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FLUID-STRUCTURE INTERACTION MODELING FOR AN OPTIMIZED DESIGN OF A PIEZOELECTRIC ENERGY HARVESTING MEMS GENERATOR

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ABSTRACT

In this paper we consider a piezoelectric energy harvesting module for a tire based wireless sensor node application. A dedicated MEMS harvester operated with a non-resonant excitation scheme is proposed. In context with this novel operation scheme, dissipative damping mechanisms have to be taken into account for the MEMS design. In this work we investigate the fluid-structure interaction of the energy harvesting MEMS generator with the surrounding gas. According to the design requirements, a COMSOL simulation setup is described. Simulation results are presented and discussed with respect to experimental results.

KEYWORDS

energy harvesting, piezoelectric, microgenerator, fluid-structure interaction, MEMS, non-resonant, 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.

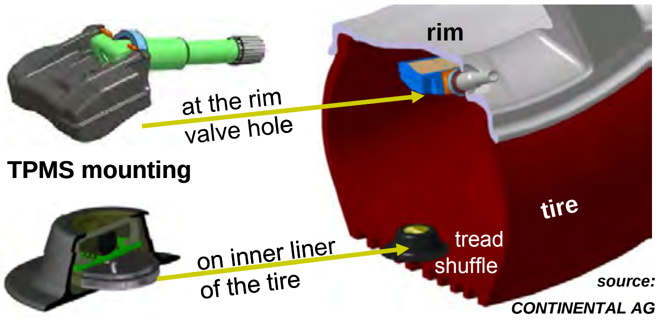


Fig. 1: TPMS mounting options: (1) at the rim, (2) on the inner liner of the tire [1].

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 severe requirements for the system implementation:

- Robustness regarding 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 the combination of the last two items is difficult to fulfil with a battery based approach and makes an energy harvesting MEMS implementation favourable. In this paper we describe a suitable MEMS device and focus on the investigation of the energy harvesting MEMS generator with the surrounding gas.

MEMS HARVESTING DEVICE

Requirements

In the addressed tire environment large dynamic ranges of different forces (e.g. centrifugal force) occur for a given seismic mass. The centrifugal acceleration is in the range of some ten up to some thousand units of gravitational acceleration. Therefore, a conventional seismic mass loaded cantilever design [2] even in the gram-range is critical.

Considering the generator excitation, there is no stable frequency spectrum available within the tire environment. Therefore, the conventional concept of energy harvesting 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.

Generator Design

To address the requirements defined above we use a piezoelectric MEMS cantilever concept as shown in Fig. 2. 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, 6]. 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 COMSOL Multiphysics to investigate various aspects which enter into the design. In this paper we focus on modeling the fluid-structure interaction of the energy harvesting MEMS generator with the surrounding gas.

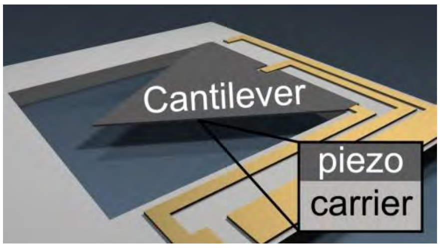


Fig. 2: Piezoelectric MEMS harvester schematic [6].

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. Tire related forces during the period of tread shuffle passage (cf. Fig. 1) are to be used for a pulsed excitation of the generator. Thereby, the cantilever starts oscillating and electric energy can be extracted with a suitable interface circuit [7, 8, 9]. The cantilever amplitude decays exponentially until it gets excited again.

FLUID-STRUCTURE INTERACTION

Motivation

The exponential decay of the mechanical generator displacement amplitude results from two types of principle damping mechanisms.

The first is the electrical damping (quality factor Q_{el}) related to the electrical energy extraction from the generator. This mechanism should be maximized by appropriate material design and by using a high efficiency interface circuitry [7, 8, 9].

The second damping type is related to dissipative mechanisms (Q_{dis}) as internal material losses (Q_{mech}) and air damping (Q_{air}) of the generator cantilever. For good system efficiency this damping should be minimized.

We use the COMSOL Multiphysics Fluid-Structure Interaction (FSI) interface to investigate the dependency of Q_{air} on the cantilever geometry (shape, area, thickness) and air pressure.

