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

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Abstract

State of the art in mechanical elements of MEMS in LTCC-technology are diaphragms and beams, e.g. for force and pressure sensors. These elements perform small strains and small deformations under loads. However a lot of sensor and actuator applications require movable elements that allow higher deformations whereas the local strains are still low. Such applications are e.g. springs, accelerometers, actuators, positioners, and valves. For an accelerometer we developed an approach for the fabrication of 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 which carry piezoresistors connected to form a measuring bridge. In a first design optimization step, we used a FEA model for finding an optimized design conforming to our sensitivity requirements, inclusive of resonance frequency. 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 design step, a design of the ceramic thick film accelerometer was calculated that minimizes the system failure propability. As a result we obtained a design optimized with concern 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

1 Introduction

LTCC technology has been recently used for various types of physical sensors measuring e.g. 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]. State of the art in mechanical elements of MEMS in LTCC-technology are diaphragms and beams that perform small strains and small deformations under loads. However a lot of sensor and actuator applications require elements that allow higher displacements whereas the local strains are still low. This applications are e.g. springs, accelerometers, actuators, positioners, and valves. Designs that include such parts are more difficult to build up.

In the past accelerometer 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 an uniaxial piezoresistive accelerometer.

Therefore the purpose of this study is (i) to introduce a LTCC compatible design and an adequate technology of its fabrication, (ii) to optimize the design based on a 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.

2 Principle and Working Model

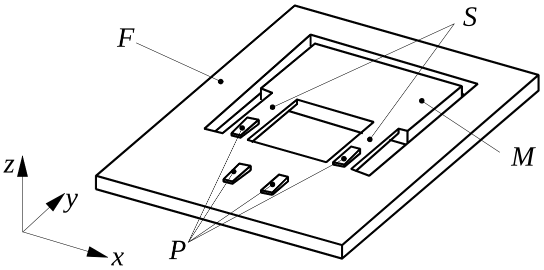

Figure 1. The uniaxial LTCC-accelerometer consists of a seismic mass M on two plate springs S fixed to a frame F. Piezoresistors P are postfired on the springs and on the frame.

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 piezo-resistors P connected to form a measuring bridge that gives an electrical output U_b when the mass is elongated by an external acceleration in z-direction.

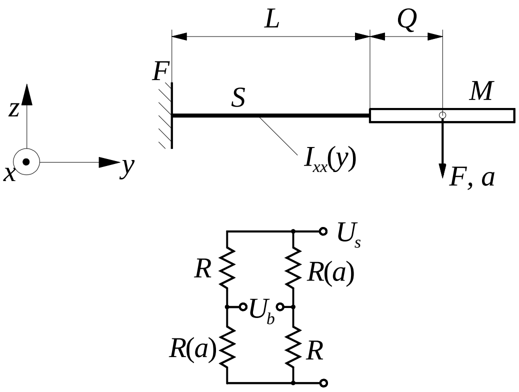

Figure 2. A lumped element model concentrates the seismic mass in a point. Piezo-resistors are arranged to a measuring bridge.

The mechanical design takes the following experiences in. A double spring design gives a lower cross sensitivity compared to those with one spring. Plane bending of the springs is better than torsion because the load is applied more even to the material. This is also true for trapezoidal springs compared to plate springs with constant cross section area. 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 piezo-resistors as mechanical-electrical transducers, and the circuit of the bridge. Finally it gives the electrical output $U_b = f(a, U_s, \mathbf{D})$ where U_b and U_s are the bridge and the supply voltage, a the acceleration effected to the sensor, and **D** a set of design parameters of dimensions and material properties. By this analytical model a primarily design can be found respecting requirements of sensitivity and resonance frequency as a starting point for the design optimization process. However the design optimization bases on a more precise FEA model we introduce in section 3. The LTCC technology will be considered in section 4.

3 Design Optimization

The design optimization contains three steps. In a first design optimization step, we use a 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 propability.

