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TECHNOLOGY CORPORATION

Disturbance-Optics-Controls-Structures (DOCS)

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Outline

- DOCS Overview
- Integrated Model Definition
- Analysis

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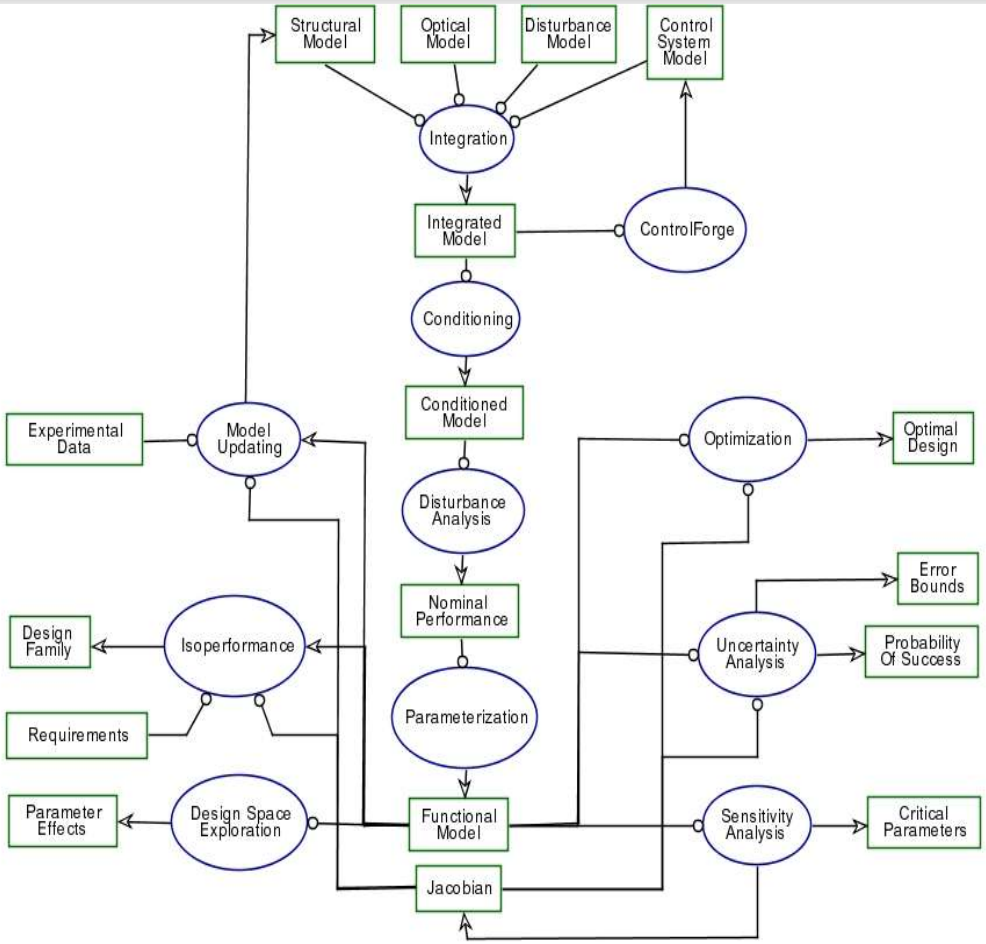
Integrated Modeling

