Connecting
our communities

Structural Health Monitoring Workshop

Data collection & analysis

Nicholas Haritos

ENGINEERS AUSTRALIA

STRUCOMP PTY LTD TechnoLab™ www.strucomp.com

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF MELBOURNE

Tell me, & I will forget. — "Straight" Lecture/Talk

Show me, & I may remember. — "Illustrated" Lecture/Demo

Involve me & I will understand. — "Hands-on" Practice !

(Confucius, circa 450BC)

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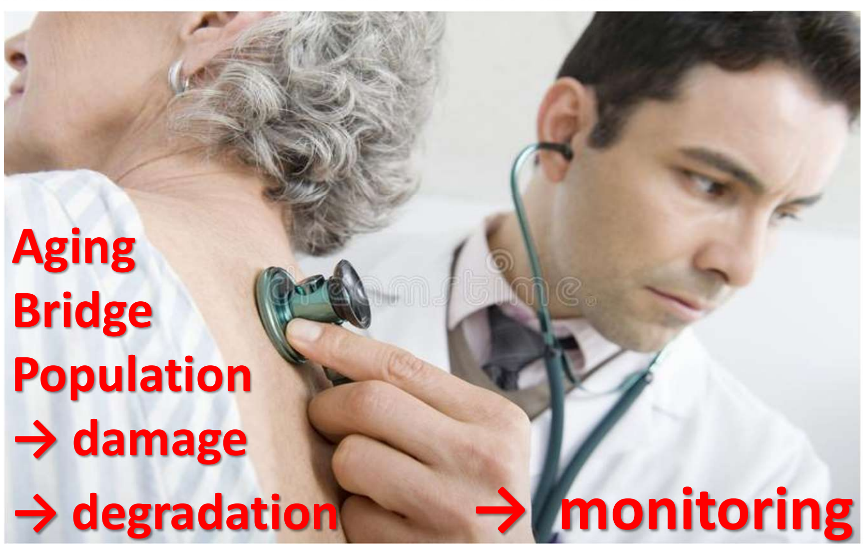
Outline

Vibration Based

- **What data to collect ?**
  - How much to collect ?
  - When to collect data ?
  - Where to collect data ?
- Analysis Options

What data to collect ?



What data to collect ?

Depends on Why you want it &
What you expect to get from it !
It's Purpose !

- **Structural Degradation**
- **Structural Damage**
  - *Detection*
  - *Location*
  - *Degree of Severity*
- **Effectiveness of a Retrofit, etc**

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What data to collect ?

$F(t) \rightarrow$ $\boxed{\textit{Struct Props}}$ $\rightarrow x(t)$

To experimentally determine the ***Structural Properties*** associated with the transformation of input ***F(t)*** to produce output ***x(t)*** for a particular structure would require measurement of both ***x(t)*** and ***F(t)*** OR the optimal fitting of theoretical models for this transformation for output only x(t) measurements*.

****Need make assumptions about properties of the force F(t)***

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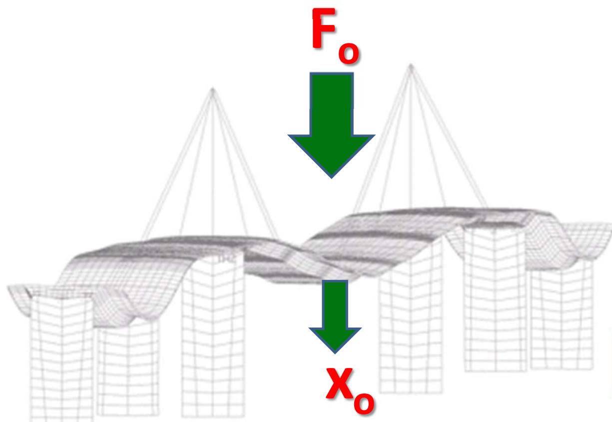
What data to collect ?



$$x_o = \frac{F_o}{k_s}$$

$F(t) \rightarrow$ Struct Props $\rightarrow x(t)$

LUSAS model of West Gate Bridge

Pre-empt Analysis Methods

Time Domain based

- *Auto-Regressive Moving Average (ARMA)*
- *Auto-Regressive Moving Average Vector (ARMAV)*
- *Random Decrement (RANDEC)*

Simultaneous, contemporaneous data capture over all response points on grid

Frequency Domain based

- *Mode frequency, damping, mode-shape (& variants)*
- *Frequency Response Function FRF (& variants)*

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Modal Analysis

Computer Packages

$$KX + M\ddot{X} = 0$$

$$Let\ \ X = \phi e^{-i\omega t} \rightarrow \ddot{X} = (-i\omega)^2 \phi e^{-i\omega t}$$

$$KX + M\ddot{X} = (K - \omega^2 M)\phi e^{-i\omega t}$$

$$\rightarrow (K - \omega^2 M)X = 0$$

Now: $X = \phi e^{-i\omega t} \neq 0$

$$\therefore\ |(K - \omega^2 M)| = \det\big((K - \lambda M)\big) = 0$$

$\lambda - eigenvalue$ $\phi - eigenvector$

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F(t) → Struct Props → x(t)

Modal Analysis – Computer Progs.

