Uncertainty-enabled Design of Electromagnetic Reflectors with Integrated Shape Control

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**SPIE Smart Structures +
Nondestructive Evaluation**
Behavior and Mechanics of Multifunctional Materials and Composites XII
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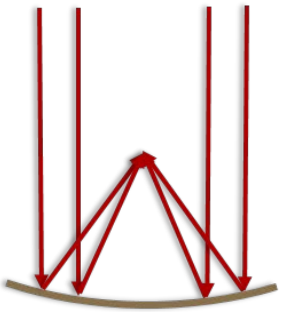
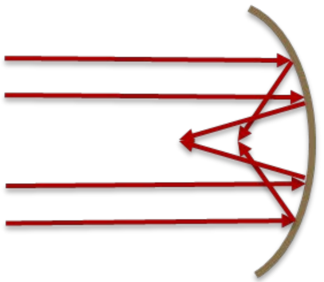
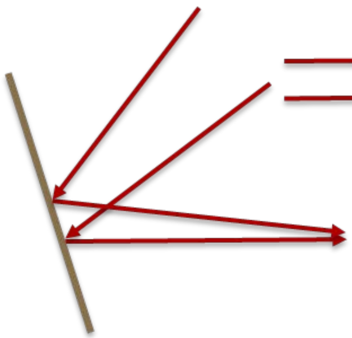
Electromagnetic Reflectors

- Surface that reflects electromagnetic radiation (often radio and visible light)
- Used in antennas, receivers and telescopes:
  - Satellite TV receivers
  - Communications systems
  - Radio observatories
  - Reflecting telescope



- Reflected signal pattern is directly related to reflector shape
- A common shape is Paraboloid
  - Allows sharp focus





Shape Matters

Hubble Space Telescope (NASA)

- Quality of reflected pattern:
  - Sensitive to reflector shape
- Controllable shape:
  - Post manufacture focus control
- Can save millions of dollars in case of a design error or equipment malfunction.

Degraded Images

Costly Repair

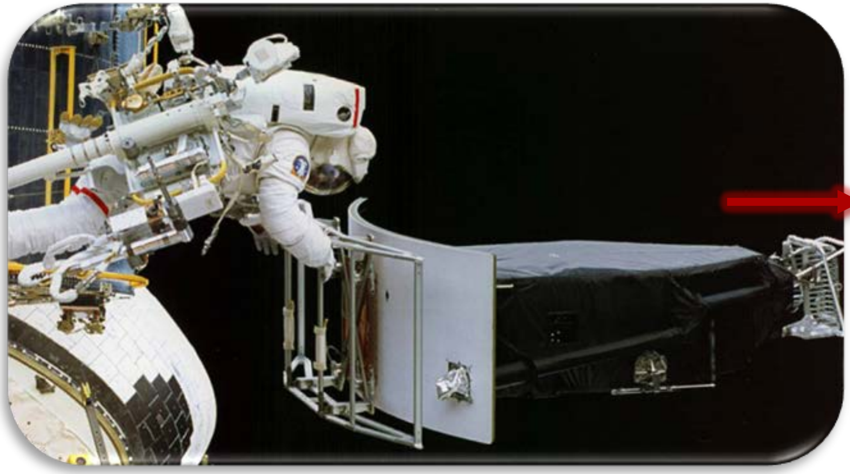
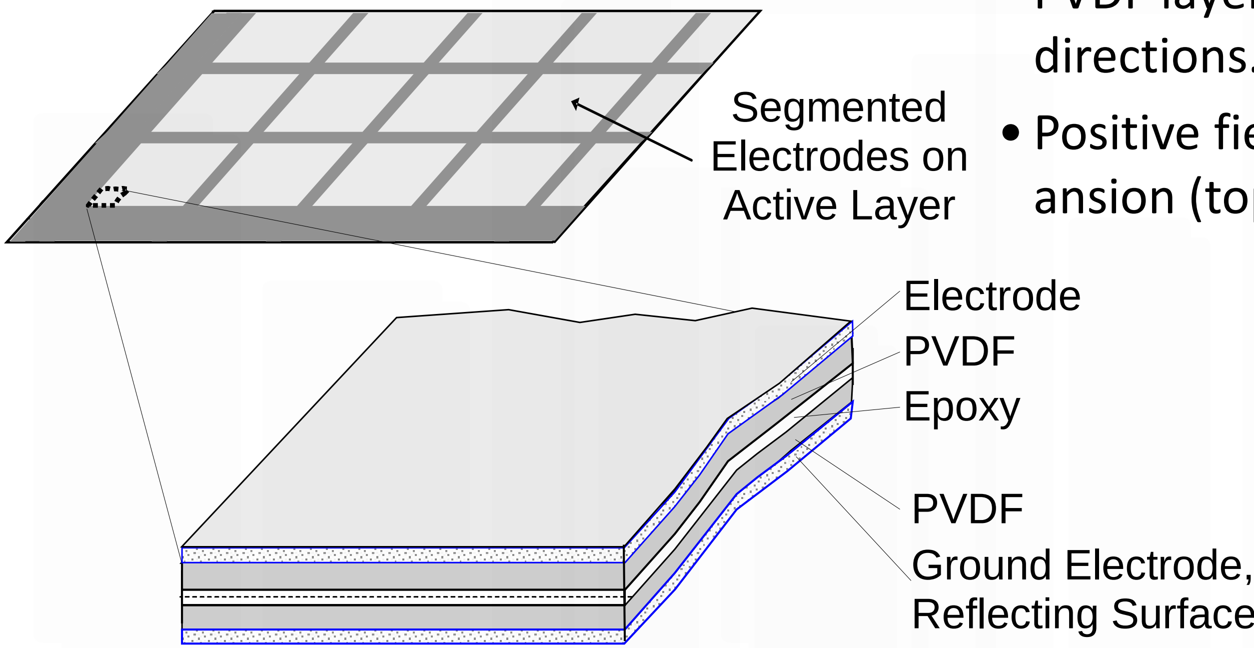


