Vehicle Assisted Bridge Health Monitoring

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Outline

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  - Nonlinear characteristics of bridges under moving vehicles
  - Vehicle-bridge system identification
- Instrumented vehicle--the vehicle as a moving sensor
  - Drive-by modal shape extraction using SSI
  - Adaptive signal decomposition for drive-by modal identification
  - Drive-by bridge damage identification using dual Kalman filter
- Summary

Vehicle assisted Bridge Health Monitoring

Monitoring Requirements of medium-span Bridges

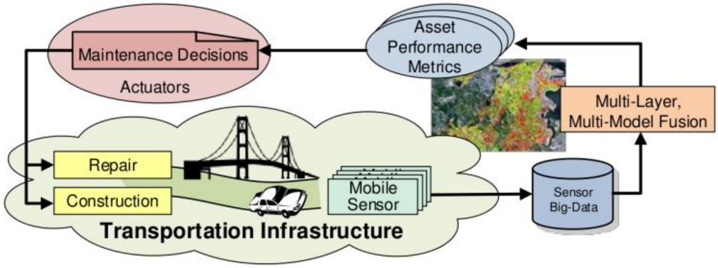
- Large stock of bridge structures—the monitoring should be a technically simple process
- Cost of implementation—should not be a labour intensive process
- Minimum disturbance to traffic—rapid measurement process
- Short-term monitoring—no permanent installed sensors
- To have a sufficient description on the damage for Engineers to make the decision—the type of the damage, residue of the prestress etc.

To address the bridge safety problem:

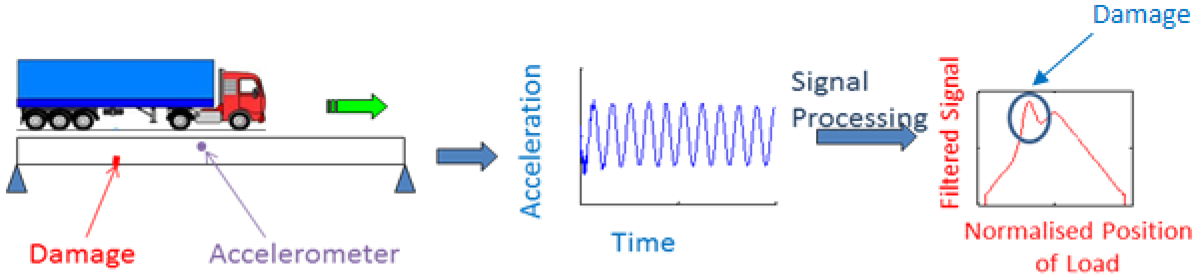
- the control of overloaded trucks
- the safety assessment/monitoring of bridges

Medium-span bridge structures

Transportation infrastructure monitoring



Vehicle assisted Bridge Health Monitoring

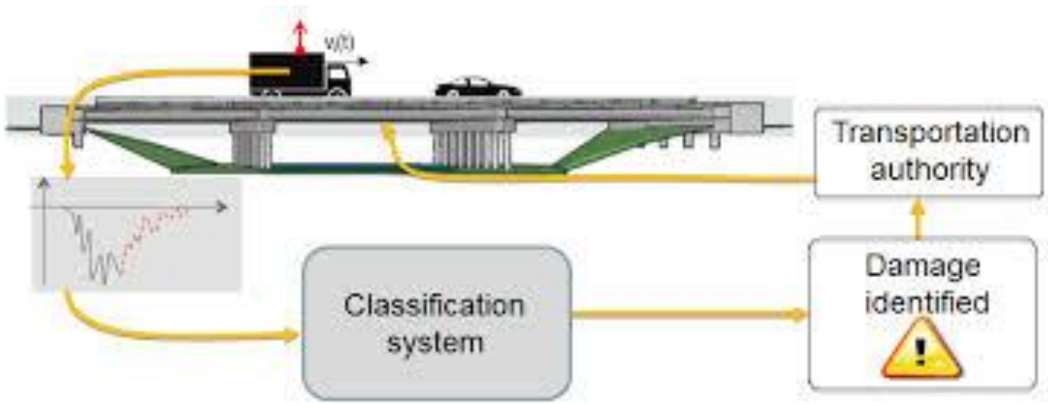


Instrumented bridge:

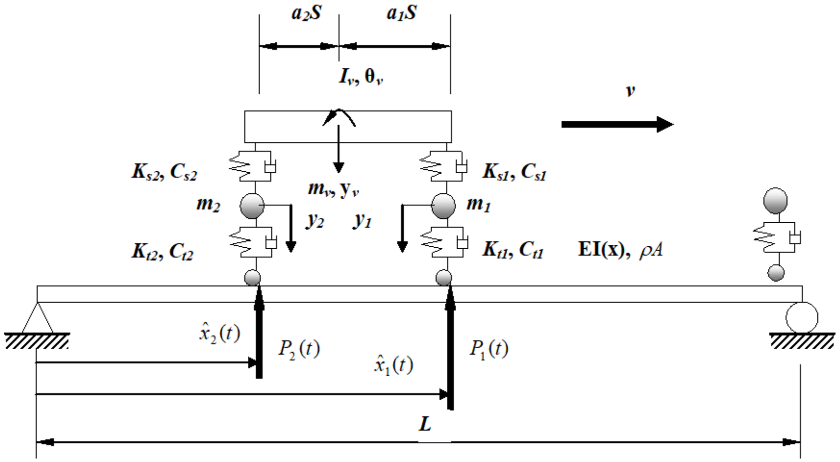
- The moving vehicle is a moving excitation.
- Bridge responses are monitored.
- Bridge condition assessment is based on bridge responses.
- A video-assisted approach could provide the traffic information.

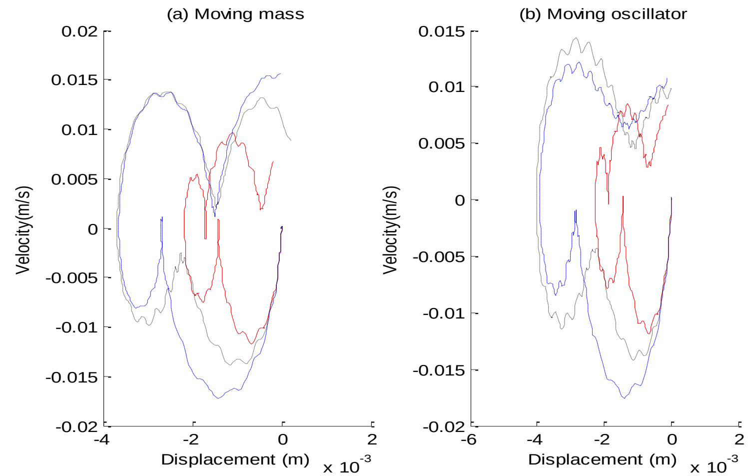
Instrumented vehicle:

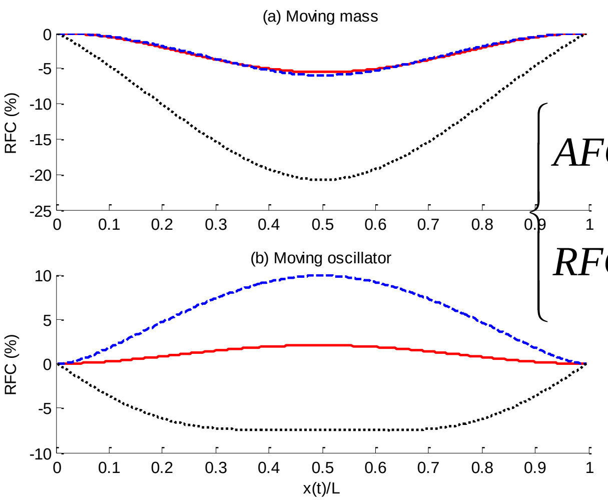
- The moving vehicle is a moving sensor to capture the bridge information.
- A passing vehicle to scan the bridge.
- A moving vehicle to catch the bridge response information.



