

Detection and Diagnosis of Plant-wide Oscillations using the Spectral Envelope Method



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Outline

- Motivation
- Spectral Envelop Method
 - Oscillation Detection
 - Variable Categorization
- Application to industrial data
 - Oscillation Index
- Conclusion
- Acknowledgement



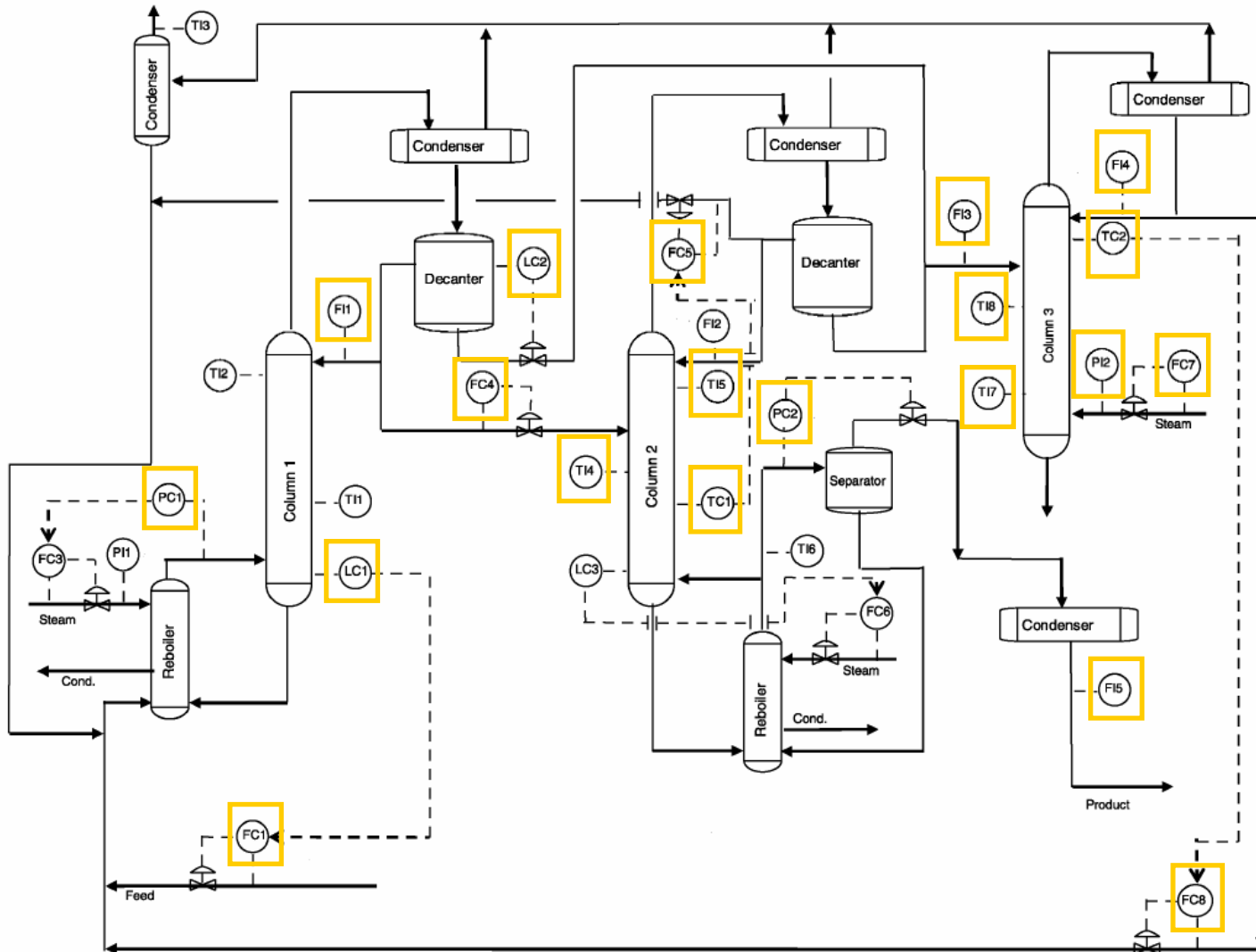
Motivation



Motivation

- Oscillations are common in many processes, whose effects propagate to many units and thus may impact the overall process performance.
- For reasons of Safety and Profitability, it is important to detect and diagnose plant-wide oscillation.

Industrial example



Objectives



- Detect oscillations in the process variables.
- Categorize the variables that have similar oscillations.
- Deliver useful information on the potential root-cause(s).



Spectral Envelop Method and its use in Oscillation Detection & Variable Categorization

Preliminaries

- Assume $\mathbf{X}(t) = \begin{bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \\ \vdots \\ \mathbf{x}_m(t) \end{bmatrix}$ is an m dimensional, vector-valued time series, for $-\infty < t < \infty$.

- Denote $g(t, \boldsymbol{\beta})$ as a linear combination of the variables of $\mathbf{X}(t)$:

$$g(t, \boldsymbol{\beta}) = \begin{bmatrix} \beta_1 & \beta_2 & \cdots & \beta_m \end{bmatrix} \begin{bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \\ \vdots \\ \mathbf{x}_m(t) \end{bmatrix} = \boldsymbol{\beta}^T \mathbf{X}(t) \quad \text{with } \boldsymbol{\beta} = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_m \end{bmatrix}$$

Preliminaries (con't)

- Denote the covariance of $\mathbf{X}(t)$ as:

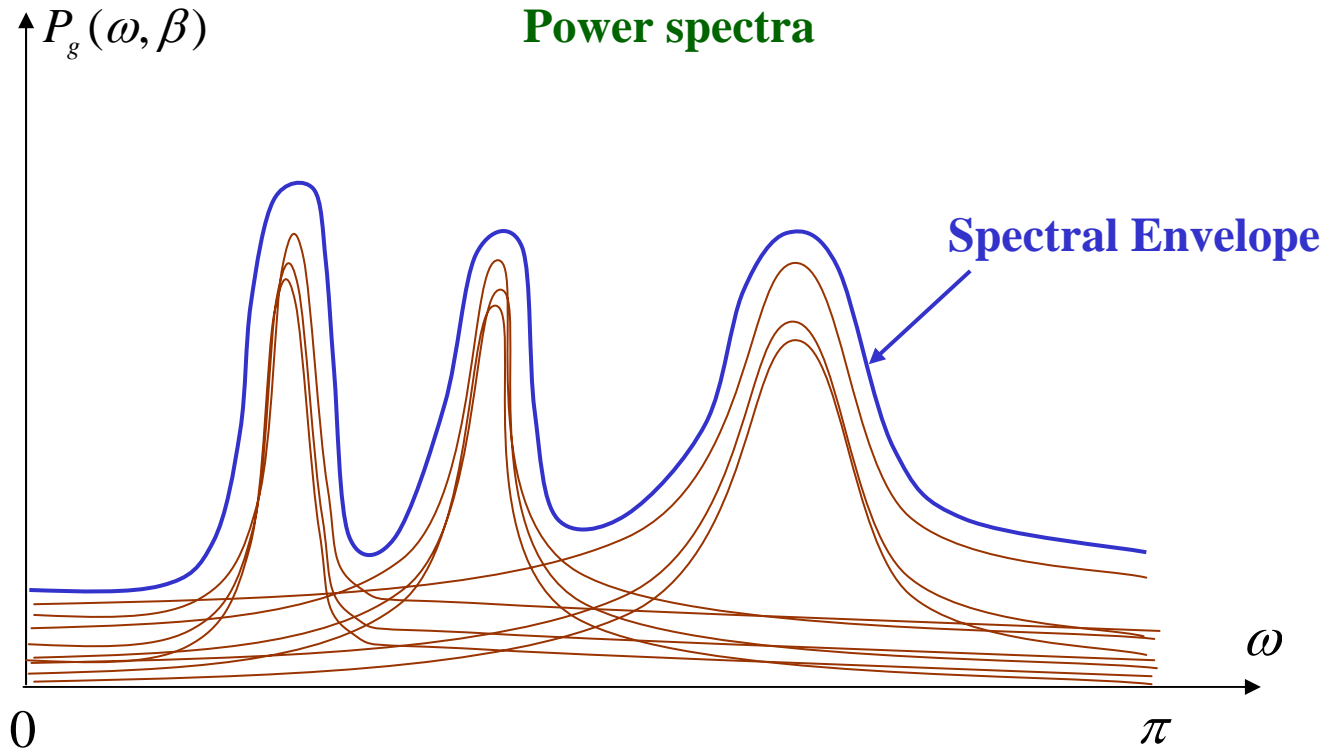
$$\mathbf{V}_{\mathbf{X}} = \text{Cov}(\mathbf{X}(t))$$

- The variance of $g(t, \boldsymbol{\beta})$ can be expressed as:

$$V_g(\boldsymbol{\beta}) = \boldsymbol{\beta}^T \mathbf{V}_{\mathbf{X}} \boldsymbol{\beta}$$

What is a Spectral Envelope?

