Journal of Microelectronics and Electronic Packaging (2008) **5**, 150-155

ISSN: 1551-4897

Thick Film Accelerometers in LTCC Technology—Design Optimization, Fabrication, and Characterization

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Abstract—**Diaphragms and beams for force and pressure sensors, e.g., are state of the art in mechanical elements of MEMS in LTCC technology. These elements sustain small strains and small deformations under load. A number of sensor and actuator applications, however, require movable elements that allow higher deformations while the local strains are still low. Springs, accelerometers, actuators, positioners, and valves are examples of such applications. For an accelerometer we developed an approach fabricate leaf springs, integrated into the LTCC technology. The working principle of the accelerometer is based on a seismic mass disposed on two parallel leaf springs that carry piezoresistors connected such that they form a measuring bridge. In the first design optimization step, we used an FEA model for finding an optimized design meeting our sensitivity requirements, inclusiding resonance frequency. In the second step, we made a tolerance analysis that calculates the probability distributions of functional variables from the probability distributions of the design parameters. This enables the probability of a system failure to be deduced. In a final design step, a design of the ceramic thick film accelerometer was calculated that minimizes the system failure probability. As a result we obtained a design optimized with respect to a set of functional requirements and design tolerances. The results of the computations using the FEA models were compared to results of measurement data acquired from prototypes of the accelerometer.**

Keywords—**Accelerometer, LTCC, tolerance analysis, robust design, probabilistic design, optimization**

Introduction

LTCC technology has recently been used for various types of physical sensors measuring, for example, temperature, distance, force, pressure, and mass flow [1-5]. Typically the measurement of force or pressure is based on the deformation of integrated parts of the sensor substrate which can be detected electrically by piezoresistive, piezoelectric, or even optical transducers [3, 4]. Diaphragms and beams that sustain small strains and small deformations under loads are state of the art in mechanical elements of MEMS in LTCC technology. However, a number of sensor and actuator applications require elements that allow higher displacements while the local strains are still low. Examples of these applications are springs, accelerometers, actuators, positioners, and valves. Designs that include such parts are more difficult to build up.

In the past, accelerometers made by thick-film technology were manufactured on alumina [6] and metal substrates [7]. We introduced a manufacturing technology of LTCC integrated leaf springs by the example of a uniaxial piezoresistive accelerometer.

Therefore the purpose of this study is (i) to introduce an LTCC compatible design and an adequate technology of its fabrication, (ii) to optimize the design based on an FEA model and an optimization approach that handles the statistical spread of the design parameters, and (iii) to evaluate experimental data and to demonstrate the accuracy of the technological approach and of the design as well as to verify the modeling approach.

Principle and Working Model

The accelerometer is composed of a seismic mass M arranged on two parallel leaf springs S fixed to a frame F (Fig. 1). The springs and also the frame carry piezoresistors P connected to form a measuring bridge that gives an electrical output U_b when the mass is elongated by an external acceleration in the *z*-direction. The main functional parameters of this arrangement are the sensitivity to an acceleration in z-axis to be measured, *S*, the cross sensitivity to accelerations acting in directions other than the z-axis, *CS*, and the first resonance frequency f_R. *S* is defined as the ratio of the bridge voltage U_b to the supply voltage U_s and the acceleration to be measured a_z. *CS* is set correspondingly, whereas the cross sensitivity to an acceleration in the direction of *y* is most critical:

$$S = U_b/(U_s \cdot a_z) \quad \text{and} \quad CS = U_b/\left(U_s \cdot a_y\right).$$

The mechanical design takes advantage of the following notes, gleaned from experience. A double spring design gives a lower cross sensitivity compared with those with one spring. Plane bending of the springs is better than torsion because the load is applied more evenly on the material. The mechanical behavior can be modeled by the lumped element approach (Fig. 2) where the mass M is concentrated into the centroid of the mass element. A system model includes the piezoresistors as mechanical-electrical transducers, and the circuit of the bridge. Finally we find two equations for *S* and f_R in the following forms:

Manuscript received August 2008 and accepted January 2009
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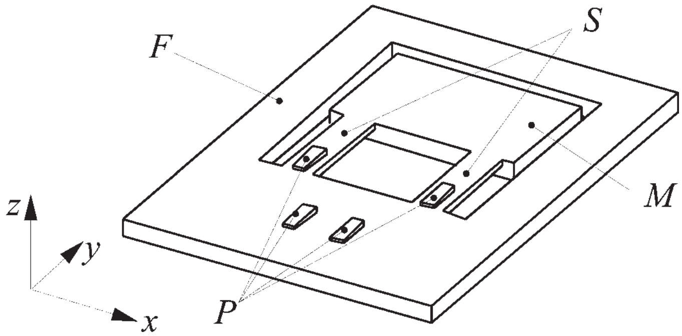

Fig. 1. The uniaxial LTCC accelerometer consists of a seismic mass M on two plate springs S fixed to a frame F. Piezoresistors P are postfired on the springs and on the frame.

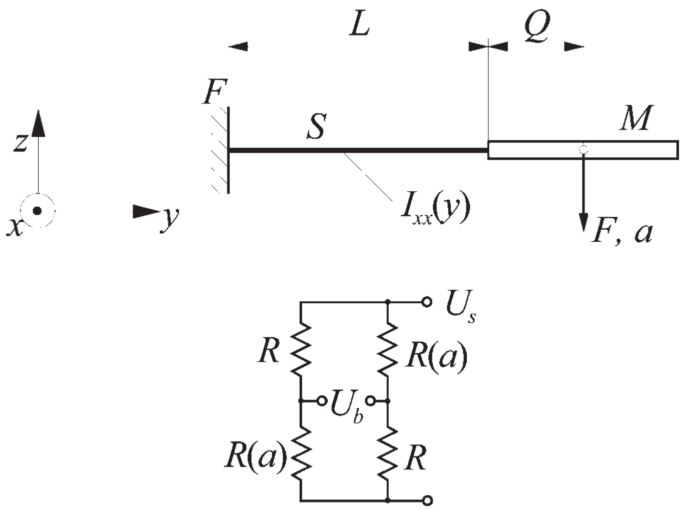

Fig. 2. A lumped element model concentrates the seismic mass in a point. Piezoresistors are arranged to a measuring bridge.

Table I
System behavior of the LTCC accelerometer at different design stages

	Constr. value	Start value	Optimal value	Robust value
S	Find maximum	27.6 µV/(V·g)	47.6 µV/(V·g)	46.4 µV/(V·g)
CS	$0 \leq CS \leq 2\%$	1.76%	1.8%	1.8%
f_R	$230\ \text{Hz} \leq f_R \leq 260$ Hz	293.7 Hz	230 Hz	234 Hz

$$f_R = \frac{1}{2\pi}\sqrt{\mathbf{D_1}} \qquad S = \mathbf{D_2},$$

where $\mathbf{D_1}$ and $\mathbf{D_2}$ are two sets of design parameters of dimensions and material properties. Because the lumped element model does not consider the departure from symmetry which causes cross sensitivity in the y-direction we cannot deduce an equation for CS from this model.

By these equations a preliminary design can be found that respects the requirements of sensitivity and resonance frequency to some extend as a starting point of the design optimization process (Table I). It is not necessary to meet the requirements accurately, because the optimization will run into the optimum design. However, the design optimization is based on a more precise FEA model that we introduce in Sect. 3. The LTCC technology will be considered in Sect. 4.

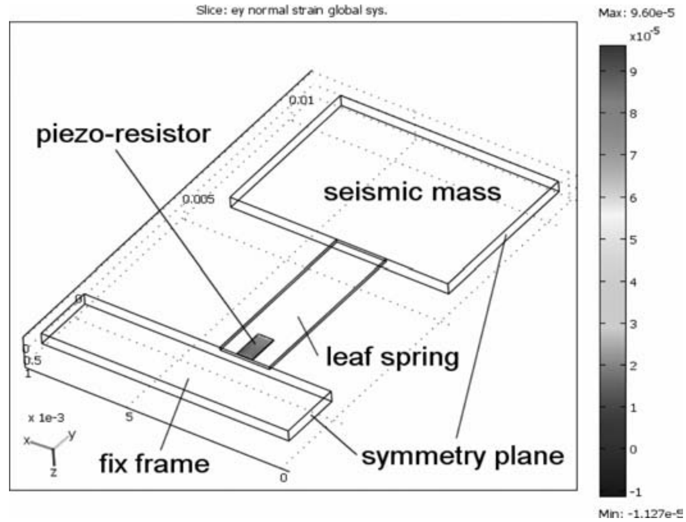

Fig. 3. An FEA model computes sensitivity S, cross sensitivity CS, and resonance frequency f_R of the accelerometer.