Image Quality Restored

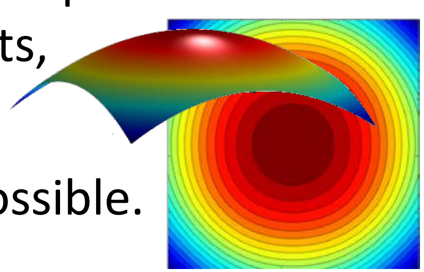
Culprit: ***0.0022 mm*** **reflector shape error.**

A Solution: Smart Laminate

Thin, Square, Active Membrane

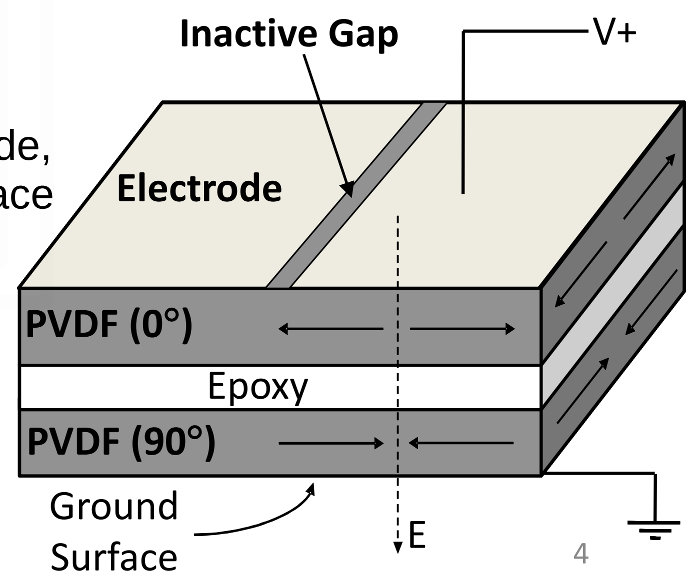


- Natural actuation into paraboloid with ideal corner supports,
- Improved flexibility,
- Large deflections possible.



How it Deforms: Bimorph Action

- PVDF layers have opposing poling directions.
- Positive field induces simultaneous expansion (top) and contraction (bottom).



Impact of Uncertainty?

How does uncertainty in design parameters and material properties affect smart laminate reflector operation and performance?

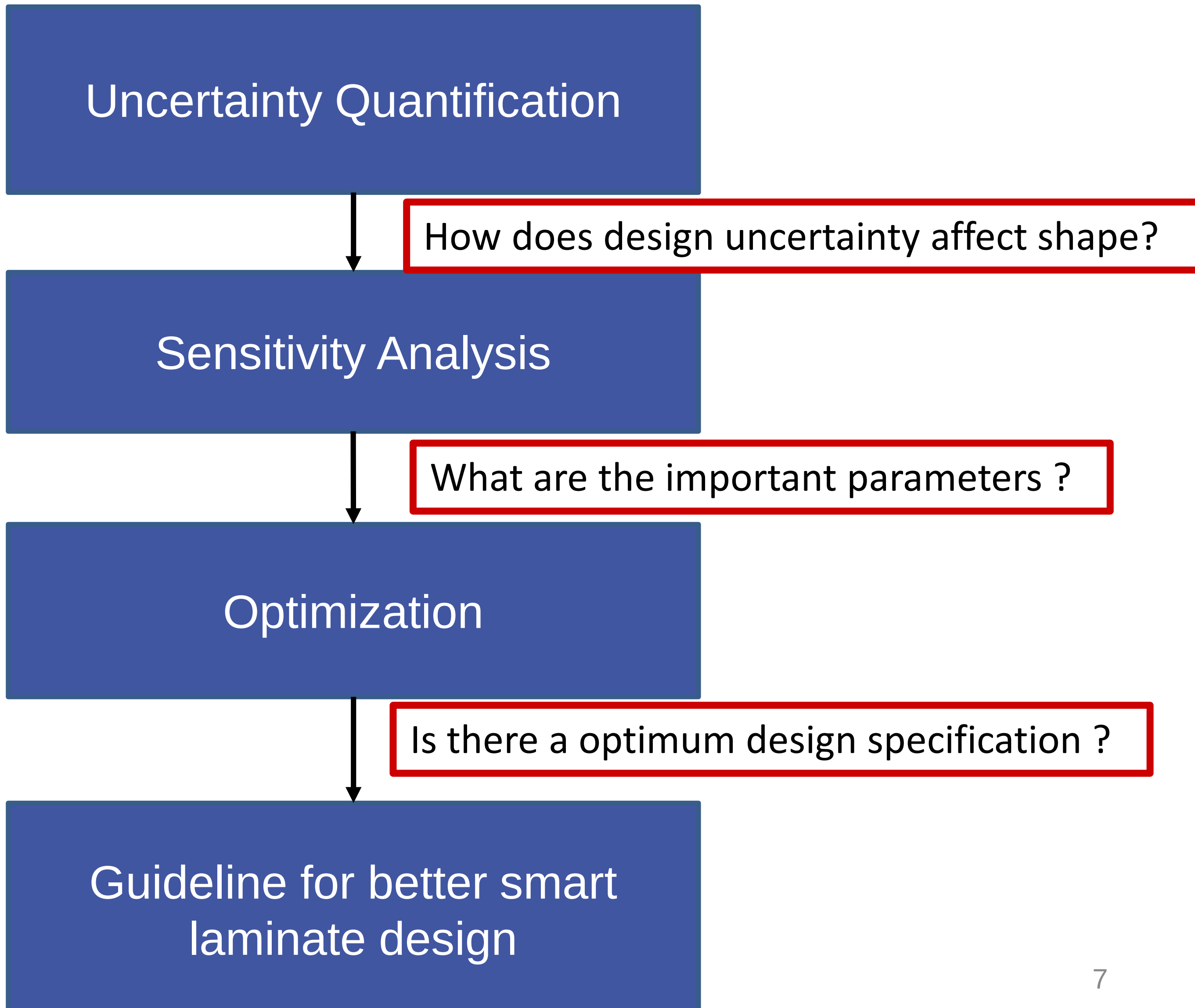
- *What are the significant model parameters?*
- *What is a statistical description of performance due to uncertainty?*