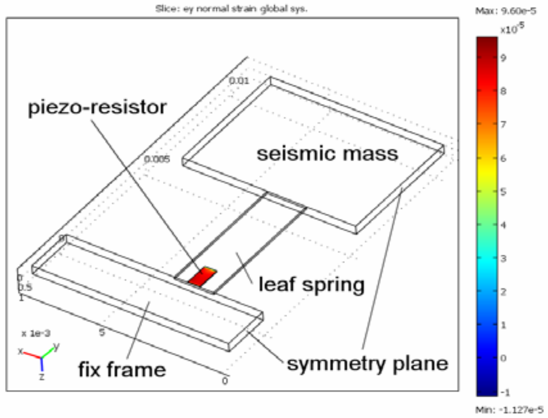

Figure 3. A FEA model computes sensitivity S, cross sensitivity CS, and resonance frequency f_R of the accelerometer.

A FEA structural mechanics model of about 40.000 DOF's contains all mentioned elements, with the exception of the electrical connections of the bridge. For simplification we assume mirror symmetry of the geometry. Thus only one half of the sensor is modeled. Furthermore the accelerometer should work far from resonance, therefore the electrical output can be calculated from a static model. The mean normal strain in y-direction in the piezo-resistors e_{ym} is a measure for the change of the resistance of the piezo-resistors ΔR multiplied by a constant factor k. Therefore we obtain for the sensitivity of the accelerometer S under an acceleration in z-direction a_z depending on the bridge voltage U_b and the feeding voltage U_s:

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

Equally we get the cross sensitivity CS for accelerations in the x- and the y-directions, where the acceleration in the direction of y is more critical:

$$S = U_b / (U_s \cdot a_y) = e_{ym} \cdot k / (2a_y).$$

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

3.1 Nominal Optimization

For finding an optimized design conforming to our sensitivity and cross sensitivity requirements, inclusive of resonance frequency. 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 piezo-resistor and distance B_{pr} between it and the frame.

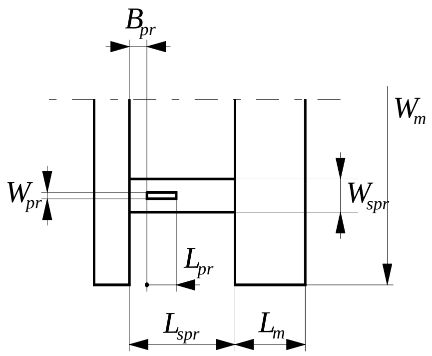

Figure 4. The optimization varies a set of design parameters.

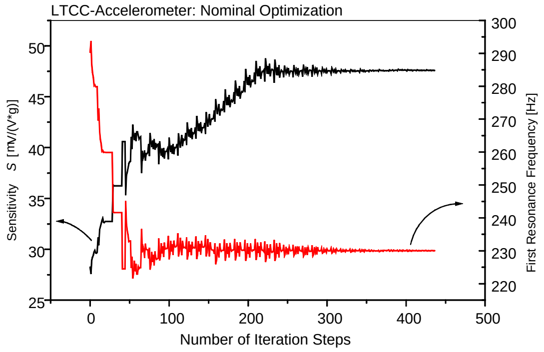

Figure 5. The sensitivity converges to an optimum constrainted by the resonance frequency.

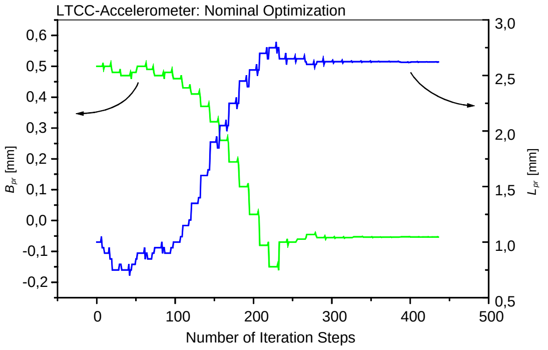

Figure 6. The design parameters B_{pr} and L_{pr} converge to the optimum design.

