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A Stepwise Regression Method for Estimating Dominant Electromechanical Modes

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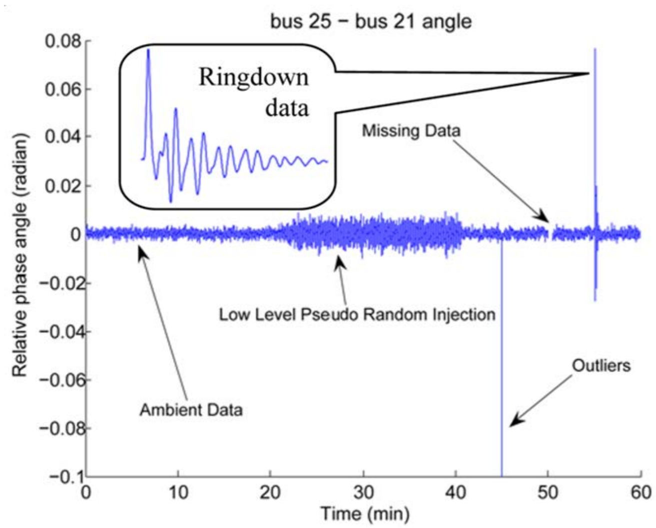
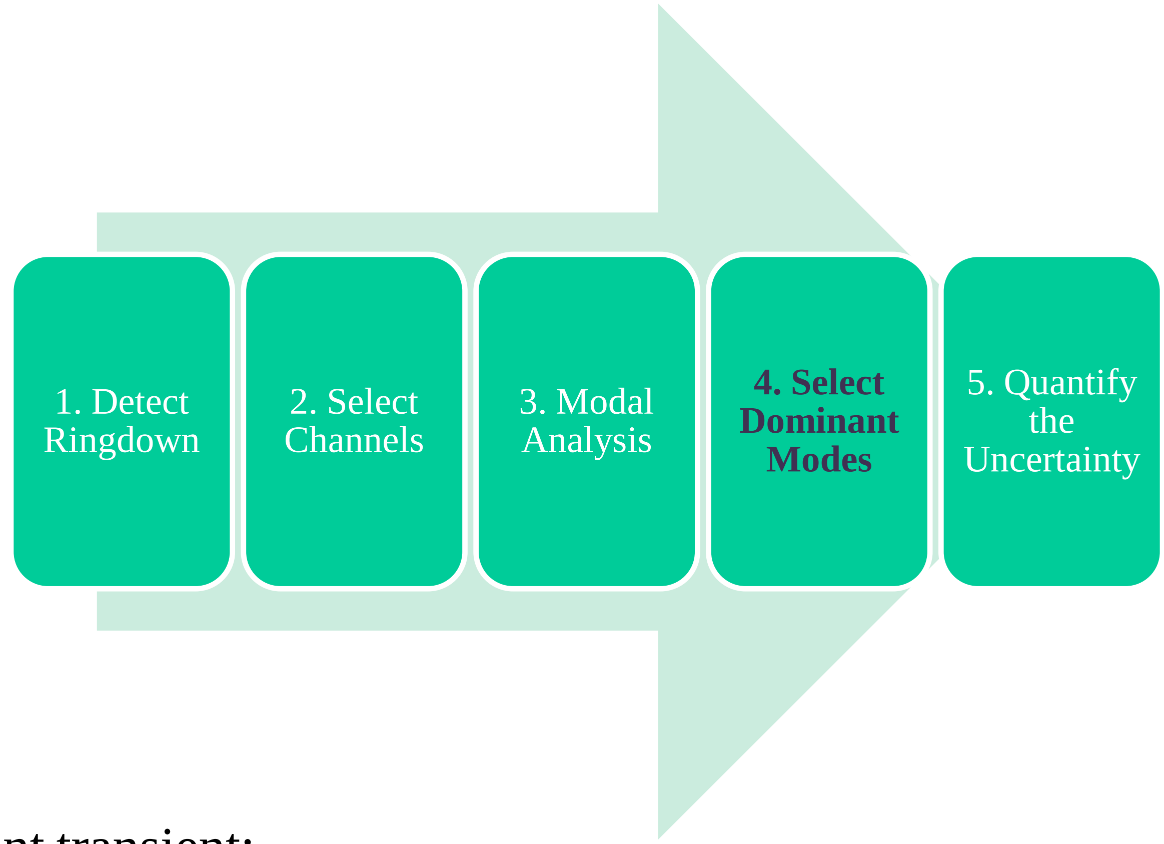
Background: Ringdown Data Analysis

