Sensors, Data Acquisition and Transmission

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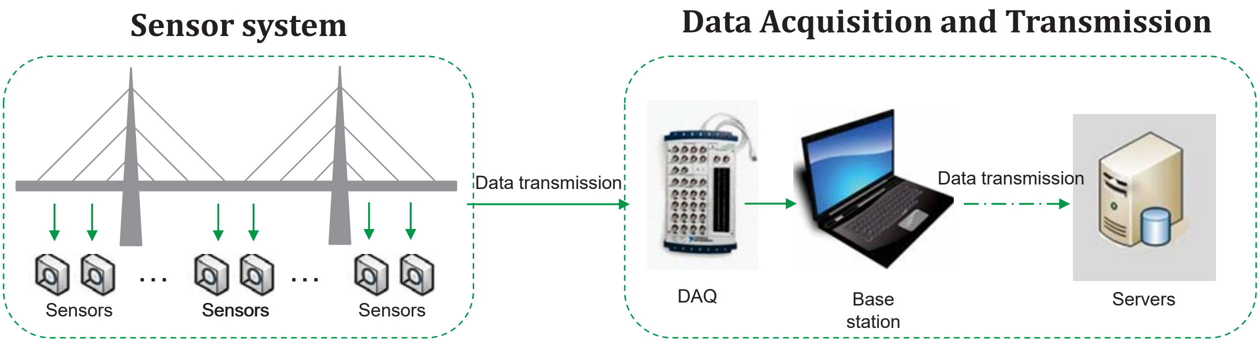
Typical SHM system



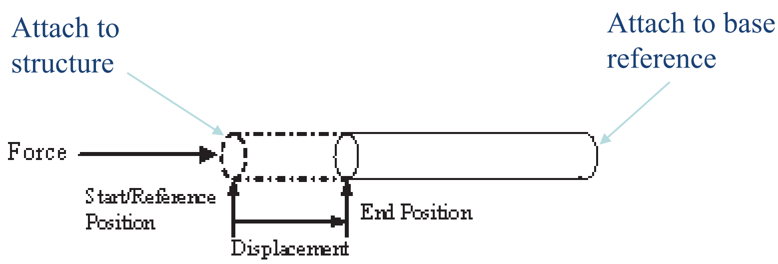
SENSORS

- ❑ Linear Displacement Transducers
- ❑ Strain Gauges
- ❑ FBG Sensors
- ❑ Accelerometers
- ❑ Wireless Sensors

Linear Variable Displacement Transducers (LVDT)

- To measure displacement
- Need a base reference
- Useful to examine load carrying capacity of structure by a static loading test

LVDT



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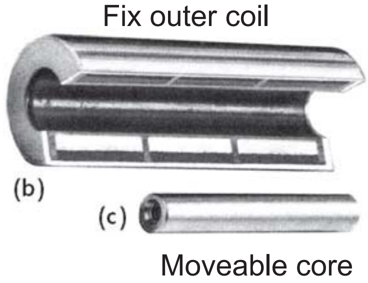
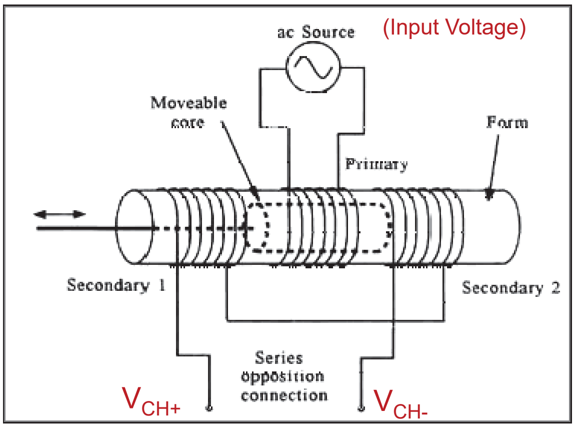
LDT: Principle



- Magnetic flux change as the core moves that consequently causes the change in output voltage.
- Measuring output voltage.

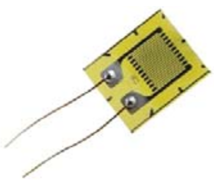
$$displacement = G \times (V_{CH+} - V_{CH-})$$

G: Gain Factor (Sensitivity)

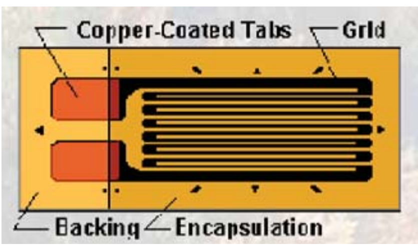


There are 4 wires in the LDT:
- 2 wires for input voltage
- 2 wires for output voltage

