YIELD ANALYSIS OF MICROSYSTEMS USING ENHANCED WCAS

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Purpose

- Address the growing needs of the MEMS design community for faster and accurate methods of parametric yield calculation
- Define a quantifiable yield metric for MEMS devices in terms of their design / statistical parameters
- Provide the designers with 'WCAS' – a parametric yield analysis suite for performing enhanced worst-case analysis of MEMS devices
- Demonstrate the capabilities of the enhanced worst-case analysis using a generic MEMS device

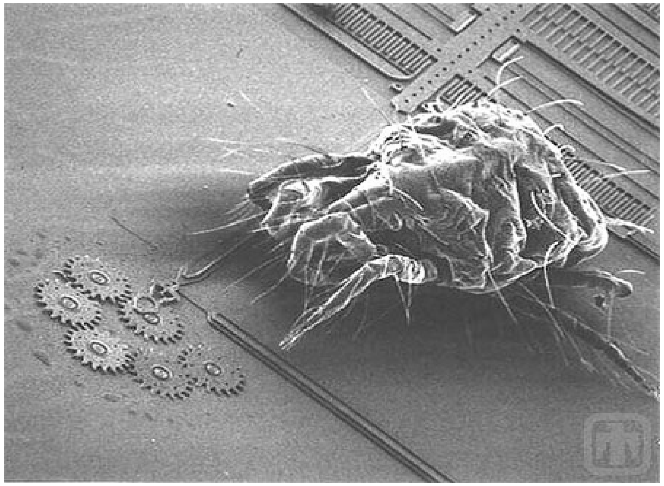
Outline

- Introduction: yield loss in microsystems
- Worst-case methods and their limitations
- Non-linear metamodels and DOE
- Enhancement in the accuracy of yield analysis in microsystems
- Demonstration of the enhanced worst-case based yield analysis methods
- Summary

Introduction

Yield loss in microsystems:

- Decreasing feature sizes cause increasing difficulties at the fabrication site (fab)
- Process variations remain inevitable even with the state-of-the-art process techniques
- A strong mismatch exists between the scaling of device feature sizes and the effects due to process variations



Courtesy: Sandia National Laboratories, SUMMiTTM Technologies, www.mems.sandia.gov

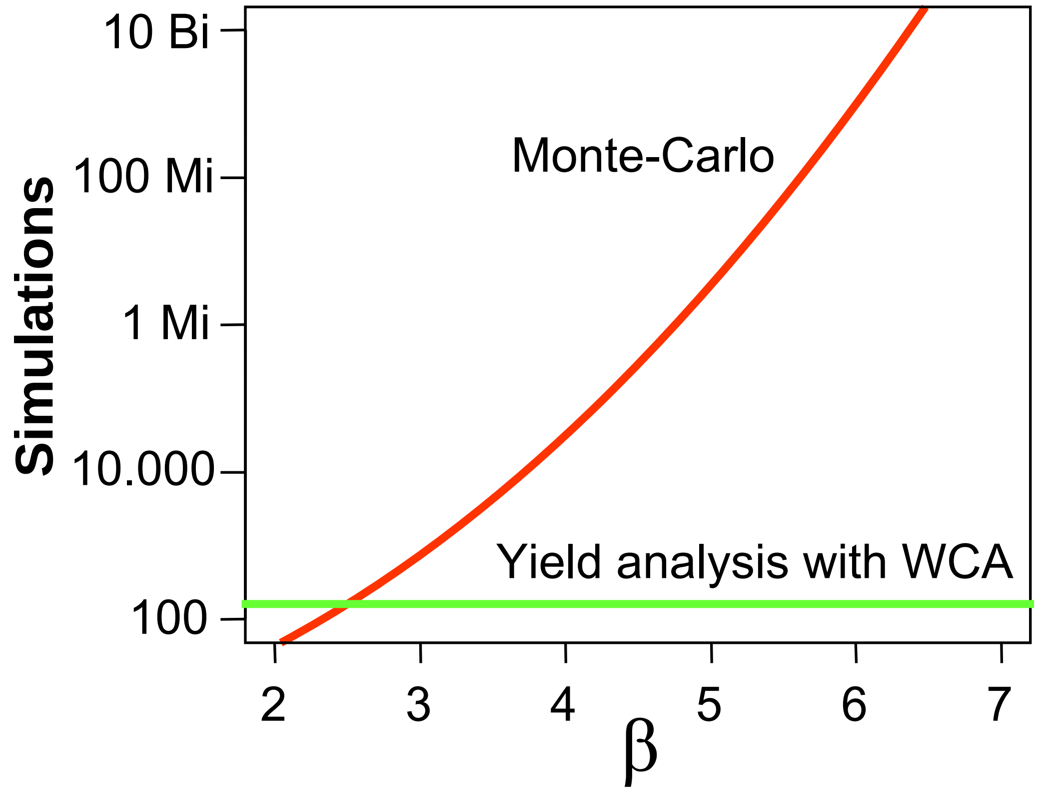
Statistical yield analysis is a must !