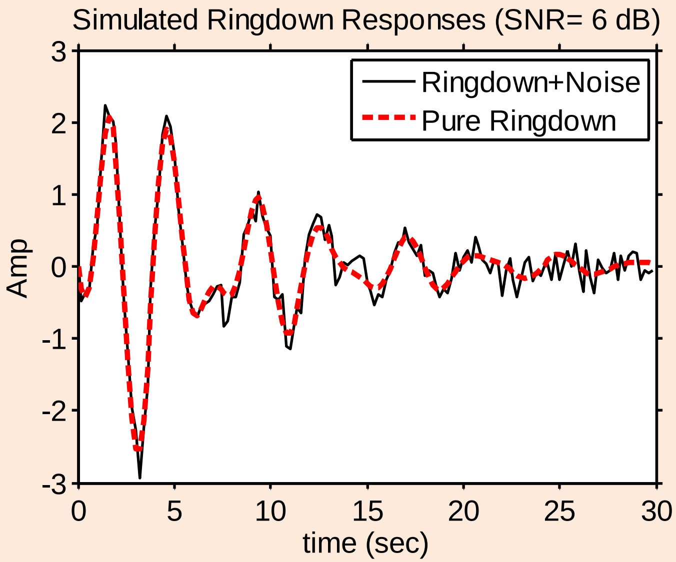


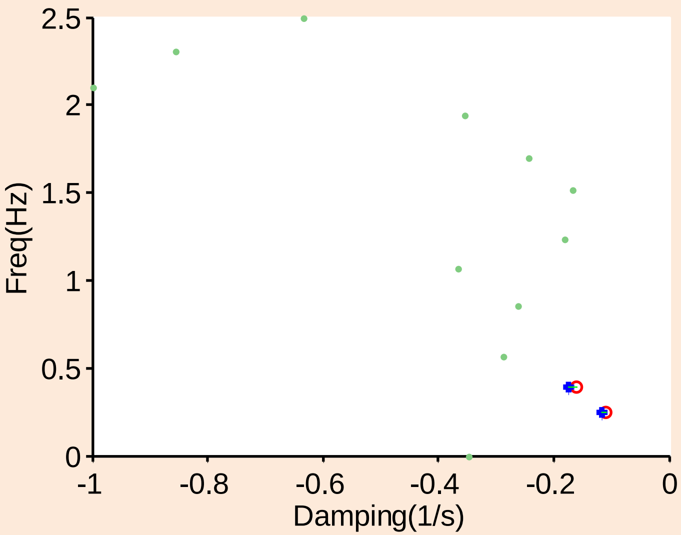


- Applicable after significant transient;
- Quick detection of light damping modes;

Problem Formulation

- **Target**: separate dominant modes and trivial modes.
  - ***Dominant modes*** represents the dynamic feature of a power system.
  - ***Trivial modes*** are artificially added to suppress the noise and improve estimation accuracy.
- **Motivations**: reduce the rate of false alarms.

