DOE/OE Transmission Reliability Program

Measurement Based Stability Assessment

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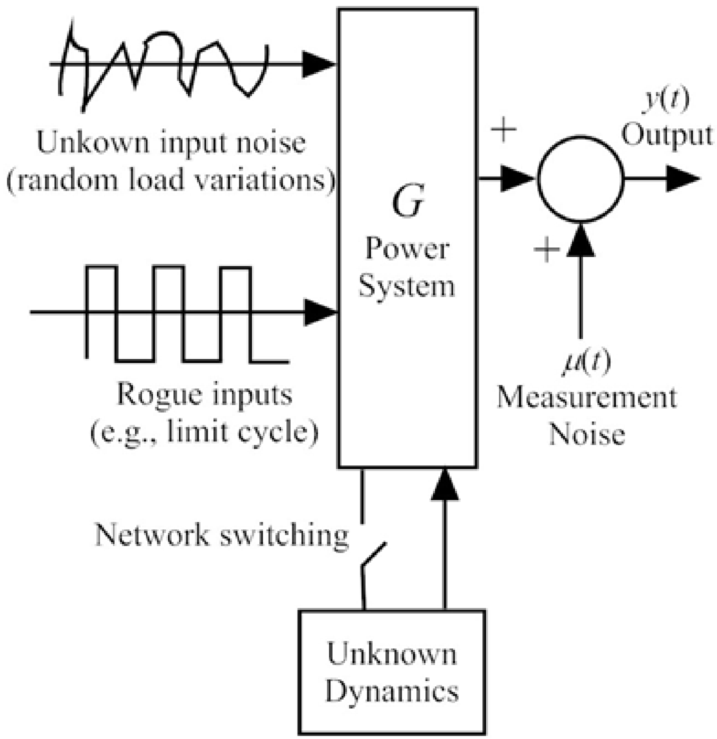
CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

