FEM-Simulation of a 3D Acceleration Sensor with Self-sufficient Energy Supply

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Abstract: A piezo buzzer is usually used as a signaler, but it can also be used to convert mechanical into electrical energy.

In this work we investigate the conventional concept of energy harvesting by stimulating the buzzer with an acceleration. Finally, the piezo buzzer should operate as an acceleration sensor, where the harvested energy should power a small microprocessor, so that the complete sensor needs no external energy sources [1].

To be able to measure accelerations in any possible direction its design has to be optimized. In this paper a qualitative analysis according to the buzzer design requirements is shown using a COMSOL Multiphysics simulation setup. The numerical results are presented and discussed with respect to experimental results from measurements with the prototypes.

Keywords: piezoelectric, energy harvesting, sensor, low-cost

1. Introduction

Acceleration sensors are used in many applications today. One of those is the monitoring of transport processes. For this, the sensor has to detect an acceleration level and has to store any exceedance of acceleration limits. Usually acceleration loggers with a battery power supply are used for this purpose [2]. But they have the disadvantage of being limited in their logging and storage time.

In this paper an acceleration sensor structure is investigated by FEM simulations, which generates the energy for detection and storing of a shock-event by itself. This enables the sensor to work without any additional energy sources [1].

For the sensor element a piezo buzzer (see figure 1) should be used. It measures the acceleration level and also supplies the electronics with energy. The piezo buzzer consists of a piezoelectric lead zirconate titanate (PZT) layer glued on a brass plate. If an alternating voltage is connected to the brass and the piezoelectric material, the buzzer generates an acoustic signal. In this application the indirect piezoelectric effect is used. But the buzzer can also be used to convert mechanical into electrical energy by using the direct piezoelectric effect. If an acceleration influences the buzzer, the structure is bent by its mass and a voltage can be measured between the connection pads.

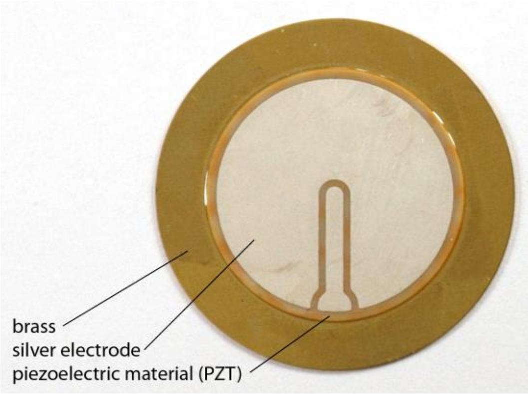

Figure 1. Piezo buzzer without connection wires.

An acceleration perpendicular to the buzzer orientation (z-axis, see Figure 2) generates a voltage, which is direct proportional to the acceleration. With a small additional mass mounted on the buzzer the occurring voltage, and this means the harvested electrical energy, becomes powerful enough to drive a small microprocessor to calculate the acceleration and store its value. Thus, the entire electrical energy needed is obtained only from the mechanical excitation and no additional energy sources are necessary.

Therefore, the sensor can „sleep" for a long time while waiting for an excitation. Thus an application where the buzzer is integrated in a package to supervise the transport, without any time restriction, becomes possible. Unfortunately, this simple sensor design is only able to measure the correct value of the acceleration in the direction perpendicular to its orientation. Experiments have shown that this simple sensor also detects accelerations in tangential directions. But in these cases the relationship between the occurring acceleration and voltage is not explicit [1].

To be able to measure accelerations in all possible directions the sensor design needs to be optimized. To keep the costs and the size of the sensor as low as possible the number of additional parts should be as small as possible. Different design modifications were tested according to the mentioned requirements, especially no additional piezo buzzers should be used.

2. Theoretical aspects

The direct piezoelectric effect refers the ability of some materials to change their electrical polarization when they are subjected to mechanical stresses. The change in polarization manifests as measurable voltages across the material. The reverse process, the indirect piezoelectric effect describes the deformation of the material when an electric field is applied [3]. The piezoelectric effect is described by two coupled equations in different forms. For example, in the strain-charge form, which is utilized in this study:

$$\boldsymbol{S} = \boldsymbol{s}^{\boldsymbol{E}}\boldsymbol{T} + \boldsymbol{d}\boldsymbol{E} \qquad (1)$$

$$\boldsymbol{D} = \boldsymbol{d}\boldsymbol{T} + \boldsymbol{\varepsilon}\boldsymbol{E} \qquad (2)$$

$\boldsymbol{T}$ and $\boldsymbol{S}$ are the stress and strain vectors. $\boldsymbol{E}$ is the electric field and $\boldsymbol{D}$ the electric displacement vector. $\boldsymbol{s}^{\boldsymbol{E}}$ is the elastic compliance tensor and ε^{T} represents the electric permittivity. $\boldsymbol{d}$ is the piezoelectric tensor with the piezoelectric coefficients. Only the three material properties $\boldsymbol{s}^{\boldsymbol{E}}$, ε and $\boldsymbol{d}$ are needed to describe the piezoelectric effect [4].