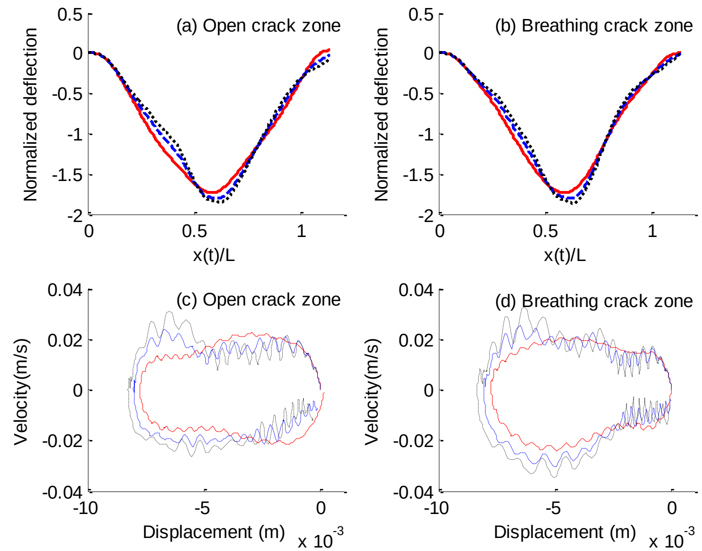
Nonlinear Characteristics of Concrete Bridge Structures under Moving Loads







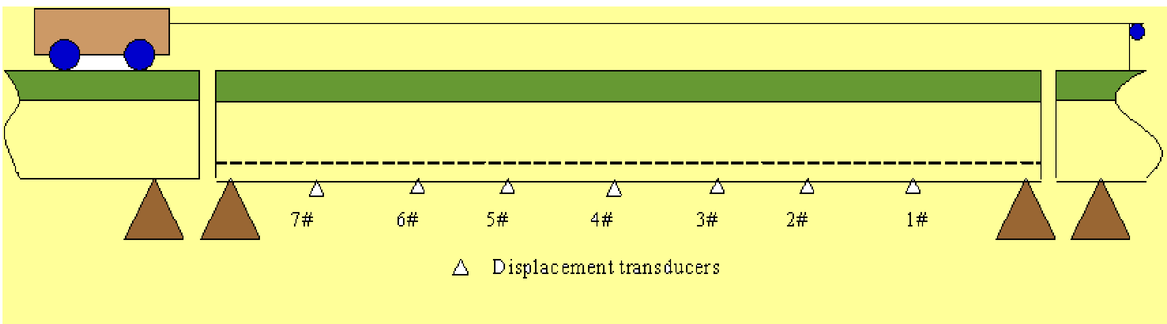
$$\begin{cases} AFC = \dfrac{\omega-\omega_n}{\omega_n}\times 100\% \\ RFC = \dfrac{\omega-\omega_0}{\omega_0}\times 100\% \end{cases}$$

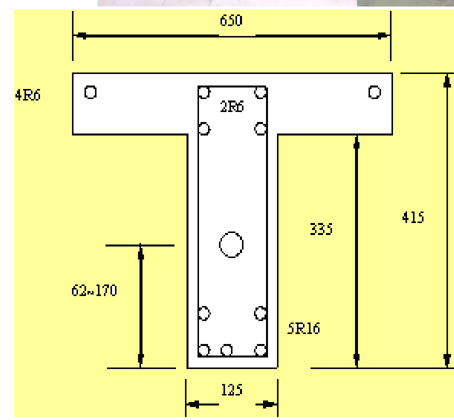


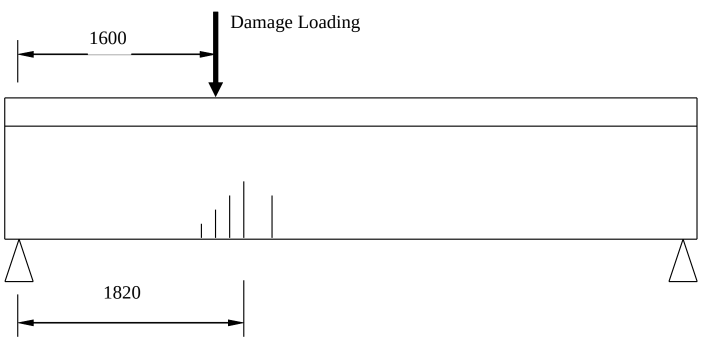
Note: S.S. Law and X.Q. Zhu (2004) "Dynamic behavior of damaged concrete bridge structures under moving vehicular loads ", Engineering Structures, 26(8), 1143-1153.

Experimental Setup

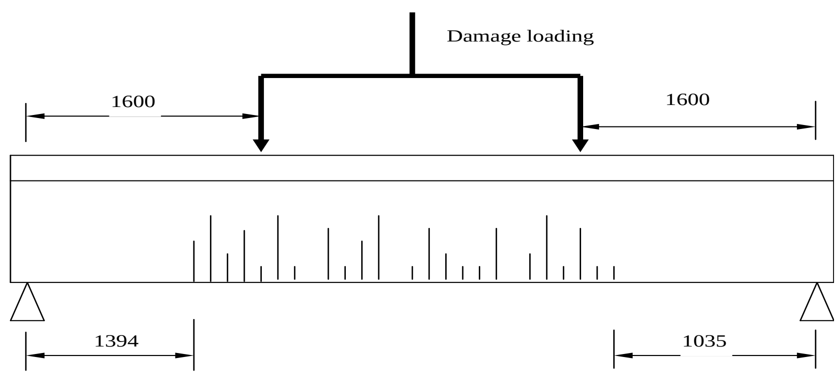
- Model car weighs 1060 kg.
- Axle spacing is 0.8 m.
- Reinforced concrete beam weighs 1050 kg.
- 5.0 m long main beam.
- 10mm gap between beams.