Design Optimization

The design optimization contains three steps. In a first design optimization step, we use an FEA model for finding an optimized design conforming to our requirements by means of optimization methods. In a second step, we performed a tolerance analysis that calculates the probability distributions of functional variables from the probability distributions of the design parameters. This enables the probability of a system failure to be deduced. In a final step, a design of the ceramic thick film accelerometer was calculated that minimizes the system failure probability.

An FEA structural mechanics model of about 40,000 degrees of freedom contains all mentioned elements, with the exception of the electrical connections of the bridge (Fig. 3). For simplification we assume mirror symmetry. Therefore only one half of the sensor was modeled. Furthermore the accelerometer should work far from resonance. Thus the electrical output can be calculated from a static model where only the static deformation of the seismic mass and the springs due to the acceleration force is estimated. The mean normal strain in the y-direction in the piezoresistors e_{ym} is a measure for the change of the resistance of the piezoresistors ΔR multiplied by a constant factor k, which characterizes the material of the resistors. Therefore we obtain for the sensitivity S under an acceleration in z-direction a_z:

$$S = e_{ym} \cdot k \big/ (2a_z).$$

and for the cross sensitivity CS for accelerations in the y-directions:

$$CS = e_{ym} \cdot k \big/ \left(2a_y\right).$$

The FEA model calculates both S and CS, and the first resonance frequency f_R as a further essential property.

A. Nominal Optimization

For finding an optimized design conforming to our sensitivity and cross sensitivity requirements, inclusive of resonance

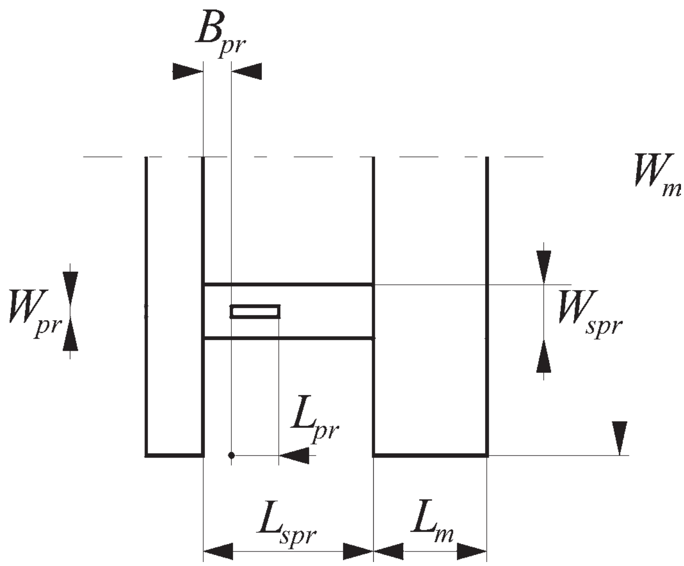

Fig. 4. The optimization varies a set of design parameters.

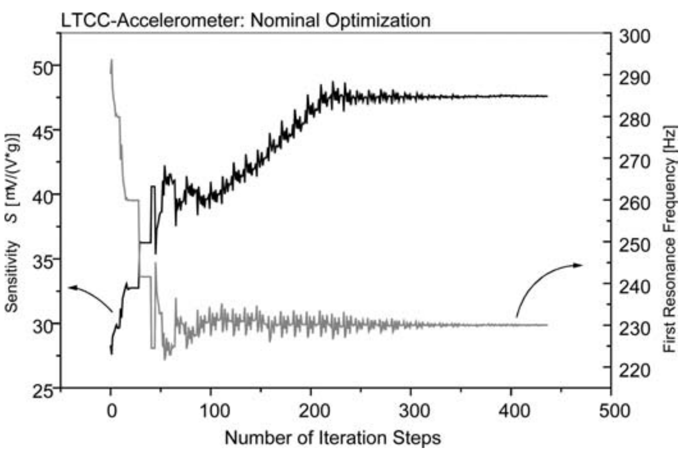

Fig. 5. The sensitivity converges to an optimum constrained by the resonance frequency.

frequency we used the FEA model. For these purposes the following design parameters are set as input variables for the optimization process (Fig. 4):

length L_{spr} and width W_{spr} of the leaf springs,
length L_m and width W_m of the mass,
length L_{pr} of the piezoresistor and distance B_{pr} between it and the frame.

