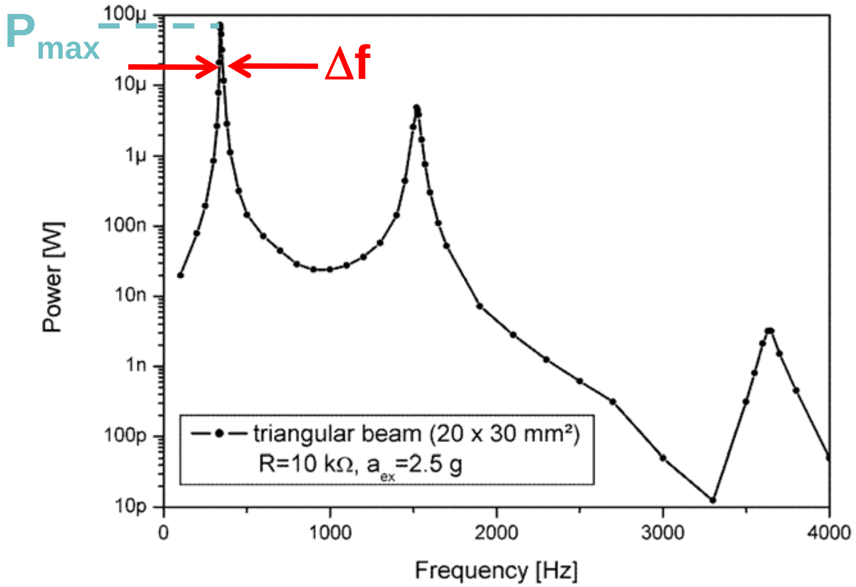
„Hard“ PZT shows a larger Q and F, hence a higher output power, despite its lower charge coefficient d_{31}.

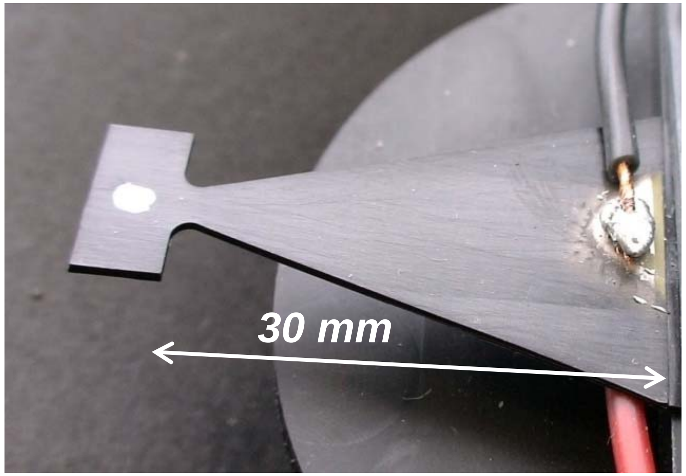
F. Goldschmidtböing, S. Neiss, M. Kröner, P. Woias, *Proc. MST-Kongress 2013*, 532-535. (in German)



Typical (non-adaptive) power output

spectral power output (no tip mass)





F. Goldschmidtböing, P. Woias, *JMM* 18, 2008, 104013

Characteristics of resonant operation

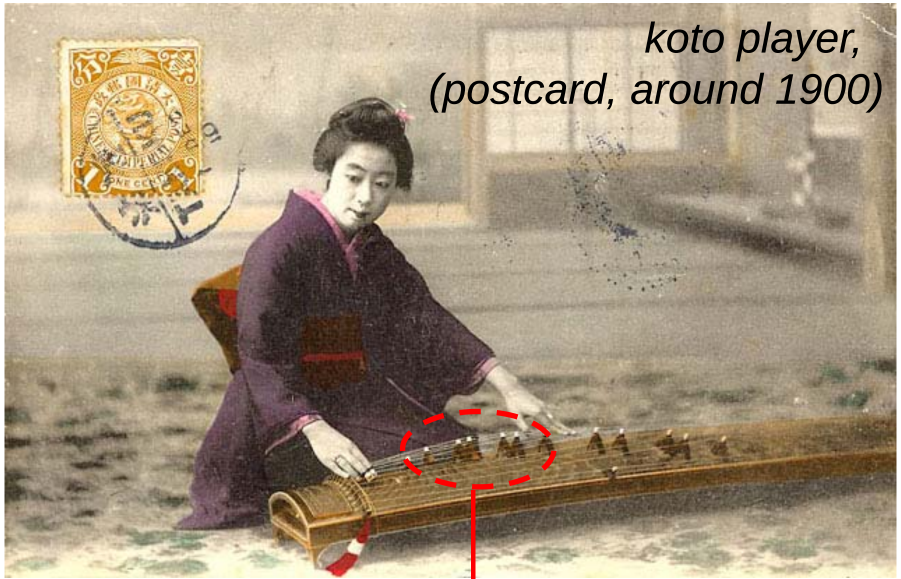
- highest output power P_{max} at resonance only
- small power bandwidth Δf at high Q factor and conversion efficiency
- **not adapted to variable input frequencies**

Frequency-tunable piezo generators ?

