Simulation of a Novel Bridge MEMS-PZT Energy Harvester for Tire Pressure System

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Abstract. Self-powering is becoming an important issue for autonomous sensor systems. By having an on-the-go power source the life span increases in comparison to a limited battery source. In this paper, simulation of an innovative design for a piezoelectric energy harvester for Tire Pressure Measurement System (TPMS) is presented. The MEMS-based thin-film PZT harvester structure is in the form of a bridge with a big central seismic mass and multiple electrodes. This design takes the advantage of the S-profile bending and a short beam length to concentrate the piezoelectric effect in a small segment along the beam and maximize the power output for a given displacement. From simulation in Comsol Multiphysics, the 9mm x 5mm bridge, seismic mass of 8.7mg and resonance frequency of 615Hz, generates 1 µW by mechanical pulses excitation equivalent to driving at 60 km/h (roughly 180G).

1. Introduction

Energy harvesting is the key enabling approach for design of future small self-powered wireless sensor systems. Such devices require often very little power, but without energy-harvesting, they are nevertheless limited by the limited lifetime provided by conventional batteries. Energy harvesting for automotive applications has been of great interest in recent years to power sensors such as Tire Pressure Monitoring System (TPMS) [1], Vehicle Speed Sensor (VSS), and Strain Monitoring Sensor (SMS) [2]. The TPMS system used today is not suitable for heavy vehicles with many tires requiring more accurate control of the actual pressure in every tire and communicate that information remotely to the information center computer in the vehicle. Therefore fully autonomous TPMS systems based on accurate Micro Electro Mechanical Systems (MEMS) sensors are required with a complemented energy supply.

Vibration piezoelectric energy harvesters convert mechanical strain into electrical energy and have received much attention due to the simple configuration and high conversion efficiency as comparing to electro-static and electromagnetic harvesters [3]. There is an abundance of vibration energy available in car tires that can be converted into electrical energy using energy harvester methods [4] for MEMS devices. Utilization of MEMS technologies allow for a totally integrated system containing sensor, electronics, communication and energy source. However, the scaling remains an issue and the unfavorable scaling of power with miniaturization is still a challenge.

2. Specifications MEMS PZT harvester

Most of the articles agree that a *constant* power of about 3µW is required [5] for the TPMS. For applications of non-constant power harvesting (e.g. mechanical pulses) a rechargeable battery or a
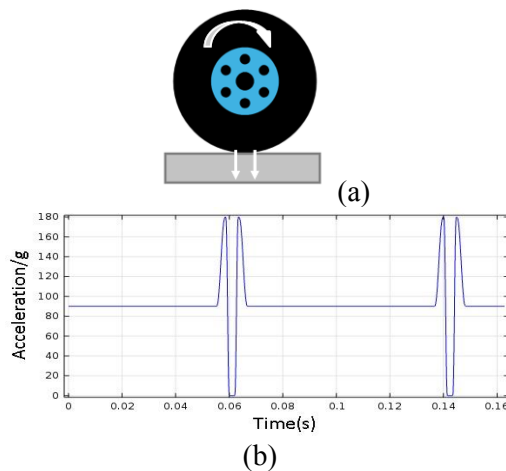
(a)

(b)

Figure 1. (a) Schematic of harvester placement at tire's inner liner, (b) Acceleration profile for 60km/h used in our simulations (calculated from [6]).
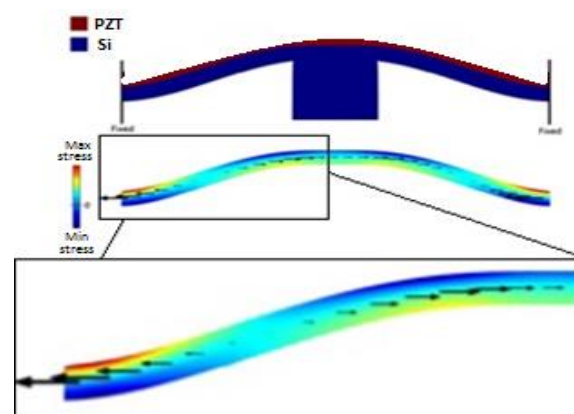
Figure 2. Schematic cross-section of bridge harvester structure showing the S-profile bending and strain (arrows) along the beam.

supercapacitor would be needed for collection of the converted energy. This is mainly for situations when the vehicle is stationary (traffic light, short parking, etc.) or at low speed whilst the tire pressure info is still needed. The current TPMS devices [6] have a weight of about 7g, a required lifetime of 8 years and it should withstand acceleration up to 2000g.