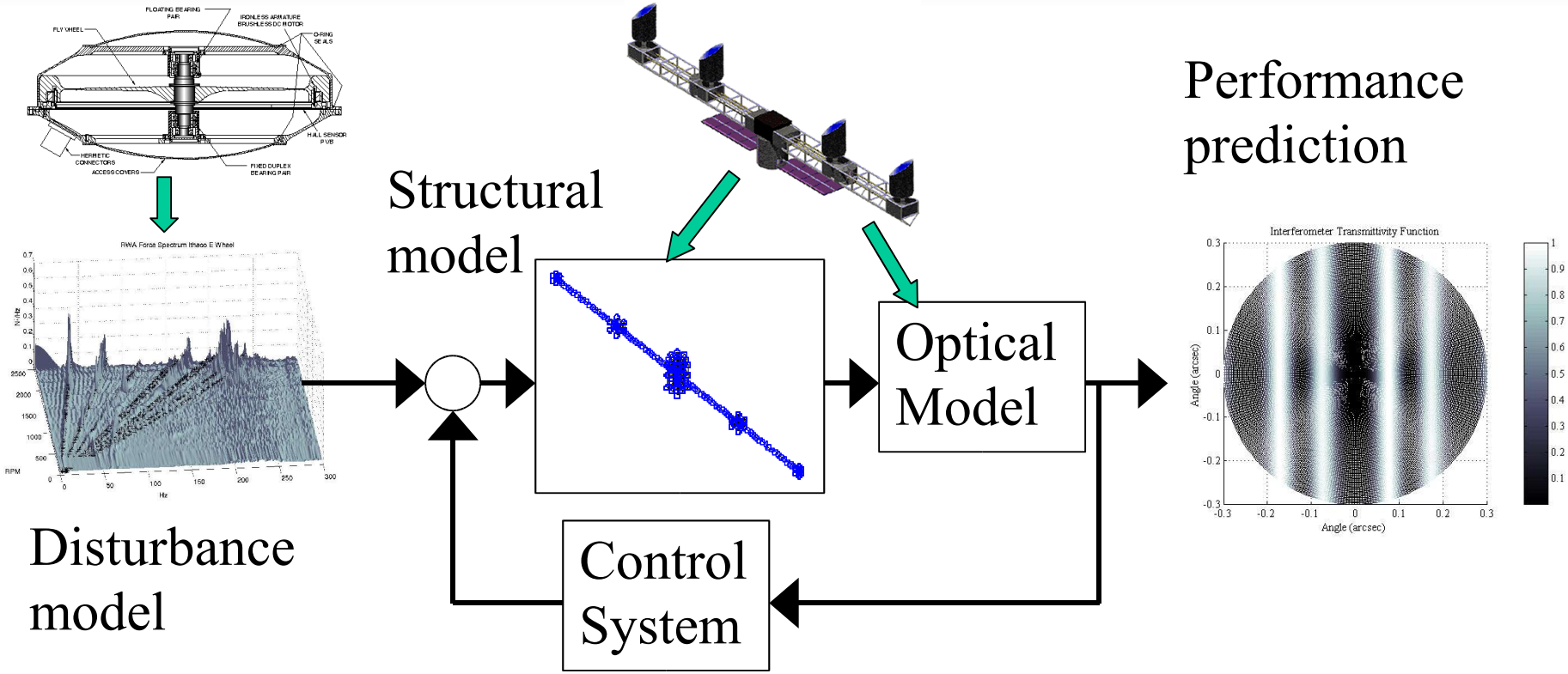
- **Goals**
  - Optimization of complex system design problems
    - **highly coupled physical processes**
  - Trade space exploration
  - Incorporation of available data to calibrate models
  - Life cycle model management
- **Developed under a NASA Phase II SBIR**
  - Gary Mosier as COTR
  - 9/02-9/04

Process Overview

- **Inputs**
  - Discipline models
  - Science requirements
- **Outputs**
  - Performance/risk optimal design
  - Critical design parameters
  - Trade space
    - **parameter and objective bounds**

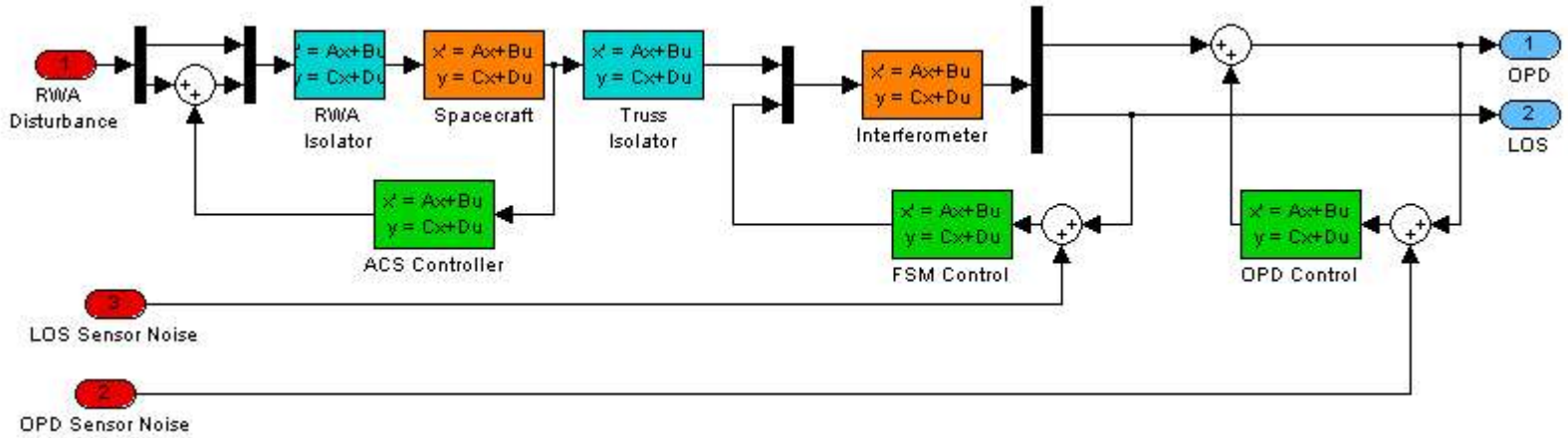


Integrated Modeling



- **Integrated Modeling: *physically accurate* representation of *entire* system**

