DOE/OE Transmission Reliability Program

Measurement Based Stability Assessment

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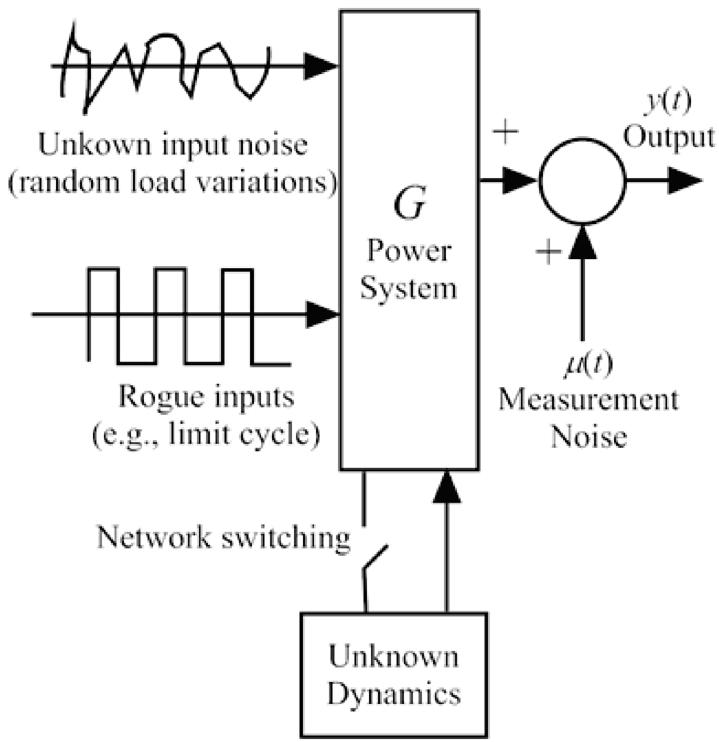
CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

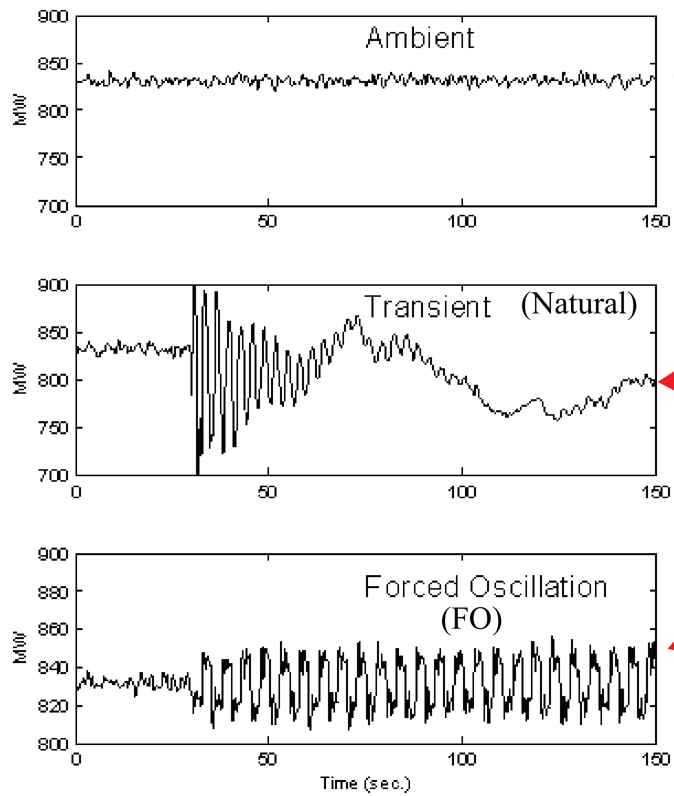
Overview

- 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
  - PNNL
  - BPA (data)

Task 1: FO Research

System Model





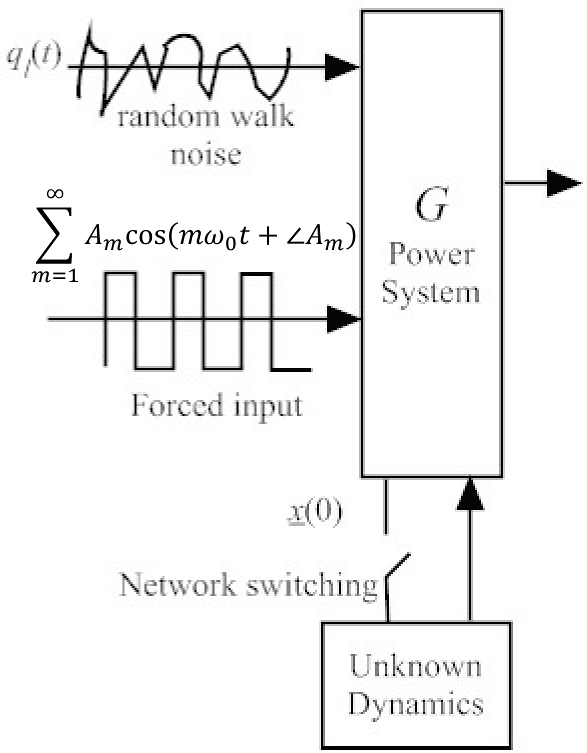
Always Present

Determines stability

Characterized by SYSTEM Modes

Caused by "Rogue" input only

FO Characteristics



FO Shape

Harmonics

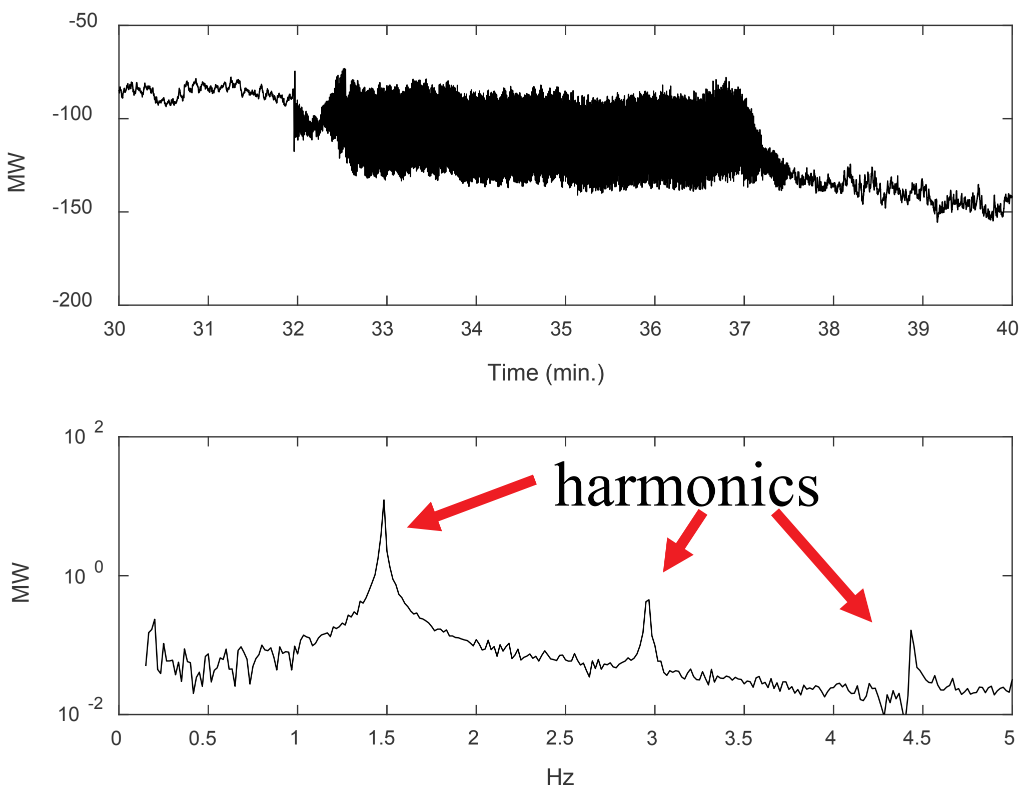
$$x_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t+\angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Longrightarrow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