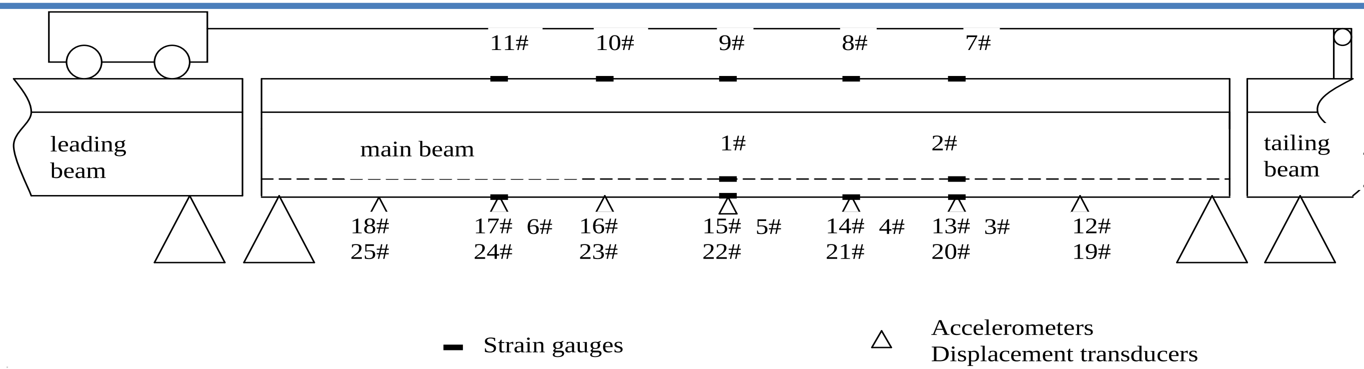


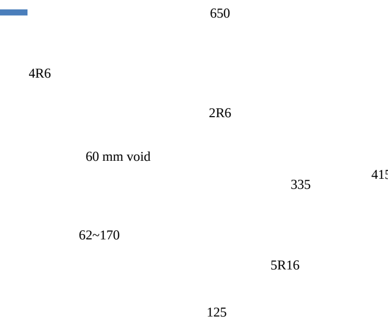
(a) A small damage zone

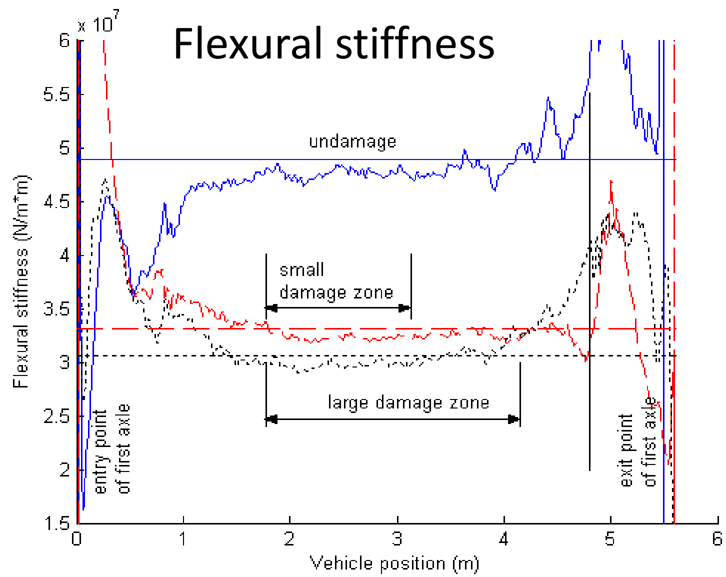


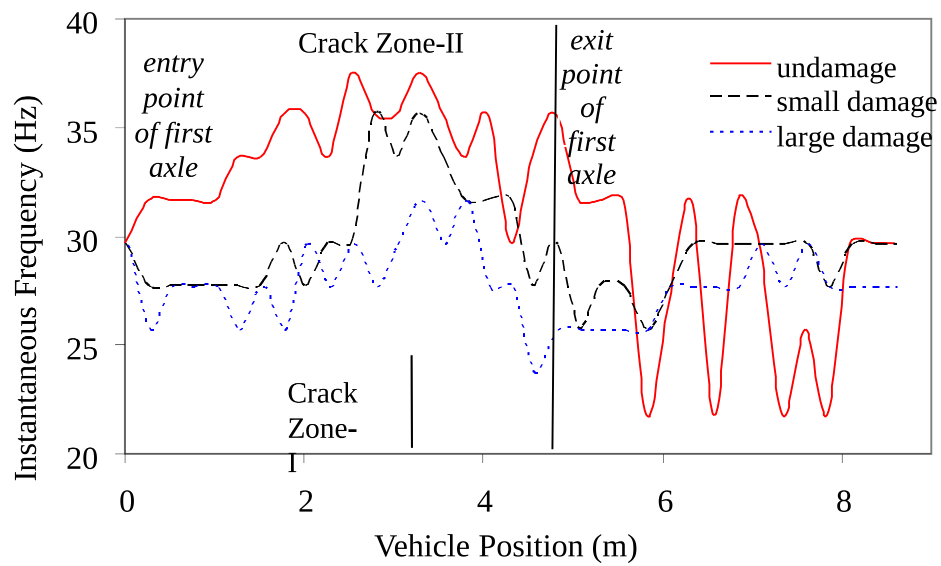
(b) A large damage zone

Nonlinear Characteristics of Concrete Bridge Structures under Moving Loads







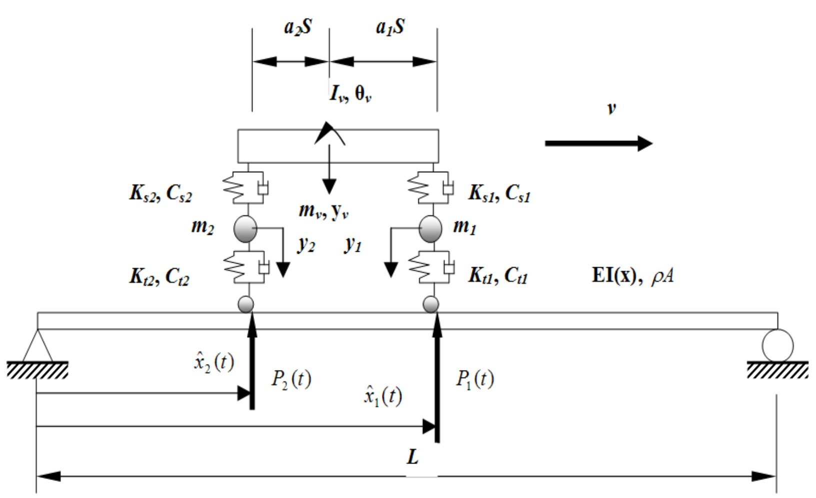


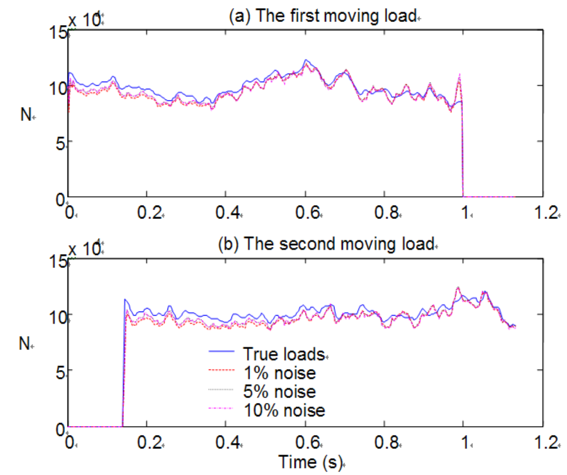
Frequency changes

$$EI_{eq} = \begin{cases} \dfrac{Pbx}{6Ly(x)}(x^2 - L^2 + b^2), & 0 < x < a \\ \dfrac{Pa(L-x)}{6Ly(x)}[(L-x)^2 - L^2 + a^2], & a < x < L \end{cases}$$

Note: Law S.S. and Zhu X.Q. (2005) “Nonlinear characteristics of damaged concrete bridge structures under vehicular loads.” *Journal of Structural Engineering ASCE*, 131(8), 1277-1285.

Iterative procedure for vehicle-bridge system identification





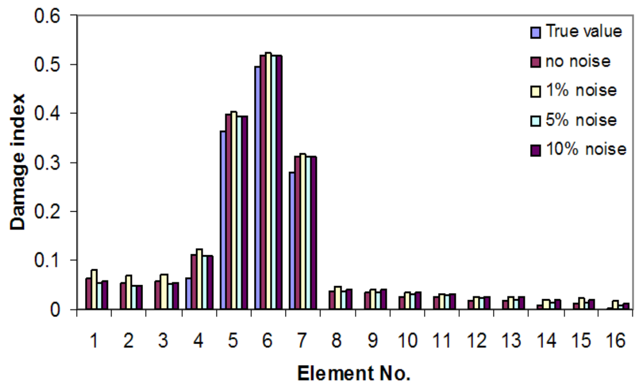
Moving load identification

- Moving load identification from bridge responses

$$J(P,\lambda) = \left\|\Phi P - U\right\|^2 + \lambda\left\|P\right\|^2$$

- Bridge condition assessment from bridge responses under moving vehicles

$$J(\boldsymbol{\alpha}) = \left\|F(\mathbf{u}) - f(\mathbf{u})\right\|^2$$

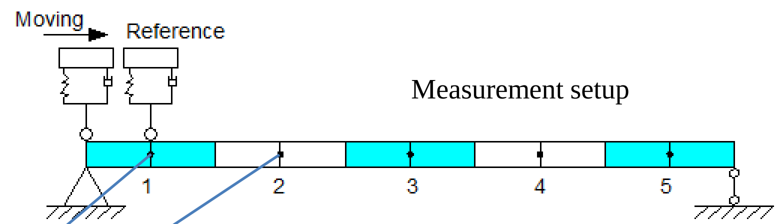


Note: X.Q. Zhu and S.S. Law (2007) “Damage detection in simply supported concrete bridge structure under moving vehicular loads”, Journal of Vibration and Acoustics ASME, 129, 58-65.

Damage detection using multiple sensors

Drive-by Bridge Modal Shape extraction using SSI

Two sensing vehicles are used: one is a fixed reference sensor, the other one is a moving sensor. Two sets of measurements are divided to form the multi-patch records according to the segmentation of the bridge.



Measurement setup

State space model

$$\mathbf{X}_{k+1} = \mathbf{A}\mathbf{X}_k + \mathbf{v}_k$$

$$\mathbf{Y}_k = \mathbf{H}_k\mathbf{X}_k + \mathbf{w}_k$$

Signal segmentation

$$\begin{cases} \mathbf{X}_{k+1}^{(j)} = \bar{\mathbf{A}}\mathbf{X}_k^{(j)} + \mathbf{V}_k^{(j)} \\ \mathbf{Y}_k^{(j,ref)} = \mathbf{H}^{(j,ref)}\mathbf{X}_k^{(j)} \\ \mathbf{Y}_k^{(j,mov)} = \mathbf{H}^{(j,mov)}\mathbf{X}_k^{(j)} \end{cases}$$

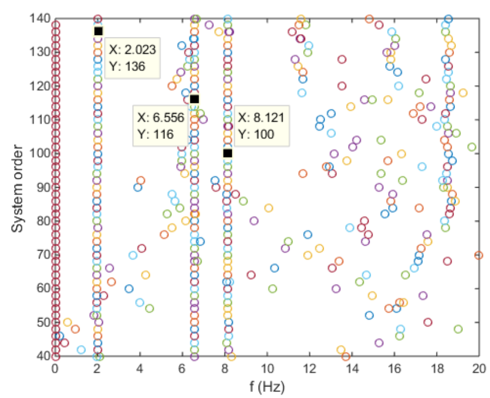
$$\mathbf{Y} = \left\{ \underbrace{\begin{pmatrix} \mathbf{Y}^{(1,ref)} \\ \mathbf{Y}^{(1,mov)} \end{pmatrix}}_{Record\ 1} \underbrace{\begin{pmatrix} \mathbf{Y}^{(2,ref)} \\ \mathbf{Y}^{(2,mov)} \end{pmatrix}}_{Record\ 2} \cdots \underbrace{\begin{pmatrix} \mathbf{Y}^{(j,ref)} \\ \mathbf{Y}^{(j,mov)} \end{pmatrix}}_{Record\ j} \underbrace{\begin{pmatrix} \mathbf{Y}^{(N,ref)} \\ \mathbf{Y}^{(N,mov)} \end{pmatrix}}_{Record} \right\}$$

