Memorial Session of Prof. Shinozuka, APSSRA2020
Tokyo, Japan, 7 October, 2020

Memories of Professor Shinozuka: System Identification and SHM

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Memories of Professor Shinozuka

The 1st Comp. Stoch. Mech. Conf. (CSMC), Corfu, 1991

APSSRA, Seoul, 2004

ICOSSAR, Rome, 2005

CSMC6, Rhodes, 2010

Prof. Shinozuka: A Great Teacher and Researcher

1. **Visionary and Pioneering Researches:**

   Emerging Technologies:

   Computational Stochastic Mech., Simulation of Random Fields, System Identification, Smart Sensors, SHM, Structural Control, …

   Global Issues:

   Lifeline System Safety for Earthquake, Disaster/Risk Management, Multi-disciplinary Issues such as Socio-economic Problems, …

2. **Caring Teaching: Graduate Advising and Mentoring:**

   Graduate Students, Post Doc, Innovative Subjects, Guidelines, Technical Writing, Mentoring Professional Career, …

3. **International Cooperation and Leadership:**

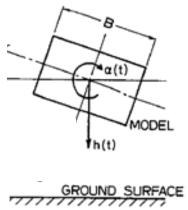
   Among the US, Japan, Europe, China, and Korea, Int'l Students, Visiting Scholars, ICOSSAR, APSSRA, J. of Prob. Eng. Mech., …

System Identification

Identification of Linear System

(My PhD Study under Prof. Shinozuka, at Columbia U.)

Akashi Suspension Bridge



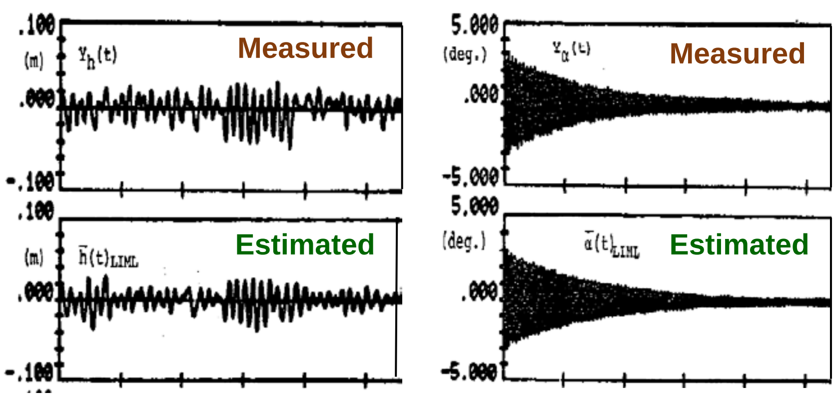
Large-scale Deck Model

Wind self-exciting forces:

$$F_{se}(t) = H_1\dot{h}(t) + H_2\dot{\alpha}(t) + H_3h(t) + H_4\alpha(t)$$
$$Q_{se}(t) = A_1\dot{h}(t) + A_2\dot{\alpha}(t) + A_3h(t) + A_4\alpha(t)$$

Eq. of Motion ⟺ *ARMAX Model*

Max. Likelihood Method for *ARMAX Parameters*



Sequential Prediction-Error Method

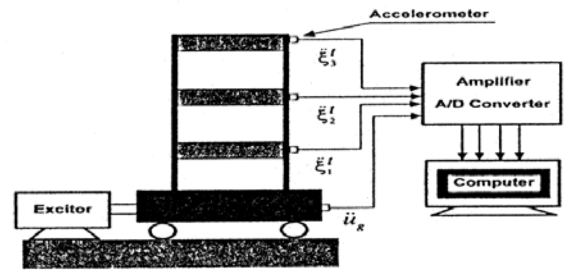
(CG Lee, HJ Lee, & CB Yun, KAIST)

-ARMAX Parameters: θ ⇒ *K & C*

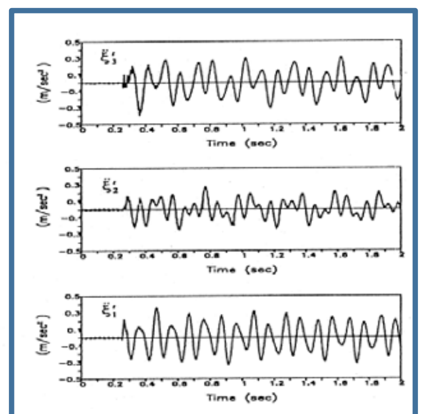
-Observation: Floor Accelerations

SPEM for Parameters, θ(k)

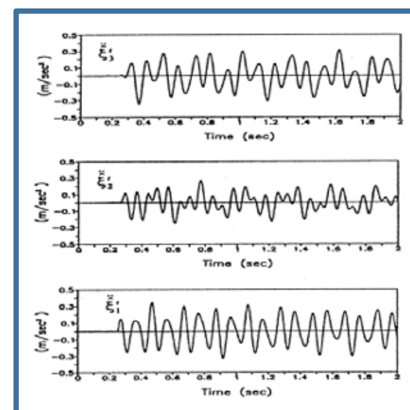
$$\hat{\theta}_{k+1} = \hat{\theta}_k + B_{k+1}\Psi_k[Y_{k+1} - \hat{Y}_{k+1}(\hat{X}_{k+1/k+1}, \hat{\theta}_k)]$$



Measured Accel.