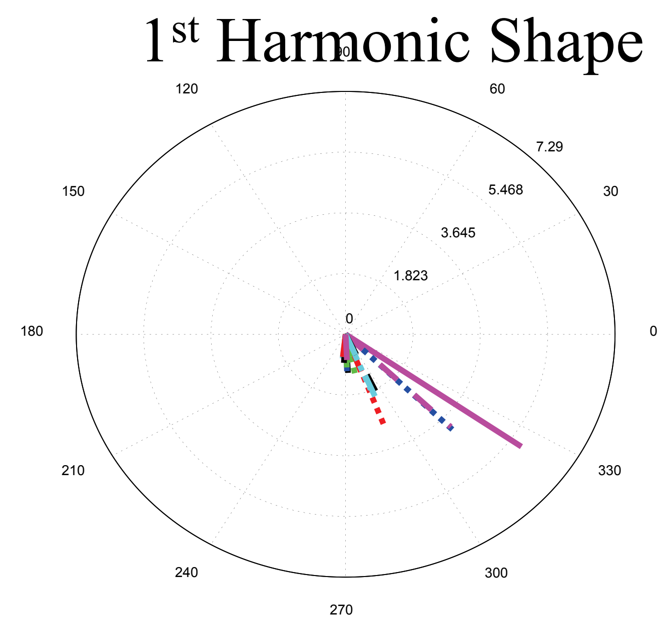
$$+\left[\sum_{i=0}^{N}2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Longrightarrow \textbf{Transient}$$

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

Colored by the **SYSTEM**

WECC FO, 2015





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Distinguishing between FO and Un-damped Transients

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Un-damped Transient vs FO

Forced

$$\hat{x}_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{u_{ir}v_i b_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t + \angle\left(A_m\sum_{i=1}^{N}\frac{u_{ir}v_i b_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Rightarrow \textbf{FO}$$

Harmonics

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

Transient

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

No Harmonics

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

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

Unique to a Transient

Detecting and Locating FO sources

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Locating FO

- If an FO is detected, where is its source?
- What is the magnitude of the source?

Approaches

1. Magnitude/Shape
   - Requires no system model or knowledge
   - Easy to implement for on-line use
   - Fails when FO is near system mode
   - Lots of experience; currently used at BPA control center

2. Energy Flow
   - Requires some network information
   - Recent research has improved calculation method for on-line approach
   - Cannot quantify the FO
   - Seems to be reliable and robust for locating the FO source; needs more testing

3. Swing Equation Estimation
   - Only applicable to real-power turbine-induced FO
   - Requires no model information but does require baselining
   - Both quantifies and locates the FO
   - Initial tests indicate a need to measure generator speed

4. Measurement/Model Matching
   - Requires some system information
   - Locates source or region of forced oscillation
   - Potential for on-line application

Task 1 Accomplishments and Plans

- Accomplishments
  - Developed fundamental understanding of how FOs propagate thru the system
  - Developed algorithm to distinguish between un-damped transient and FO. Tested it on simulation data and one actual-system case.
  - Develop concept for locating FO using a full system model.
  - Develop concept for locating mechanical power FO with no model information.
  - Developed a frequency-domain version of the Energy-Flow method to enable online applications.
  - Conducted a detailed comparison of FO locating approaches.
- Plans
  - Testing using actual system data

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Task2: Mode Meter Comparison

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Task 2: Objective

- Many algorithms have been researched and developed (including commercial products)
- Performance Questions:
  - How accurate is the mode estimate?
  - How sensitive is the estimate to algorithm settings?
  - How sensitive is the estimate to system conditions (ambient vs. transient)?
  - How quickly does the algorithm respond to a system change?
  - **How does the presence of a forced oscillation affect the mode estimate?**
- Research Approach
  - Monte Carlo simulations with the miniWECC model
  - Tests with actual system data

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Algorithms Tested

- Established Approaches
  - Yule-Walker ARMA
    - Modified Yule-Walker (MYW) (single channel)
    - Modified Extended Yule-Walker (MEYW) (multichannel)
  - Subspace (currently being tested)
- Newer Approaches
  - Least Squares ARMA
    - Two-Stage Least Squares (2S-LS) (single channel)
    - Multichannel Transfer Function (MCTF) (multichannel 2S-LS)
    - Recursive Maximum Likelihood (RML) (single channel, MLE)
  - Forced-Oscillation-ready algorithms
    - YW ARMA+S (MYW, incorporates FOs)
    - LS ARMA+S (2S-LS, incorporates FOs)
  - Stochastic Subspace (currently being tested)

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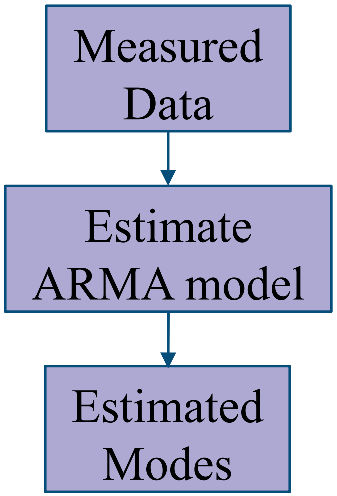
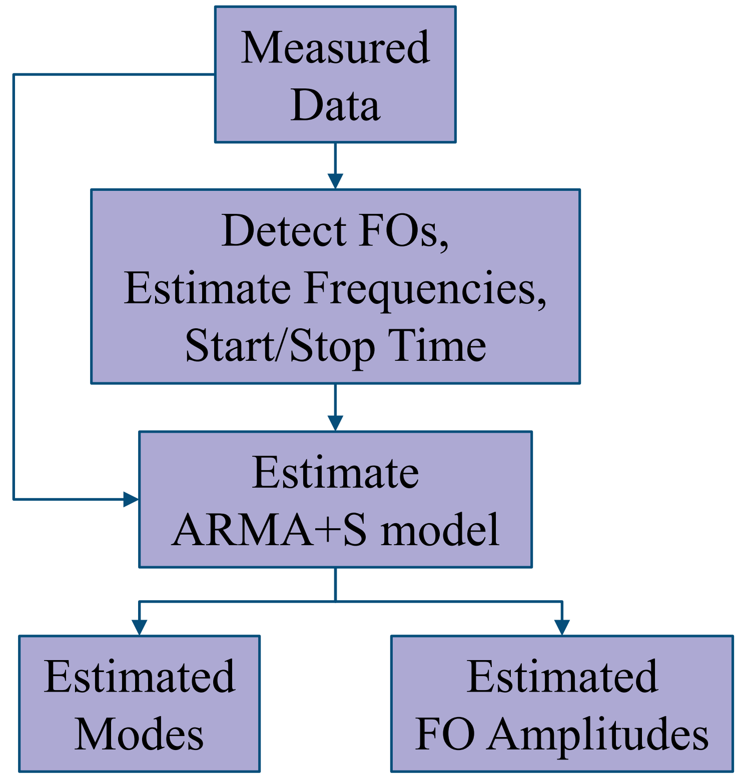
Including FOs in Mode Meter Models

- Established methods:



- If a FO is present in the Measured Data, the Mode Estimates can be (severely) biased
- May result in False Alarms

- Research has shown that if we first detect Forced Oscillations and include them in our model structures, we get better mode estimates



