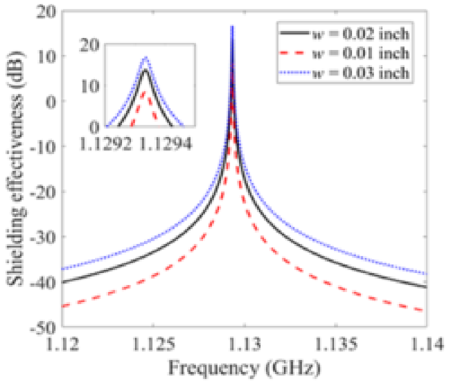
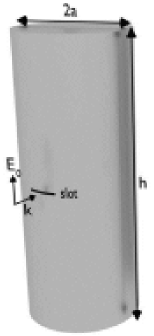
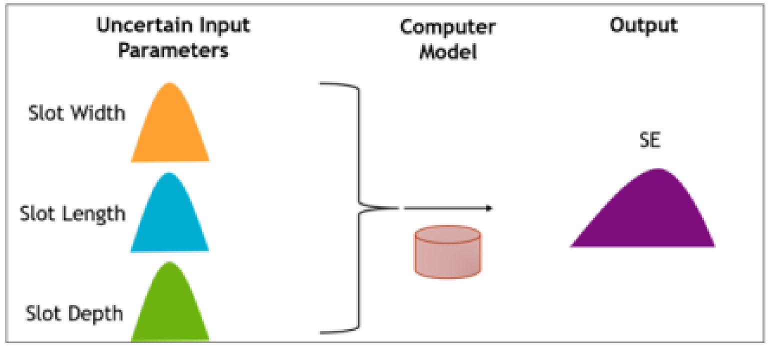
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