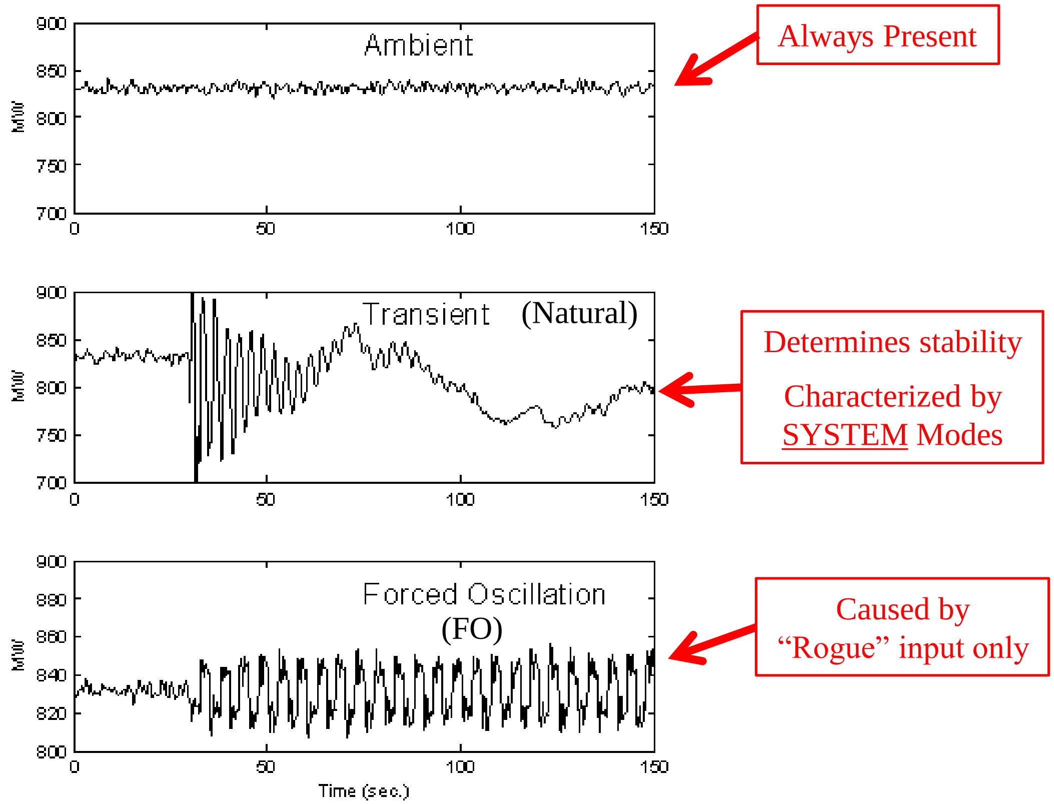
Overview

- Task 1: Force Oscillations:
  - Distinguish between natural and FO.
  - Detecting and locate the source of a FO.
- Task 2: Conduct detailed comparison of Mode Meter algorithms.
- Participants:
  - Dan Trudnowski (co-PI), Montana Tech
  - John Pierre (co-PI), University of Wyoming
  - Luke Dosiek, Union College
  - Graduate students
- Collaborations
  - Bernie Lesieutre, University of Wisconsin
  - BPA (data)

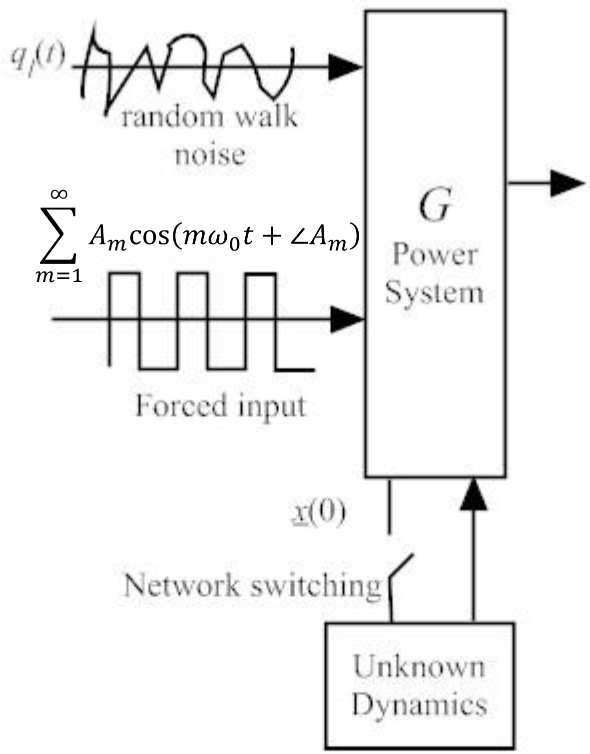
Task 1: FO Research

System Model





FO Characteristics



FO Shape

Harmonics

$$x_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t+\angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Longrightarrow \textbf{FO}$$

$$+\left[\sum_{i=0}^{N}2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Longrightarrow \textbf{Transient}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Longrightarrow \textbf{Colored Noise}$$