Methods for statistical yield analysis:

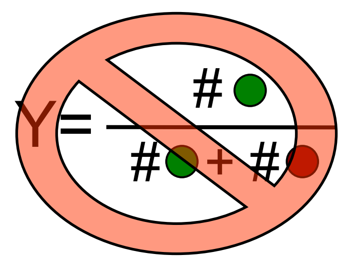
- Monte Carlo Analysis (MCA)
- Statistical Process Control (SPC) – at fab site
- Worst-case methods

Why worst-case methods?

- One of the Intelligent Statistical Analysis (ISA) methods
- Advantages over conventional techniques:
  - reduced number of simulations (for 3σ and above designs)
  - existence of a parametric yield metric, unlike MCA



More efficient than MCA for designs with yields > 3σ



Worst-Case Analysis (WCA)

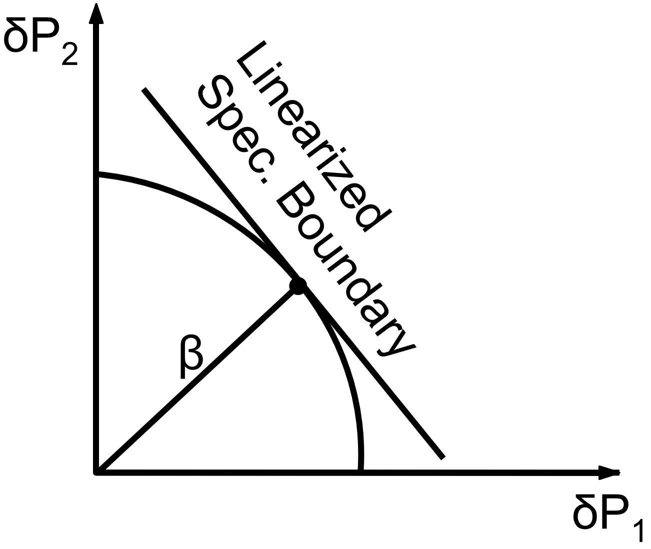
- **Essential Glossary:**
  - Worst-Case point (WCP): A set of parameters that leads to the maximum of the performance objective for the chosen confidence level
  - Worst-case distance (β): Euclidean norm between the nominal point and the WCP that serves as a yield metric
- **Yield Calculation from *β*:**

$$Yield = \frac{1}{2}\left(1 + erf\left(\frac{\beta}{\sqrt{2}}\right)\right) \times 100$$

Limitations in worst-case methods

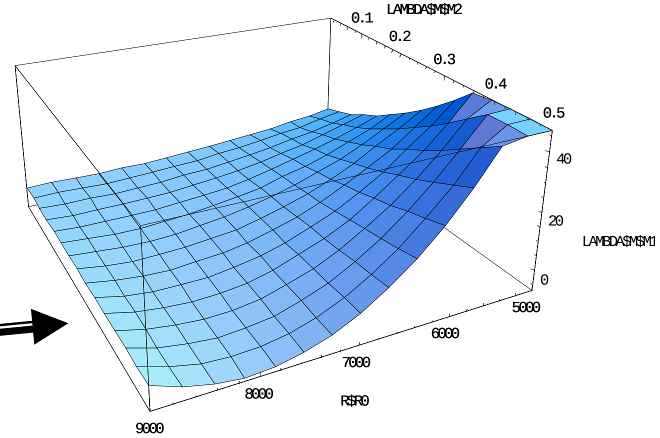
- Most microelectronics circuitry (with exceptions) exhibit linear characteristics around the operating point which might assert that the loss of accuracy is insignificant