Multipatch records

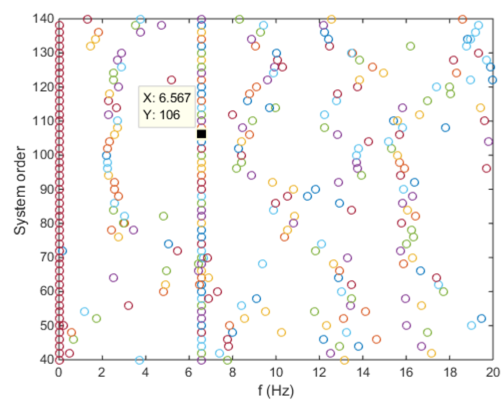
Rescale

$$\mathbf{\Phi}_j = \frac{\mathbf{\Phi}_{ref}}{\boldsymbol{\varphi}_{j,ref}} \boldsymbol{\varphi}_{j,j}, \qquad (j = 2,3,\cdots N)$$

Stabilization diagram



(a) Class A surface roughness



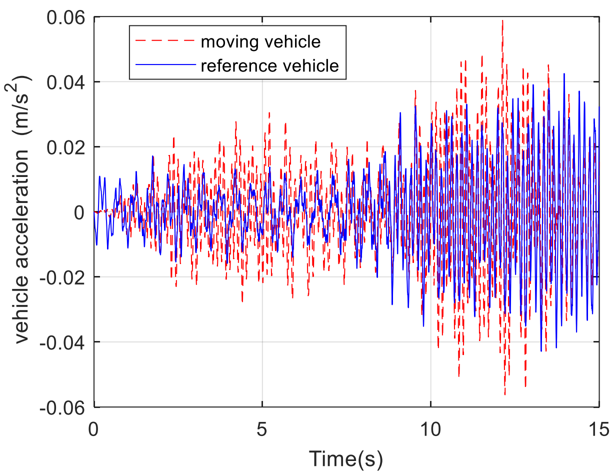
(b) Class B surface roughness

Note: J.T. Li, X.Q. Zhu, S.S. Law and B. Samali (2019) “Indirect bridge modal parameters identification with one stationary and one moving sensors and stochastic subspace identification”, Journal of Sound and Vibration, 446, 1-21.

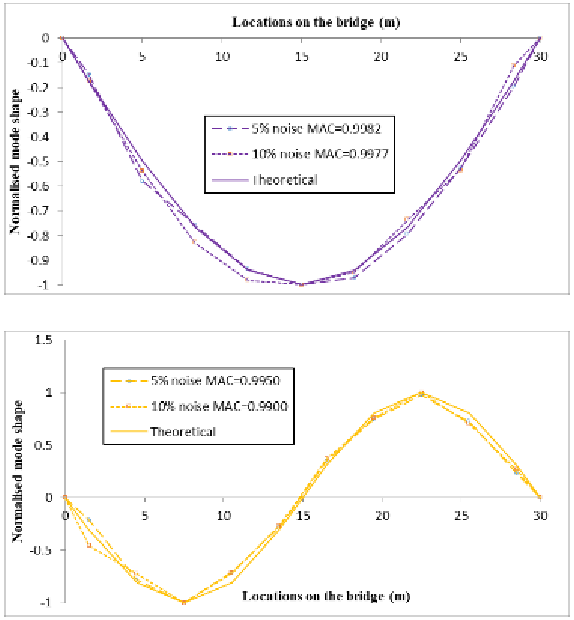
Drive-by Bridge Modal Shape extraction using SSI

Numerical results

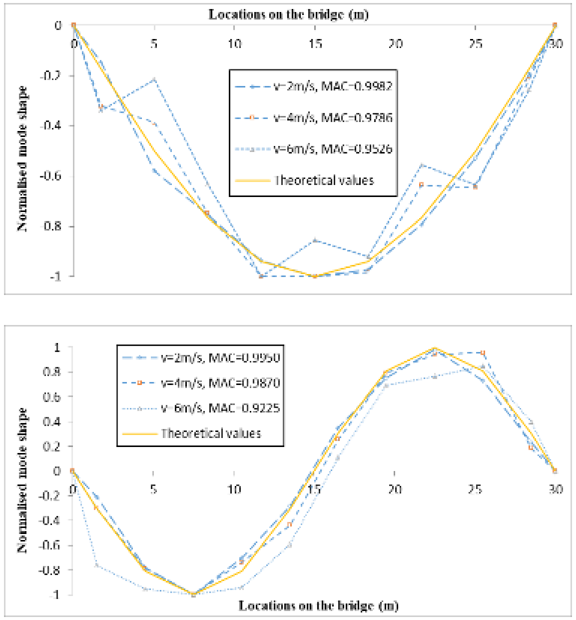
The parameters of the bridge: *L=30m, ρ=10700kg/m, I=0.494m4, E=29.43GPa*. The first three natural frequencies of the bridge are 2.03, 8.12 and 18.30 Hz, respectively. The properties for the vehicle are: *mv=100kg, kv=170kN/m*. The vehicle modal frequency is 6.50Hz. The moving speed of the vehicle is constant at *2m/s* and the time step is set as 0.001s in the simulation.



Responses from two sensors



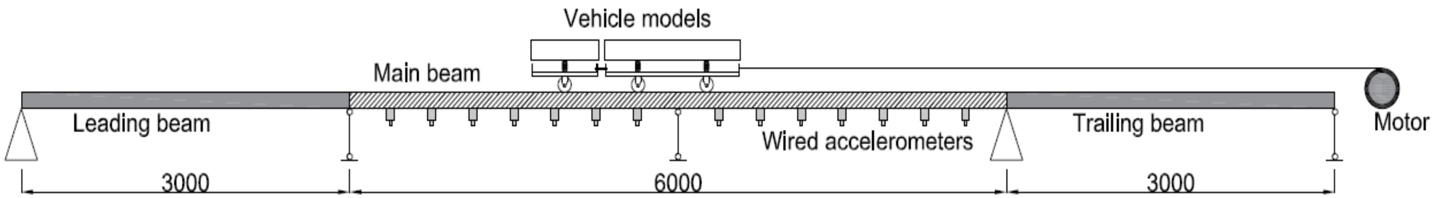
Identified first two modes considering different measurement noise



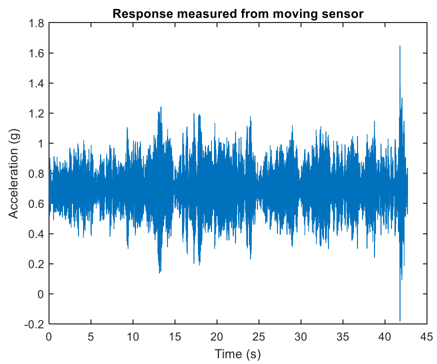
Identified first two modes considering different vehicle speeds

Drive-by Bridge Modal Shape extraction using SSI

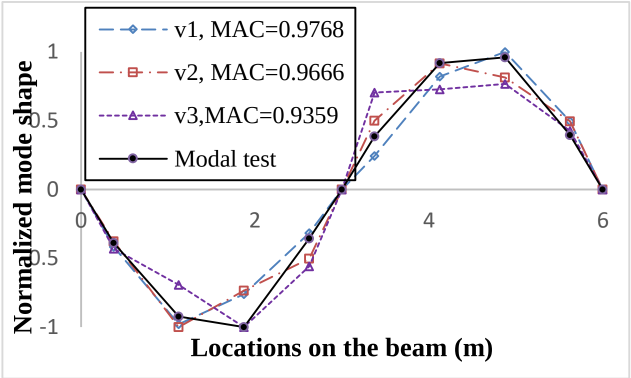
Experimental study



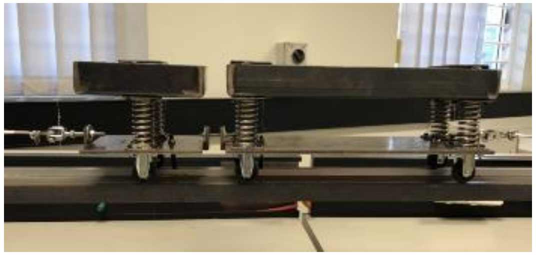
(a) The vehicle-bridge model



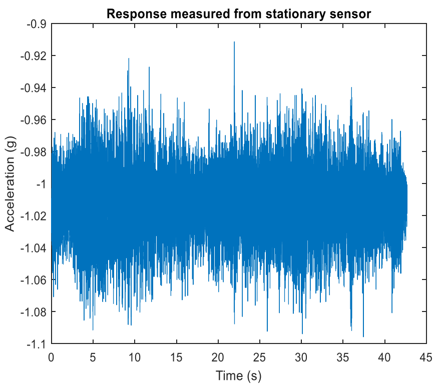
Response measured from moving sensor



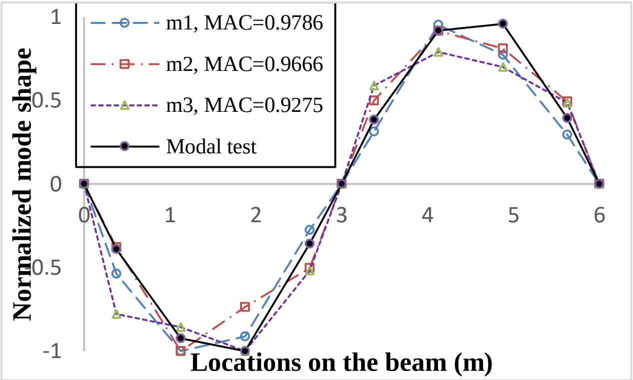
Identified mode shapes with different moving speeds



