TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Electrical Engineering and Information Technology Institute of Electromechanical and Electronic Design

Robust Design and Optimization of Thick Film Accelerometers in COMSOL Multiphysics with OptiY

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Outline

1. Concept of Tolerance Analysis with OptiY

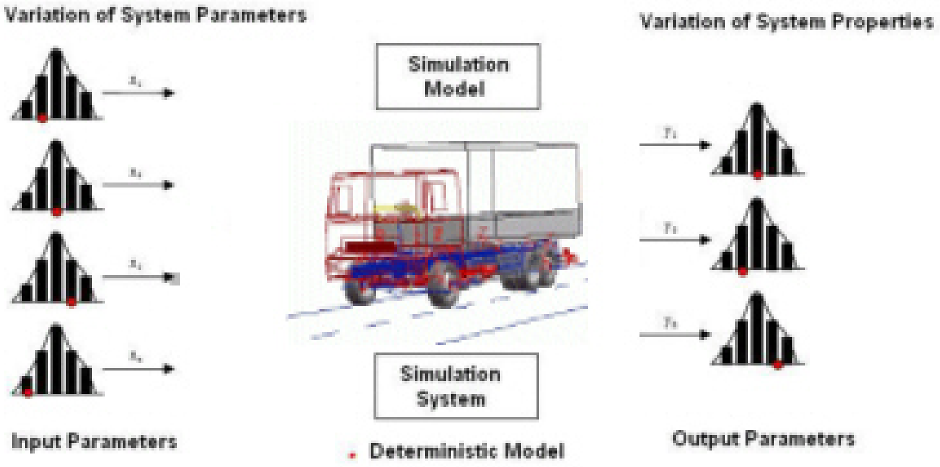
Virtual Design Process

- Design parameters must be specified so that all specified requirements are met
- Variability and uncertainty of design parameters (tolerances) caused by:
  - Manufacturing inaccuracy
  - Process uncertainty
  - Scattering of material properties
  - Environmental influences
  - Abrasion
  - Human factors
- This produces variability and uncertainty of performance, functional variables, output parameters, and rejections

1. Concept of Tolerance Analysis with OptiY

Involving Tolerances into the Design Optimization

- Distributed input parameters
- Deterministic simulation model, e.g.:
  - Analytic model
  - Lumped element model
  - FE-model
  - ...
- Output distributions



1. Concept of Tolerance Analysis with OptiY

Methods of Computation of Output Distributions (implemented in OptiY)

- Monte-Carlo methods
- Analytic methods:
  - Second Order Analysis (SOA)
  - Reduced SOA (RSOA)

$$f = f_0 + \sum_{j=1}^{n} \frac{\partial f}{\partial x_j}\left(x_j - x_0\right) + \frac{1}{2}\sum_{j=1}^{n} \frac{\partial^2 f}{\partial x_j^{\,2}}\left(x_j - x_0\right)^2$$

Methods of Optimization (implemented in OptiY)

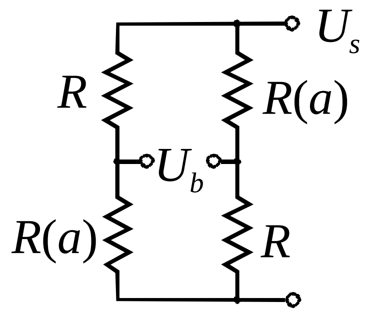
- Grid search
- Hooke-Jeeves method
- Evolutionary algorithms