Estimated Accel.



Identification of Nonlinear System Using Extended Kalman Filter

Identification of Nonlinear System

(My PhD Study under Prof. Shinozuka, at Columbia U.)

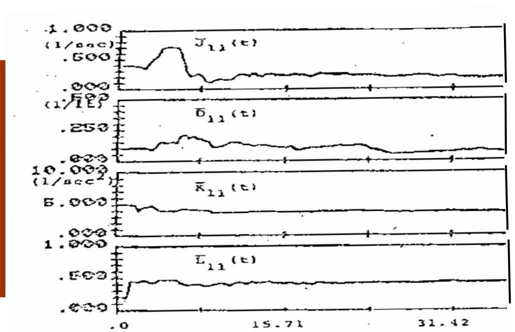
A fixed offshore tower and its model

Eq. of Motion for NL Wave Forces:

$$M_0\ddot{\xi}+C_0\dot{\xi}+K_0\xi=-M_a\ddot{\xi}+C_D\{(\dot{v}-\dot{\xi})\left|\dot{v}-\dot{\xi}\right|\}+C_M\ddot{v}$$

- -Augmented State *X* including *Parameters*
- -Extended Kalman Filter *(EKF)* for *X*

$$J=(M_0+M_a)^{-1}C_0$$
$$D=(M_0+M_a)^{-1}C_D$$
$$K=(M_0+M_a)^{-1}K_0$$
$$L=(M_0+M_a)^{-1}C_M$$



Estimated Parameters

Identification of Hysteretic System

(KJ Lee & CB Yun, KAIST)

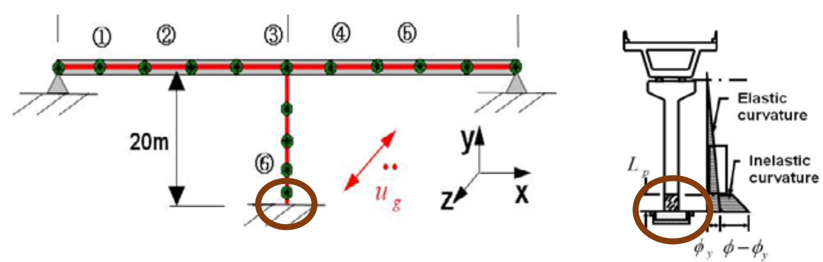
- -State *X by EXF*: Modal Responses
- -Observations *Y*: Accel. on Deck & Pier

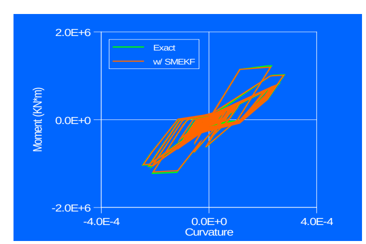
Extended Kalman Filter for State, X(k)

$$\hat{X}_{k+1/k+1}=\hat{X}_{k/k}+K_{k+1}[Y_{k+1}-\hat{Y}_{k+1}(\hat{X}_{k+1/k},\hat{\theta}_k)]$$

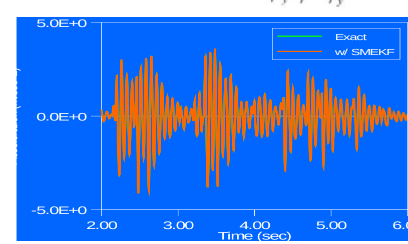
SPEM for Bouc-Wen Parameters, θ(k)

$$\hat{\theta}_{k+1}=\hat{\theta}_k+B_{k+1}\Psi_k[Y_{k+1}-\hat{Y}_{k+1}(\hat{X}_{k+1/k+1},\hat{\theta}_k)]$$





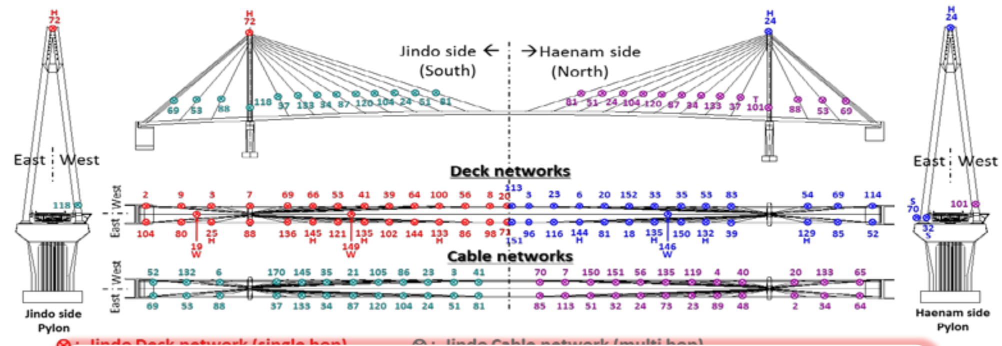
Estimated M-φ



Estimate Accel. at 6

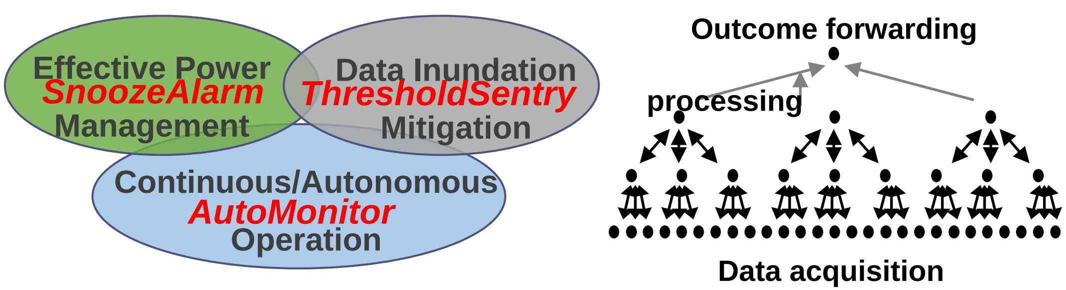
Smart Wireless Sensor Network for Bridge SHM