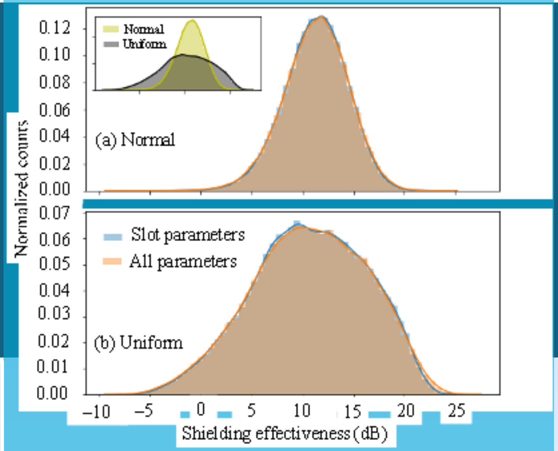
SAND2020-13796C

UNCERTAINTY QUANTIFICATION IN ELECTROMAGNETIC PROBLEMS OF HIGHLY RESONANT CAVITIES USING DAKOTA









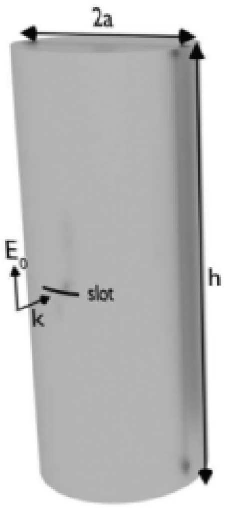
Presented By

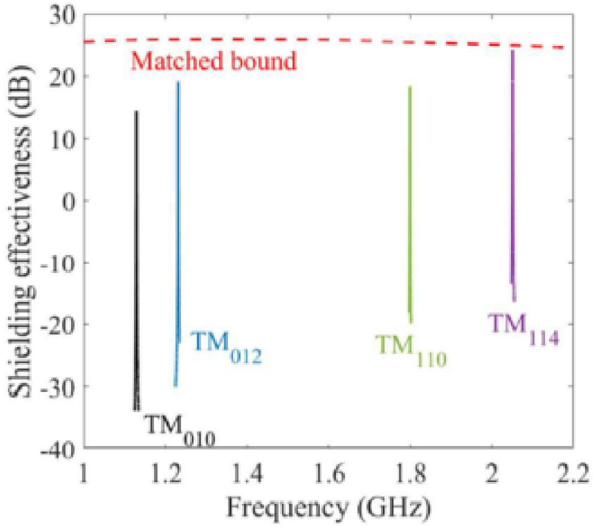
Adam M. Jones

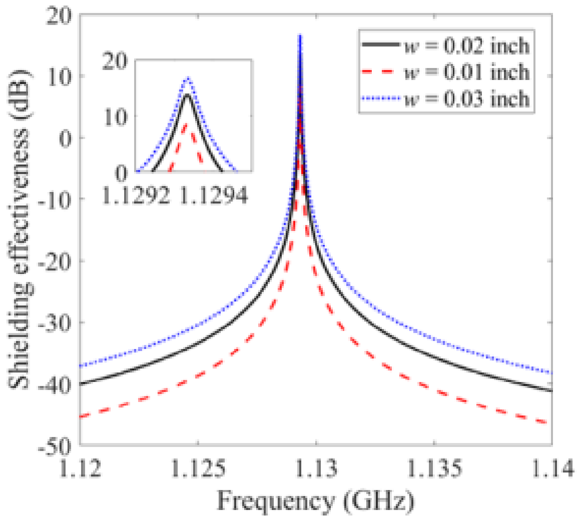
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Computational Simulation Credibility

- Involves assembling and documenting evidence that can be used to ascertain and communicate the believability of prediction that are produced from computational simulations
- Often has a specific use case in mind
- An important part of credibility is Uncertainty Quantification (UQ) or the understanding of the range of values that may be expected based on simulation results
- The goal of this work is to provide UQ analysis for the case of a canonical geometry for use in electromagnetic shielding applications



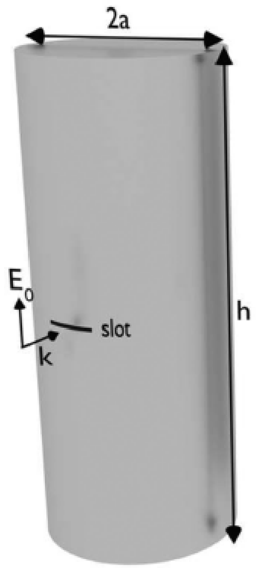




Electromagnetic (EM) Environments and Shielding Effectiveness (SE)

- Unmitigated external EM environments can cause upset and/or damage to electrical circuits and systems
- Some form of enclosure (often metallic) is often used to mitigate these environments and protect the devices and systems of interest.
- Ports of Entry (POEs) arise at joints and seams used to assemble these enclosures leading to penetration of the shield by external EM fields.
- Resonant enhancement of the internal fields may lead to degradation of the shielding provided and can potentially result in enhancement of the impinging field.
- Shielding Effectiveness (SE) is defined as the ratio of the field within the cavity E_{cavity} at some point r within the cavity arising due to the presence of an external field E_0.
  - All data here is presented in log scale; the oft-preferred representation.
- SE can be very sensitive to geometric variation in POEs, material properties of the contents of the cavity, and geometric variation of the vessel itself.
- This work seeks to characterize the relative sensitivity of SE to these input parameters and gain a better understanding of the uncertainties associated with characterizing resonant cavities for use in electromagnetic shielding applications.

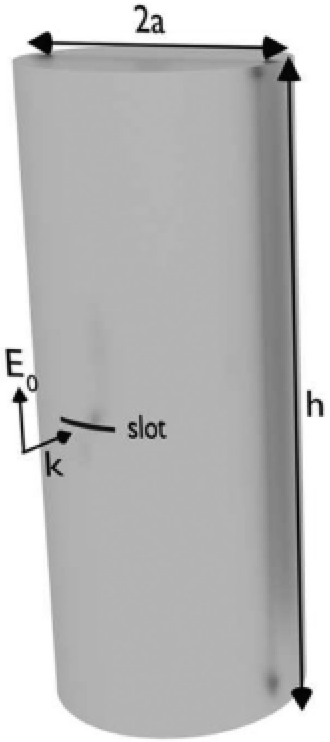
Example EM Enclosure



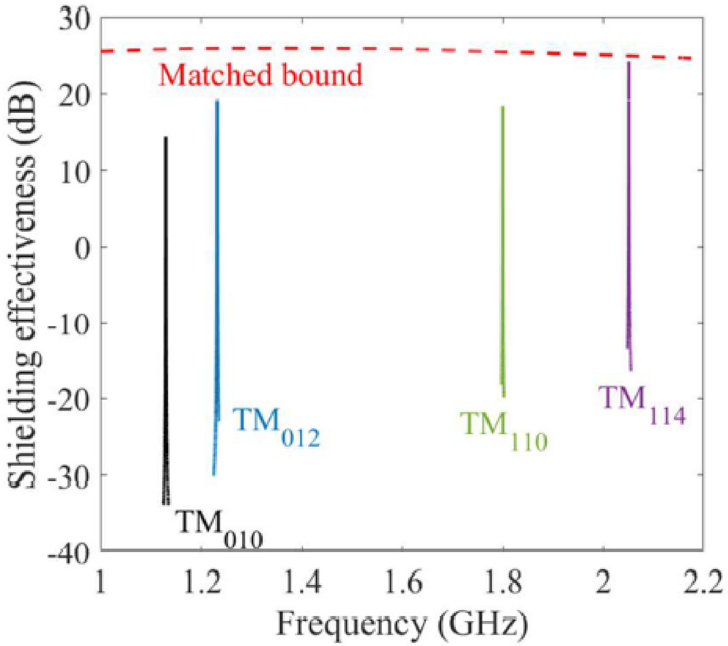
$$SE(r) = 20log\left(\frac{|E_{cavity}(r)|}{E_0}\right)$$

