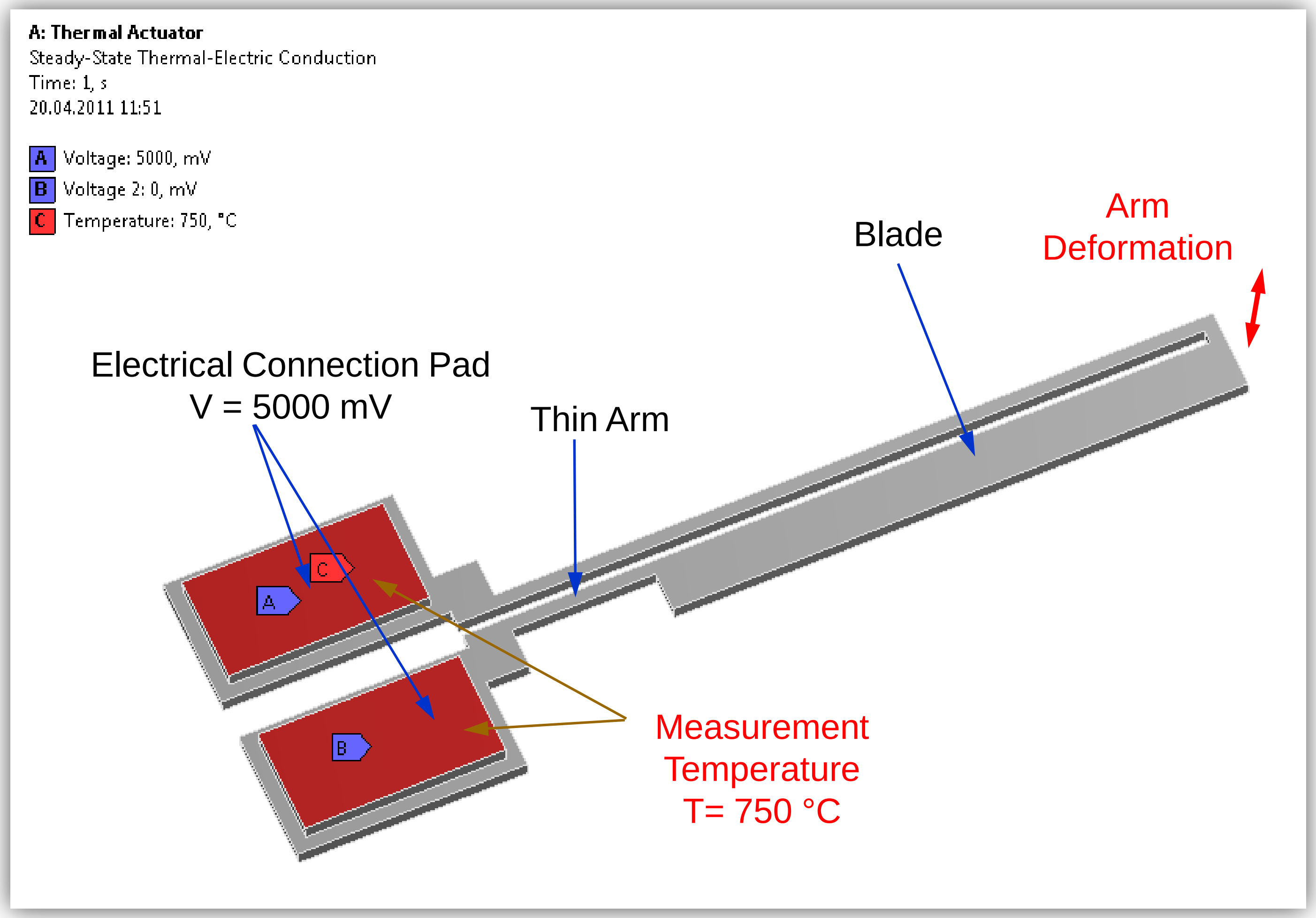
Robust Design

of Micro-Electro-Mechanical Systems (MEMS) on the Example of a Thermal Actuator

OptiY GmbH - Germany

Thermal Actuator



Initial Nominal Parameters

Design Parameters

Name	Nominal	Unit
Blade Length	40	um
Blade High	3	um
Thin Arm High	1	um
Thin Arm Length	10	um
Arm Gap	1	um
Pad High	6	um
Pad Length	12	um
Pad Distance	2	um
Base Length	3	um
Base High	3	um
Arm Thickness	1	um
Thermal Conductivity	124	W mm^-1 C^-1
Scale of Thermal Expansion	1	
Material Density	2330	kg mm^-3
Pad Voltage	5000	mV
Temperature	750	C
Material Resistivity	0.1	ohm mm

Variable Design Parameters:

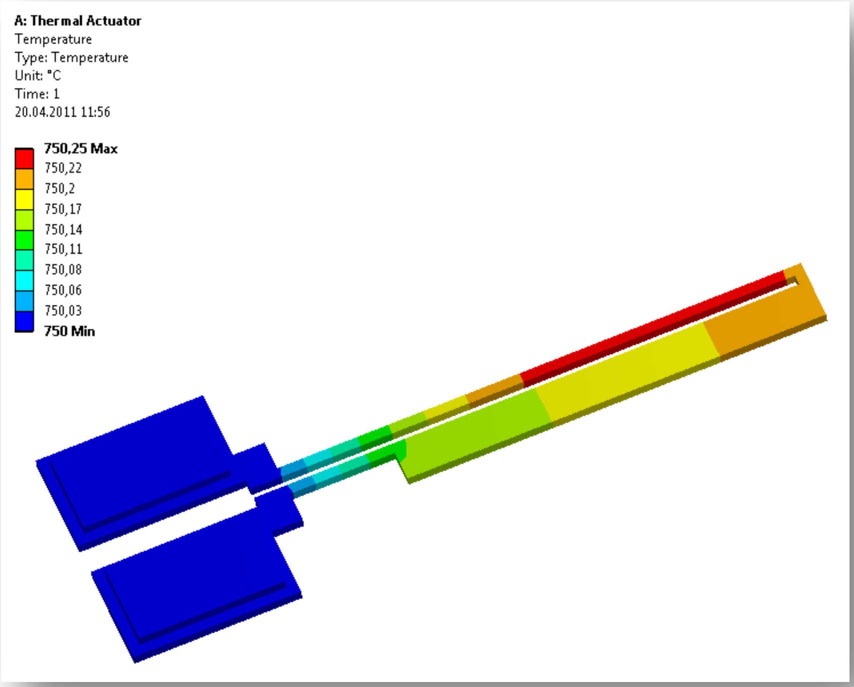
- Blade Length
- Blade High
- Thin Arm High
- Thin Arm Length
- Arm Gap
- Pad High
- Pad Length
- Pad Distance
- Base Length
- Base High
- Arm Thickness

Fix Process Parameters:

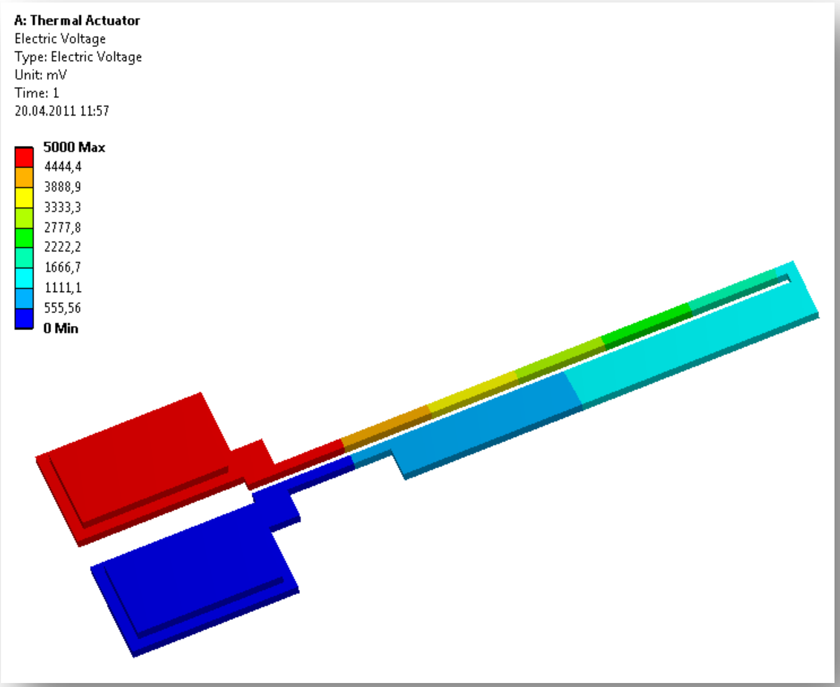
- Thermal Conductivity
- Scale of Thermal Expansion
- Pad Voltage
- Temperature
- Resistivity