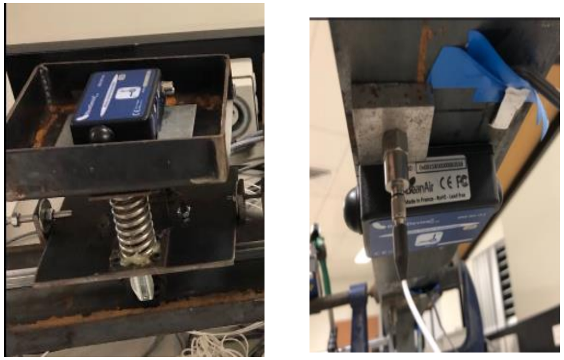
(b) Bridge model subjected to moving vehicles



Response measured from reference sensor

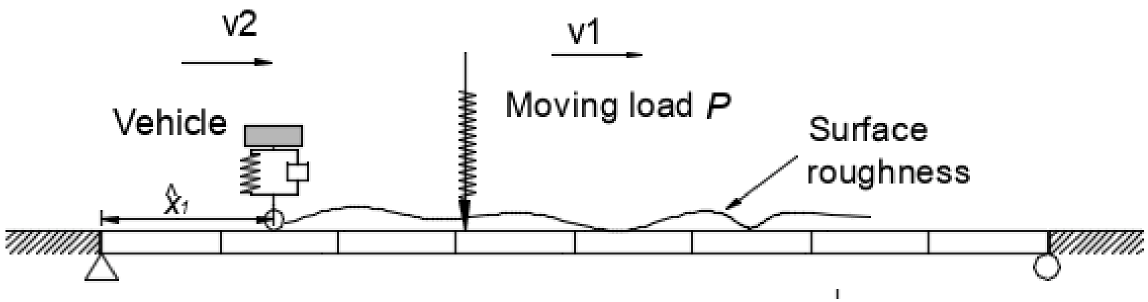


Identified mode shapes using vehicles with different weights



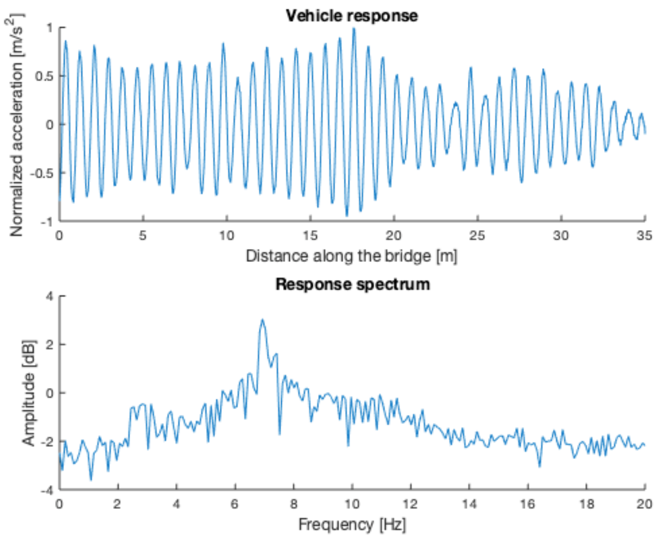
(c) Wireless sensors on the vehicle and bridge

Adaptive signal decomposition for drive-by bridge modal identification



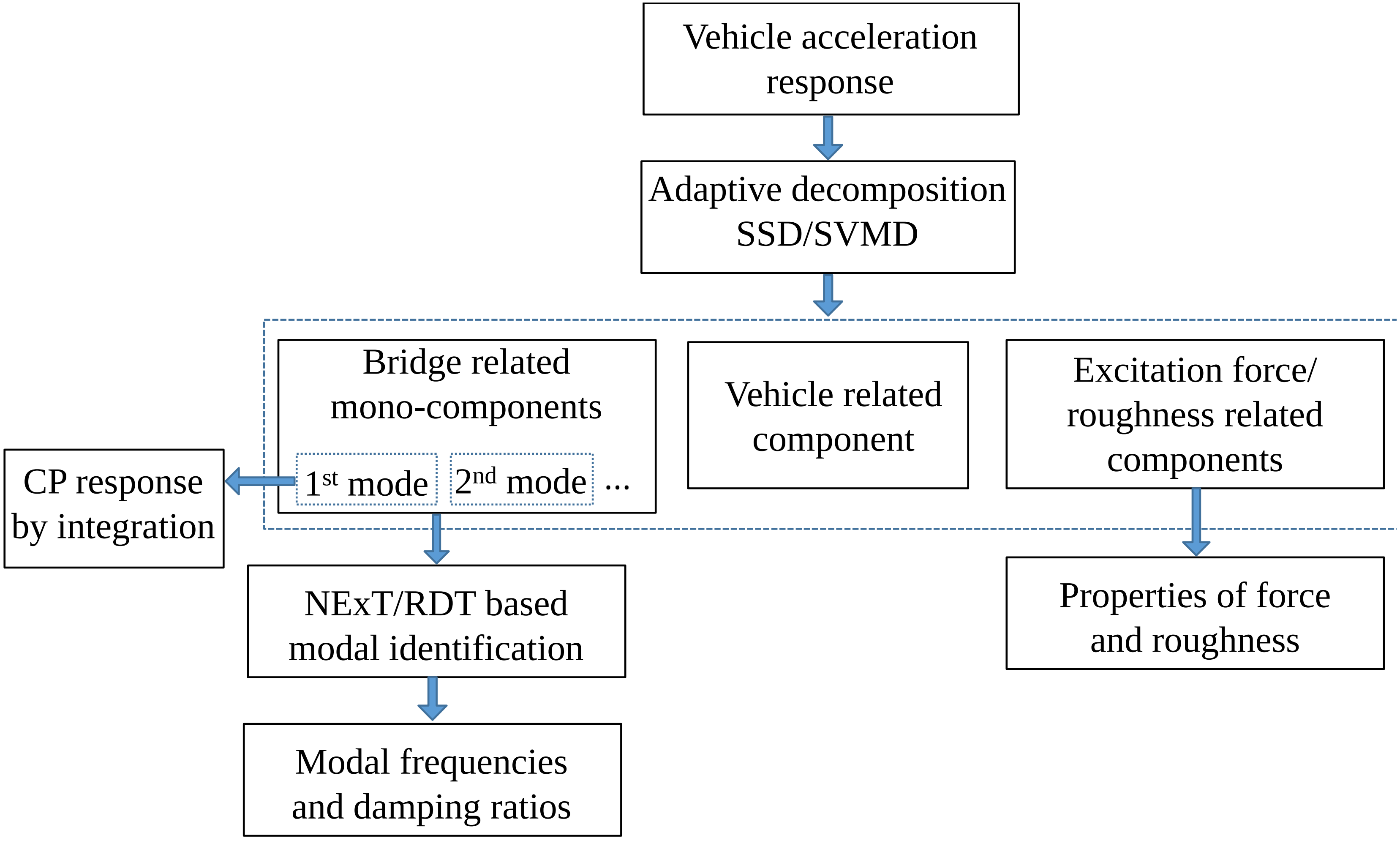
For a bridge subjected to a medium to large volume of random operational traffic, the spatio-temporal load pattern can be modelled as a random white noise and it is represented by the moving load P with a speed v1. The sensing vehicle is with a speed v2.

The vehicle response includes the bridge, vehicle and bridge surface roughness information. The big challenge is to separate those components to extract the bridge information.



Note: J.T. Li, X.Q. Zhu and J. Guo (2022) “Bridge modal identification based on successive variational mode decomposition using a moving test vehicle”, Advances in Structural Engineering, 25(11), 2284-2300.

Adaptive signal decomposition for drive-by bridge modal identification



Note:
SVMD—Successive variational mode decomposition; SSD—Singular spectrum decomposition; CP—contact point.