Impact of Uncertainty?

Can we design a reflector which is tolerant to uncertainty ?

- *What are the optimum parameter values?*
- *What are the optimum parameter tolerance bounds?*

Approach


Uncertainty Quantification
How does design uncertainty affect shape?
Sensitivity Analysis
What are the important parameters ?
Optimization
Is there a optimum design specification ?
Guideline for better smart laminate design

Computational Model

Total Deformation Energy

$$U = U_\epsilon + U_{act}$$

Energy Minimization

$$\nabla U_p = 0$$

Corner-supported Shape Function

$$w(x,y) \approx \sum_{j=1}^{j_{max}} \phi_j(x,y)$$

$$\phi_j(x,y) = a_j \cos\left(m_j \pi \frac{x}{a}\right) \sin\left(n_j \pi \frac{y}{b}\right) + b_j \cos\left(m_j \pi \frac{y}{b}\right) \sin\left(n_j \pi \frac{x}{a}\right)$$

Results

Voltage distribution

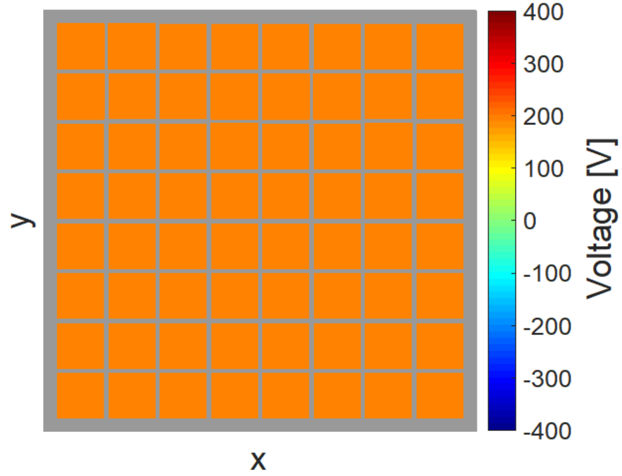
$$H(\mathbf{p}) \begin{pmatrix} \mathbf{a} \\ \mathbf{b} \end{pmatrix} = R(\mathbf{p})\, \mathbf{V}$$

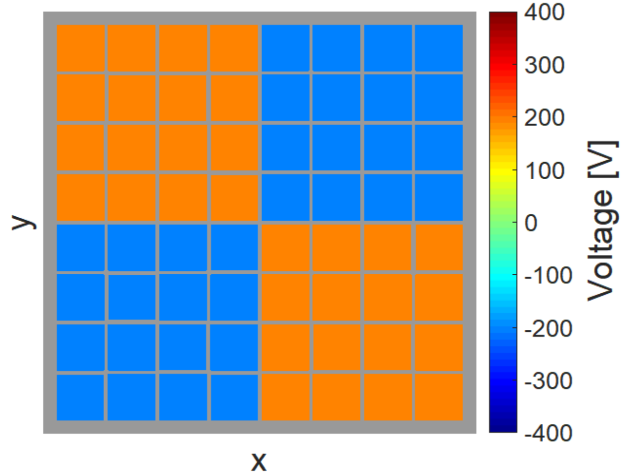
Nonlinear functions of parameters $\mathbf{p}$