Nominal FE-Simulation

Temperature Distribution
Operating Point = 750 °C

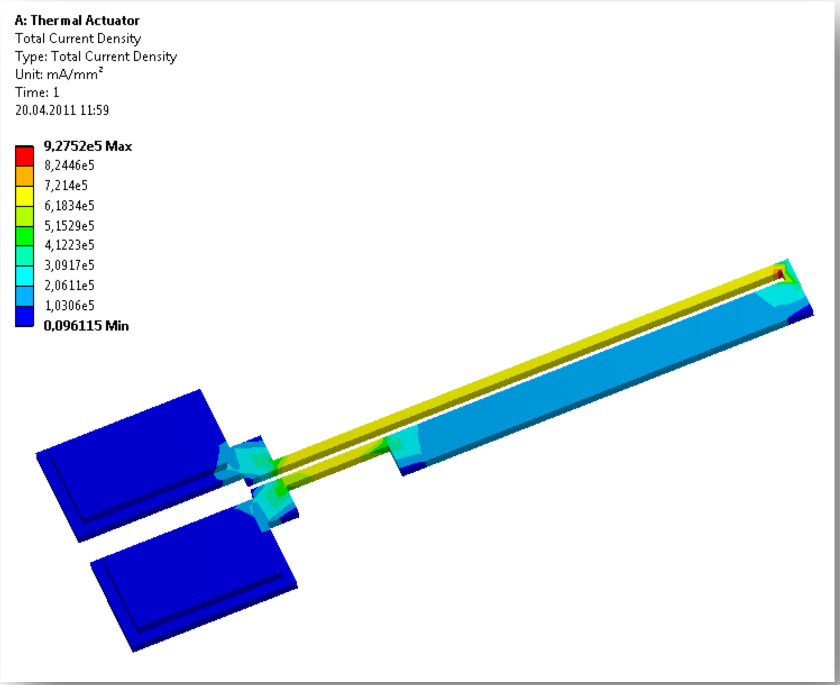


Electric Voltage Distribution
U = 5000 mV

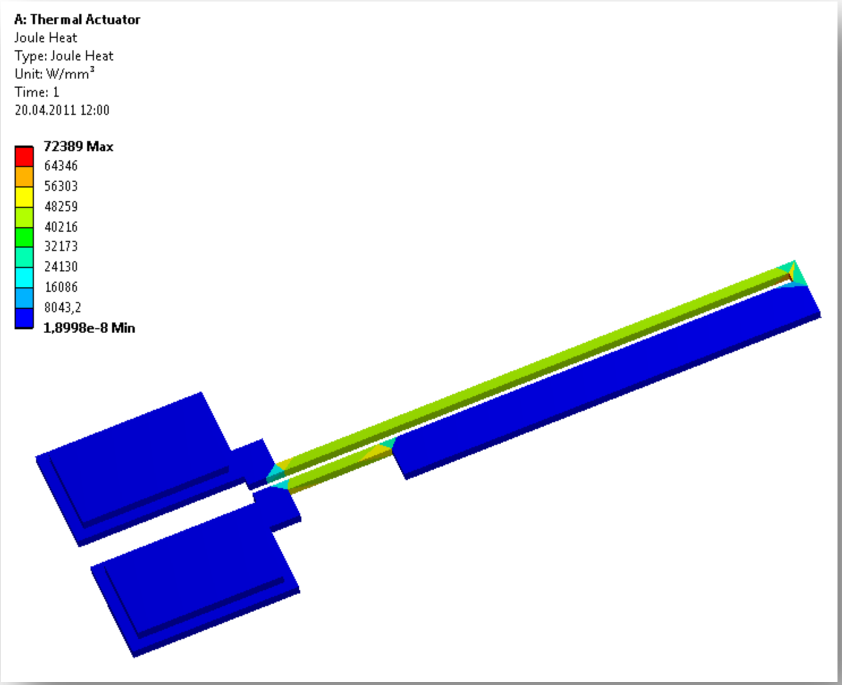


Nominal FE-Simulation

Current Density Distribution

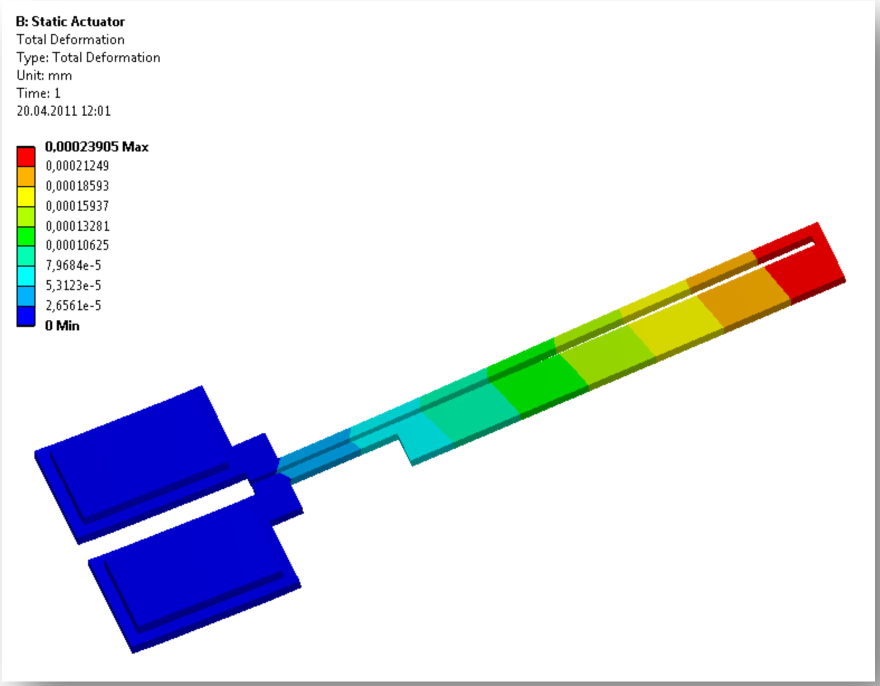


Joule Heat Distribution

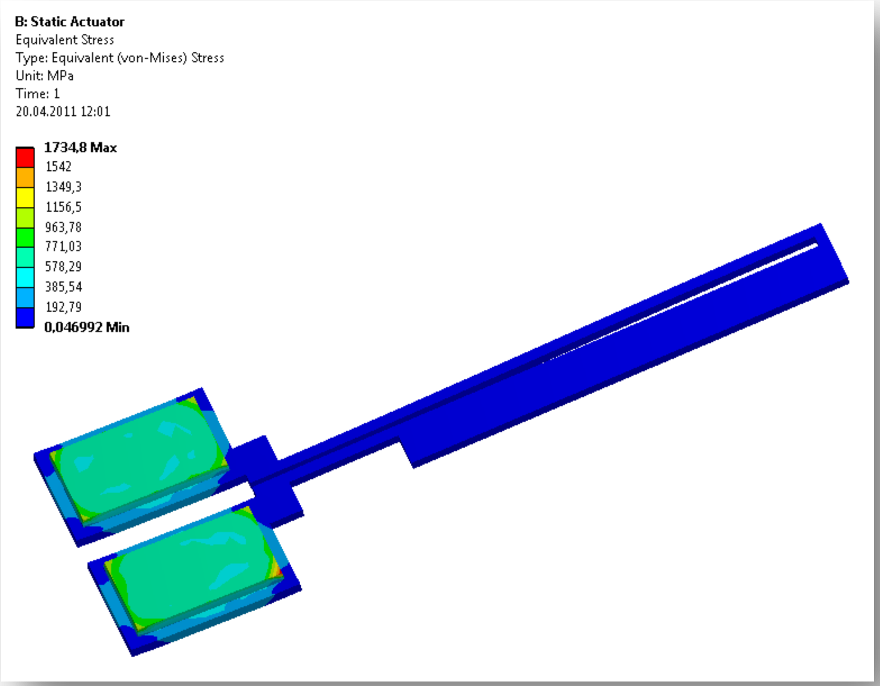


Nominal FE-Simulation

Arm Deformation
X = 0.23 µm (max)