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miniWECC – Ambient Data

- 300 realizations of 20 minutes of data were created
- Analyzed voltage angles (differenced for single-channel, separately for multichannel algorithms)
- Estimated North-South B mode (0.37 Hz, 4.67 % damping)
- Used Root Mean Squared Error (RMSE) to compare
- Swept through several model orders (~800 cases):
  - AR from 10 to 40
  - MA from 1 to AR

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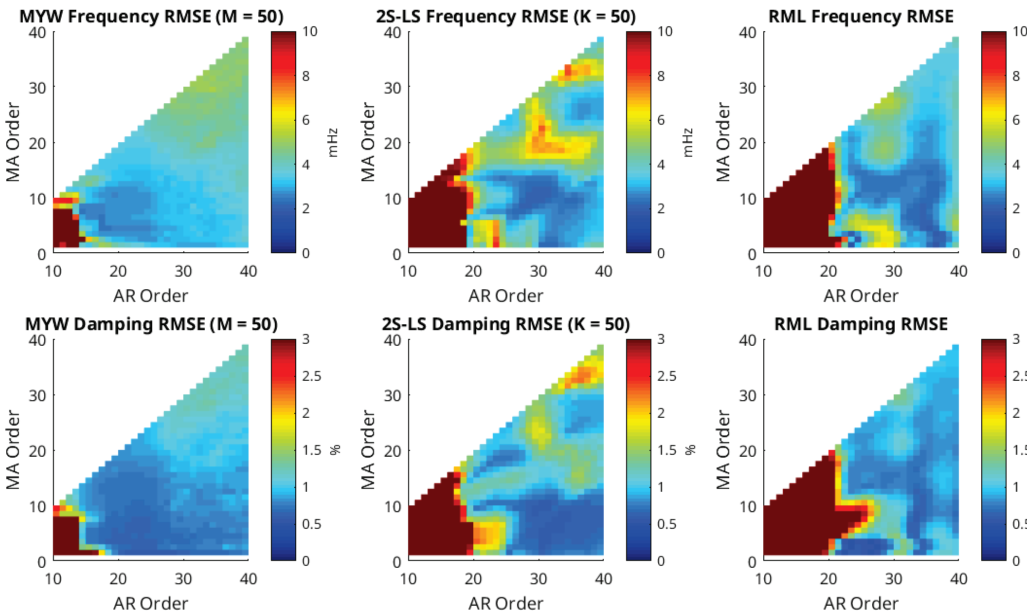
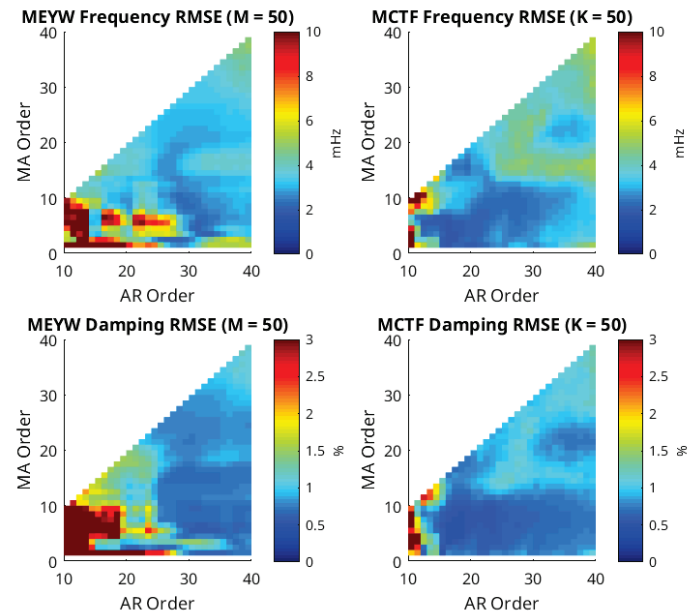
Model Order Sensitivity

Single Channel Algorithms

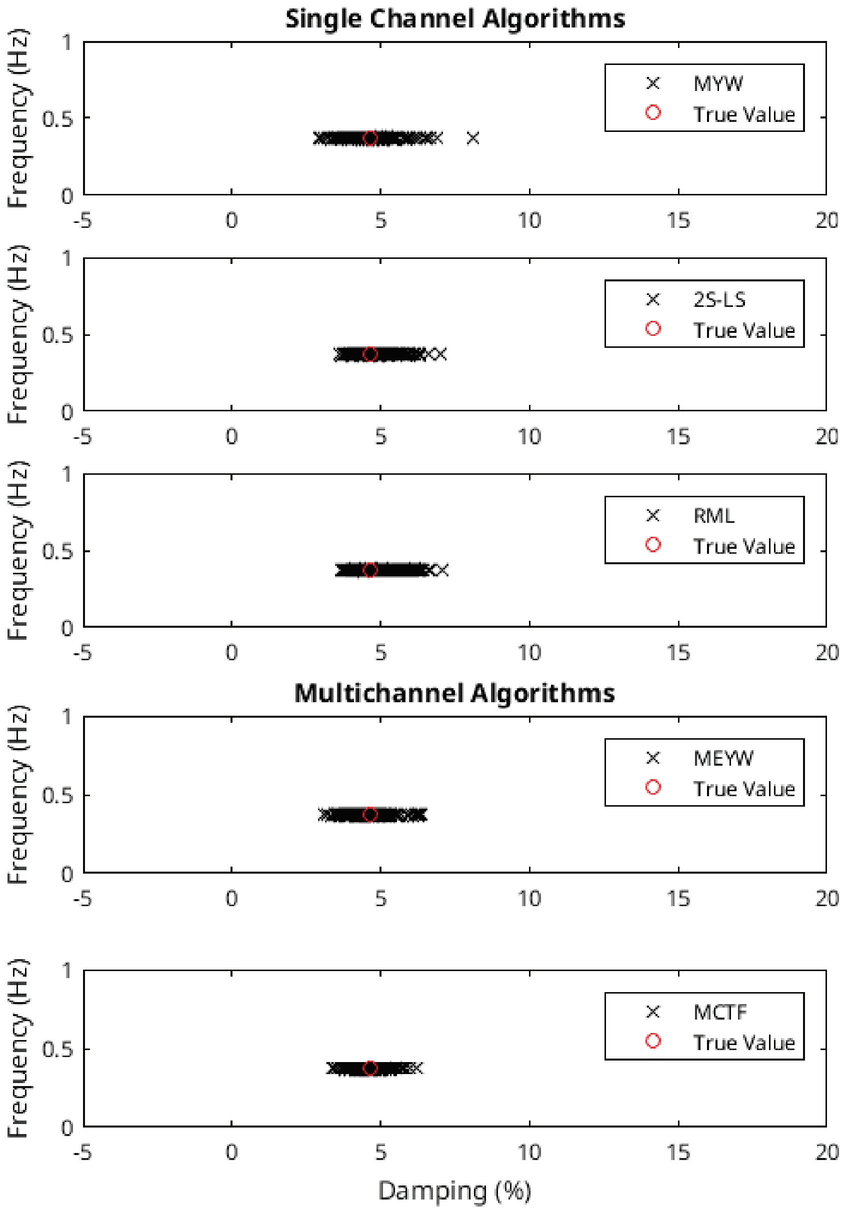
(FO-Algorithms virtually identical)