- WC methods linearly approximate the performance specification (spec) around the operating point



$$f(\bar{d}) = f(\bar{d}_0) + \nabla f(\bar{d}_0)(\bar{d} - \bar{d}_0)$$

Some of the assumptions are not widely valid in microsystem design and specific microelectronic circuitry



Consideration of higher order metamodels

The previous and the state of the art WCA only consider linear and first order models and neglect all other higher order terms.

$$f(\bar{d}) = f(\bar{d}_0) + \nabla f(\bar{d}_0)(\bar{d} - \bar{d}_0) \quad \text{first order terms}$$

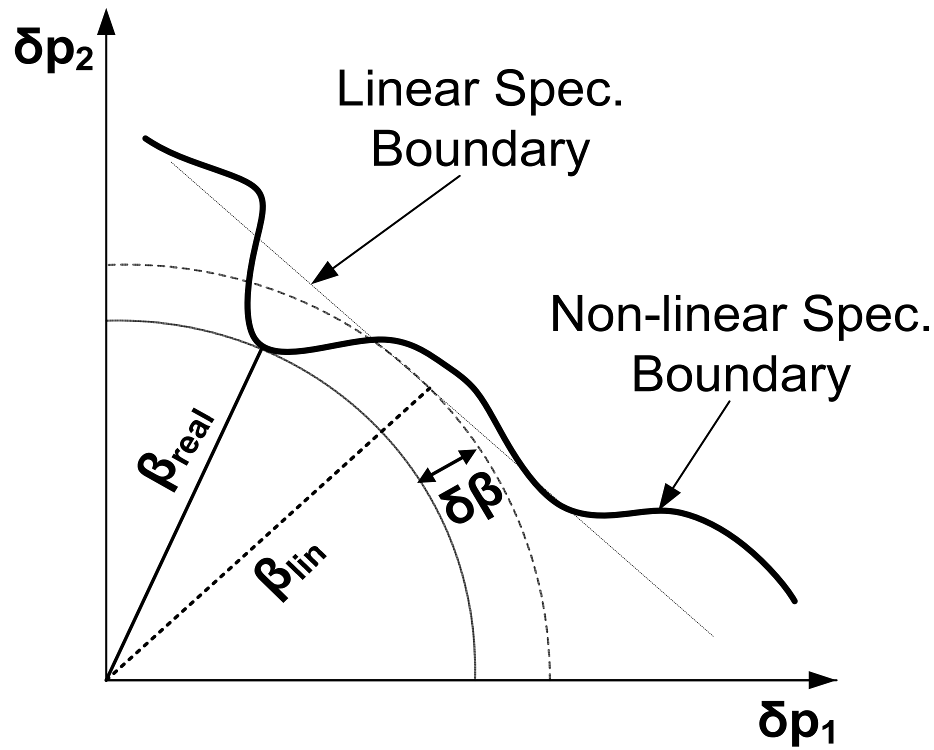
$$+\frac{1}{2}(\bar{d} - \bar{d}_0)'\nabla^2 f(\bar{d}_0)'(\bar{d} - \bar{d}_0) + \ldots \quad \text{second / higher order terms}$$

One could consider second and higher order metamodels. A typical second order model with interaction effects looks like:

$$f(\bar{d}) = \varphi_0 + \sum_{i=1}^{k} \varphi_i d_i + \sum_{i<j} \sum_{j=2}^{k} \varphi_{ij} d_i d_j + \sum_{i=1}^{k} \varphi_{ii} d_i^2$$

Enhanced WCA

- The state of the art WCA considers linearized spec. boundaries
- When the WCP_{real} is placed:
  - closer than the WCP_{lin} it represents a pessimistic approach
  - farther from the WCP_{lin} it represents an optimistic approach
- Linearization of spec boundary throws the design either into the optimistic or pessimistic approaches of yield calculation



Pessimistic approach of yield calculation using worst-case methods

Enhanced WCAS avoids this pitfall completely!

