Multi-Objective Optimization of a Ball Grid Array Using modeFRONTIER & COMSOL Multiphysics

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Abstract: Capacitive MEMS accelerometers may be directly soldered to the printed circuit board by an array of solder balls. Differences in the thermal expansion coefficients of the pertinent materials cause deformations of the accelerometer under temperature change. This may cause a relative movement of the sensing masses with respect to the sensing electrodes, resulting in a change in capacitance and a false acceleration output. A multi-objective optimization was used to find the best location of the solder balls which minimized the measurement error under varying temperature and, at the same time, maximized the expected service life due to fatigue of the solder balls. While the achieved improvement in service life was moderate, an order of magnitude improvement was achieved for the predicted measurement error.

Keywords: Multi-objective optimization, MEMS accelerometer, ball grid array

1. Introduction

VTI Technologies Oy develops and manufactures micro electro mechanical systems (MEMS) and the main products are capacitive low-g accelerometers which for instance are used in automotive electronic stability control (ESC) systems. An accelerometer is attached to the printed circuit board (PCB) by an array of solder balls. The attachment type is referred to as a ball grid array (BGA) due to the shape and layout of the solder balls, see figure 1.

The measurement principle for a low-g accelerometer is outlined in figure 2. A mass is attached to an anchor via a spring, and under acceleration the mass which holds the sensing electrodes moves with respect to the static electrodes. The movement changes the gap and thus the capacitance which is then measured. The final product which is soldered to the PCB includes multiple materials, each with a different thermal expansion coefficient. Unfortunately this may cause the sensing elements to move as temperatures change and send out a false acceleration output, referred to as an offset error.

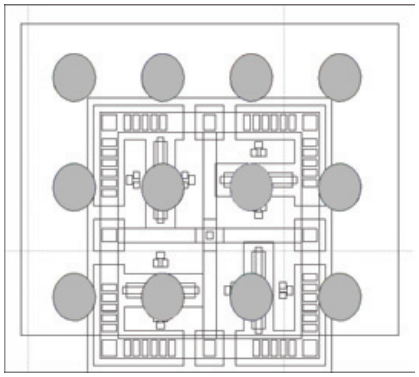

Figure 1. The baseline design of the ball grid array is evenly spread over the available surface. The MEMS structure may be seen behind the gray solder balls.

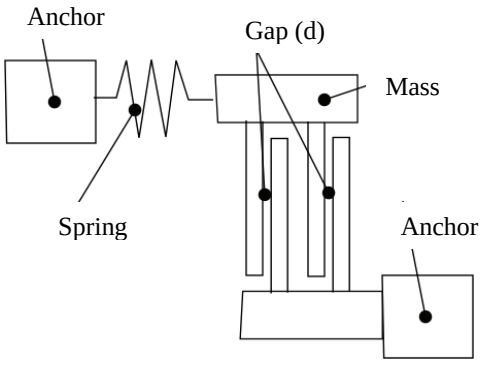

Figure 2. A low-g accelerometer measures the change in capacitance with varying gap size. The gap, typically 1.5 to 3 μm, changes when acceleration forces move the mass.

Accelerometers are normally exposed to small vibrations which may cause fatigue and failure of the electrical connection between the accelerometer and the PCB. Both the offset error and the fatigue life are affected by the layout of the BGA and the objective of the study is therefore to minimize the offset error and, at the same time, maximize the expected service life.

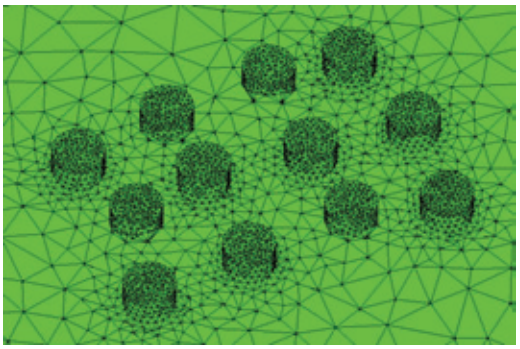

Figure 3. The solder balls, seen on top of the PCB, have a refined mesh.