Two main vibration dynamics are applied on the harvester depending on its position on the tire. At the tire rim there are low amplitude and low frequency vibrations [7] while on the inner liner it consists of cyclic, high amplitude pulses / shocks [5]. The harvester structure (seismic mass) will respond to the mechanical pulses with decaying oscillations at its resonance frequency. During this relaxation, part of the mechanical energy is harvested.

Piezoelectric harvesters based on cantilever structure with rectangular or trapezoidal profile are the main design solutions proposed in the literature for TPMS. For these devices, d31 or d33 modes are employed [3, 7]. However, these designs cannot fulfil properly the application requirements as obtained from our simulations in Comsol Multiphysics (not shown here [8]). In order to find a suitable design, the power must be maximized while keeping the displacement of the vibrating structure within the MEMS cavity limits. We choose the inner liner as a suitable placing of harvester on the tire thus energy is harvested from mechanical pulse excitation. In Figure 1 the acceleration profile is presented (normalized g) at the inner liner of a standard tire diameter for a speed of 60km/h, calculated from [6] and used in the simulations giving a constant centripetal acceleration of 90g and a pulse width of 2.3ms.

The range of parameters utilized for the design which depend not only on TPMS requirements but also on the available MEMS fabrication technologies are shown in Table 1.

Table 1. Range of parameters utilized for our simulations.

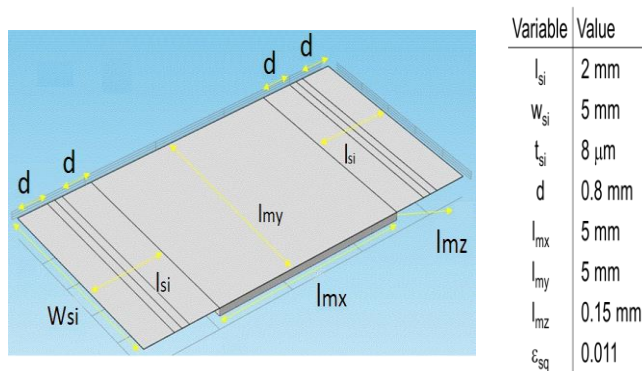| Parameter	Range	Parameter	Range
l_{si}	2 to 10 mm	l_{mz}	$\leq 400\mu m$
w_{si}	2 to 10 mm	e_{31}	-15 C/m^2
t_{si}	8,10,40 and 100μm	$\varepsilon_{r\,PZT}$	1200
t_{PZT}	1μm	Frequency	100-600Hz
l_{PZT}	0 to l_{si}	Cavity pressure	10^{-3}mBar
Cavity heigth	450μm		

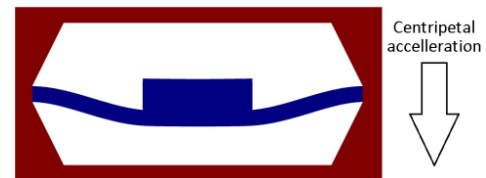**Figure 3.** Bridge design with final parameter values.

Figure 4. Proposed harvester position inside MEMS cavity.

3. Comsol simulations for MEMS PZT harvester

These solutions were implemented for the new design:

- Short beam with big seismic mass giving high stress localized in a small sections along the beam.
- Bridge structure gives S-profile during vibrations for displacement reduction and stress maximization.

By placement at the inner liner, we found the optimal resonance frequency of the bridge structure of 600Hz (oscillation period 1.6ms). This is the first key factor for inner liner harvester design.

Due to the strain profile of the bridge structure, shown in Figure 2, special solution for harvesting the generated electric field is required. Due to opposite strain (opposite generated voltage), the piezoelectric material has to be polarized in opposite direction during the fabrication process. This gives an electric field uniformly aligned in the whole beam. Alternatively, different electrodes can be placed over the different strain zones along the beam. These electrodes can be connected in parallel or in series, depending on which values of current and voltage is needed. Nevertheless, the total power output is always the sum of the power of each single part. High acceleration amplitude, due to high speed, means that the beam needs high stiffness otherwise the displacement would be too high and the vibrations will be limited by the cavity height. The displacement is the second key factor in the design.