Colored by the **SYSTEM**

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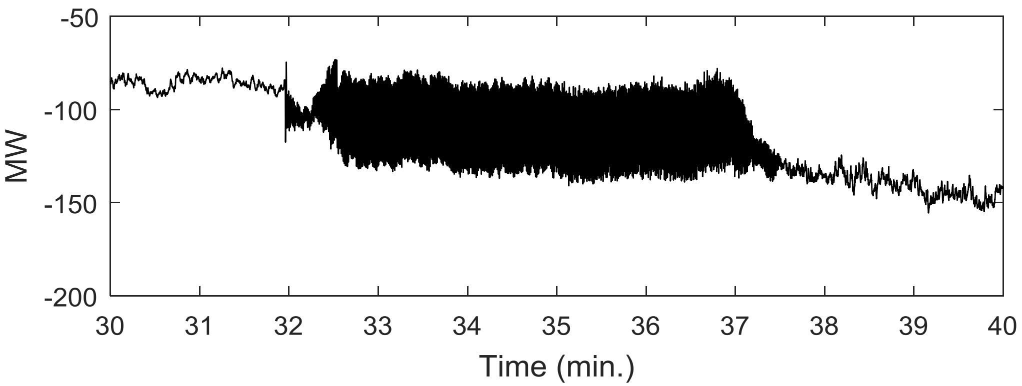
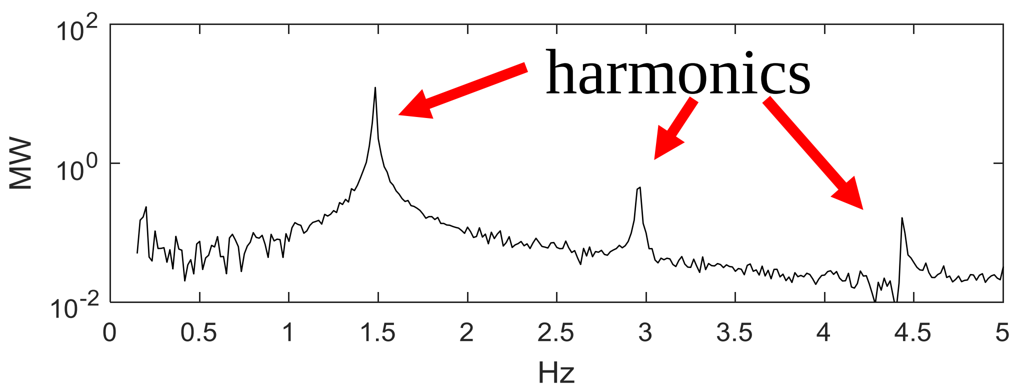
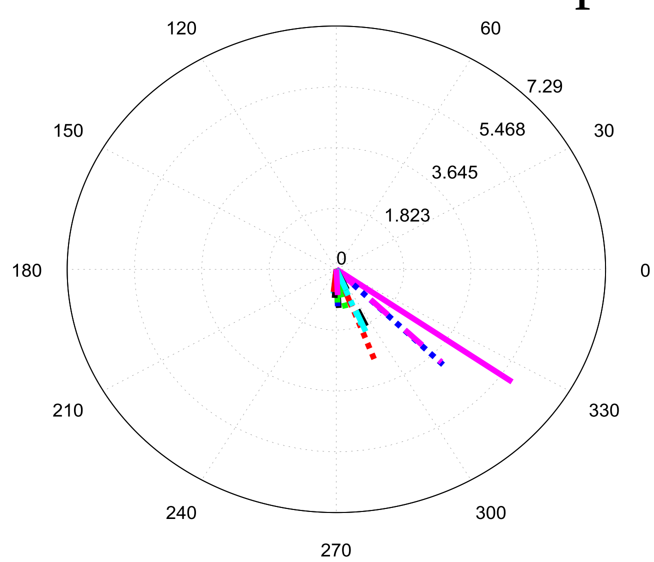
WECC FO, 2015





1st Harmonic Shape



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Distinguishing between FO and Un-damped Transients

Un-damped Transient vs FO

Forced

$$\hat{x}_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t + \angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Longrightarrow \textbf{FO}$$

Harmonics

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Longrightarrow \textbf{Colored Noise}$$

Transient

$$\hat{x}_r(t) = 2\left|\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right|\cos\left(\omega_n t+\angle\left(\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right)\right) \Longrightarrow \textbf{Transient}$$

No Harmonics

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{\substack{i=1\\ i\neq n}}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Longrightarrow \textbf{Colored Noise}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\left|\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}\right|\cos\left(\omega_n t+\angle\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}\right)\right]\right] \Longrightarrow \textbf{Sinusoid Noise}$$

Unique to a Transient

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Distinguishing Between FO and Transient

- Consider oscillating signal y_r at location r broken into 3 windows. The "**cross-spectrum difference function**" is defined as:

$$S_r[\Omega] \triangleq \tilde{Y}^*_{rw_1}\tilde{Y}_{rw_2} - \tilde{Y}^*_{rw_2}\tilde{Y}_{rw_3}$$

- We now define a "**cross-spectrum index**" between channels r and g:

$$C_{rg}[\Omega] \triangleq \frac{\left|\mathrm{E}\{S^*_r[\Omega]S_g[\Omega]\}\right|^2}{\mathrm{E}\{S^*_r[\Omega]S_r[\Omega]\}\ \mathrm{E}\{S^*_g[\Omega]S_g[\Omega]\}}$$