1. Concept of Tolerance Analysis with OptiY

Steps in Tolerance Analysis and Optimization

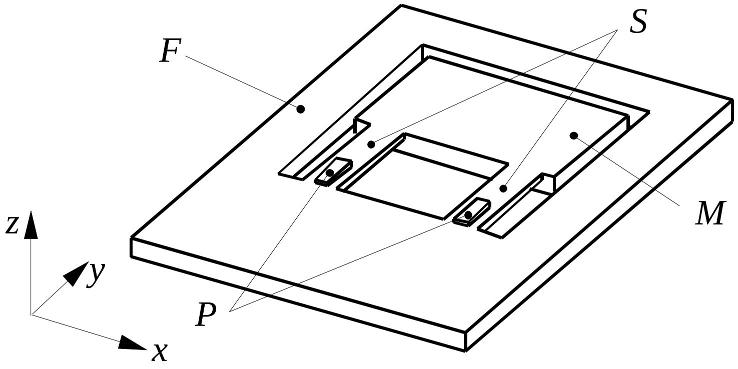
▪ Nominal Optimization	⇒ Set of design parameters for an optimal function
▪ System Failure Analysis	⇒ Rejection Probability caused by tolerances
▪ Sensitivity Analysis	⇒ Importance of the tolerances to the function
▪ Design for Minimal Rejections	⇒ Set of design parameters for an optimal function with regard to the tolerances
▪ Design for Robustness	⇒ Set of design parameters for minimized scattering of the function

2. Thick Film Accelerometer



Working Principle

- Elements:
  - Seismic mass M
  - Leaf springs S
  - Bonded frame F
  - Piezo-Resistors P
  - Measuring Bridge



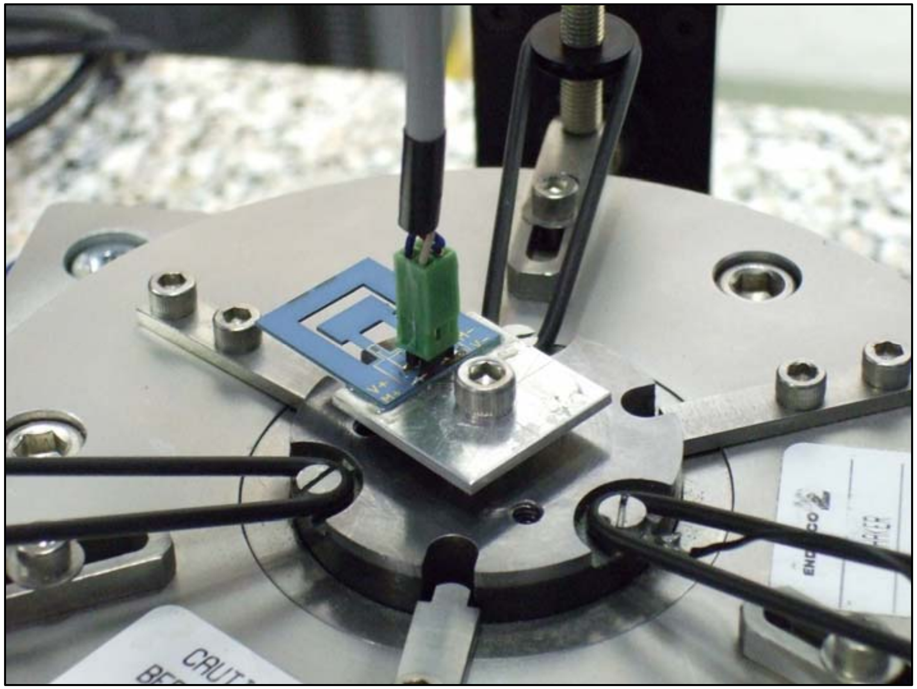
- Sensitive for acceleration in z-direction

