SYSTEM DESIGN OF A PIEZOELECTRIC MEMS ENERGY HARVESTING MODULE BASED ON PULSED MECHANICAL EXCITATION

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Abstract: In this paper we describe the system design of a piezoelectric MEMS energy harvesting module based on analytical modeling. The application example of a wireless sensor node for tire condition monitoring is considered. Key specifications which are taken into account are the power budget for the system operation, the system mass and the area consumption. System considerations comprise the generator design, material impact and the generator interface circuitry. A design procedure is presented, which allows identifying a geometry design space for the piezoelectric microgenerator consistent with required boundary conditions and specifications.

Keywords: energy harvesting, piezoelectric, microgenerator, MEMS, non-resonant, system design, TPMS

INTRODUCTION

Energy harvesting systems have been under continuous research. There are various possible energy sources to be used for a large variety of application scenarios. Here, we consider a piezoelectric based generator principle to power an automotive wireless sensor node used for tire pressure monitoring.

Conventional tire pressure monitoring systems (TPMS) are powered by battery and are mounted on the wheel rim as shown in Fig. 1.

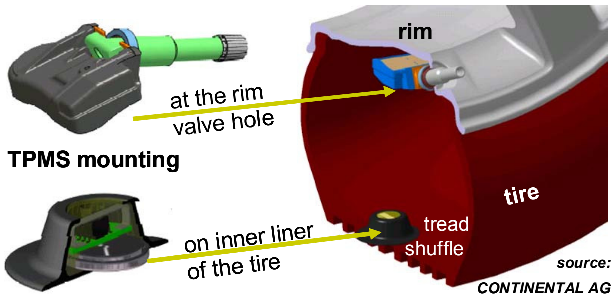


Fig. 1: TPMS mounting options: (1) at the rim (2) on the inner liner of the tire [1].

An alternative assembly of the monitoring system on the inner liner of the tire (cf. Fig. 1) would allow for the detection of a number of additional parameters. Information about tire temperature, friction, wearout and side slip could be used to optimize tracking and engine control. However, the innovative approach sets sever boundary conditions for system implementation:

- Robustness against high magnitudes of gravitational acceleration (up to *2500 g*).
- Maximum system weight below *7 grams* to avoid tire unbalance.
- Minimum life time of *8 years*.

In particular a combination of the last two items is difficult to fulfil with a battery based approach and make an energy harvesting implementation favourable.

In this paper we describe the system design of such a piezoelectric MEMS energy harvesting module based on analytical modeling.

SYSTEM DESIGN

Requirements

In the addressed tire environment a large dynamic range of force occurs for a given seismic mass. The acceleration is in the range of some ten up to some thousand units of gravitational acceleration. Therefore, a conventional spring-loaded cantilever design [2] with a mass even in the gram-range is critical.

Considering the generator excitation, there is no stable frequency spectrum available. Therefore, the conventional concept of tapping the environmental mechanical energy by stimulating the generators seismic mass with an acceleration field at the resonant frequency is not suitable. Alternative generator concepts have to be developed, which exhibit a minimum mass and are operated with a non-resonant excitation scheme.

In order to replace the battery, the harvesting module should have comparable area consumption of less than $100\ mm^2$. Finally, considering the power consumption of the pressure sensor, microcontroller and RF-frontend a minimum average power of $3\ \mu W$ is required to send data every *60 seconds*.

System Components

The design of a miniaturized piezoelectric power module requires a system approach. In Fig. 2 the system components are schematically shown. The generator stack consisting of a piezoelectric thin film on a carrier layer establishes a mechanical spring (for more details cf. generator section). An external excitation force is used to load this spring with mechanical energy. This process is combined with creating a mechanical stress within the layer stack. The stress within the piezoelectric layer is transformed into a piezo-voltage V_p and an according electrical energy $E_{e,p}$. The efficiency of this process depends on the piezo material properties: charge constant d_{31}, compliance constant s_{p11} and permittivity ε_{33}. The indices result from the perpendicular orientation of the polarization with respect to the exploited stress. The primary energy is processed by an interface circuit in order to rectify the voltage and to adjust the magnitude to V_{DC}. Depending on the used circuit scheme this transfer consumes a considerable amount of energy and has to be taken into account for the system design. The energy stored in the buffer capacitance C_b can be consumed by the load R_{load}.