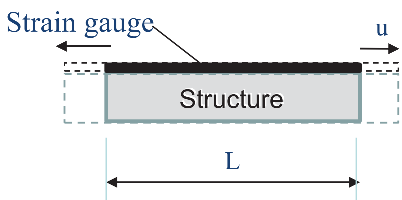
Strain Gauges



- To measure strain
- Sensor is surface bonded to the structure
- Useful to examine local stress via strain and then stiffness of structure components



$$\varepsilon = u/L$$



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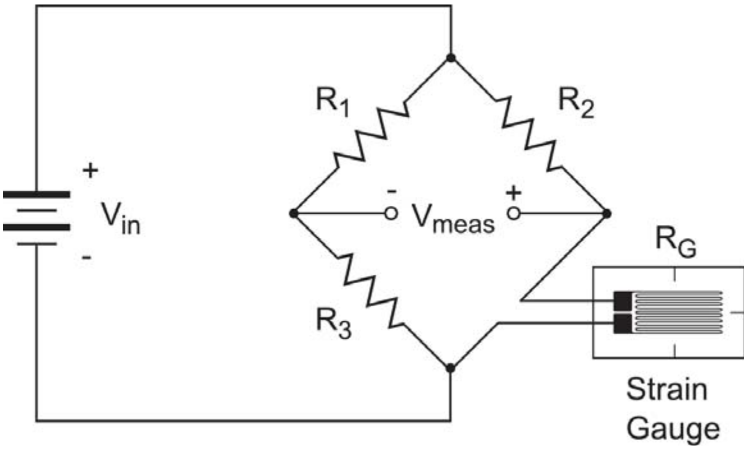
Strain Gauges: Principle

- Measuring voltage.
- Based on resistance changes when the strain gauge deforms
- Sensitive instrumentation is required to measure the small changes in resistance.

Wheastone bridge is typically used to measure resistances accurately.



$$V_{meas} = V_{in}\left[\frac{R_G}{R_2 + R_G} - \frac{R_3}{R_1 + R_3}\right]$$

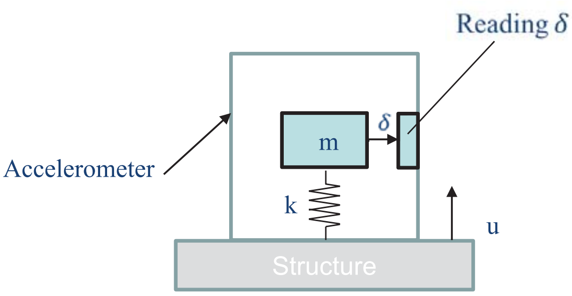
If all resistances are equal

$$\epsilon = \left(\frac{4}{GF}\right)\left(\frac{V_{meas}}{V_{in}}\right)$$

GF: Gain Factor (Sensitivity)

Accelerometers

- To measure acceleration ($\ddot{u}$)
- No need for reference base
- Most popular means for vibration measurement
- Can be used to further acquire natural frequency and mode shape of the structure

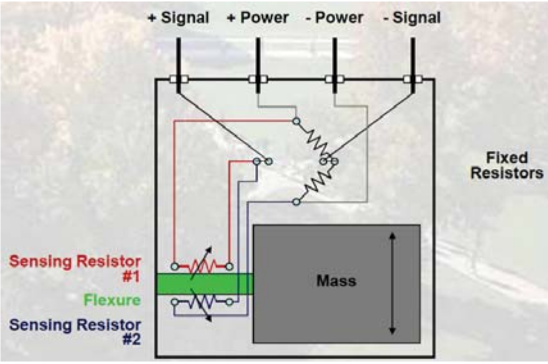


δ: relative motion between the mass m and the structure

$$\ddot{u} = -(\ddot{\delta} + \frac{k}{m}\delta)$$

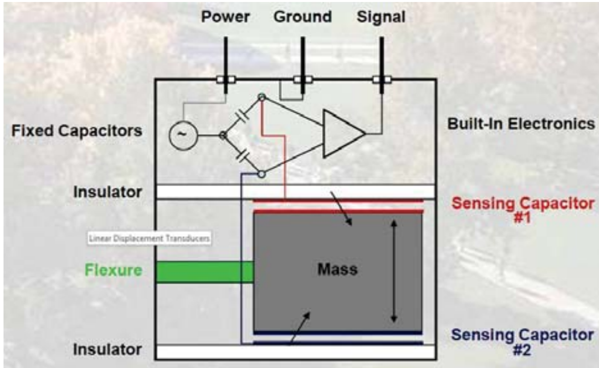
Accelerometers: Principle

Resistive Accelerometers



- Measuring output voltage.
- Relative motion causes the change in resistor that consequently changes the output voltage.

Capacitive Accelerometers



- Measuring output voltage
- Relative motion causes the change in capacitor that consequently changes the output voltage

Wireless Accelerometers

- Mostly based on MEMS (Micro-Electro-Mechanical System)
- Output as digital number.
- Data is transferred to base station wirelessly.
- Has integrated data acquisition (DAQ) system.
- Some wireless sensors can perform signal processing.

Advantages

- Cost effective
- Easy to install
- Wireless communication
- Low power
- Enabling long-term monitoring

Disadvantages

- Time-synchronization problem
- Less durability
- Communication is interfered by environment condition

Sensor Specifications

Sensitivity: $S = \dfrac{Output(voltage)}{Input(g)}$

Frequency range: The range over which the sensitivity does not vary more than the stated value

Measurement range: The maximum magnitude of measurable acceleration

Sensor types	Model	Sensitivity	Freq. Range	Meas. Range	Gage length
Accelerometers	Kistler 8630B5	1 V/g	0.05 Hz – 2 kHz	5g	-
	PCB 393B05	10 V/g	0.7 Hz – 450 Hz	0.5g	-
LVDT	CDP-5	2000 (x10e-6 strain/mm)	Any	5mm	-
	CDP-50	200 (x10e-6 strain/mm)	Any	50mm	-
Strain gauge	PL-60-11	2.13	Any	2-4%	60mm

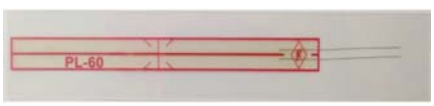
Selection of sensors depends on purpose (vibration, static, global or local, etc.) and structure characteristics (structure scale, vibration range, frequency range, etc.)