Demonstration with a U-Shaped Electro Thermal Actuator

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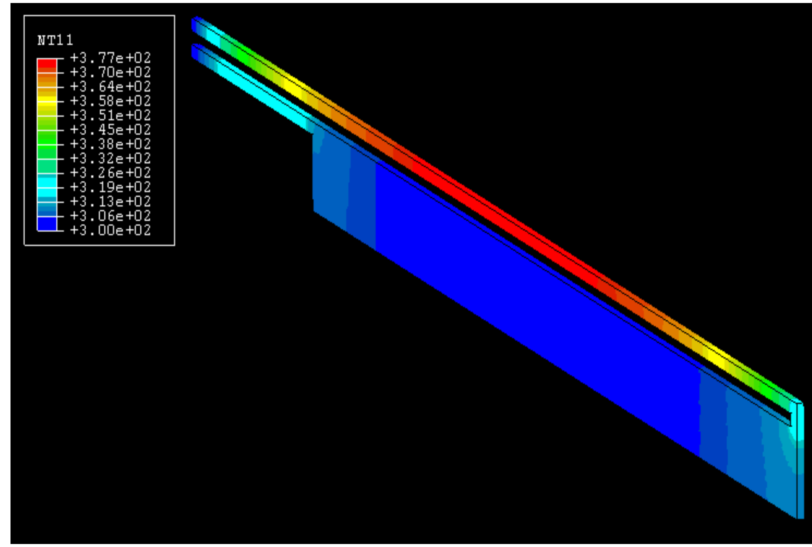
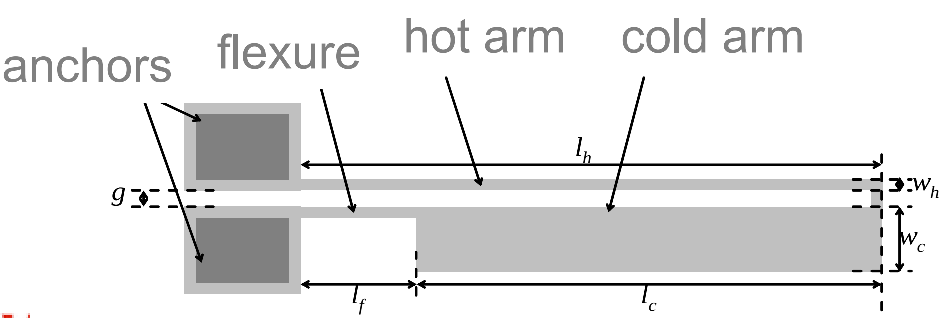
Operation:

- Current circulation in the structure results in unequal thermal expansion caused by ohmic heating of varied dimensions
- Higher current density in the hot beam causes it to expand more than the cold beam, thus producing a lateral motion
- Flexure arm helps to restore the original position in the structure



