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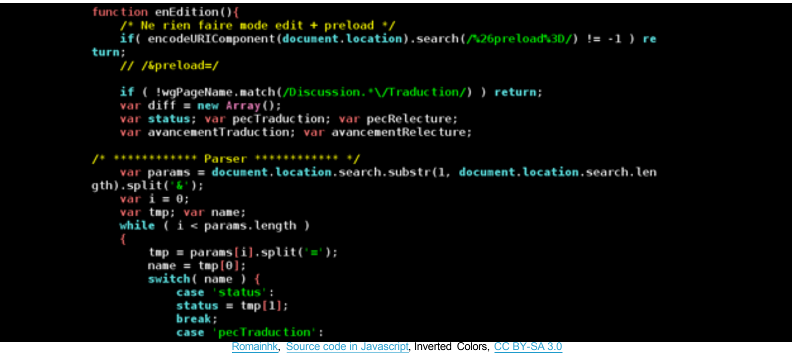

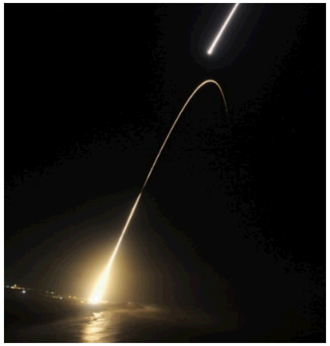

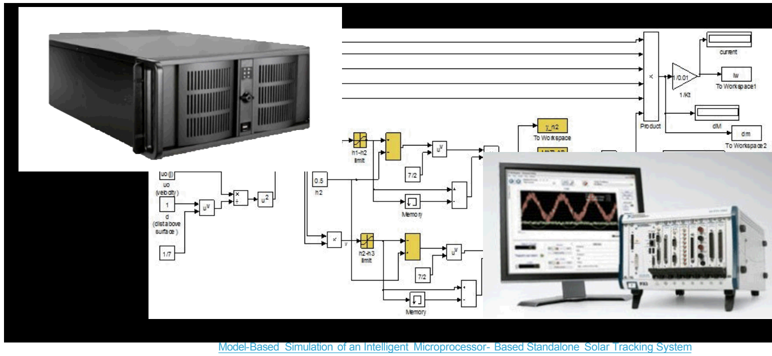

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Model-Based Simulation of an Intelligent Microprocessor- Based Standalone Solar Tracking System

Modeling and Implementation Of Variable Structural Dynamics for Software Verification

Matthew S. Bigelow

AIAA SciTech Forum

MST-04/SOF-01, Modeling and Simulation Based Software Development and Verification

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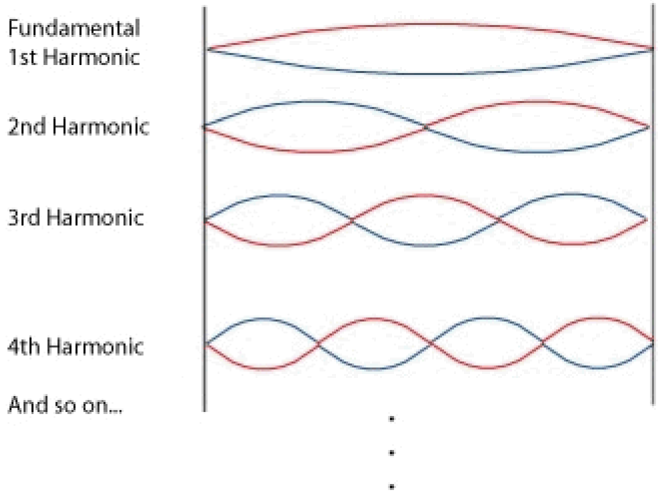
Overview

- Background
  - Structural Dynamics
  - Application Goals
  - Finite Element Analysis
  - Modeling and Simulating Structural Dynamics
- Variable Structural Dynamics
- Example
  - Configuration
  - Results
  - Implementation
- Additional Implementation Details
- Summary

Background: Structural Dynamics

- All structures have natural modes at which they vibrate when exited
- Typically modeled as many parallel second-order mass-spring-damper linear systems
- $\ddot{x} = -\omega_n^2 x - 2\zeta\omega_n \dot{x} + \frac{u}{m}$

https://opencurriculum.org/5576/standing-waves-and-musical-instruments/



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Background: Application Goals

- Software verification for vehicles with active control systems and structural dynamics that vary smoothly and significantly
  - Thrust-vectored rockets
  - Airtankers during operations
  - Variable-sweep wing aircraft when changing wing sweep
  - V-22 Osprey during conversions
- Need method to simulate the variable structural dynamics for control software verification
  - Structural dynamics should be added disturbances to an existing rigid body simulation
  - Need to vary frequency, magnitude, and damping per simulation run to account for uncertainties
  - Model should not have unintentional adverse affects on downstream consumers such as inertial sensors

Background: Finite Element Analysis

- Structures are modeled as many (often millions) 6DOF mass-spring elements and nodes
- Modes are then solved for:
  - Eigenvalues (ω_n) are mode frequencies
  - Eigenvectors ($\boldsymbol{\phi}$) are mode shapes