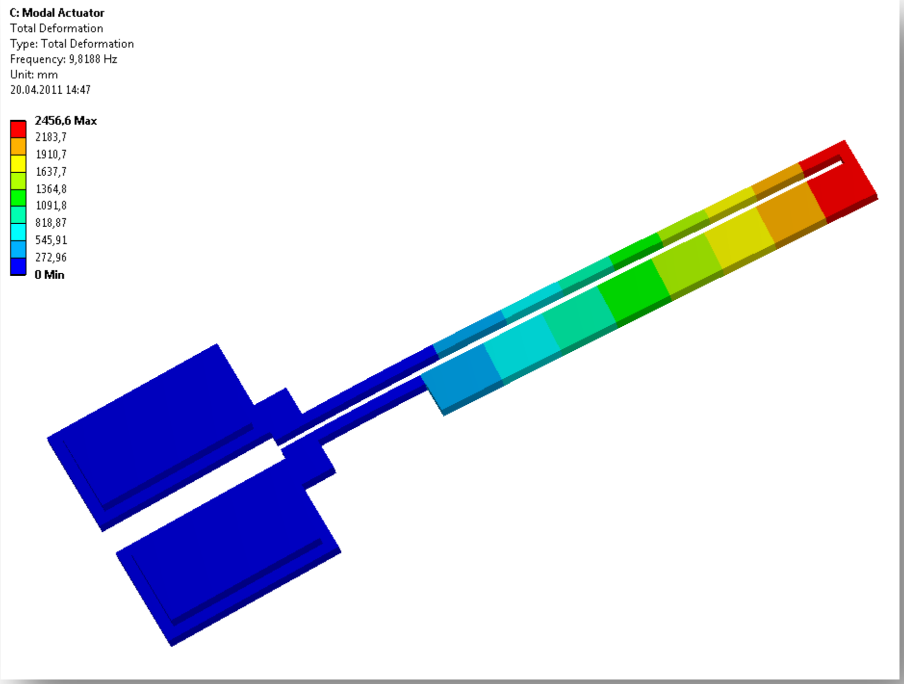
Equivalent Stress (von Mises)
P = 1734 Mpa (max)

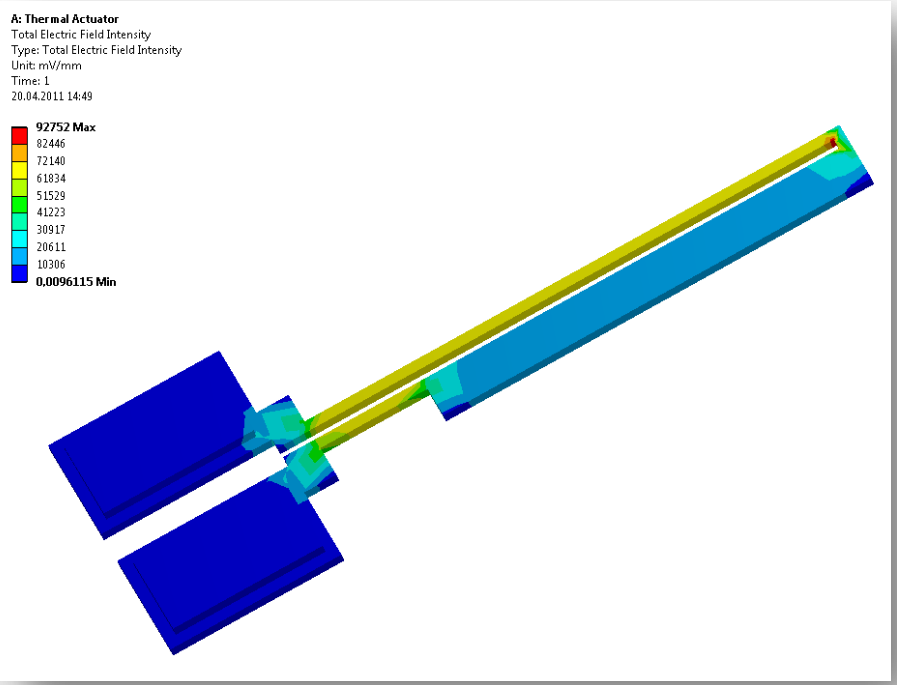


Nominal FE-Simulation

1. Resonance Frequency
f = 9,81 Hz

Electric Field Intensity





Design Specifications

Design Parameter Space:

• Blade Length	= [37.5, 42.5]	µm
• Blade High	= [2, 5]	µm
• Thin Arm High	= [0, 3]	µm
• Thin Arm Length	= [7.5, 12.5]	µm
• Arm Gap	= [0.5, 1.5]	µm
• Pad High	= [5, 7]	µm
• Pad Length	= [11, 13]	µm
• Pad Distance	= [1.5, 2.5]	µm
• Base Length	= [2.5, 3.5]	µm
• Base High	= [2.5, 3.5]	µm
• Arm Thickness	= [0.5, 1.5]	µm

Geometry Tolerances = 0.2 µm
With Normal Distribution

Fix Process Parameters:

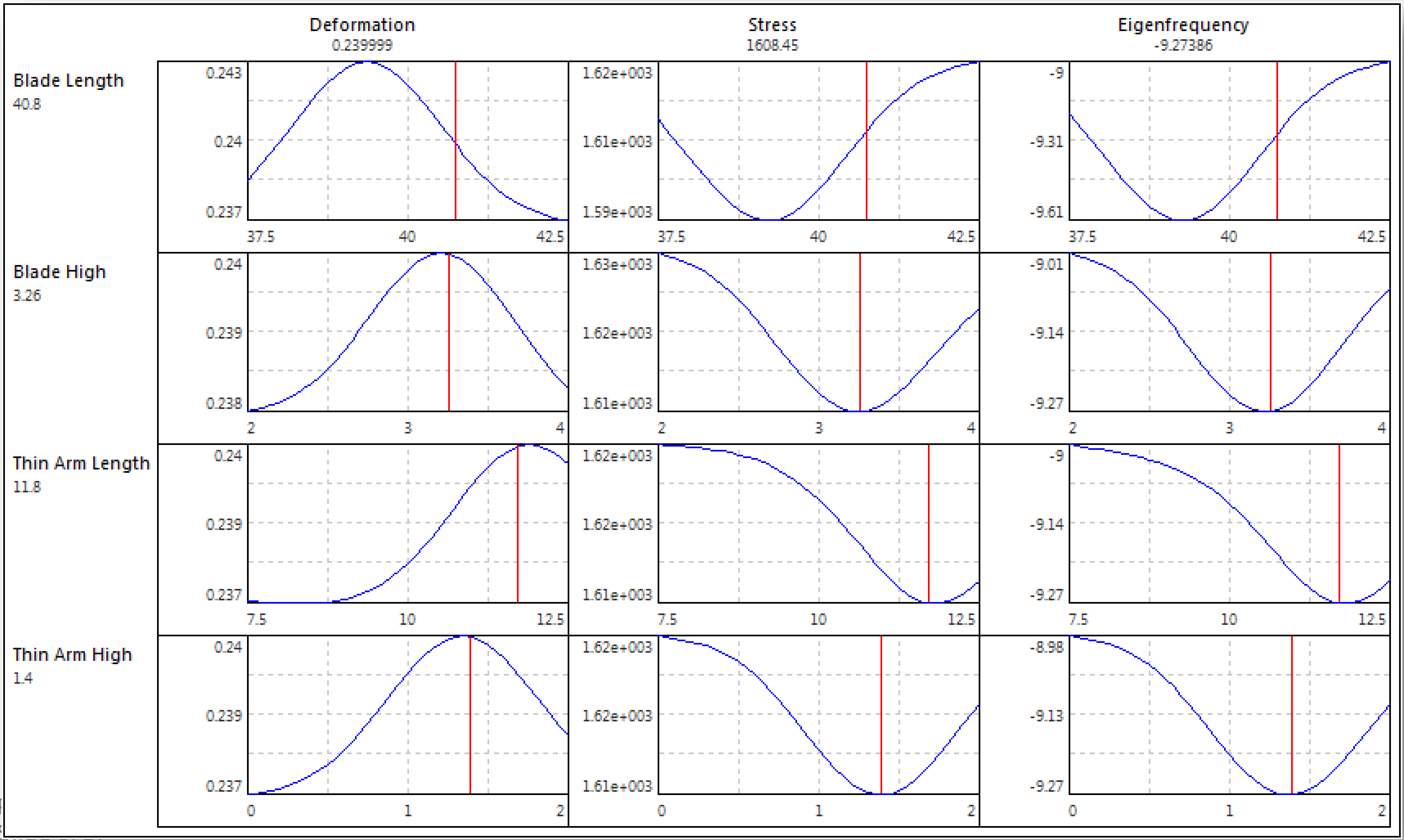
- Thermal Conductivity = 124 W mm^-1 C^-1
- Scale of Thermal Expansion = 1
- Pad Voltage = 5000 mV
- Temperature = 750 °C
- Resistivity =0.1 ohm mm

