Minor Structural Damage Detection Using Chaotic Excitation Technique

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Background

- Health monitoring needs to be robust against noise and sensitive to minor damages.
- Damage detection techniques using chaotic excitation and attractor-based analysis is applied
  - Compare attractors between healthy and damaged structures.
  - Robust against noise and sensitive to minor change
- Identification of parameter deterioration
- Introduction of on going experimental research

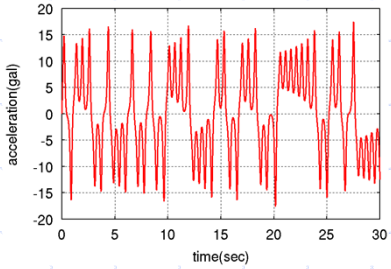
Damage detection

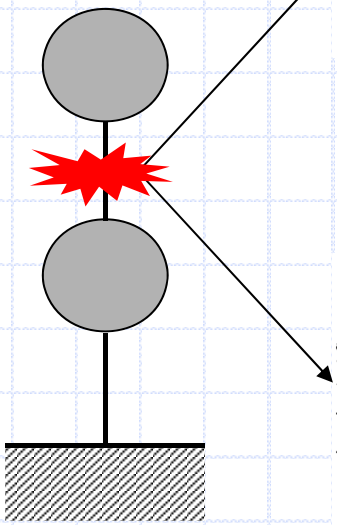
- Recurrence Analysis (RA)
  - Analyze the geometrical relationship between two attractors quantitatively.

- We propose an attractor-based damage detection method using chaotic excitation and Recurrence Analysis.
  - Compare indicator defined by RA between healthy and damaged structures.
  - Detect minor damage using input excitation and observations contaminated by high noises

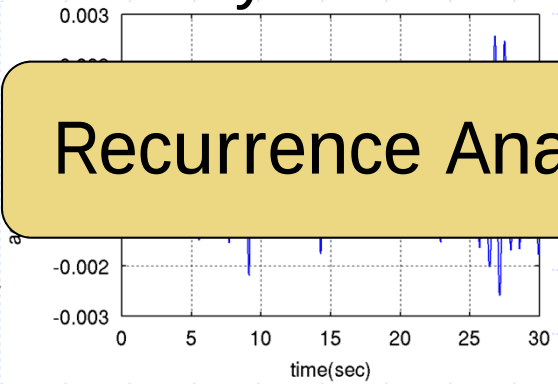
Attractor-based Damage Detection

Chaotic excitation



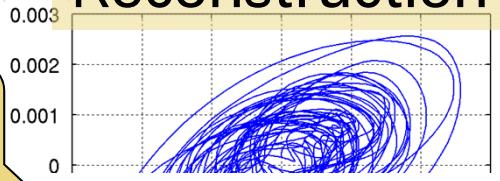


Healthy condition

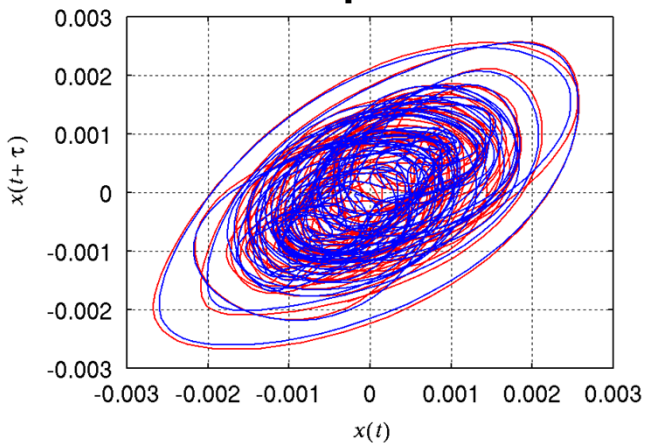


Recurrence Analysis

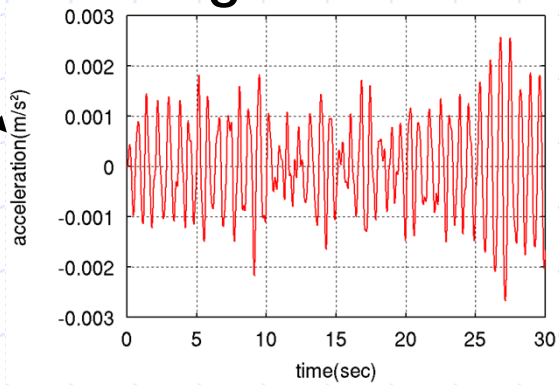
Attractor Reconstruction

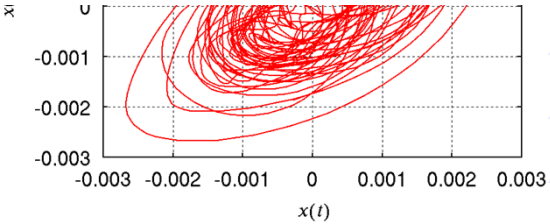


Compare



Damaged condition





Merit of Chaotic Excitation

- Attractor-based analysis assumes that the system is low-dimensional and deterministic.