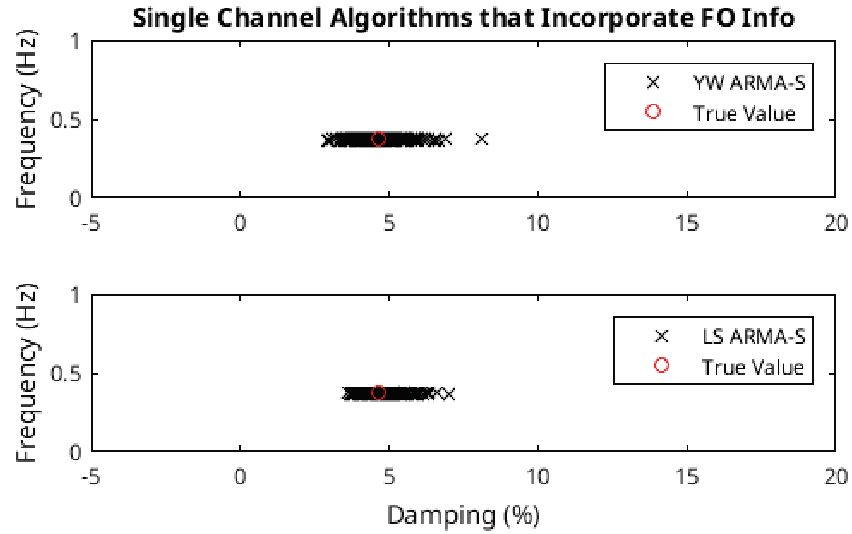


Multichannel Algorithms



Ambient Performance





- Model order fixed (n=32, m=6)
- All methods have comparable performance
- New FO mode meters virtually identical to classic counterparts

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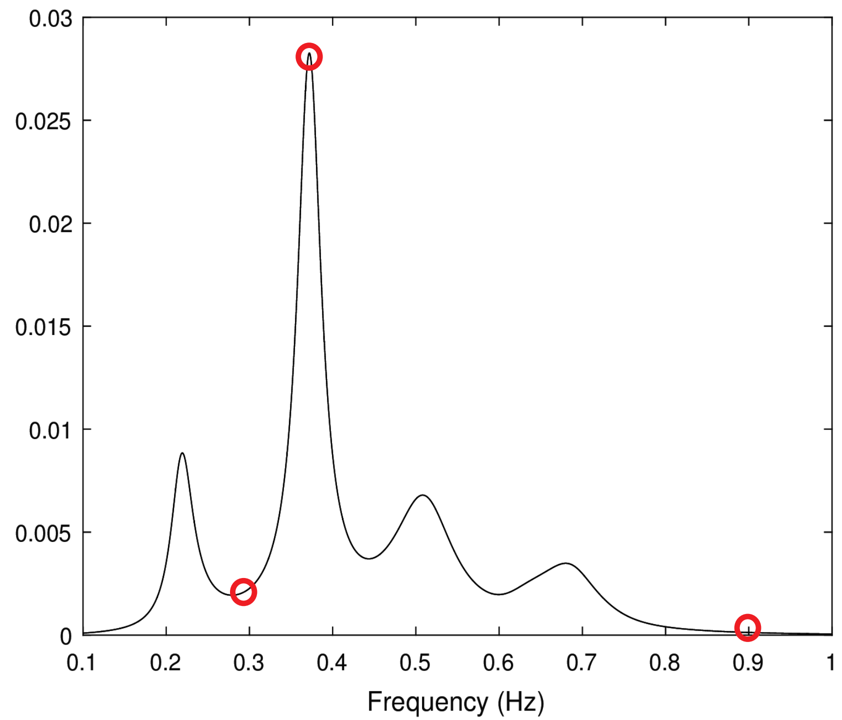
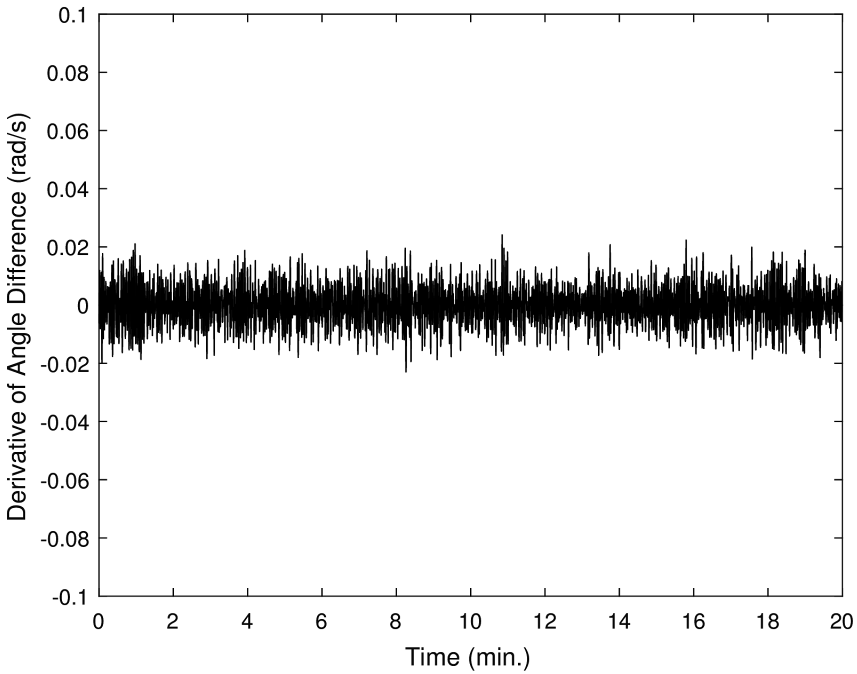
miniWECC – Forced Oscillations

- Underlying ambient data same as before
- FOs generated as square wave mechanical power inputs to a particular generator
- 27 cases - all combinations of:
  - 0.3, 0.37, and 0.9 Hz fundamental frequency
  - 3 different durations
  - 3 different amplitudes

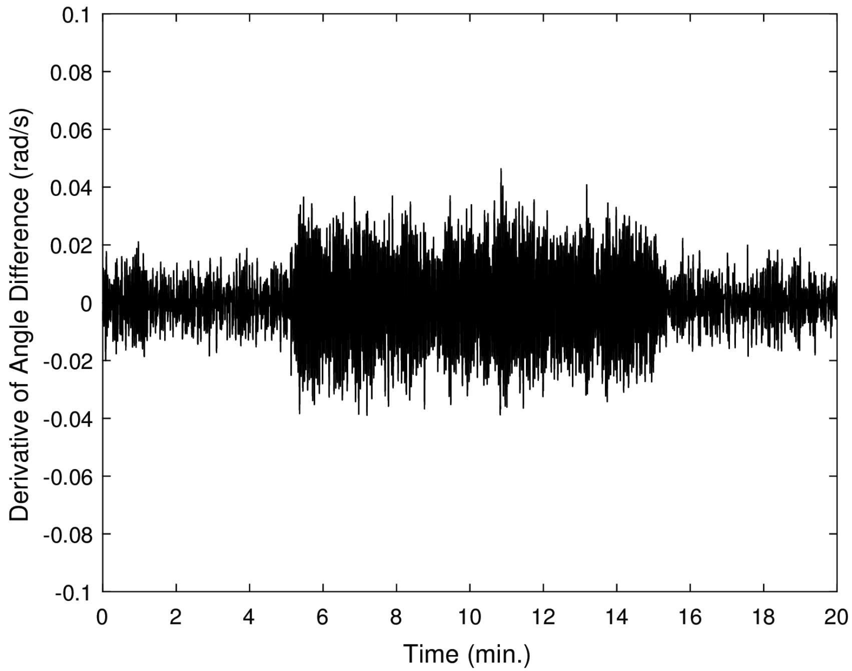


True power spectral density (PSD) of simulated system output with FO fundamental frequencies circled

FO Performance: 0.37 Hz, -20 dB, 10 min.