Sensor Illustration (1)

- **Linear Variable Displacement Transducer: CDP-50 (Tokyo Sokki Kenkyujo Co.)**

Important Specs	
Meas. Range	5 mm
Sensitivity	2000 (x10e-6 strain/mm)

- **Strain Gauge: PL-60-11 (Tokyo Sokki Kenkyujo Co.)**



Important Specs	
Gauge length	60 mm
Resistance	120 Ohm
Gage factor	2.13
Meas. Range	20,000-40,000 $\mu\varepsilon$

Sensor Illustration (2)

- Accelerometer: 8630B5 (KISTLER)

Important Specs	
Meas. Range	5g
Sensitivity	1 V/g
Freq. Range	0.05 Hz – 2 kHz

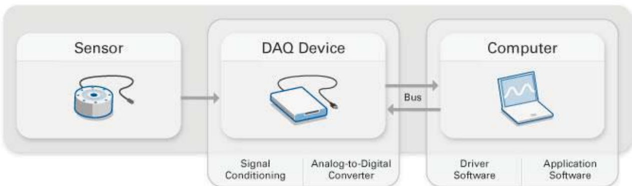
- Wireless Accelerometers

GLink2-LXRS (Micro Strain)

Glink200-8G (Micro Strain)

Important Specs		
Model	GLink2-LXRS	Glink200-8G
No. Channels	3	3
Meas. Range	2g	8g
Sensitivity	16,384 bits/g	65,536 bits/g
Freq. Range	0-100 Hz	0-1000 Hz
Radio Range	800 m	800 m

Data Acquisition



- Data acquisition is the process including:
  - measuring an output from a sensor in term of analog electrical signal such as voltage or current.
  - and representing that analog signal as a series of digital values with a analog-to-digital converter (ADC)
- This can be done with a DAQ Device.
- Quality of data is related to:
  - Sampling.
  - Measurement duration.
  - Amplifier.
  - Filter.

NI 9237 NI 9235 NI 9234

Input voltage and measure output voltage

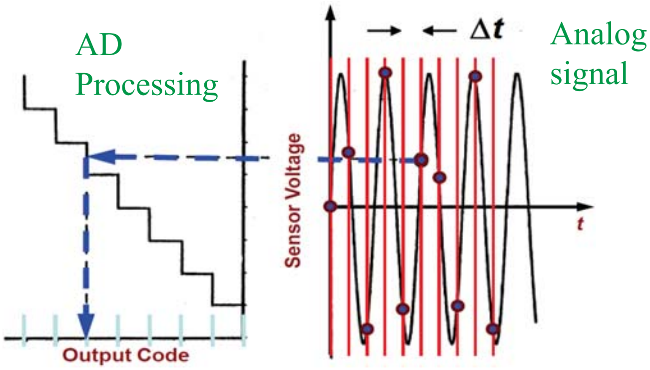
measure output voltage

Analog-to-Digital Converter

Used to convert analog signal (voltage) from a sensor to a series of digital number that can be stored in the computer.

ADC Specification

- Dynamic range: 1V, 2V, 10V
- ADC code: 8 bits, 16 bits, 24 bits (Higher no. of bits gives better accuracy)
- The dynamic range is only meaningful if the input covers all the bits of the ADC



Example:

- Range: [-1;1]V, ADC code: 4 bits.
- Number of AD steps: 2^4 = 16
- Resolution (Res): 2/16 = 0.125 V

- If sample input is 0.8V (analog)
- Output = round(0.8/Res)*Res

= round(6.4)*0.125 = 6*0.125 = 0.75V (digital)

- Quantization error = 0.05V

Quality control of data

Sampling

- Sampling (Hz) means the number of data collected per a unit time (second).
- Higher sampling rate gives higher frequency coverage, but more data is stored.

Measurement duration

- Longer measurement duration gives higher resolution in frequency analysis.

Amplifiers

- Can be used to boost small signals before input to low-cost/low-sensitivity DAQ device. That generally improve the accuracy of measurement.

Filters

- Can be used to filter the unwanted frequency range.
- Filtered signal is generally better to used for modal analysis.