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 Figure 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 1.

3.2 System Failure Analysis

Any design parameter can be modeled as a nominal value and a probabilistic distribution in a tolerance range. 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 takes into account also their probability distributions. State of the art is the Monte-Carlo simulation [11]. 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 reresentative sample size has to be calculated. Considerable less computing power is necessary when the probabilistic distributions of the output variables, i.e. 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 purposes.

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 piezo-resistors on the springs, represented by the distance from the frame B_{pr}, were investigated. We assumed normal distributions with a standard deviation of 50µm for B_{pr}, and 33µm for L_{spr} and W_{spr}, but any kind of distribution may be involved. The computated output distributions are given in Fig. 7.

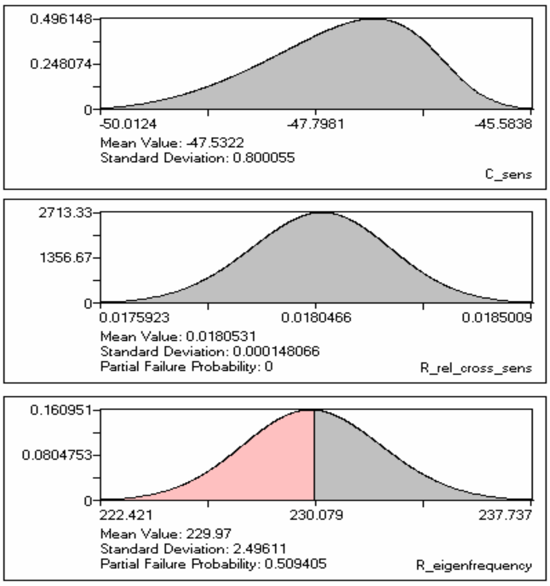

Figure 7. The distributions of the system behavior variables involve a system failure probability of about 50%, caused by a violation of the f_R requirement.

A red 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 doesn't exist and can't be violated.

3.3 Minimizing the System Failure Propability

The design of the LTCC accelerometer found in the nominal optimization has to be changed such that a lower failure probability is achieved, at best about zero. This is performed by a robustness analysis, illustrated in Fig. 7. The robust design point has to be found for minimizing the percentage of solutions that come outside of the permissible range lays slightly apart from the constraint boundary. For this purpose an second optimization based on 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 1. The system failure probability decreases to about 5.5%, caused by a residual violation of the resonance frequency requirement.

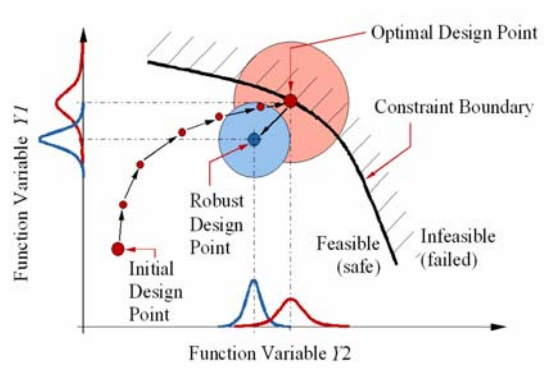

Figure 8. An robust optimization involves the computation of the distributions of the system behavior for findung a robust design point.

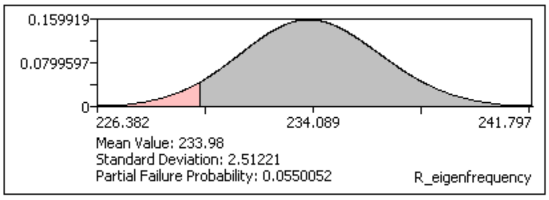

Figure 9. The robust design point decreases the system failure probability to 5.5%.