SPACE GASS Structural Engineering Software

ANSYS

Strand7 Software

ETABS 2016 INTEGRATED ANALYSIS, DESIGN AND DRAFTING OF BUILDING SYSTEMS

SOFiSTiK

LISA Free / Affordable FEA

etc . . . . .

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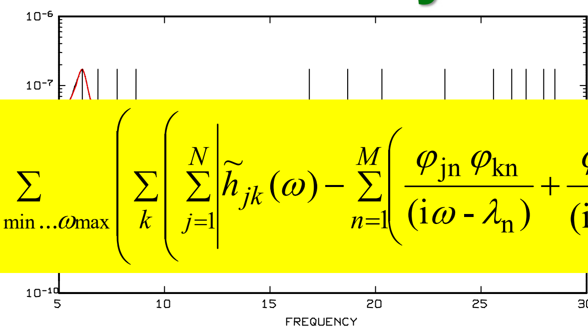
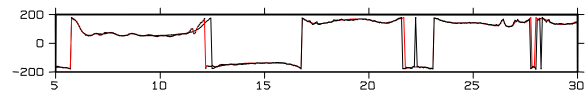
Experimental
Modal Analysis

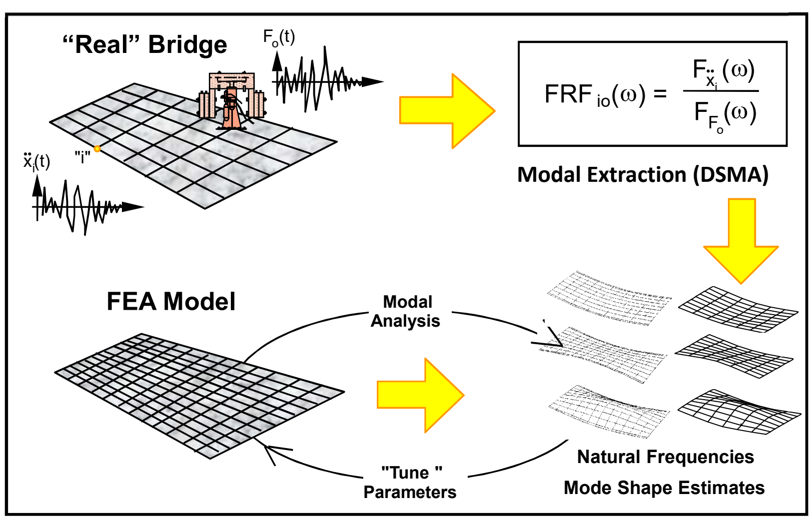


$$\min_{\{\lambda_s,\varphi_{jn}\}} \sum_{\omega=\omega_{\min}\ldots\omega_{\max}} \left(\sum_k \left(\sum_{j=1}^{N} \left| \tilde{h}_{jk}(\omega) - \sum_{n=1}^{M} \left(\frac{\varphi_{jn}\varphi_{kn}}{(i\omega-\lambda_n)} + \frac{\varphi^*_{jn}\varphi^*_{kn}}{(i\omega-\lambda^*_n)} \right) \right|^2 \right) \right)$$



λ – ***eigenvalue*** ϕ –***eigenvector***

"Traditional" EMA using a Shaker

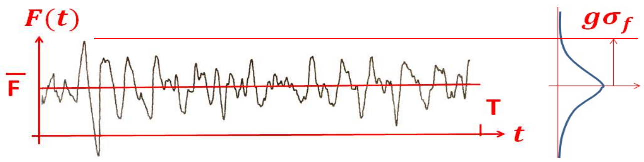


What data to collect ?