Principle and inspiration

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

robot violinist *© Toyota, 2010*

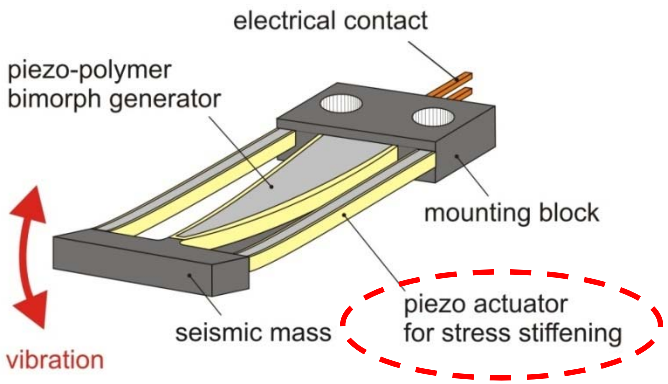


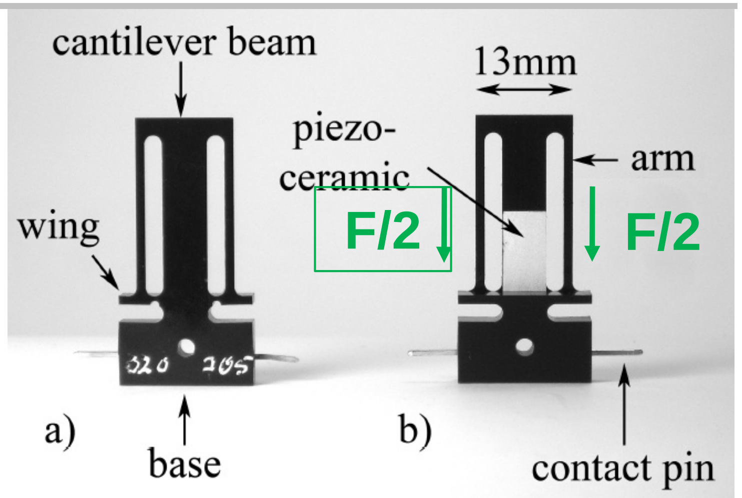
koto player, (postcard, around 1900)