- With the constraint that $V_g(\beta) = \beta^T \mathbf{V}_X \beta = 1$ then $g(t, \beta)$ is unit-variance.



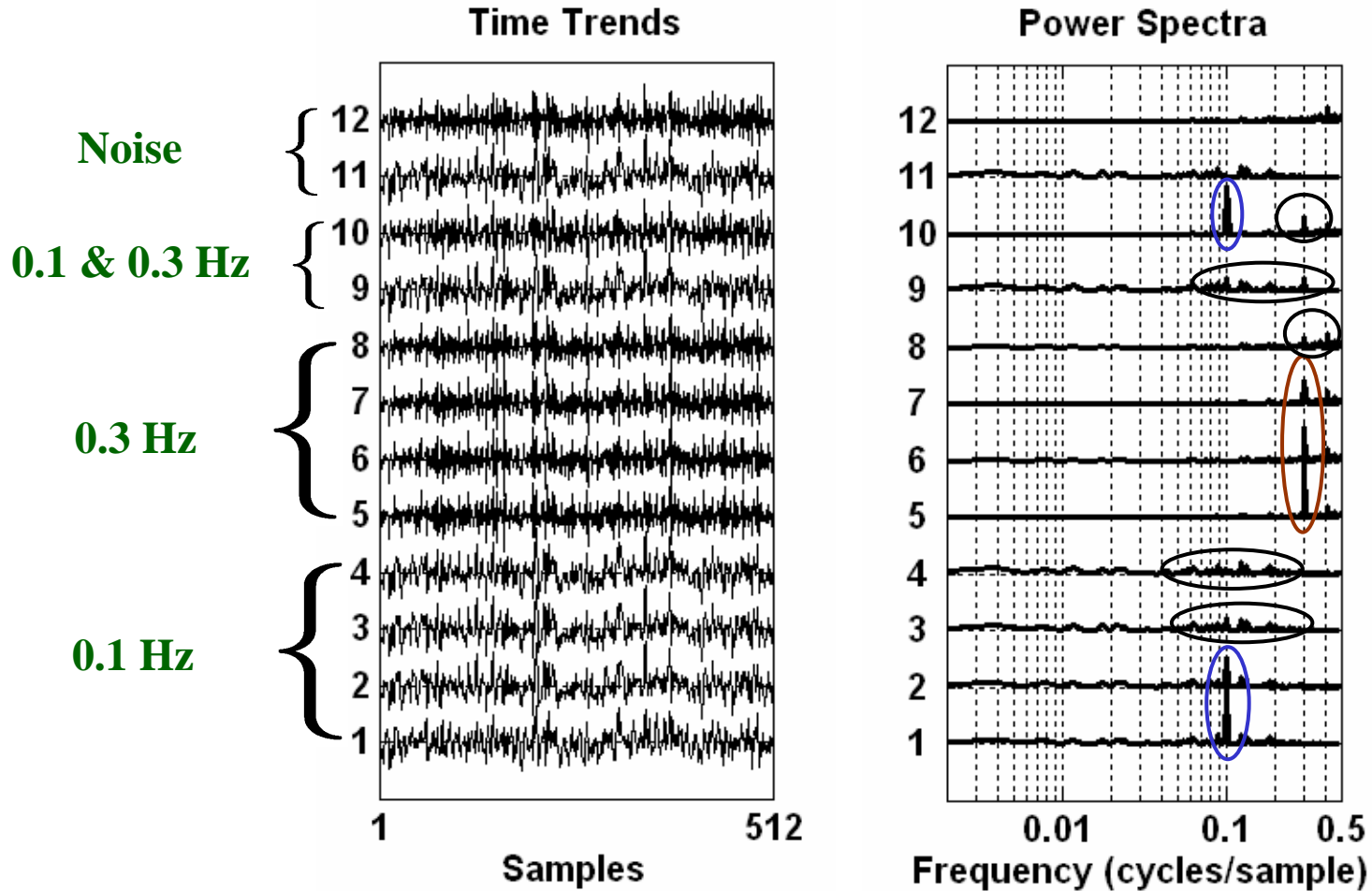
Definition of Spectral Envelop

- The Spectral Envelope of $X(t)$ is defined to be

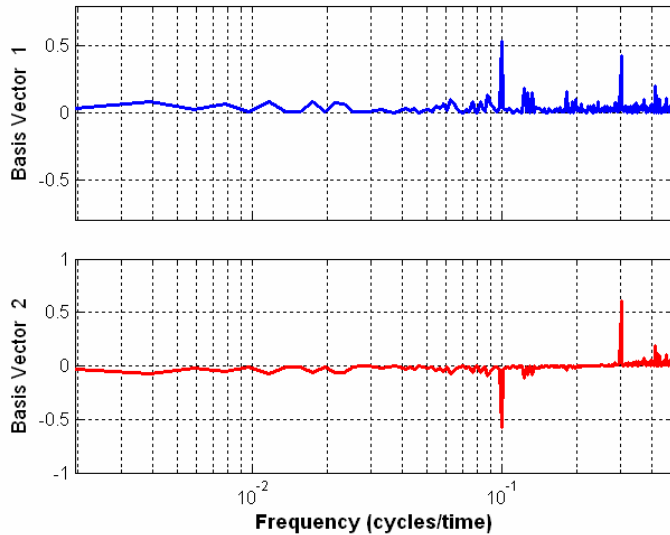
$$\begin{aligned}\lambda(\omega) &= \sup \{ \text{Power of the scaled series at frequency } \omega \} \\ &= \sup_{\beta \neq 0} \{ P_g(\omega, \beta) \} \quad \text{with} \quad \beta^T \mathbf{V}_X \beta = 1\end{aligned}$$

- The quantity $\lambda(\omega)$ represents the largest power (variance) that can be obtained at frequency ω for any unit-variance scaled series, which is a linear combination of the variables of $\mathbf{X}(t)$.