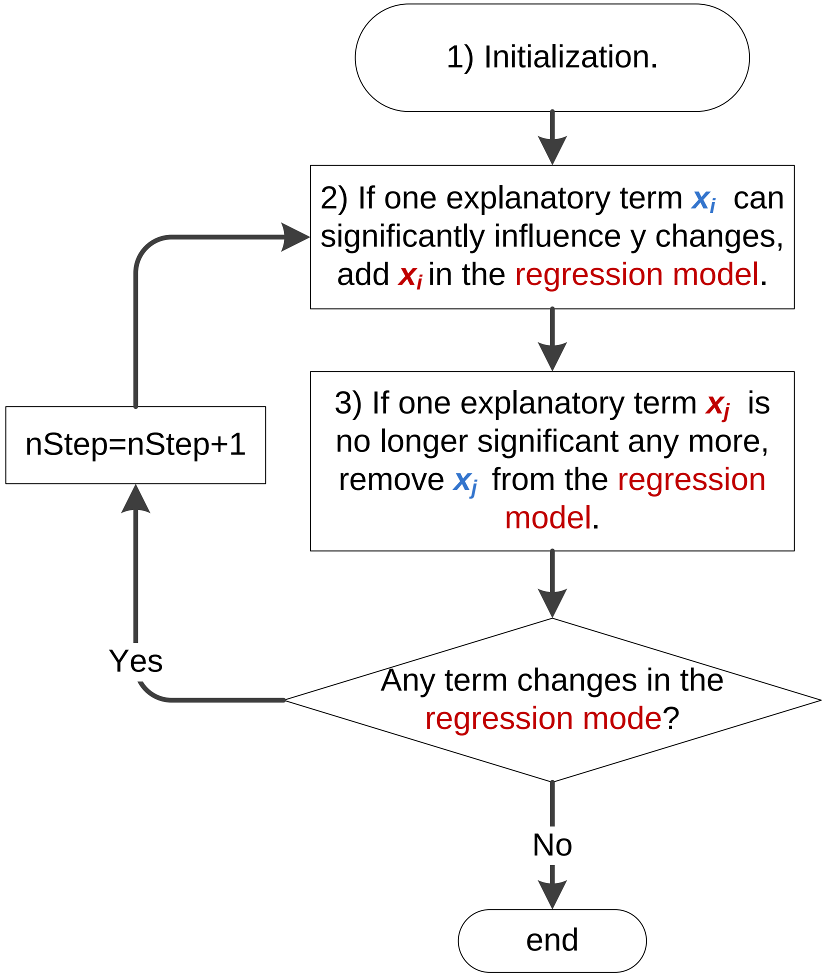




Available Methods

- Find the best-fit model using **parsimony principle**:
  - Akaike information criterion (AIC).
  - reduced-order model using the singular value decomposition (SVD).
- **Empirical Study**:
  - Sorting Energy.
- **Proposed Method:**
  - Stepwise regression**.**
  - **Motivation**: better performance under low Signal Noise Ratios (SNR).

The Stepwise Regression Method



- The stepwise-regression method provides a **systematic way** of identifying the dominant modes in a statistical framework, which takes a noise model into consideration.
- **Significance:** Is β_i close to 0 enough? (t-test).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i + \cdots + \beta_m x_m + e$$

Apply the Stepwise Regression on the Prony

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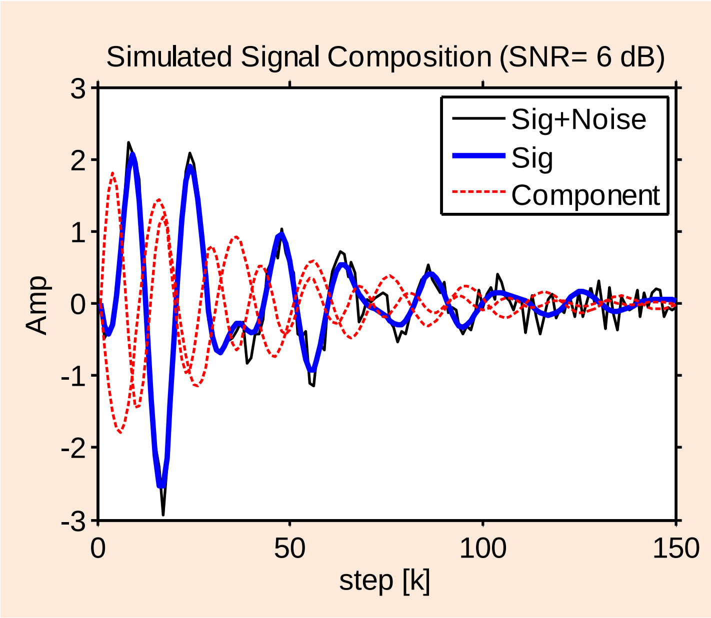
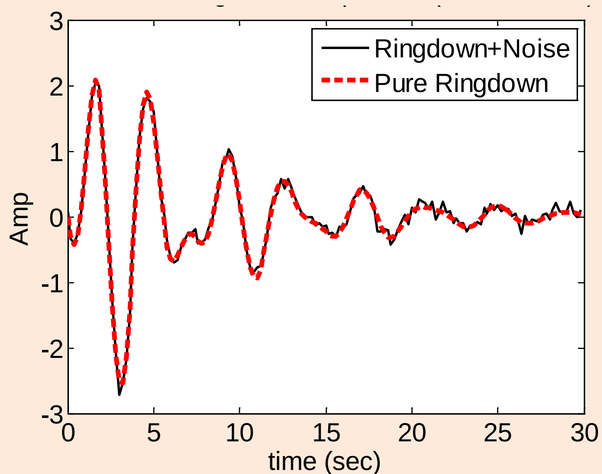
- Reconstruct the ringdown responses for each mode.
  - Real modes: $X_{real} = real\left(\hat{c}_i\left[\hat{z}_i^0 \quad \hat{z}_i^1 \quad \cdots \quad \hat{z}_i^{N-1}\right]^T\right)$
  - Complex modes: $X_{complex} = 2 \cdot real\left(\hat{c}_j\left[\hat{z}_j^0 \quad \hat{z}_j^1 \quad \cdots \quad \hat{z}_j^{N-1}\right]^T\right)$
- Apply the stepwise regression to check how significant the responses from each mode contribute to original measurement y.
  - Significant ⇔ dominant modes;
  - Insignificant ⇔ trivial modes;