Ambient data



Ambient plus FO data

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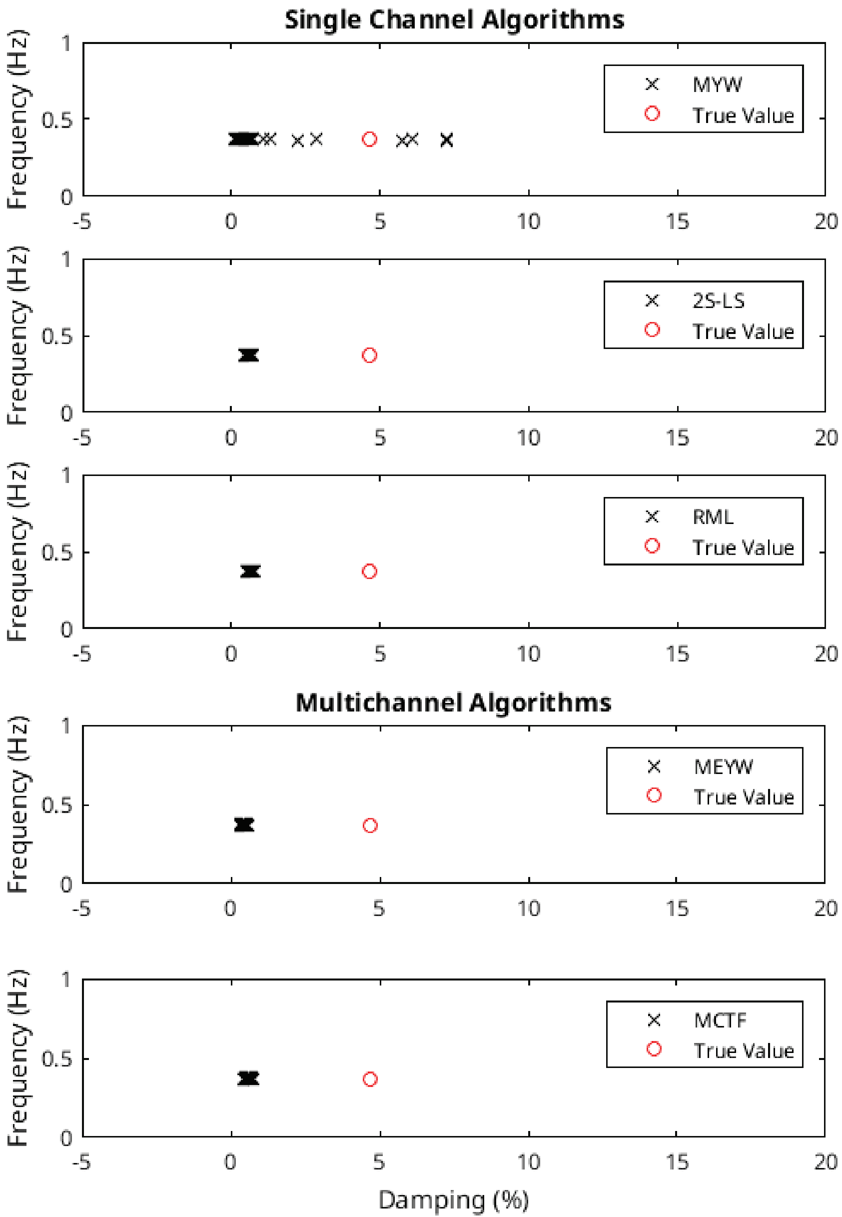
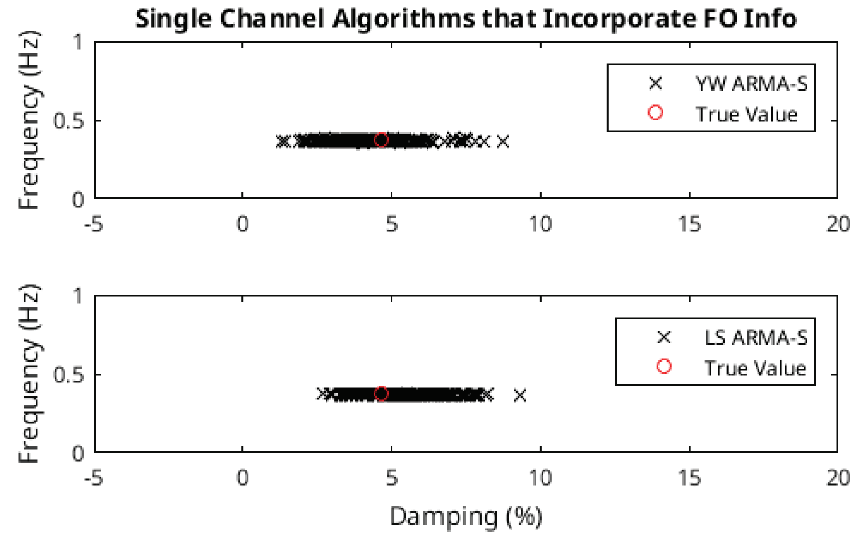
FO Performance: 0.37 Hz, -20 dB, 10 min.





- 0.37 Hz resonates with NS-B mode
- This causes traditional mode meters to estimate a mode with ~0% damping while ignoring NS-B mode
- FO-ready methods show dramatic improvement

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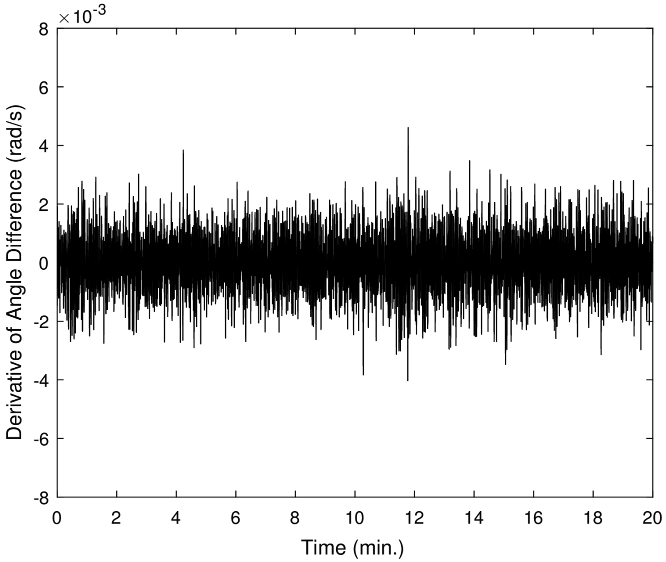
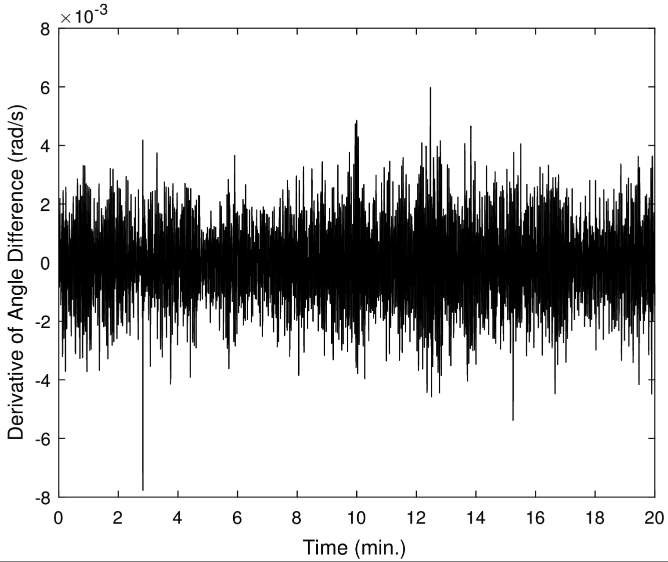
WECC Data – Sept. 2014 FO Event