- Cross sensitive for accelerations in x-, y-direction

2. Thick Film Accelerometer

Working Model

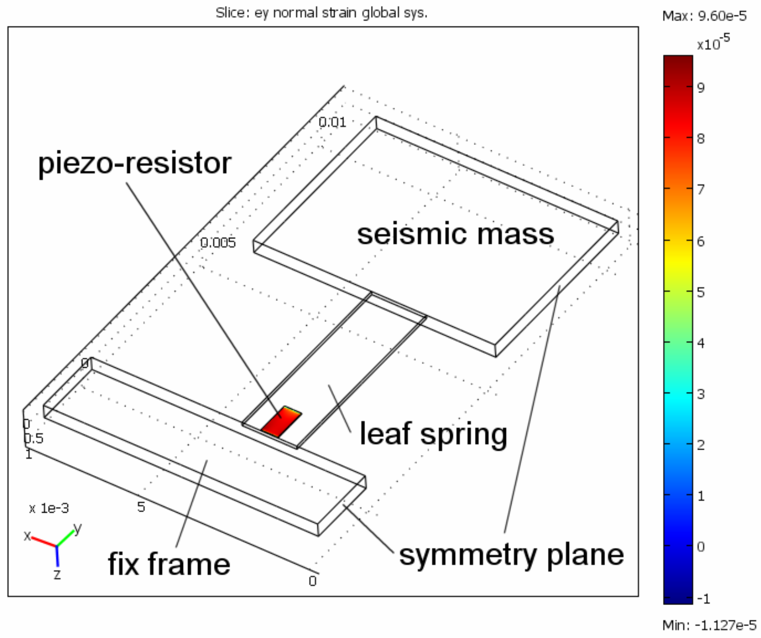
- Made of Low Temperature Cofired Ceramics (LTCC)
- Manufactured at the Fraunhofer-Institute for Ceramic Technologies and Systems, Dresden, Germany
- Characterization by a vibration exciter



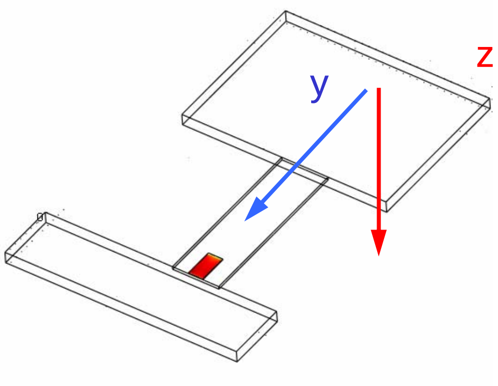
2. Thick Film Accelerometer

COMSOL Multiphysics Model

- Excitation far from resonance $\Rightarrow$ static structural mechanics model
- Plane symmetry $\Rightarrow$ one half sensor is modeled
- Linear material, small deformations
- Acceleration as a volume force
- Lower boundary of the frame is fixed
- 40.000 DOF's



2. Thick Film Accelerometer



COMPOSL Multiphysics Model

- Mean normal strain in the piezo-resistors measures ΔR
- Solved for:
  - Sensitivity S to acceleration in z-direction
  - cross sensitivity CS to acceleration in y-direction
  - First resonance frequency f_R