System Integration



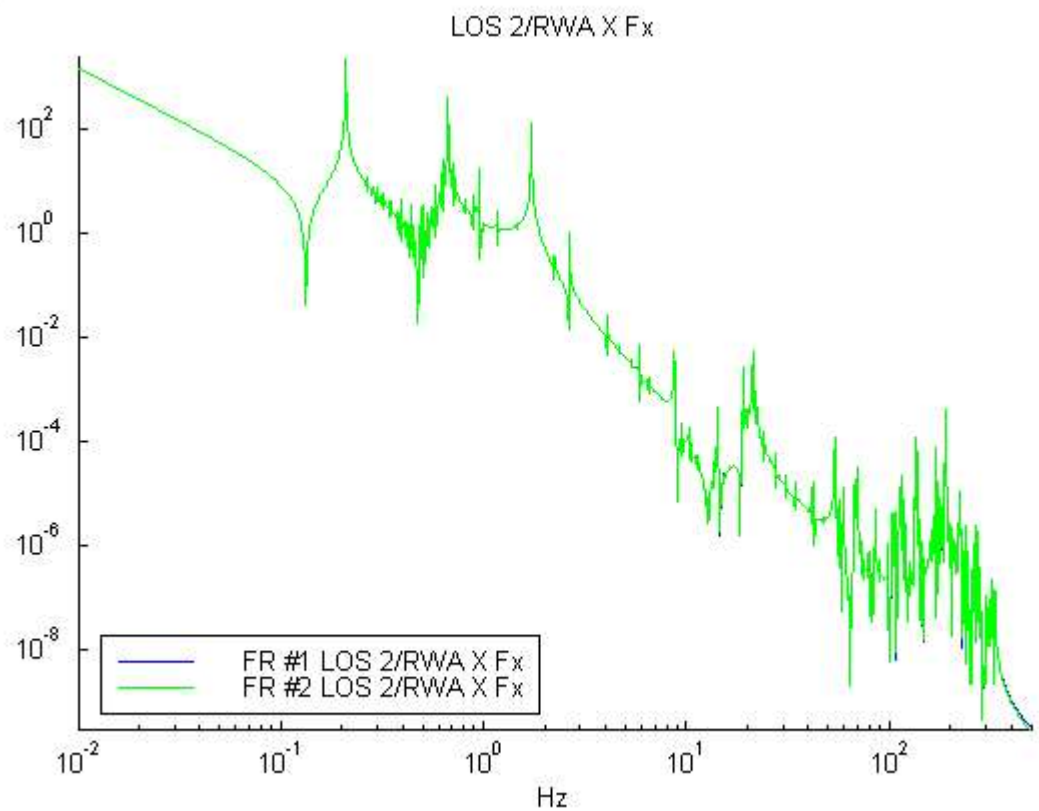
- **Automatic computation of the coupled optomechanical dynamics**
  - User defines component models
  - DOCS computes aggregate state space model dynamics
  - Units checking and conversion

Integrated Model dynamics:

$$\dot{x} = A\,x + B\,w$$
$$z = C\,x + D\,w$$

Model Conditioning

- **Balanced reduction**
  - numerically stabilized for large order systems
- **FRF reduction**
  - preserves FE state basis
- **Input/output scaling**
  - equalize input/output weight for high dynamic-range outputs
- **State transformations**
  - numerically conditioned large order models



1200-mode vs. 872-mode optomechanical model

Disturbance Analysis

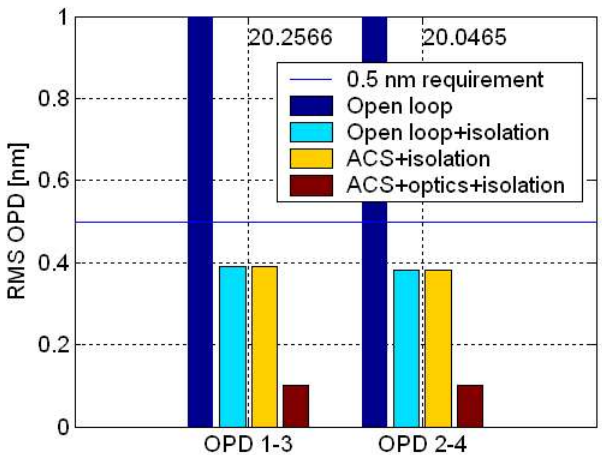
- **Time domain**
  - nonlinear analysis
- **frequency domain**
  - frequency content
- **state space shaping filter**
  - speed