Based on Sumali, Massad, 2003-2007

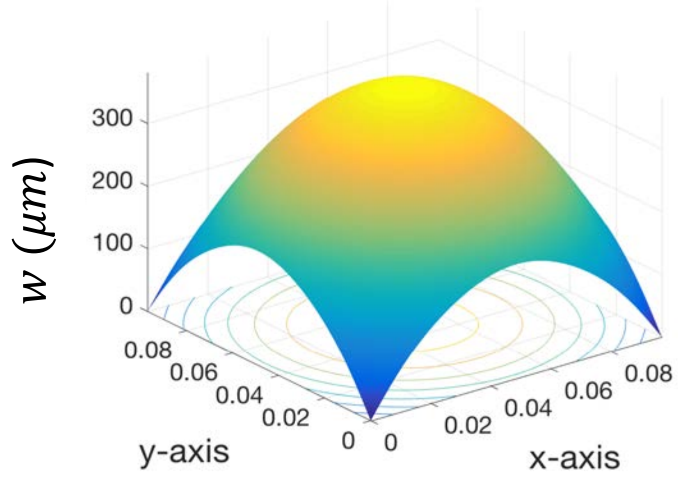
Electrode Patterns and Deflection

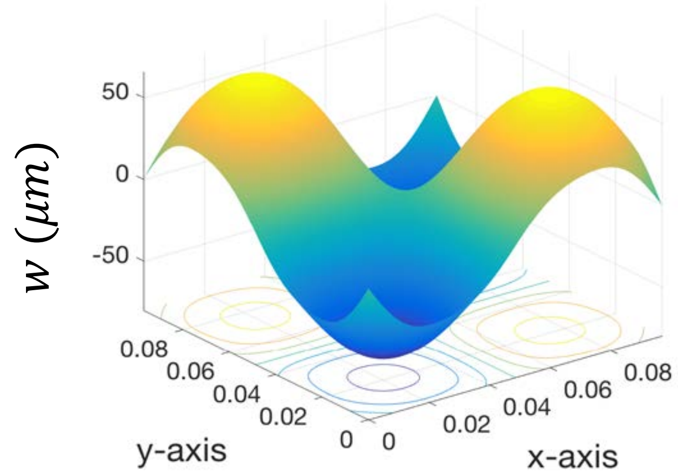
Electrode Pattern





Deflection





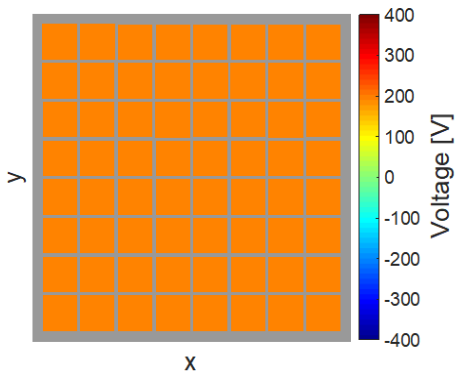
Define Shape Error

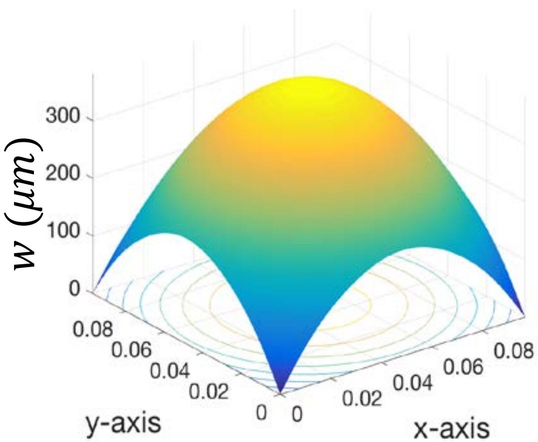
- With respect to a perfect Paraboloid

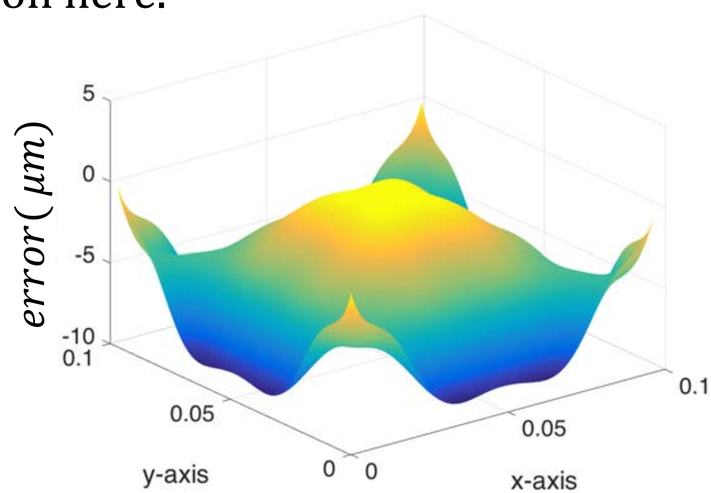
$$\text{Relative Shape Error} = \frac{\| w - w_{ref} \|_2}{\| w_{ref} \|_2}$$

Our Quantity of Interest (QoI)

Type equation here.