Input - Force

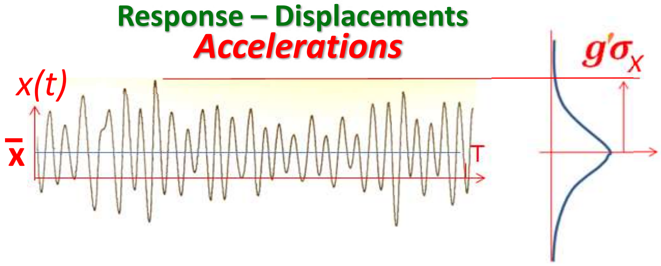
$F_{max} = \bar{F} + g.\sigma_f$

Peak Factor

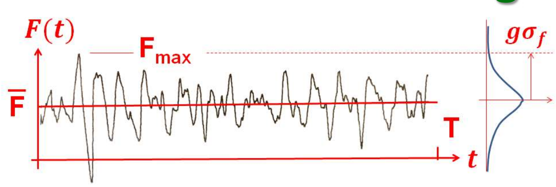


Details of response determined by dynamic characteristics of structure & frequency characteristics of forcing

Response – Displacements
Accelerations



Modelling Stochastic (Random-like) Forcing



$$F(t) = \bar{F} + f(t)$$

$$f(t) = \sum_{n=0}^{\infty}\left(a_n cos\left(\left(\frac{2\pi n}{T}\right)t\right) + b_n sin\left(\left(\frac{2\pi n}{T}\right)t\right)\right)$$

$$f(t) = \sum_{n=0}^{\infty} A_n cos\left(\left(\frac{2\pi n}{T}\right)t - \phi_n\right) = \sum_{n=0}^{\infty} A_n cos(2\pi f_n t - \phi_n)$$

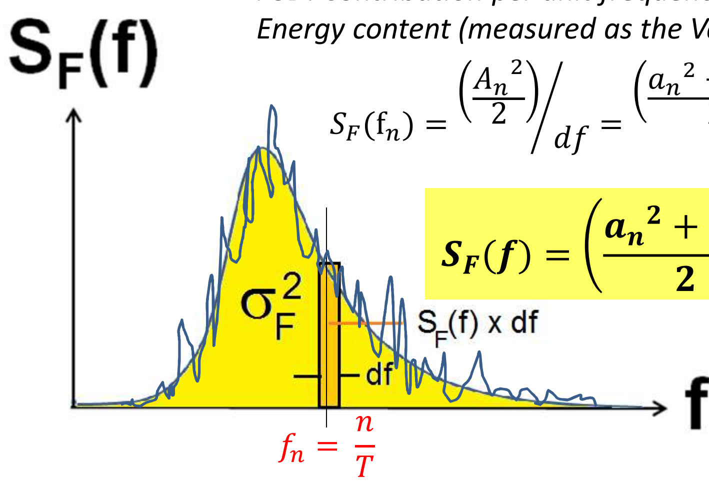
$$\sigma^2{}_f = 0 + \sum_{n=0}^{\infty}\left(\frac{a_n{}^2}{2}\right) + \sum_{n=0}^{\infty}\left(\frac{b_n{}^2}{2}\right) = \sum_{n=0}^{\infty}\left(\frac{a_n{}^2 + b_n{}^2}{2}\right)$$

Force Power Spectral Density (PSD)

PSD: Contribution per unit frequency towards Energy content (measured as the Variance)

$$S_F(f_n) = \left(\frac{A_n{}^2}{2}\right)\Big/_{df} = \left(\frac{a_n{}^2 + b_n{}^2}{2}\right)\Big/_{\frac{1}{T}}$$

$$\boldsymbol{S_F(f) = \left(\frac{a_n{}^2 + b_n{}^2}{2}\right)\frac{T}{1}}$$



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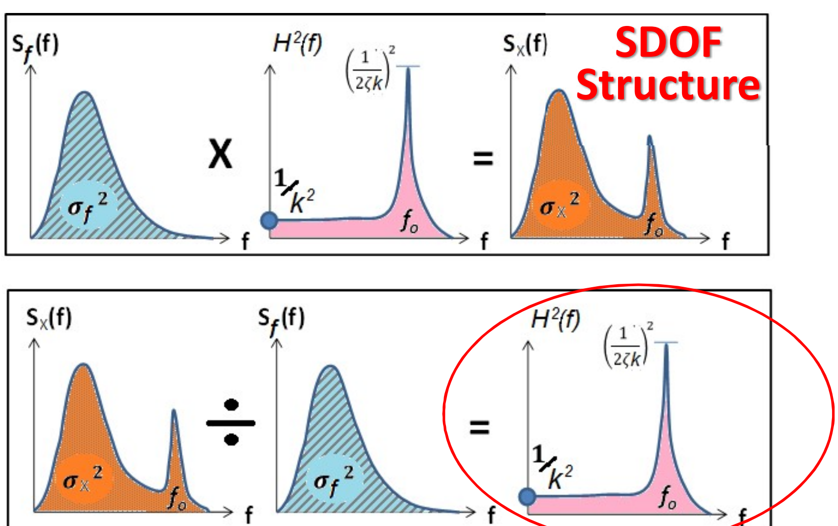
Frequency Response Function (FRF)



