Chapter 3. Health Sensing for PHM

Prognostics and Health Management (PHM)

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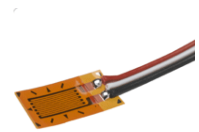
CONTENTS

1. Introduction

Objective of Health Sensing

- To acquire the health-relevant signal in a cost-effective and highly detectable manner
- Sensor Selection
  - To select proper sensors capturing health-relevant signal

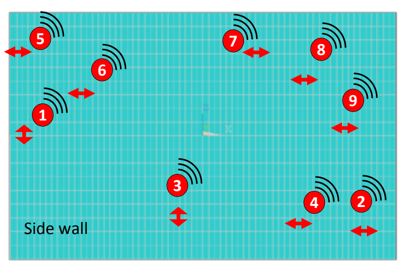
Acceleration



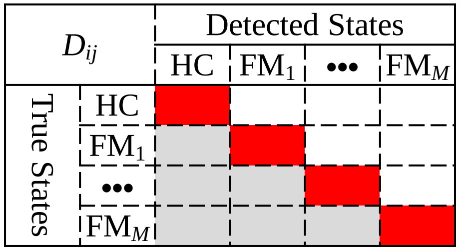
Strain

Temperature

- Data Acquisition
  - Amount of data, sampling rate/duration/period, logging capability, optimal DAQ system
- Sensor Networks Design
  - Optimizing sensor position, minimizing the number of sensors



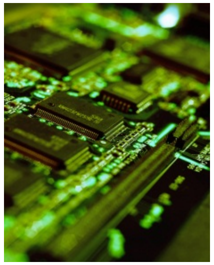
Confusion (or Detectability) Matrix



1. Introduction

Various Sensors for PHM

Thermal Sensor	Acoustic Sensor	Strain Sensor	Current Voltage Sensor	Vibration Sensor	Oil Sensor	Load Sensor	Flow Sensor
Electric components hot spots	Component excitation	Stress level	Cabling isolation faults	Acceleration, velocity, displacement	Components with excessive wear	Stress	Hydrometer Flux
Electronics, Bearings	**Bearings, Gearboxes, Engines**	**Blades, Bearings**	**Engine, Switches, Cables**	**Bearings, Gearboxes, Shafts**	**Bearings, Gearboxes, Engines**	**Rotor, Dams, Bridges**	**Hydraulic Components**


Electronics


Gearboxes


Blades


Cables


Bearings


Engines


Rotor


Hydraulic Component

2. Failure Identification

Failure Modes, Effects and Criticality Analysis (FMECA)

- FMECA is a disciplined method to identify and analyze :
  - All potential failure modes of the various parts of a system
  - Effects of the failures may have on the system
  - How to avoid the failures, and/or mitigate the effects of the failures on the system

- Purposes in System Design Process
  - Assist in selecting design alternatives with high reliability and high safety for avoiding the failure modes
  - Provide an effective method for evaluating the effect of proposed changes to the design and/or operational procedures on mission success and safety

- Purposes in Prognostics and Health Management (PHM)
  - Provide information of proper physical quantities to be acquired for fault diagnosis and prognosis
  - Develop early criteria for test planning and requirements for test equipment
  - Decide priorities of maintenance after some potential failures may happen

2. Failure Identification

Failure Modes, Effects and Criticality Analysis (FMECA)

- Bottom-Up Approach
  - Each component on the lowest level of indenture is studied one-by-one
  - The analysis is complete since all components are considered

- Top-Down Approach
  - The analysis starts with the main system functions and how these may fail
  - It will not complete, but it focuses on problem areas

- Procedure

Step 1: Define the system to be analyzed

Step 2: Understand operation principles of the system using diagram

Step 3: Identify failure frequency and modes in unit level

Step 4: Select the main unit and identify failure modes, effects and criticalities of it