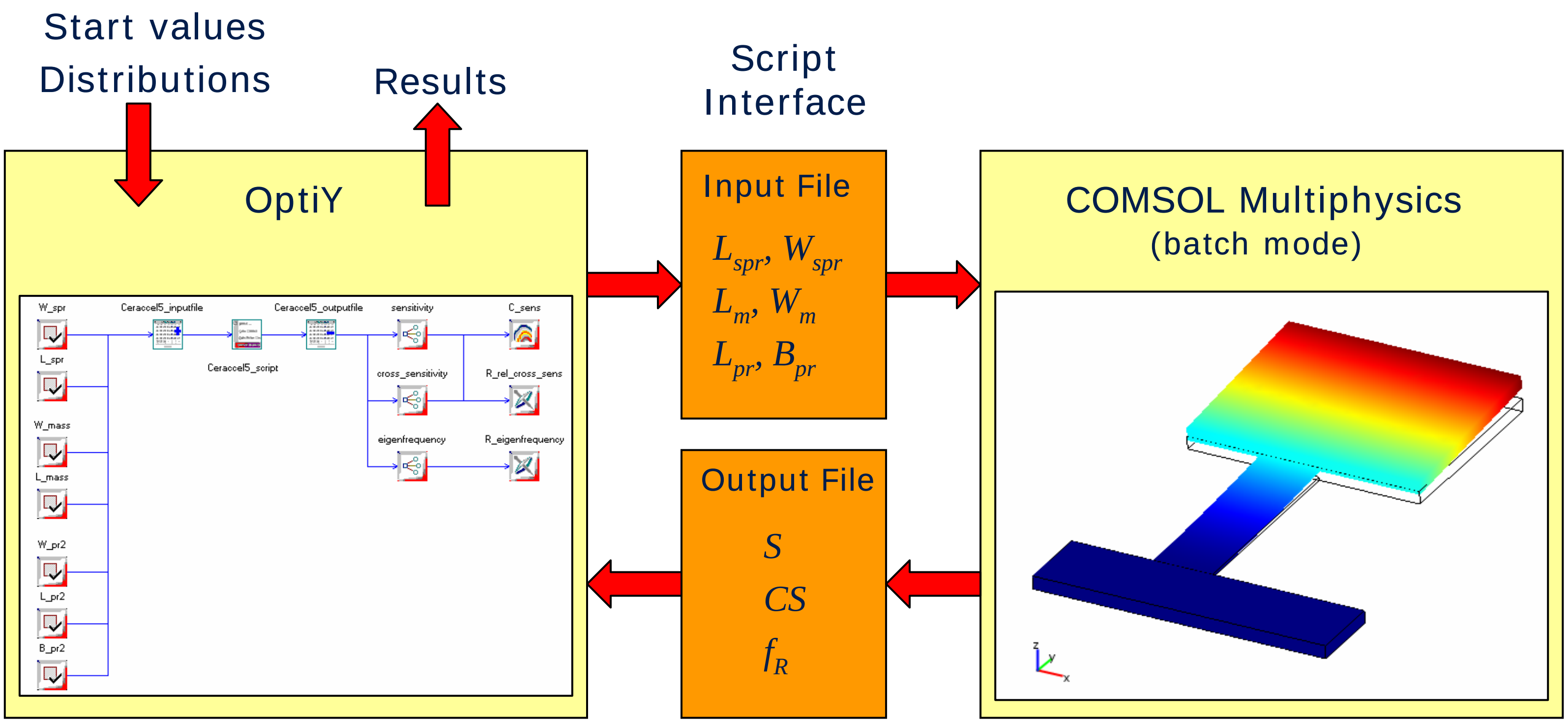
$$\frac{\Delta R}{R} = e_{ym} \cdot k$$

$$S = \frac{U_b}{U_s \cdot a_z} = \frac{\Delta R}{2R \cdot a_z} = \frac{e_{ym} \cdot k}{2a_z}$$

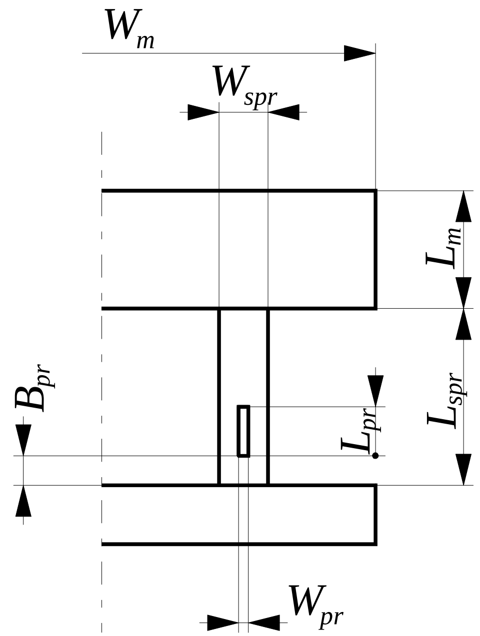
$$CS = \frac{U_b}{U_s \cdot a_y} = \frac{\Delta R}{2R \cdot a_y} = \frac{e_{ym} \cdot k}{2a_y}$$

2. Thick Film Accelerometer

Coupling of OptiY and COMSOL Multiphysics



3. Nominal Optimization



Input Parameters for optimization:

- Length L_{spr} and width W_{spr} of the leaf springs
- Length L_m and width W_m of the seismic mass
- Length L_{pr} of the piezo-resistor
- Distance B_{pr} between the piezo-resistor and the frame