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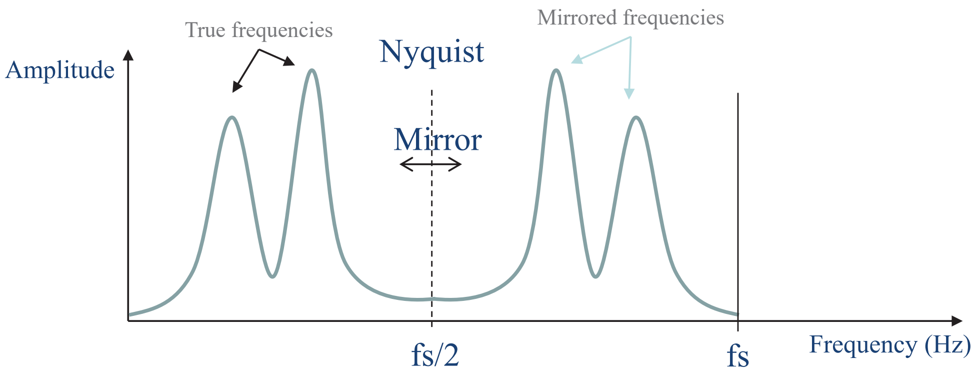
Sampling

- fs: sampling rate (Hz)
- Frequency coverage: [0 Hz- fs/2], where fs/2 is the Nyquist frequency
- Reliable frequency coverage: [0 - fs/3] (will be explained later in filter part)

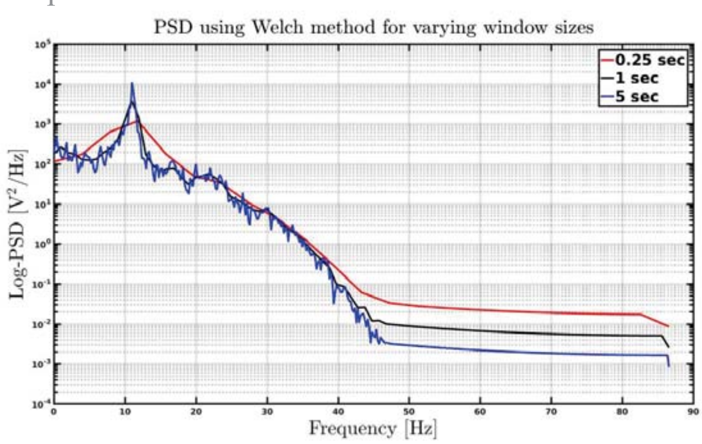
Example:
If a bridge has a highest frequency of interest as 10 Hz, we need to set up a sampling rate of at least 20 Hz. Recommended sampling rate would be 30 Hz.



Measurement duration

- Δf = frequency resolution (Hz)
- N = number of data points
- $\Delta f = \frac{f_s}{N} = \frac{f_s}{f_s t} = \frac{1}{t}$
- Longer measurement duration gives higher frequency resolution, that means better accuracy.
- For bridges, natural frequencies are [0.1-10Hz], long measurement is required (e.g., 10-30 minutes) to have an acceptable resolution.

Measurement duration vs freq. resolution



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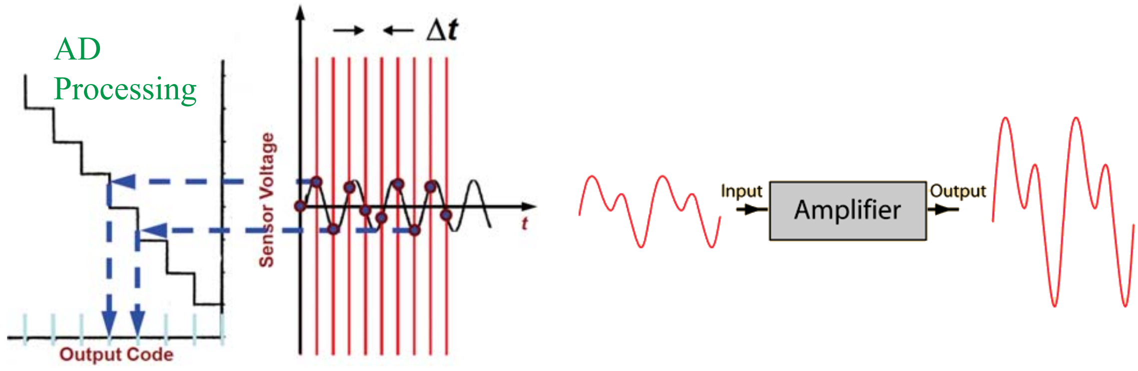
Amplifiers

When amplifiers are used?

- Sensor output has small amplitude (e.g., 0.1g) but the Analog Digital Convertor (ADC) has high input scale (10g). That makes the digital output (what is stored in the PC) have low magnitude resolution compared to its range.
- Amplifier is used to boost the low-magnitude signal before inputted to the ADC.



Low-magnitude signal

Aliasing Effect

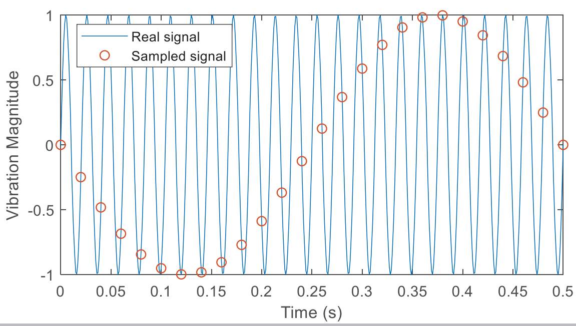
Aliasing is an effect that causes different signals to become indistinguishable when sampled.

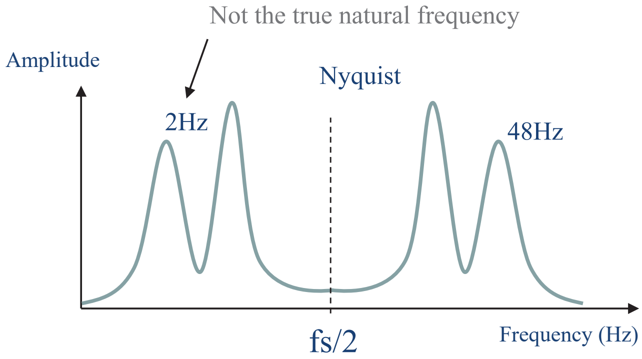
When this happens?