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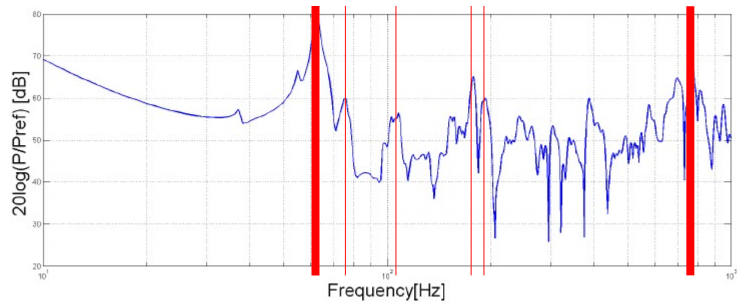
FRF



Lowest Frequency of Interest, f_o

Highest Frequency of Interest, f_H

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How much/when to collect?

- Sampling Rate, f_s of data must be > 2 * f_H
- Minimum Sampling Rate suggest be > 3 * f_H
- Preferred Sampling Rate of Data > 5 * f_H
- Suggested frequency of resolution, < αf_o
  $df < 1/T = \alpha f_o$, *eg* α of 1% → $\underline{T > 100/f_o}$
- Number of data points/record N = $T^*f_s = f_s/(\alpha f_o)$
  eg for: $f_s = 4^*f_H$, α of 1% → $N = 4f_H/(\alpha f_o)$
  for f_H / f_o = 10 (say f_o = 8Hz) → N = 4,000 points

(Useful if using EXCEL for N = 4096 - largest power of 2 for FFT algorithm in EXCEL)

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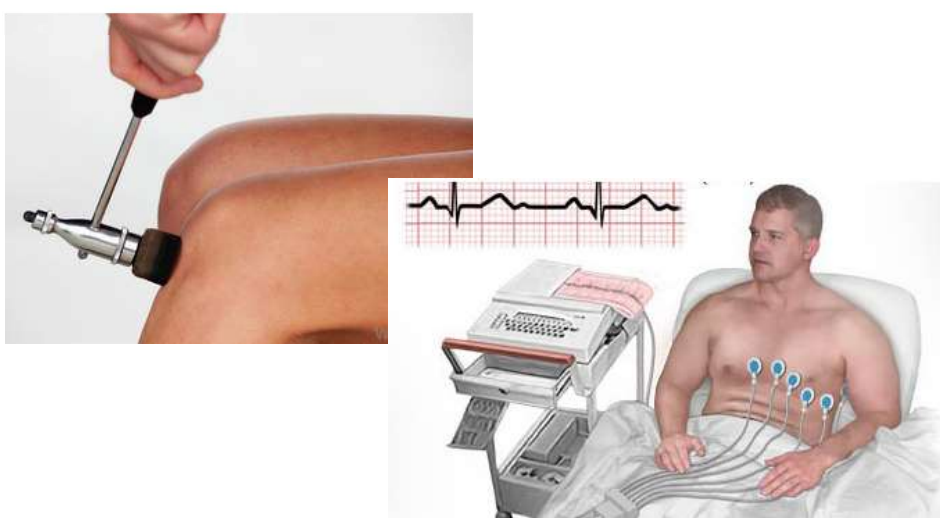
What data to collect ?



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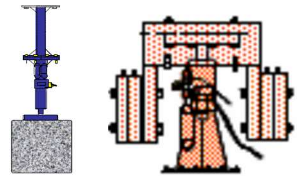
What data to collect ?

Input - Force

Instrumented impact hammer

Virtually impossible to measure except if structure (bridge) closed to traffic & using a Controlled Shaker



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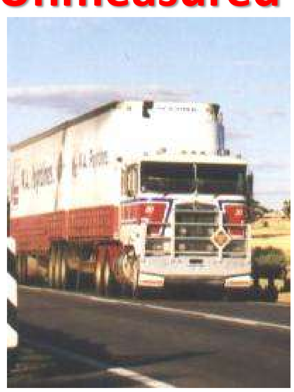
What data to collect ?

Input – Forcing

Unmeasured



Natural Traffic

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What data to collect ?

Response – Displacements

LVDT's

Laser Vibrometers

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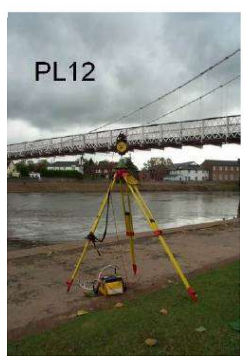
What data to collect ?