COMSOL Modeling

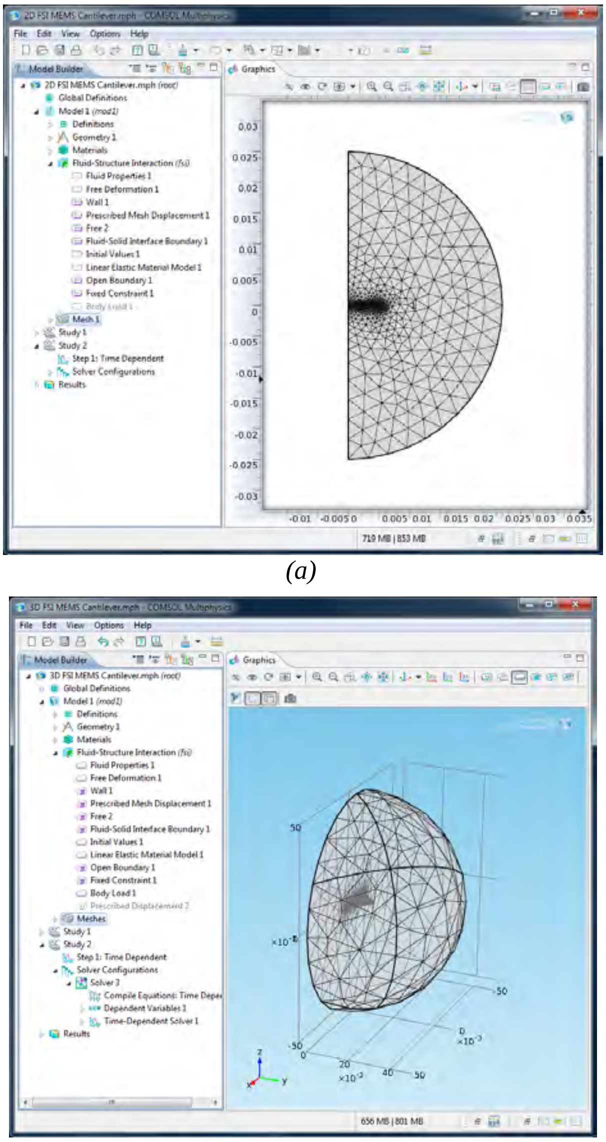
COMSOL Multiphysics„ FSI interface allows the coupled solving of time-dependent structural deformations and fluid flow variables (velocity and pressure) in a moving mesh geometry consisting of a solid deformable object surrounded by a fluid (liquid or gas). The viscous forces and fluid pressure impose forces on the surface of the solid object causing mechanical deformations. In turn, the mechanical deformation influences the fluid flow characteristics. In this type of mutual interaction, the model geometry changes in a dynamic way.

In terms of modeling, the choice of solid and fluid domains will automatically create the FSI boundaries setting up the force definitions, the fluid flow definitions as well as the moving mesh definitions.

The physics describing the FSI interface is that of the Navier-Stokes equations for the fluid flow and that of linear elastic material equations for the structural mechanics. The moving mesh functionality is that covered by the implementation of the ALE (arbitrary Lagrangian-Eulerian) technique.

At the geometrical interface between the fluid and the solid object the fluid‟s viscous forces will be predefined as a boundary load for the solid object. Vice versa, the time-dependent movement of the solid object will be predefined as a moving wall boundary condition for the fluid flow. The moving mesh method provides an additional coupling between the fluid flow and the structural mechanics such that a force transformation is possible between the fluid flow in the spatial geometry frame and the structural mechanics in the material (reference) frame.

Fig. 3 shows the 2D and 3D simulation setup with appropriate model settings. In a first step a stationary study is performed. The initial deformation of the solid object is simulated, by means of a Body Load.



(a)

(b)

Fig. 3: COMSOL Multiphysics Fluid-Structure Interaction: (a) 2D and (b) 3D simulation setup.

The result of the stationary study is the starting point, in terms of initial values, for a subsequent time-dependent study of the vibration effects in the FSI geometry. Further essential model settings include:

- Compressible flow (Ma < 0.3).
- No turbulence.
- Geometric nonlinearity included in the *Linear Elastic Material* definition.
- *Fixed Wall* (no slip) to which the deformable solid is attached.
- For remaining external boundaries: *Open Boundary* with normal stress condition.
- Specific manual scaling settings for the dependent variables in order to enable the efficient solution process for both the stationary and the time-dependent simulation.

Simulation Results

Based on the COMSOL FSI setup described in the previous section we first performed 2D simulations. Fig. 4 displays a typical result regarding the velocity magnitude of the gas surrounding a moving 2D cantilever structure. The picture visualizes the dissipative damping mechanism caused by feeding mechanical cantilever energy into disordered kinetic energy of the surrounding gas.