Uncertainties = 5%
with Normal Distribution

Functional Requirements:

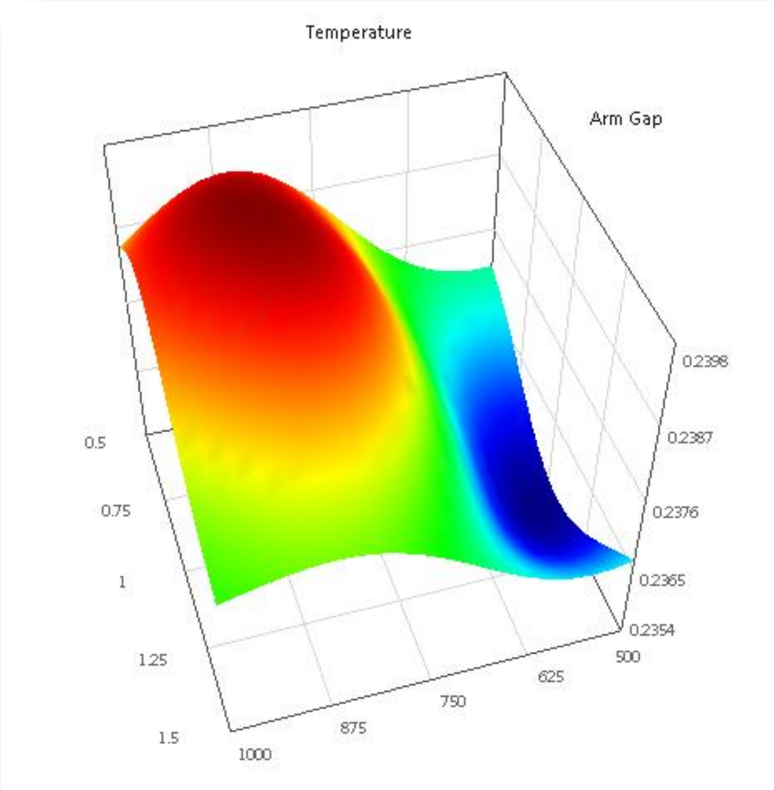
- Deformation = [0.2 , 0.24] µm
- Stress = minimal as possible
- Frequency = maximal as possible