Natural frequencies are higher than the Nyquist frequency

Example:

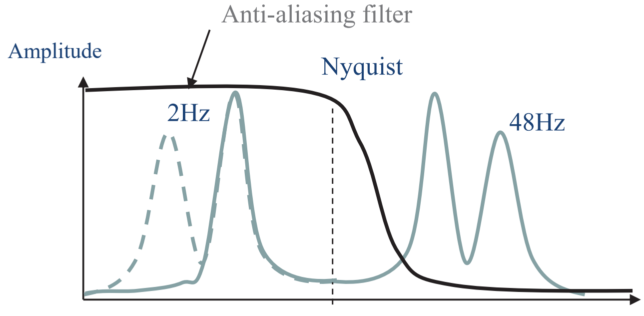
Consider a 48 Hz signal with the sampling rate of 50 Hz. The resulting frequency response will contain a 2Hz (=50-48) peak.



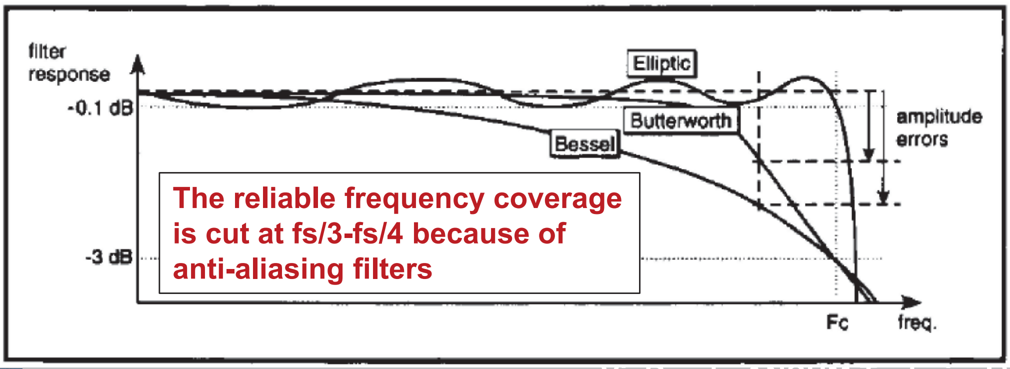


Anti-aliasing Filters

Anti-aliasing filter are a low-pass filters with cut-off at fs/2



Different anti-aliasing filters



Commercial DAQ Devices

Traditional Wired SHM

NI 9234

- 4 Channels
- ADC Code: 24 bits
- Range: 5V

Analog signal (Accelerometer output) → [Anti-aliasing filter → AD Converter] → Digital signal (stored in PC)

Wireless SHM

G-Link2 - LXRD

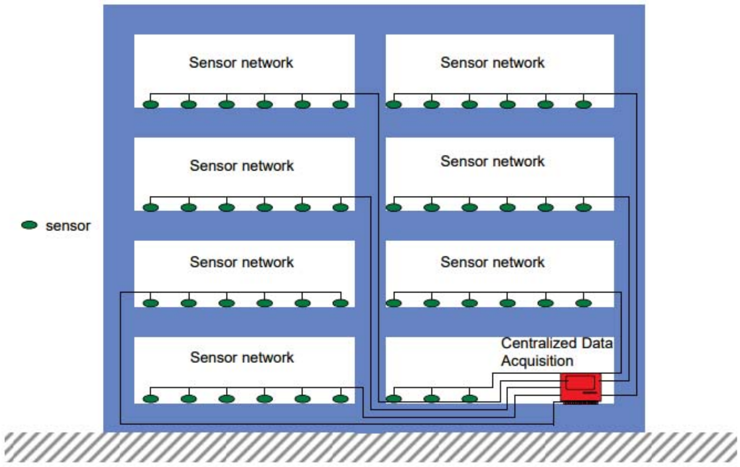
Analog signal (Accelerometer) → Anti-aliasing filter → AD Converter → Digital signal (stored in Memory Slots)

- 3 channels
- ADC code: 16 bits
- Range: 2g

Data Transmission

Traditional Wired System:

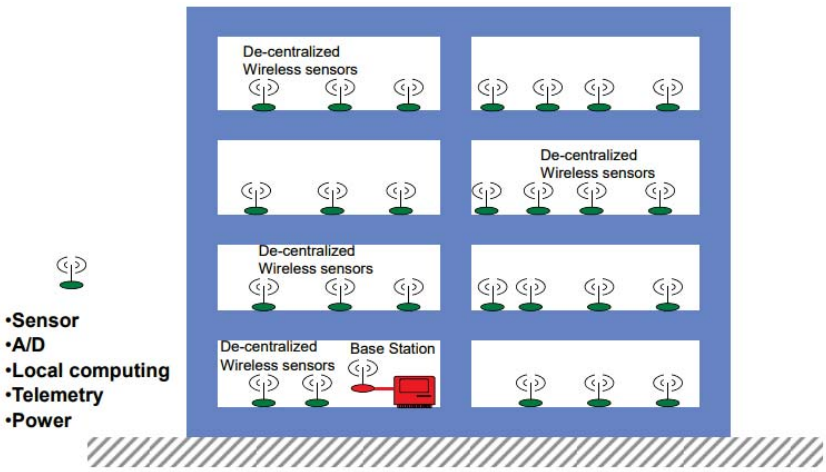
- Data acquisition systems transmit the analog signal (sensor output) to the DAQ Device through hard-wire connections (i.e., cables).
- Reliable transmission.
- High-cost associated with cables and cabling.