2. The numerical model

In order to keep the model size reasonable, the active sensor elements were not included in the FEM model. We assume the movement of the anchors can be directly mapped to the offset error, i.e. the larger the movement, the larger the offset error as a function of temperature.

Mesh controls were employed to ensure dense mesh in critical parts of the model and to achieve a consistent mesh between different geometries. Ten noded tetrahedral elements were used in the linear model and typical model size was 400000 elements or 1.65 million degrees of freedom. Plasticity and creep of the solder was omitted and two load cases with different temperature were used, +85°C and –40°C.

The model geometry was created using the 3D solid modeller SolidWorks and imported into Comsol in the Parasolid format. Figure 3 displays a part of the meshed model, the solder balls on the PCB.

3. Multi-objective optimization

The general multi-objective optimization software modeFRONTIER was used to automate the design evaluations and steer the process towards its optimum. The generalized process has been outlined in figure 4 and consists of setting input parameters, running the simulation, reading the results and deciding which design to evaluate next. The loop is then repeated until the optimum has been found or, more commonly, good enough results are obtained and resources are needed better elsewhere.

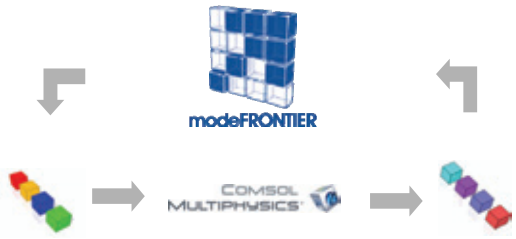

Figure 4. The general multi-objective optimization software modeFRONTIER was used to automate and steer the search for optimal designs. The process may be generalized to set the input parameters, let Comsol Multiphysics evaluate the design, read the results and decide which design to evaluate next.

3.1 What to measure

An optimization task always starts with the definition of the objectives and how to measure them. The selected result should in a single number capture how well the design performs with respect to the objective. In this case the value function F_{tot} was a measure of the relative movement of the anchors of the sensing and static electrodes:

$$\begin{vmatrix} F(D_{11},D_{12},D_{13},D_{14},D_{15},D_{16}) \\ + F(D_{31},D_{32},D_{33},D_{34},D_{35},D_{36}) \end{vmatrix} + \begin{vmatrix} F(D_{21},D_{22},D_{23},D_{24},D_{25},D_{26}) \\ + F(D_{41},D_{42},D_{43},D_{44},D_{45},D_{46}) \end{vmatrix} \quad (1)$$

where the average displacement of the top surface of an anchor is defined as

$$D_{ij} = \frac{1}{A_{ij}} \int_{A_{ij}} u_{ij}(x,y)\,dydx \quad (2)$$

The sensor was identified through i=1,2,3,4 and j=1,…,6 identifies the anchor within the sensor, see figure 5. Sensors i=1,3 measure in the x-direction and sensors i=2,4 in the y-direction. u is the x-displacement for i=1,3 and the y-displacement for i=2,4.

To maximize the service life, one aims to minimize the solder fatigue through minimizing the peak stress in the solder balls. The expression to minimize was

$$\sqrt{S_{\text{mchip}}^2 + S_{\text{mPCB}}^2} \quad (3)$$

where S_{mchip} and S_{mPCB} denote the maximum shear stress in solder balls evaluated in two

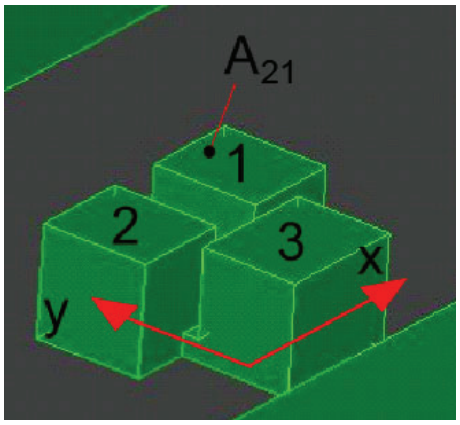

Figure 5. Anchors and their numbering within one of the sensors measuring in the y-direction.