Representative Electromagnetic Enclosure

- A high Q cylindrical, Aluminum cavity with an azimuthal slot is used as a canonical study vessel
- The cylinder is defined with an interior radius a and height h
- The slot is defined parametrically as follows
  - Slot width (w): vertical gap width of the slot, in this case
  - Slot depth (d): thickness of the vessel wall, in this case
  - Slot length (l_p): projected azimuthal slot length; defined as $l = 2asin^{-1}(l_p/2a)$
- This study focuses on the TM_{010} mode (~1.3 GHz) with the expectation that other modes will exhibit similar behavior



Parameter	Value Range	Units
Cavity Height (h)	[21.6,26.4]	inch
Cavity Radius (a)	[3.6,4.4]	inch
Wall Conductivity (σ)	[2.2e7,3e7]	S/m
Slot width (w)	[5,25]	mils
Slot depth (d)	[0.2,0.3]	inch
Slot length (l_p)	[1.5,2.5]	inch



Simulation Tools Utilized

EIGER

- Full-wave Methods of Moments (MoM) code
- High fidelity computational capability
- Utilized here to tune the initial setup of the Reduced Order Modeling (ROM) capability

Power Balance

- Analytical model; defines an wide-band upper bound for the SE response
- Matched formulation
  - Treats the backing cavity as a uniformly distributed matched load
  - Used to perform the sensitivity analysis simulations
- Unmatched formulation
  - Similar to Matched formulation; however, a backing cavity with appropriate field profile and losses are included such that resonant modes are fully represented in the response
  - Used to perform uncertainty quantification simulations

Dakota

- Software toolkit for optimization, sensitivity analysis, and uncertainty quantification (UQ)
- Used here to study the impact of parametric inputs on the peak SE of the test vessel

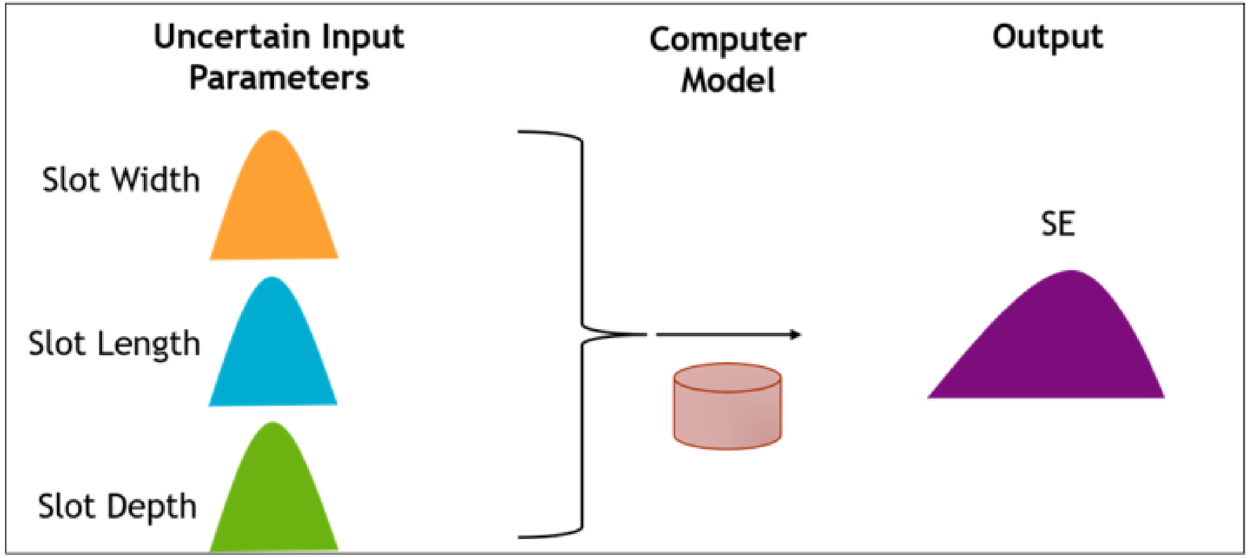
* All codes developed by Sandia National Laboratories