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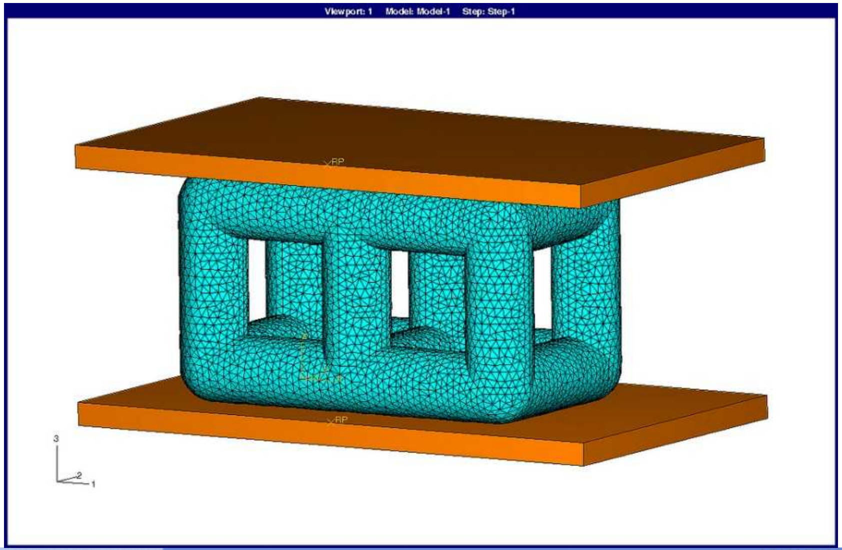

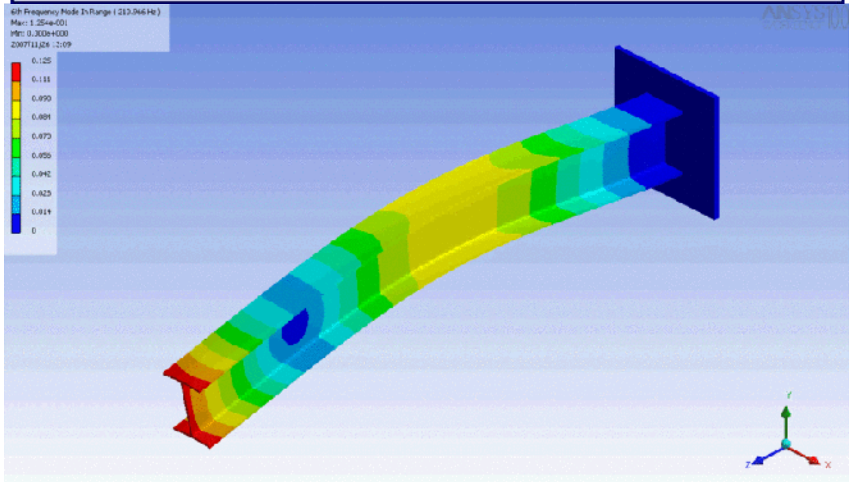

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Background: Modeling and Simulating Structural Dynamics

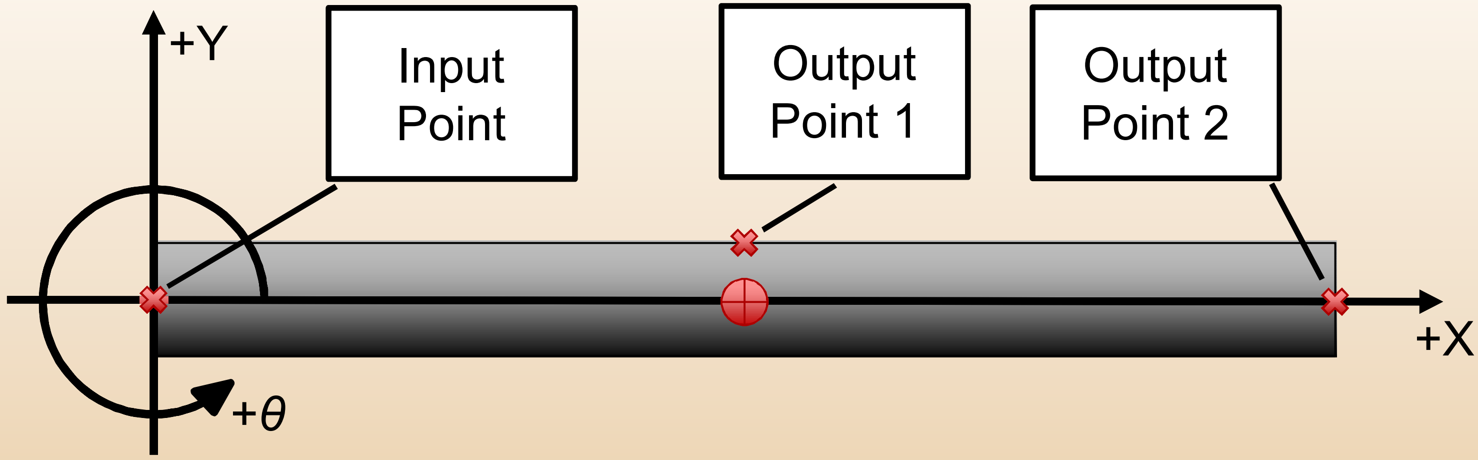
- Eigenvectors ($\boldsymbol{\phi}$) convert from physical coordinates to modal coordinates and back again and have already been normalized by the modal mass
- Eigenvectors contain relative displacement information at every node so size is reduced by only selecting desired node locations
  - Input node(s) ($\boldsymbol{\phi}_{in}$): Location(s) where excitation occurs
    - Example: Actuator forces and moments
  - Output node(s) ($\boldsymbol{\phi}_{\omega out}$ and $\boldsymbol{\phi}_{Aout}$): Sensor location(s)
    - Example: An IMU sensing rotational rate and translational acceleration
- Modes that do not significantly involve the selected nodes can be removed for performance purposes
- Damping (ζ) needs to be determined
- Combine in parallel the state space form for each mode:
  - $$A = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\zeta\omega_n \end{bmatrix} \qquad B = \begin{bmatrix} \mathbf{0}^T \\ \boldsymbol{\phi}_{in}^T \end{bmatrix}$$ $$C = \begin{bmatrix} \mathbf{0} & \boldsymbol{\phi}_{\omega out} \\ -\omega_n^2 \boldsymbol{\phi}_{Aout} & -2\zeta\omega_n \boldsymbol{\phi}_{Aout} \end{bmatrix} \quad D = \begin{bmatrix} \underline{0} \\ \boldsymbol{\phi}_{Aout} \boldsymbol{\phi}_{in}^T \end{bmatrix}$$