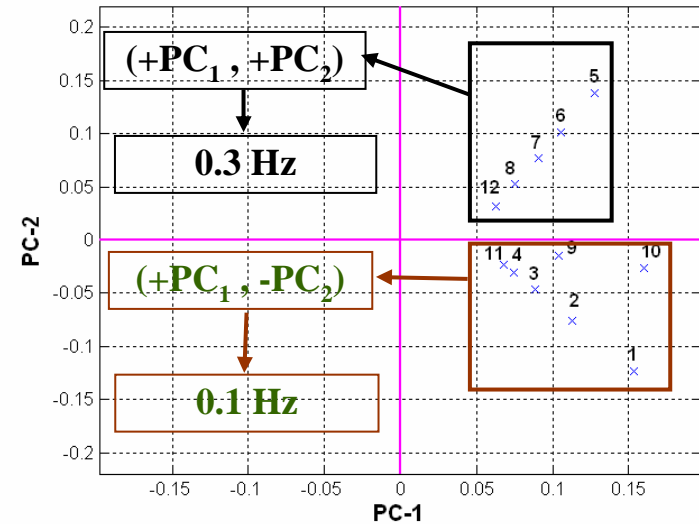
Simulation example



Spectral Principal Component Analysis (PCA)



1st and 2nd PC

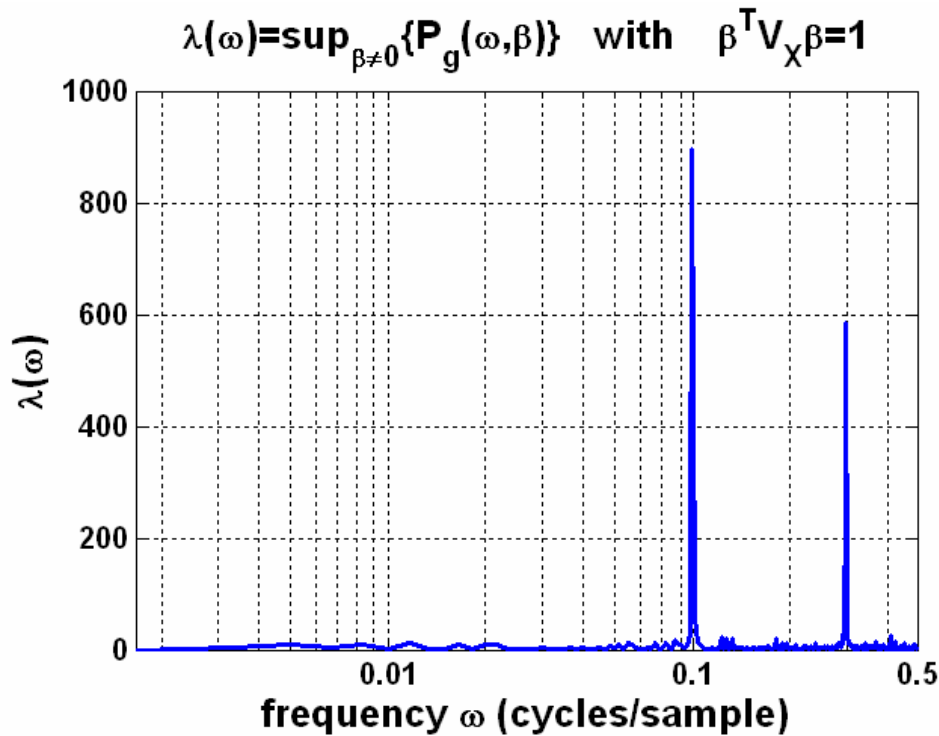


Scores plot

Remarks:

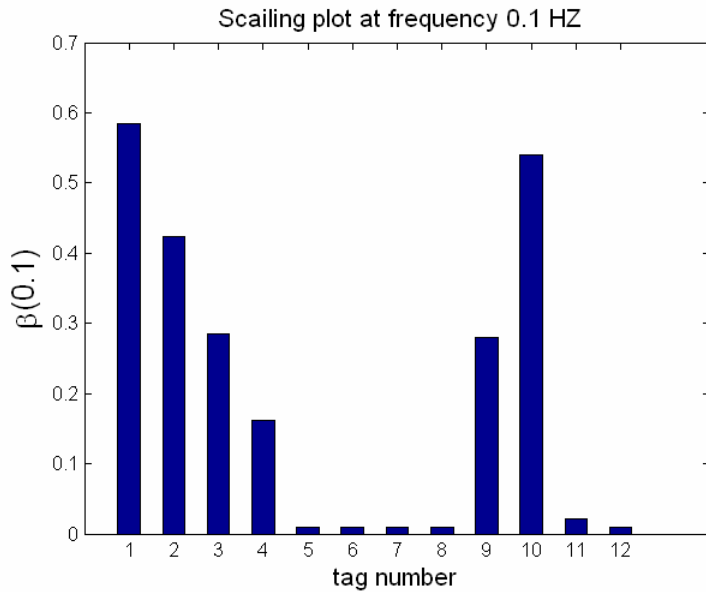
1. Have indication of the oscillation frequency at 0.1 and 0.3 Hz, but the grouping is not obvious.
2. It is not easy to analyze the oscillation frequency of each variable, especially difficult for variable 9, 10, 11 and 12.

Spectral Envelope

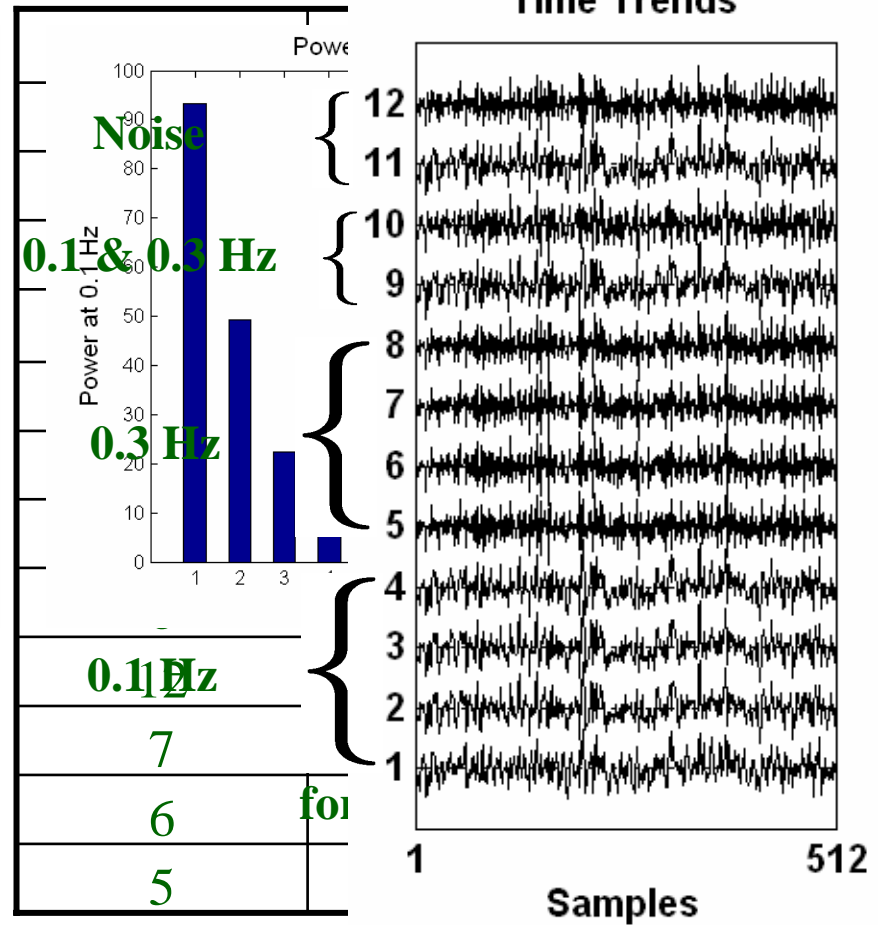


Spectral envelope can CLEARLY identify the oscillations at 0.1 and 0.3 Hz.