The piezoelectric effect is associated with noncentrosymmetric crystals. The positive and negative ions create an electric dipole as a result of stress.By default, the single dipoles, or regions of dipoles which are called domains are randomly orientated, i.e. a net polarization of zero. Within the poling process the material is subjected to a sufficiently high and static electric field that rotates the dipoles and orientates them permanently. The poled material now shows the direct and indirect piezoelectric effect.

PZT is a ceramic, piezoelectric material which is based on the perovskite structure. To date, it is one of the most widely used piezoelectric materials, together with barium titanate due to their very high piezoelectric and dielectric properties [4].

3. Use of COMSOL Multiphysics®

The simulation model is realized with the Piezoelectric Devices interface from the MEMS Module. The geometry is shown in figure 2. It is fixed on the outer edge of the brass plate, all other boundaries are free. As simplification for the excitation a static force acting on the end of the lever is used. Instead of an acceleration a well defined static force is easier to realize in the laboratory as well. Via comparison of experimental results with results of this simple simulation setup the piezoelectric coefficients from the unknown PZT were determined. This verification was made to simplify the simulation model as far as possible by neglecting manufacturing tolerances.

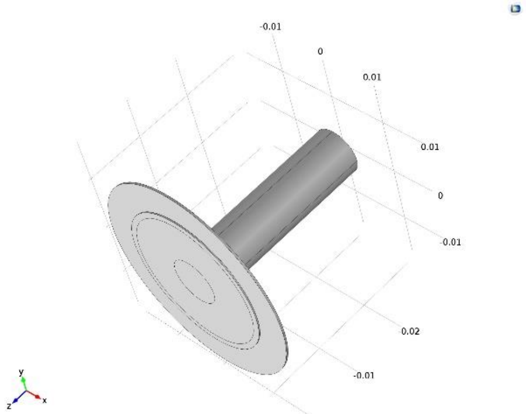

Figure 2. COMSOL model of the buzzer with a lever to bend the structure.

The experimental and numerical results are in good agreement so that the model shows in a comprehensible way how voltages arise in the piezo layer if a force bends the structure. The focus of the further investigations is on the qualitative behavior of the piezo buzzer for different design modifications.

In the final prototype the piezoelectric material is cut into four same sized areas. The numerical results for this “optimal” design are shown in figures 3, 4 and 5.

Sensor designs with less than four areas do not show the desired behavior, because they show a significant sensitivity drop for some directions of the force. Different lever forms, multiple levers or different PZT forms do not solve the problem too.

Figure 3 and 4 show the arising voltage distributions in case the force acts parallel to the buzzer orientation within the x-y-plane.

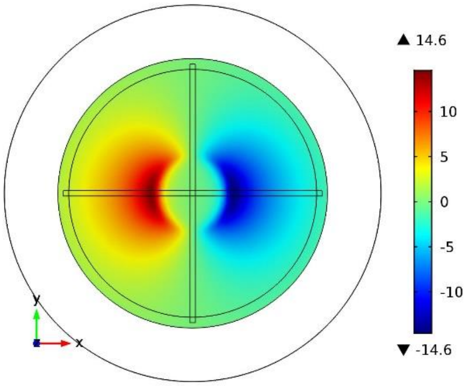

Figure 3. Arising voltage distribution when the force acts in direction of the x-axis.

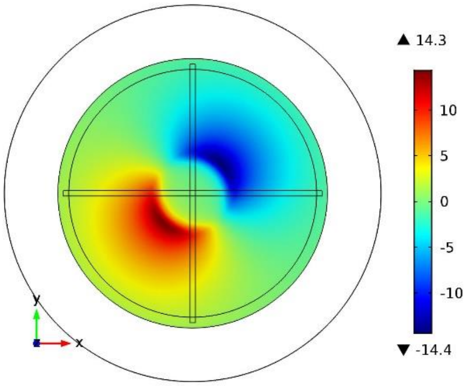

Figure 4. Arising voltage distribution when the force acts exactly between the x- and y-axis.