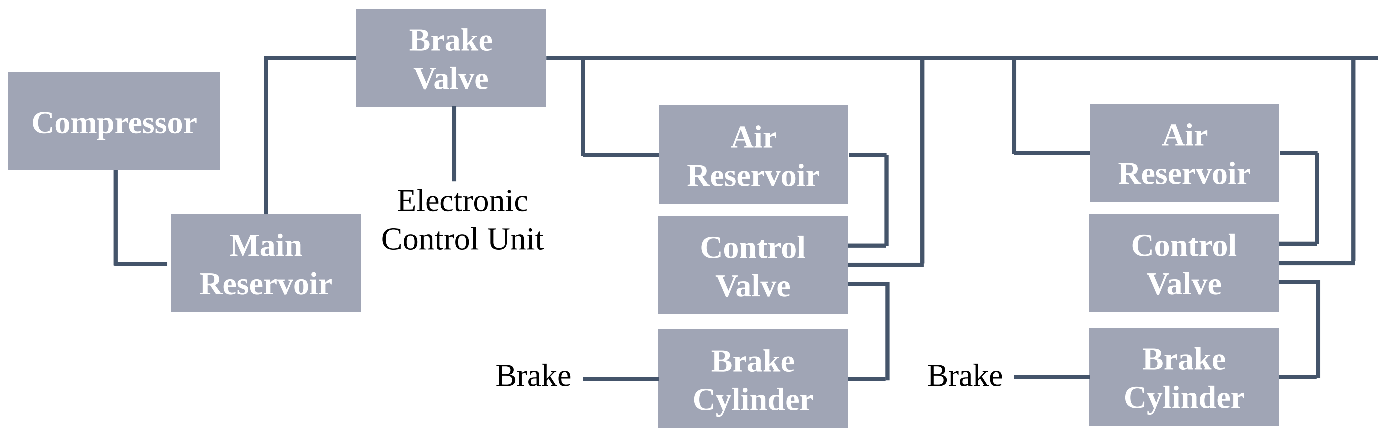
2. Failure Identification

Example: FMECA on Solenoid Valve in Urban Railway Vehicle

- Step 1: Define the system to be analyzed
  - Consider schematics and operational detail of the system
  - Clarify the function of the system and identify the system indenture levels

Major System (Railway Vehicle) → **System (Power Transfer)** → **Subsystem (Braking System)** → **Unit (Valve, Compressor)**

- Step 2: Understand operation principles of the system using diagram
  - A functional diagram representing the operation, interrelationship and interdependencies of functional entities of the system should considered
  - It provides the ability to trace the failure mode effects through each level of indenture



2. Failure Identification

Example : FMECA on Solenoid Valve in Urban Railway Vehicle

- Step 3: Identify failure frequency and modes in unit level
  - It provides a rationale to select the particular unit from the perspective of failure frequencies and modes

Unit	Air Compressor	Solenoid Valve
Failure Frequency	522 times for 13 years	1757 times for 13 years
Failure Mode	▪ Oil deterioration ▪ Rust by moisture	▪ Burnout of coils ▪ Rubber damage ▪ Debris accumulation

- Step 4: Select the main unit and identify failure modes, effects and criticalities of it
  - Based on the information obtained from this FEMCA and failure cause, some of physical quantities for detecting each failure mode can be considered

Item	Failure Mode	Failure Effect	Failure Criticality	Failure Cause	Signals
Solenoid coil	Burnout of coils	Abnormal valve bar behavior	20%	Interruption of coils	Current
Valve seat	Rubber damage	Valve bar jamming	10%	Fatigue failure	Pressure
	Debris accumulation	Air leakage	70%	Impurities in air	Pressure

2. Failure Identification

Accelerated Life Test (ALT)

- Purpose
  - The product life test would require a long-time test (e.g., $10^4 \sim 10^5$ hours) under normal stress condition
  - These cause practical difficulty when planning the tests and analyzing failure data

- ALT Applications
  - Materials testing and evaluation : concrete, metals, ceramics, fibers, plastics, etc.
  - Parts testing and evaluation : Semiconductors, bearings, motors, generators, etc.
  - Testing and evaluation of engineered systems : aircraft, automobiles, etc.

Acceleration Method (1/2)

- Compressed-Time Testing
  - Many products experience on-off operation cycles instead of continuous operation. (e.g. appliance doors are more frequently opened and closed)
  - The tests are frequently used, but the loads and environmental stresses are maintained at the level expected in normal use

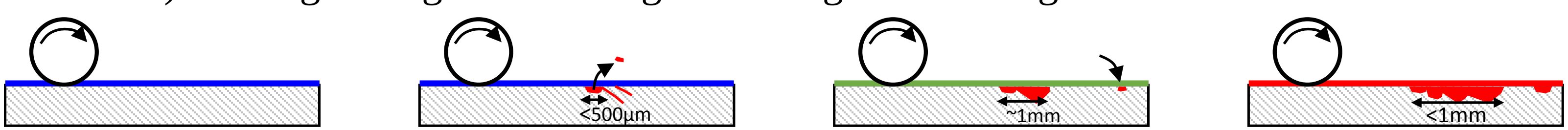
2. Failure Identification

Acceleration Method (2/2)