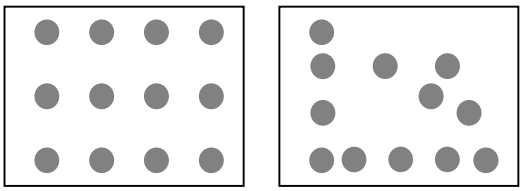

Figure 6. It was desirable to try out very different BGA layouts such as the example on the right, compared to the baseline design to the left.

planes located 28.5 μm from the chip and from the PCB, respectively. The solder ball height was 190 μm. The shear stress is defined as

$$S_m = \frac{\sigma_1 - \sigma_3}{2} \qquad (4)$$

where σ_1 and σ_3 are tensile and compressive principal stresses, respectively.

3.2 Parameterization of the BGA layout

It was desirable to investigate a large design space which included fundamentally different designs compared to the baseline, see figure 6. For that reason the parameterization had to be very general, allowing each solder ball to move freely over most of the surface, see figure 7.

The built-in move command in Comsol was used to relocate each solder ball and the simplest parameterization possible was chosen: absolute x- and y-coordinates.

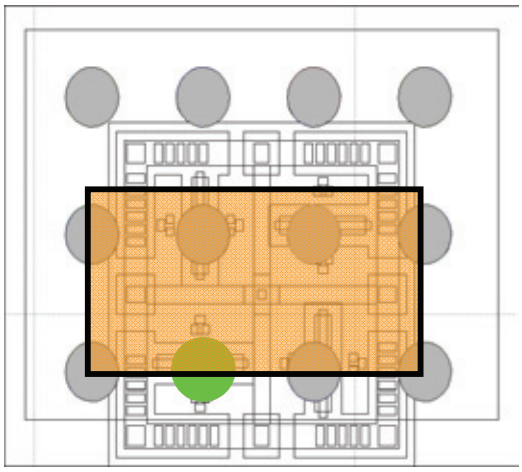

Figure 7. In order to realize probably every possible design configuration, the parameter ranges of each solder ball had to be generous. The orange rectangle shows the parameter space of the green solder ball.

In order to take manufacturing constraints into account, the minimum allowed distance between center to center of two solder balls was increased from 330 μm, respecting only the solder balls, to 500 μm.

3.3 Process automation

Each design candidate was evaluated in an automatic process, including import of CAD geometry and moving each solder ball to the specified location. The design was then meshed, solved and the offset error, as well as the stresses, was extracted. Based on the log files, a command file in Matlab format was assembled which carried out the process above. The command file included the move command of each solder ball as well as a set of custom postprocessing commands. Besides saving the specified results to an ascii file, several plots of interesting results were saved for continuous monitoring.

For each new design, modeFRONTIER created a new command file with the correct x- and y-locations for each solder ball. Comsol Multiphysics was then run in batch and the results were read from the ascii file.

In order to capture designs where solder balls were located too close, a collision detection check was implemented directly in

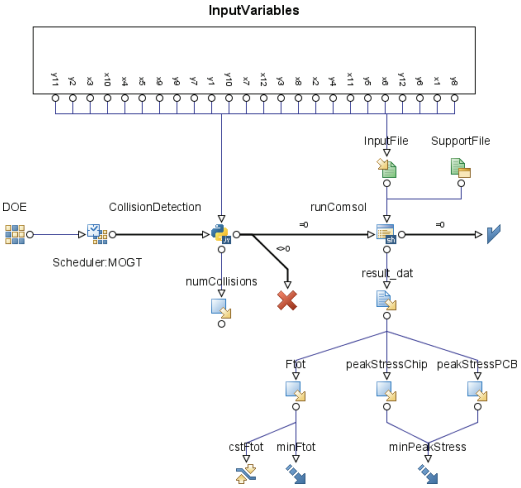

Figure 8. The optimization logic is visualized by the modeFRONTIER workflow. At the top are the 24 input variables and below the bold process line we find extraction of results and specification of constraints and objectives. Each design is checked for collisions and only zero-collision designs are passed on to Comsol Multiphysics for evaluation.

modeFRONTIER. As can be seen in figure 8, each design candidate is first checked for collisions. Only designs with zero collisions are passed on to Comsol for evaluation.