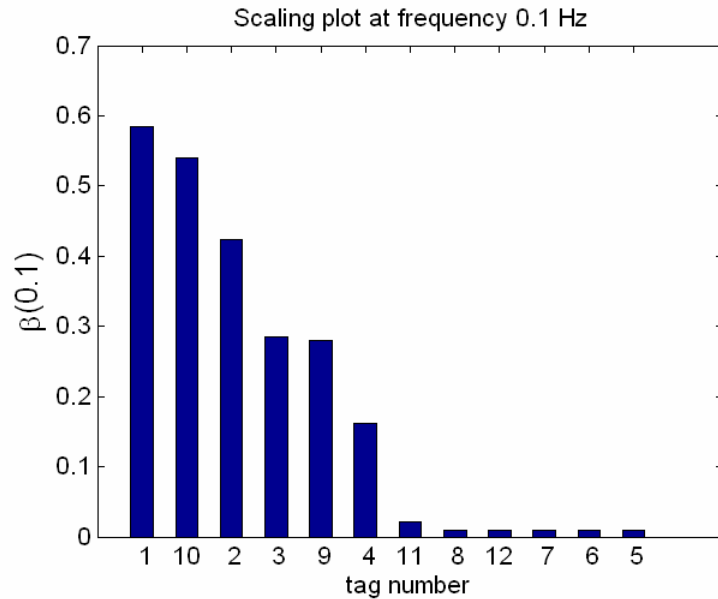
Optimal Scalings at 0.1 Hz



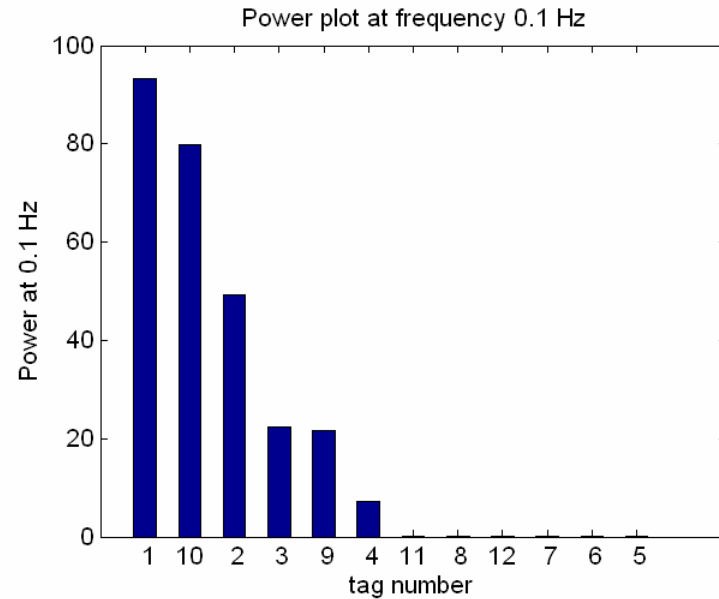
**Magnitude of scaling
for each variable**



Scaling plot *VS* Power plot at 0.1Hz



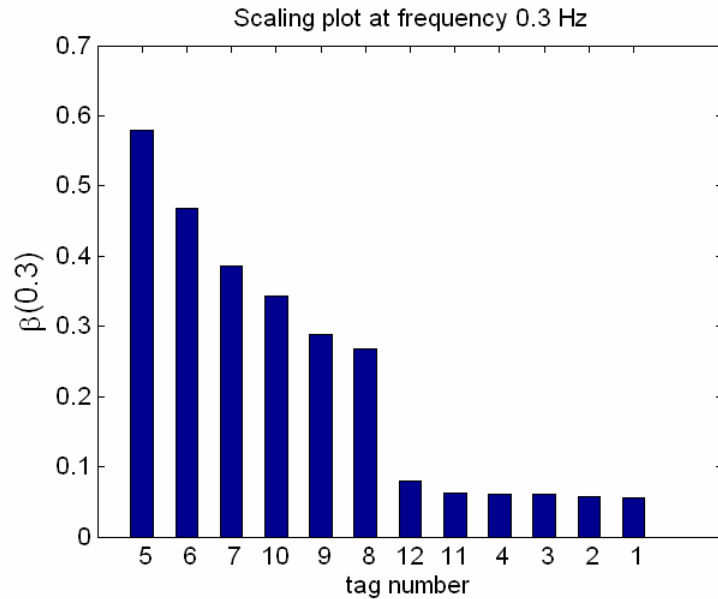
Scaling plot



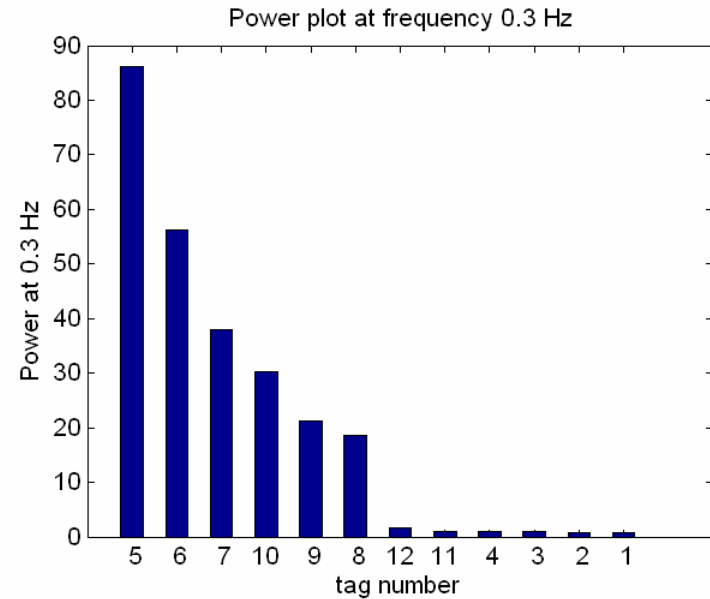
Power plot

Both plots can help us to categorize variables.

Scaling plot *VS* Power plot at 0.3Hz



Scaling plot



Power plot

Both plots can help us to categorize variables.



Application to industrial data (1)

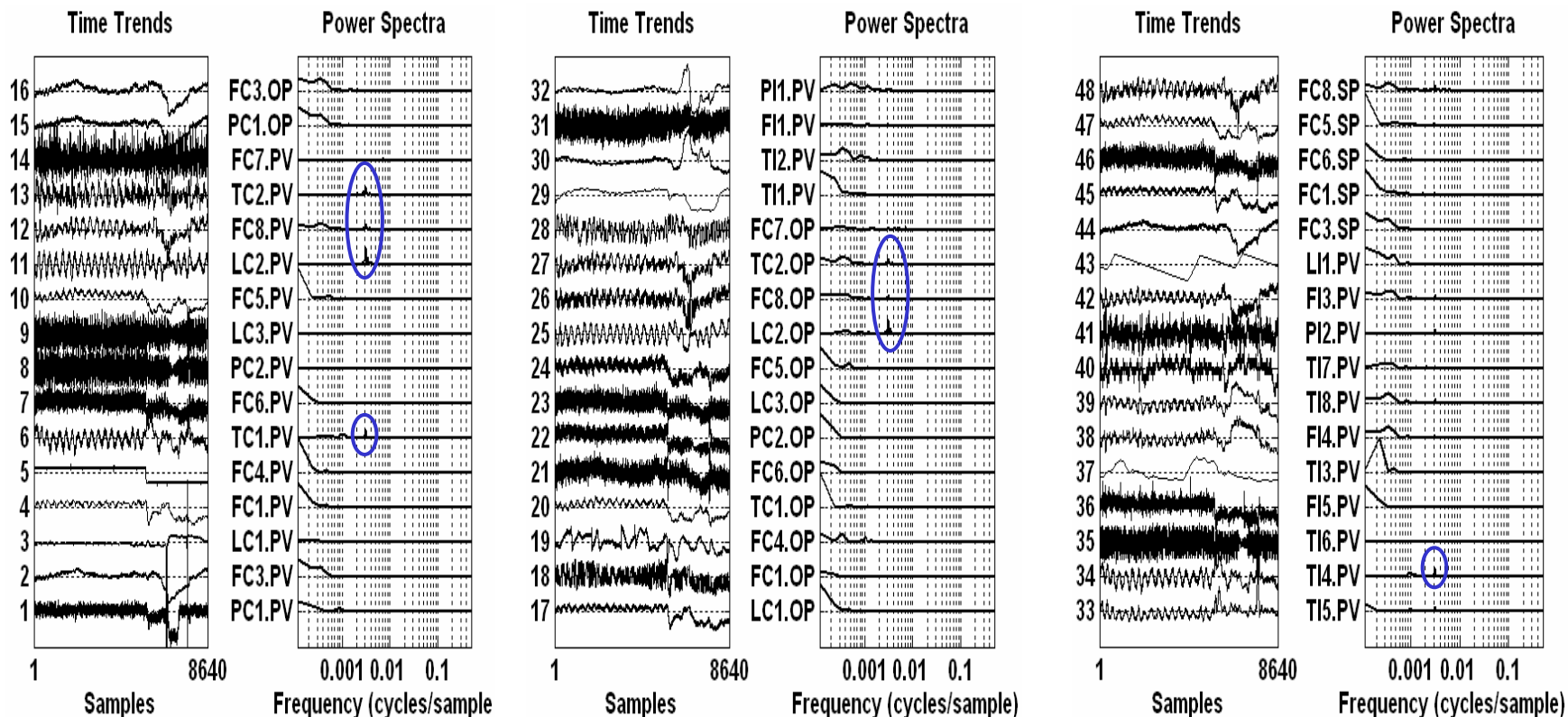


Distillation plant example

- Data from Eastman Chemical Company, USA.
- 48 process variables from a distillation plant.
- 8640 observations sampled at 20s interval.