We used the OptiY tool performing the optimization [8]. After about 350 runs of the model inside of the Hooke-Jeeves algorithm the optimization converges. This is shown for C and f_R in Fig. 5, and for the design parameters B_{pr} and L_{pr} as an example in Fig. 6. As a result we get the set of design parameters that fulfill the restrictions and functional demands at optimum, given in Table I.

B. System Failure Analysis

Any design parameter can be modeled as a nominal value and a probabilistic distribution in a tolerance range.

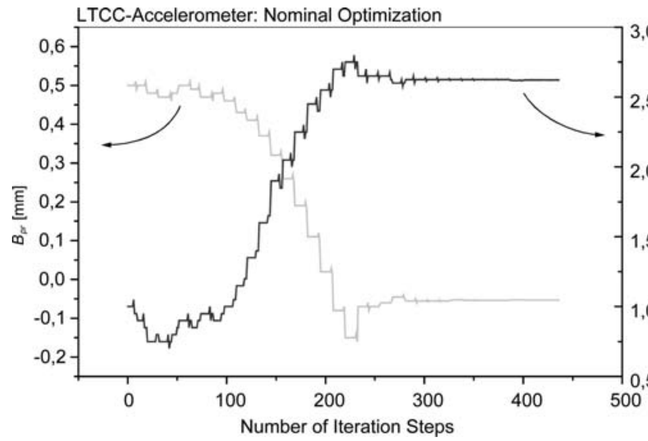

Fig. 6. The design parameters B_{pr} and L_{pr} converge to the optimum design.

Most physical variables and design parameters may thus be viewed as random variables and have to be controlled to achieve reliable products [9, 10]. Classical deterministic simulations deal only with the mean or nominal values of the design parameters, whereas a tolerance analysis or a probabilistic design study also takes into account their probability distributions. The Monte Carlo simulation method is the current state of the art [11, 12]. In this method, for every input parameter, a sample size is generated. With each of the samples, a deterministic simulation is carried out to get output variables. Finally, a statistical evaluation of these calculations provides the desired probabilistic distributions of the output parameters. Unfortunately, the Monte Carlo method is computation-intensive when a representative sample size has to be calculated. Considerably less computing power is necessary when the probabilistic distributions of the output variables, that is, their center moments, are deduced from the center moments of the input variables by an analytical calculation or approximation. We used a second order analysis based on the second order Taylor series for this purpose.

For the accelerometer the influence of the tolerances of the length L_{spr} and the width of the leaf springs W_{spr}, and of the location of the printed piezoresistors on the springs, represented by the distance from the frame B_{pr}, were investigated. We assumed normal distributions with a standard deviation of 50 µm for B_{pr}, and 33 µm for L_{spr} and W_{spr}, but any kind of distribution may be involved. The computed output distributions are given in Fig. 7.

Adark area stands for a behavior outside the acceptable range. The ratio of inoperable solutions to all scattering solutions is called failure probability. It is obviously seen that the distribution of the cross sensitivity CS is inside the specified interval, whereas that of the resonance frequency f_R causes an inoperable system with a failure probability of about 50%. Such a behavior is typical since the optimum design is normally located on the boundary of the permissible design parameter space. Since we searched for the maximum of the sensitivity S, a constraint interval of S does not exist and cannot be violated.