(US-Japan-Korea Project: BF Spencer, Y Fujino, HJ Jung, & CB Yun)

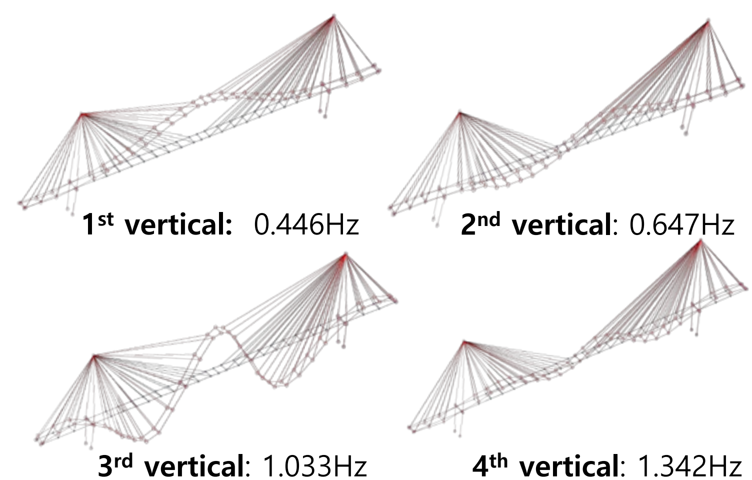


113 Sensor Nodes (339 channels)
(Cables: 48, Deck: 56, Pylons: 6, Wind: 3)

Smart Wireless Sensor Nodes (Imote2+SHM-A)



Power/Data Management



Identified Modes

SHM Activities at Zhejiang University, China

(YZ Luo & B Shen, Zhejiang Univ.)

Beijing Olympic Stadium (Bird's Nest)

Wireless Node for Strain & temperature

Hangzhou Olympic Sports Center

Shaoxin Stadium

SHM Center at CCEA, ZJU

Zhejiang Univ. Gymnasium

Hangzhou East Railway Station

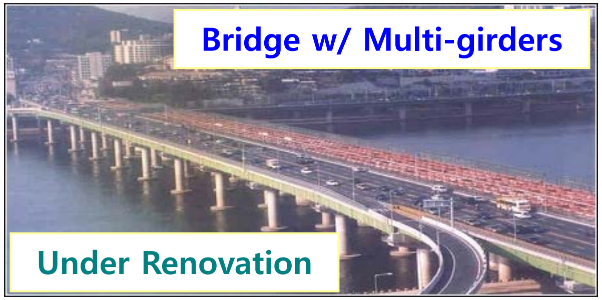
Shaoxing Stadium (Retractable Roof)

Chongqing Int'l Airport

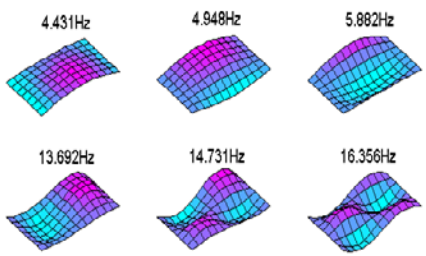
Damage Identification by Machine Learning

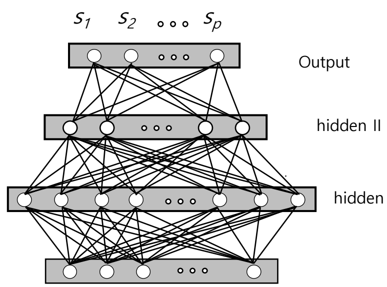
Damage Detection Using Ambient Vibration and *NN*

(JJ Lee, JW Lee, & CB Yun, KAIST)

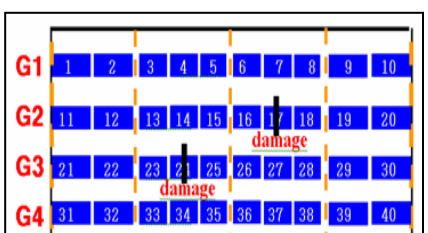


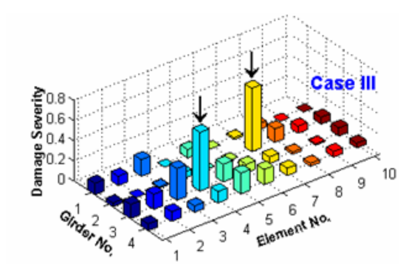
Inflicted Damage





Extracted Modes **Neural Networks**



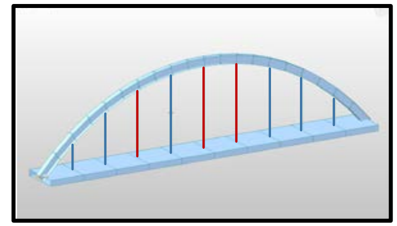


Identified Damage Locations & Severities

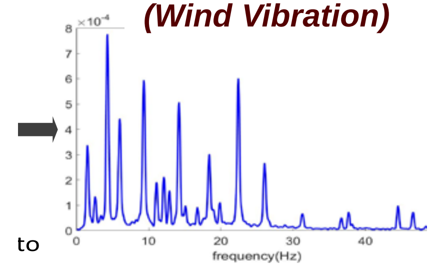
Bridge Hanger Monitoring Using Wind Vibration and *CNN*