Overview of the data

Interested in identifying tags with oscillation period of nearly 2 hours
 (about 300 samples/cycle, or $1/300=0.0033$)

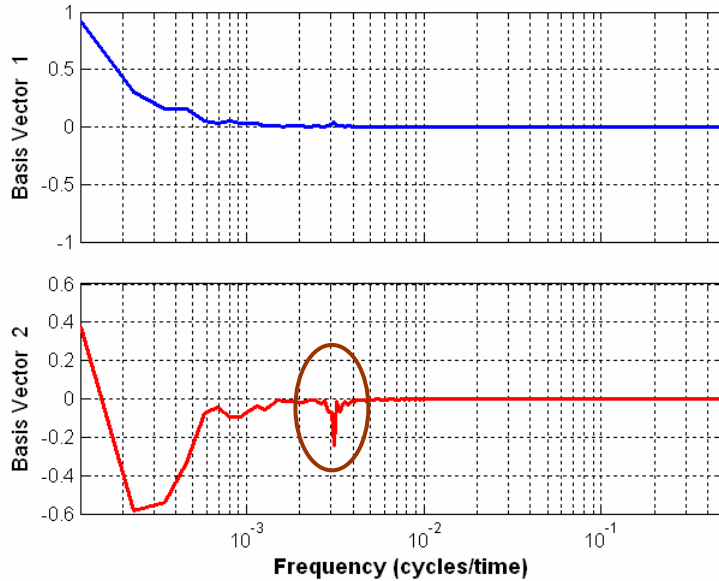


Tag 1-16

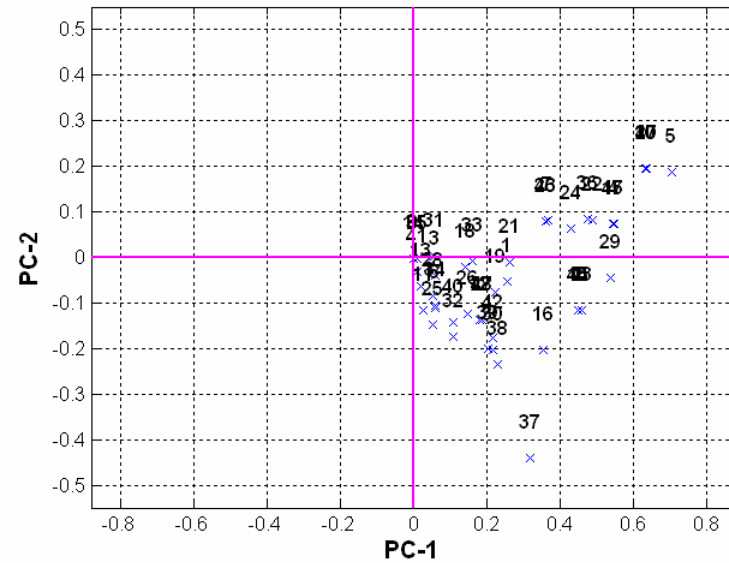
Tag 17-32

Tag 33-48

Spectral PCA analysis



PC plot

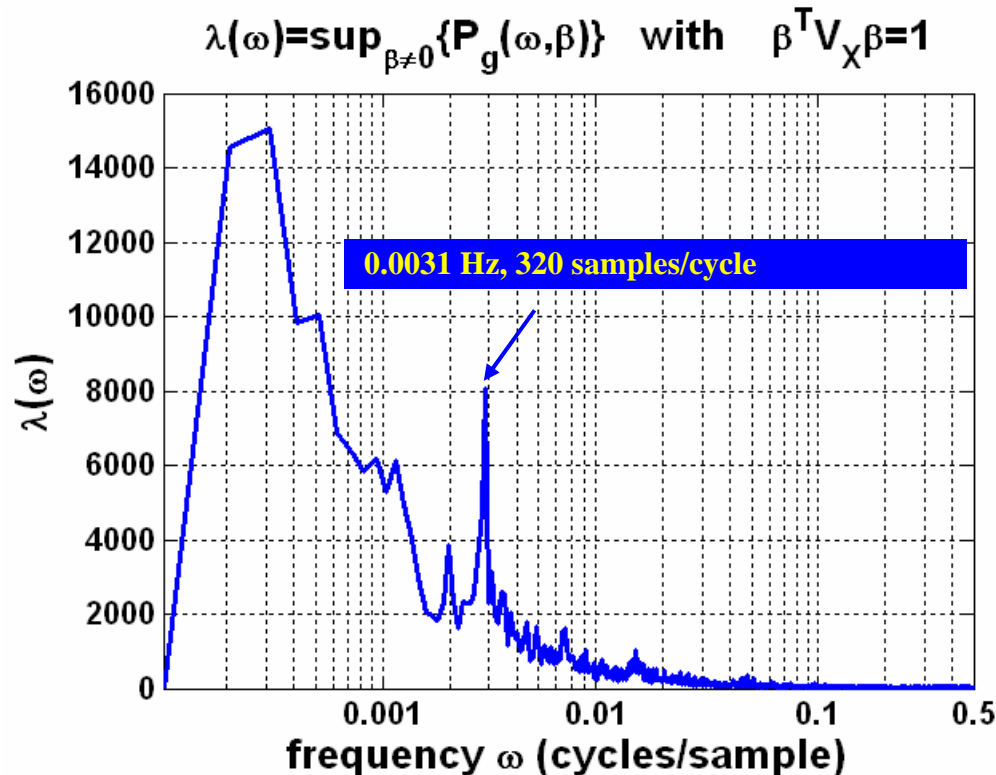


Scores plot

Remarks:

1. Gives indication of interesting oscillations with a period of 2 hours (about 300 samples/cycle).
2. However no obvious clusters are formed.

Spectral Envelope



Spectral envelope can CLEARLY detect the oscillations with a period of 320 samples/cycle.

Oscillation Index (OI)

- Denote $P_i(\omega)$ as the power of $x_i(t)$ at frequency ω , $\sigma_P(\omega)$ as the standard deviation of the sequence $\{P_1(\omega), P_2(\omega), \dots, P_m(\omega)\}$.

Then OI of variable $x_i(t)$ at frequency ω is defined as :

$$OI = \frac{P_i(\omega)}{\sigma_P(\omega)}$$

- The variables that have $OI > 1$ are the likely root cause(s) variables.