Variable Structural Dynamics

- Leveraging finite element analysis, eigenvalues and eigenvectors can be found for multiple configurations of the same structure
- The eigenvalues and eigenvectors may be interpolated between configurations, however…
  - Modes of interest must be identified and correlated between configurations
  - Eigenvector polarity must be identical across all configurations
    - $\frac{\boldsymbol{\phi}_k \cdot \boldsymbol{\phi}_{k+1}}{\|\boldsymbol{\phi}_k\| \cdot \|\boldsymbol{\phi}_{k+1}\|} \geq 0$, where k is configuration index
  - Modes not present in all configurations must be properly tapered in and/or out between appropriate configurations
    - This can be accomplished by duplicating the eigenvalue and setting the eigenvector to 0 for configurations where a mode is absent

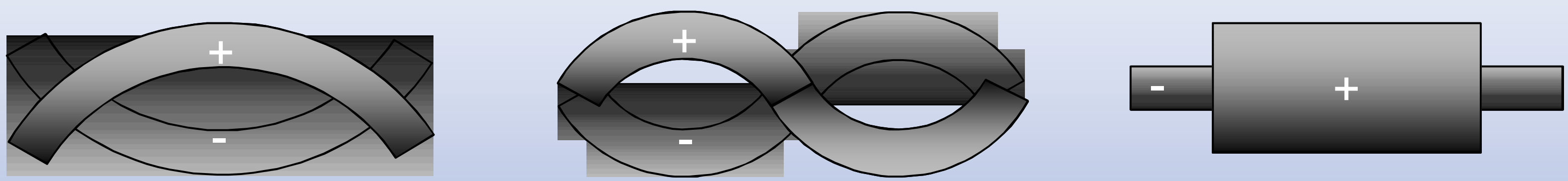
Example: Configuration

Physical Coordinates



Modal Coordinates

Mode 1: 2-3Hz (ζ: 0.3%)   Mode 2: 4-6Hz (ζ: 0.6%)   Mode 3: 6-9Hz (ζ: 0.9%)