C. Minimizing the System Failure Probability

The design of the LTCC accelerometer found in the nominal optimization has to be changed such that a lower failure

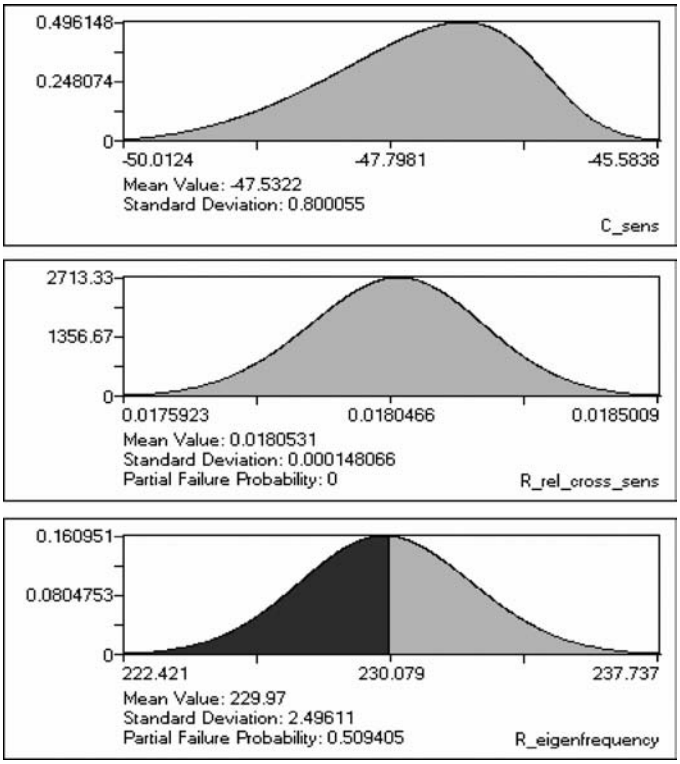

Fig. 7. The distributions of the system behavior variables involve a system failure probability of about 50%, caused by a violation of the f_R requirement.

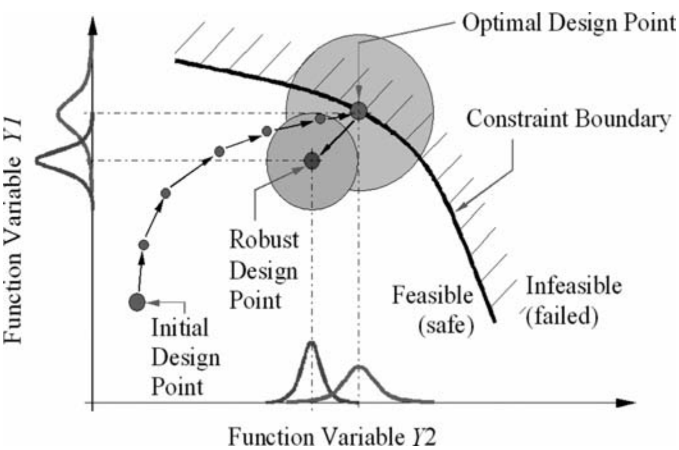

Fig. 8. A robust optimization involves the computation of the distributions of the system behavior for finding a robust design point.

probability is achieved, at best about zero. This is performed by a robustness analysis, illustrated in Fig. 8. The robust design point has to be found for minimizing the percentage of solutions that come outside of the permissible range, which lies slightly apart from the constraint boundary. For this purpose, a second optimization based on the Hooke-Jeeves algorithm is performed that involves the computation of the distributions of S, CS, and f_R in every iteration step. As a result we obtain a design that is optimized for a set of functional requirements and design tolerances, given in Table I. The system failure probability decreases to about 5.5%, caused by a residual violation of the resonance frequency requirement (Fig. 9).

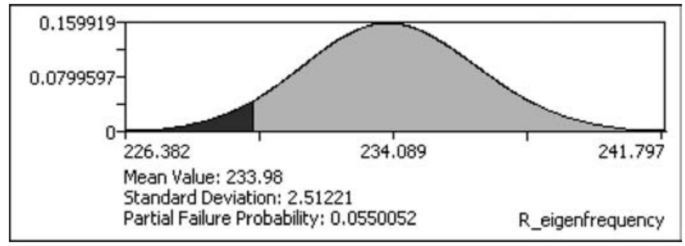

Fig. 9. The robust design point decreases the system failure probability to 5.5%.