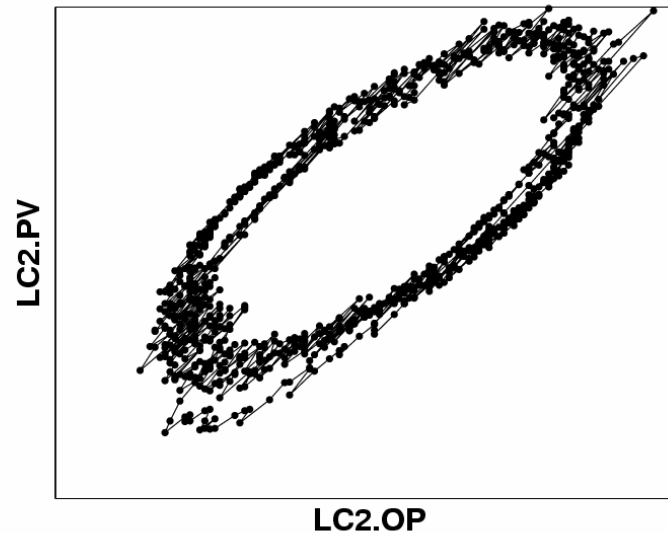


Major oscillating variables

Tag	LC2.pv	LC2.op	TI4.pv	TC1.pv	TC2.pv	TI5.pv
<i>OI</i>	4.77	3.86	2.56	2.45	2.27	1.53

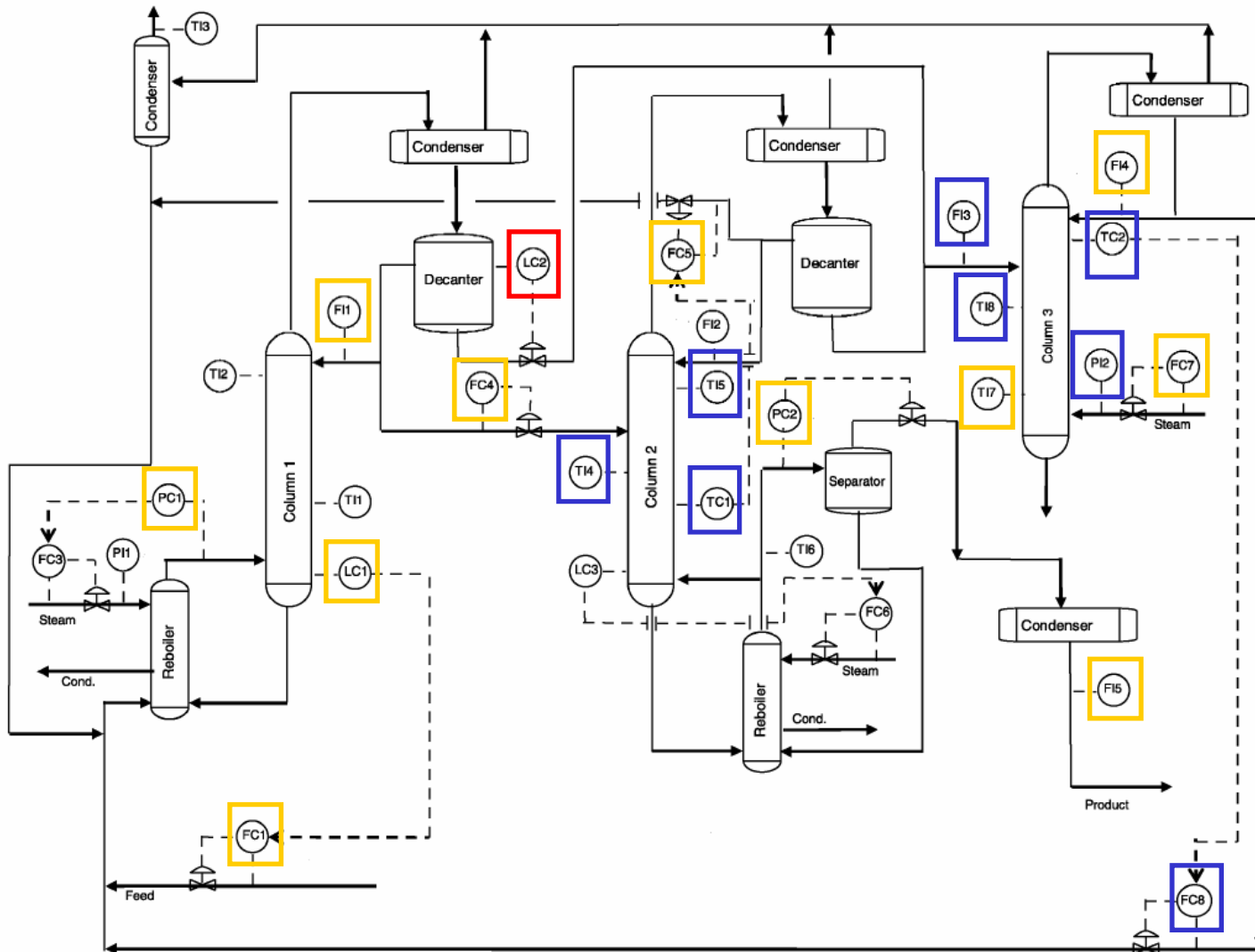
Tag	FC8.pv	TC2.op	FC8.sp	TI8.pv	FI3.pv	PI2.pv
<i>OI</i>	1.50	1.35	1.35	1.18	1.07	1.04

Valve Stiction Diagnosis



1. The plot shows a pattern of valve stiction.
2. Plant test had confirmed that there was 4% stiction in the valve. This was exactly the root-cause of the plant-wide oscillations.

Root cause Diagnosis





Application to industrial data (2)

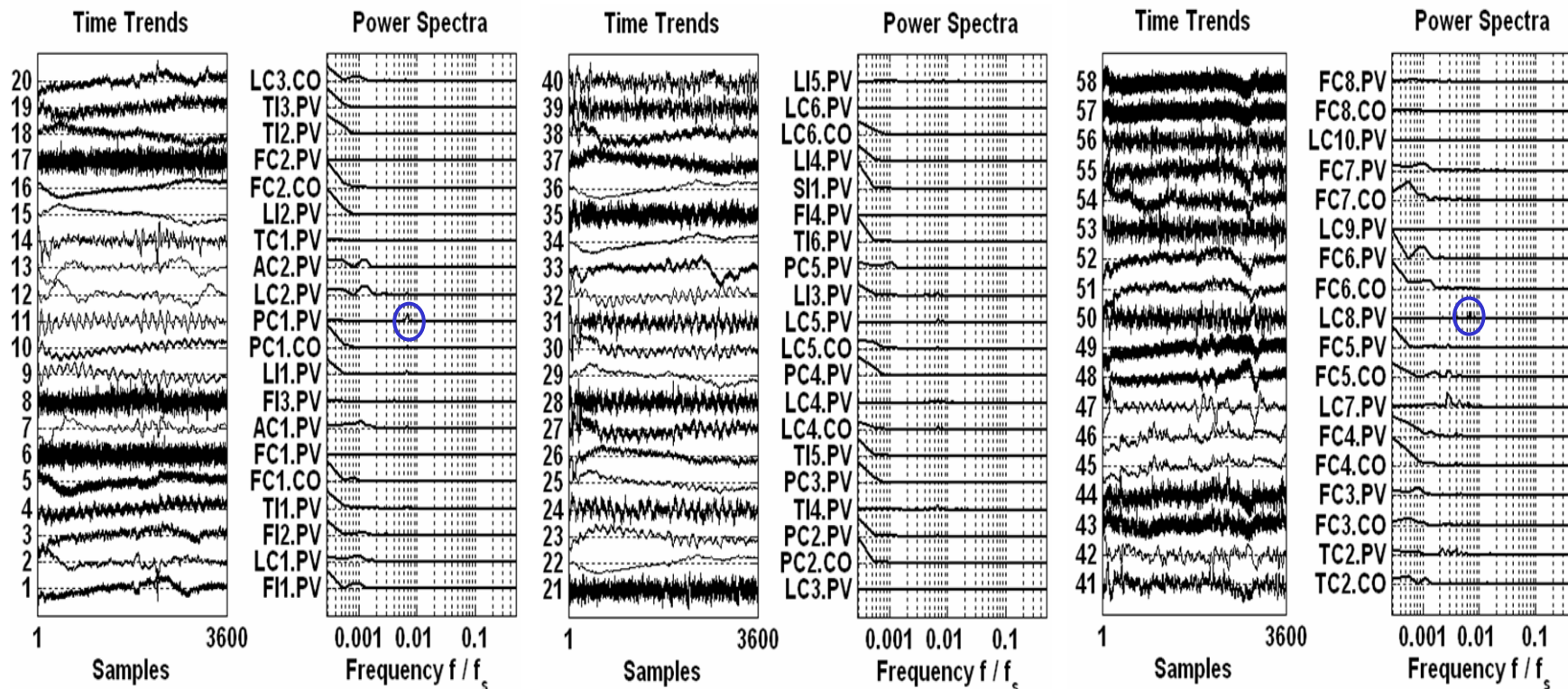


Distillation plant example

- Data from Mitsubishi Chemical Corporation
- 58 process variables from a distillation plant
- 3600 observations sampled at 1 min interval