- LOTS of math shows:

$$C_{rg}[\Omega_n] \cong 1 \text{ for a transient}$$

$$C_{rg}[\Omega_n] < 1 \text{ for an FO}$$

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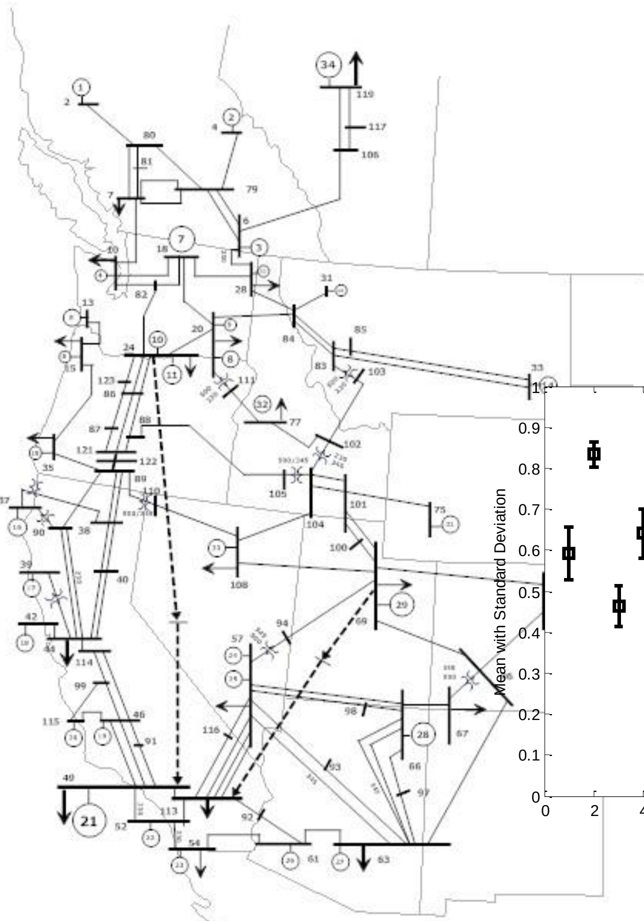
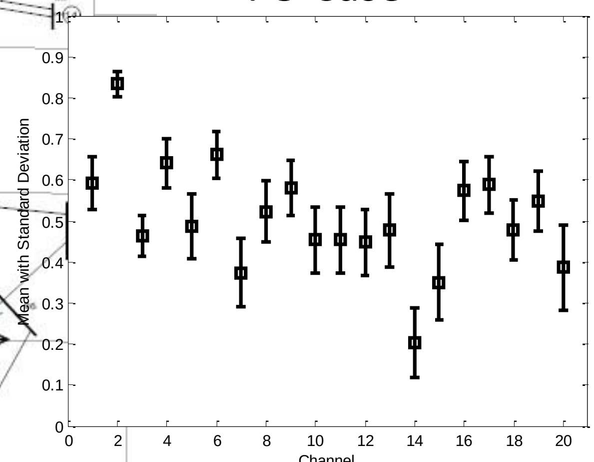
Simulation Example

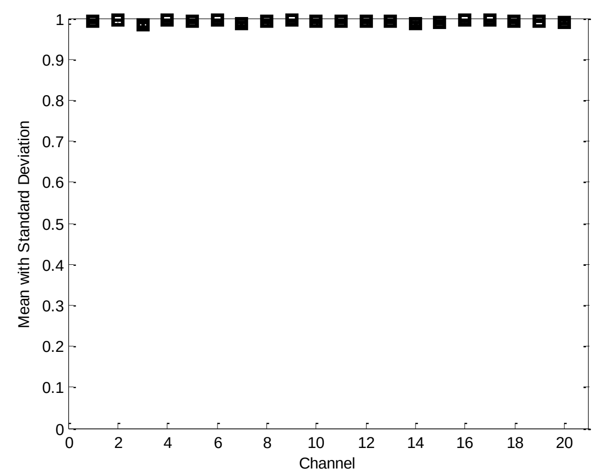
- Monte Carlo Simulation.
- System mode near 0.37 Hz.
- FO at system mode.