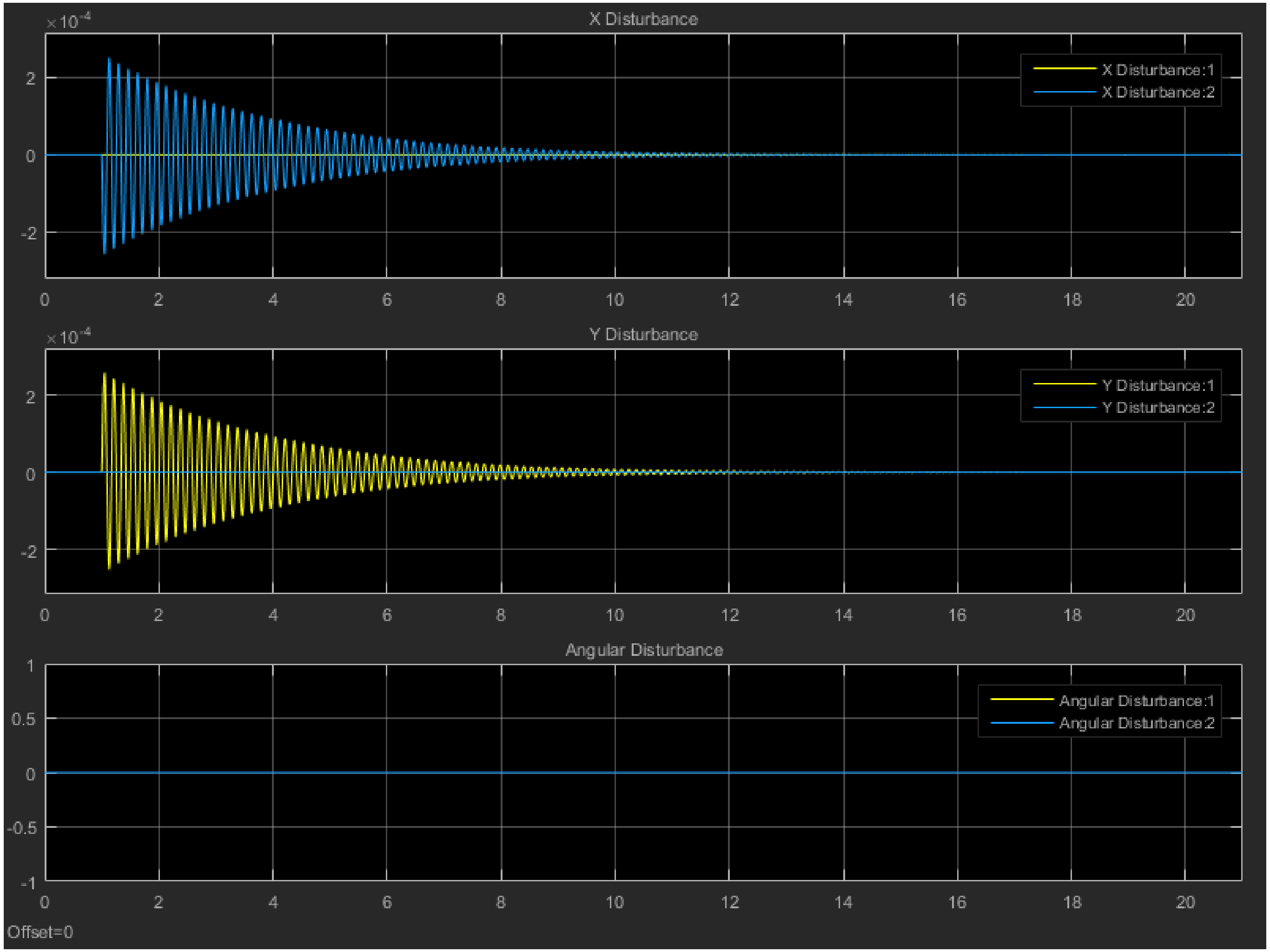
Coordinate Transformations

Pt	X	Y	θ
In	0	-1	+1
O1	0	+1	0