Overview of the Study

Quantity of Interest (QoI): Peak SE for the TM_{010} mode at ~1.3 GHz

Goals of the Study

- Determine and rank the importance of geometrical and material parameters
- Understand the sensitivity of the response to input variation → sensitivity analysis
- Quantify the change in SE as a function of input variation → uncertainty quantification
- Determine the impact of input parameter distribution on the output parameter distribution → full uncertainty propagation
- Understand the potential interactions between variables



Uncertain Input Parameters

Computer Model

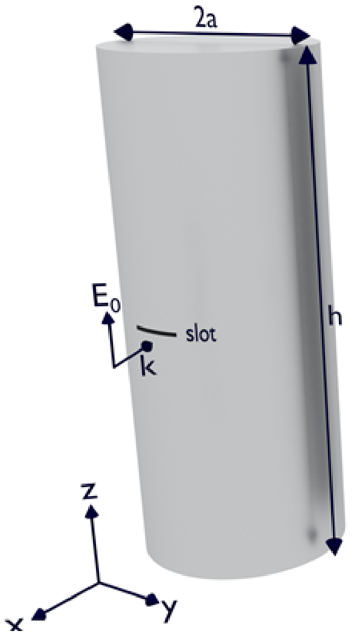
Output

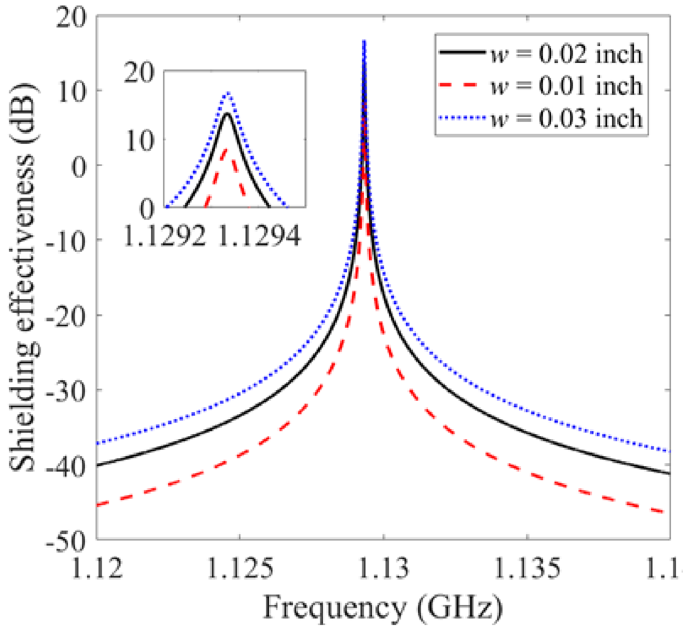
Slot Width

Slot Length

Slot Depth

SE





Sensitivity Analysis – Determination of Sobol Indices

Goals of the Study

- Reduce the dimensionality of the input space → hold insensitive inputs constant in further studies
- Understand which uncertain inputs have the strongest impact on SE → explore these in more detail

Approach

- Dakota used to create a Polynomial Chaos Expansion (PCE) surrogate to Matched Power Balance
- PCE model trained using 448 points across the parameter space generated via Latin Hypercube Samp
- Monte Carlo simulation performed using Dakota & PCE surrogate → Sobol indices for each parameter

For Inputs

$$\mathbf{x} = [x_1, \mathrm{K}, x_6]$$

The Sobol Indices are

$$S_j = \frac{Var_{x_j}\left(E_{\mathbf{x}_{(-j)}}\left[\mathrm{SE} \mid x_j\right]\right)}{Var(\mathrm{SE})}$$

Results

- Slot width and length are the dominant parameters
- Cavity height, radius, and conductivity are all negligible contributors