- Chaos is low-dimensional and deterministic.

Chaotic excitation yields to low-dimensional and deterministic responses.

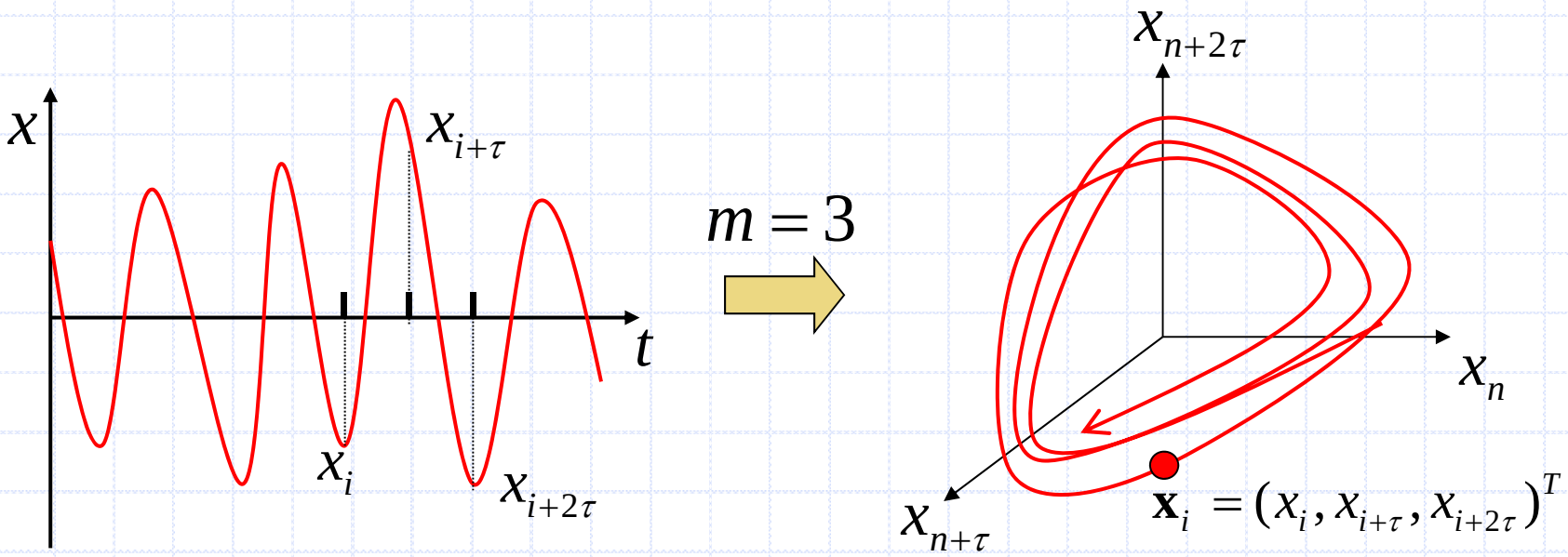
Attractor-based analysis of responses becomes possible.

Attractor Reconstruction

Embedding vector

$$\mathbf{x}_i^m = (x_i, x_{i+\tau}, \ldots, x_{i+(m-1)\tau})^T \qquad i = 1,2,\ldots,N$$

m : Embedding dimension τ : Delay time



Recurrence Analysis (RA)

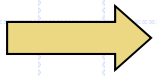
Evaluate geometrical close contacts of two attractors.