Frequency tuning via change of …

- mechanical stress
- size (length)
- seismic mass

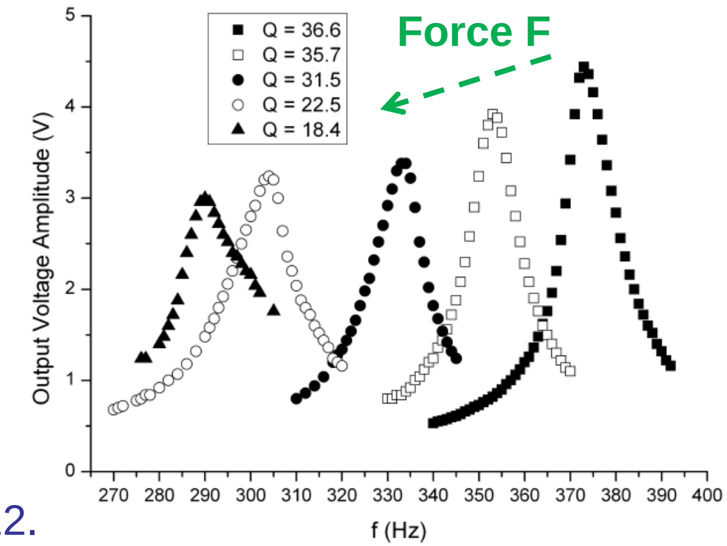
Frequency-tunable piezo generator





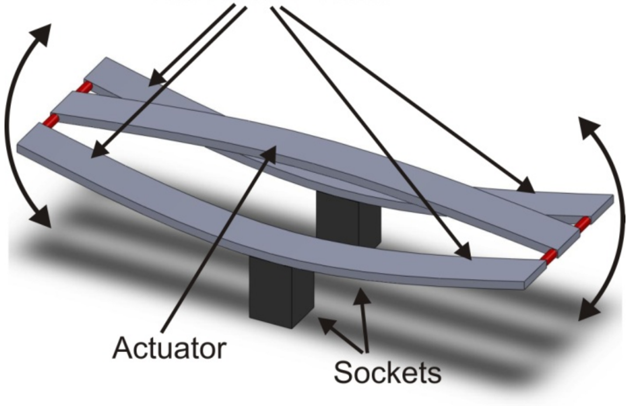
Principle of „stress tuning“

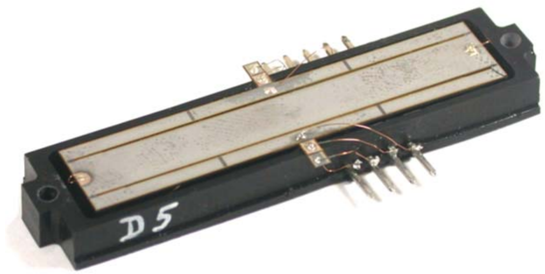
- Actuation force in the „arms“ will stiffen the resonating beam and thus change its resonance frequency
  - ➡ ***high tuning range (22%)***
  - ➡ ***loss of Q factor with increasing force***

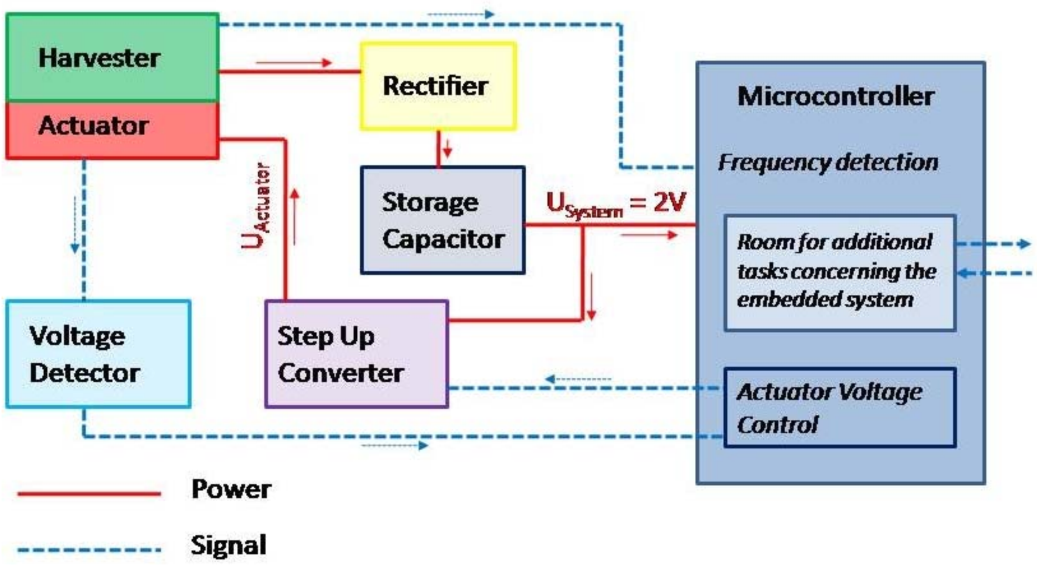


C. Eichhorn *et al.*, *Proc. PowerMEMS 2008*, 309-312.

Frequency-tunable generator system







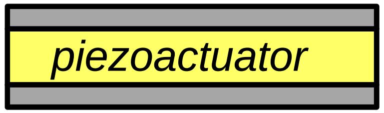
C. Eichhorn *et al.*, *Proc. PowerMEMS 2010*, 207-210.