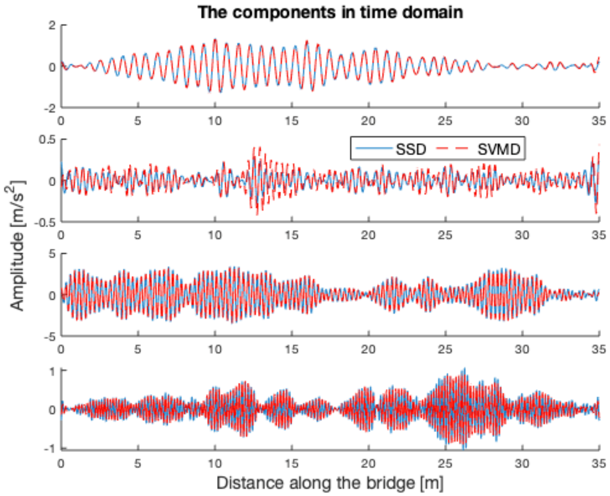
Numerical studies

Vehicle and bridge model parameters:

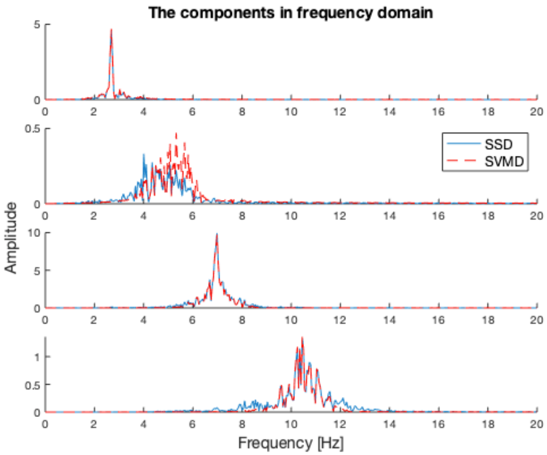
The parameters of the bridge: *L=35m, ρ=5000kg/m, EI=2.178e10Nm*^{2}. The first three natural frequencies of the bridge are 2.68, 10.71 and 24.09 Hz, respectively.

The properties for the vehicle are: m_v*=466.5kg*, k_v*=9.00e5N/m,* suspension damping c_s=0.14e3 N s/m and its fundamental frequency f_v is 6.99Hz.

The moving speed of the vehicle is constant at *2m/s* and the time step is set as 0.005s in the simulation. The Class A bridge surface roughness is used (ISO 8606).



In time domain



In frequency domain

Indirect Bridge Structural Health Monitoring

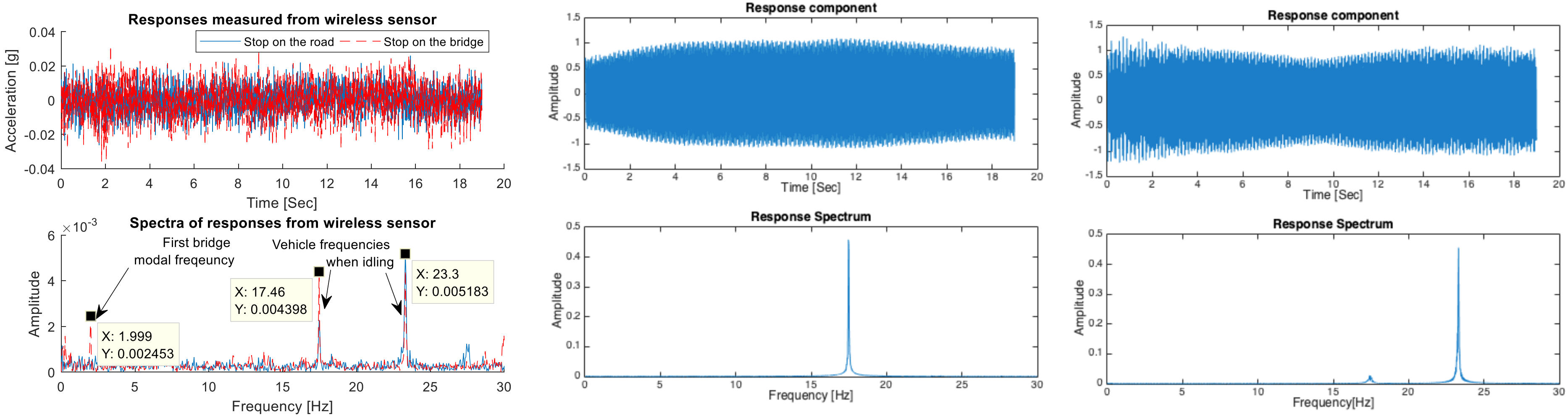
a cable-stayed bridge

By the modal testing, the first natural frequency of the bridge is 2.00Hz.

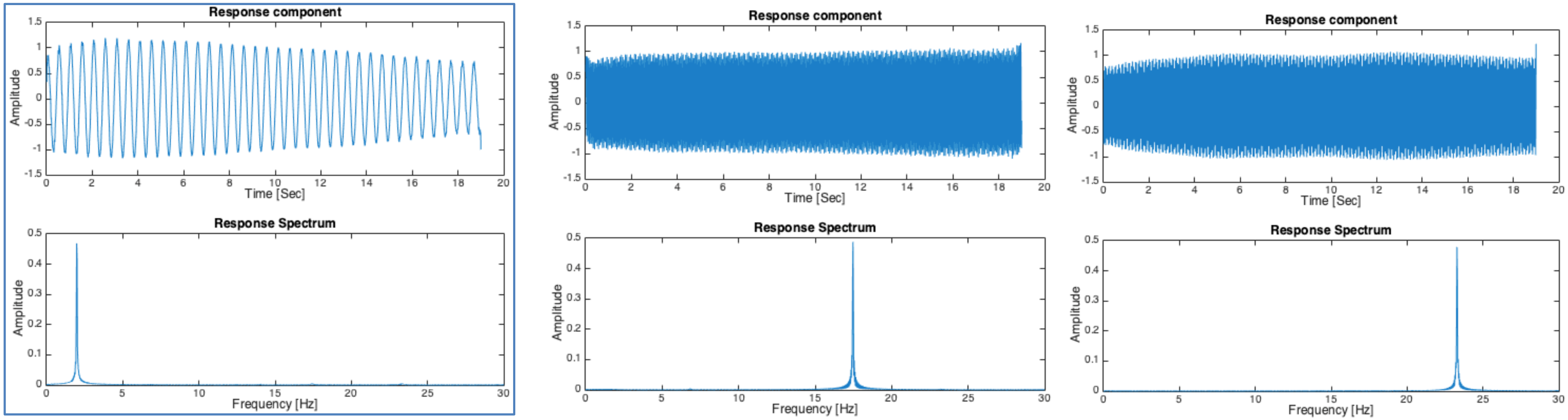
(a) Test vehicle

(a) Wireless sensor

Vehicle stop on the road and the bridge

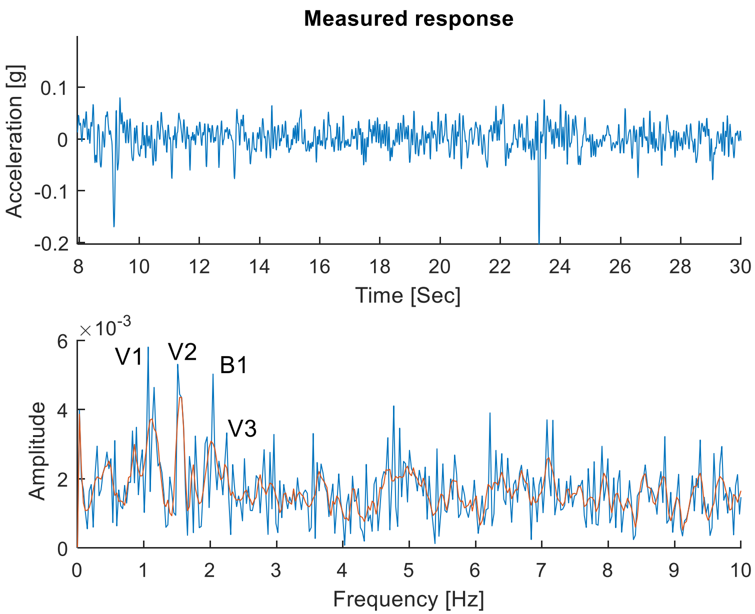


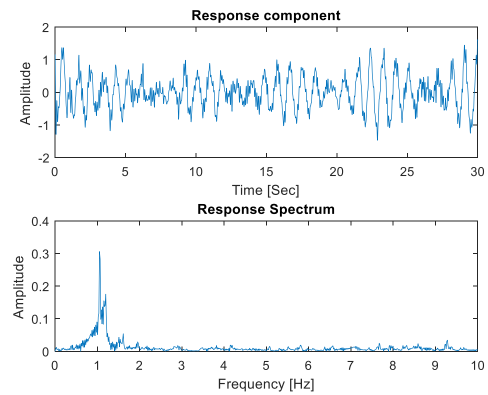
Extracted response components when vehicle park on the road