- Advanced-Stress Testing (or Physical Acceleration Testing)
  - Advanced-stress testing may be employed to accelerate failures, since as increased loads or harsher environments are applied to a device, an increased failure rate may be observed
  - Some engineering instances include :
    1) Electronics industry - components are tested at elevated temperatures to increase the incidence of random failure
    2) Nuclear industry - pressure vessel steels are exposed to extreme levels of neutron irradiation to increase the rate of failure

Conditions for ALT (1/2)

- Condition 1 : Determination of the rate stage
  - Faults rarely occur in response to a single physical or chemical reaction.
  - Ex) Bearing rolling contact fatigue and degradation stage



Sub-surface crack: Acoustic emission from crack	Spall initiation: Metal particle detached, Plastic deformation	Spall propagation: Friction, temperature ↑ Lubricant viscosity ↓	Extend spall & fatigue: Excessive heat from contact, Lubricant burn

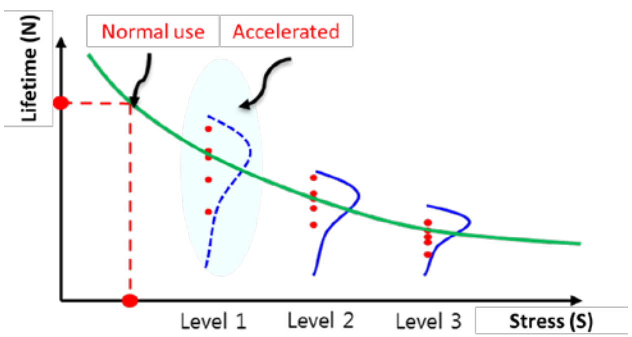
2. Failure Identification

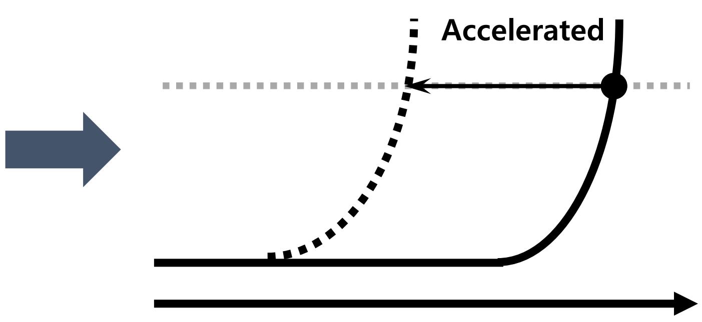
Conditions for ALT (2/2)

- Condition 2 : Consistency of the failure mechanism
  - Even if the same stress is applied, different failure mechanisms (e.g. physical, chemical, etc.) can occur depending on the stress level
  - Therefore, the applied stress level should be set appropriately within the operating limit

    Ex) Weibull Distribution: same failure mechanism → the same shape factor of the life distribution
- Condition 3 : Necessary condition of ALT for validity
  - Should satisfy $t_d = AF \times t_a$

t_d : lifetime under normal use condition
AF : acceleration factor
t_a : lifetime under accelerated condition