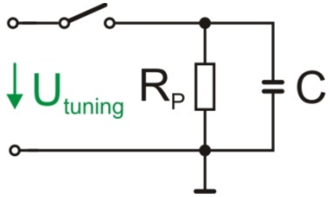
Fundamental questions

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

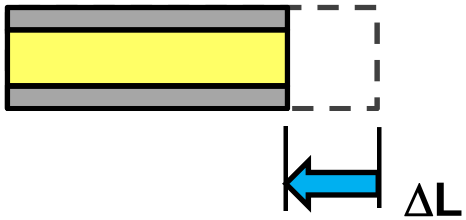
Quasi-static tuning of piezoactuators

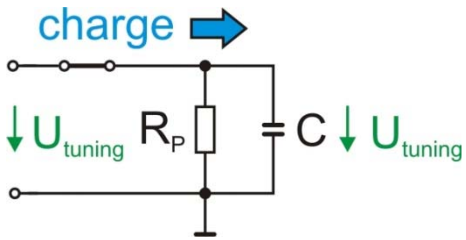
1. untuned



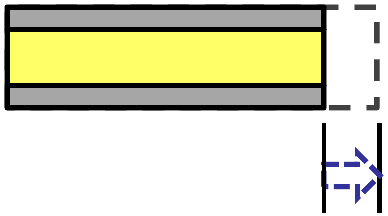


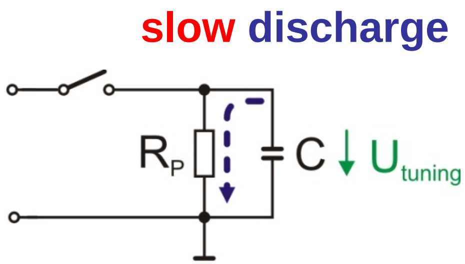
2. fast tuning



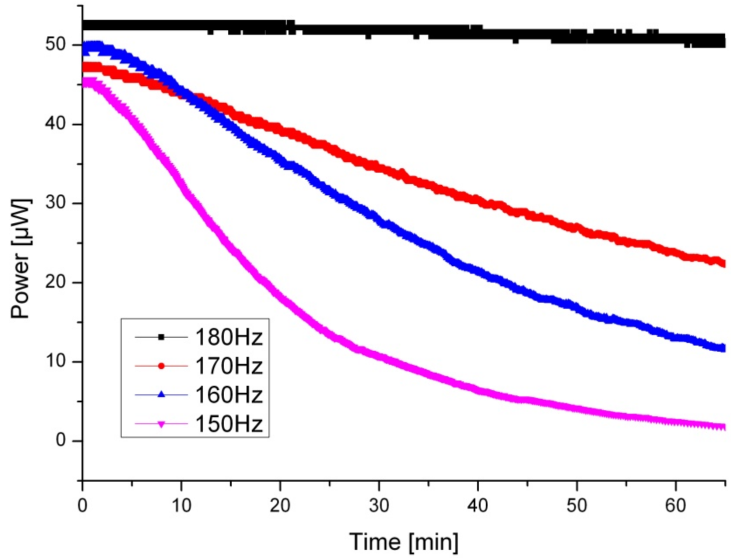


3. **slow relaxation**





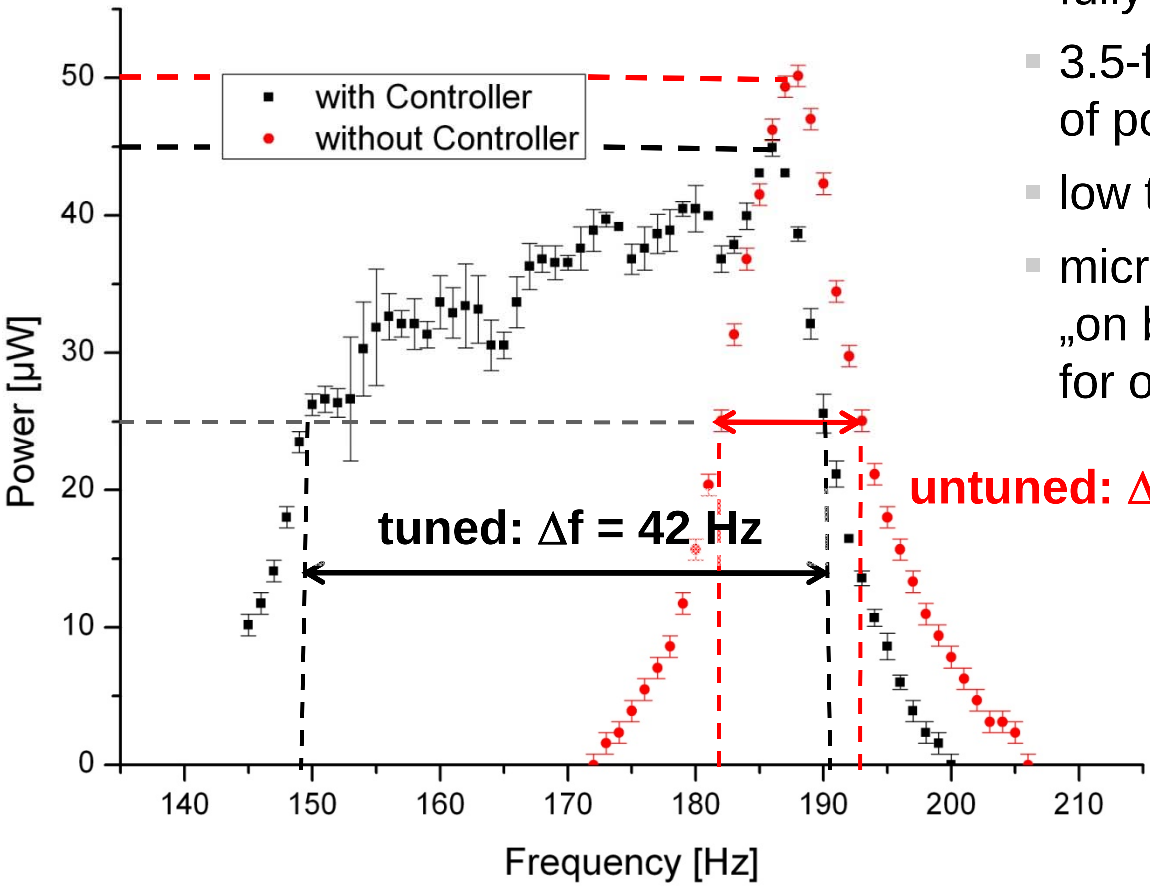
effect of relaxation on the harvested power vs. time