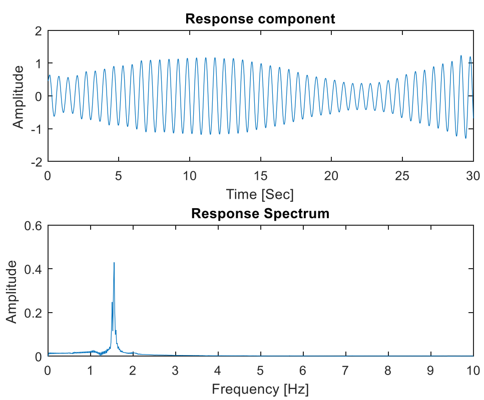


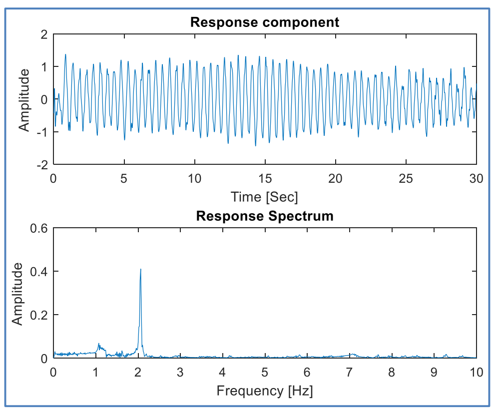
Extracted response components when vehicle park on the bridge

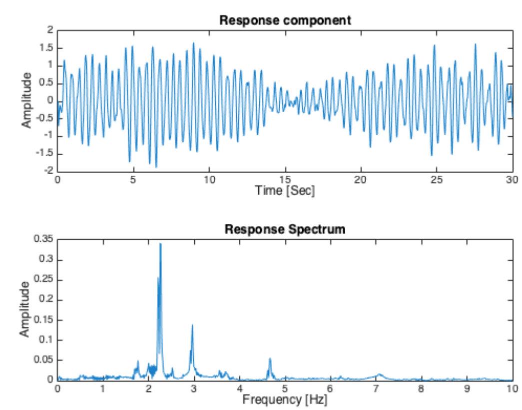
Vehicle passing the bridge with 10km/h











Extracted response components from response when vehicle speed is 10km/h

A two-step drive-by bridge damage detection using dual Kalman filter

Analytical study

State space model with Newmark-β method

$$\begin{bmatrix}\mathbf{x}_{i+1}\\ \dot{\mathbf{x}}_{i+1}\\ \ddot{\mathbf{x}}_{i+1}\end{bmatrix} = \begin{bmatrix}\mathbf{A}_0\\ \mathbf{B}_0\\ \mathbf{C}_0\end{bmatrix}\mathbf{LP}_{i+1} + \begin{bmatrix}\mathbf{A}_d & \mathbf{A}_v & \mathbf{A}_a\\ \mathbf{B}_d & \mathbf{B}_v & \mathbf{B}_a\\ \mathbf{C}_d & \mathbf{C}_v & \mathbf{C}_a\end{bmatrix}\begin{bmatrix}\mathbf{x}_i\\ \dot{\mathbf{x}}_i\\ \ddot{\mathbf{x}}_i\end{bmatrix}$$

$$\begin{cases}\mathbf{X}_{i+1} = \mathbf{A}\mathbf{X}_i + \mathbf{B}\mathbf{P}_{i+1} + \boldsymbol{v}_i^x\\ \mathbf{y}_i = \mathbf{R}\mathbf{X}_i + \boldsymbol{w}_i\end{cases}$$

$$\bar{\mathbf{X}}_i = \mathbf{X}_i - \mathbf{B}\mathbf{P}_i$$

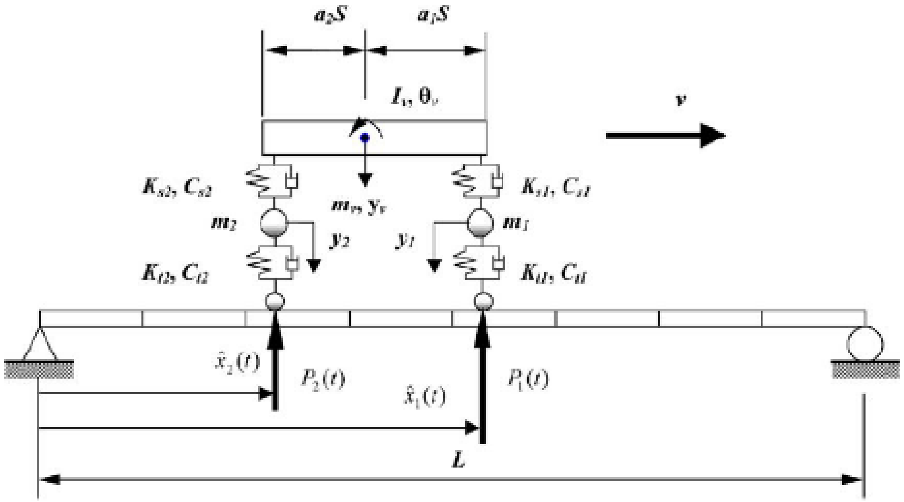
$$\begin{cases}\bar{\mathbf{X}}_{i+1} = \mathbf{A}\bar{\mathbf{X}}_i + \mathbf{ABP}_i + \boldsymbol{v}_i^x\\ \mathbf{y}_i = \mathbf{R}\bar{\mathbf{X}}_i + \mathbf{RBP}_i + \boldsymbol{w}_i\end{cases}$$

DKF

X P

Random walk model on force

$$\begin{cases}\mathbf{P}_{i+1} = \mathbf{P}_i + \boldsymbol{v}_i^p\\ \mathbf{y}_i = \mathbf{RBP}_i + \mathbf{R}\bar{\mathbf{X}}_i + \boldsymbol{w}_i\end{cases}$$



Vehicle-bridge interaction model

Interaction force sensitivity analysis based damage detection

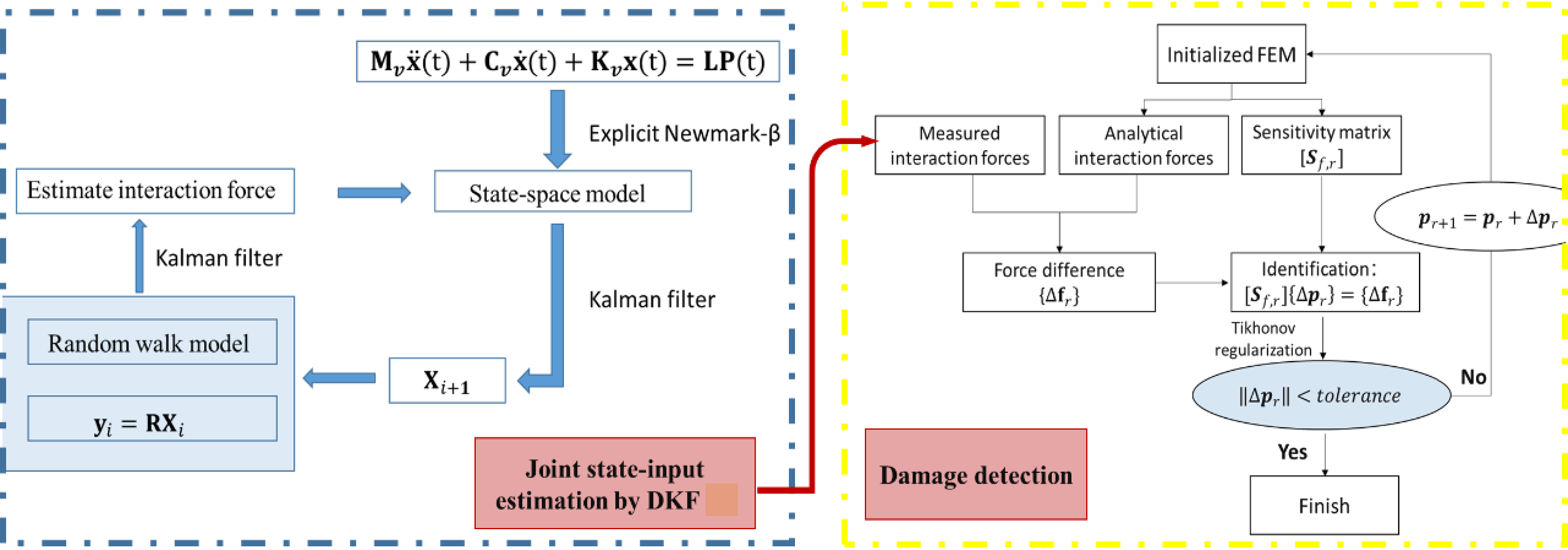
$$\boldsymbol{S}_f = \frac{\partial \mathbf{f}_{int}}{\partial(\alpha_s^j)} = (\mathbf{L}^T\mathbf{L})^{-1}\mathbf{L}^T\left(\mathbf{M}_v\frac{\partial \ddot{\mathbf{x}}_v}{\partial(\alpha_s^j)} + \mathbf{C}_v\frac{\partial \dot{\mathbf{x}}_v}{\partial(\alpha_s^j)} + \mathbf{K}_v\frac{\partial \mathbf{x}_v}{\partial(\alpha_s^j)}\right)$$

Note: J.T. Li, X.Q. Zhu, S.S. Law and B. Samali (2020) "A two-step drive-by bridge damage detection using dual Kalman filter", International Journal of Structural Stability and Dynamics, 20(10), 2042006.