If the force acts parallel to one of the cuts, voltages can be measured in all four PZT areas (figure 3). The sum of the amount of the voltages is the maximum sensitivity of this design. The minimum sensitivity within the x-y-plane can be found, when the force acts directly between the two axes (figure 4). In this case only in two of the four areas voltages can be measured, because negative and positive voltages compensate each other in two areas. The corresponding minimum sensitivity is 70% of the maximum sensitivity. Between these two directions shown in the figures the sensitivity changes continuously from 100% to 70%. Figure 5 shows the voltage distribution if the force acts perpendicular to the buzzer orientation, i.e. in direction of the z-axis. In this case voltages in all four areas can be measured. The sensitivity in this case is important to optimize the length of the lever, because the arising voltage is independent of the length. To find the smallest sensor design the length of the lever should be as short as possible without losing sensitivity. The optimal length of the lever is found when the arising voltages caused by a force either parallel to one of the cuts or perpendicular to the buzzer are equal. In this case the sensor can be realized without downgrading the sensitivity.

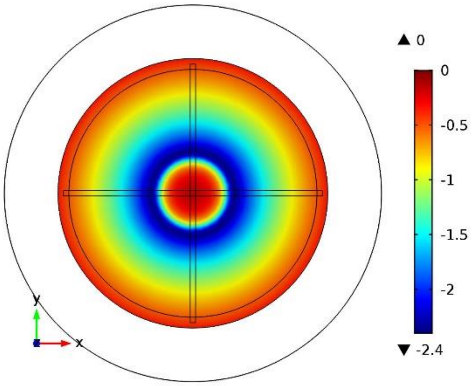

Figure 5. Arising voltage distribution when the force acts perpendicular to the buzzer, i.e. in direction of the z-axis.

4. Verification Prototype

Finally, to verify the result, a real prototype was built manually. The prototype shows the same qualitative behavior as expected from the simulation. Measurement results are shown in figure 6 and 7. Figure 6 shows the four measured voltages when the force acts parallel to one of the cuts. Similar to the numerical results in figure 3 voltages with the same amount can be measured in all four areas.

Figure 7 shows the measured voltages when the force acts exactly between the cuts related to the case shown in figure 4. As expected only in two areas significant values of the voltage can be measured. The minimum sensitivity is about 60% of the maximum which is reasonable for a manual factored prototype.

5. Conclusions

The result is simple and comprehensible. The optimal design of the sensor for our scope of work can be archived if the layer of piezoelectric material is cut into four equally sized areas and the amount of voltages is added together.

The final sensor design has a minimum sensitivity of ca. 70% of the maximum in case of using only one single buzzer. It could be shown, that only a few design modifications are necessary to be able to measure accelerations in different directions with one single buzzer, which is not possible with a non-modified buzzer. The positive and negative voltage areas have to be separated.

Of course, the main idea to cut the PZT into four areas could have been found without simulation only by experiments too, but using a simulation model in the development process helped to find the optimal design in a cheap and very fast way.

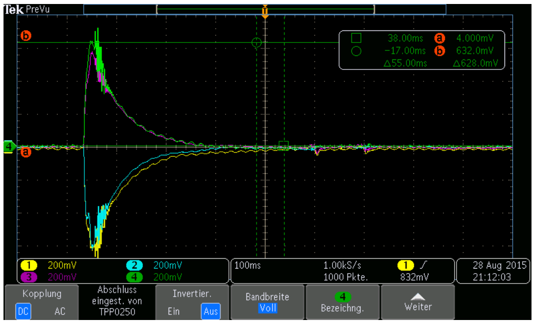

Figure 5. Measured voltages when the force acts in the direction of the x-axis

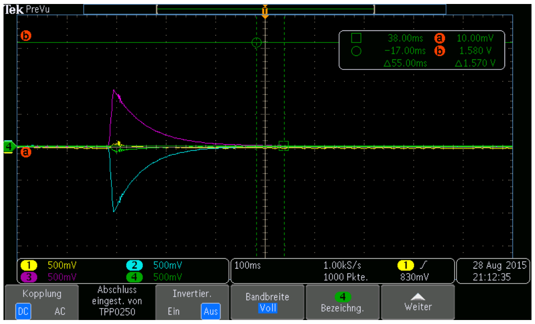

Figure 6. Measured voltages when the force acts exactly between x- and y-axis.

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