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 Δf
- low tuning power (5…25 µW)
- microcontroller already „on board“, can be used for other purposes as well

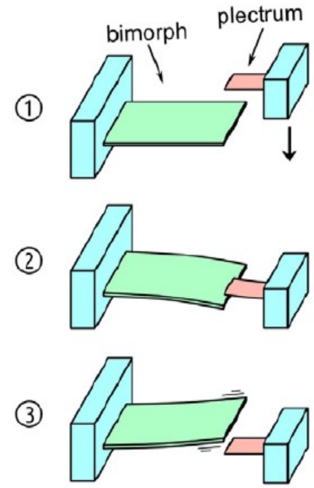
output power in tuned and un-tuned operation (tuning intervals: 20 s, acceleration: 0.6 G)

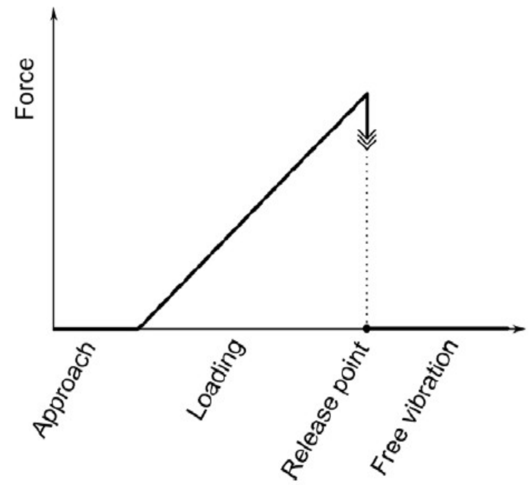
C. Eichhorn *et al.*, *Proc. PowerMEMS 2010*, 207-210.