FO Case



Natural Case



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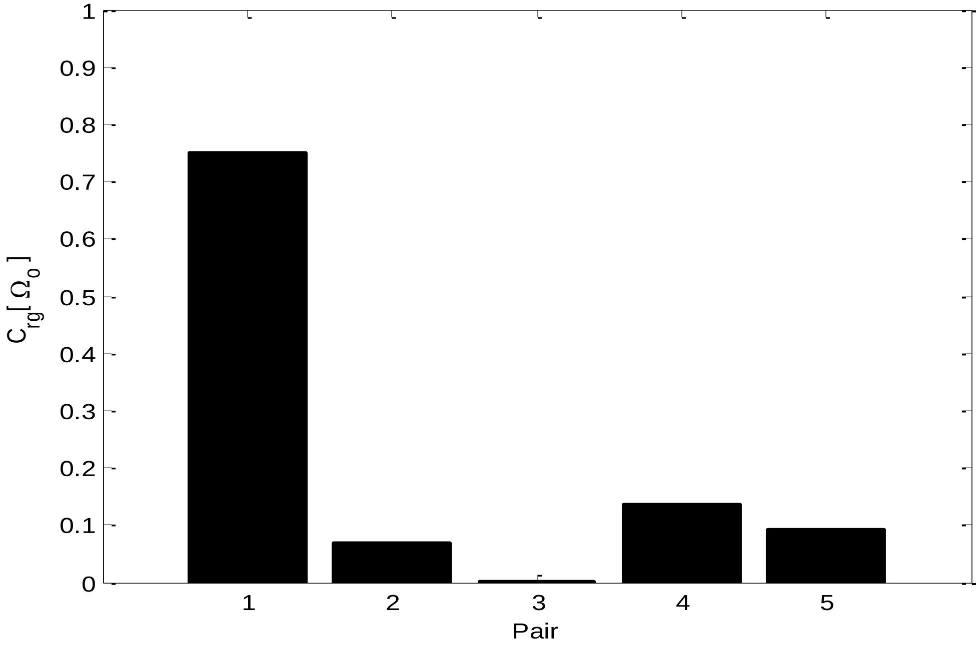
Real-Life Example

WECC FO near system mode at 0.345 Hz for 15 min. (About 10 MW).



Research has shown:

- Algorithm works great at inter-area modes.
- Works OK at local modes.
- Requires LOTS of data (minutes).

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Detecting and Locating FO sources

Detection vs. Locating FO

- Detection
  - Can one detect the existence of an oscillation? Statistics of a detection algorithm (e.g., likelihood oscillation exists)?
  - Distinguishing between an un-damped transient and FO.
  - Current research:
    - Studying the statistics of energy-based detection algorithms (which are commercially used).
- Locating
  - If an FO is detected, where is its source?
  - What is the magnitude of the source?

Locating FO

- Most FO locating research based on signal processing approaches with no model knowledge
  - ASSUME that an observed oscillation is an FO
  - ASSUME the source location is where the largest amplitude (or shape) is observed
    - Often true if FO is not near a system's natural mode
    - If FO is at system mode, FO shape converges to mode shape; therefore, amplitude and shape are misleading
- Current research is focusing on bringing power-system knowledge into the locating logic
  - Complete model knowledge
  - Minimal model knowledge

Example: Locating Mechanical Torque FO

- Many FO originate from a faulty turbine control system (e.g., valve in a limit cycle).
- Consider the equation of motion for generator i:

$$2H_i s\Delta\omega_i(s) = \underbrace{G_{gov,i}(s)}_{\substack{\text{Mechanical} \\ \text{Torque from governor}}}\Delta\omega_i(s) + \underbrace{\Delta T_{f,i}(s)}_{\substack{\text{Mechanical} \\ \text{Torque from FO}}} - \Delta T_{e,i}(s)$$

- If H_i and $G_{gov,i}$ are known (or approximated), signal processing can be used to estimate the existence of $\Delta T_{f,i}$
- Current research is looking at this approach
  - Can we DETECT the location of $\Delta T_{f,i}$ while reducing the dependence on the measurements?
  - How accurately can we estimate $\Delta T_{f,i}$?

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Task 2: Mode Meter Comparison