- Ambient only (no known FO present)
- No FOs detected



	Frequency	Damping	FO Amp.
MYW	0.38 Hz	9.48 %	N/A
2S-LS	0.38 Hz	9.51 %	N/A
RML	0.39 Hz	9.10 %	N/A
MEYW	0.37 Hz	8.48 %	N/A
MCTF	0.37 Hz	10.29 %	N/A
YW ARMA-S	0.38 Hz	9.48 %	N/A
LS ARMA-S	0.38 Hz	9.51 %	N/A

- Ambient with FO present throughout
- FO detected at 0.34 Hz



	Frequency	Damping	FO Amp.
MYW	0.35 Hz	2.95 %	N/A
2S-LS	0.35 Hz	3.70 %	N/A
RML	0.35 Hz	4.11 %	N/A
MEYW	0.35 Hz	3.60 %	N/A
MCTF	0.34 Hz	4.68 %	N/A
YW ARMA-S	0.34 Hz	6.51 %	0.0015 rad/s
LS ARMA-S	0.35 Hz	5.07 %	0.0010 rad/s

Task 2 Accomplishments and Plans

- Accomplishments
  - Extensive model order sensitivity study under ambient conditions that revealed robustness of Yule-Walker approach
  - Conducted a battery of tests under a variety of Forced Oscillation conditions that illustrated the effectiveness of FO-ready mode meters
- Plans
  - Include subspace methods in test scenarios (i.e., stochastic subspace and N4SID)
  - Additional test cases
    - Explore how FO mode meters behave in presence of transients (ringdowns) – preliminary testing suggests they may falsely detect short-duration FOs, but mode estimates do not suffer
    - Forced oscillations from un-modeled system dynamics, rather than oscillatory system input (e.g., generator rough zone)
    - System mode with nearly 0% damping (sustained natural oscillation)
    - Multiple oscillation types at once
    - Lots of WECC data

Areas of Future Research

- Task 1
  - Faster and automated approaches for distinguishing between FOs and transients
  - Faster automated methods for locating FO sources
  - Extensive testing
- Task 2
  - Should model orders be changed when FO is detected?
  - Does increasing the number of signals in the multichannel algorithms improve things? Is there a point of diminishing return?
  - Improved automated FO detection.
  - Modify additional mode meter algorithms to include FO information
  - Can we incorporate transients into a mode meter?

Recent Publications

1. R. Xie and D. Trudnowski, "Distinguishing Between Natural and Forced Oscillations Using a Cross-Spectrum Index," *IEEE PESGM*, July 2017 (Best Conference paper award).
2. R. Xie and D. Trudnowski , "Comparison of Methods for Locating and Quantifying Turbine-Induced Forced-Oscillations," *IEEE PESGM*, July 2017.
3. U. Agrawal, J. Pierre, J. Follum, D. Duan, D. Trudnowski, and M. Donnelly, "Locating the Source of Forced Oscillations using PMU Measurements and System Model Information," *IEEE PESGM*, July 2017 (Best Conference paper award).
4. L. Dosiek, D. Trudnowski, J. Pierre, "Model Order Sensitivity in ARMA-based Electromechanical Mode Estimation Algorithms Under Ambient Power System Conditions ," *IEEE PESGM*, July 2017.
5. J. Follum, J. Pierre, and R. Martin, "Simultaneous Estimation of Electromechanical Modes and Forced Oscillations," *IEEE Trans. on Power Systems*, (accepted).
6. R. Xie and D. Trudnowski, "Tracking the Damping Contribution of a Power System Component Under Ambient Conditions," *IEEE Trans. on Power Systems*, (accepted).
7. D. Trudnowski, R. Xie, and I. West, "Shape properties of forced oscillations," *NAPS*, Sep. 2016.
8. J. Follum, F. Tuffner, L. Dosiek, and J. Pierre, "Power System Oscillatory Behaviors: Sources, Characteristics, & Analyses," NASPI2017TR003/PNNL26375, North American Synchrophasor Initiative, May 17, 2017
9. J. Follum, J.W. Pierre, "Detection of Periodic Forced Oscillations in Power Systems," IEEE Trans on Power Systems, vol. 31, no. 3, pp. 24232433, May 2016.

Extra Slides

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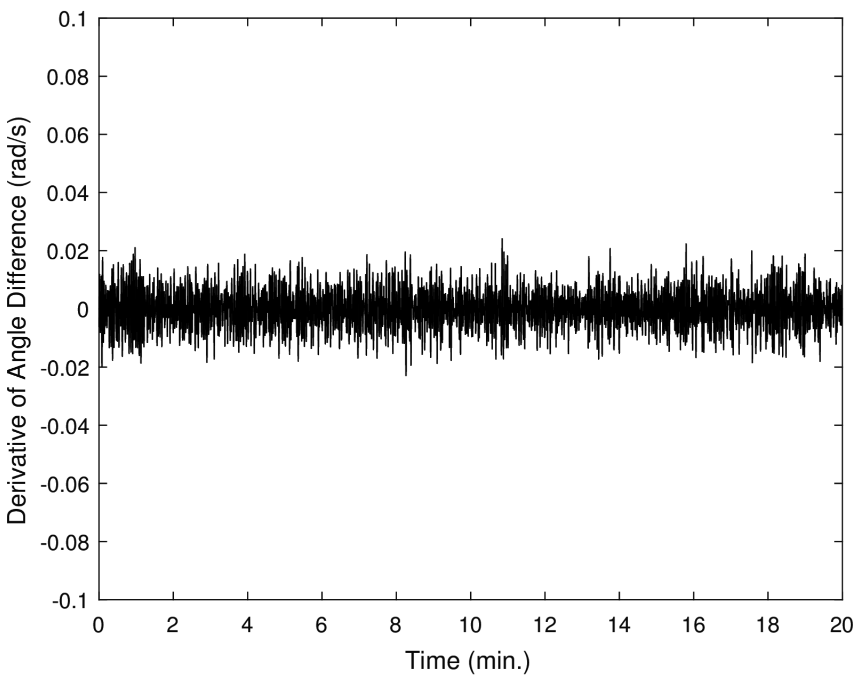
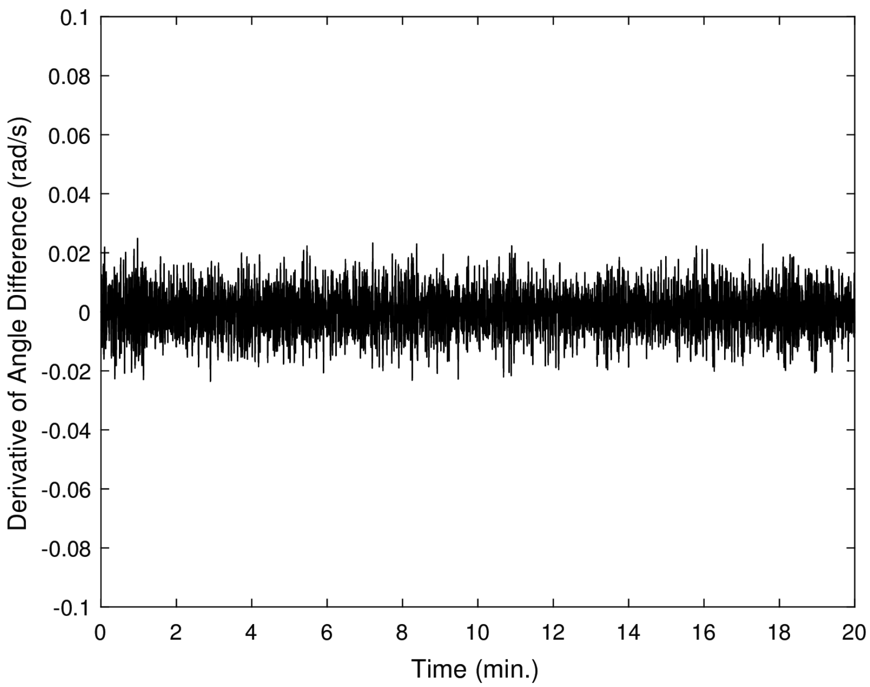
FO Performance: 0.9 Hz, -10 dB, 20 min.