Table 1. System Behavior of the LTCC accelerometer at different design stages

	Constr.	Start Value	Optim. Value	Robust Value
S	Find Maximum	27,6 µV/(V.g)	47,6 µV/(V.g)	46,4 µV/(V.g)
CS	[0; 2%]	1,76%	1,8%	1,8%
f_R	[230Hz; 260Hz]	293,7Hz	230Hz	234Hz

4 Materials and Manufacturing Technology

For the manufacturing of the accelerometers Du Pont's LTCC system Green Tape 951™ was used. Different pre-investigations [4] identified the DP 2041 as a suited resistor system for strain measurements. All metallizations and resistors were deposited after firing of the LTCC-sensor body and were fired in a post-fire step. Regarding the simulation and optimization results the springs had a nominal thickness of 100 µm fired. 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 of four as shown in Fig. 10. In addition to the design with rectangle leaf springs we introduced also trapezoidal springs. Their advantage is a more homogeneous stress in the material.

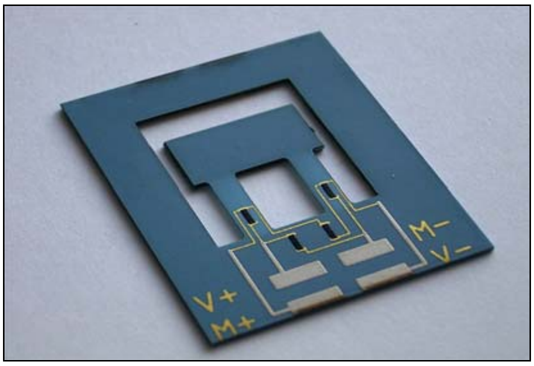

Figure 10. The LTCC Accelerometer was made of DuPont'S LTCC System 951^{TM}.

5 Experimental Characterization

Our working models were tested by a Spektra vibration exciter under sinusoidal excitation frequencies 50, 75, and 100 Hz (Fig. 11) and different peak acceleration levels up to 200 m/s^2. The measument results are given in Fig. 12 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. If a constant frequency is applied the linearity of U_b is very good.

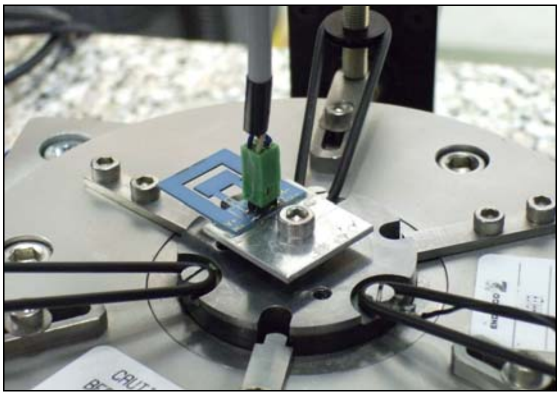

Figure 11. The accelerometers were characterized by a Spektra vibration exciter.

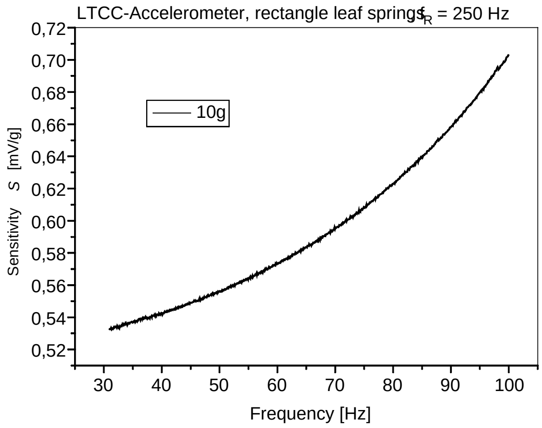

Figure12. Sensitivity S increases with frequency.