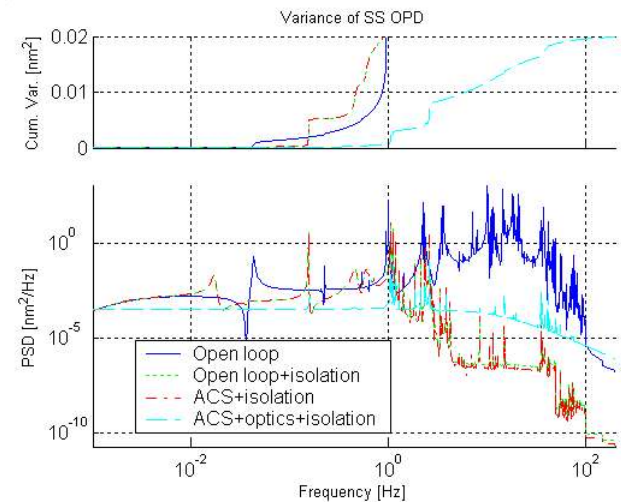
$$J = \frac{1}{T}\int_0^T z(t)^2 \partial t$$

$$J = \int_{\omega_{min}}^{\omega_{max}} Z(j\omega) Z(j\omega)^H \partial \omega$$

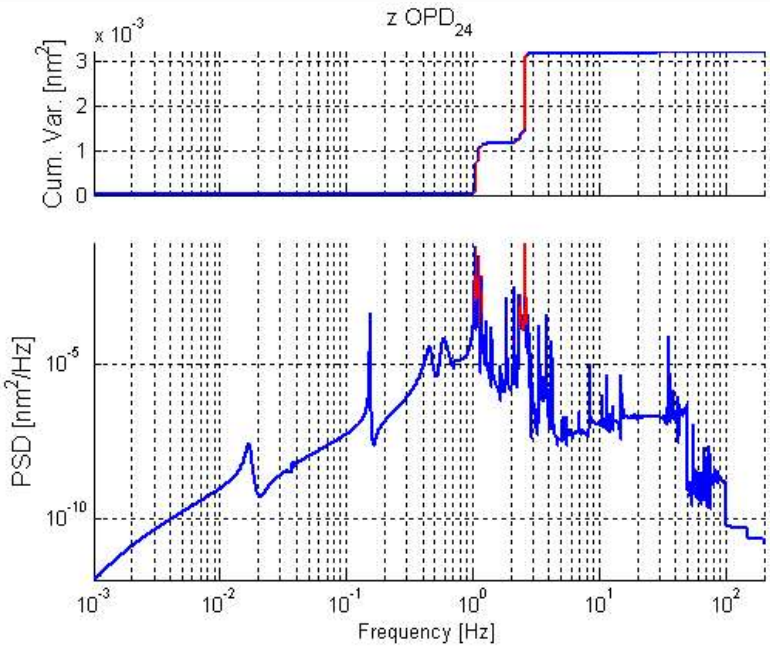
$$J = trace(C^T C S_{xx})$$

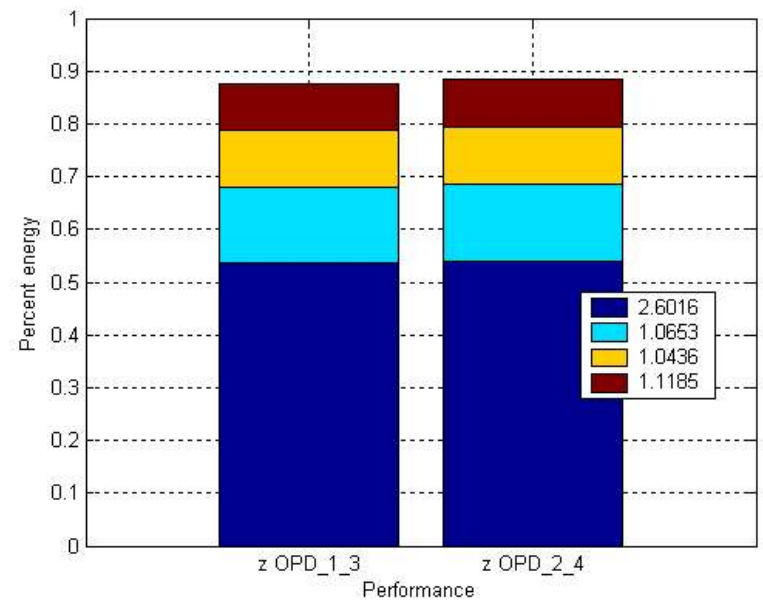
$$A S_{xx} + S_{xx} A^T + BB^T = 0$$





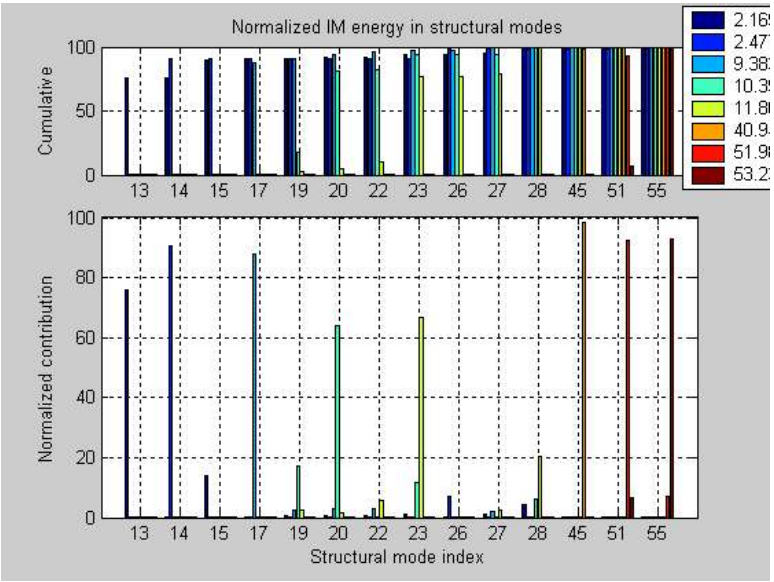
Critical Mode Identification

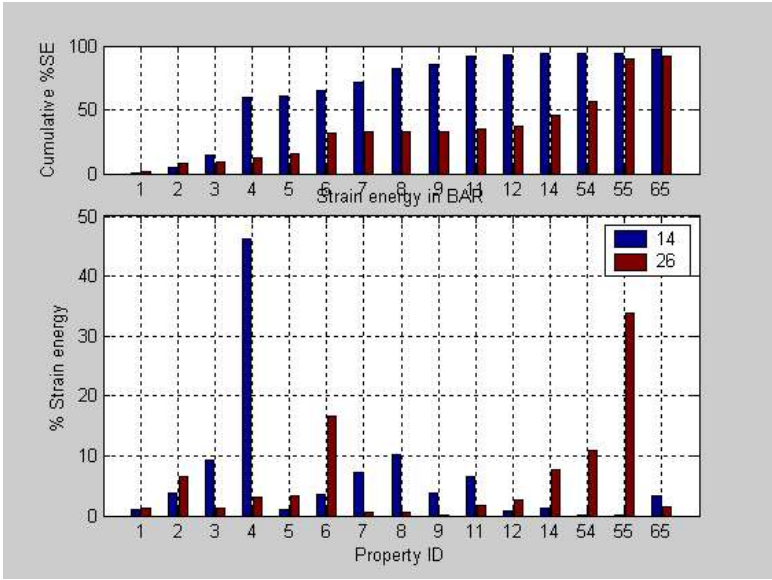