The optimization was run on a 64-bit Linux system and the solution time for a design evaluation with Comsol Multiphysics varied from 9 to 15 minutes.

4. Optimization strategy

In order to allow BGA design layouts which were very different from the baseline design, the range of each input parameter had to be wide. It was therefore not possible to avoid collisions. As the collision check stops impossible designs from being evaluated, the learning process of the optimization algorithm is slowed down.

A good choice for this type of situation is the Multi-Objective Genetic Algorithm (MOGA-II), one of the most popular algorithms available in modeFRONTIER. By using a population of designs, it mimics the genetic mechanisms found in nature to search for the best designs. Here, an initial population of about 50 designs would be suitable.

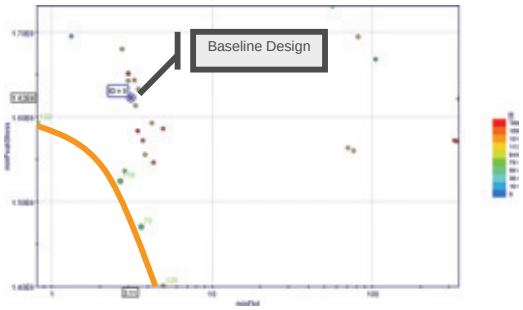

Figure 9. Starting from the baseline design, the Multi-Objective Game Theory algorithm was able to find significantly improved designs in 5 hours. The orange line marks the Pareto front between the conflicting objectives: minimization of offset error (x-axis) and minimization of peak stress (y-axis).

4.1 Creating the initial population

The initial population may be created by setting up a large Design of Experiments (DoE), running the collision test and then selecting 50 well separated designs from those who pass. Unfortunately, a Sobol space filler DoE of 256000 designs was executed in 1.5 hours without finding a single feasible design. In this 24 dimensional input parameter space, collisions between the solder balls are obviously common.

In the second attempt, 6 interesting and different BGA layouts were designed manually. Unfortunately, only the baseline design solved without errors. A later investigation revealed that the root cause was the mesh control settings but at this stage, the model was not changed.

The third attempt used the baseline design as a starting point for the Multi-Objective Game Theory (MOGT) algorithm. Despite being a pretty efficient and sensitive algorithm, MOGT evaluated 168 designs in 5 hours before it was manually stopped. Out of the 168, 140 designs failed to evaluate, mainly due to colliding solder balls, but some 5 percent due to geometry, meshing and solver errors.

Figure 9 shows the two conflicting goals where the utopia point, located in the lower left corner, implies a vanishing offset error at the lowest peak stress possible. The best designs with respect to the conflicting objectives are called the Pareto set (marked by green rings), and are located at the Pareto front (orange line). As a welcome side effect in our search for a

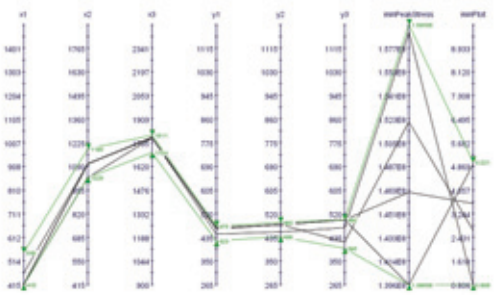

Figure 10. The parallel coordinates chart shows both objectives and the input parameters in the same diagram for the 4 Pareto designs. Compared to the specified input ranges, showed by the full height of the axes, the Pareto designs are concentrated to a narrow zone. Based on this, the parameter ranges were reduced before starting the MOGA optimization.

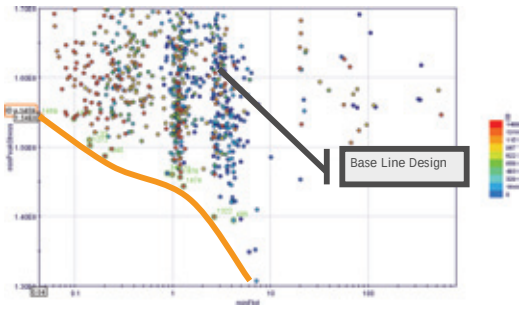

Figure 11. The multi-objective optimization aims to reveal the Pareto front, marked by the orange line. The marked designs in the lower left corner represent the best trade-off designs between offset error and service life. Note the two zones with accumulation of designs which indicate some issue with the analysis.

suitable initial population for MOGA, we found a design which had 2% lower stress and 74% lower offset error than the baseline design.