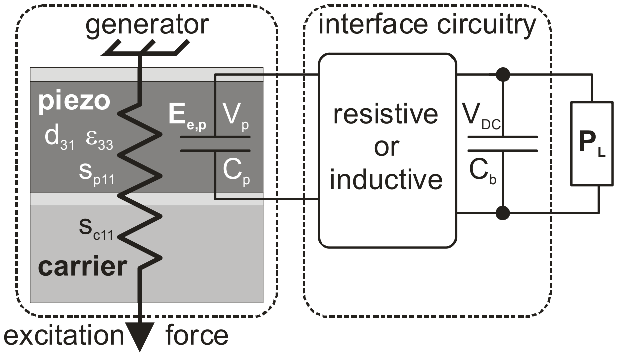


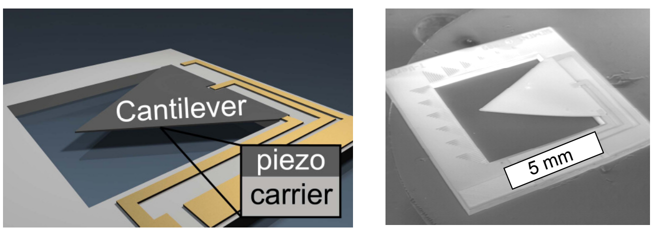
Fig. 2: System components of the piezoelectric energy harvesting module. The generated electrical energy $E_{e,p}$ is provided through the interface circuit as load power P_L.

Generator

To address the requirements defined above we use a piezoelectric MEMS cantilever concept as shown in Fig. 3. The cantilever consists of a silicon carrier layer and a self-polarized piezoelectric PZT thin film layer realized with a MEMS compatible sputtering technology (for process details cf. [3, 4]).

The carrier layer serves three purposes: it provides mechanical stability of the structure, it contains the neutral axis and it is used as a storage element for the harvested mechanical energy.

The generator has a triangular shape to realize a uniform stress distribution and therefore a maximum amount of harvested energy per active piezoelectric area [4, 5]. The geometry of the generator is completely defined by three parameters: area (some ten mm^2), carrier thickness (some ten µm) and the piezoelectric layer thickness (some µm). Designing the MEMS generator actually means finding suitable values for these parameters for a given carrier and piezoelectric material. We use an analytical system model for this purpose as described below.



a) *b)*

Fig. 3: MEMS piezo cantilever generator: a) device schematic showing the triangular cantilever consisting of the piezoelectric and carrier layer, b) SEM photograph of a realized test structure.

The chosen MEMS generator approach minimizes the seismic mass of the generator. The intrinsic mass of the cantilever is in the microgram region and the resulting acceleration forces are very small even in case of the tire environment.

For the energy transfer from the environment to the generator we suggest a non-resonant excitation scheme. Deformation forces during the period of tread shuffle (cf. Fig 1) passage are to be used for a pulsed excitation of the generator. Thereby, the cantilever starts oscillating. During each oscillation electric energy can be extracted by the interface circuit. The cantilever amplitude decays exponentially until it gets excited again. The principal behavior can be seen from the measured data shown in Fig. 4.

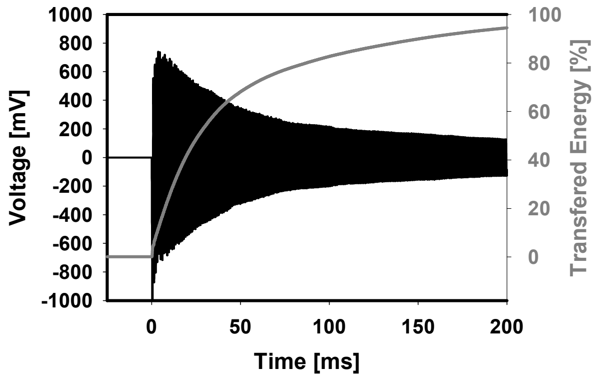


Fig. 4: Pulsed excitation of MEMS generator structure according to Fig. 3. At t = 0 the cantilever is loaded with external mechanical energy. The black line shows the measured transient behavior of the generated voltage and the gray line indicates the amount of transferred energy over time.

Interface Circuitry

The interface circuitry has to rectify the generator voltage. The rectification can be done passively with diodes or actively by controlled switches.

In order to transfer the primary energy from the piezoelectric capacitance C_0 into the buffer capacitance C_b, the elements have to be electrically connected for some period of time. A crucial system design issue is the decision whether or not to use an inductive element for that purpose.