(JJ Chen, YF Duan, & CB Yun, ZJU)

Tied-Arch Bridge



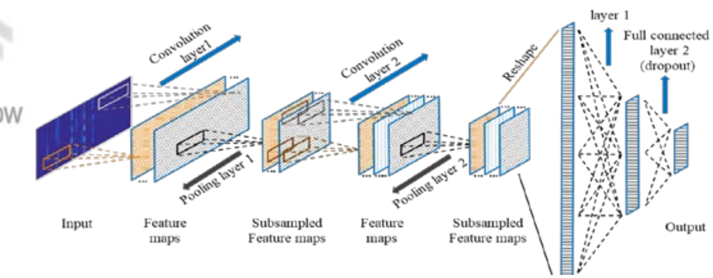
FA of Deck Responses *(Wind Vibration)*



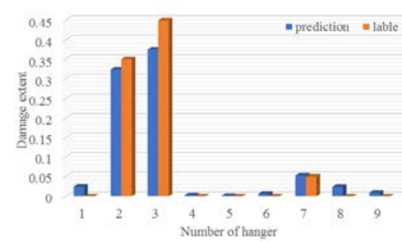
to

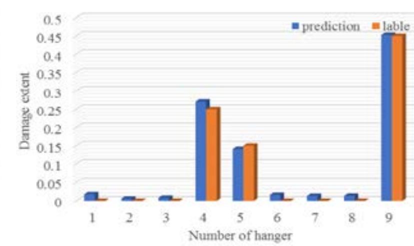
CNN-based Damage ID.