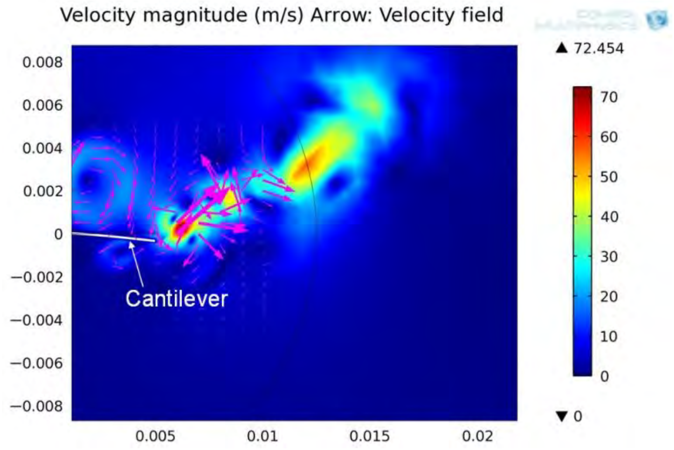


Fig. 4: 2D Fluid-Structure Interaction simulation of the moving cantilever within a surrounding gas.

To extract more quantitative results the cantilever deflection is considered in Fig. 5 as a function of carrier thickness. The different initial deflections for the various thicknesses result from a maximum stress requirement. E.g. increasing the thickness of the cantilever will reduce the maximum deflection amplitude consistent with a given maximum stress value. Q-values extracted from simulations of Fig. 5 are summarized in Tab. 1. Increasing the carrier thickness clearly improves the damping behavior of the MEMS harvester.

Table 1: Q-values extracted from 2D simulations of Fig. 5.

carrier thickness [µm]	50	95	250
Q-value	21.1	62.3	100.2

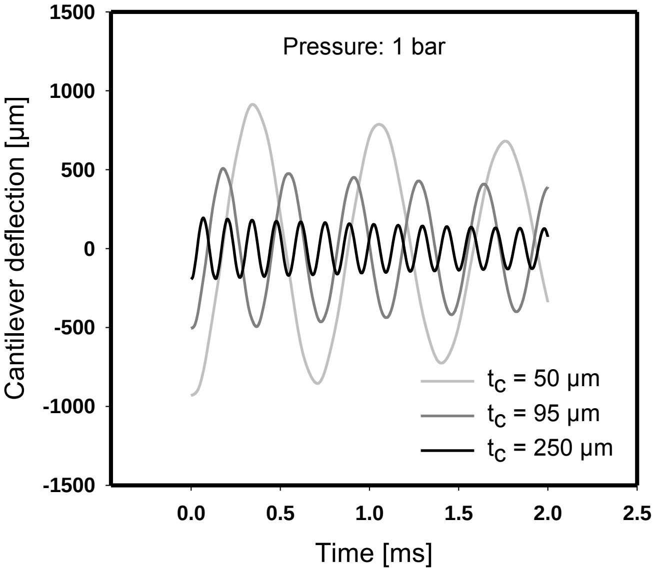


Fig. 5: 2D simulations of fluid-structure interaction at a gas pressure of 1 bar for varied carrier thickness.

In order to consider the triangular cantilever geometry as shown in Fig. 2 we had to perform 3D simulations. Fig. 6 displays the simulated transient cantilever deflection as a function of gas pressure. The results are summarized in Tab. 2. Increased air pressure results in an increased damping as expected.

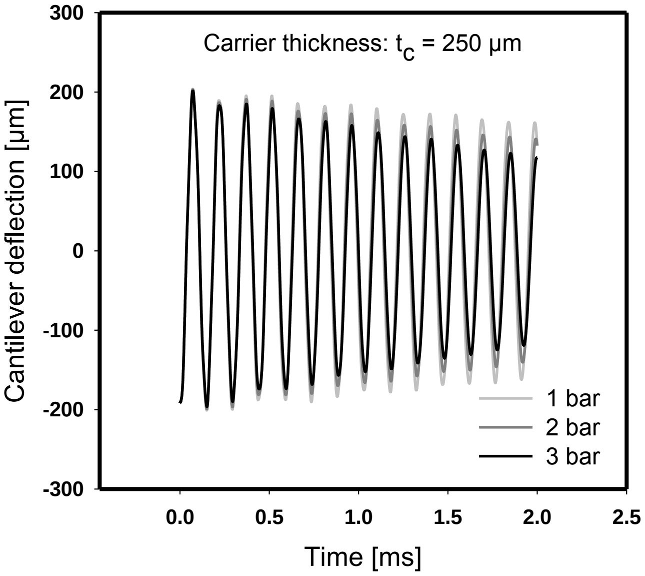


Fig. 6: 3D simulations of fluid-structure interaction for a carrier thickness of 250 µm as a function of gas pressure.