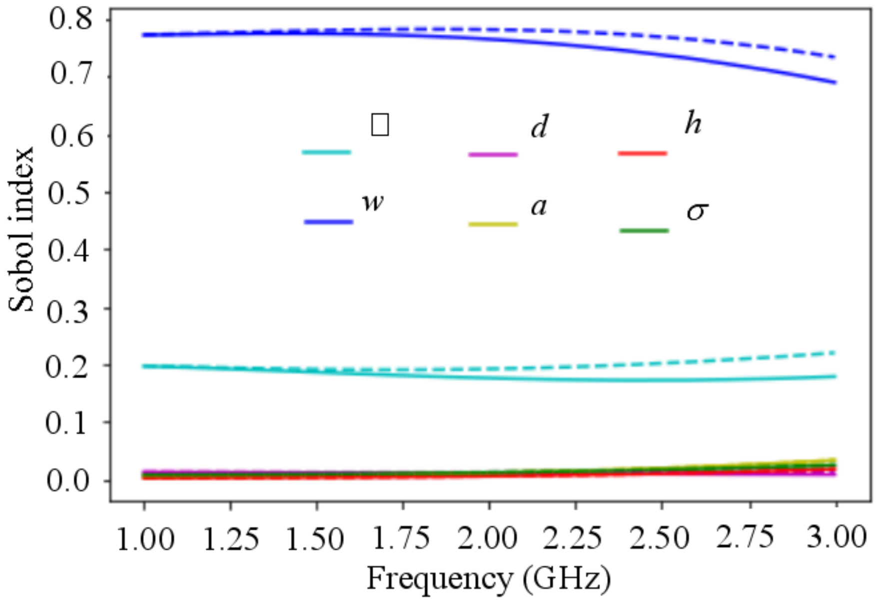
Parameter	Value Range	Units
Cavity Height (h)	[21.6,26.4]	inch
Cavity Radius (a)	[3.6,4.4]	inch
Wall Conductivity (σ)	[2.2e7,3e7]	S/m
Slot width (w)	[5,25]	mils
Slot depth (d)	[0.2,0.3]	inch
Slot length (l)	[1.5,2.5]	inch

→

→

→

Result
Negligible impact, fix at 24 inches
Negligible impact, fix at 4 inches
Negligible impact, fix at 2.6e7 S/m
Greatest impact, study in detail
Somewhat impactful, warrants further study
Somewhat impactful, warrants further study



Sensitivity Analysis – Matched Power Balance

Goals of the Study

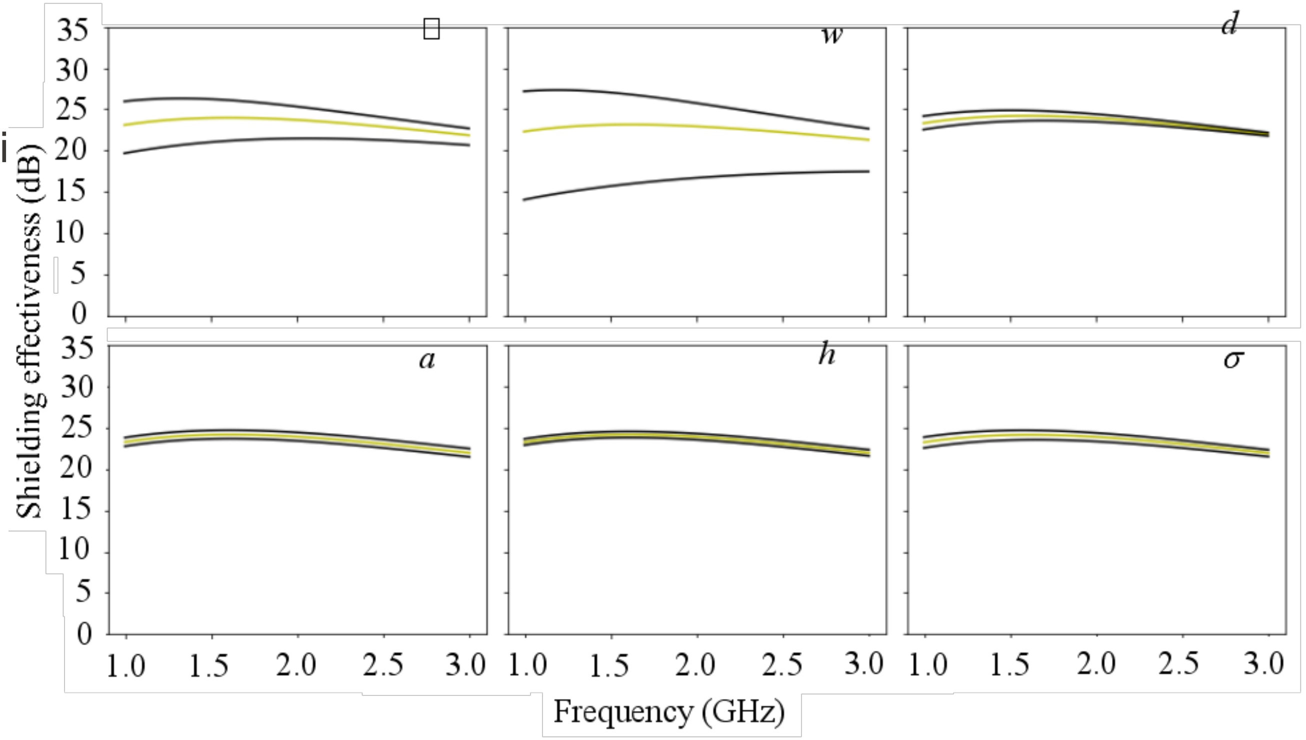
- Provide initial study results to gauge the need for detailed analysis
- Understand the impact of frequency on parametric dependence