Quality factor, Q, is the third key factor that is mainly due to the mechanical damping, in particular the squeeze film damping. To increase the oscillation time after the initial pulse, Q needs to be maximized which corresponds to a minimum squeeze film damping. These three key factors are mostly influenced by the same structural parameters, but with different effects. Thus a compromise is needed for an optimal design.

Transient analyses for various shapes and sizes of the bridge structure have been performed using the acceleration profile from Figure 1. The bridge design with the best performance is shown in Figure 3 with the parameter values while the bridge harvester encapsulation is shown Figure 4.

The stationary displacement for a constant input acceleration of 90g is roughly 60μm. The mounting of the harvester will have the mid mass towards the centre of the tire such that the stationary displacement due to centripetal acceleration makes the distance between cavity wall and seismic mass larger (Figure 4). The quality factor, which mainly depends on the squeeze film damping ζ_{sq}, is calculated using the equations in [9] and [10]. For this design we obtain Q= $\frac{1}{2\zeta_{sq}}$ = 45.8 and a resonance frequency at 614Hz with optimal load resistance of 1000 Ohm.

The simulated displacement and power output for 60km/h (Figure 5) show that the oscillations are contained within the limits of the cavity. For this moderate speed, the average oscillations are 60μm and an average power output of 1μW is obtained; the maximum displacement is around 160μm, with power output of 46μW. The extra energy can be stored in a rechargeable battery or in case of intelligent wireless sensors it is better on a supercapacitor [11] due to a much higher amount of energy density over time.
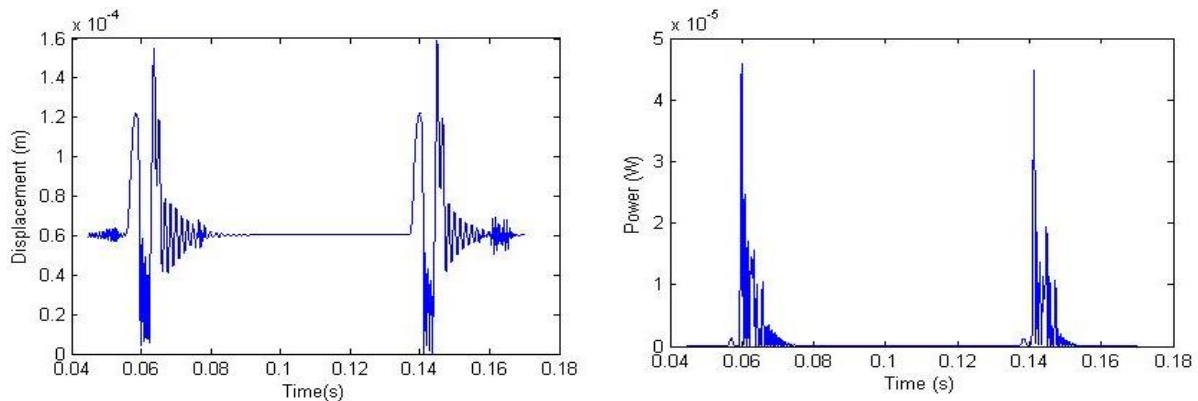
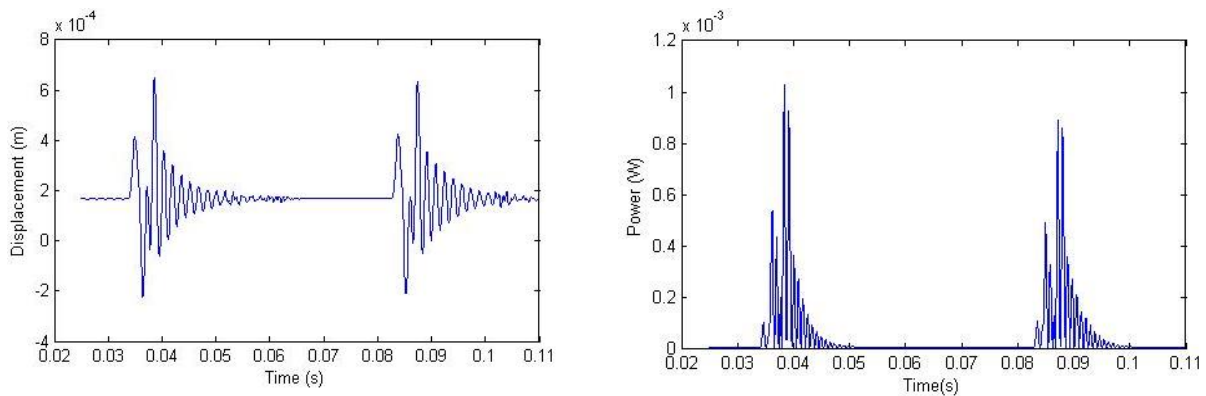**Figure 5.** Simulated displacement and power for the design in Figure 3 at a vehicle speed of 60km/h.