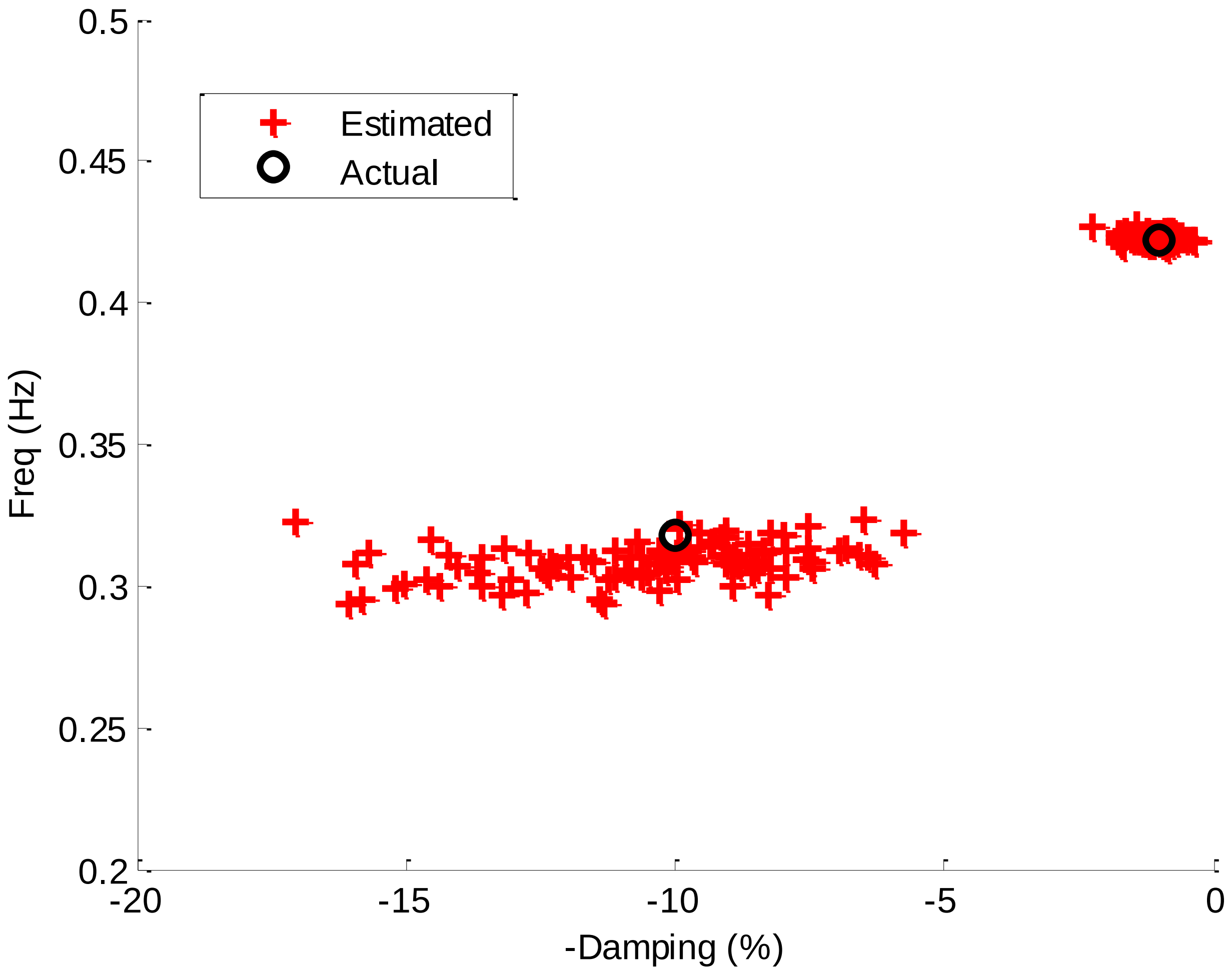
Motivation and Approach

- Many algorithms and been researched and developed (including commercial products).
- Fundamental Questions:
  - How accurate is the mode estimate?
  - Sensitivity to algorithm settings
  - Sensitivity to system conditions (e.g., ambient vs transient)
  - Percentage of time you get an answer
  - Response time (slowly changing ambient, sudden transient)
  - Impact of forced oscillation
  - Can the MM handle bad data?
- Approach
  - Monte Carlo simulations via the miniWECC model.
  - Transient simulations
  - Actual system tests cross-validated against ring down analysis