- *Critical modes*: modes that contribute majority of energy to output

Localization





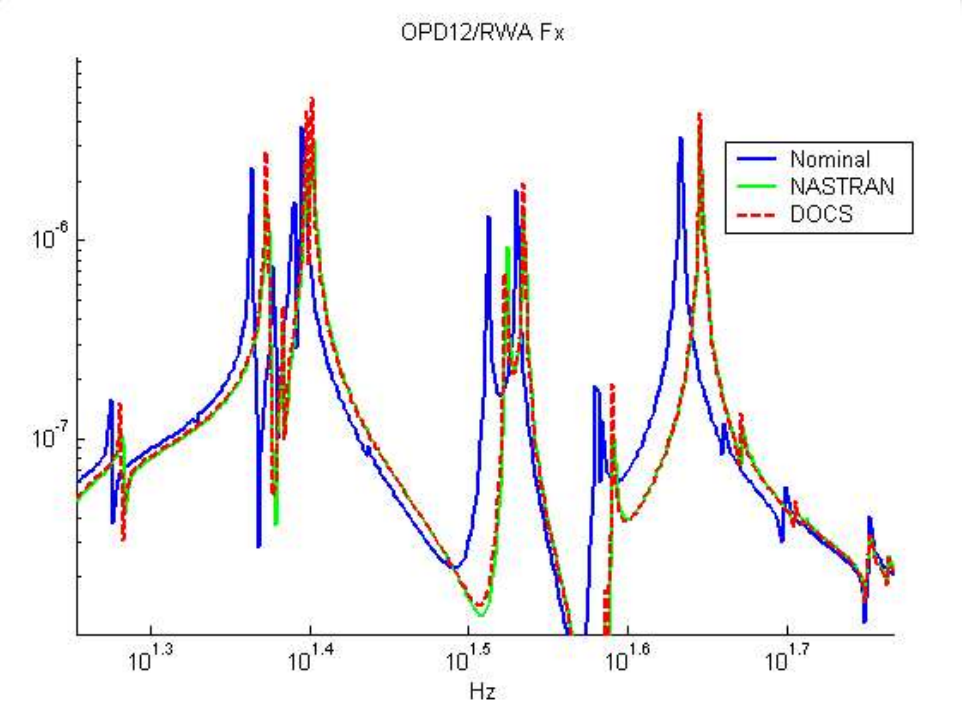
- ***Localization*: identification of structural elements and properties that influence the critical modes**

Parameter Dependence

- **Structural changes modify mass and/or stiffness**
  - delta-K, delta-M for specific groups of elements
- **Transform to modal coordinates and add to structural model**

$$M\ddot{x}+(K+\Delta K\alpha)x=B_f f$$

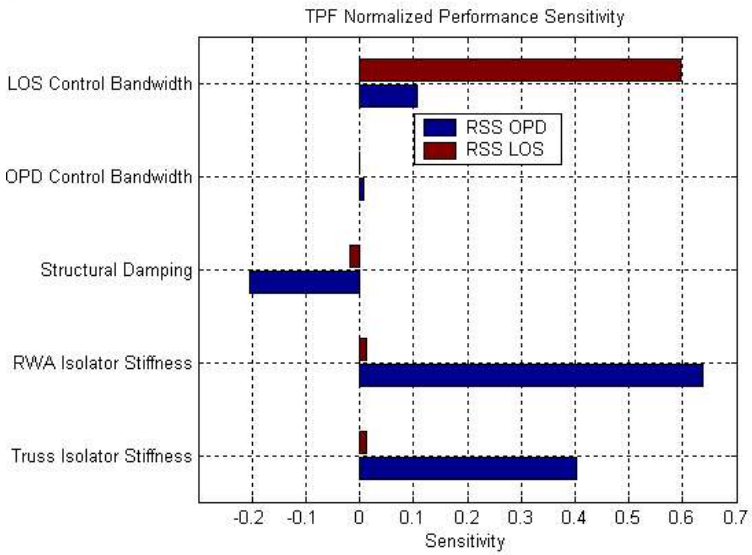
$$I\ddot{q}+\left(\Omega^2+\Phi^T\Delta K\alpha\Phi\right)q=\Phi^T B_f f$$



Predict structural dynamics at off-nominal parameters without re-running FEM

Sensitivity Analysis

- **DOCS parametrization enables exact gradients**
- **Utility**
  - Parameter ranking
  - Optimization
  - Isoperformance



Time

$$\frac{\partial \Sigma_{zz}}{\partial p} = \frac{1}{T}\int_0^\infty \frac{\partial z}{\partial p} z^T + z \frac{\partial z}{\partial p}^T \partial t$$