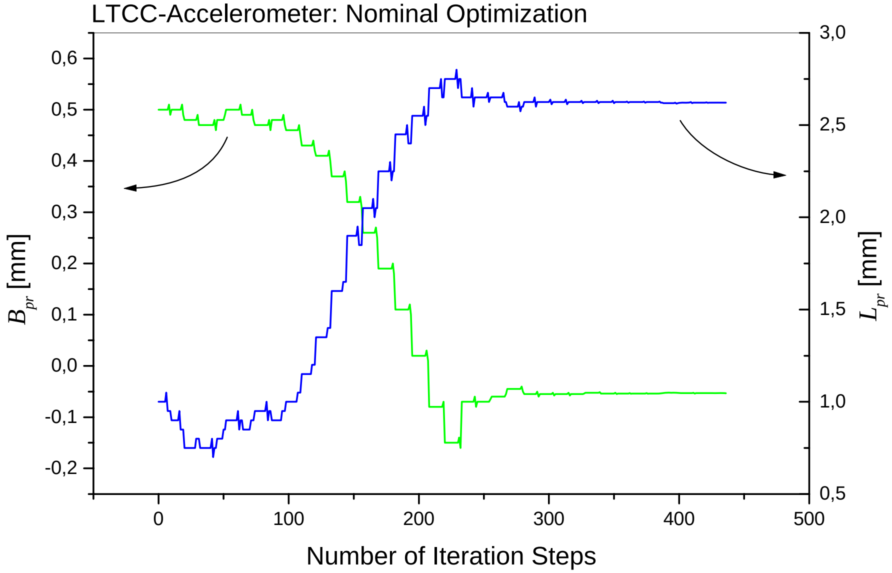
Output Parameters for Optimization:

- Sensitivity S ⇒ find maximum, 50 µV/(V*g) expected
- Rel. cross sensitivity $CS_{rel} = CS / S$ ⇒ constrained [0; 2%]
- First resonance frequency f_R ⇒ constrained [230 Hz; 260 Hz]

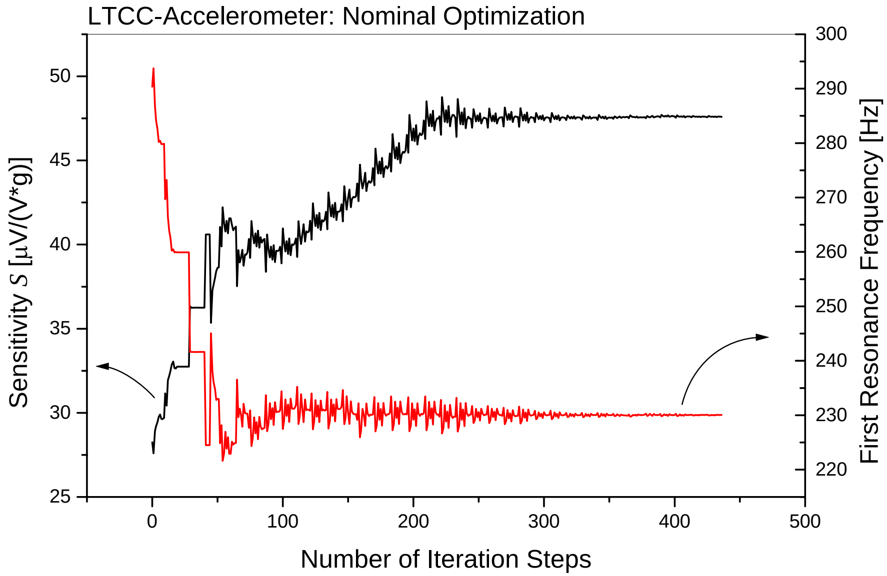
3. Nominal Optimization

Optimization Process

Design variables iteration process



Function variables iteration process



3. Nominal Optimization

Performance Parameters:

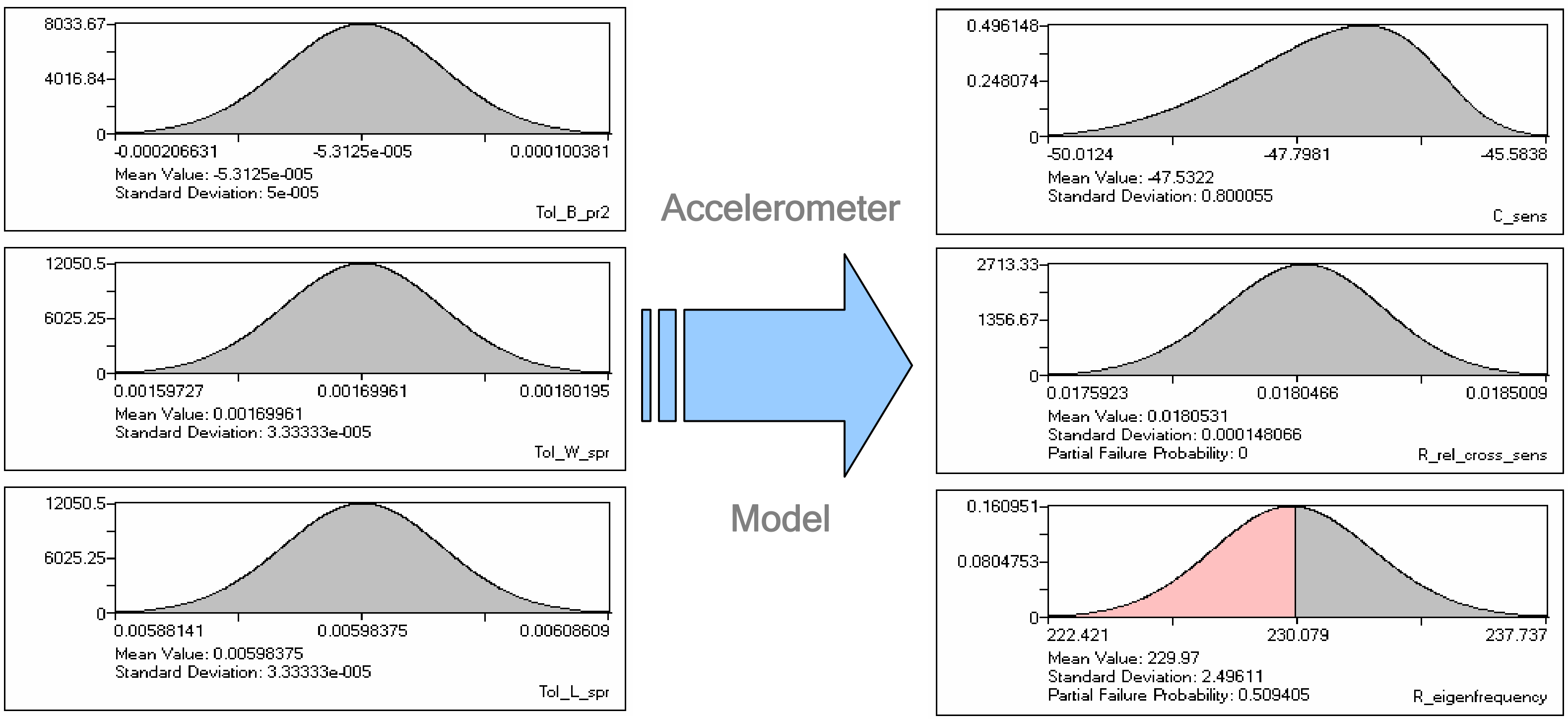
Funtional Parameter	***Constraint***	***Start Value***	***Optimal Value***
Sensitivity	find maximum	27,6 µV/(V*g)	47,6 µV/(V*g)
Relative Cross Sensitivity	[0; 2%]	1,76 %	1,8 %
1. Resonance Frequency	[230 Hz; 260 Hz]	293,7 Hz	230,0 Hz