4.2 Multi-objective optimization

Good initial designs are one of the most efficient ways to speed up the optimization process for obvious reasons. Another is to reduce the size of the design space which is being searched. In this case, the reduction of possible combinations was not the main reason. Instead, smaller parameter ranges decreased the risk of collisions and hence increased the possibility for the algorithm to learn.

Using the parallel coordinates chart, see figure 10, the variation between the current Pareto designs was evaluated for each input parameter. In order not to limit the performance of the best solutions, a margin of approximately the same size as the variation was added when each input parameter got a new reduced range.

It was decided not to follow the recommended size of the initial population but rather use a significantly smaller set. The main reason for this was the inability to create an initial population with non-colliding BGA layouts from all regions of the input design space. The 10 best designs of the MOGT optimization were therefore chosen, trusting that MOGA would make a steady evolution towards better designs while avoiding colliding BGA layouts.

The strategy worked and MOGA let Comsol Multiphysics evaluate 990 new designs of which 759 completed successfully in 5 days. As can be seen in figure 11, the Pareto front has been stretched out and filled with more designs. While the stress levels were moderately improved compared to the first optimization, the offset error was now close to being eliminated.

5. Results

An extended Pareto front was found which showed improvements in both objectives compared to the baseline design. As always in multi-objective optimization, there is no single best design but rather a set of trade-off designs between the conflicting objectives. The best design with respect to peak stress had 14% lower stress and 15% lower offset error. The best design with respect to offset error had 5% lower stress and 99% lower offset error compared to the baseline design.

Figure 12 show the shear stress in two planes, close to the PCB and close to the MEMS chip. Close to the chip, the stresses appear to concentrate on the balls in the corners of the grid.

The achieved reduction in the offset error by two decades is a significant improvement to the temperature stability in comparison with the base line design.

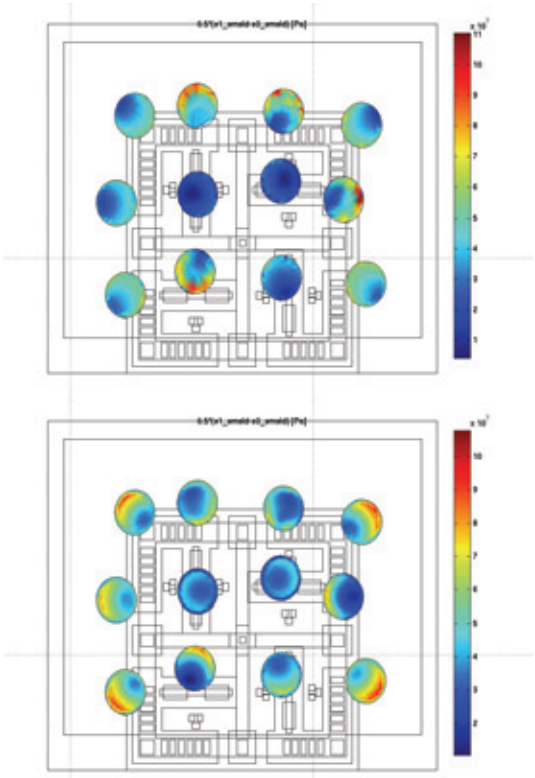

Figure 12. Shear stress in the plane close to the PCB (upper) and the MEMS chip (lower)

6. Discussion

6.1 Automation, stability and throughput

Optimization favors analysis throughput over the shortest solver time for a single design, as the optimization algorithm often exploit parallel design evaluations. When running a large number of analyses, management of errors will also have an impact on the overall throughput. In this project a simple check for errors, sent to standard error (stderr) by Comsol, helped maximizing the number of analyzed designs. The analysis was barely able to fit into the available RAM memory. Running more than 1000 designs in a week with multiple error sources pushed the computing platform to its very limits. During the project, the combination of 64-bit SUSE Linux, Matlab, Comsol and modeFRONTIER proved to give high throughput with absolute stability.