Frequency

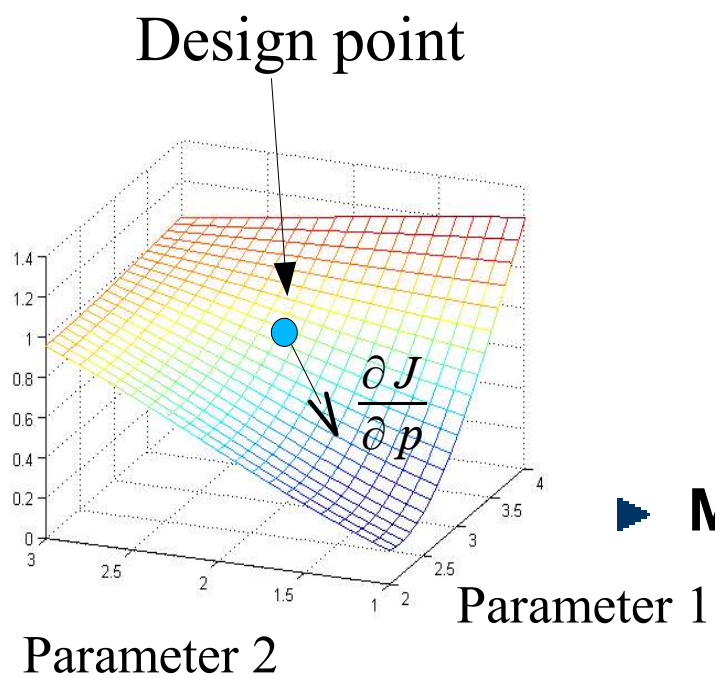
$$\frac{\partial \Sigma_{zz}}{\partial p} = 2\int_0^\infty \frac{\partial G_{zw}}{\partial p} S_{ww} G_{zw}^H + G_{zw} S_{ww} \frac{\partial G_{zw}}{\partial p}^H \partial \omega$$

Lyapunov

$$A^T L_i + L_i A + C_i^T C_i = 0$$

$$\frac{\partial \sigma_i^2}{\partial p} = trace\left[\Sigma_{xx} \frac{\partial (C_i^T C_i)}{\partial p}\right] + trace\left[L_i\left(\frac{\partial A}{\partial p}\Sigma_{xx} + \Sigma_{xx}\frac{\partial A}{\partial p}^T + \frac{\partial (BB^T)}{\partial p}\right)\right]$$

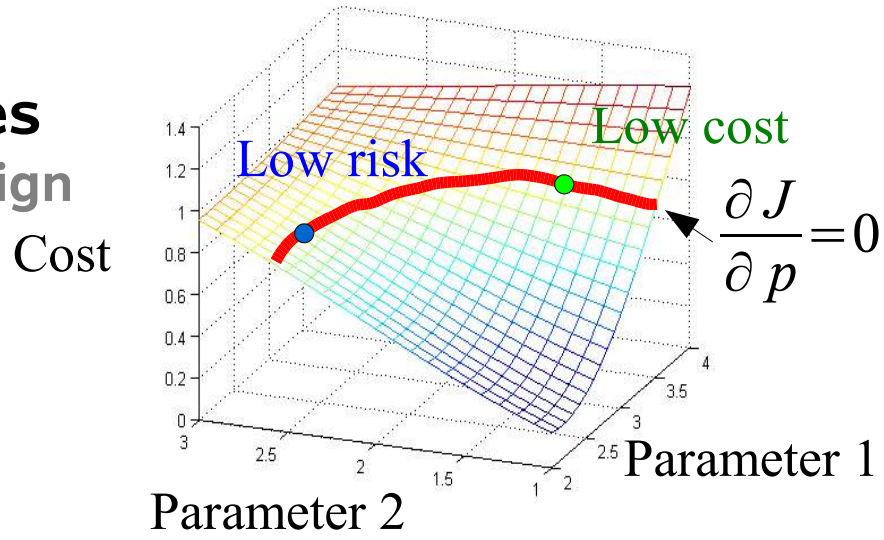
Optimization



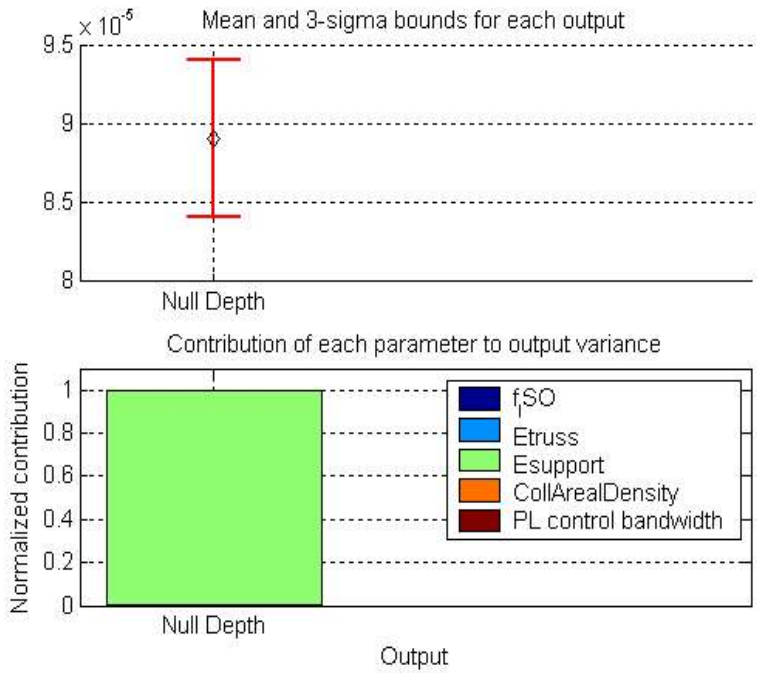
- **Automatic minimization of objective function**
  - Zeroth order
    - **Simulated annealing, genetic algorithms**
    - **discrete and multi-modal (nonconvex) problems**
  - First order
    - **gradient search**
- **Multi-objective search**
  - Goal seek
    - **all metrics below a target value**
  - Pareto optimal