O2	0	-1	-1

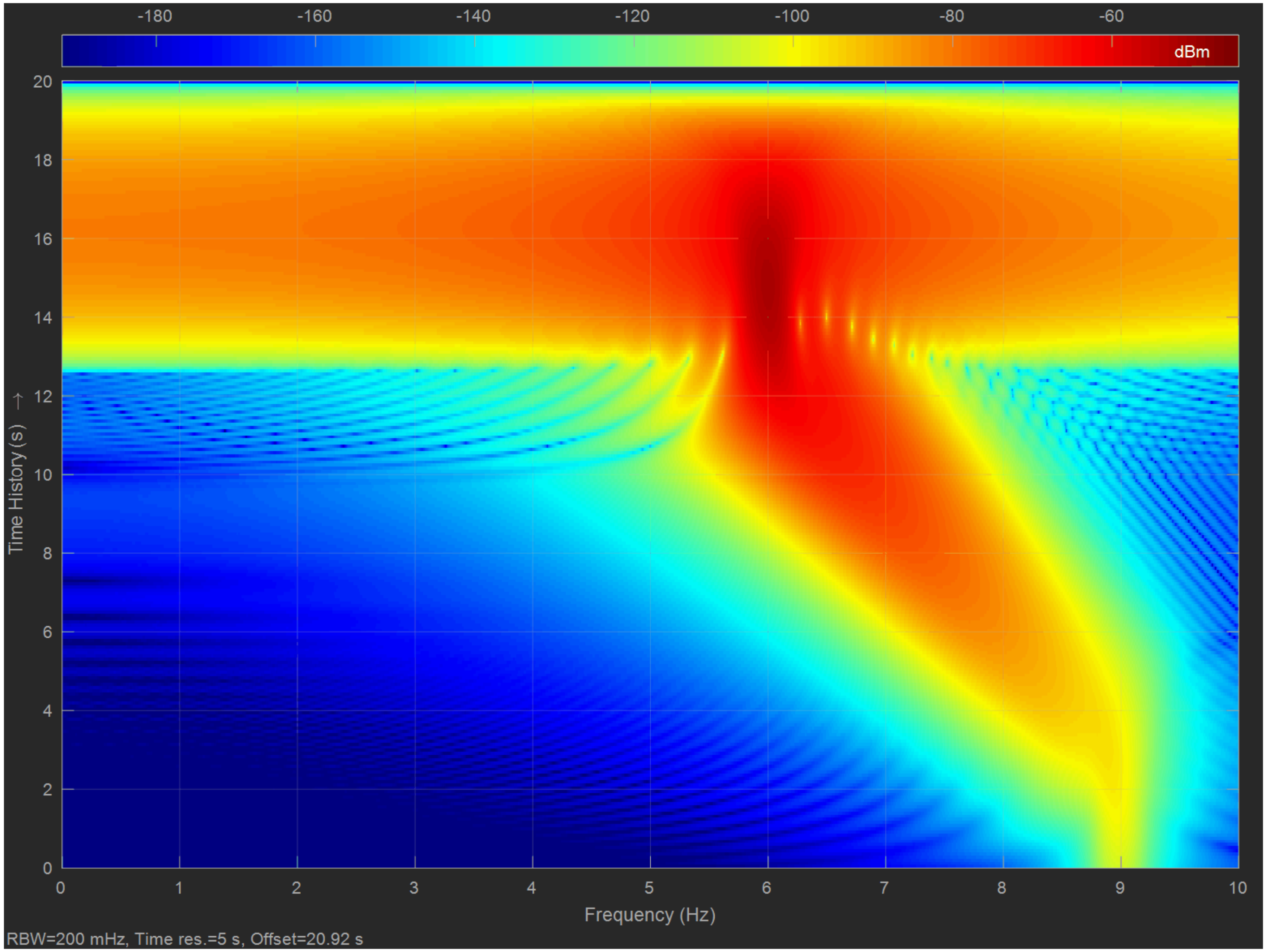
Pt	X	Y	θ
In	0	0	+1
O1	+1	-1	-1
O2	0	0	+1