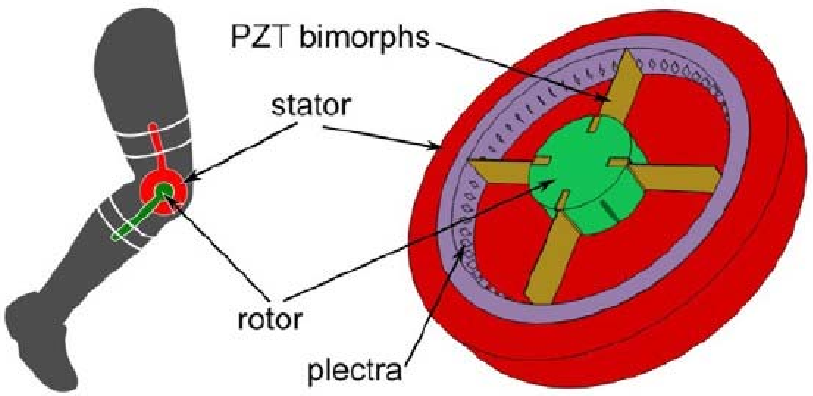
Plucking-type piezogenerators

Example: Knee-joint harvester

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



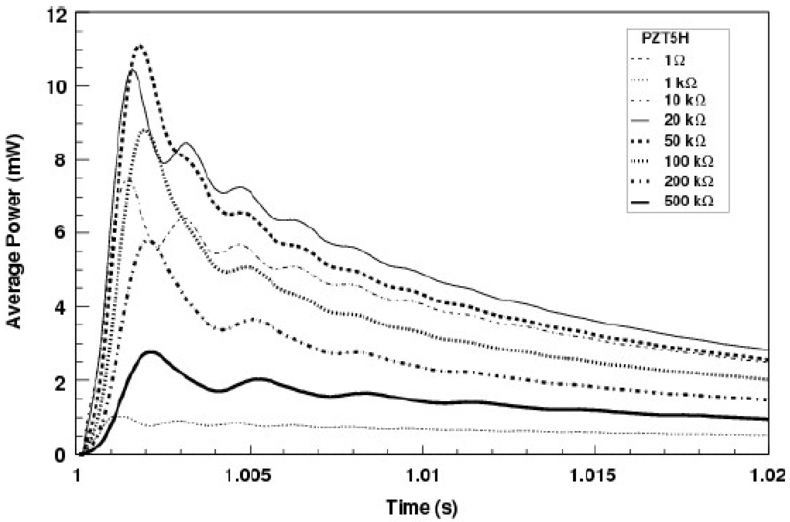




M. Pozzi, M. Zhu,
Smart Mater. Struct. 20, 2011, 055007.

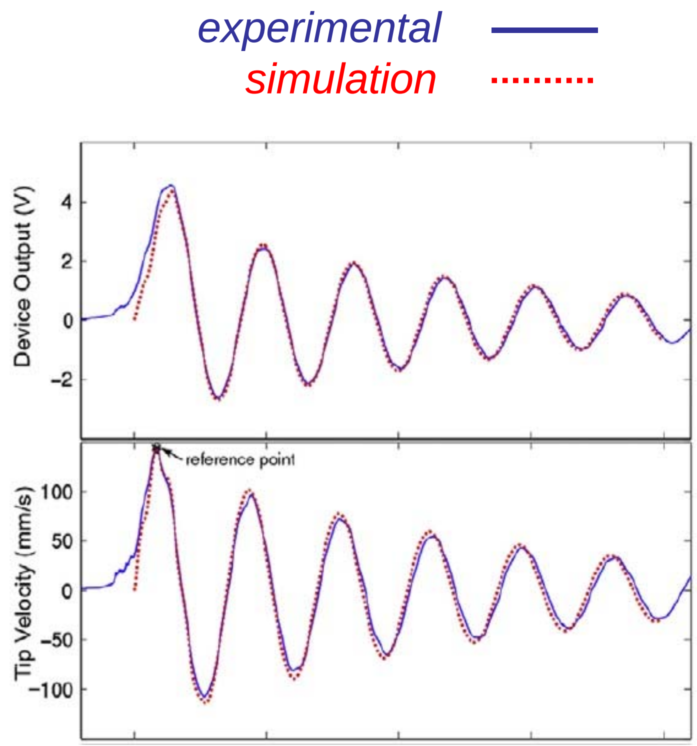
Plucking-type piezogenerators

Knee-joint harvester: output voltage and output power



calculated output power during one plucking event (averaged values)