Design Space: 2D Section Diagrams

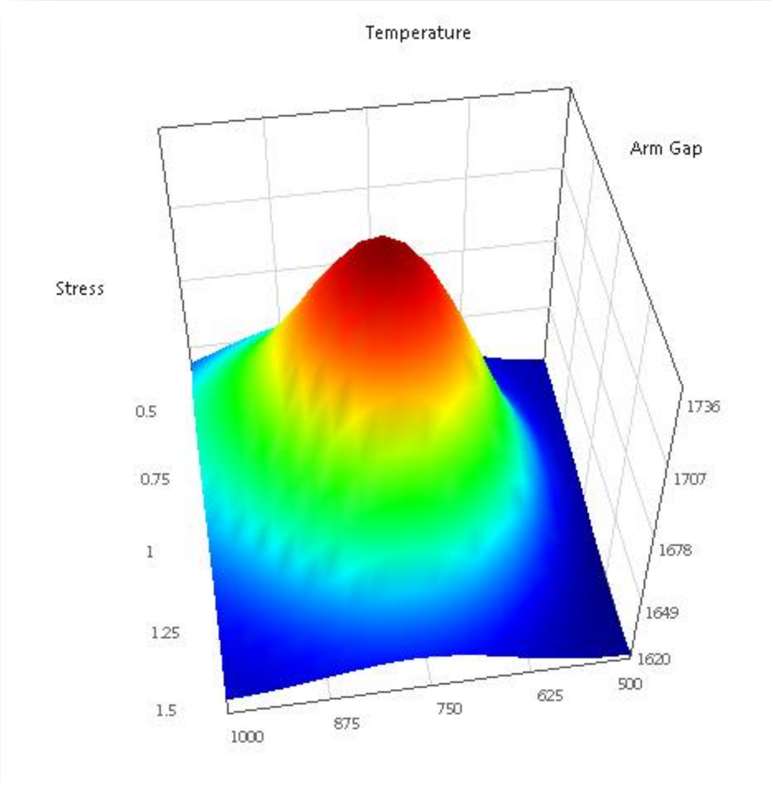


Design Space: 3D Graphics

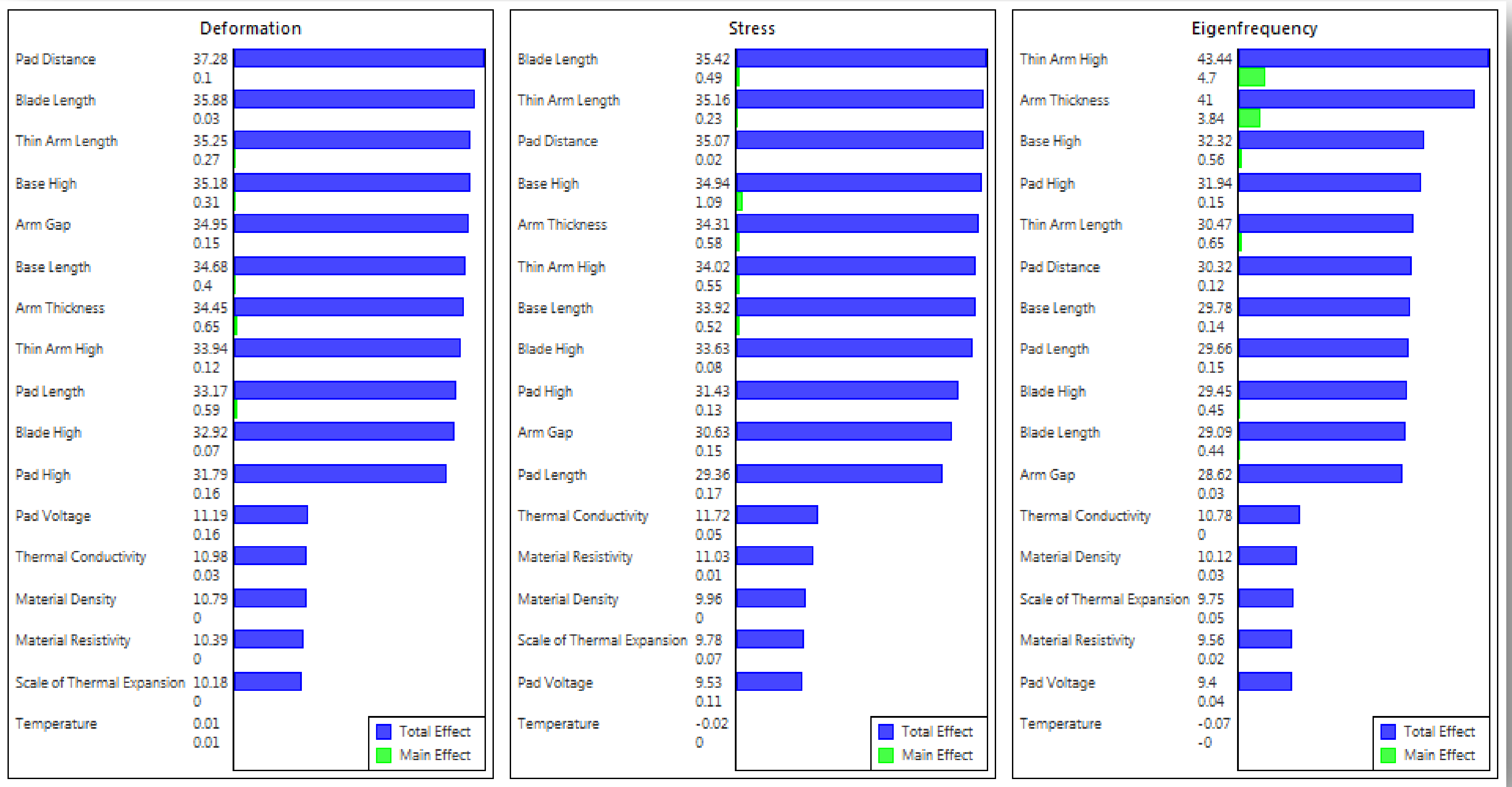
Deformation



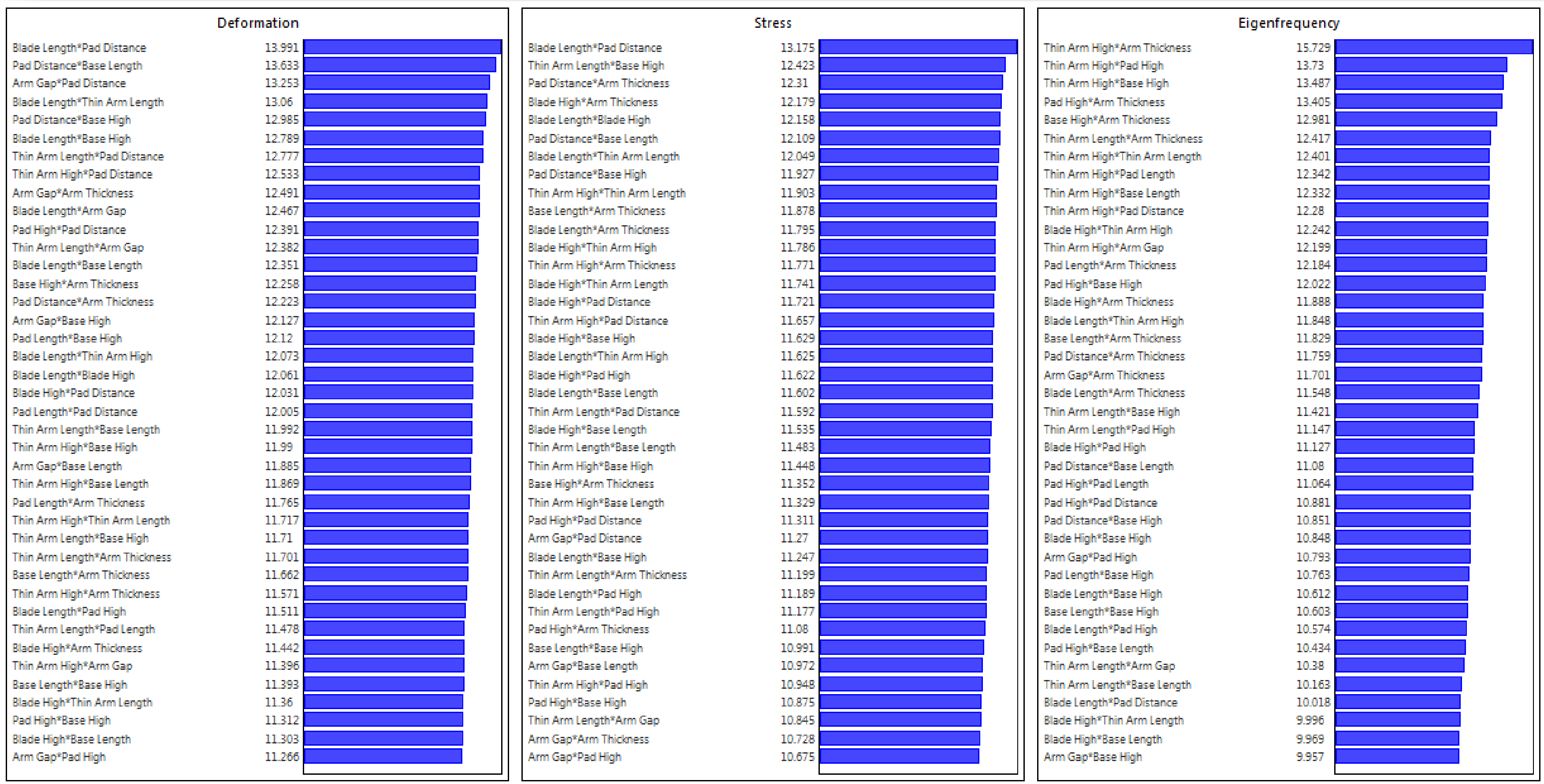
Stress



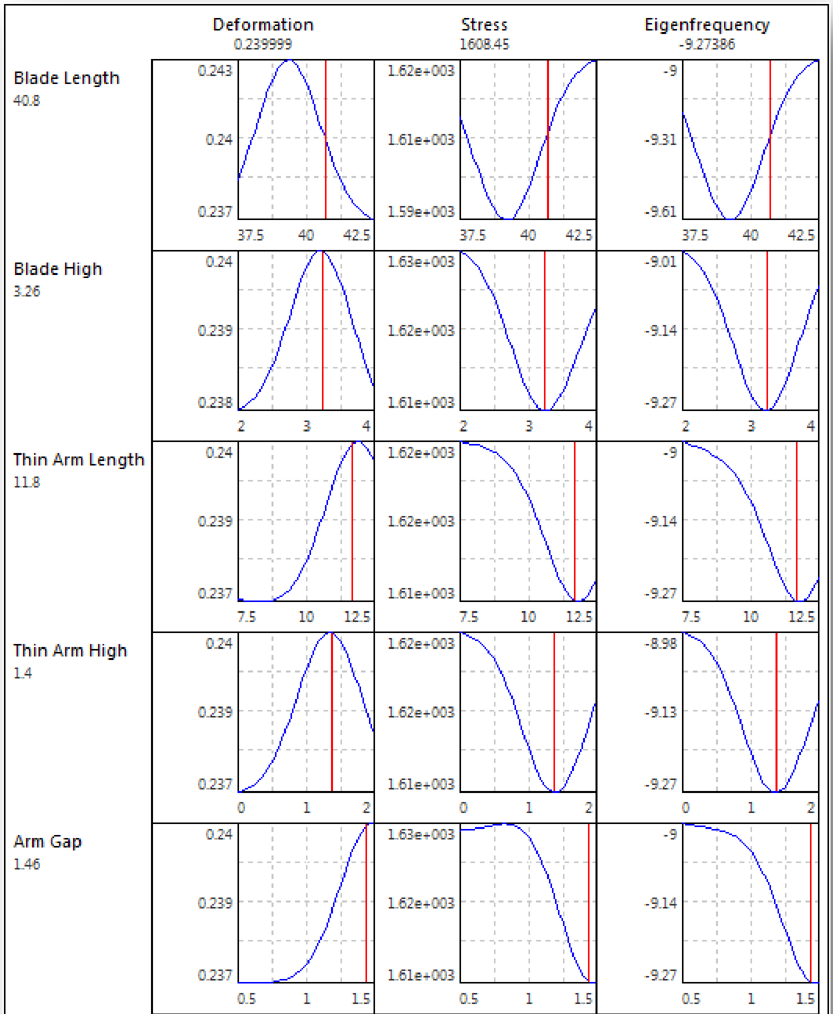
Global Sensitivity: Parameter Importance [%]



Global Sensitivity: Parameter Interaction [%]



Nominal Design Optimization



Optimization Goals:

- Constraint: 0.2 µm ≤ Deformation≤ 0.24 µm
- Criteria: Minimize Stress and Frequency