Distance matrix

$$D_{ij} = \begin{cases} 1 \ (\left\| \mathbf{x}_i^m - \mathbf{y}_j^m \right\| \le \varepsilon) \\ 0 \ (\left\| \mathbf{x}_i^m - \mathbf{y}_j^m \right\| \ge \varepsilon) \end{cases}$$

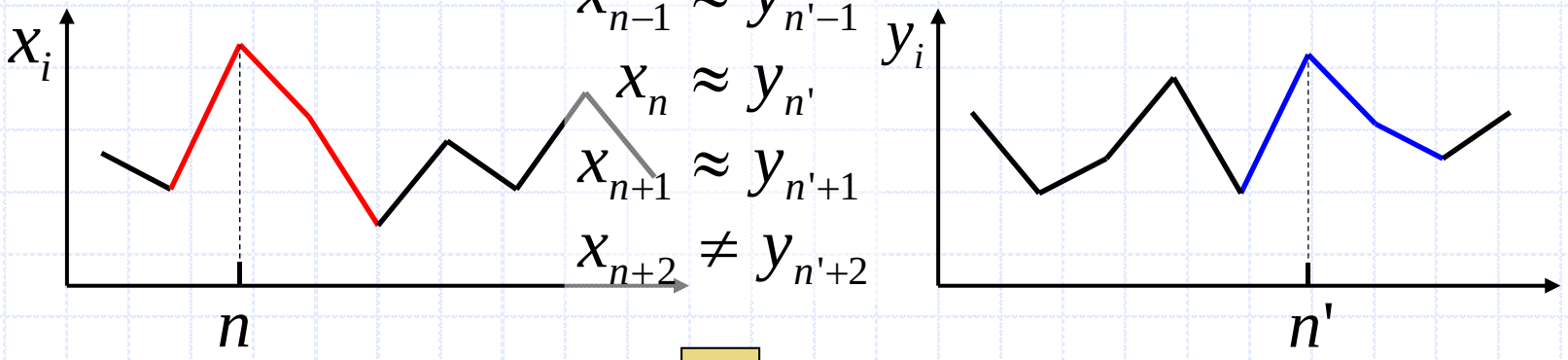
ε : Radius $\quad i, j = 1,2,\ldots, N$

$$\%REC = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} D_{ij}}{N^2}$$



Frequency of close contacts

Relationship between time history and attractor

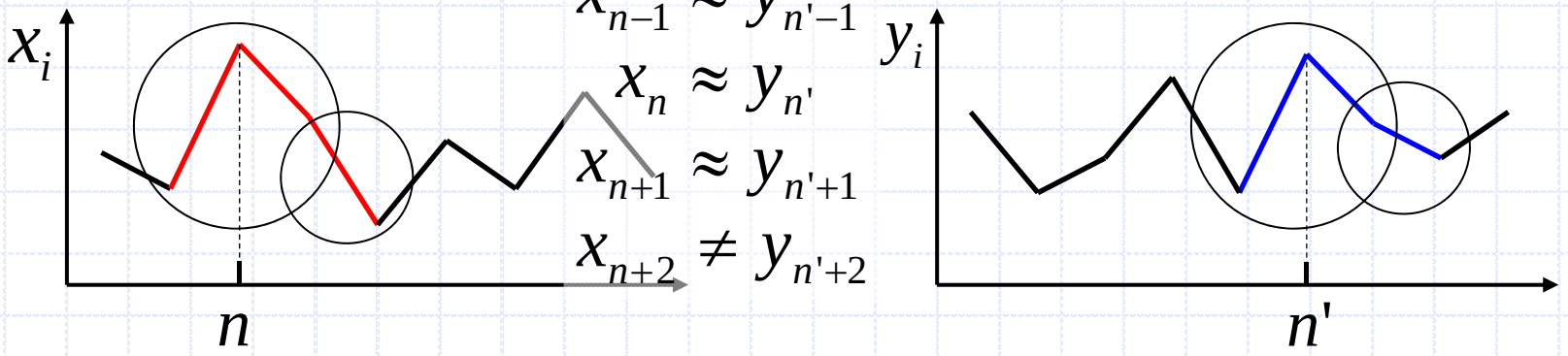


$$x_{n-1} \approx y_{n'-1}$$
$$x_n \approx y_{n'}$$
$$x_{n+1} \approx y_{n'+1}$$
$$x_{n+2} \neq y_{n'+2}$$

$$\mathbf{x}_i = (x_i, x_{i+1})^T$$
$$\mathbf{y}_i = (y_i, y_{i+1})^T$$

$$\mathbf{x}_{n-1} \approx \mathbf{y}_{n'-1}$$
$$\mathbf{x}_n \approx \mathbf{y}_{n'}$$
$$\mathbf{x}_{n+1} \neq \mathbf{y}_{n'+1}$$