M. Pozzi, M. Zhu,
Smart Mater. Struct. 20, 2011, 055007



simulated and measured tip displacement and output voltage

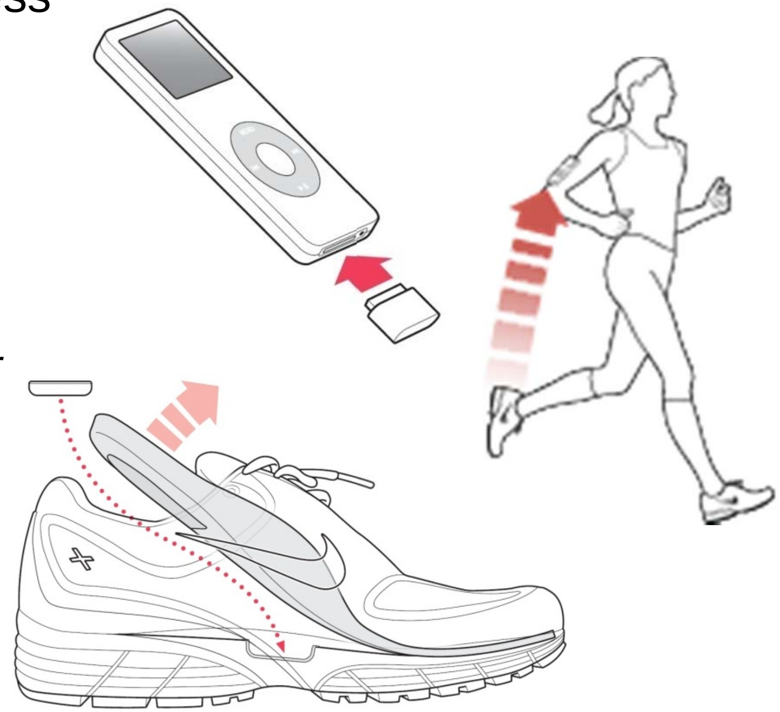
Energy-autonomous pedometers

Battery-powered pedometer: example Nike+

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

receiver

sensor



Drawbacks

- completely encapsulated sensor
- no battery exchange is **possible**

➡ limited lifetime

➡ sensor with empty battery = waste

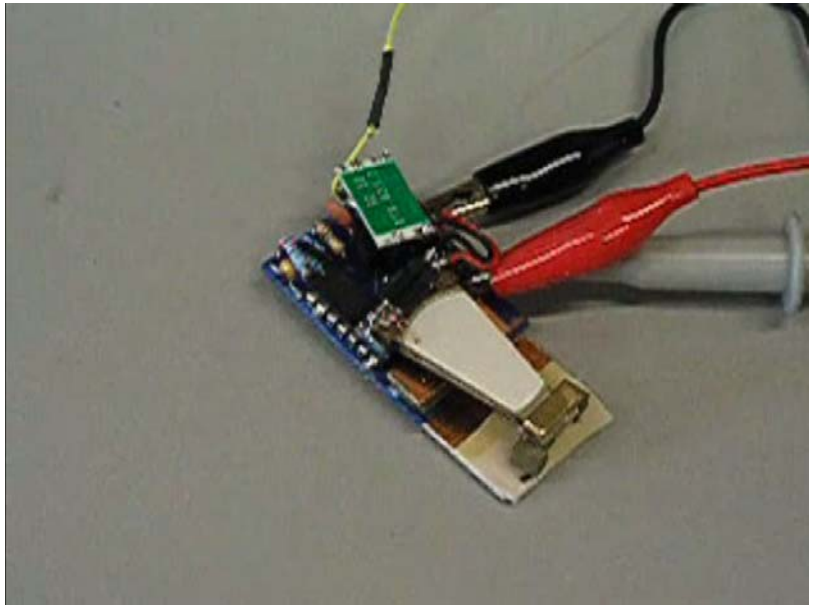
➡ **energy-autonomous alternative ?**

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

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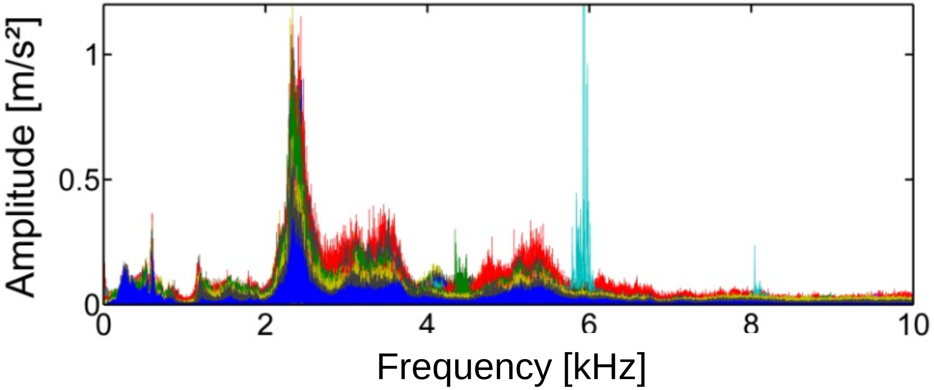
Harvesting from vibrations at the rail

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 concret rail sleeper, measured in the Arlberg tunnel, Austria