Response – Displacements

GPS Measurement Node



Pseudolites
(~ground satellites) ↑
improve accuracy

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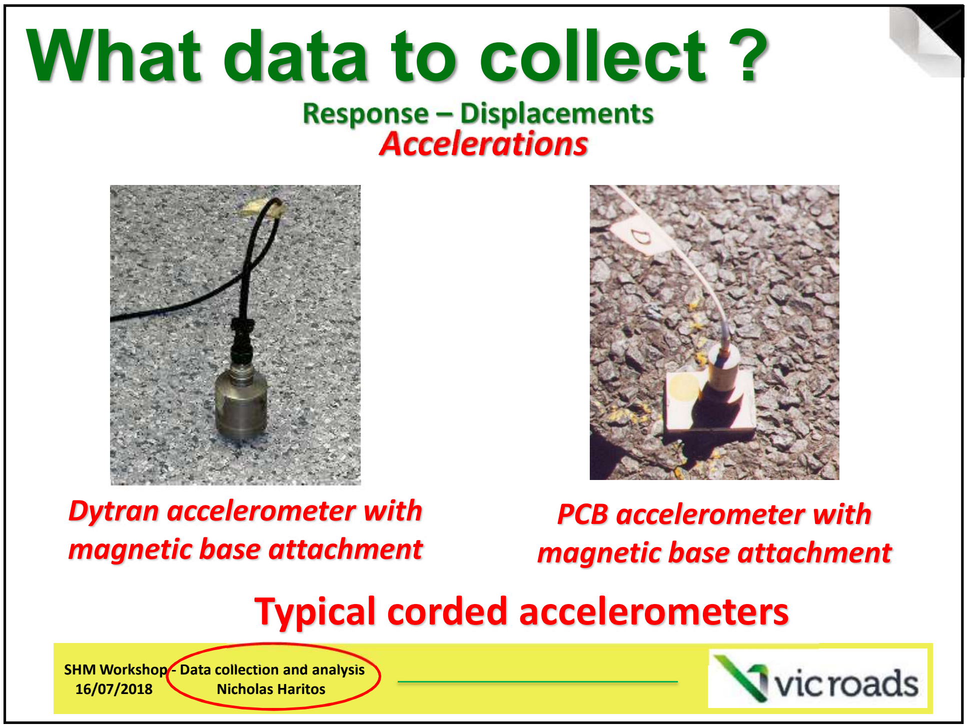
What data to collect ?
Response – Displacements
Accelerations
Dytran accelerometer with magnetic base attachment
PCB accelerometer with magnetic base attachment
Typical corded accelerometers
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What data to collect ?
Response – Accelerations
Wireless
Smart Phones
Android
Apple iOS
External BT Accelerometers
Coordinator (WSN Manager)
Wireless Sensor
Wireless Sensor
Wireless Sensor
Wireless Sensor
BeanAir
MEL-X2
GCDC Data-logging Accelerometers
X2-2
Serious Stuff!
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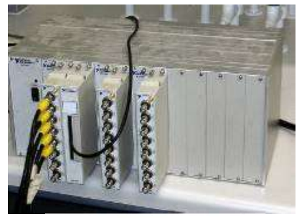
What data to collect ?

Response – *Measurement*

(a) 16-channel 20mA constant current power supply



(b) NI - SCXI Signal Conditioning Unit

(c) NI – based DAS using 16-bit ADDA and a notebook computer

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Where to collect data?

Depends on Why you want it &
What you expect to get from it !
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- **Structural Degradation**
- **Structural Damage Detection**
  - *Location*
  - *Degree of Severity*
- **Effectiveness of a Retrofit, etc**

→Fine grid

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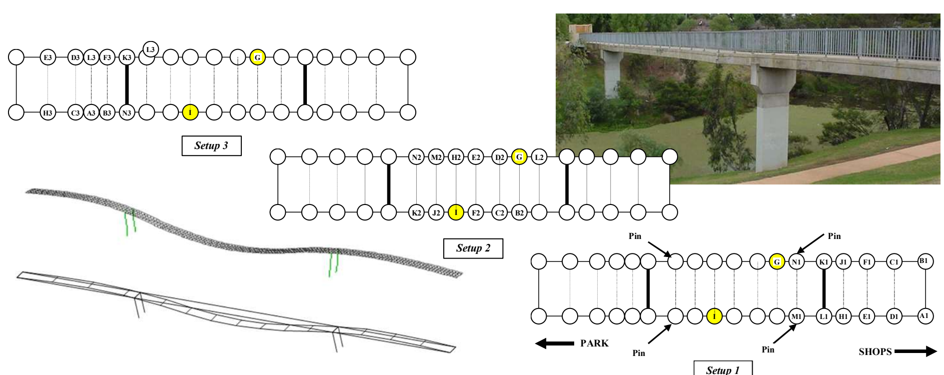
Where to collect data?