Pt	X	Y	θ
In	+1	0	0
O1	0	+1	0
O2	-1	0	0

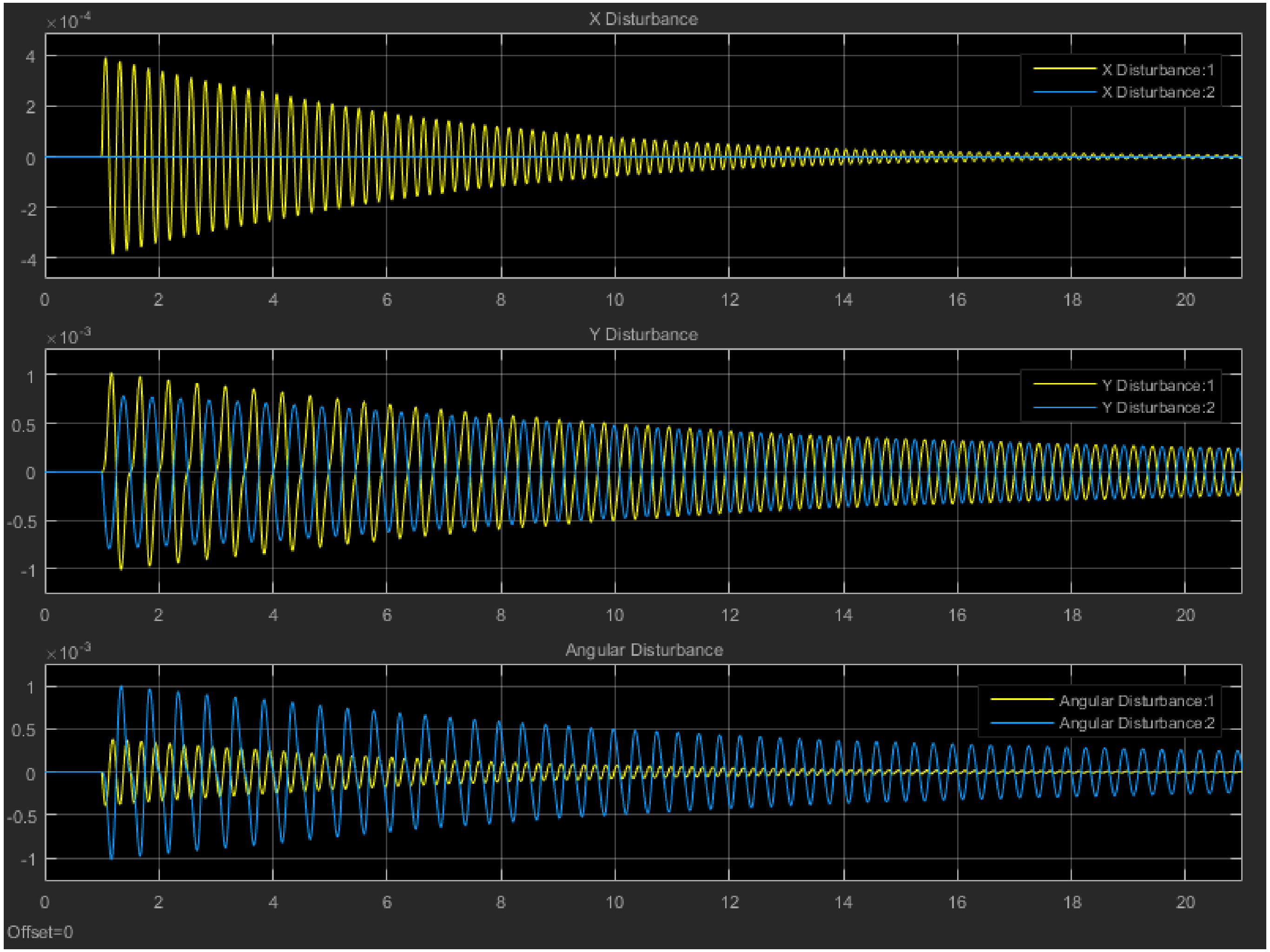
Example: Unity +X Force Response



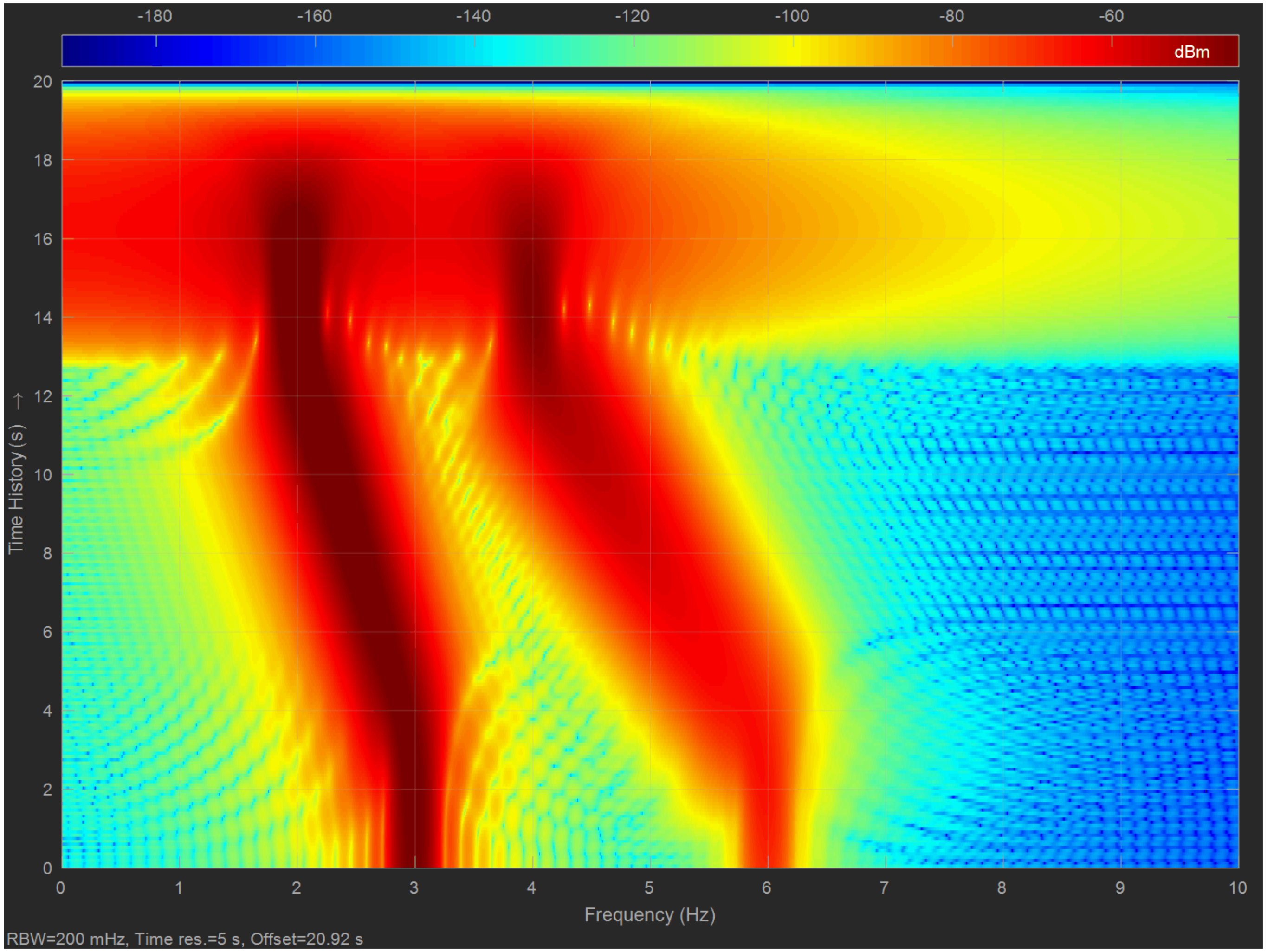
Example: Unity +X Force Response Spectrogram of Point 2 X Axis