TensorFlow



Identified Damage

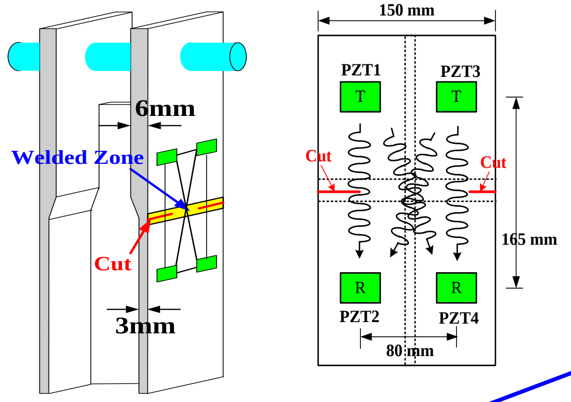


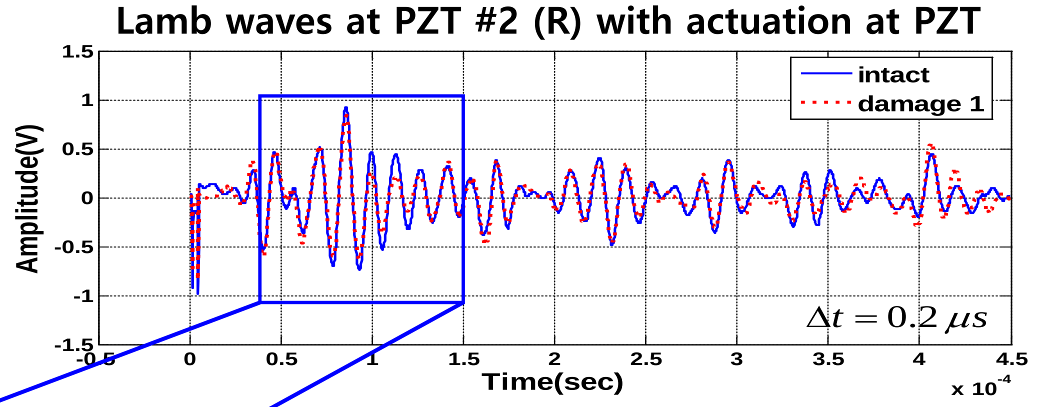


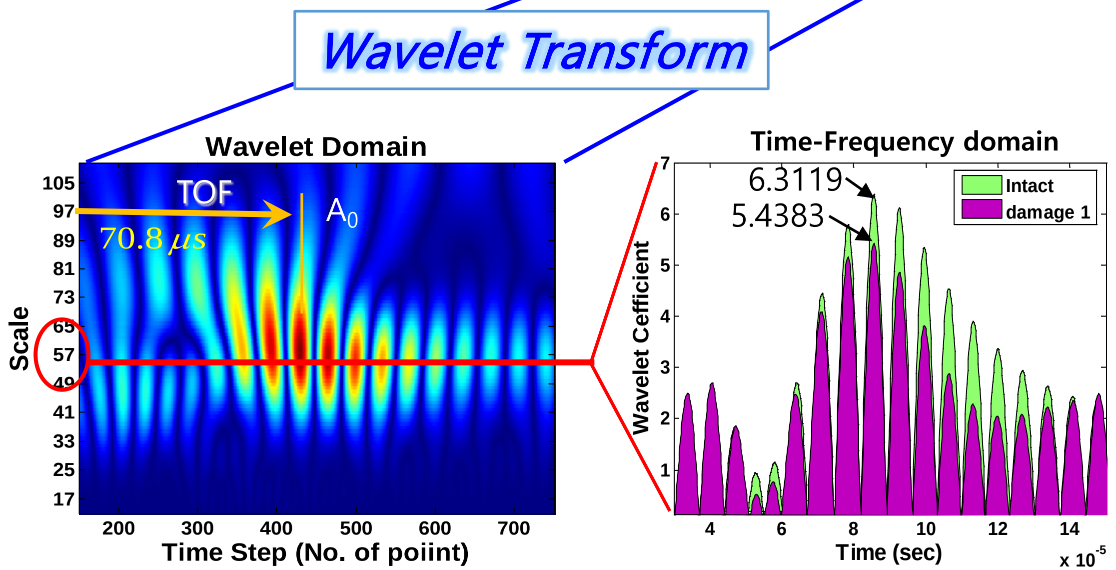
Guided Waves-based SHM Using Active Sensors

(SH Park & CB Yun, KAIST)

-Using Active Piezoelectric Sensors (Pitch-catch Mode)





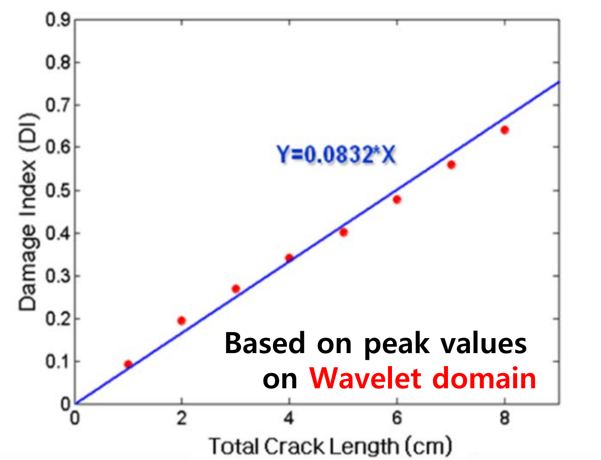


(At Central Frequency of 72kHz)

$$\mathrm{DI}(k) = \sqrt{\sum_{i=1}^{l} (C_i^d(k) - C_i^0)^2 \Big/ \sum_{i=1}^{l} (C_i^0)^2}$$

$l =$ No. of pitch-catch combination

$k =$ Damage step $(1, \cdots, 8)$

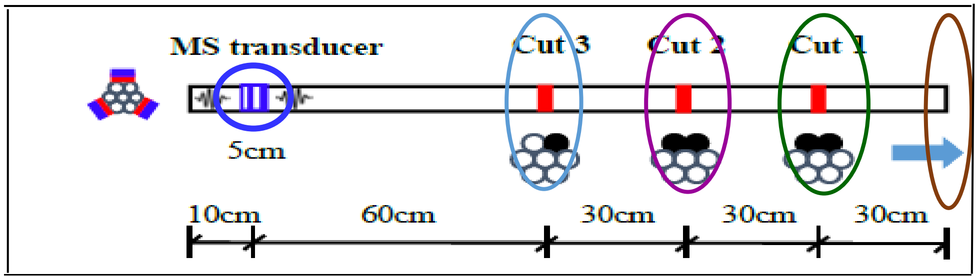


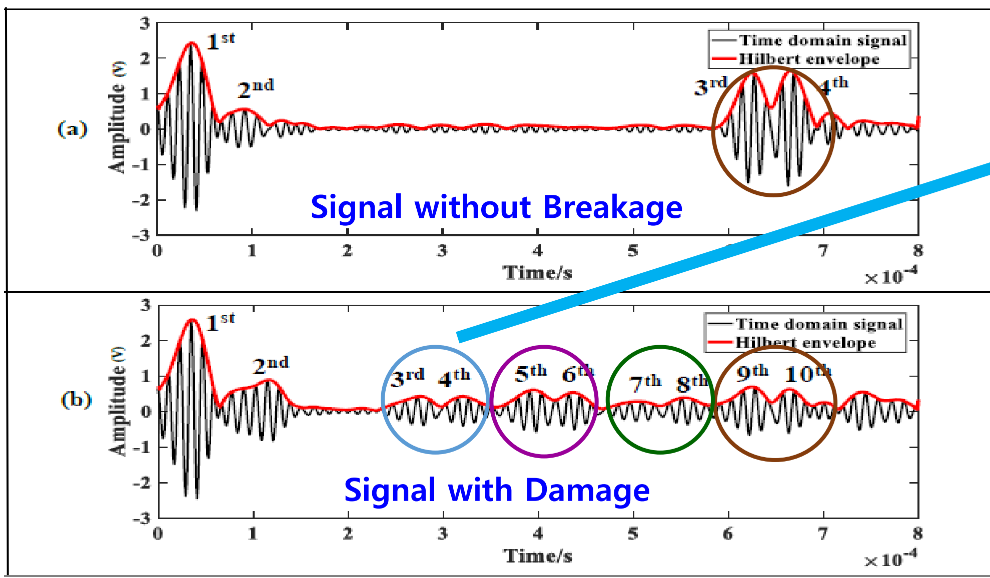
Based on peak values on Wavelet domain

Detection of Cable Wire Breakages Using MS Sensors

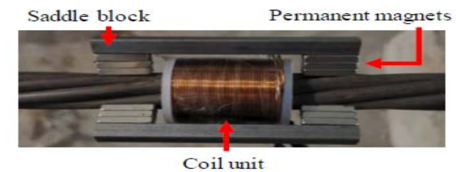
(XD Sui, ZF Tang, YF Duan, & CB Yun, ZJU)