Narrow/Cantilever Bridges

- Response modes largely flexural & torsional
- Can use two lines of edge nodes as a minimal grid



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Where, to collect data ?

Narrow/Cantilever Bridges

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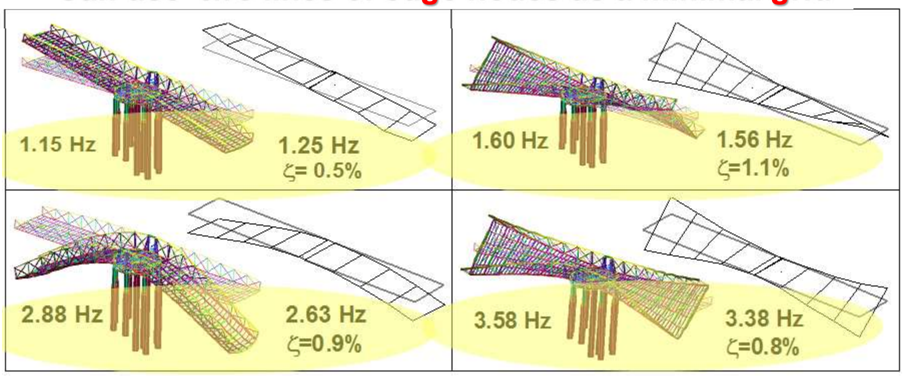

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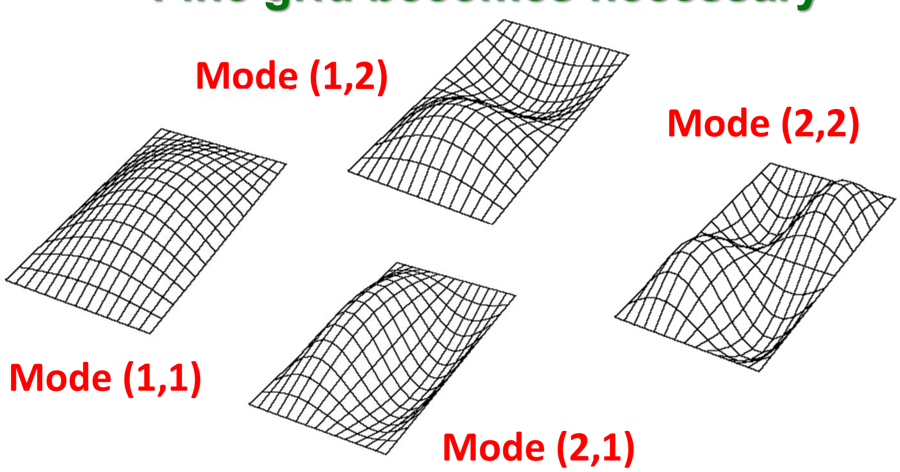
Plate-like behaviour

→ Fine grid becomes necessary



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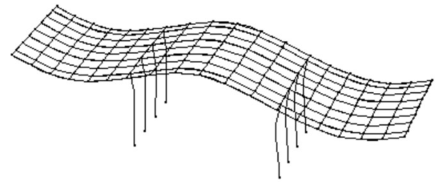
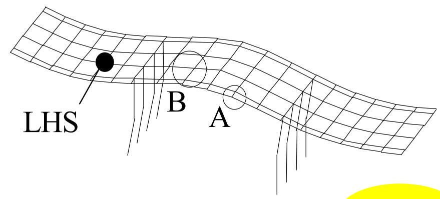
Example Grids (EMA)



FEA Mode#1 f_o = 8.91 Hz



Concongella Creek Bridge: Mode#1

EMA Mode#1 f_o = 8.92 Hz ζ = 2.7%

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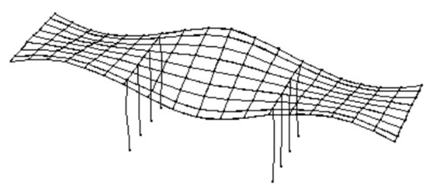
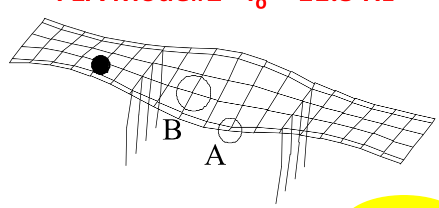
Example Grids (EMA)