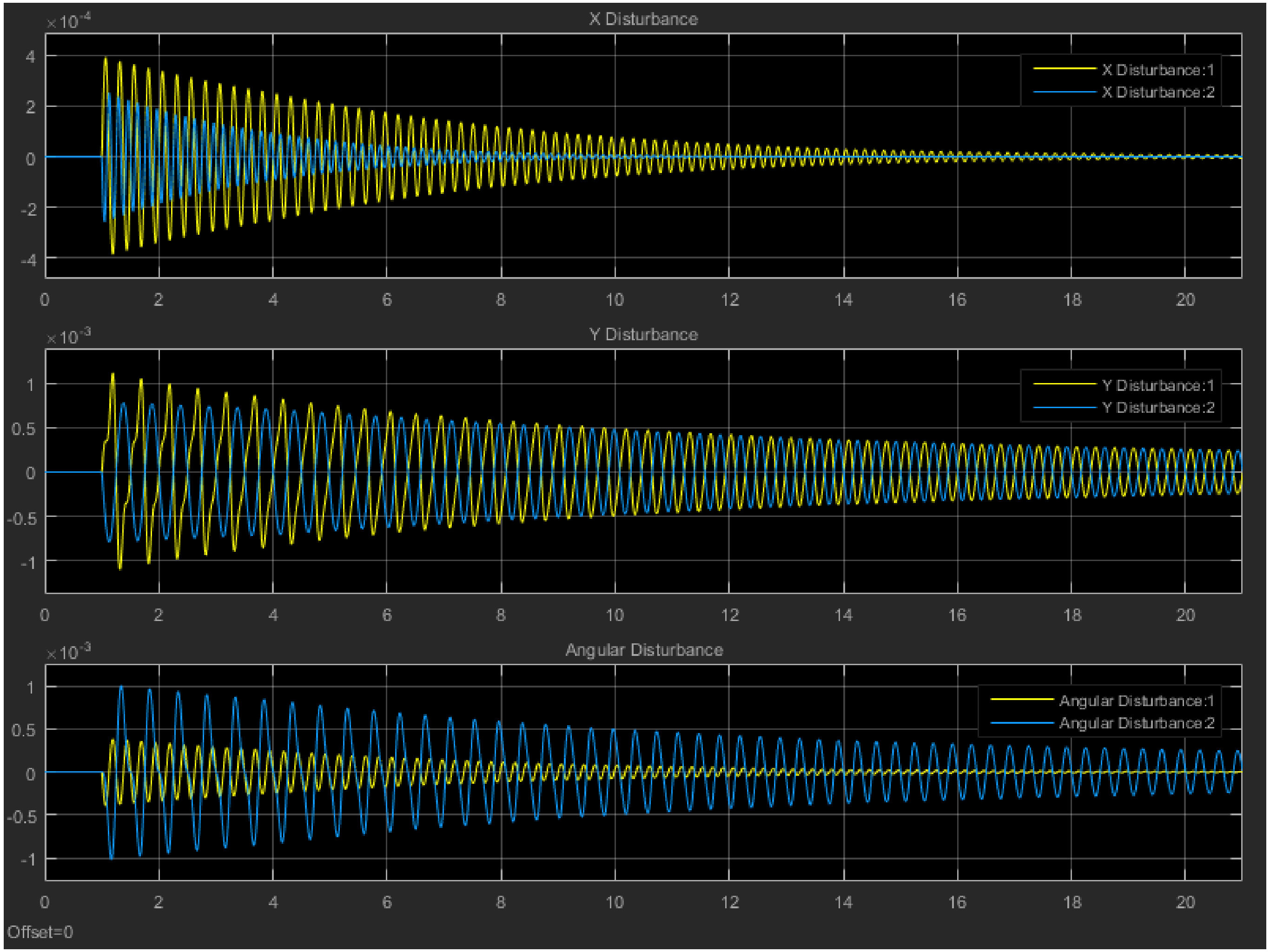
Example: Unity +Moment Response



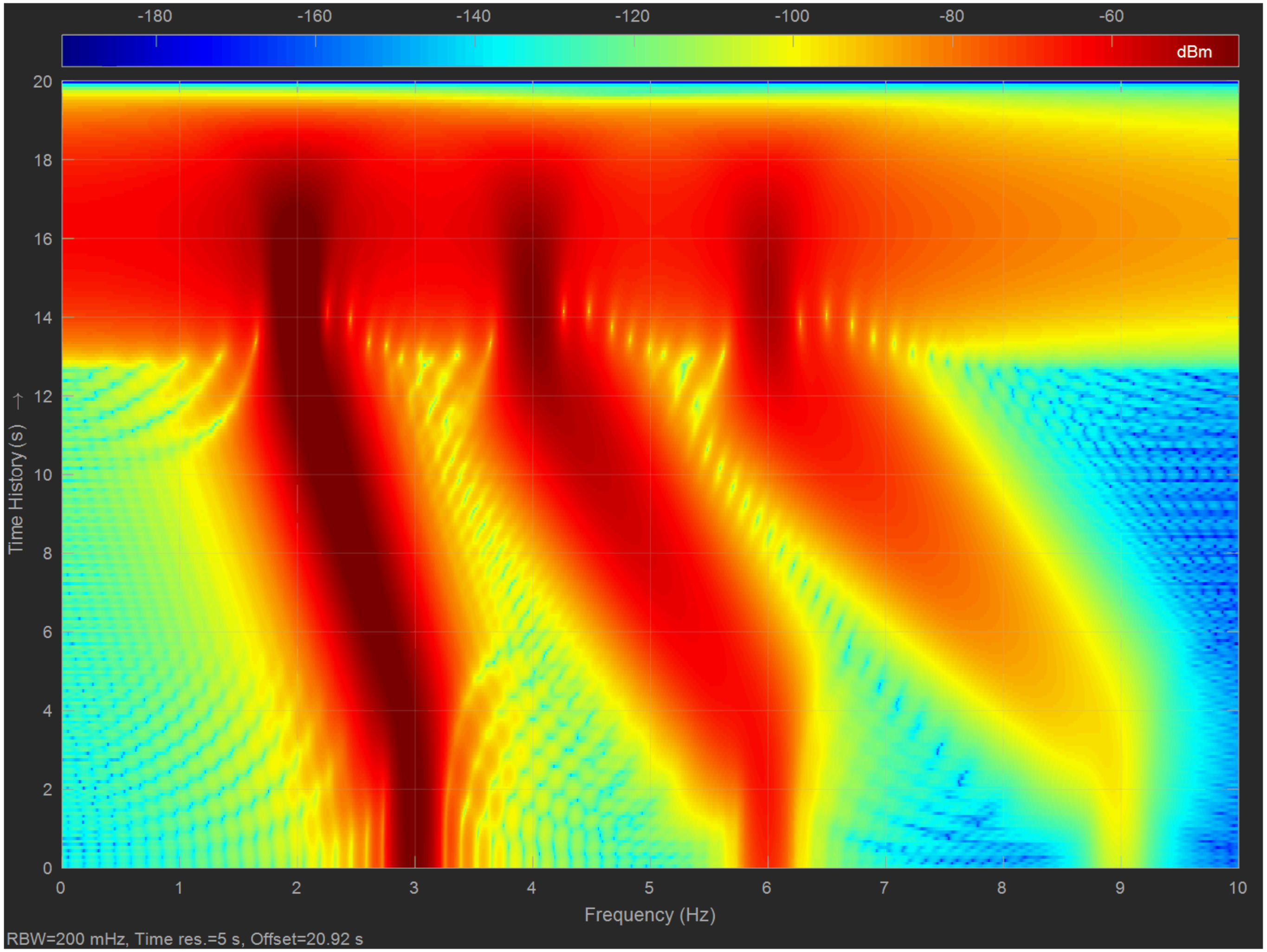
Example: Unity +Moment Response Spectrogram of Point 2 θ Axis