Overview of the data

Interested in identifying tags with oscillations of period 2.5 hours
 (about 150 samples/cycle, or $1/150 = 0.0067$)

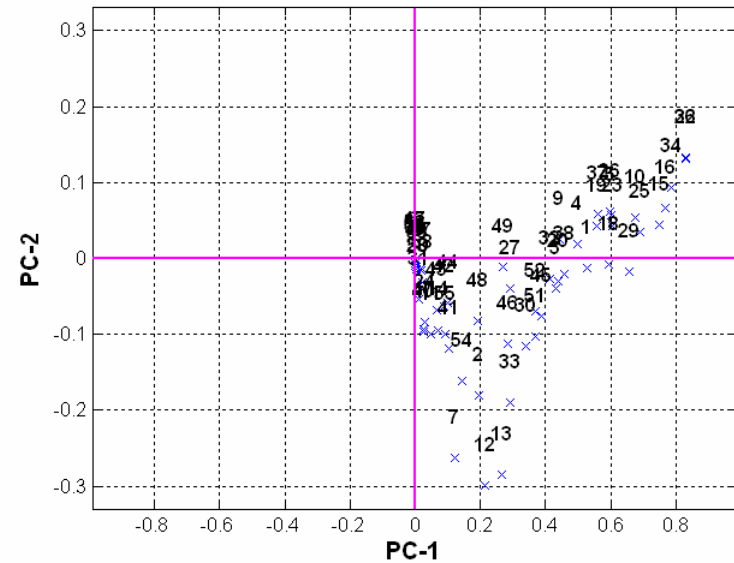
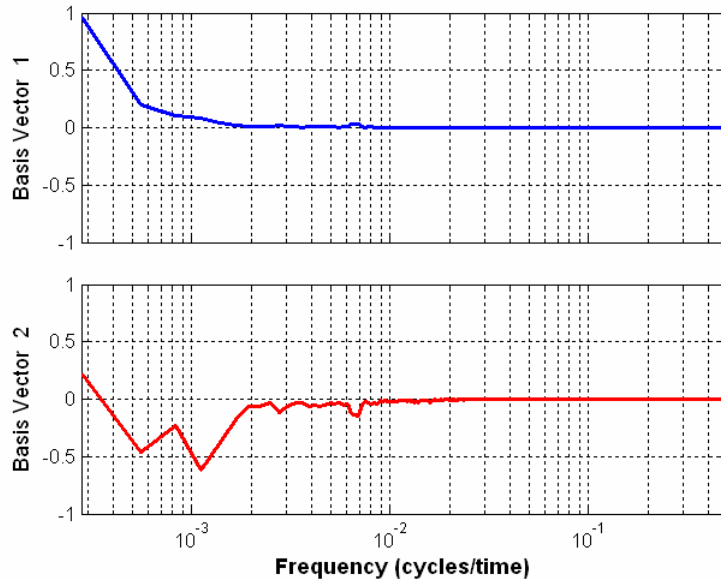


tag 1- 20

tag 21- 40

tag 41- 58

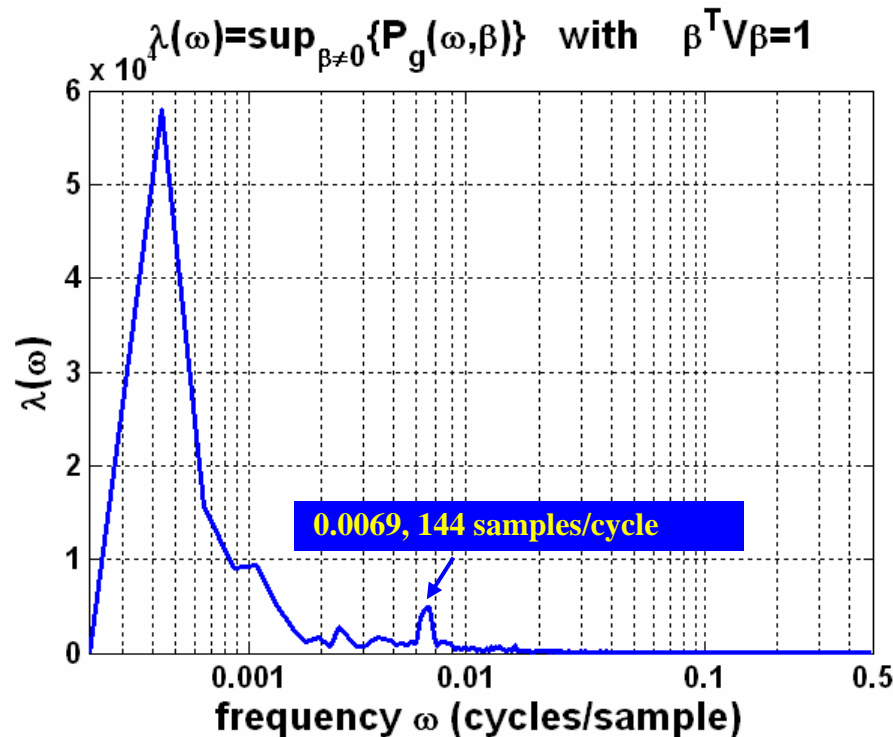
Spectral PCA analysis



Remarks:

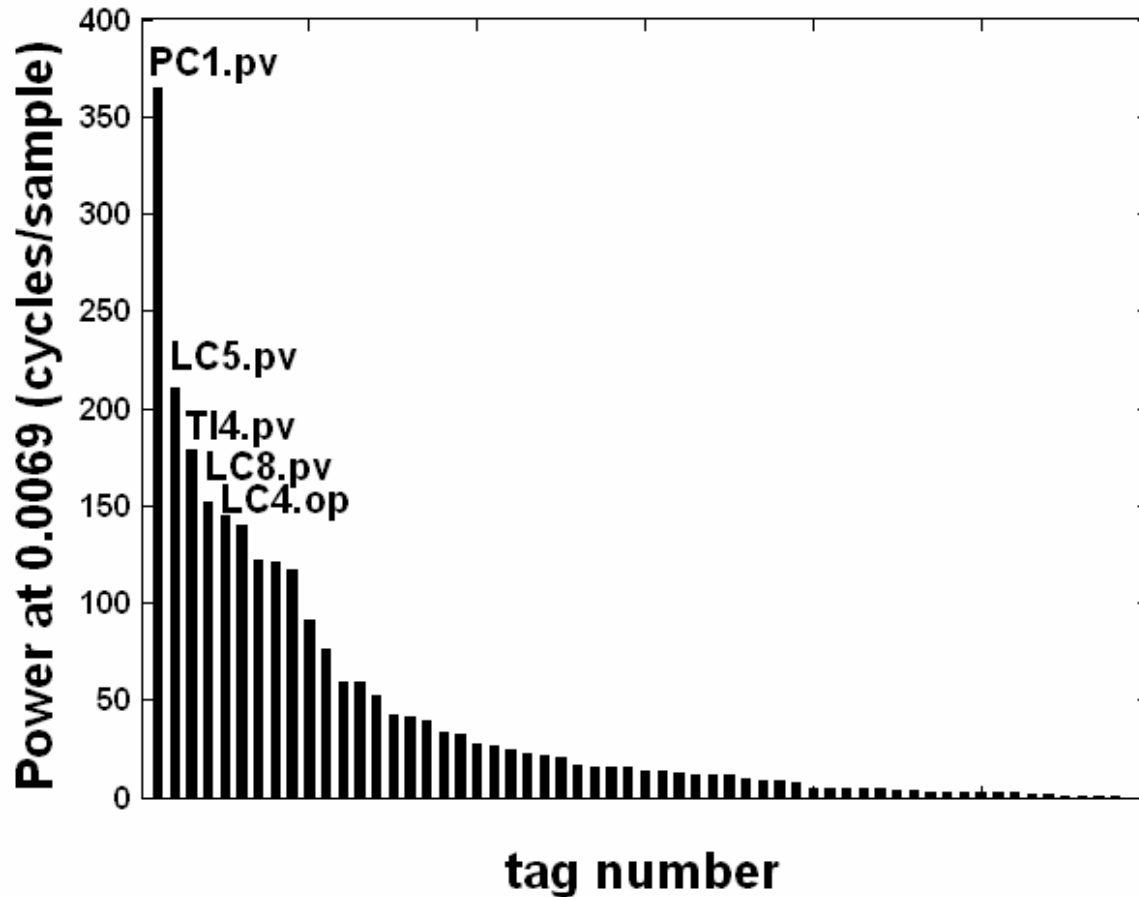
1. No clear indication about the interesting oscillations with a period of 2.5 hours.
2. No obvious clusters are formed.