FEA Mode#2 f_o = 11.3 Hz



Concongella Creek Bridge: Mode#2

EMA Mode#2 f_o = 12.9 Hz ζ 3.7%

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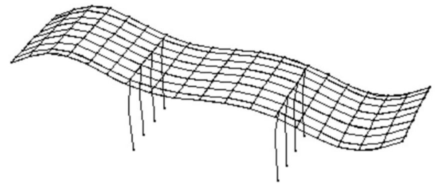
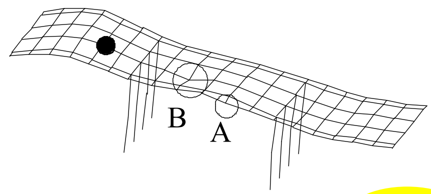
Example Grids (EMA)

Concongella Creek Bridge: Mode#3



FEA Mode#3 f_o = 12.6 Hz



EMA Mode#3 f_o = 13.0 Hz ζ = 12.3%

Outline

Vibration Based

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- **Analysis Options**

Analysis Options

Depends on **Why** you want it &
What you expect to get from it !
It's Purpose !

- Structural Degradation
- Structural Damage Detection
- Effectiveness of a Retrofit, etc

Simple EMA → Tier#1
'Ambient' EMA → Tier#2
Traditional EMA → Tier#3

Simple EMA → Tier#1

Single Point Monitoring →

- Can determine dominant (modal) frequencies
- In conjunction with an EMA model may be able to infer participation of detected modes
- May be sufficient to infer "all is well"

‘Ambient’ EMA → Tier#2

Multi- Point Monitoring →

- Can determine dominant (modal) frequencies
- Can obtain Operational Deflected Shapes ~ mode shapes when freqs. separated
- May be sufficient to infer “possible” deterioration and/or damage

‘Traditional’ EMA → Tier#3

Multi- Point Monitoring →

- Can determine dominant (modal) frequencies and damping
- Can determine mode shapes even when modes may be closely spaced in frequency
- Provide the basis for damage identification, location and its extent, more . . . .

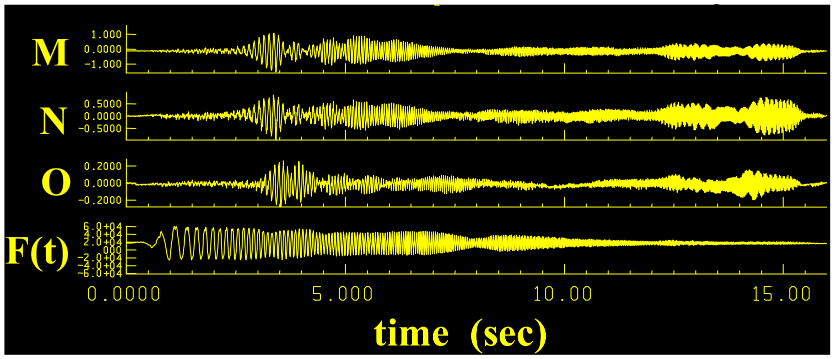
Software

- Purpose-specific "research" style software possessed by several universities

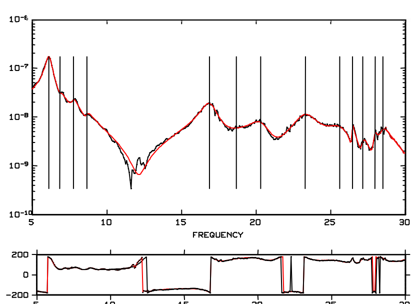
Data Acquisition System (DAS) with Simultaneous Sample and Hold, and anti-aliasing filters,
$\rightarrow$ 16-channel Spectral Analyser