Table 2: Q-values extracted from 3D simulations of Fig. 6.

pressure [bar]	1	2	3
Q-value	188.8	114.6	78.0

EXPERIMENTAL RESULTS

In order to compare the simulated behavior with experiments we used the prototype piezoelectric MEMS energy harvesting module shown in Fig. 7. The cantilever was periodically excited and the generated piezoelectric voltage was recorded as shown in the example of Fig. 8.

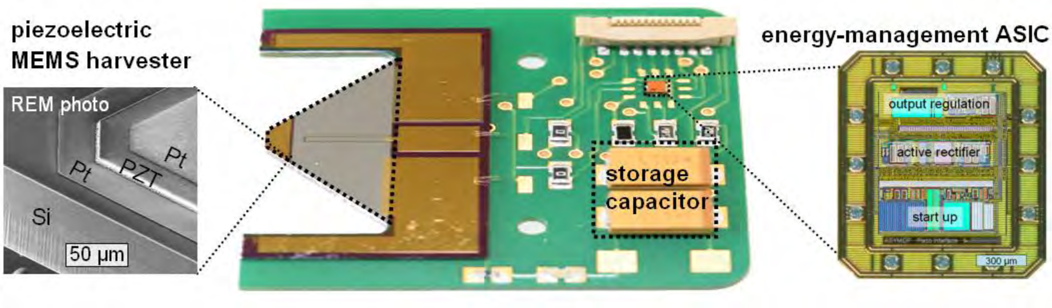


Fig. 7: Prototype piezoelectric MEMS energy harvesting module.

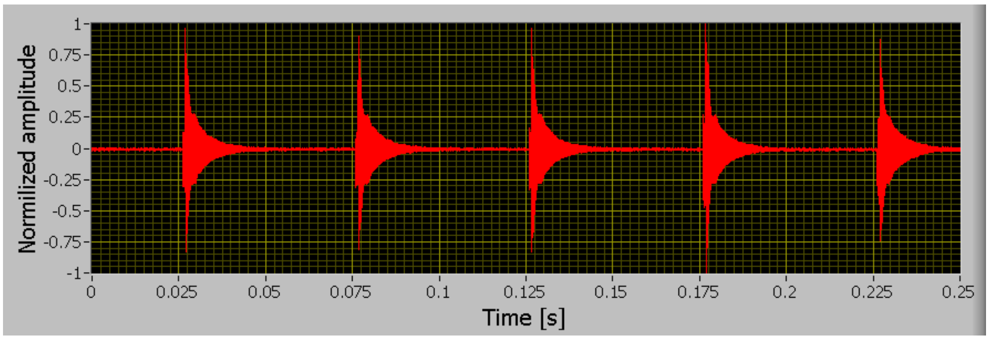


Fig. 8: Measurement result for a MEMS harvester with a carrier thickness of 250 µm carrier @ 1 bar. The experimental damping behavior is characterized by $Q_{meas} = 97$.

We find an experimental damping behavior characterized by $Q_{meas} = 97$. In order to explain the difference to the simulated value $Q_{sim} = 189$ (cf. Tab. 2) we have to assume an additional damping mechanism Q_a. Using the relation $1/Q_{meas} = 1/Q_{sim} + 1/Q_a$ we calculate $Q_a = 199$. Such a value can be attributed to internal material loss and/or clamping loss not yet considered in the simulation model.

CONCLUSION

Design aspects of a piezoelectric energy harvesting micro generator for an energy autonomous tire pressure monitoring wireless sensor node were discussed. The MEMS generator Q-value is identified as a critical design parameter.

We used a COMSOL Multiphysics Fluid-Structure Interaction application mode to investigate the impact of the surrounding air to the damping behavior of a MEMS cantilever energy harvester operated in a new kind of pulsed excitation operation mode.

The combination of the predefined FSI interface with the essential model settings has allowed the successful model development for the simulation of a strongly coupled FSI process including the effective damping of the FSI vibration.

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