If the connection is established by a resistive path, as realized for example in [6], an external inductor and related costs and additional weight are avoided. In this case the best operation condition is achieved by keeping the buffer capacitance voltage V_{DC} at half the magnitude of the open circuit piezoelectric voltage. At maximum a quarter of the energy harvested at the piezoelectric element can be transferred to the buffer.

By using an inductive interface scheme, as implemented for example in [7, 8], the complete energy can be transferred theoretically. The costs related to the external inductor can be compensated by reducing the MEMS generator area in that case. Therefore, the decision about the interface scheme requires a system model to investigate the tradeoffs.

SYSTEM MODELING

Analytical System Model

There are powerful simulation tools available for the individual component design. Typically, *FEM* is used to model the MEMS generator and *Spice* is suitable to simulate the interface circuitry. However, there are no well established general interfaces between the two modeling domains to perform a system simulation. In this work we use an analytical approach to gain system level inside and to address the items motivated in previous sections.

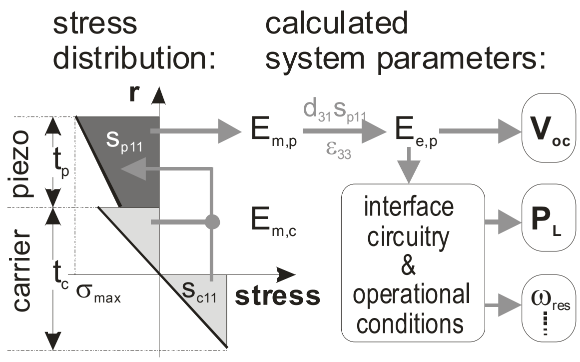
In Fig. 5 the used calculation scheme is sketched. According to the cantilever geometry we assume a uniform stress distribution for the in plane direction. For the perpendicular direction we calculate the stress distribution consistent with maximum values for either the piezoelectric or the carrier layer. Based on that information the mechanical energy in the piezoelectric layer can be calculated [9]:

$$(1)\quad E_{m,p} = \frac{A_g \cdot s_{p11}}{2} \cdot \int_{r_{\min}}^{r_{\max}} \sigma_r^2(r) \cdot dr$$

with A_g being the generator area and σ_r the stress in radial direction. For one oscillation cycle the electrical energy is determined from [9]:

$$(2)\quad E_{e,p} = E_{m,p} \cdot \frac{d_{31}^2}{\varepsilon_p \cdot s_{p11}} = A_g \cdot \frac{d_{31}^2}{2\varepsilon_p} \cdot \int_{r_{\min}}^{r_{\max}} \sigma_r^2(r) \cdot dr$$

The open circuit voltage is directly calculated from this energy considering the piezoelectric capacitance (cf. Fig. 2). For the transformation of the piezoelectric energy into a load power the operational conditions (e.g. rotation speed) and the utilized interface circuit scheme are taken into account.

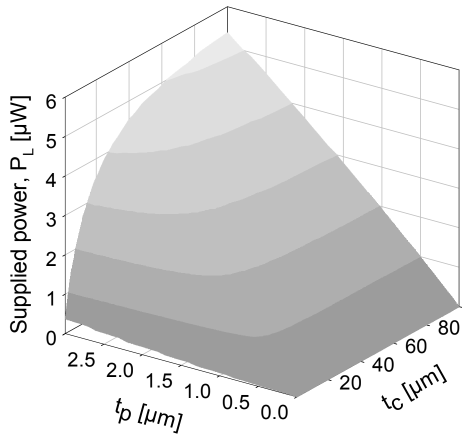


t_p thickness of piezoelectric layer
t_c thickness of carrier layer
s_{p11} compliance constant of piezoelectric layer
s_{c11} compliance constant of carrier layer
σ_{max} maximum allowed stress
d_{31} piezoelectric charge constant
ε_{33} permittivity of piezoelectric layer
$E_{m,p}$ mechanical energy in piezo layer
$E_{m,c}$ mechanical energy in carrier layer
$E_{e,p}$ generated electrical energy (cf. Fig. 2)
P_L power supplied to load (cf. Fig. 2)
V_{oc} open circuit voltage
ω_{res} resonance frequency of cantilever beam

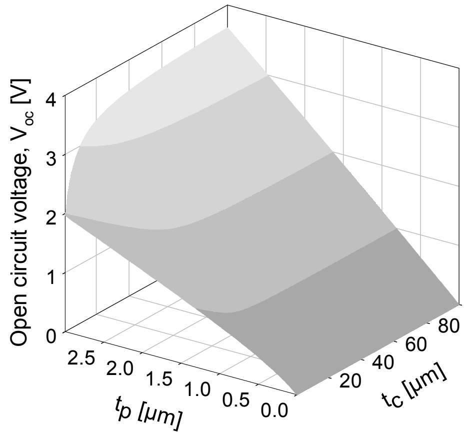
Fig. 5: Calculation scheme for the modeling.