Cable with Wire Breakages

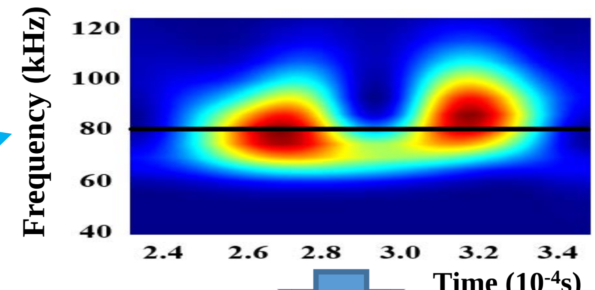


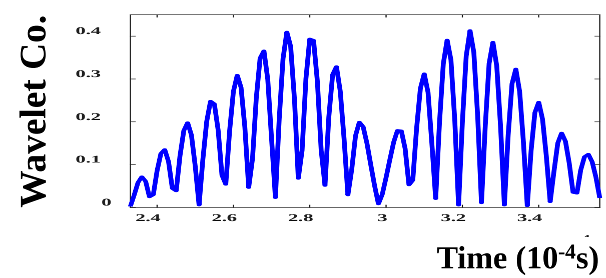


Magneto-strictive Sensors



Wavelet Transform
(3^{rd} & 4^{th} Packets)



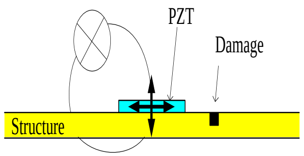


-Damage Locations: from the time of flight information.
-Severities: from the estimated wave energy transmission coefficients at damage.

Impedance-based SHM and Wireless Node

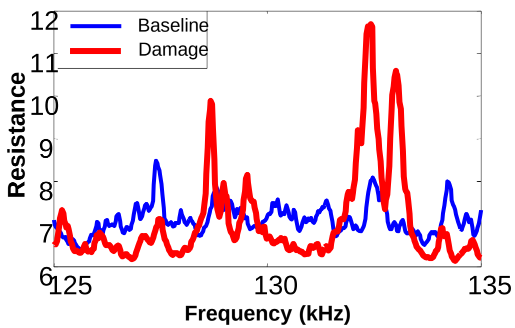
(SH Park, JY Min, & CB Yun, KAIST)

Electro-mechanical Impedance



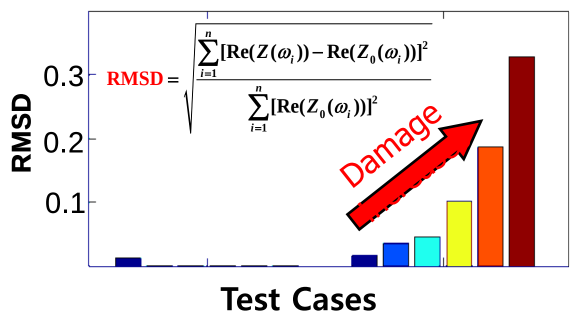
$$Z(\omega) = \underbrace{\mathrm{Re}[Z(\omega)]}_{\text{resistance}} + i\,\underbrace{\mathrm{Im}[Z(\omega)]}_{\text{reactance}} = \left[i\omega C \left(1 - \kappa_{31}^{2} \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} \right) \right]^{-1}$$

Impedance Signals

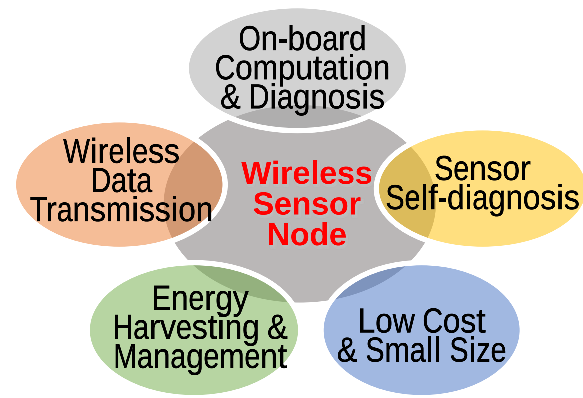


Damage Index: RMSD

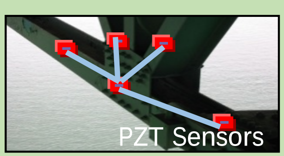
$$\mathrm{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}[\mathrm{Re}(Z(\omega_i)) - \mathrm{Re}(Z_0(\omega_i))]^2}{\sum_{i=1}^{n}[\mathrm{Re}(Z_0(\omega_i))]^2}}$$