Figure 6. Simulated displacement and power for the design in Figure 3 at a vehicle speed of 96km/h.
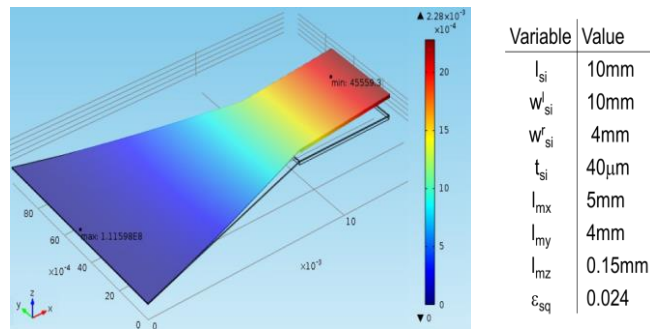
In our study we performed test also for high vehicle speed (96km/h), in this case the acceleration profile is the same as the one reported in [6]. The simulated displacement and power output for 96km/h are shown in Figure 6, the oscillation average is around 300µm resulting in an average power of 40µW. The peaks at 610µm for displacement generates 1mW power output; these are not taken into account, since this displacement is beyond the cavity wall and for the study we did not use any contact model between the mass and the wall. This means the results for 96km/h must be considered only as an approximation of the harvester behaviour for high speed; from these we can have an idea about the magnitude of displacement and power output.

After transient analyses we performed a static shock test simulation for information on the maximum stress developed in the structure. For this, a constant load of $10^5 g$ along the 3 coordinates was applied.

From [12] the fracture strength of Si is around 7GPa and we obtained maximum stress and displacement as shown in Table 2. The maximum displacement of the bridge allowed by the cavity is about 450µm and this would correspond to a static stress of 0.43GPa which is much lower than the Si fracture strength value. The same bridge structure presented in figure 3 was also studied for a continuous input vibration and compared with a similar in dimensions trapezoidal cantilever as in Figure 7. For 1m/s^2 a power of 3.9nW for the bridge and 8.4nW for the cantilever is obtained. In this case the power for the bridge is lower, but the displacement amplitude in the cantilever is 18µm while for the bridge it is only 0.65µm. The structure presented in this work (Figure 3) is optimized for mechanical pulses with high accelerations thus high stiffness. For 1m/s^2 and an optimized bridge design for continuous vibrations, the obtained power in the order of 150nW with displacement around 20µm. Thus the bridge structure has a performance 20 times higher than standard cantilever showing the advantages of this bridge design structure.

Table 2. Shock analysis for acceleration of 10000g

Direction	Stress [GPa]	Deflection
x	0.15	100μm
y	0.41	450μm
z	6.24	6.49mm

Variable	Value
l_{si}	10mm
w^l_{si}	10mm
w^r_{si}	4mm
t_{si}	40μm
l_{mx}	5mm
l_{my}	4mm
l_{mz}	0.15mm
ε_{sq}	0.024

Figure 7. Trapezoidal harvester simulated in comparison to bridge design.

4. Conclusion

The presented bridge design shows significant improvements in comparison to standard cantilever-based MEMS harvesters. All of the important requirements for a MEMS harvester for TPMS application are fulfilled in this design regarding MEMS-scale dimensions, power output above 1μW for medium / high car velocity, and withstanding accelerations of 10^5g. Further work is on MEMS harvester manufacturing and characterization for design validation.

Acknowledgements

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