Approach

- Dakota used to perform Monte Carlo simulations using the Matched Power Balance code
- Each input parameter uniformly sampled at each frequency

Results

- Slot width and length are the dominant parameters
- Cavity height, radius, and conductivity are all negligible contri
- Supports the results derived from the Sobol indices
- Provides further credibility to the study



Parameter	Value Range	Units
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Slot width (w)	[5,25]	mils
Slot depth (d)	[0.2,0.3]	inch
Slot length (l	[1.5,2.5]	inch

Interval and Probabilistic Uncertainty Analyses

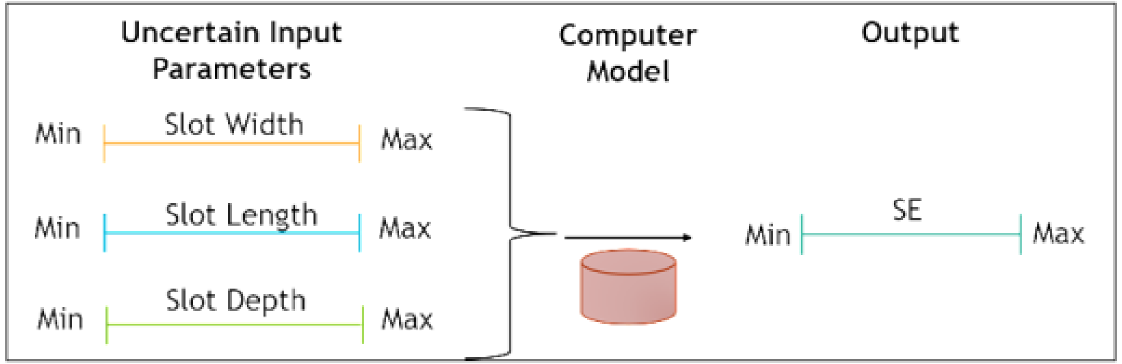
Interval Uncertainty Analysis

- Uncertain inputs bounded by minimum/maximum values
- Objective is to estimate minimum and maximum SE values based on the range of inputs
- Does not require knowledge of the input parameter distribution
- Requires relatively fewer runs in the case of roughly linear input/output relationships

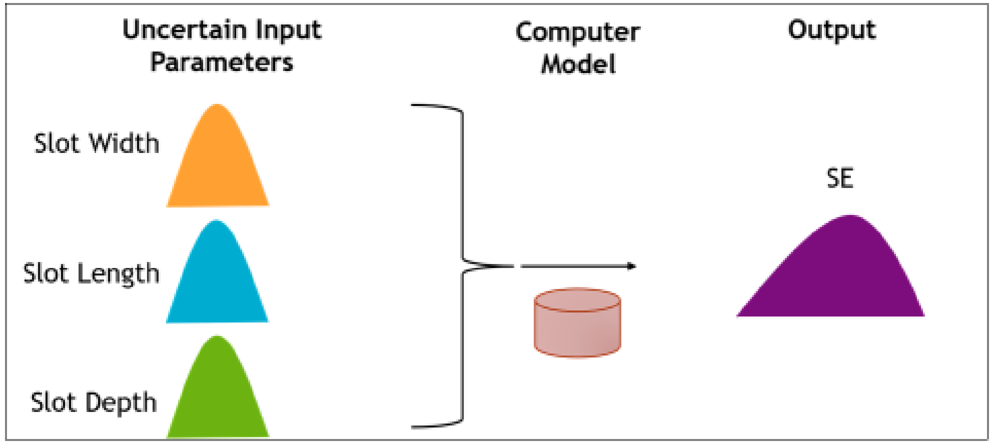
Probabilistic Uncertainty Analysis

- Input parameter distributions are required
- Yields information about the output parameter distribution as opposed to simply minimum/maximum bounds
- Often more useful when detailed information about the output parameter sensitivity is required or the computer model exhibits nonlinear behavior or significant interaction between parameters