Data Transmission

Innovative Wireless System:

- Data acquisition systems transmit the digital signal from sensor node to a computer.
- Low-cost as requiring no cables.



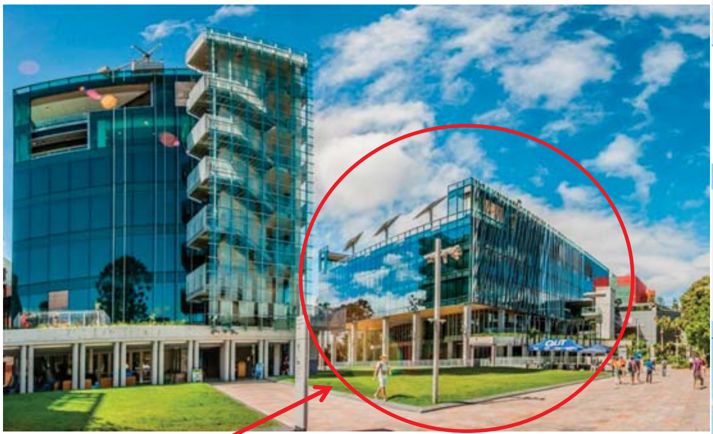
General Issues of Wireless Transmission

- Data loss due to radio interference and out of communication range.
- Data transmission rate is lower than wired system, that will affect real time measurement.
- Data in each sensor node is transferred turn by turn, that increase the duration of data collection.

Solutions:
- Selecting appropriate communication channel.
- Improving radio devices that give higher communication range.
- Data compression.
- Improving network topology: decentralized data collection.