4. Tolerance Analysis

System Failure Analysis

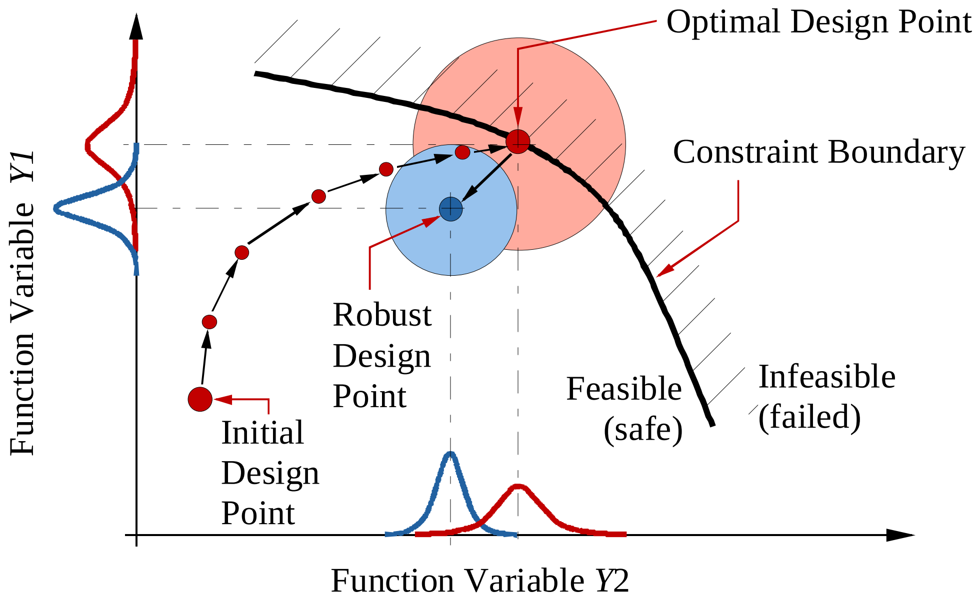
Design variables distributions

Function variables distributions



5. Probabilistic Design

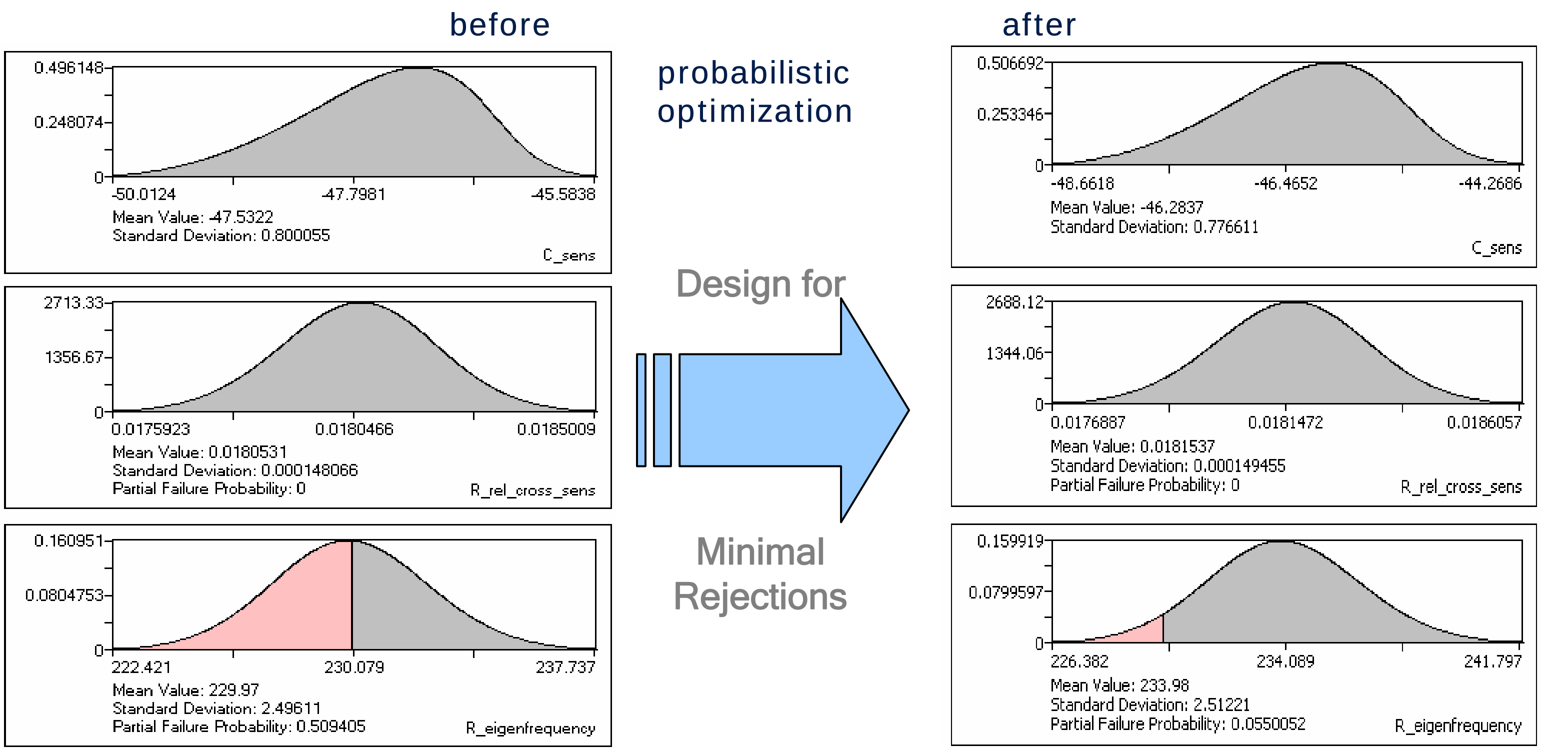
Minimizing Rejections (Design for Minimum Rejections)