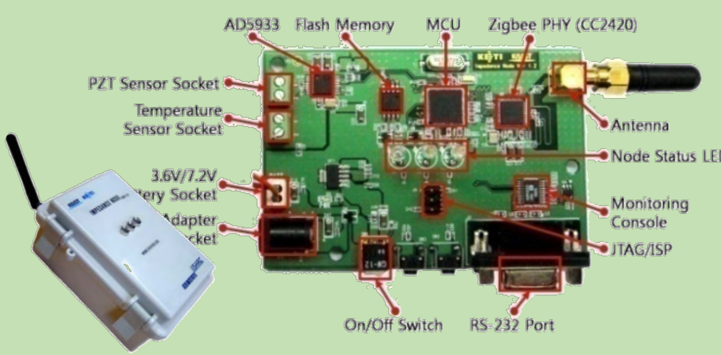


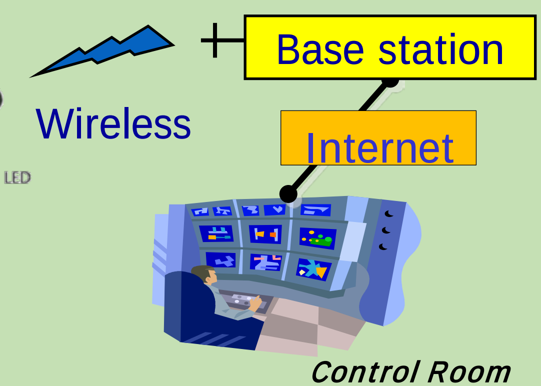
Multi-functional WISN



Wireless Impedance Sensor Node *(WISN, KAIST & Cytroniq)*



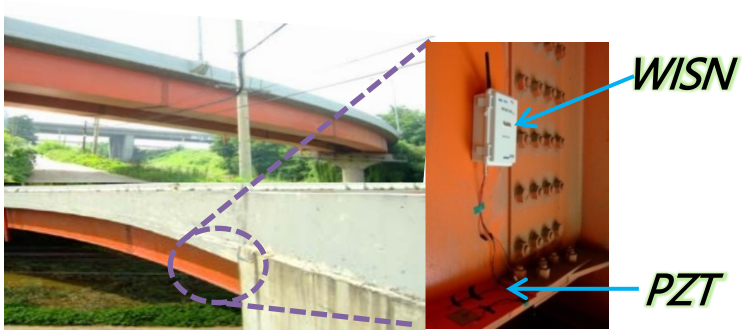


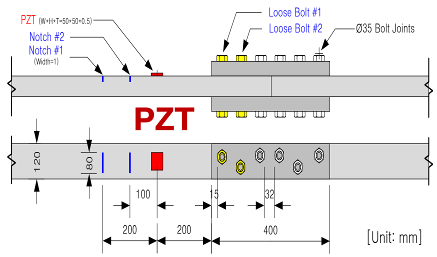


Impedance-based SHM for a Bolt Joint Using NN

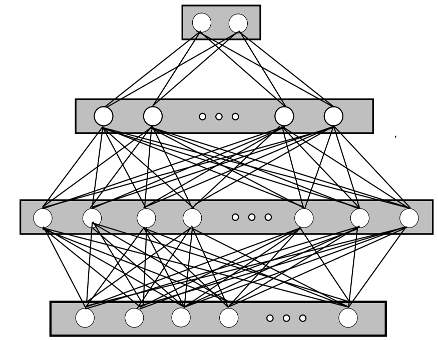
(JY Min, SH Park, & CB Yun, KAIST)

❖ **Diagnosis by Autonomous Frequency Segment Selection**





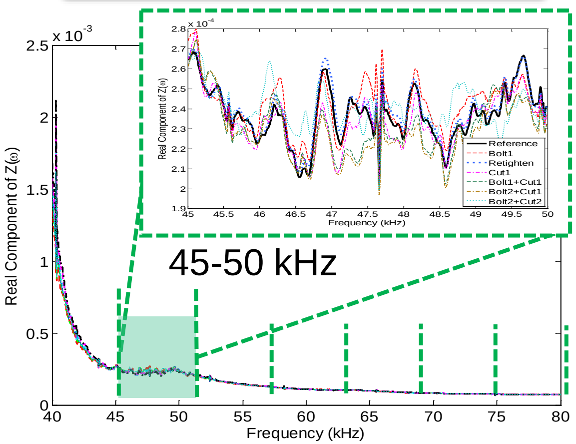
Damage Type & Severity



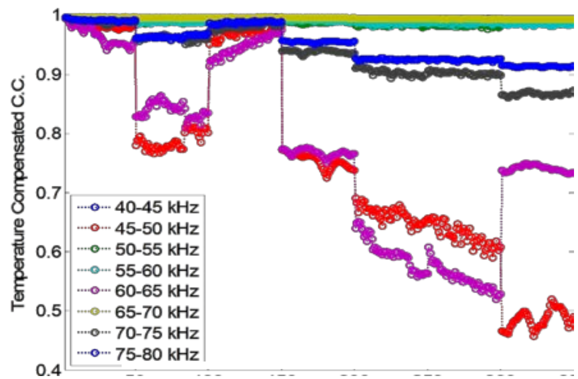
CC Values in 8 Frequency Ranges

❖ *Impedance Signals and CC-DI for Various Freq. Segments*

Impedance for Single Freq. Ranges (45-50 kHz)