Spectral Envelope



Spectral envelope is able to CLEARLY detect the oscillation of concern with a period of 144 samples/cycle.

Power plot at 0.0069 (144 samples/cycle)



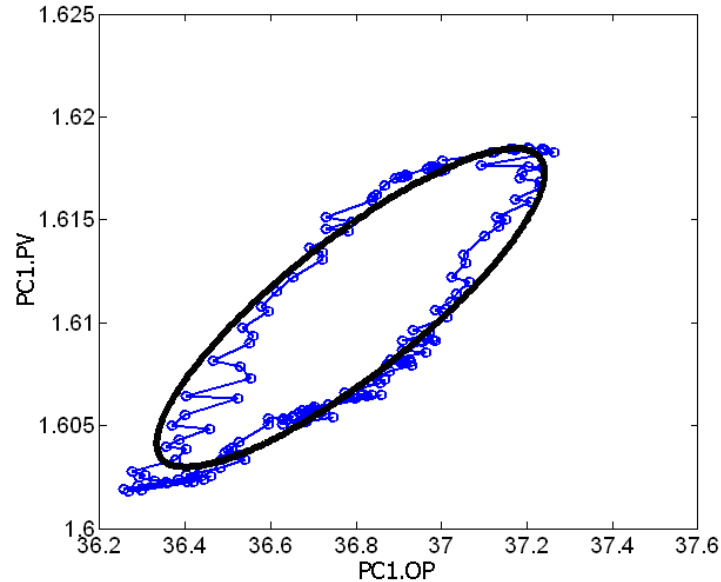
Power plot

Major oscillating variables

Tag	PC1.pv	LC5.pv	TI4.pv	LC8.pv	LC4.op	LC4.pv
<i>OI</i>	5.01	3.17	2.70	2.29	2.19	2.11

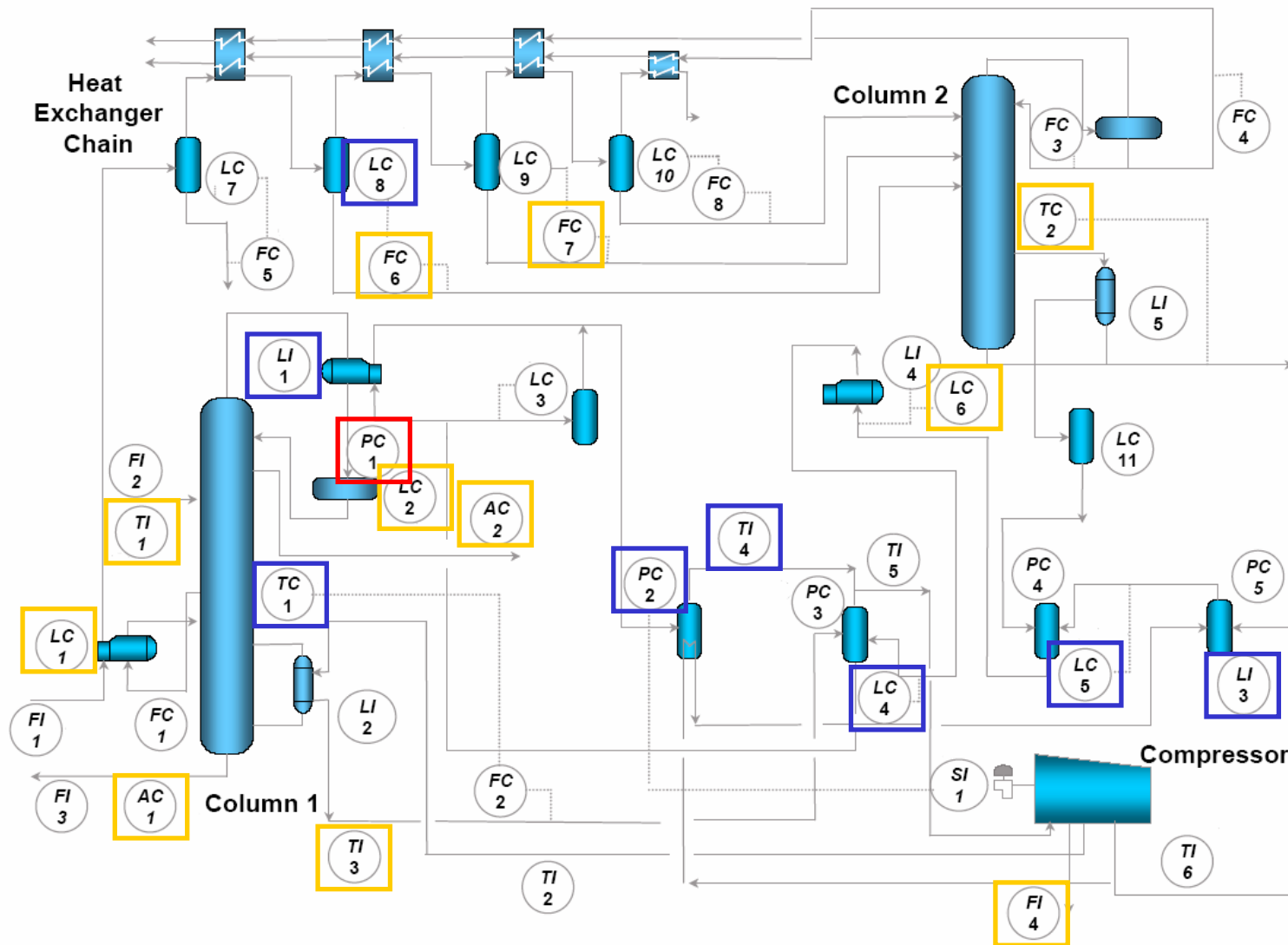
Tag	TC1.pv	LI1.op	LI3.sp	LC5.pv	PC2.pv
<i>OI</i>	1.85	1.83	1.76	1.38	1.14

Valve Stiction Diagnosis



1. This plot shows a pattern of valve stiction.
2. Simple closed-loop plant test had confirmed that the valve really has stiction problem.
3. Further plant test and maintenance has been scheduled during the next plant shutdown.

Root cause Diagnosis





Conclusion

New Procedure

- I. Normalize the data matrix;
 - II. Calculate the spectral envelope;
 - Oscillation detection
 - III. Plot power plot (or scaling plot);
 - Variable categorization
 - IV. Calculate *OI*.
 - Root cause diagnosis
-

Conclusion

- Spectral Envelop (SE) method has been successfully applied to industrial data to identify the oscillation frequencies and categorize the variables that have the same oscillations.
- Compared with Spectral PCA, SE method is more sensitive to oscillations and has better resolution in categorizing the variables.
- New procedure to carry out oscillation analysis has been proposed.



Acknowledgement

Acknowledgement



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Thank you!