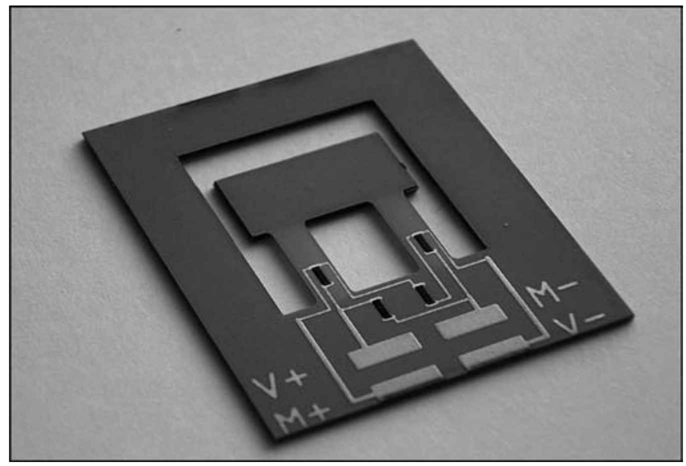

Fig. 10. The LTCC accelerometer was made of DuPont'S LTCC System 951™.

Materials and Manufacturing Technology

For the manufacturing of the accelerometers, Du Pont's LTCC system Green Tape 951™ was used. Different preinvestigations [4] identified the DP 2041 as a suitable resistor system for strain measurements. All metallizations and resistors were deposited after firing of the LTCC sensor body and were fired in a postfire step. Regarding the simulation and optimization results, the springs had a nominal thickness of 100 µm after the firing step in manufacturing was complete. The manufacturing technology followed the standard LTCC process.

A special challenge was the integration of the warpage-free thin springs and the combination with the seismic mass. To achieve this feature a special lamination technology was developed. Additional retaining bars for the seismic mass were integrated and removed by laser (Nd:YAG) after firing. For the shaping of the springs a laser cut step was used as well. The springs consist of one layer whereas the frame and the mass are four layers as shown in Fig. 10. In addition to the design with rectangle leaf springs, we also introduced trapezoidal springs. The advantage of trapezoidal springs is a more homogeneous stress in the material.

Experimental Characterization

Our working models were tested by a Spektra vibration exciter under sinusoidal excitation frequencies of 50, 75, and 100 Hz (Fig. 11) and different peak acceleration levels up to 200 m/s^2. The measurement results are given in Figs. 12

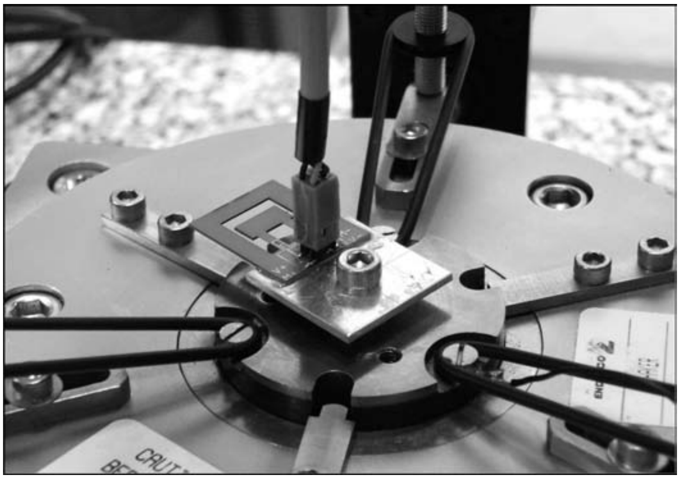

Fig. 11. The accelerometers were characterized by a Spektra vibration exciter.

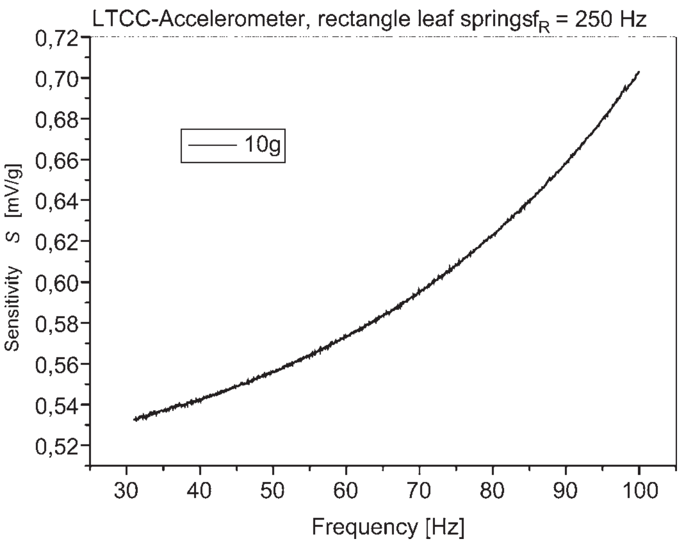

Fig. 12. Sensitivity S increases with frequency.