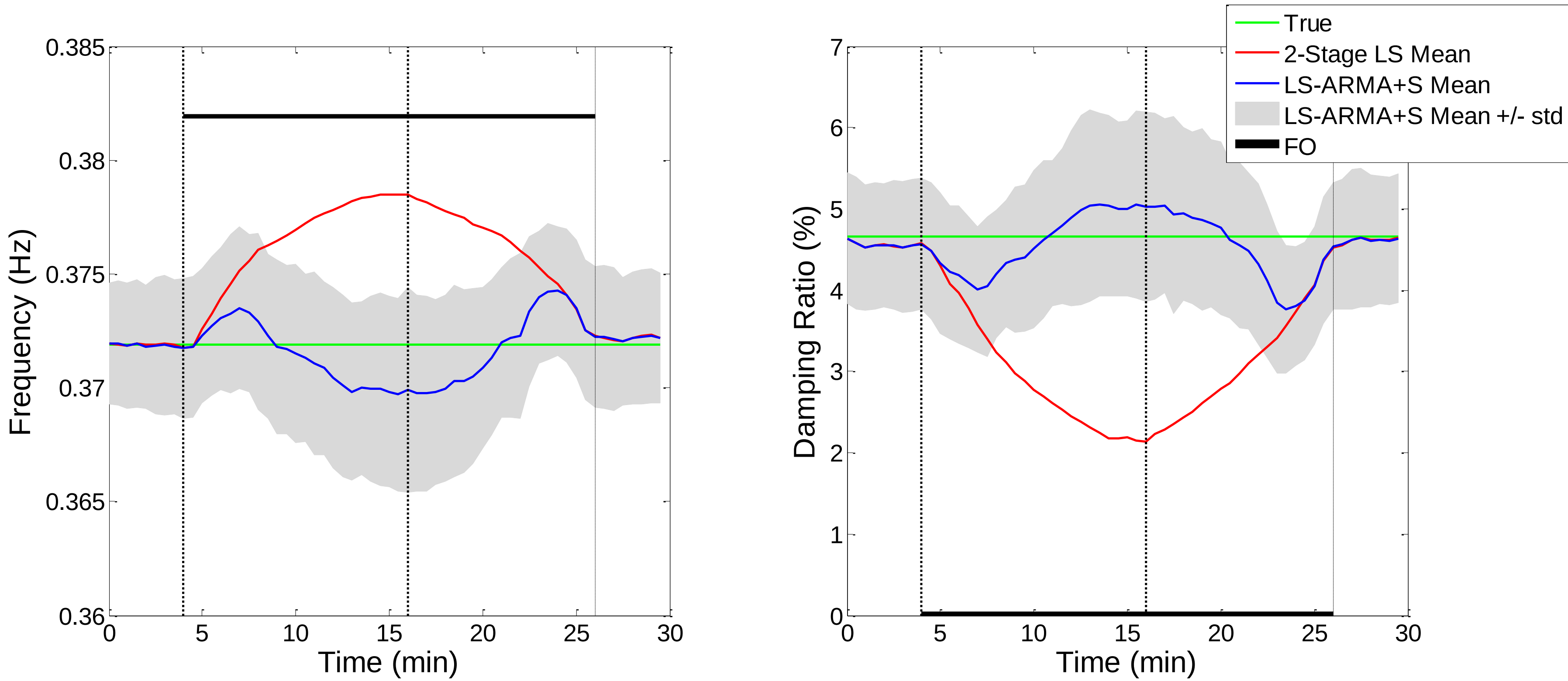
Algorithms to be Tested

- Established Approaches
  - YW, YW Spectral, N4SID
- Newer Approaches
  - LS ARMA+S
    - A two-stage LS algorithm which incorporates forced oscillations
  - YW ARMA+S
    - A reformulation of Yule-Walker method incorporating forced oscillations
  - RML (Recursive Maximum Likelihood Method)
  - Multichannel Transfer Function (Multichannel 2-stage LS)
  - Subspace Methods
  - VARPRO via Auto-correlation (U of Wisconsin)

NO MODE ESTIMATOR IS PERFECT!



Mode Meter Performance in Presence of FO



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Approaches to Simultaneously Estimating Modes and Forced Oscillations

- Increase model order of existing mode estimation algorithms in an attempt to resolve both the forced oscillation and the modal oscillation.
  - Classic signal processing problem of resolving closely space frequency components
  - Higher model orders can lead to more variability in mode estimates

- Directly incorporate forced oscillations into the model and redevelop mode meter algorithms accordingly

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Project Accomplishments and Plans

- Accomplishments
  - Task 1 (Detecting and Locating FO)
    - Developed algorithm to distinguish between un-damped transient and FO. Tested it on simulation data and one actual-system case.
    - Develop initial concept for locating FO using a full system model.
    - Develop initial concept for locating mechanical power FO with minimal model information.
  - Task 2 (Mode Meter Testing)
    - Developed testing approach.
    - Developed a set of test models and data.
    - Identified algorithms to tested.
- Plans
  - Task 1
    - Improve performance of FO/Transient distinguishing algorithm.
    - Further develop and test locating approaches that incorporate model information.
  - Task 2
    - Run Mode Meter algorithms thru tests.

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