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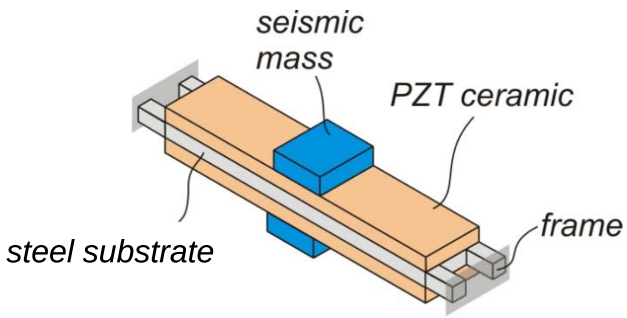
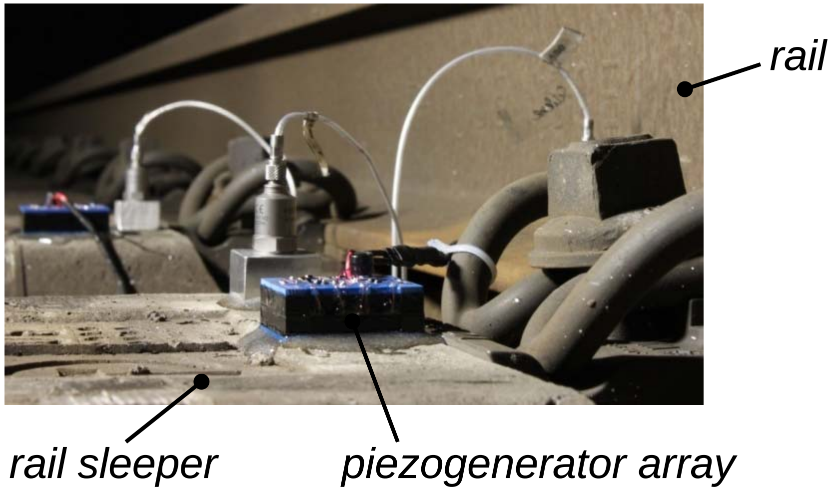
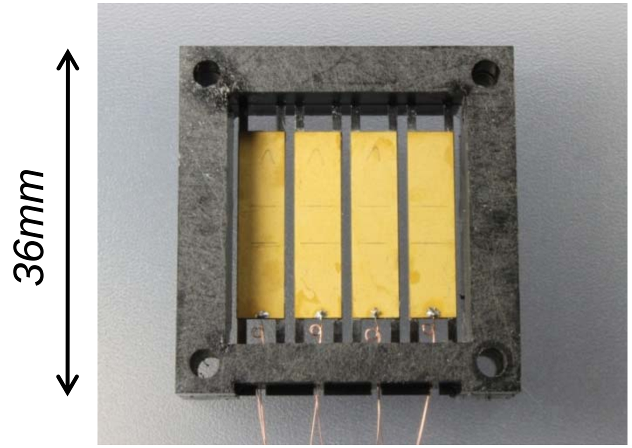
Harvesting from vibrations at the rail

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)







piezogenerator array (without seismic masses)

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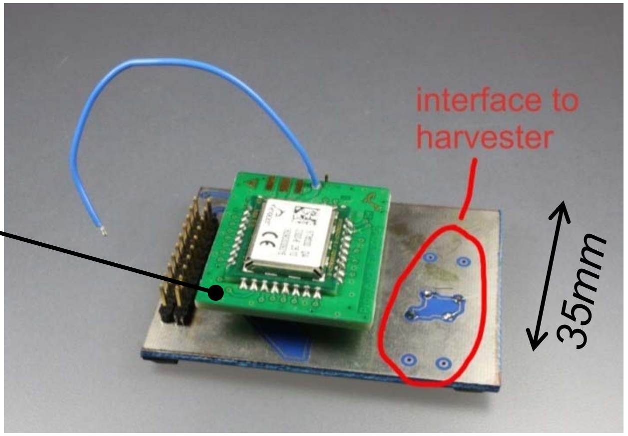
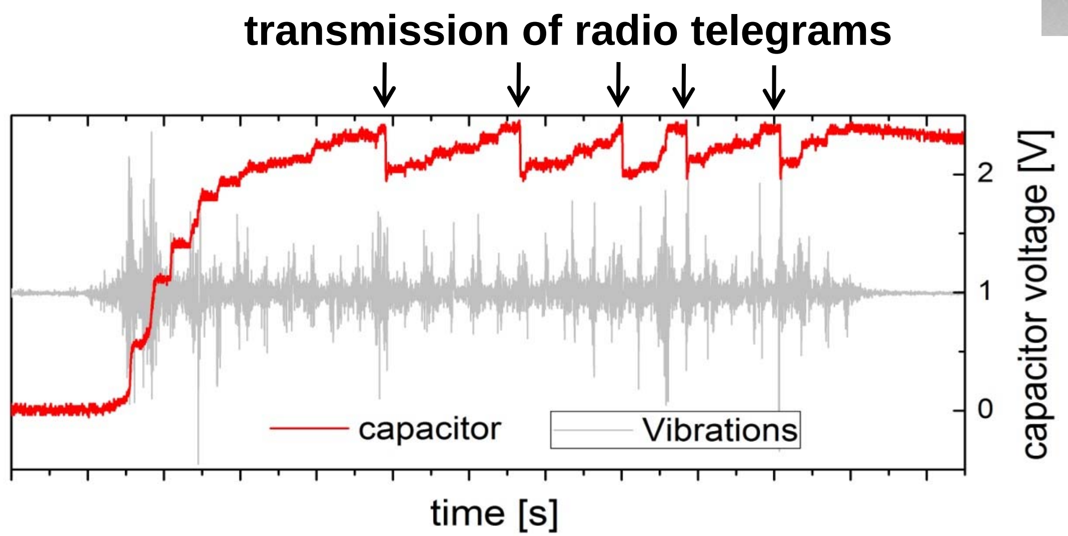
Harvesting from vibrations at the rail

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



energy-autonomous train passage detector



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