Modeling Results

Based on the analytical modeling we calculate relevant system quantities like the supplied power, the open circuit generator voltage or the resonant frequency of the cantilever structure as a function of the geometrical design parameters of the MEMS generator. Examples of calculation results are shown in Fig. 6. Using a fixed value for the generator area the quantities are plotted over the carrier layer thickness t_c and the dimension of the piezoelectric film t_p.



a)



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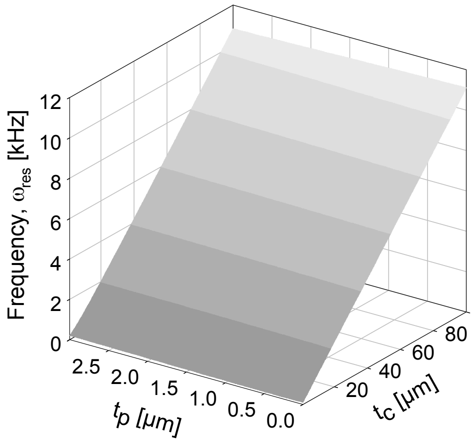

c)

Fig. 6: Examples for calculated system parameters: power, voltage and natural frequency, displayed over the geometry design space (area is fixed to 25 mm²).

The results are utilized to identify a design space consistent with the given boundary conditions. Fig. 7 shows an example. A minimum load power of *3 µW*, a minimum open circuit voltage of *1.5 V* and a maximum resonant frequency of *10 kHz* are specified here. For a given generator area (*25 mm^2*) system parameter contour lines are plotted over the geometrical design space of the layer thicknesses. The black line represents the *3 µW* contour in case of a resistive interface scheme, while the gray line provides this information in case of an inductive scheme. The dashed black line indicates layer thickness combinations, which provide an open circuit voltage of *1.5 V*. Finally, also a contour for the required maximum resonant frequency is calculated. Based on the contour lines suitable regions are given by the shaded regions.

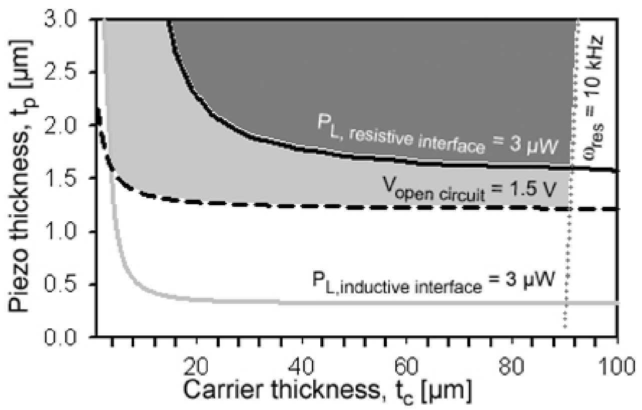

Fig. 7: System parameter contour lines on generator design space. Resistive interface schemes require geometries in dark grey area. Requiring a minimum open circuit voltage of 1.5 V the inductive interface schemes allow for additional design space in the light grey region.

CONCLUSION

A system design approach for a piezoelectric MEMS energy harvesting module was presented. The example of an energy autonomous TPMS application was considered. The realized generator implementation allows for unique features like a seismic mass in the microgram-range and a pulsed excitation scheme. The crucial impact of the interface circuitry scheme on the system design was discussed. An analytical system model was developed and utilized to identify a generator geometry design space consistent with given boundary conditions.

Based on the modeling results we conclude the feasibility of a piezoelectric energy harvesting module for a TMPS wireless sensor node with an average power consumption of *3 µW*. Using an active piezo area of 25 mm^2 and some micrometer thickness is sufficient to generate this power. For the considered PZT piezoelectric thin film, a CMOS compatible voltage level in the volt range can be provided.

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