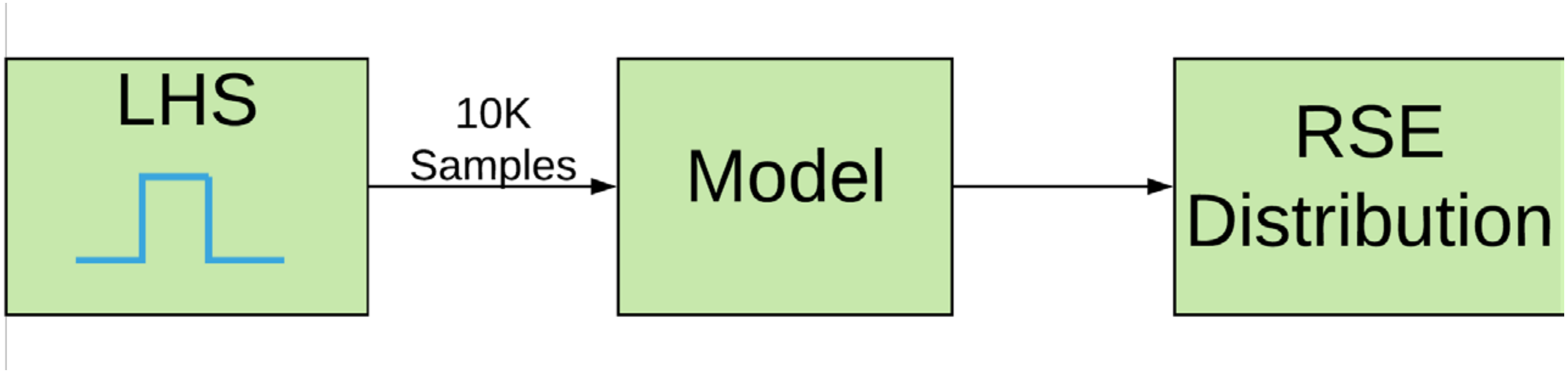


Shape Difference with a perfect paraboloid

Uncertainty Quantification

- *What is the shape error distribution under parameter uncertainty?*

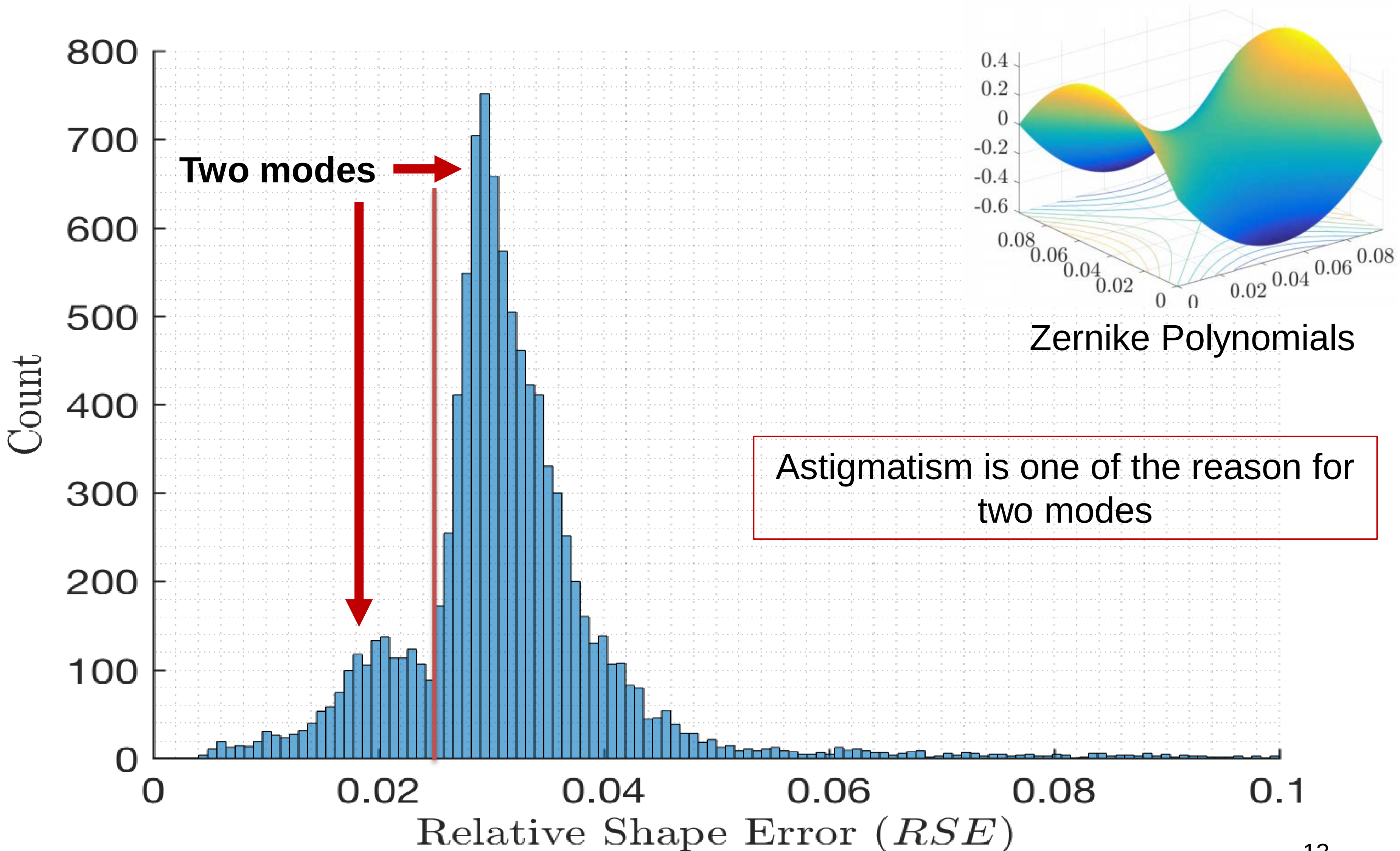
- 15 Parameters including dimensions, material properties, and input voltages.
- Assumed uniform distributions based on guidance and known design tolerances.
- Latin Hypercube Sampling