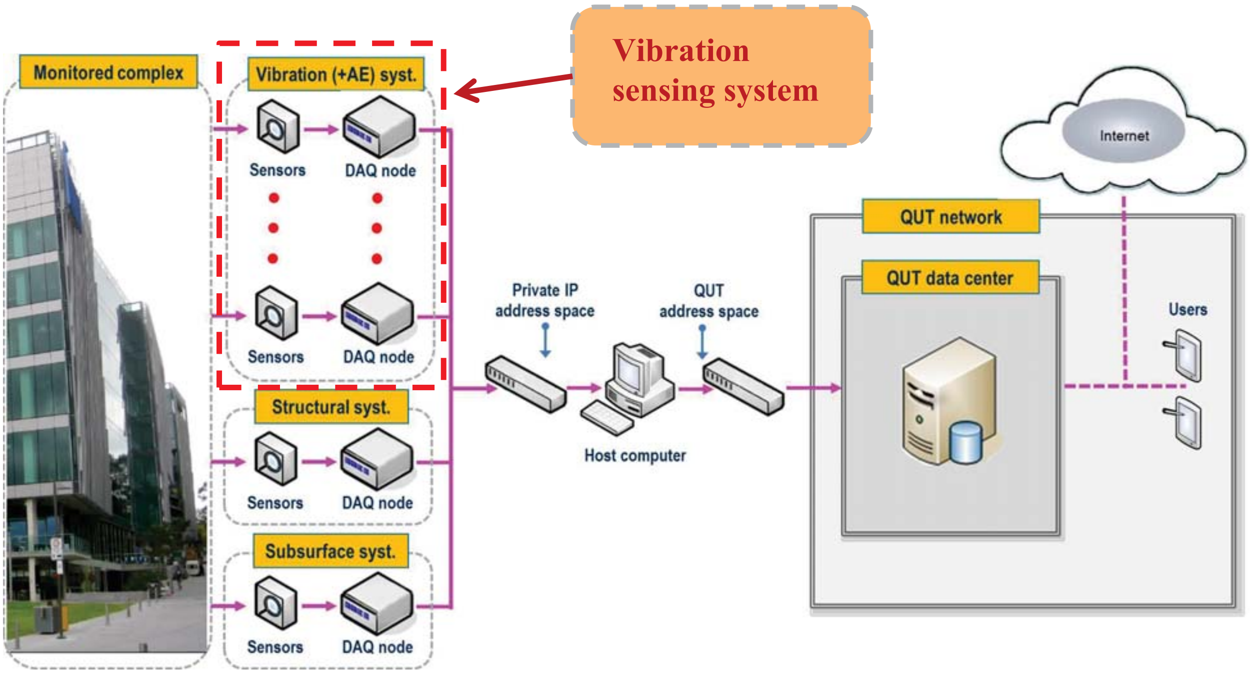
EXAMPLES OF LATEST DEVELOPMENT

A real-world testbed

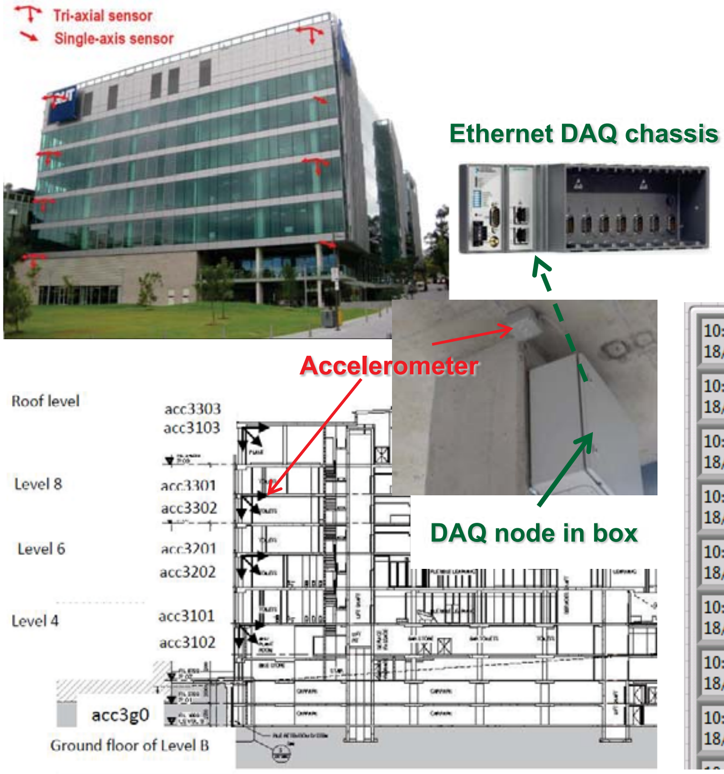


- P block
  – the main site for system deployment
- 3 systems: vibration (accel-based), structural (strain-based) & subsurface monitoring

Diagram of monitoring systems



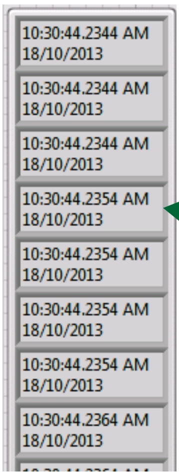
AE: Acoustic Emission (with two sensors) sharing one DAQ with the accelerometers nearby



Data synchronization solutions

Due to **sparse coverage**

~~Traditional **hardware-based** synchronization **very costly** as it requires a **dedicated synchronization network**~~

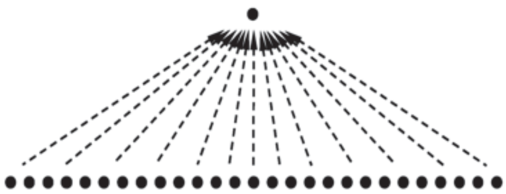


→ Use **TCP/IP command based synchronization**

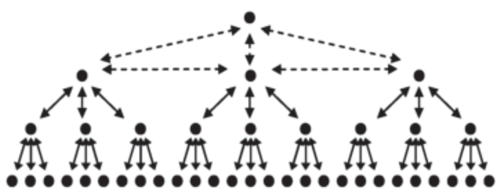
- **Initial synchronization** provided by **high-resolution timestamp**
- **Synchronization** with **time** maintained simply by **periodic resynchronization**

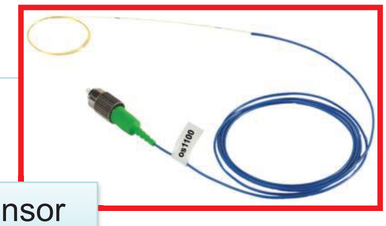
Decentralized Data Collection

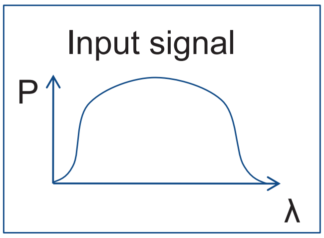
Centralized System:
Each sensor node transmits data directly to the base station



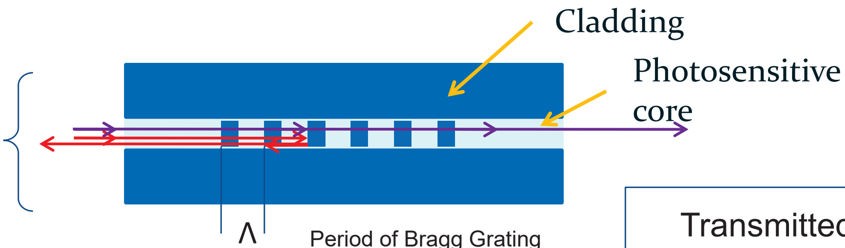
Decentralized System:
Representative sensor nodes collect the data and transmit to the base station



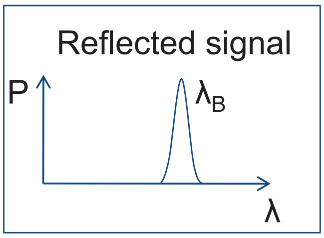


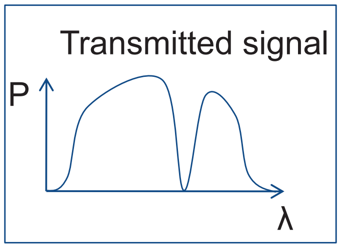


FBG (Fiber Bragg Grating) Approach
-Measure the vertical displacement indirectly



$\lambda_B = 2\Lambda n_{eff}$





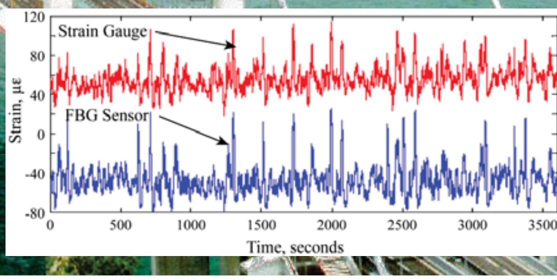
$$\Delta\lambda_B = K_\varepsilon \varepsilon + K_T \Delta T + K_P P$$

Cross-sensitivity of strain, pressure and temperature

What are their advantages?