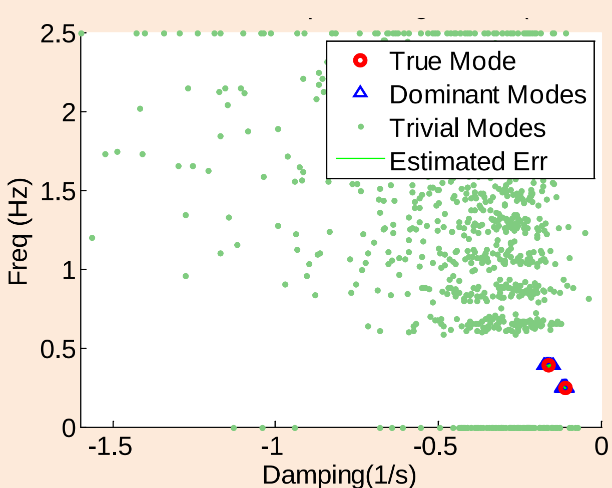
A Simple Example: SNR=10 dB



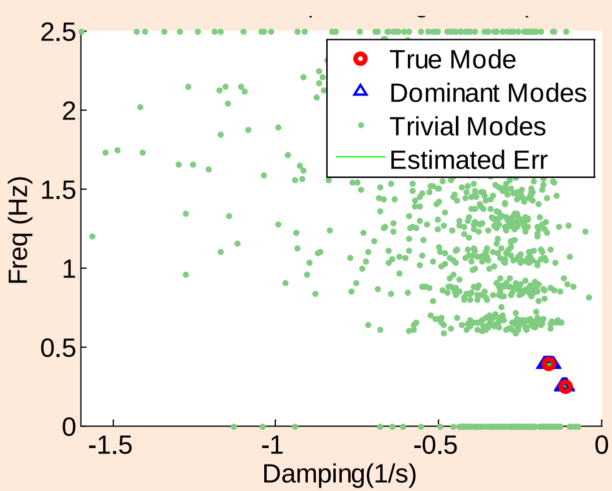
Simulated ringdown responses with SNR=10 dB.

Observations:

1. When SNR is high, both the proposed stepwise regression method and energy sorting method work well in identifying dominant modes.
2. There are some trivial modes with very light damping.

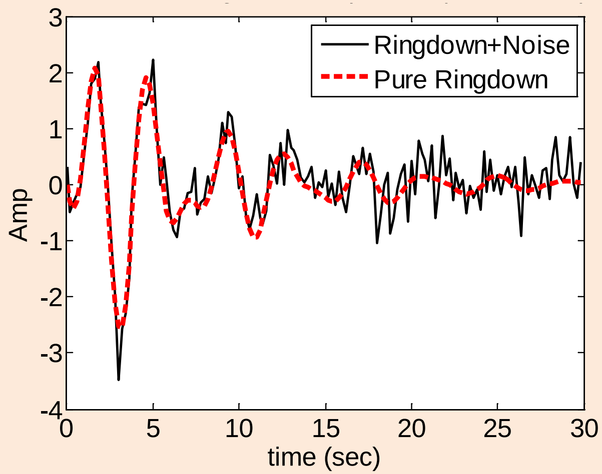


Identified modes from the proposed **stepwise-regression** method (*n*=24 for 100 Monte Carlo).