5. Probabilistic Design

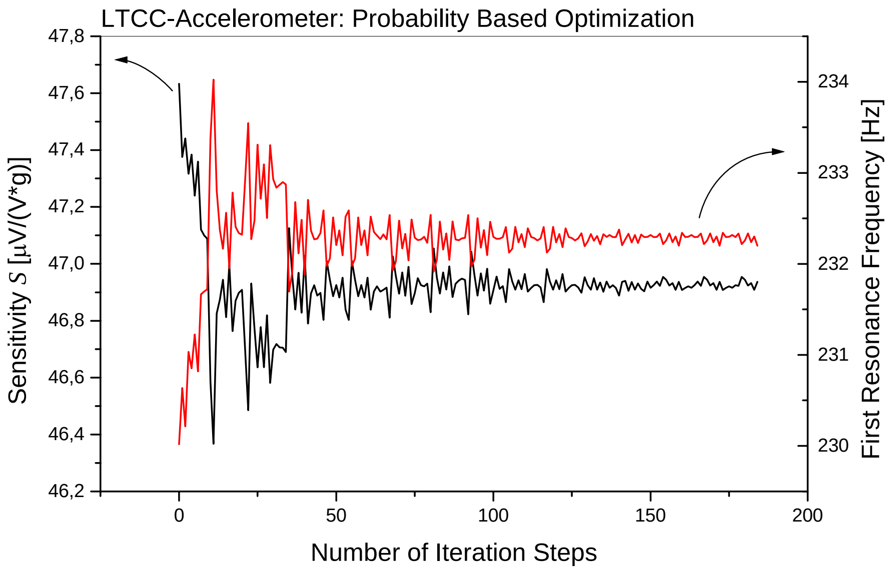
Minimizing Rejections

Function variables distributions



5. Probabilistic Design

Performance Parameters:



Funtional Parameter	***Constraint***	***Start Value***	***Optimal Value***	***Robust Value***
Sensitivity	find maximum	27,6 µV/(V*g)	47,6 µV/(V*g)	46,4 µV/(V*g)
Relative Cross Sensitivity	[0; 2%]	1,76 %	1,8 %	1,8 %
1. Resonance Frequency	[230 Hz; 260 Hz]	293,7 Hz	230,0 Hz	234,0 Hz

6. Conclusions

- OptiY and COMSOL Multiphysics are easy to connect at the script interface
- OptiY tool allows to perform different numerical experiments, e.g.
  - Nominal optimization
  - Tolerance analysis (sensitivity analysis, failure probability)
  - Probability based design optimization (design for minimal rejections, design for robustness)
- Solution times (COMSOL model requires 5 minutes to solve, 3 tolerances):
  - Nominal optimization: 1 day
  - Tolerance analysis: 1 hour
  - Probability based design optimization: 1 week
- Probability based design was performed for an thick film accelerometer