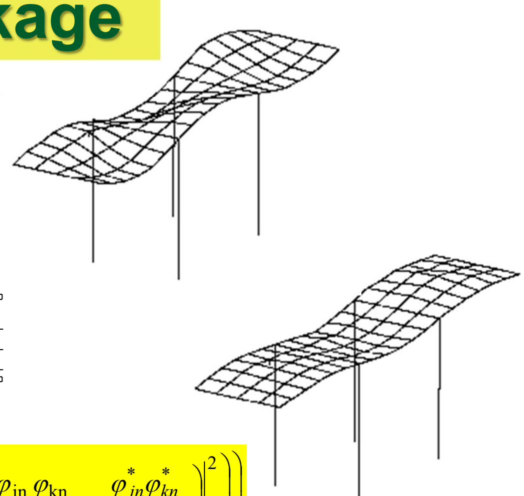
Research Software

Software



DSMA Package





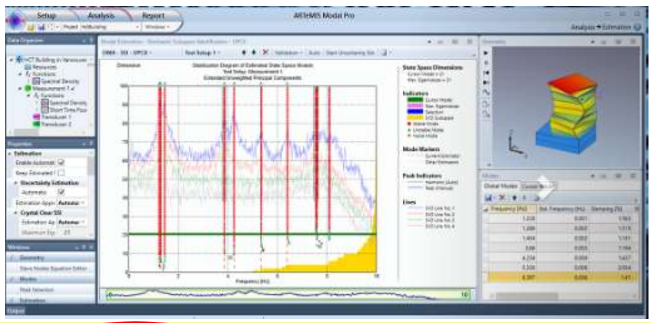
$$\min_{\{\lambda_s,\varphi_{jn}\}} \sum_{\omega=\omega_{min}\ldots\omega_{max}} \left(\sum_k \left(\sum_{j=1}^{N} \left| \tilde{h}_{jk}(\omega) - \sum_{n=1}^{M} \left(\frac{\varphi_{jn}\,\varphi_{kn}}{(i\omega-\lambda_n)} + \frac{\varphi^*_{jn}\varphi^*_{kn}}{(i\omega-\lambda^*_n)} \right) \right|^2 \right) \right)$$

Commercial Software

Structural Vibration Solutions

ARTeMIS Modal Product Information

- Operational Modal Analysis (OMA)
- Experimental Modal Analysis (EMA)
- Operating Deflection Shape Analysis (ODS)
- Structural Health Monitoring (SHM)



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Commercial Software

Vibrant TECHNOLOGY

ME'scopeVES™
Visual Engineering Series

- ODS Animation
- FRF-Based Modal Analysis
- Operational Modal Analysis
- Vibro-Acoustic Analysis
- Dynamics Modeling & Simulation
- Structural Dynamics Modification
- FEA Model Updating

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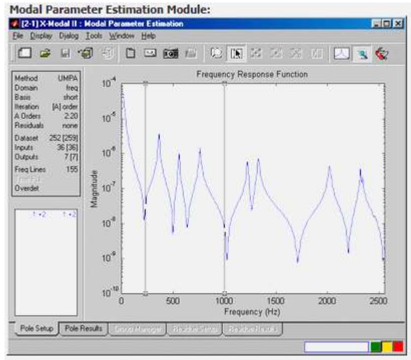
SDRL
Structural Dynamics Research Lab

UNIVERSITY OF Cincinnati

X-Modal (Experimental Modal Analysis Software)

Modal Parameter Estimation Module:



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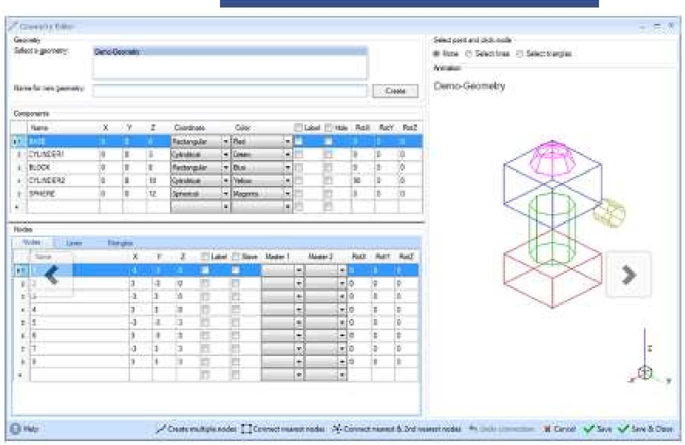
m+p INTERNATIONAL

Test and Measurement Solutions ...



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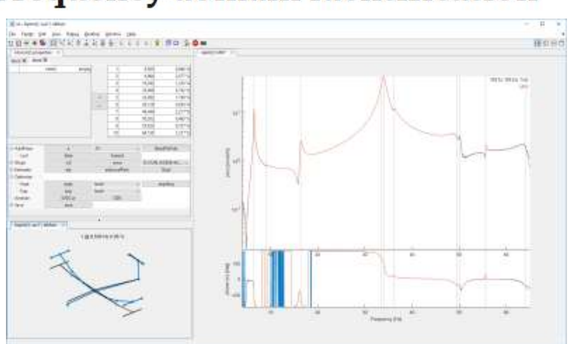
Commercial Software

SDTools
VIBRATION SOFTWARE & CONSULTING

Experimental Modal Analysis

Frequency domain identification



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Commercial Software

REAL VIBRATIONS
SYSTEMS DEVELOPERS

http://www.realvibrations.com/

Australian Product

Multi-axis Vibration Shaker Controllers; Field Data Analyser
Multi-channel Real-time Signal Recorder;
Multi-channel Signal Analyser
Dual-channel Spectrum Analyser - Impact Excitation
Dual-channel Spectrum Analyser - Random Excitation
Cushion / Impact Analyser
Vibration Fatigue Analyser; Seismic Motion Analyser