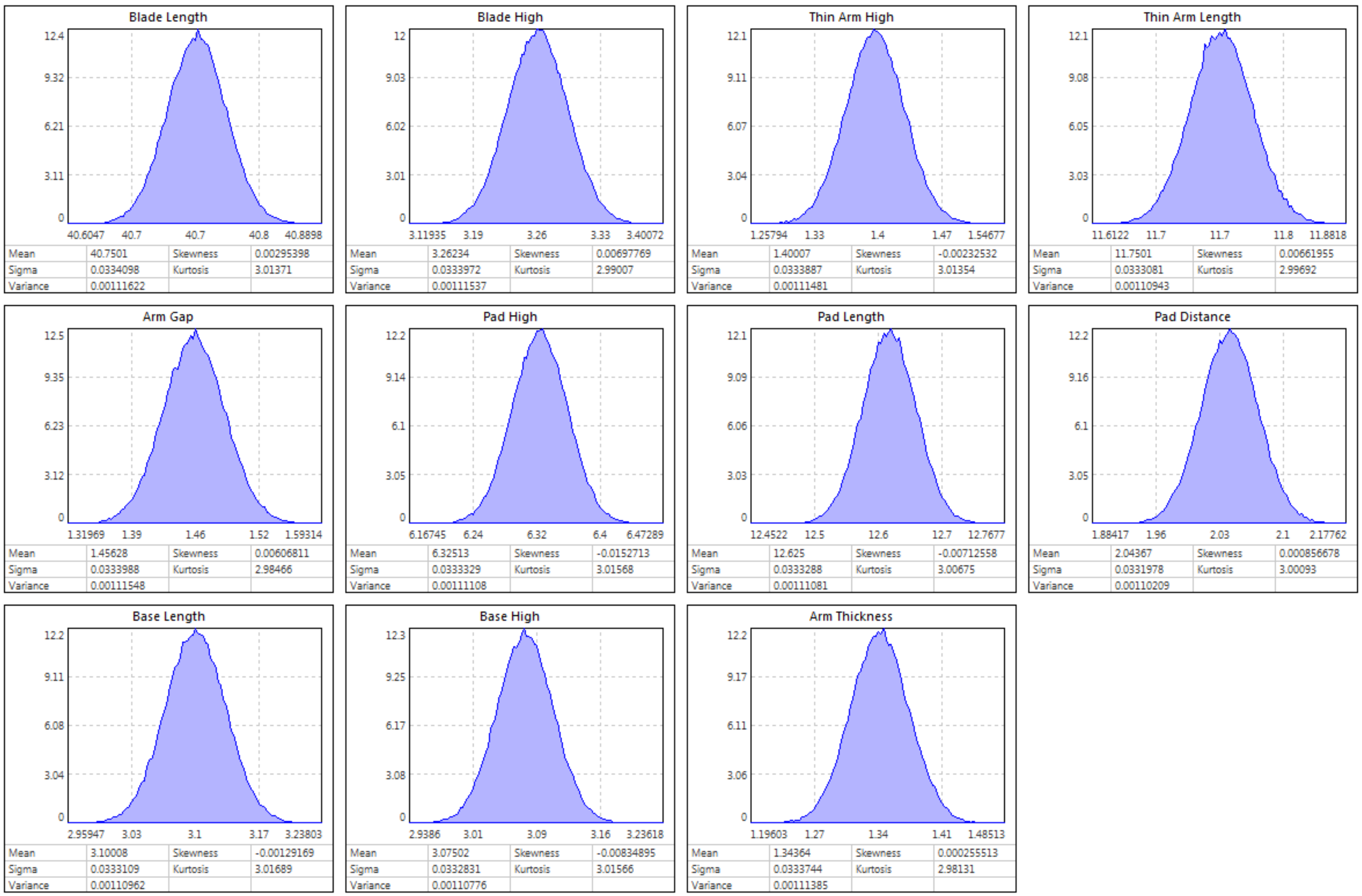
Nominal Design:

- Arm Deformation = 0.24 µm
- Stress von Mises = 1608 Mpa
- Frequency = 9.27 Hz

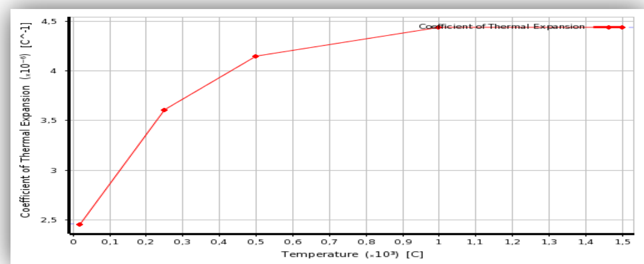
Design Parameters

Name	Nominal	Tolerance	Unit
Blade Length	40.75	0.2	um
Blade High	3.2625	0.2	um
Thin Arm High	1.4	0.2	um
Thin Arm Length	11.75	0.2	um
Arm Gap	1.45625	0.2	um
Pad High	6.325	0.2	um
Pad Length	12.625	0.2	um
Pad Distance	2.04375	0.2	um
Base Length	3.1	0.2	um
Base High	3.075	0.2	um
Arm Thickness	1.34375	0.2	um
Thermal Conductivity	124	6	W mm^-1 C^-1
Scale of Thermal Expansion	1	0.05	
Material Density	2330	116	kg mm^-3
Pad Voltage	5000	250	mV
Temperature	750	10	C
Material Resistivity	0.1	0.005	ohm mm