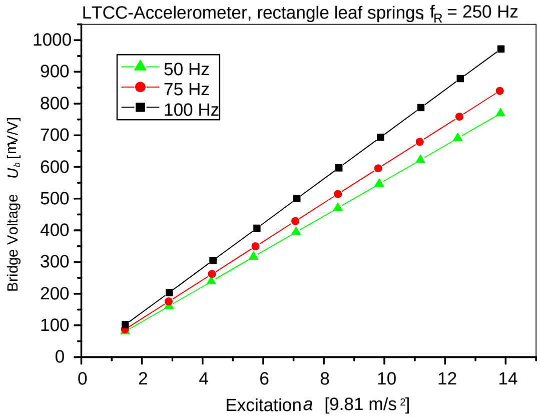

Figure 13. Bridge voltage U_b depends linearly on excitation a.

6. Conclusions

It is shown 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. This was our main intention.

For finding an optimized design we successfully used the OptiY tool connected to a FEA model. By this means we handled the statistical spread of the design variables inside of the optimization. Finally a 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 higher temperature range and lower costs in small-series production.

References

[1] L.J. Golonka, T. Zawada, H. Roguszczak, K. Malecha, M. Chudy, D. Stadnik, A. Dybko, "Three-dimensional fluidic microsystem fabricated in low temperature cofired ceramic technology", Elektronik, Poing Vol. 56, No. 2, pp. 30-31, 2007

[2] M. Gongora-Rubio, L.S. Laguna, M. Smith, J.J.S. Avriles, "LTCC technology multilayer eddy-current proximity sensor for harsh environments", Proc. SPIE Vol. 3906, Proceedings of the 1999 Int. Symp. on Microelectronics. Assembled and Edited by the 1999 Technical Program Committee and the IMAPS Staff., p.676-681

[3] H. Birol, Th. Maeder, I. Nadzeyka, M. Boers, P. Ryser, "Fabrication of a millinewton force sensor using low temperature co-fired ceramic (LTCC) technology", Sens. Actuators A, Vol. 134, Issue 2, pp. 334-338, 2007

[4] U. Partsch, S. Gebhardt, D. Arndt, H. Georgi, H. Neubert, D. Fleischer, M. Gruchow, "LTCC-based sensors for mechanical quantities", 16th European Microelectronics and Packaging Conference & Exhibition (EMPC), Oulu, Finland, June 17 - 20, pp.381-388, 2007

[5] U. Schmid, H. Seidel, "Miniaturized sensor elements based on LTCC technology for automotive and airborne applications", IMAPS/ACerS Int. Conf. and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technol. (CICMT), April 10-13, Baltimore, Maryland, pp. 1-10, 2005

[6] R.P. Sion, J.K. Atkinson, J.D. Turner, "A novel accelerometer using think-film technology", Sens. Actuators A, Vol. 37-38, pp. 348-351, June-August, 1993

[7] D. Crescini, D. Marioli, A. Taroni, “Low-cost accelerometers: two examples in thick-film technology”, Sens. Actuators A, Vol. 55, Issues 2-3, pp. 79-85, July, 1996

[8] T.Q. Pham, “OptiY Software and Documentation Version 2.3”, OptiY e. K., www.optiy.de, 2007

[9] M.W. Long, J.D. Narciso, “Probabilistic Design Methodology for Composite Aircraft Structures”, Report DOT/FAA/AR-99-2, U.S. Department of Transportation, Federal Aviation Administation, 1999

[10] A. Saltelli, K. Chan, E.M. Scott, “Sensitivity Analysis”, John Willey & Sons Chichester, New York, 2000

[11] N.P. Koch, B. Wujek, O. Golovidov, “A Multi-stage, parallel Implementation of Probabilistic Design Optimization in an MDO Framework”, 8th Symposium on Multidisciplinary Analysis and Optimization, Sept. 6-8, Long Beach, CA, 2000

[12] W. Chen, J.K. Allen, K.-L. Tsui, F. Mistree, “A Procedure for Robust Design: Minimizing Variations Caused by Noise Factors and Control Factors”, ASME Journal of Mechanical Design, Vol. 118, pp. 478-485, 1996