Parameter Ranges

Parameter	Description	Nominal value	Tolerance
Physical Parameters			
Y_{11}	PVDF Young's modulus	2.7 GPa	±35%
Y_{22}	PVDF Young's modulus	2.5 GPa	±35%
G_{12}	PVDF shear modulus	0.935 GPa	±5%
Y_e	Epoxy Young's modulus	1.03 GPa	±50%
ν_{12}	PVDF Poisson ratio	0.326	±5%
ν_e	Epoxy Poisson ratio	0.35	±10%
d_{31}	Piezoeletric strain constant	23×10^{-12} m/V	±25%
d_{32}	Piezoeletric strain constant	2.3×10^{-12} m/V	±25%
Geometric Parameters			
a, b	Laminate length, width	97 mm	±5%
h_p	PVDF thickness	52 μm	±20%
h_e	Epoxy thickness	30 μm	±100%
Bor	Non active PVDF border	5 mm	±10%
Sep	Separation between the electrodes	1 mm	±5%
Other Parameter			
V	Voltage	Between ±200 V	±5%

Uncertainty Propagation

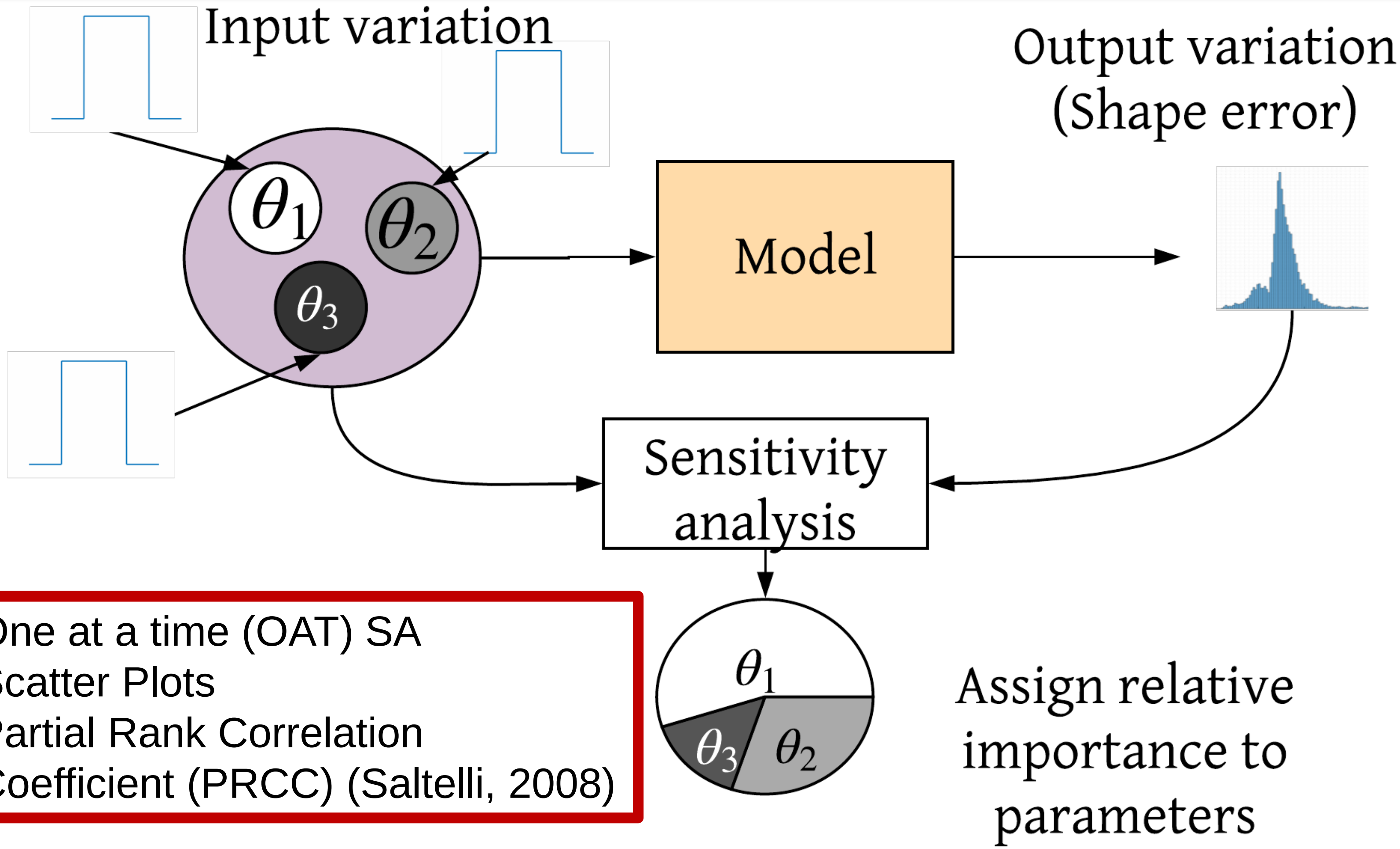


Zernike Polynomials

Astigmatism is one of the reason for two modes

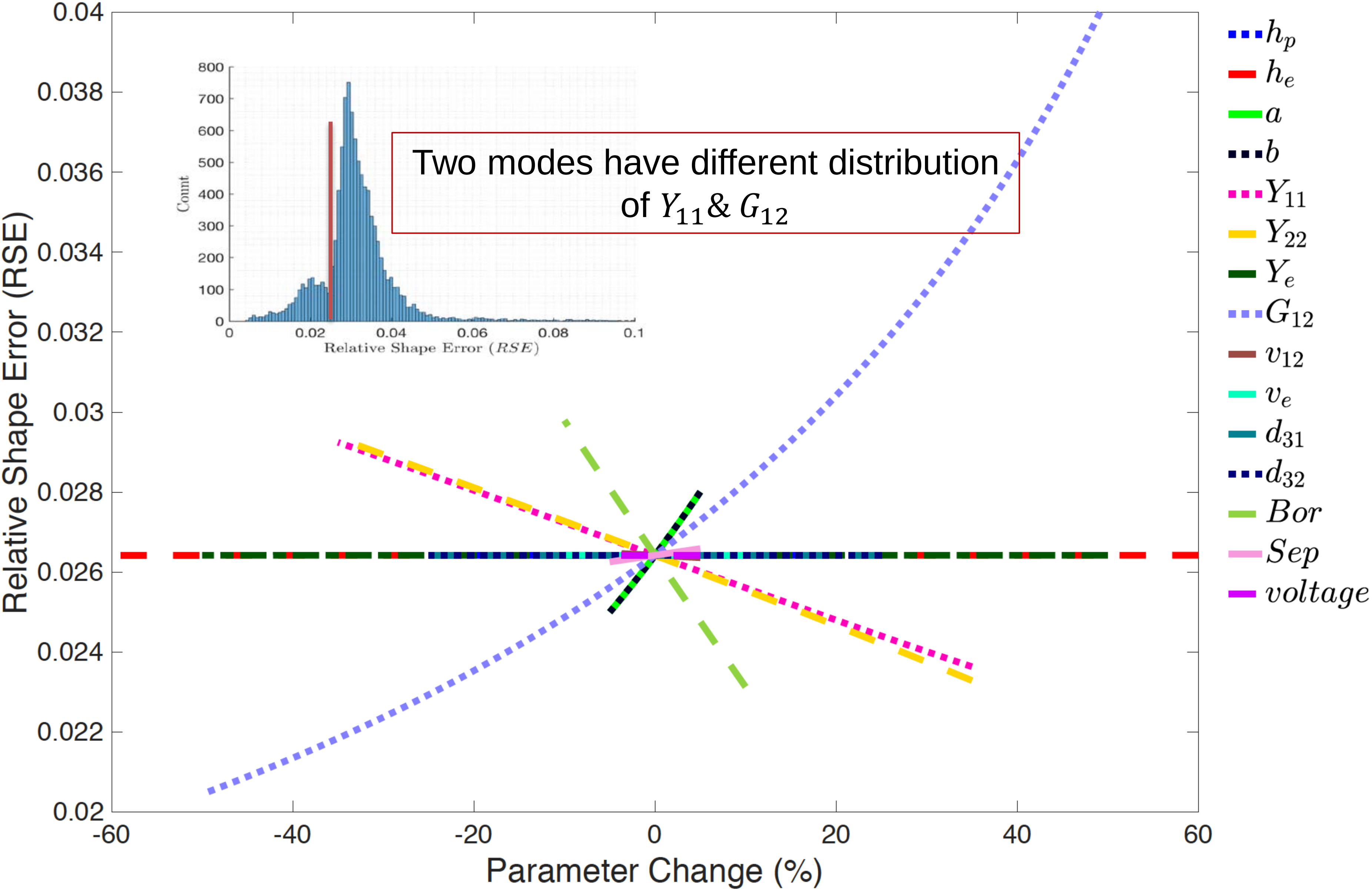
Sensitivity Analysis (SA)

What are the significant model parameters?