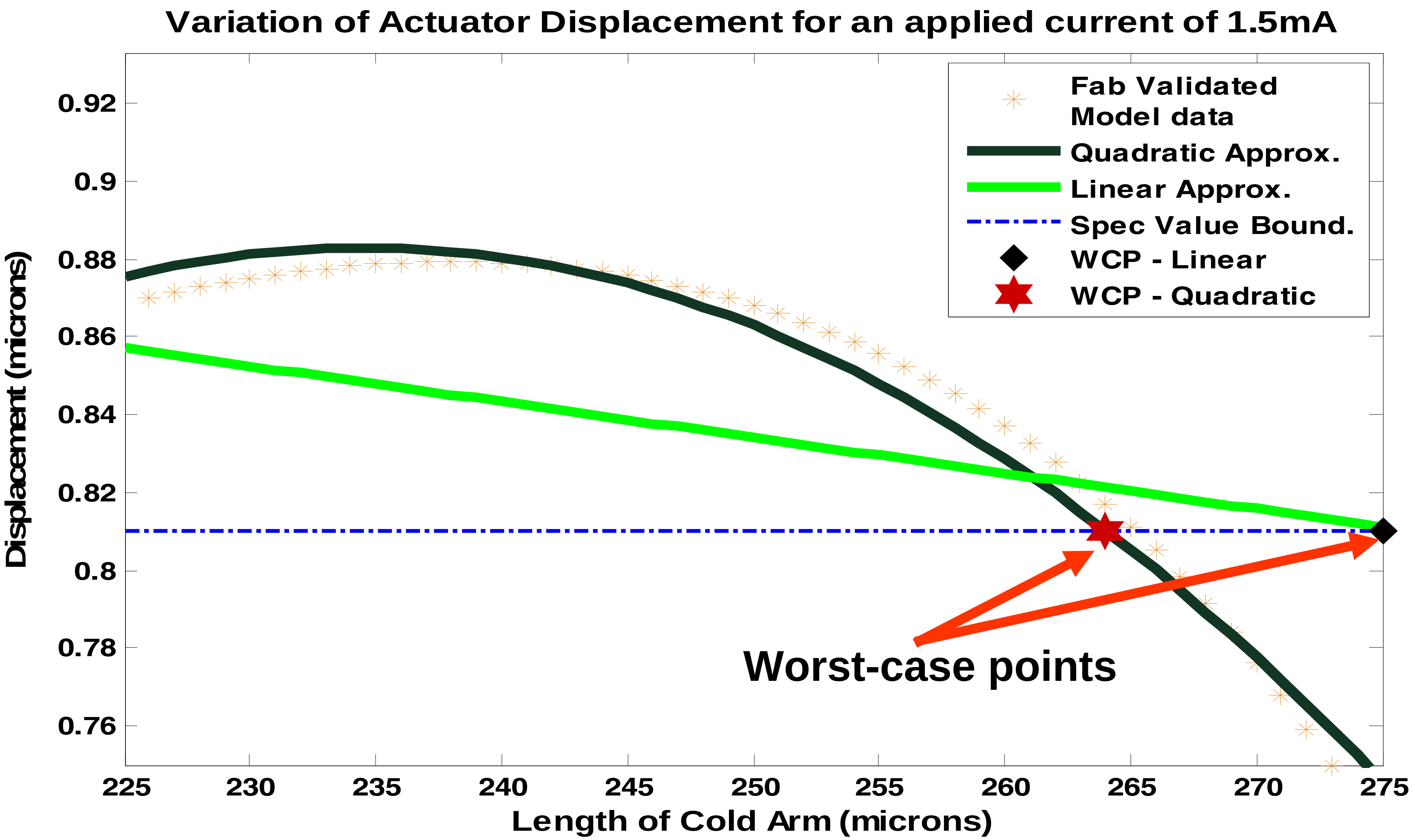
FEM View



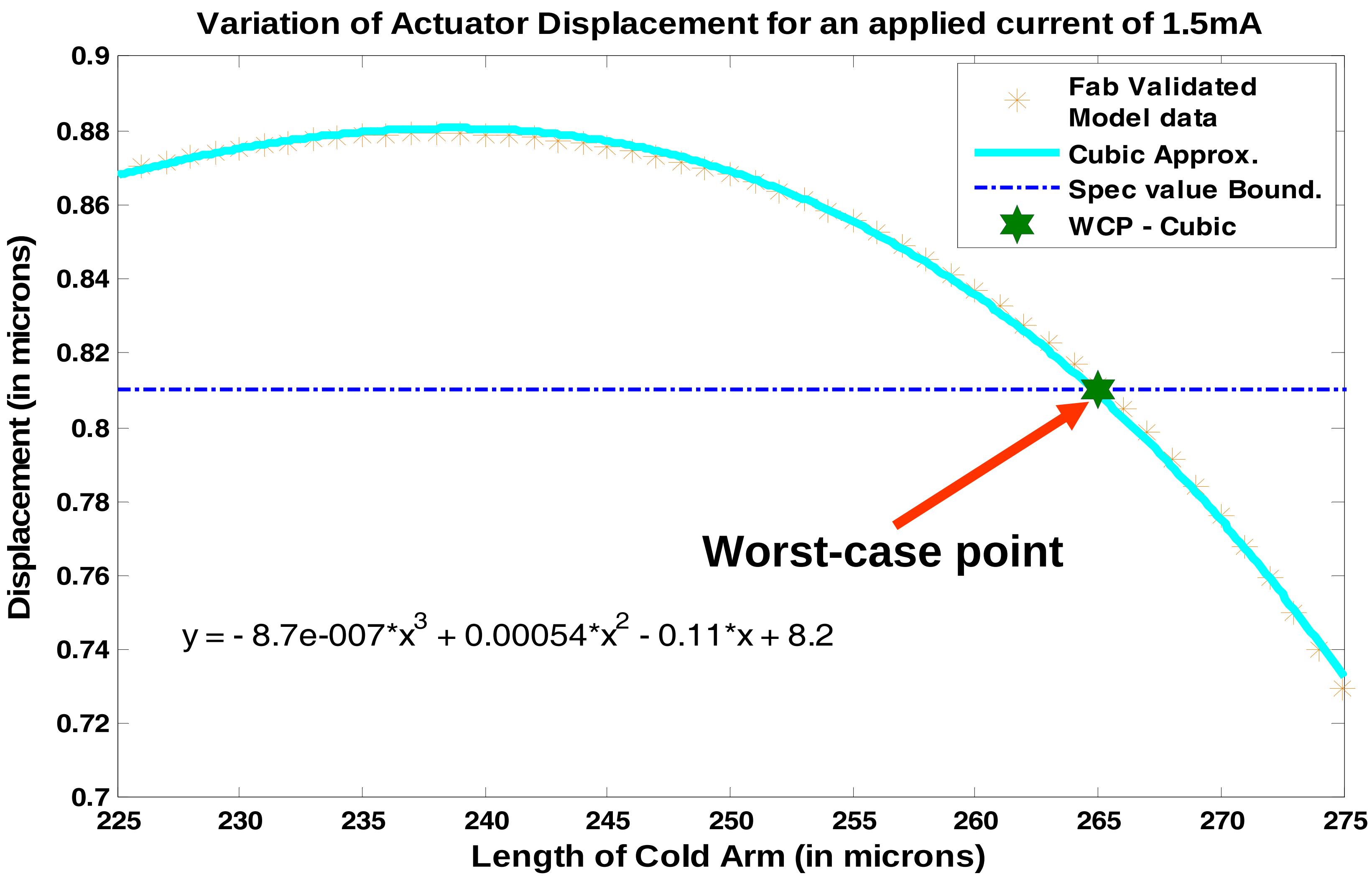
Schematic View

SEM View

Demonstration of WCAS (1)



Demonstration of WCAS (2)



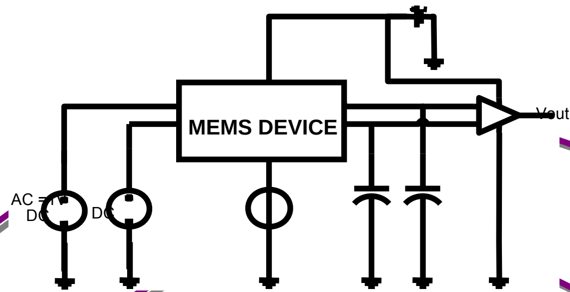
Results obtained using WCAS

Yield Calculation Technique	Calculated Yield	Relative Error
Monte Carlo Analysis (with 10,000 simulations)	**89.85%**	**Ref. value**
Worst-Case Analysis (with linearized spec. boundaries)	**98.139%**	**9.225%**
Worst-Case Analysis (with simple non-linear spec. boundaries)	**87.833%**	**2.244%**
Worst-Case Analysis (with cubic non-linear spec. boundaries)	**89.435%**	**0.461%**

Enhancements achieved in WCA by an error percentage of **8.76%**

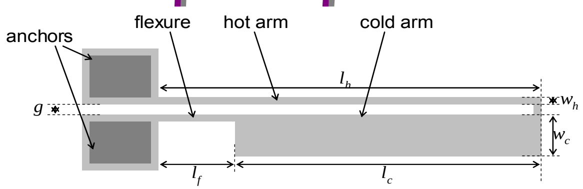
The enhanced version of WCA can now be productively applied for the yield analysis of microsystems!

Statistical analysis of microsystems with WCAS



High abstraction models

Performance selection and test bench setup



Selection of a ckt./ MEMS as a DUT

WCAS

Fast and accurate yield analysis

WCD for each performance

Yield Optimization

Summary

- A time efficient and accurate yield analysis is becoming important as it is a key aid in yield optimization
- WCA in the yield analysis of microsystems is vital because of:
  - faster yield calculations
  - the presence of a quantifiable parametric measure for yield
- A critical enhancement in the yield analysis of microsystems and specific microelectronic circuitry has been presented and demonstrated with help of a generic MEMS device
- The enhancement in the accuracy has been achieved by considering non-linear metamodels for spec. boundaries
- An important pre-requisite for yield optimization of MEMS and other microsystems has been accomplished

A Brief Overview of the Proposal

- As a proposal to the next phase, we intend to use these worst-case methods for achieving Design for Yield and Design for Reliability in MEMS

- These methods also find applications in specific MEMS reliability problems where critical operational parameters are required to analyze the reliability issues of the devices

- We intend document a best practice method for inducing DfY and DfR requirements in the design cycles of MEMS devices