- FBGs are extremely small and lightweight
- Immunity to electro-magnetic interference (EMI)
- Many FBG sensors (>100) can be created on a single strand of optical fibre.
- Permit remote sensing (>50 km)
- Non-corrosive and very stable
- Serve as both the sensing element and the signal transmission medium

Sensors Tested on the TMB and Railway



Sensor Illustration (cont'd)

- **FBG Strain Gauge: OS3100 (Micron Optics)**

Important Specs	
Gauge length	22 mm
Sensitivity	1.4 pm/$\mu\varepsilon$
Meas. Range	2,500 $\mu\varepsilon$

Sensitivity → $\frac{\text{Change in wavelength}}{\text{Strain}}$

Meas. Range → Much smaller than PL-60-11

- **FBG Temperature Sensor: OS4310 (Micron Optics)**

- Similar principle as FBG strain gauge considering the linear relationship between strain and temperature variation.

Important Specs	
Sensitivity	10 pm/°C
Meas. Range	-40 to 120°C
Response time	0.7 seconds

FBG-based displacement measurement

Methodology

Curvature approach

Curvature Measurement 2 pairs of FBG array

$$\kappa_i = \frac{\varepsilon_i^b - \varepsilon_i^t}{h}$$

Curvature data, k3

Curvature curve, K3

Vertical displacement function, D3

$$\iint \kappa \, dx \, dx$$

Inclination approach

Slope Measurement 5 FBG tilt sensors

Slope data, s2

Slope curve, S2

Vertical displacement function, D2

$$\int \theta \, dx$$

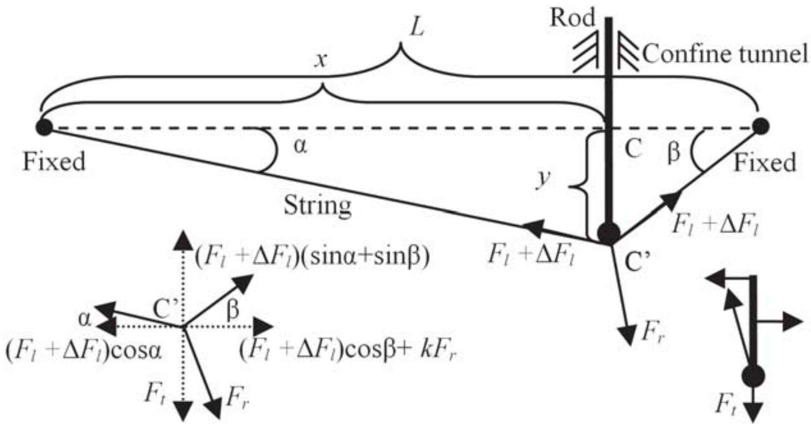
Comparing with reference

Interrogator, sampling of 1kHz

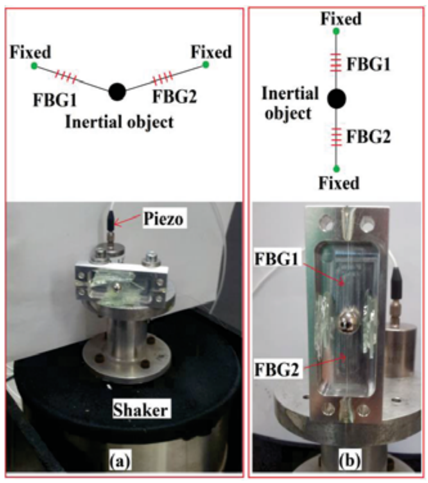
FBG: Fiber Bragg Grating

FBG-based accelerometer

Theory of the nonlinear string transverse force amplifier

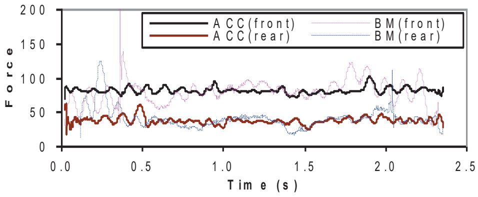


Biaxial FBG-based Accelerometer



FBG: Fiber Bragg Grating

Force Identification for prestressing tendon/bridge cable



The project aims to develop various methods to identify prestressing forces by:

- ✓ Using MFI methods
- ✓ Using VBDI methods
- ✓ Non-destructive testing techniques such as EMAT

Intended to be validated with real highway/pedestrian bridges such as Neville Hewitt bridge in Rockhampton (pictured) and V-Z link bridge at QUT

MFI: Moving Force Identification; VBDI: Vibration Based Damage Identification; EMAT: Electromagnetic Acoustic Transducers

Thank you for your attention!

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