Interval Uncertainty Analysis



Probabilistic Uncertainty Analysis



Interval Uncertainty Analysis

Goals of the Study

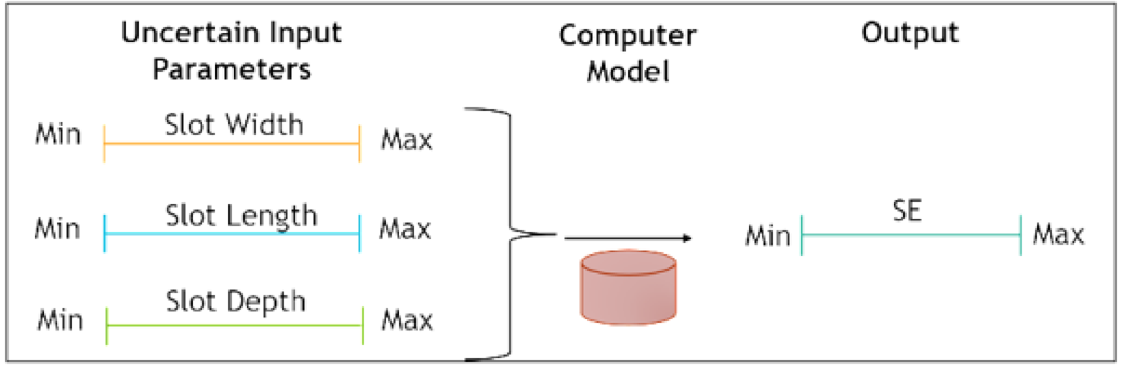
- Estimate the range of SE based on the range of the remaining three uncertain inputs (i.e. interval uncertainty analysis)
- Compare results from the analytical code to full-wave simulations → assess suitability of the analytical code for probabilistic uncertainty analysis

Approach

- A 4^3 full factorial DOE study was performed and used to compare the Unmatched Power Balance compared against full-wave EIGER simulations → each of 3 varied input parameters was simulated at four levels resulting in a total of 64 simulations.

Results

- Determined that the Unmatched Power Balance code was suitable for use in probabilistic uncertainty analysis
- Confirmed the presumed linear relationship between the input and output parameter distributions
- Confirmed the comparable accuracy between the analytical and full-wave simulation tools the TM_{010} mode of this geometry
- Found relatively little interaction between input parameters