Nominal Design: Geometry Tolerances

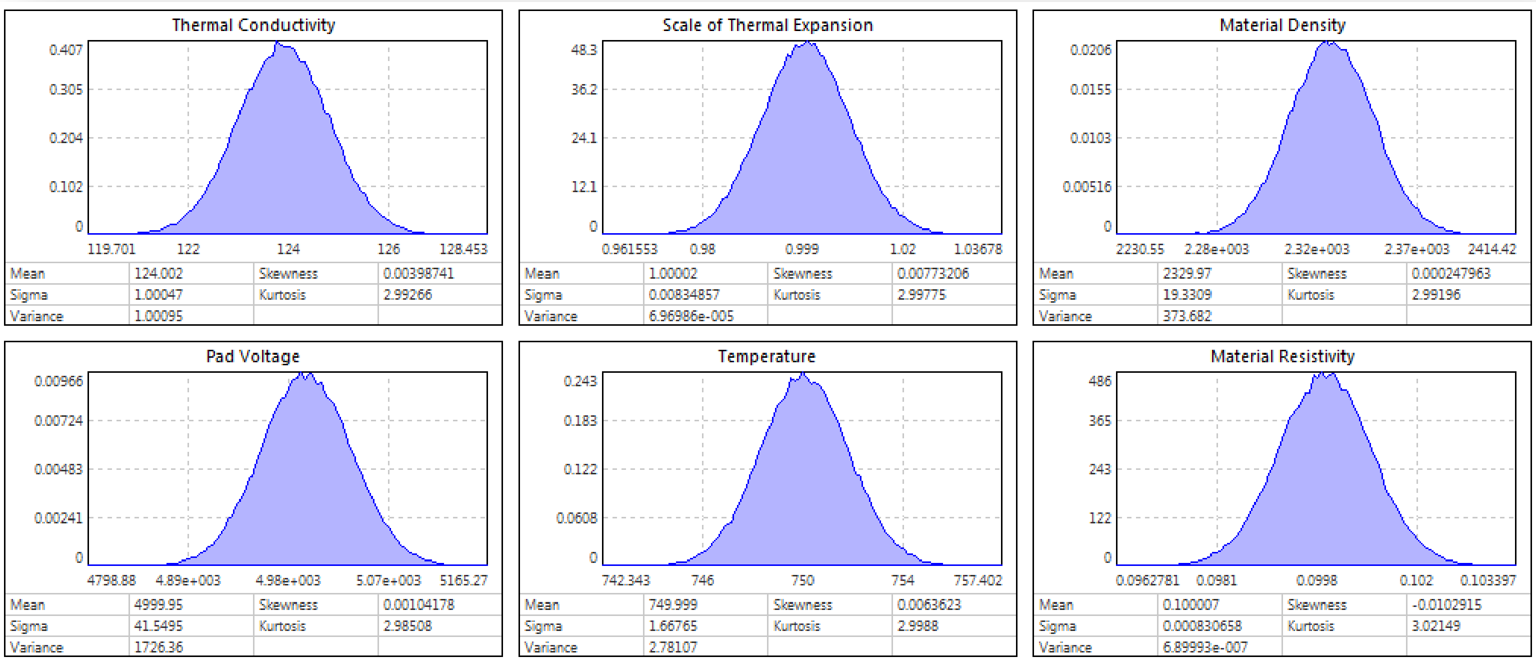


Nominal Design: Uncertainty Parameters



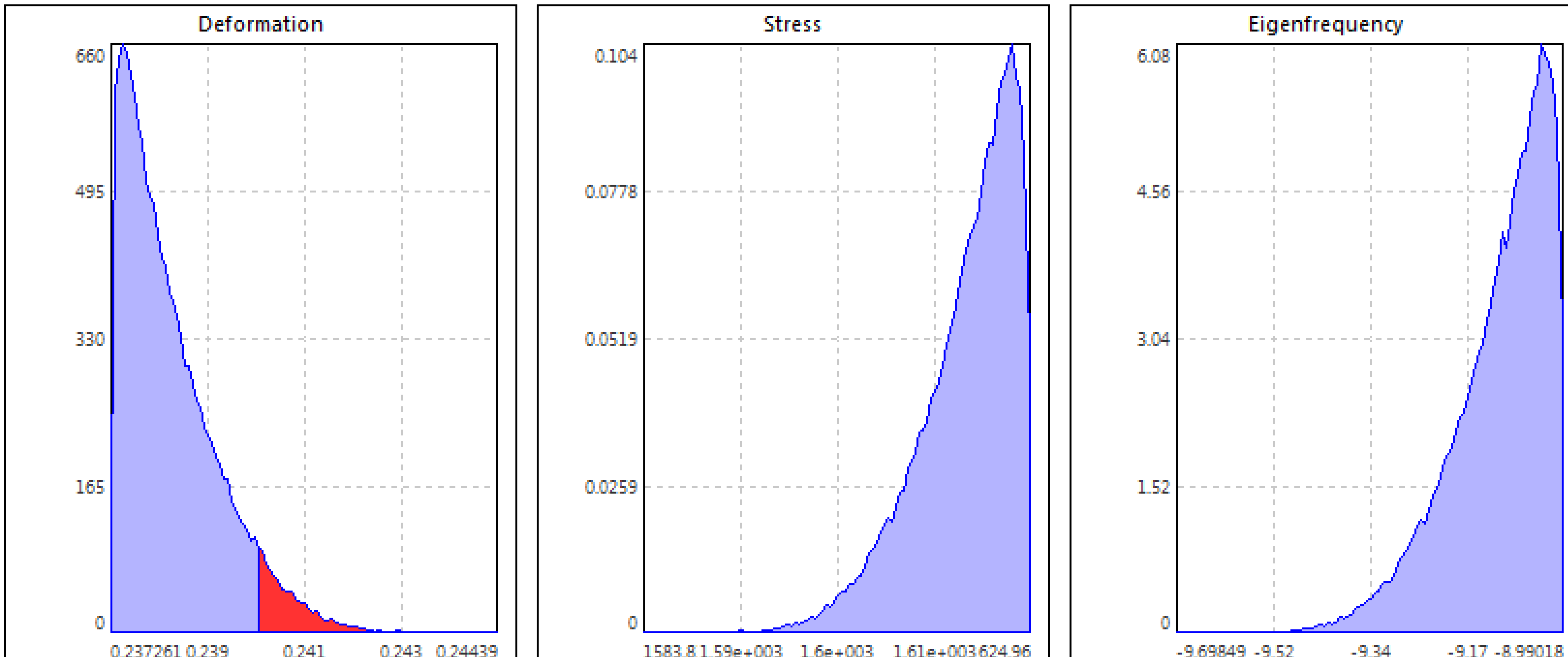
Thermal Expansion Curve
(Material: Silicon Anisotropic)

Scale Factor = 1 (Nominal)
Uncertainty = 0.05 (Range)



Nominal Design: Reliability Analysis

0.2 µm ≤ X ≤ 0.24 µm
Failure Probability = 6,69%



Deformation

Mean	0.238392	Skewness	1.15813
Sigma	0.00090997	Kurtosis	4.20141
Variance	8.28045e-007	Failure Probabili	0.06688/0.0668

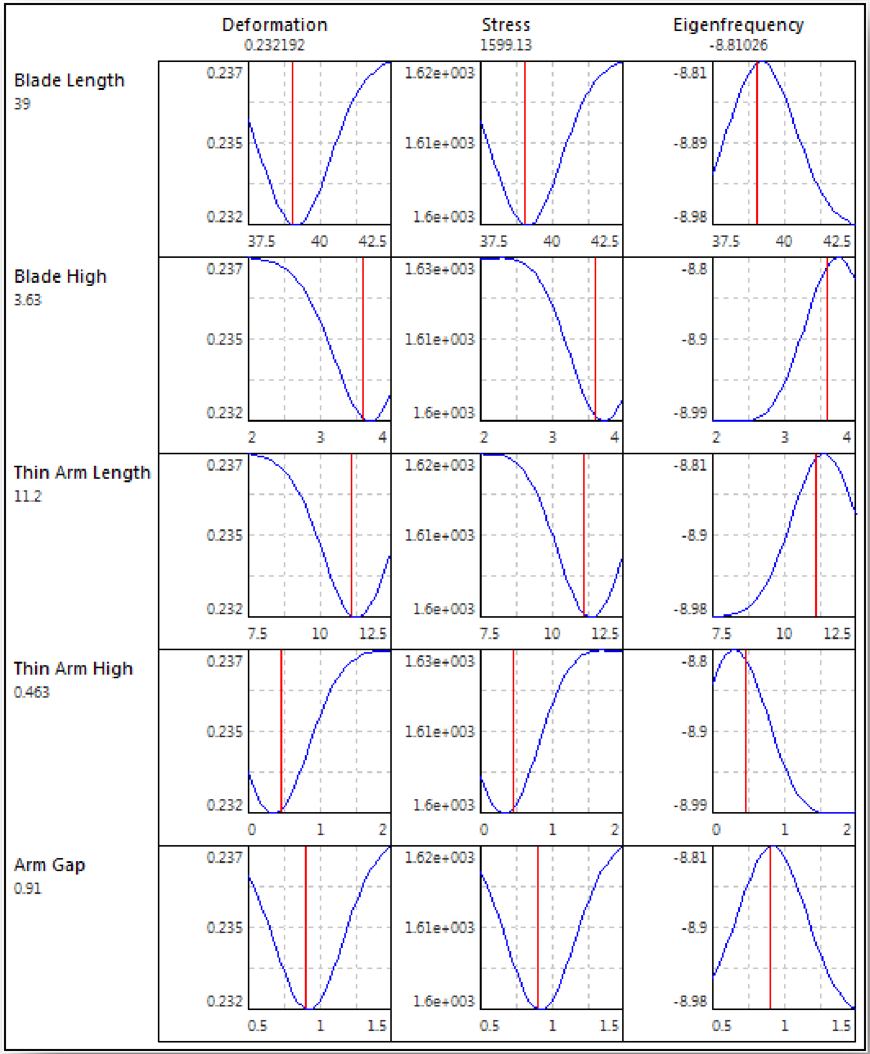
Stress

Mean	1618.24	Skewness	-1.09044
Sigma	5.28729	Kurtosis	4.02824
Variance	27.9554		

Eigenfrequency

Mean	-9.10518	Skewness	-1.1001
Sigma	0.0913791	Kurtosis	4.04303
Variance	0.00835014		