Relationship between time history and attractor



Similar pattern

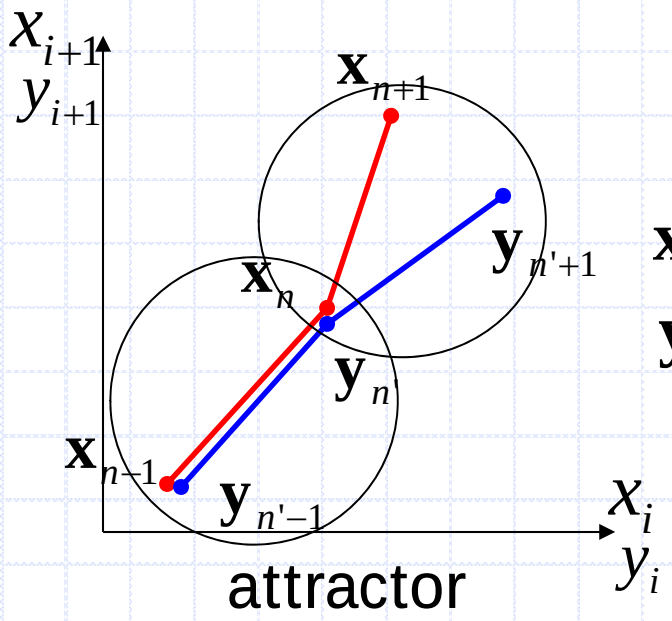
↓

Similar attractor

Dissimilar pattern

↓

Dissimilar attractor



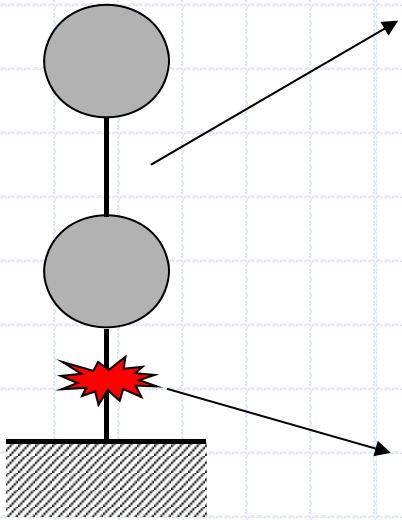
$$\mathbf{x}_i = (x_i, x_{i+1})^T$$
$$\mathbf{y}_i = (y_i, y_{i+1})^T$$

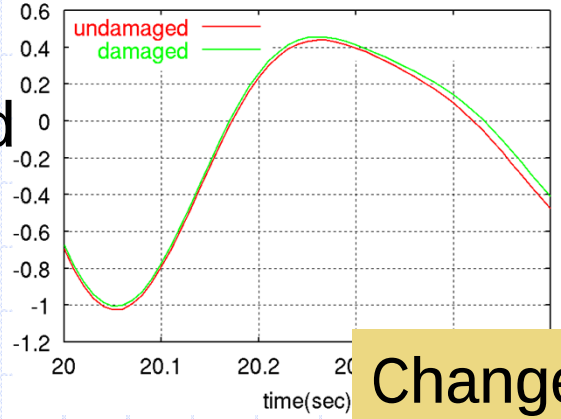
Mechanism of attractor-based damage detection