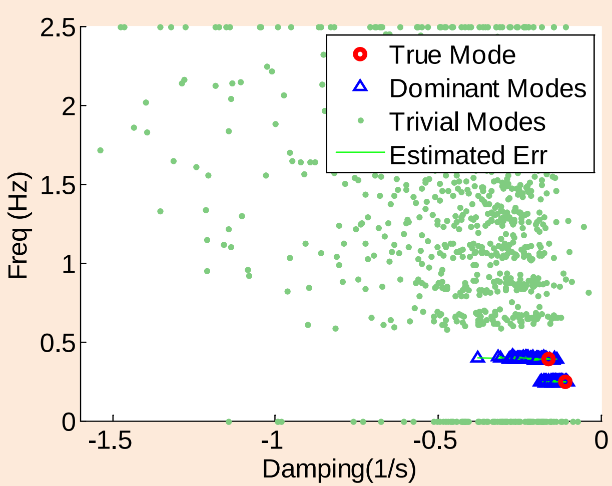
Identified modes from the **energy sorting** method (*n*=24 for 100 Monte Carlo).

A Simple Example: SNR= 3 dB

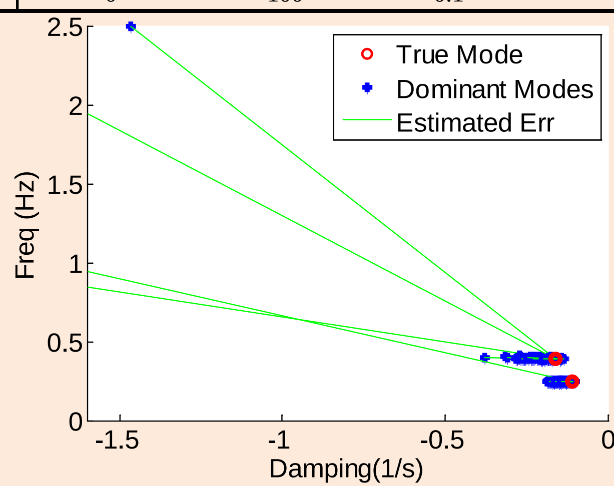


Simulated ringdown responses with SNR=3 dB.

Mode Index	Mode Freq (Hz)	Mode DR (%)	Energy Level	p-Value
1	1.07	32.7	8.6	0.13
2	0.25	8.4	7.1	$4.1X10^{-45}$
3	0.39	8.7	6.1	$4.9X10^{-35}$
4	1.12	11.1	5.6	0.10
5	0.97	8.7	3.7	0.27
6	1.58	4.5	2.0	0.08
7	1.4	3.2	1.6	0.10
8	2.5	2.8	1.2	0.87
9	0.7	5.6	1.1	0.06
10	2.3	2.5	0.8	0.35
11	2.1	3.6	0.6	0.10
12	1.8	0.9	0.4	0.76
13	0	100	0.1	0.74



Identified modes from the proposed **stepwise-regression** method (*n*=24 for 100 Monte Carlo).



Identified modes from the **energy sorting** method (*n*=24 for 100 Monte Carlo).

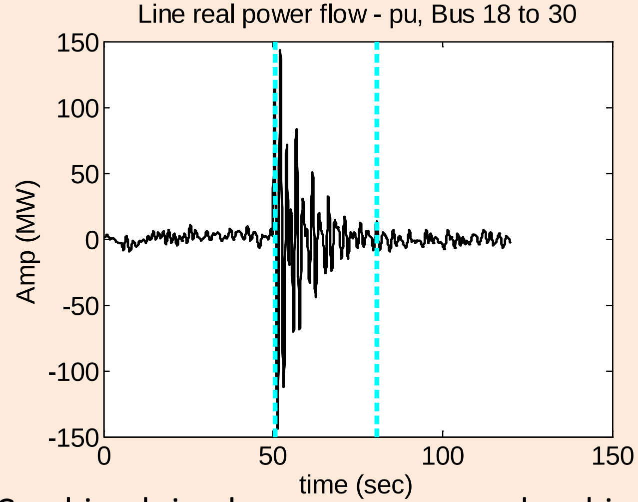
A Simple Example: Outliers v.s. SNR

SNR (dB)	***Number of Outliers Using the Energy Sorting***	***Number of Outliers Using the Stepwise-regression***
10	0	0
6	2	0
3	4	0
1	31	5
0	55	13

Observations:

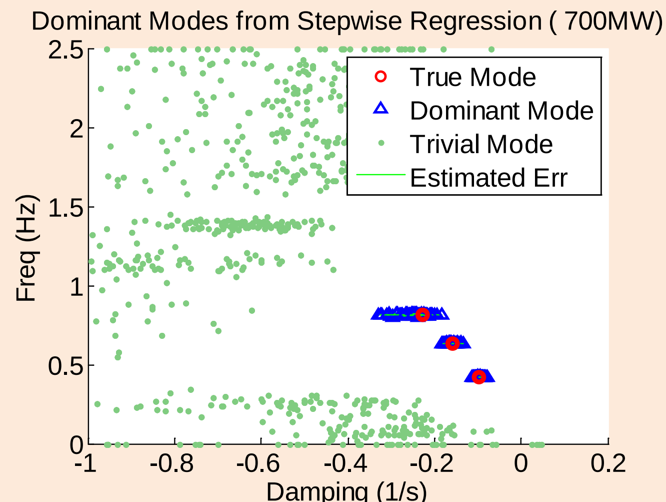
1. The number of outliers increase when SNR is decreases.
2. The stepwise-regression method has less outliers than the energy sorting method.

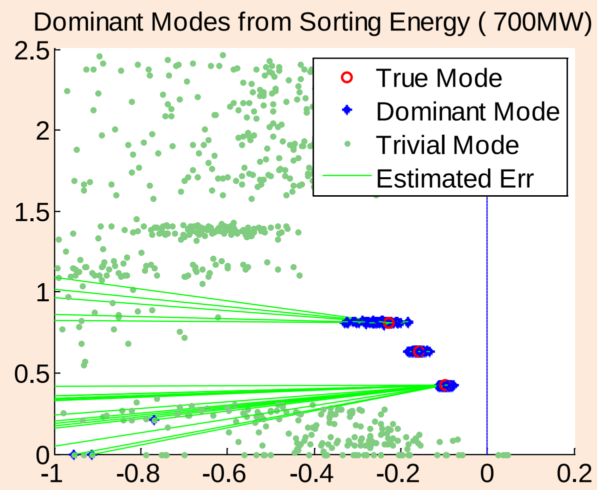
17-machine Model: 700MW Brake



Combined ringdown responses and ambient data.

Insertion Amp (MW)	*Outliers Using Energy Sorting*	*Outliers Using Stepwise-regression*
2800	2	0
1400	6	0
700	20	0
350	42	8





Identified modes from the proposed **stepwise-regression** method (*n*=24 for 100 Monte Carlo).

Field Measurement: Aug 10th, 1996 Breakup

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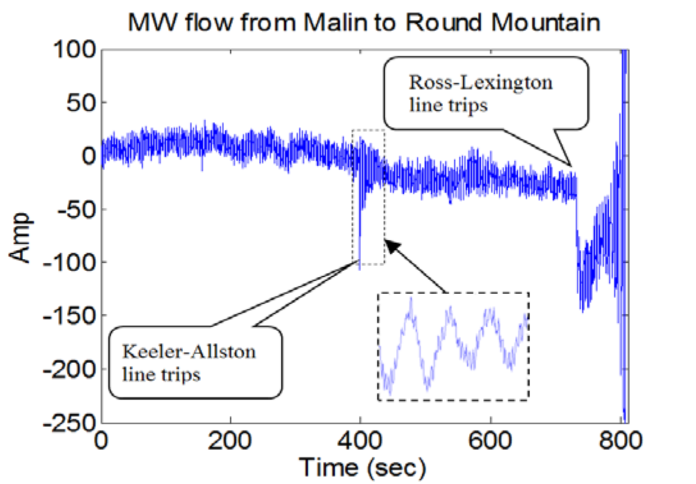


Fig. 9. Recorded real power flow from Malin to Round Mountain with detected oscillation. (Reference time: August 10, 1996, 15:35:30 PDT).

Number of Outliers for the Identified Dominant Mode from 100 Monte Carlo Simulations For Measurement Data

SNR (dB)	***Energy Sorting***	***Stepwise-regression***
10	1	0
6	7	0
3	13	0
1	21	0
0	27	1

Energy Levels and *P*-Values from Studying the Ringdown Responses.