A two-step drive-by bridge damage detection using dual Kalman filter

Analytical study

The procedure



A two-step drive-by bridge damage detection using dual Kalman filter

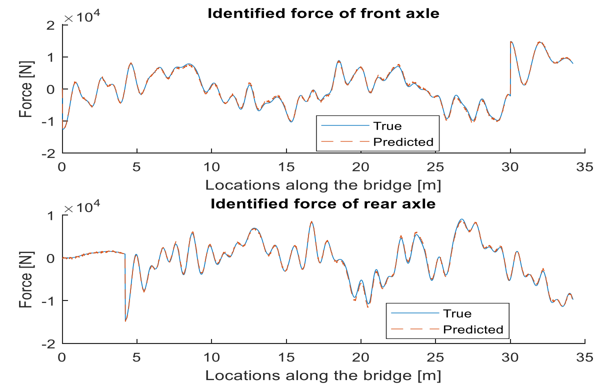
Numerical results

Properties of the target bridge model studied are: $L = 30m,\ \rho A = 6.0 \times 10^3\ kg/m,\ EI = 2.5 \times 10^{10} Nm^2$. The coefficients for Rayleigh damping are $\alpha_1 = 0.343$ and $\alpha_2 = 0.001$. Parameters of the vehicle are: $m_v = 17735kg, I_v = 1.47 \times 10^5 kgm^2, S = 4.2m, a1 = 0.519, a2 = 0.481, m_1 = 1500kg, k_{s1} = 2.47 \times 10^6 N/m, k_{t1} = 3.74 \times 10^6 N/m, c_{s1} = 3.00 \times 10^4 N/m/s, c_{t1} = 0.00N/m/s, m_2 = 1000kg, k_{s2} = 4.23 \times 10^6 N/m, k_{t2} = 4.60 \times 10^6 N/m, c_{s2} = 4.00 \times 10^4 N/m/s,\ c_{t2} = 0.00N/m/s$.

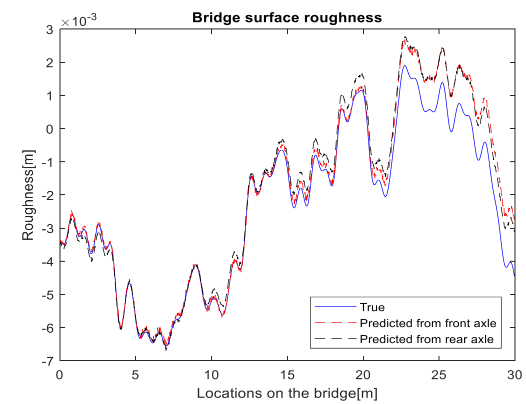
Effect of measurement noise

Noise level (%)	Forces		Roughness	
	Front	Rear	Front	Rear
0	0.00	0.00	2.61	2.61
2	2.06	3.25	6.86	10.41
5	5.88	6.79	18.30	17.98
10	11.75	13.59	36.3	35.72

	Sampling frequency=1000 Hz				Sampling frequency=5000Hz			
Moving speed (m/s)	Forces		Roughness		Forces		Roughness	
	Front	Rear	Front	Rear	Front	Rear	Front	Rear
10	4.78	2.79	52.97	52.36	3.07	1.72	34.81	40.84
20	5.88	6.79	18.30	17.98	4.04	4.74	13.74	27.71
30	5.12	8.98	5.23	8.68	4.14	5.96	4.91	2.91



(a) Identified forces



(b) Identified roughness

Identified forces and surface roughness with 5% measurement noise

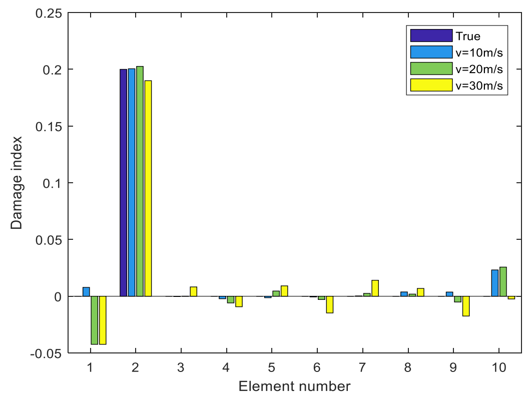
A two-step drive-by bridge damage detection using dual Kalman filter

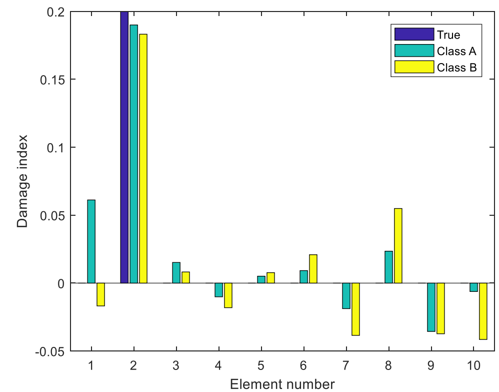
Numerical results

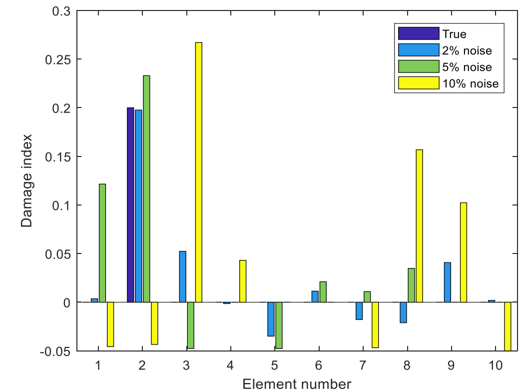
Numerical verification

Single damage

$\alpha_s^2 = 0.20$

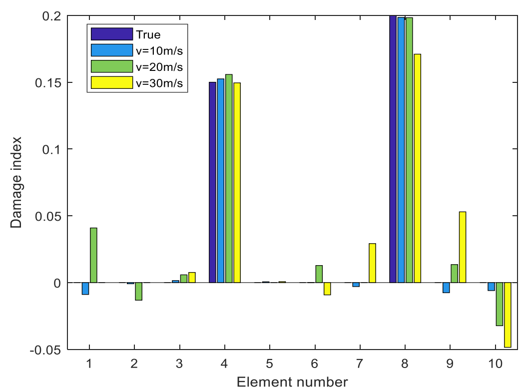


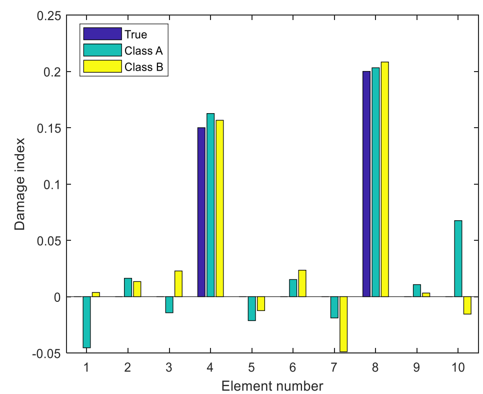


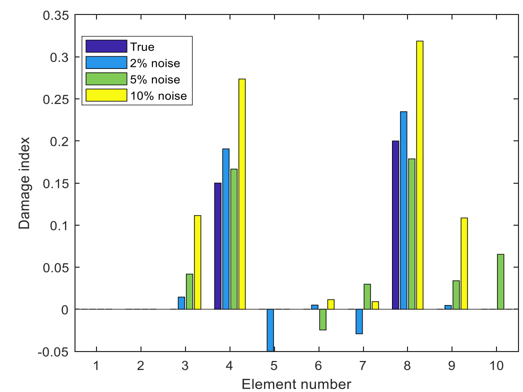


Multiple damage

$\alpha_s^4 = 0.15, \alpha_s^8 = 0.20$







Bridge surface is smooth

Bridge surface roughness is known

Bridge surface roughness is unknown

Conclusions and Future Research

- **Direct bridge health monitoring with the instrumented bridge:** The direct approach is useful for monitoring a critical member of a bridge structure or evolution of a particular known damage condition, but with the disadvantages of intensive labour in sensor placement and maintenance. The lifespan of the sensory system is short relative to the lifespan of the monitored structure.
- **Indirect approach refers to data collection from sensors installed on vehicles crossing the bridge**: The instrumented vehicle can be used to have a quick scan on the large volume of highway bridges, and any suspected bridge will be monitored for a refined detection of the bridge damage.
- **Integrated approach:** Integrated with wireless sensor networks, the vehicle-bridge interaction can further be captured for more accurate bridge health monitoring.
- **Uncertainties in the vehicle-bridge interaction system:** 1) the effect of road surface roughness ; 2) the wheel-surface contact model.

Thank You!

Questions?