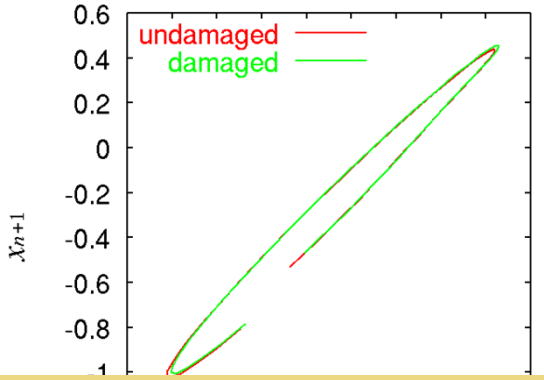
Time history

Attractor

undamaged

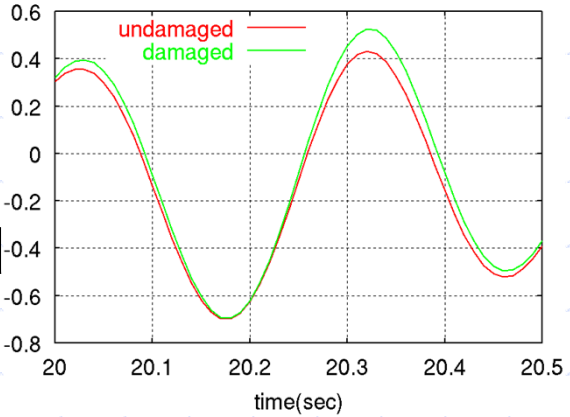


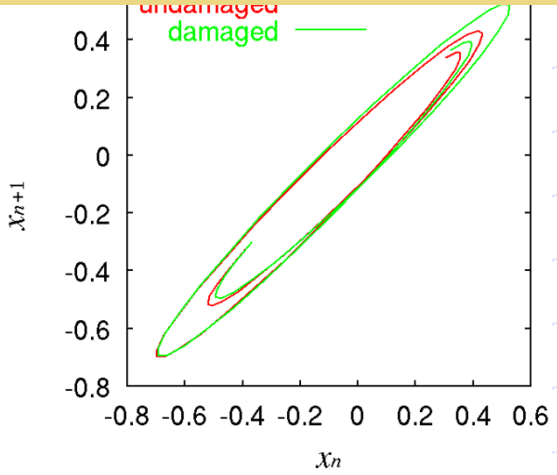




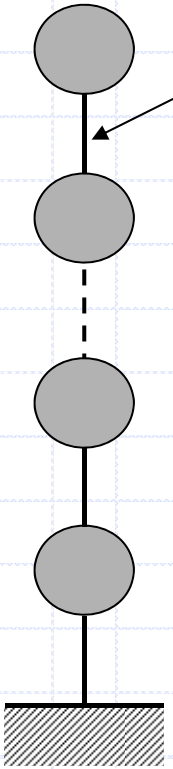
Change of attractor develops at damage parts

damaged





Damage Detection Algorithm



Response of healthy structure → Base data

Response of damaged structure → Test data

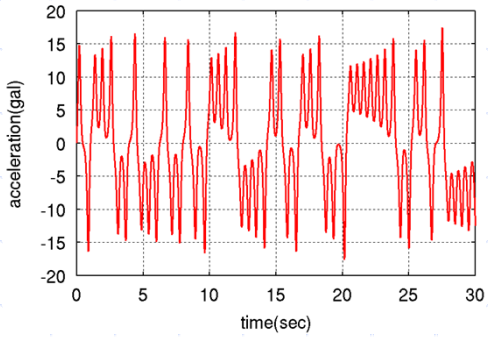
$$\%REC_{ratio} = \frac{\%REC_{Test}}{\%REC_{Base}}$$