Mode Index	***Mode Freq (Hz)***	***Mode DR (%)***	***Energy Level***	***p-Value***
1	0.270	3.59	111.0	$1.8\text{X}10^{-39}$
2	0.032	70.48	19.5	$7.2\text{X}10^{-6}$
3	0.652	5.93	12.0	0.46
4	0.805	4.90	9.2	0.81
5	0.483	19.71	8.5	0.25
6	1.955	2.95	7.7	0.84
7	1.398	6.86	6.2	0.64
8	1.524	3.14	5.6	0.94
9	2.417	1.34	5.1	0.90
10	1.045	2.75	4.6	1.00
11	1.728	2.50	3.6	0.98
12	2.180	2.48	2.9	0.37

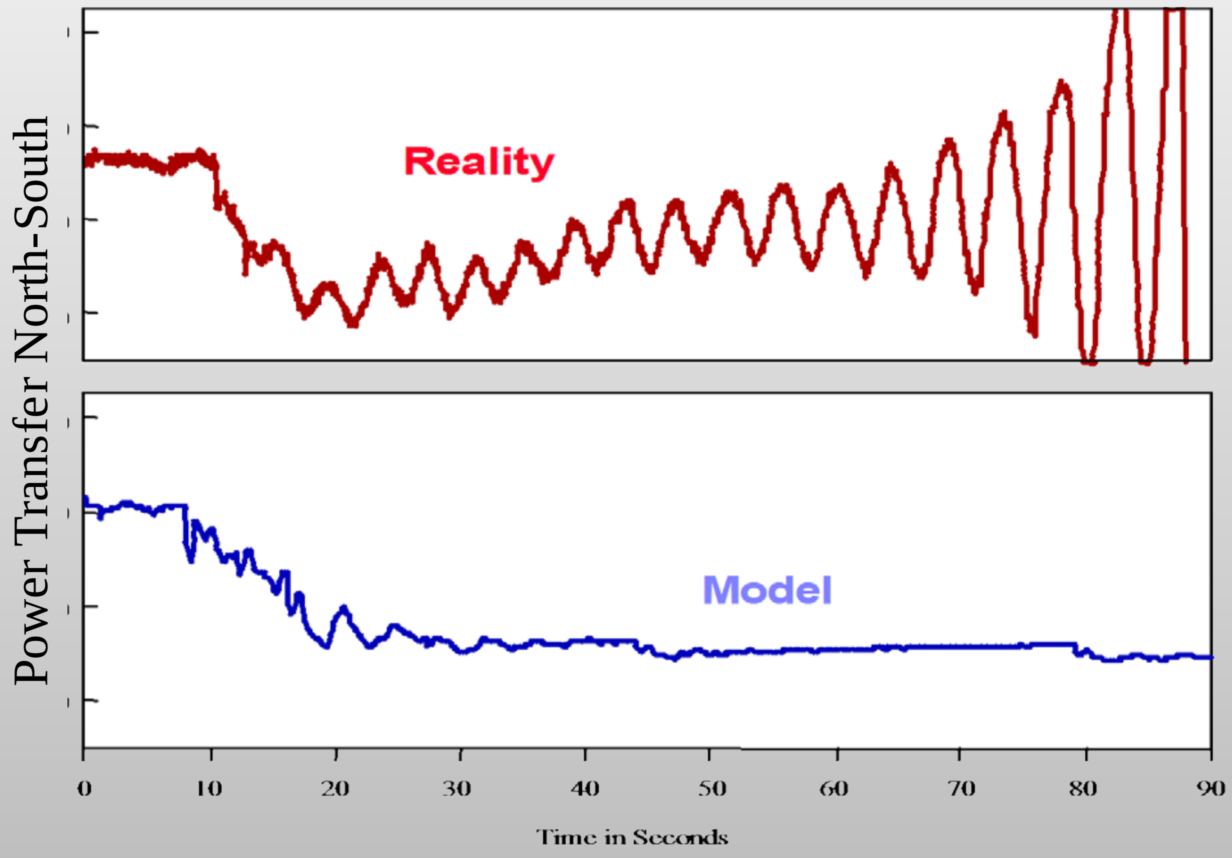
Conclusions

- A **stepwise-regression method** is proposed for selecting the dominant modes.
- The stepwise-regression method **outperforms** the energy sorting method when the SNR is low.
- The performance of the proposed method **improves with increasing SNR**.
- The proposed method can automatically distinguish trivial modes with light damping and, therefore, **reduce** the rate of false alarms.

Questions?

Spare slide #1:

Measurements vs. Model Simulation



Initial Results from the Comprehensive Simulation Model using Component-based Modeling Method

[1] Kosterev, D. N., C. W. Taylor, and W. A. Mittelstadt, "Model Validation for the August 10, 1996 WSCC System Outage," IEEE Transactions on Power Systems, vol. 14, no. 3, pp. 967-979, August 1999.

Spare Slide #2:

Early Warnings based on PMU data