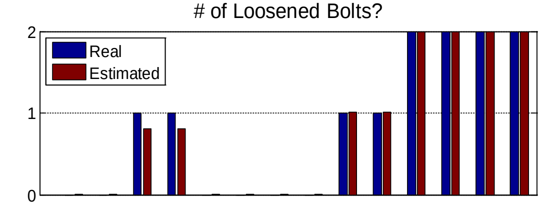
DI for Various Freq. Ranges (40-80 kHz)



350 Training Patterns

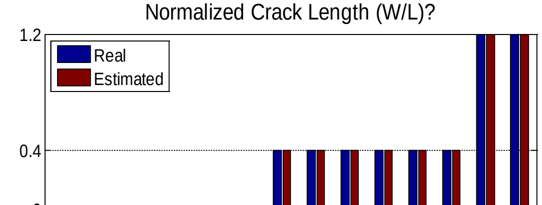
Loose Bolts Detection

\# of Loosened Bolts?



Crack Detection

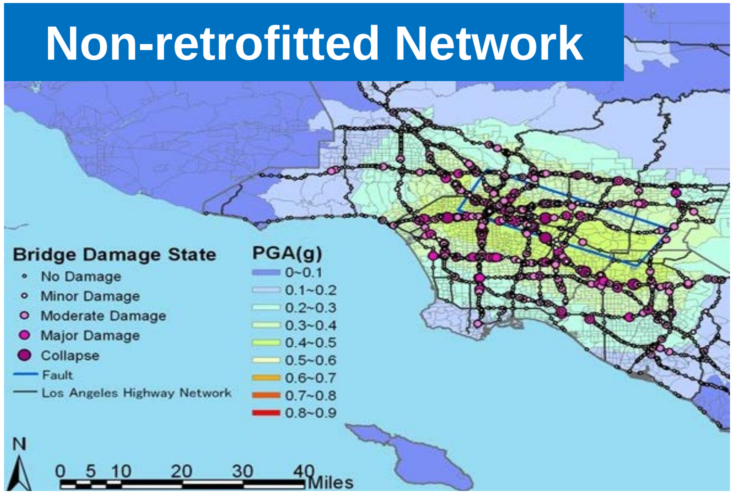
Normalized Crack Length (W/L)?

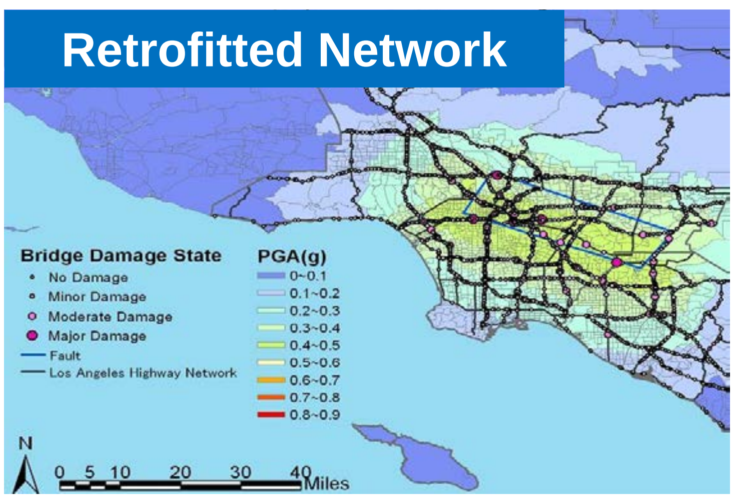


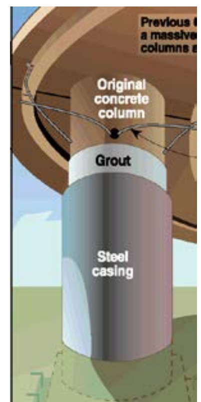
Social Cost Analysis Related to Bridge Retrofit

(Profs Shinozuka and Feng, UCI)

Bridge Damage States







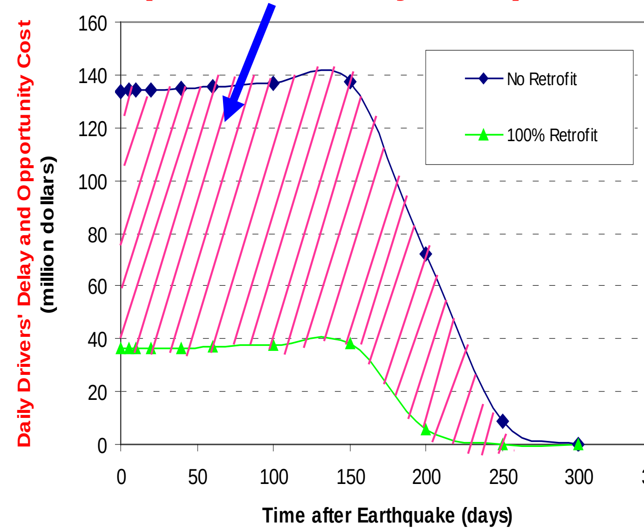
Steel Jacket

Social Cost Analysis

(Over the restoration period: 10 Months)

Social Cost Avoided = Shaded Area

(Drivers' Delay Cost)



Socio-economic Impact Analysis

➡ Disaster/risk Management Policy

My Whole-Hearted Gratitude to Prof. Shinozuka

for his Great Teaching and Guidance throughout my Career

and my Best Wishes for his Eternal Peace in the Heaven!!