$\%REC_{Base}$: $\%REC$ between the same two Base data

$\%REC_{Test}$: $\%REC$ between Base and Test data

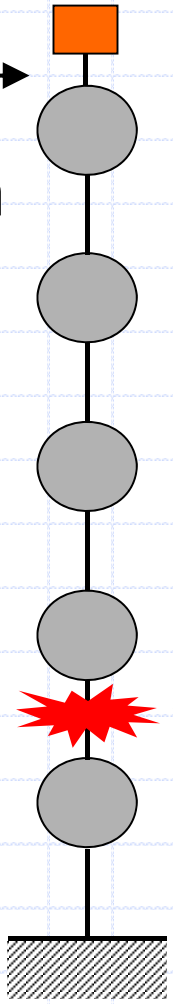
$\%REC_{ratio} < 1$ ⇒ Damaged

Numerical Example



x

Relative acceleration



$$m_{oscillator} = 0.01 \times m_{node}$$

10% white noise on input and response

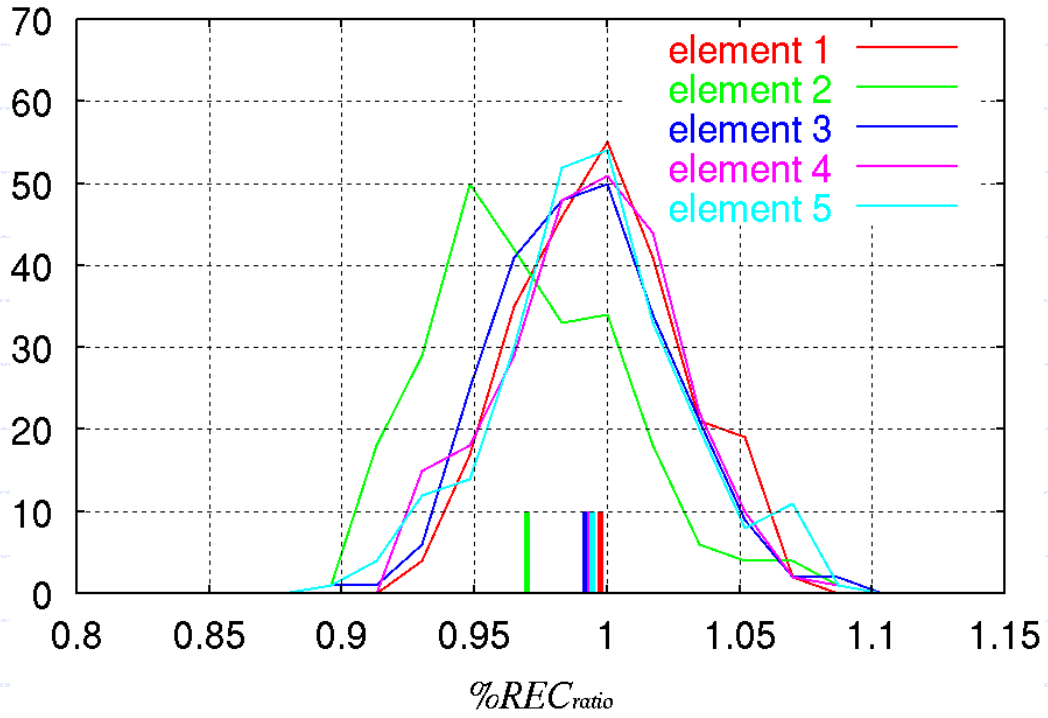
1.0% decrease of stiffness

Lorenz model

$$\begin{cases} \dfrac{dx}{dt} = -\sigma(x-y) \\ \dfrac{dy}{dt} = -xz + \gamma x - y \\ \dfrac{dz}{dt} = xy - bz \end{cases}$$

Result

We computed many $\%REC_{ratio}$ to improve reliability.

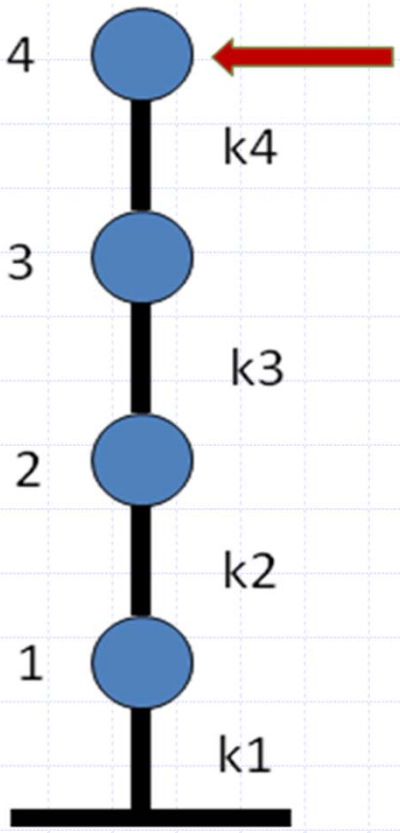


Histogram and mean value of $\%REC_{ratio}$ for each element

Structural Parameter Identification by Kalman Filter

- With the attractor, miner structural deterioration can be easily detected.
- However, such deterioration can hardly be quantified and evaluated.
- Kalman Filter is used to identify the structural parameters, and the evaluate the structural deterioration using all nodes observation data