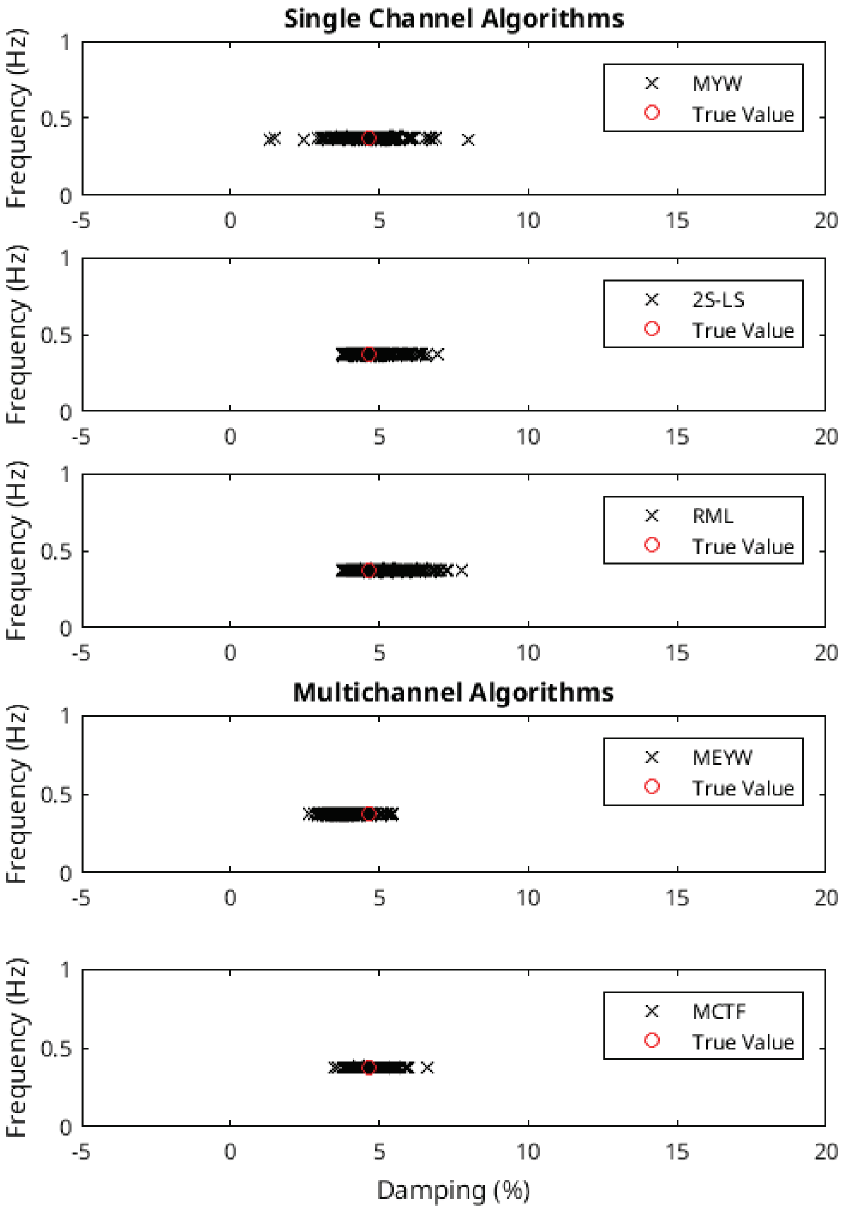


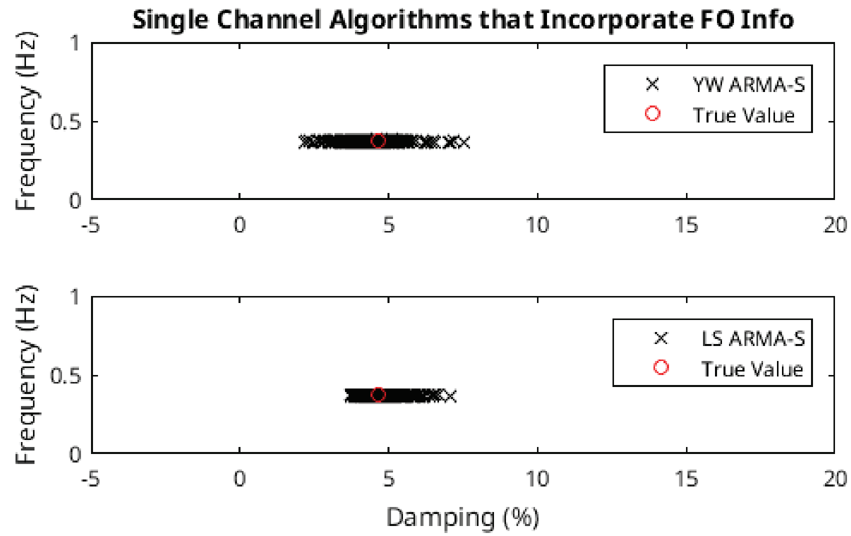
Ambient data



Ambient plus FO data

FO Performance: 0.9 Hz, -10 dB, 20 min.





- 0.9 Hz is well-attenuated by system
- 0.9 Hz is well-separated from NS-B mode
- This FO is not big enough to seriously affect traditional mode meters
- FO detected in all 300 trials
- FO-ready methods perform on par with others