- One at a time (OAT) SA
- Scatter Plots
- Partial Rank Correlation Coefficient (PRCC) (Saltelli, 2008)

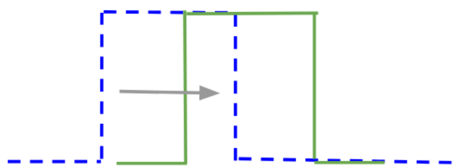
SA Results (OAT)



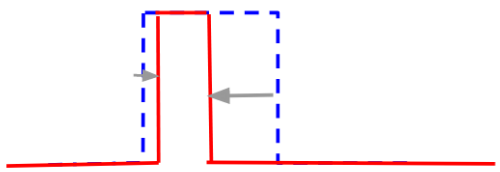
Optimization Under Uncertainty

- *What are the optimum parameter values?*
- *What are the optimum parameter tolerance bounds?*

- Obtaining a better shape error distribution



Optimized mean value

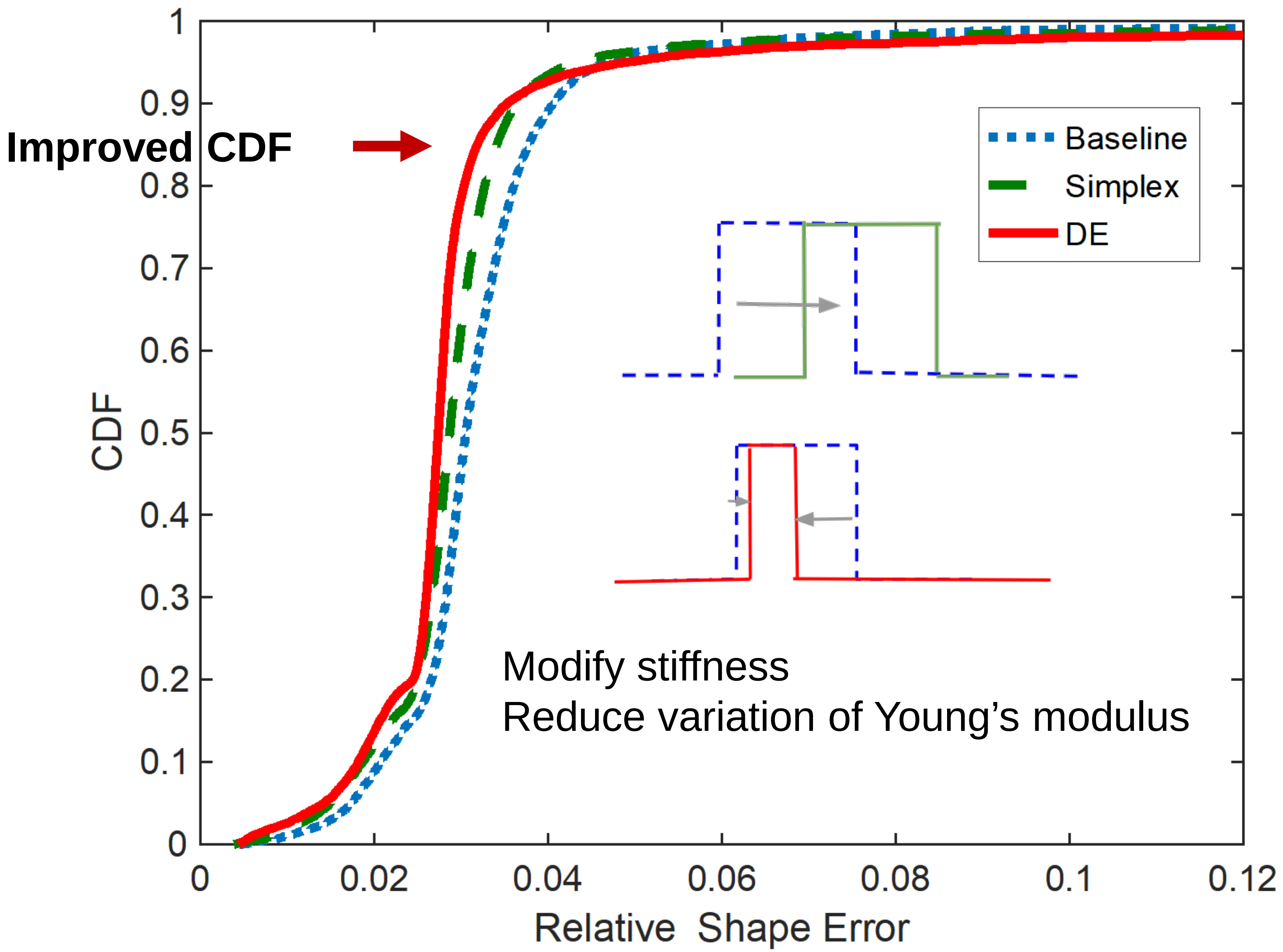


Optimized tolerance bound

Optimization approaches

- Simplex (fminsearch)
- Constrained Differential Evolution (DE) (Price,1996)

Optimization Under Uncertainty



Conclusions

- Implemented model to simulate laminate deformation given variable electrode pattern; accelerated computation
- Quantified shape error and determined its distribution
- Identified sensitive and significant design parameters
- Bi-modal nature of RSE distribution was discovered
- Optimized the design under uncertainty to improve shape error distribution

Acknowledgements

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