Simulation



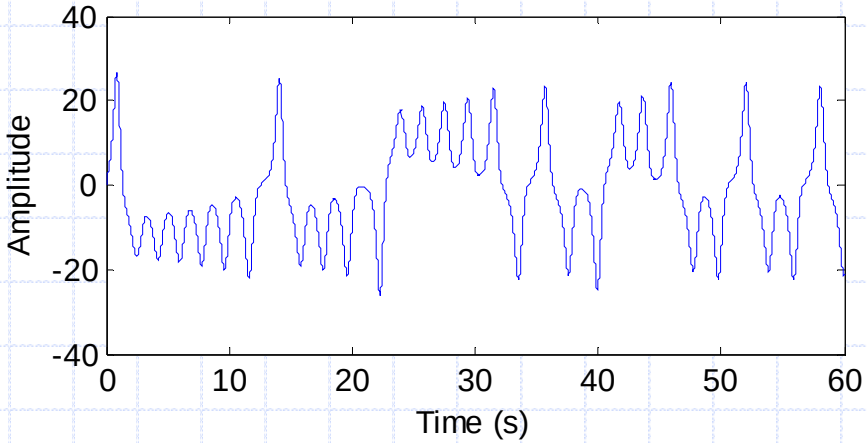
External chaotic force

M=100Kg

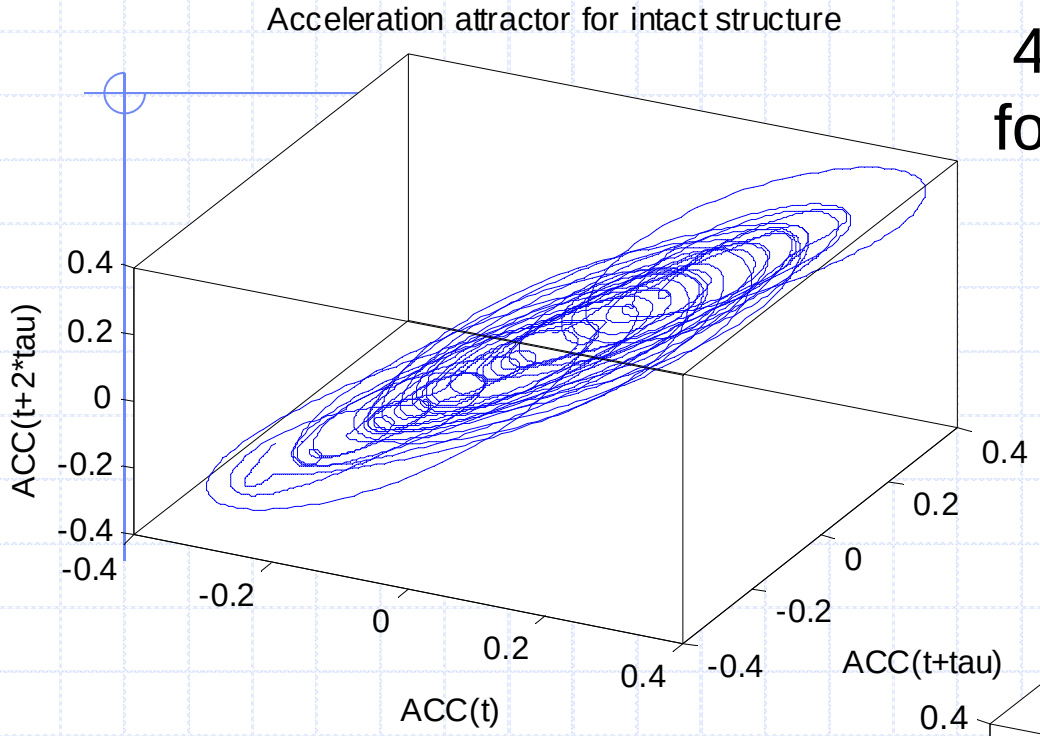
K=1000N/m

DR=0.03

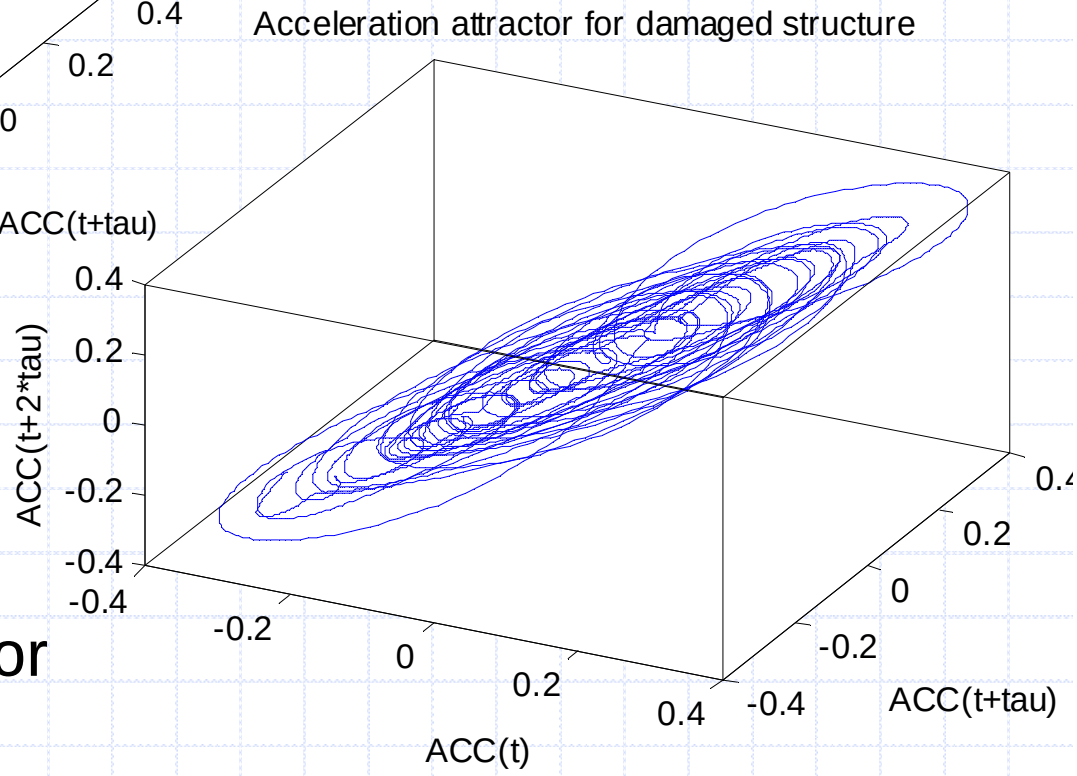
Input chaotic force



Reconstructed attractor

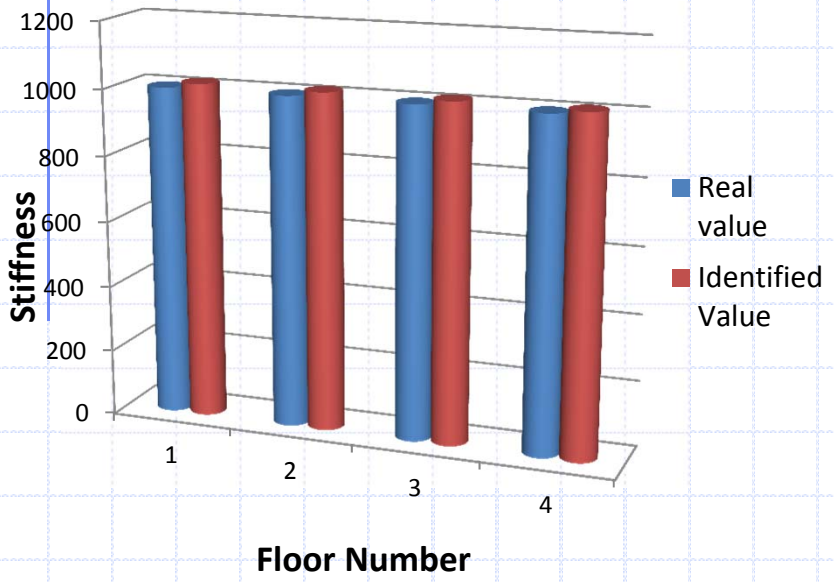


4th floor acceleration attractor for intact structure.

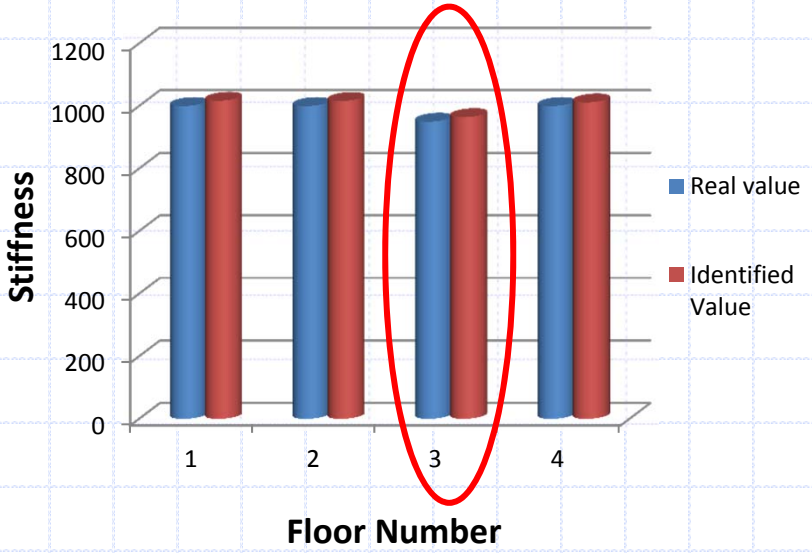


4th floor acceleration attractor for damaged structure.

Parameter Identification



Intact Structure



5% Stiffness Reduction at 3rd Floor

On Going Experiment

- Exciter can generate chaotic signal
- A 4 stories frame model structure

Conclusion

- We developed a damage detection method using chaotic excitation.
  - Damage indicator based on Recurrence Analysis.
  - Detect damage by comparing the indicator between healthy and damaged structures.
- The robustness against noise and sensitivity to minor damage was shown through a numerical example.
- Identification of deterioration of structural parameters using Kalman filter
- On going experiment

Thank you very much