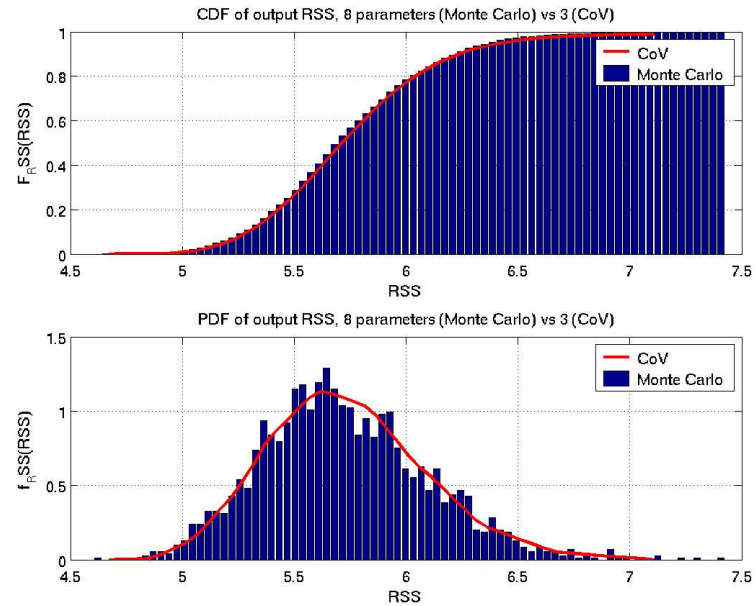
Isoperformance

- **Treat performance as a constraint**
  - find combinations of design variables that produce the same performance
- **Requirements trades**
  - find better design alternatives
    - **cheaper**
    - **less risk**
- **Multidimensional**
  - 20 parameters



Uncertainty Analysis





$$E[J] \approx J(\mu_\alpha)$$

$$E[J^2] \approx \frac{\partial J}{\partial \alpha} \Sigma_{\alpha\alpha} \frac{\partial J^T}{\partial \alpha}$$

- **Range of techniques for obtaining confidence bounds**
  - fast but approximate
    - Linear Covariance Propagation
  - accurate but slow
    - Change of Variables

$$f_J(J) = \left|\frac{\partial \alpha}{\partial J}\right| f_\alpha(\alpha)$$

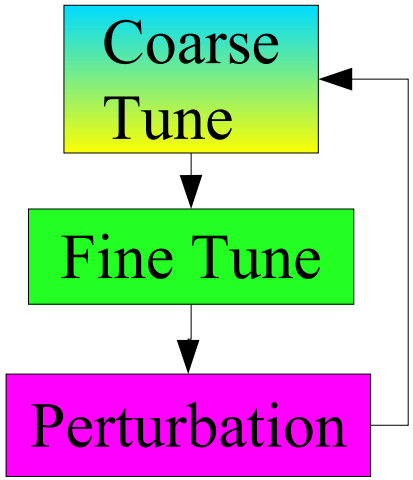
Model Updating

- Calibrate models using data
- Objective functions
  - Modal frequency
  - Mode shape
  - FRF
- Search parameters
  - Modal
    - Frequency
    - Damping
    - Residue
  - Physical
    - Material properties
    - Geometry

$$J(x)=\sum_{i=1}^{N}\left(\omega_i-\hat{\omega}_i(x)\right)^2$$

$$J(x)=\|\Phi-\hat{\Phi}(x)\|_2$$

$$J(x)=\|W\left[\log(G+\mu)-\log(\hat{G}(x)+\mu)\right]\|_2$$



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Additional Features

- **Speed, accuracy, memory efficiency**
  - State transformation to canonical forms
  - Specialized eigensolvers for canonical model forms
  - Fast Lyapunov solvers
  - Fast frequency and time response functions
    - **C mexfiles**
  - Fast Frequency Response Function manipulation
    - **multiplication, singular value decomposition, …**