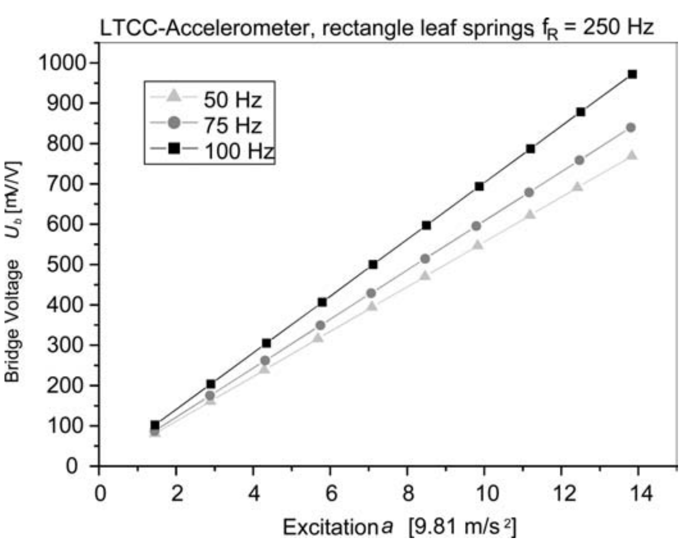

Fig. 13. Bridge voltage U_b depends linearly on excitation a.

and 13. As expected from the working principle, the sensitivity increases with the frequency. Hence, the sensitivity calculated from the static FEA model is somewhat lower than the measured sensitivity. If a constant frequency is applied, the linearity of U_b is very good.

Conclusions

Summarizing the study, it is shown (i) that LTCC is a promising material to build up integrated springs that perform large deformations suitable for mechanical parts of MEMS. For that purpose, we introduced laser ablation steps into the standard LTCC process. We found an LTCC-compatible accelerometer design and a suitable technology to fabricate it. This was our main intention. Future studies will investigate laser ablation within the standard LTCC technology for sensors measuring mechanical quantities other than acceleration, such as pressure, force, and flow rate. This is a promising approach for high-sensitivity sensors, because integrated flexible parts can be manufactured with a high aspect ratio, comparable to the springs we designed in this study.

(ii) For finding an optimized design of the accelerometer, we successfully used the OptiY tool connected to an FEA model build in COMSOL Multiphysics. Starting from a preliminary design, calculated by a lumped element model, we found the nominal optimum of the accelerometer design. We analysed the influence of the scattering of the laser ablation and the screen printing on the function of the accelerometers and we deduced the failure probability of the manufacturing. In the second optimization step we handled the statistical spread of the design variables within the optimization and computed a robust design that has a slightly lower sensitivity but on the other hand, a lower manufacturing failure probability. (iii) Finally, good accuracy of the modeling approach was found by experimental evaluation of the fabricated prototypes.

Today's accelerometers made in thin-film technology offer sufficient functionality in a cost-effective way. Nevertheless, thick-film accelerometers made of Low Temperature Cofired Ceramics (LTCC) are of interest, since they promise a wider temperature range and lower costs in small-series production.

We consider the probabilistic optimization including analytical calculations of the distribution functions of the functional parameters from the distribution functions of the design parameters to be a general approach for designing robust products using parametric models. This was exemplarily shown for an accelerometer. Future work will pursue the elaboration of the method by utilizing it in designing other sensors of mechanical quantities, made of LTCC.

Acknowledgements

The authors gratefully acknowledge the SPEKTRA Schwingungstechnik und Akustik GmbH Dresden for calibrating some accelerometers. We appreciate Birgit Manhica's excellent work in the laboratory.

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