Uncertain Input Parameters

Computer Model

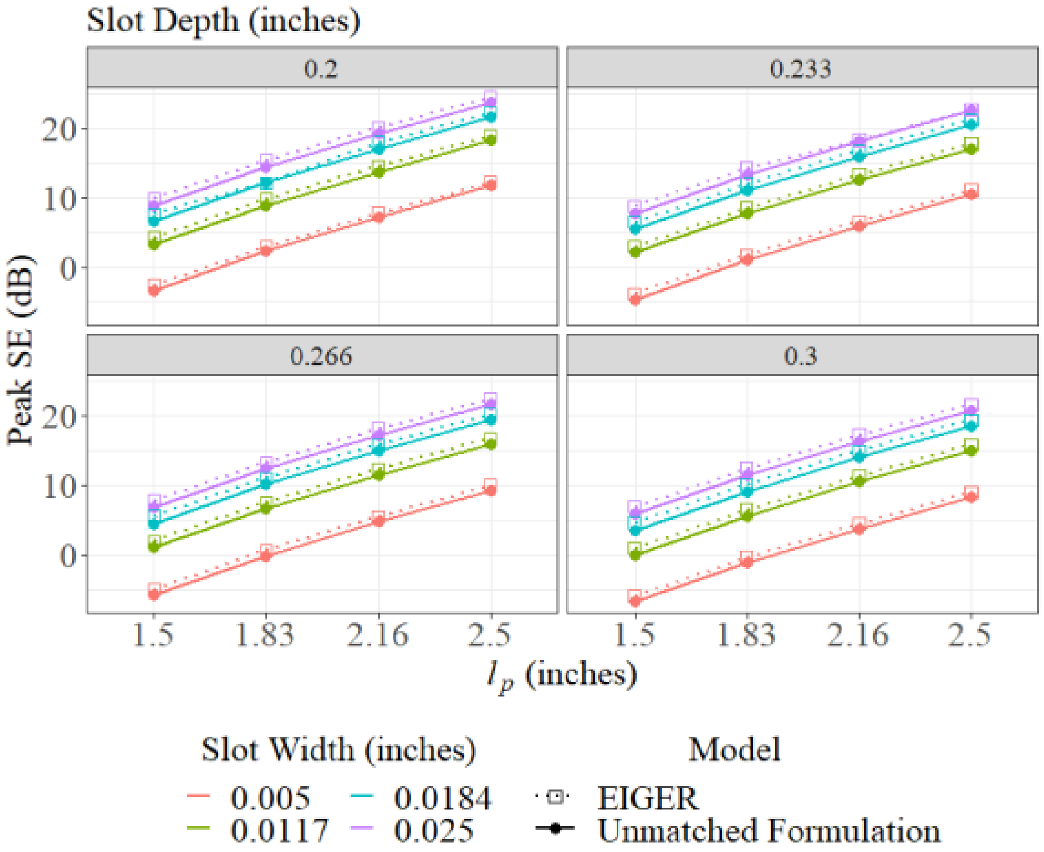
Output

Min Slot Width Max

Min Slot Length Max

Min Slot Depth Max

Min SE Max



Probabilistic Uncertainty Analysis

Parameter	Value Range	Units
Cavity Height (h)	[21.6,26.4]	inch
Cavity Radius (a)	[3.6,4.4]	inch
Wall Conductivity (σ)	[2.2e7,3e7]	S/m
Slot width (w)	[5,25]	mils
Slot depth (d)	[0.2,0.3]	inch
Slot length (l_s)	[1.5,2.5]	inch

Goals of the Study

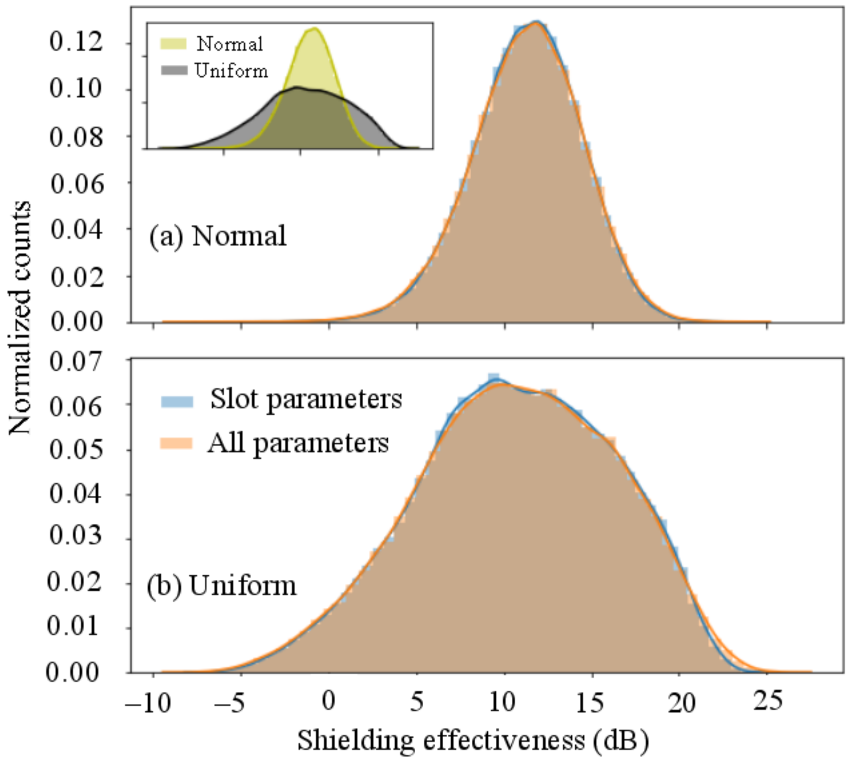
- Understand the impact of input parameter distributions on the output parameter distribution
- Exercise Dakota for uncertainty propagation
- Examine the consequences of reducing the initial six parameter input space to three parameters

Approach

- Use both uniformly and normally distributed input parameter distributions for the three input parameters of interest
  - The means are the same while the standard deviation for the normal distribution was chosen to be 1/6 the range of the uniform distribution in an attempt to achieve comparable responses from the model
- Utilize a PCE surrogate generated in similar fashion as the previously discussed sensitivity analysis

Results

- Exclusion of three input parameters based on their low Sobol indices appears, in fact, to have negligible impact on the output of the study (top vs bottom figure)
- The centroids of the SE distributions are similar for the uniformly and normally distributed input parameters
- The breadth of the distribution; however, appears to be sensitive to the input parameter distribution
  - Standard deviation for the uniform case is >75% greater than the normal case



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