The number of input variables and the chosen parameterization, which invited to collisions between solder balls, put the optimization algorithm through a hard test. While the collision test effectively removed certain regions of the design space, various other errors mentioned above inserted a sort of semi-randomness and added significant complexity to the design task. From an engineering point of view, this situation is not uncommon and some of the most popular algorithms in modeFRONTIER have the power to work on real world problems like this.

6.2 Misplaced mesh controls

The root cause of most, if not all, meshing and out of memory errors was missing or misplaced mesh controls. In order to get accurate stress results in the solder balls, the mesh size was approximately a ¼ of the default element size. Unfortunately, the built-in Comsol move command sometimes provided a different numbering scheme of the geometry entities. When that happened, the mesher created a very fine mesh in unwanted regions while the stress results of the solder balls suffered from low accuracy.

There are several ways to apply mesh controls in a more robust way. Selection may be based on location or, to fix the numbering issue, new geometry may be created at the correct location by Comsol or a CAD system. The latter also opens up the possibility to work with and optimize complex geometry. While import via the geometry import command is straight-forward, using the bi-directional communication between Comsol and the CAD system shows the greatest potential with regards to power and ease of use. It is good practice to save some plots of the mesh in critical regions to be reviewed while the optimization runs.

Figure 11 shows two stretched-out regions where designs have accumulated. Given the underlying physics of the design task, these regions were not expected and implied that some phenomenon with a great influence on the results is shifting between a few modes. A problem with the mesh of the solder balls was immediately suspected and later confirmed. It is safe to assume that the performance of the optimization algorithm was significantly degraded due to this problem. Fortunately, being a global search algorithm, it found Pareto designs on both sides of these regions.

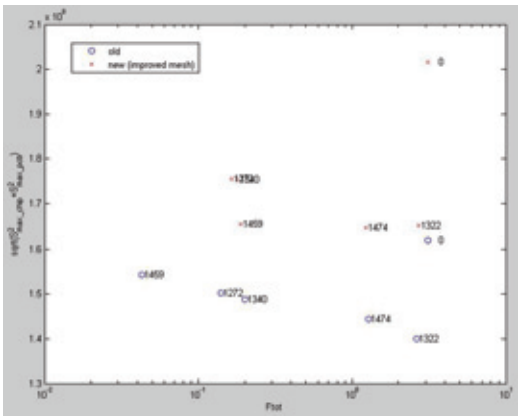

Figure 13. Using a high-accuracy mesh, five Pareto designs were validated. Design 1459 maintains a 94% reduction in offset error compared to the 99% achieved in the optimization.

6.3 Validation with a high-accuracy mesh

The baseline and five Pareto designs were validated using a high accuracy mesh. As can be seen in figure 13 the new mesh relocated and reordered the Pareto front. All designs got higher stresses and the offset error for the previously best designs increased somewhat. The offset error of the former best design, 1459, changed from a 99% to a 94% reduction. Unintentionally, this exemplifies the relative relationship between the trends of design improvement versus various random error sources. In this case, where the random errors are in the range of 5-10%, we may still obtain over 90% design improvement.

6.4 Future directions

The presented work has showed that the offset error may be close to eliminated. In order to increase the accuracy of the model a capacitance calculation should be included. This enables minimization of computed offset error in acceleration units instead of the current anchor displacements.

Manufacturability may also be studied by analysing the sensitivity of the results due to small changes in the location of the solder balls. In other words, we are looking for a robust global optimum.

7. Conclusions

Comsol Multiphysics is well suited for parametric optimization and the combination with modeFRONTIER invites to deeper understanding and more efficient exploration of large design spaces. In this case, the Pareto designs provided a better understanding of the relevant aspects in the behavior of the MEMS accelerometer under temperature load.

While revealing a problem with the numbering of geometric entities, the study demonstrated the power of a global search algorithm which proved itself also under very harsh conditions.

An order of magnitude improvement in measurement error was achieved which may validate the sensor to a wider range of applications which are demanding with respect to specified offset error.

9. Acknowledgements

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