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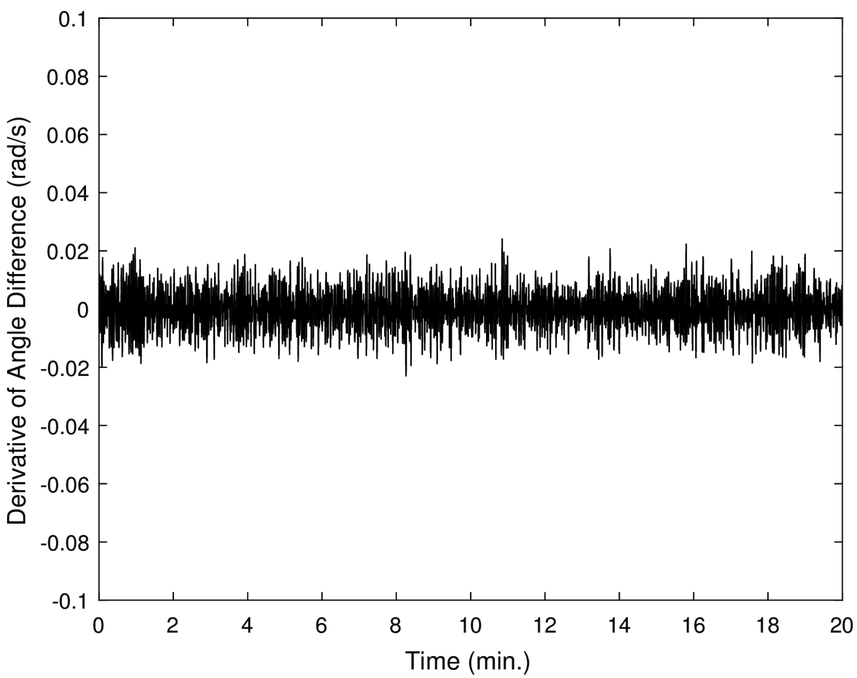
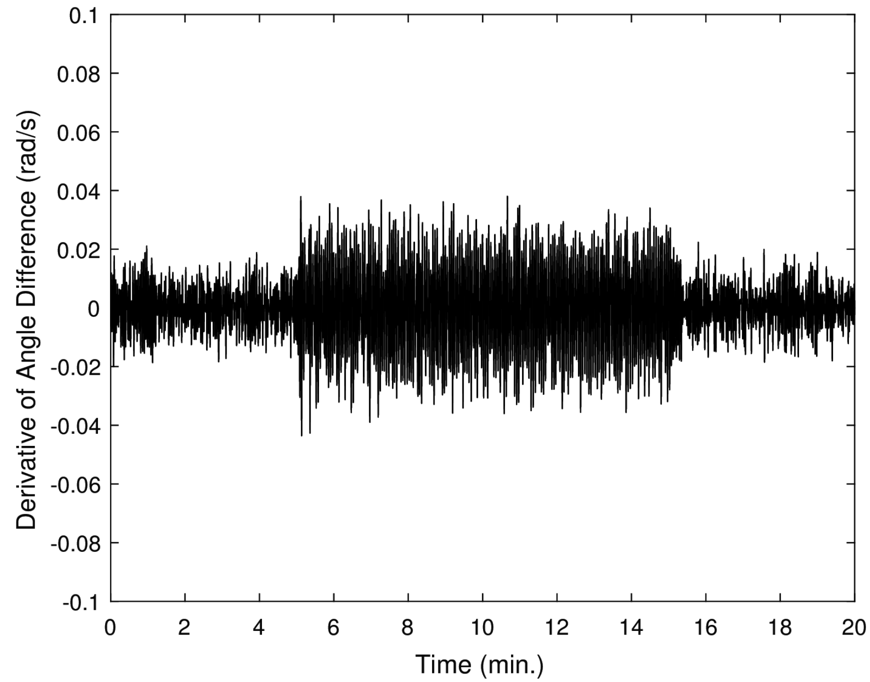
FO Performance: 0.3 Hz, -10 dB, 10 min.



Ambient data



Ambient plus FO data

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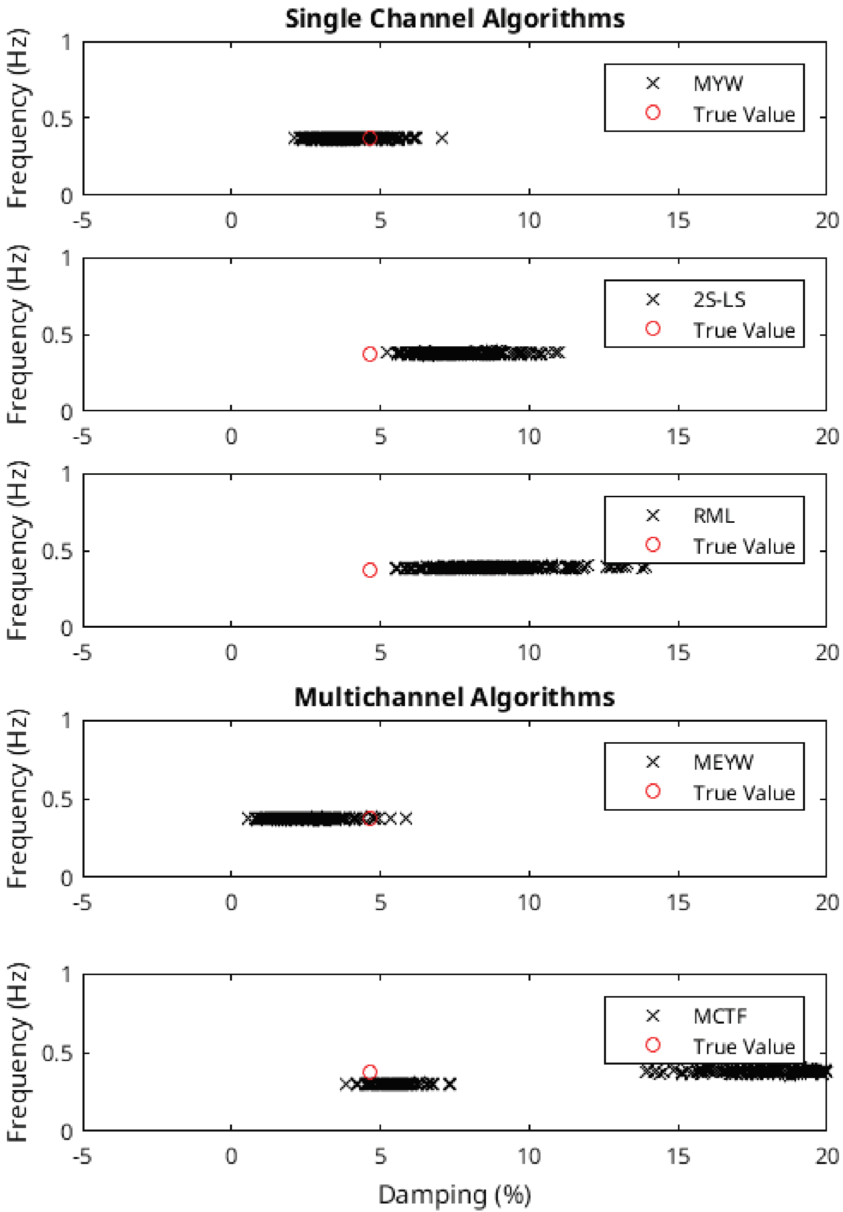
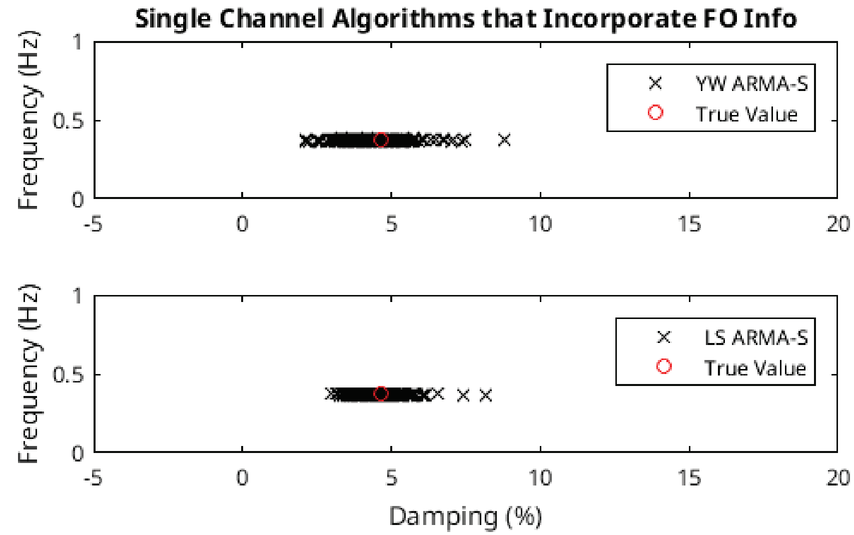
FO Performance: 0.3 Hz, -10 dB, 10 min.





- 0.3 Hz is in the region dominated by N-S modes
- This FO seriously affects all traditional mode meters except MYW
- FO detected in all 300 trials
- FO-ready methods show excellent improvement

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