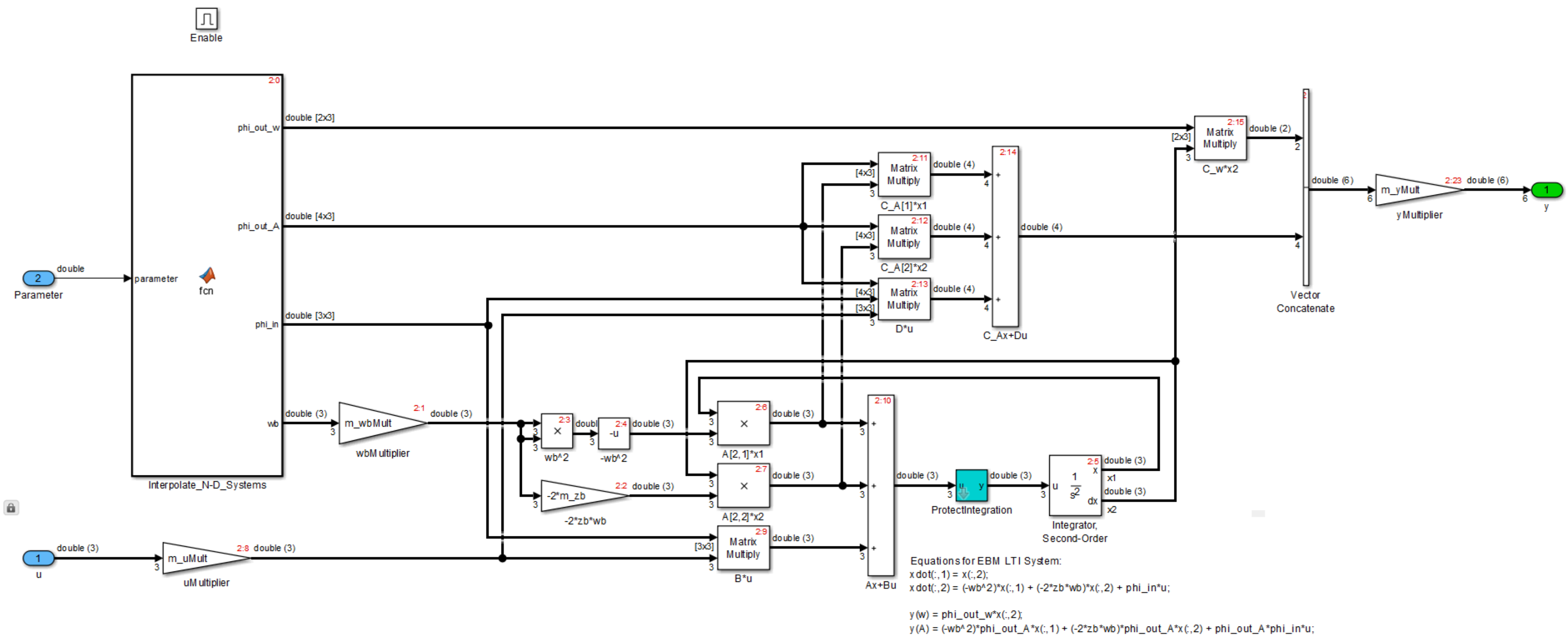
Example: Combined Response



Example: Combined Response Spectrogram of Point 1 Y Axis



Example: Implementation



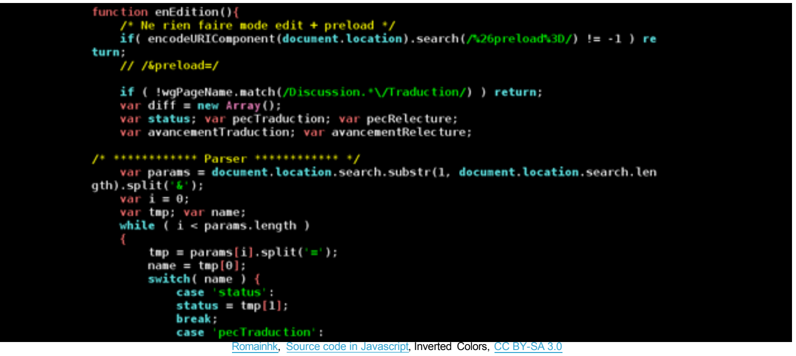
- Note that outputs are interpolated appropriately to produce previous data plots

Additional Implementation Details

- Interpolation allows for low inertial sensor drift versus discrete switching
  - Drift is still dependent on eigenvector angle differences between configurations
    - $\cos\theta = \frac{\boldsymbol{\phi}_k \cdot \boldsymbol{\phi}_{k+1}}{\|\boldsymbol{\phi}_k\| \cdot \|\boldsymbol{\phi}_{k+1}\|}$, where k is configuration index
- If structural dynamics model is abruptly shut off before modes are fully damped out, drift may be unacceptable
  - A simple proportional and/or PD controller can be used to quickly and smoothly return the appropriate outputs to zero after model is shut off

Summary

- Simulating variable structural dynamics is valuable for the verification of control software that must operate in those environments
- Existing finite element analysis tools can be leveraged to produce multiple configurations as interpolation points
- Example demonstrates ability to vary
  - Structural dynamics at runtime to nominally model system
  - Frequency, magnitude, and damping before run for uncertainty
- Additional output modification may be necessary to reduce/prevent unintentional adverse affects to downstream consumers



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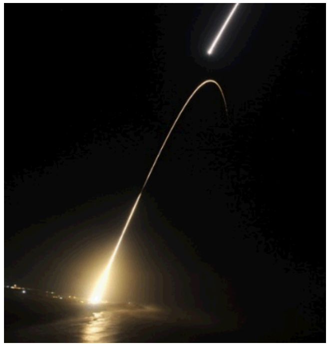

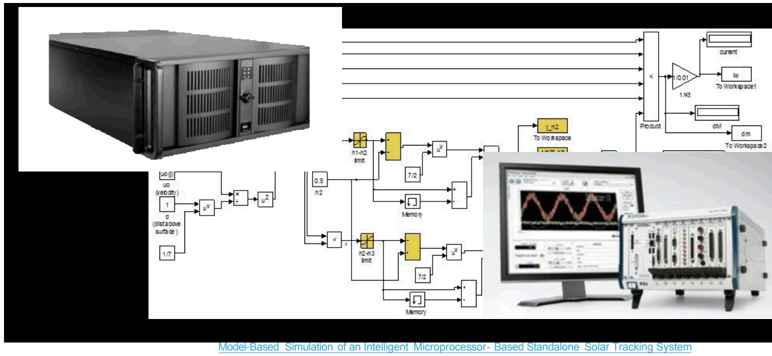

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Questions?

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