Robust Design Optimization



Optimization Goal for Arm Deformation:
Minimize Taguchi Quality Loss Function

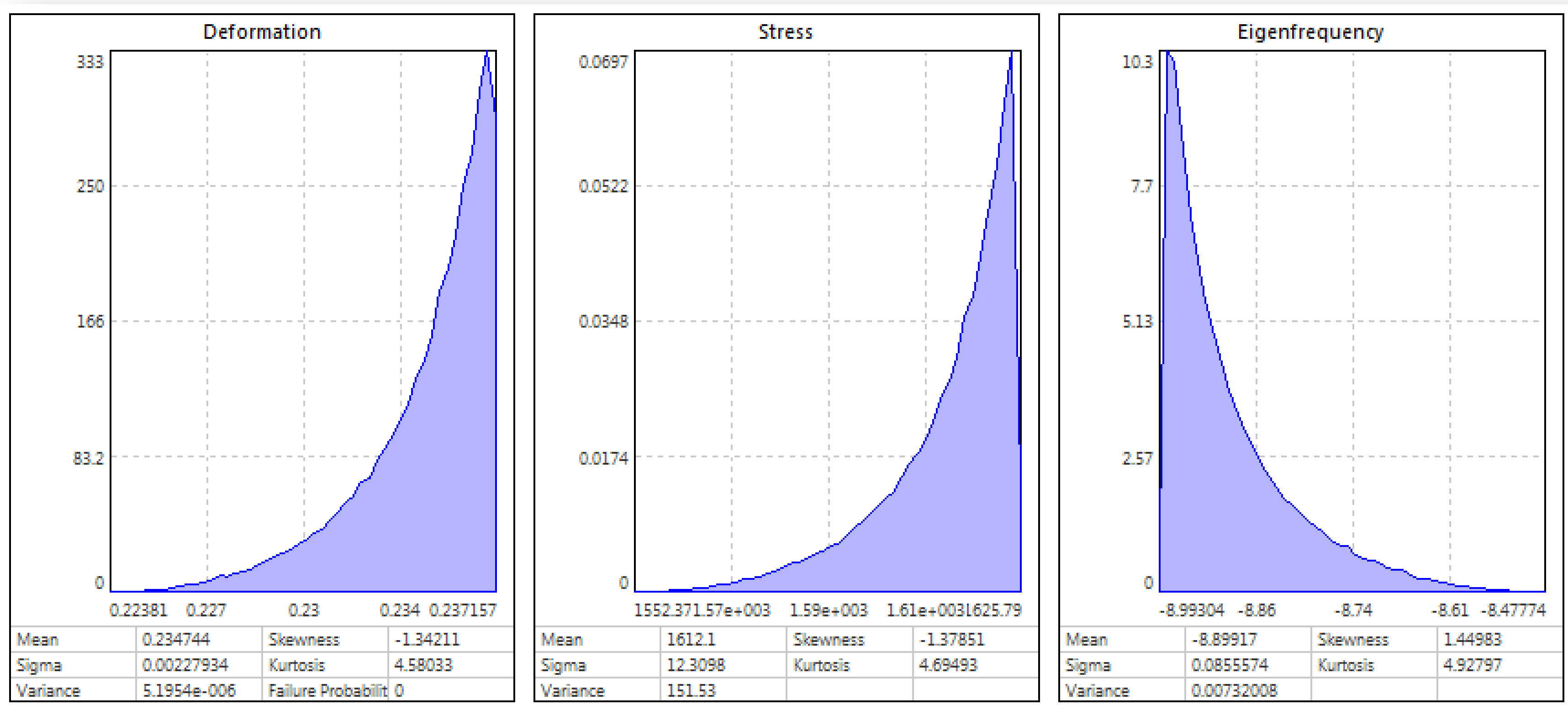
L = Cost*(Variance + (Mean – Target)^2)

- Cost = 1 Unit
- Target = 0.22 µm (Center of [0.2, 0.24] µm)

Design Parameters

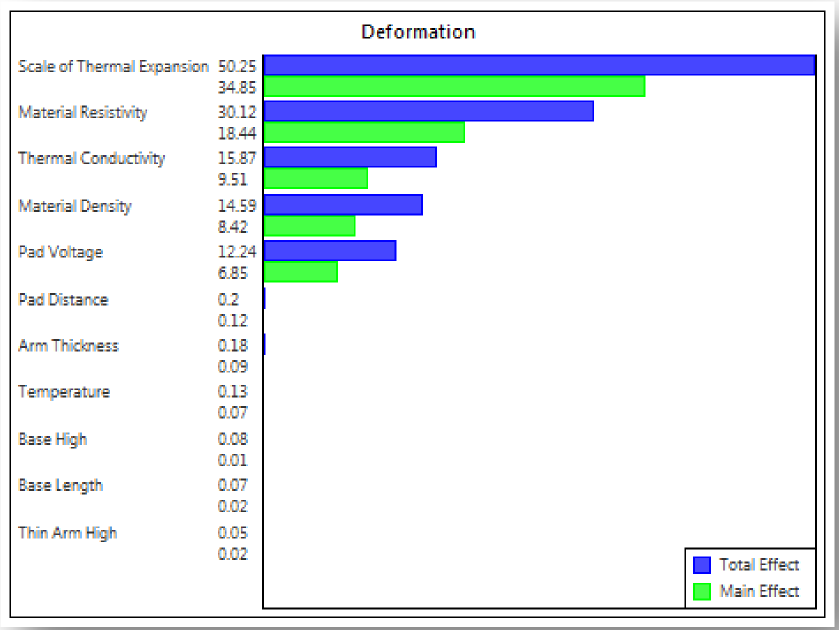
Name	Nominal	Tolerance	Unit
Blade Length	39.0434436	0.2	um
Blade High	3.63425021	0.2	um
Thin Arm High	0.462617002	0.2	um
Thin Arm Length	11.1842729	0.2	um
Arm Gap	0.910124825	0.2	um
Pad High	5.44489182	0.2	um
Pad Length	12.3354025	0.2	um
Pad Distance	2.21580326	0.2	um
Base Length	2.7344334	0.2	um
Base High	3.0540857	0.2	um
Arm Thickness	1.03574304	0.2	um
Thermal Conductivity	124	6	W mm^-1 C^-1
Scale of Thermal Expansion	1	0.05	
Material Density	2330	116	kg mm^-3
Pad Voltage	5000	250	mV
Temperature	750	10	C
Material Resistivity	0.1	0.005	ohm mm

Robust Design: Probabilistic Analysis

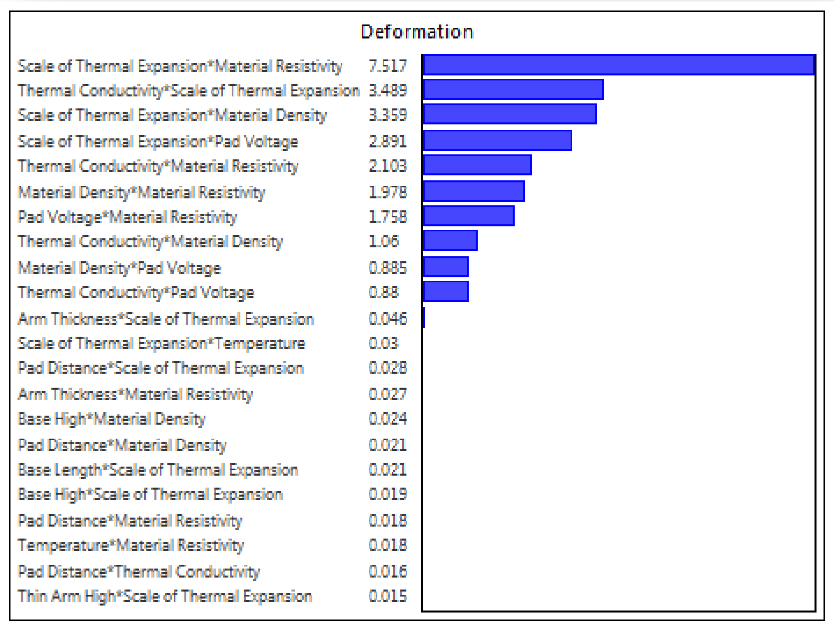


Robust Design: Design Sensitivity

Parameter Importance



Parameter Interactions



Conclusion

Nominal design using classical nominal simulation cannot warranty the reliability and quality of the products, because the nominal parameters are only one fix value.

Six sigma design is a power-full tool for design of reliable and quality MEMS in the early design stage without any cost. It considers the uncertainty parameters as stochastic distributions.

In the case of the thermal actuator, we have got a robust design with zero failure probability for the manufacturing.

OptiY® is the leading software platform for robust design of all engineering fields using different commercial CAD/CAE-software or in-house codes.