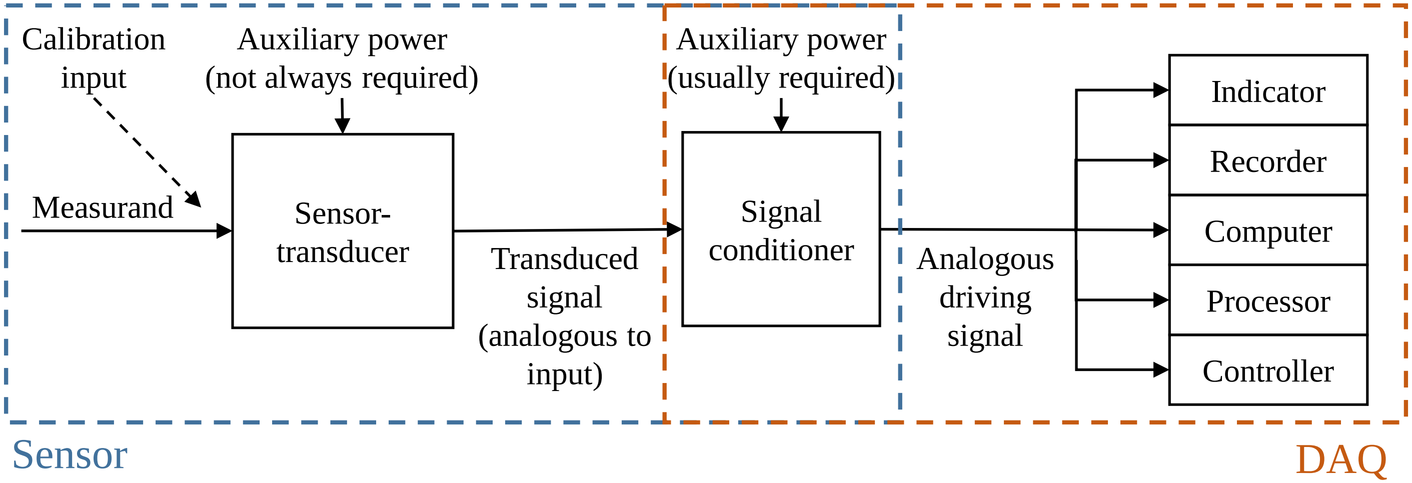




3. Fundamentals of Sensing System

Framework of Measuring Systems of Three Stages

- Stage 1. Sensor-transducer stage
  - The primary function of the first stage is to detect or to sense the measurands
  - Unwanted sensitivity is a measuring error, called noise
- Stage 2. Signal conditioning stage
  - To modify the transduced information so that it is acceptable to the third stage.
  - It may performs many operations, such as amplification, filtering to remove noise, analog-to-digital convertering, integration, differentiation, as may be required
- Stage 3. Readout-recording stage
  - The third stage provides the information sought in a form comprehensible to one of the human senses or to a controller

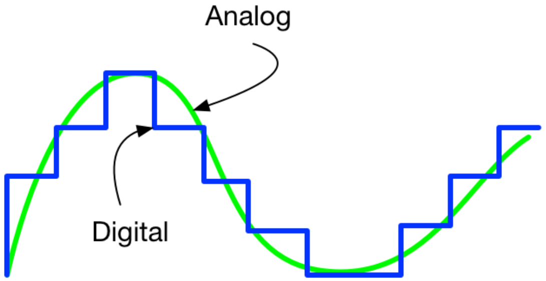


3. Fundamentals of Sensing System

Types of Input Quantities

- Classification of mechanical quantities by time dependence
  - Static : constant in time, the most easily measured
  - Dynamic : varying in time, can be classified as 1) steady state periodic and 2) nonrepetitive or transient

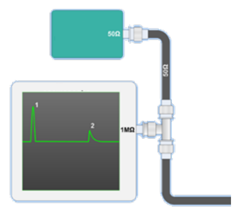
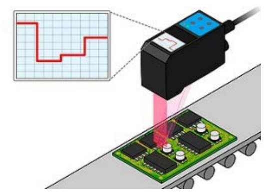
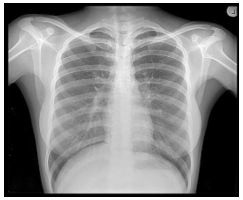
- Analog and Digital Signals
  - Analog signal: A signal whose magnitude is continuously changed with respect to time. The physical quantities that we commonly know and the values measured by analog sensors are analog signals
  - Digital signal: A signal whose magnitude is discontinuously changed with respect to time. Mechanical quantities normally behave in an analog manner. Distinct advantages are often obtained in converting an analog signal to an equivalent digital signal for the purposes of signal conditioning and/or readout



3. Fundamentals of Sensing System

Sensor Dimensionality

- Sensors measure through physical processes that span a multidimensional space–time environment. In most cases, these processes occur over single, multiple dimensions.

	Point sensors (0D)	1D sensors	2D sensors	3D sensors
Examples	accelerometer 	TDR 	2D imaging 	Radiography 

Precision and Accuracy

- Precision : The size of the smallest quantity that can be distinguished by a system
- Accuracy : The quality and/or confidence in a given measurement

Accurate
Precise

Not Accurate
Precise

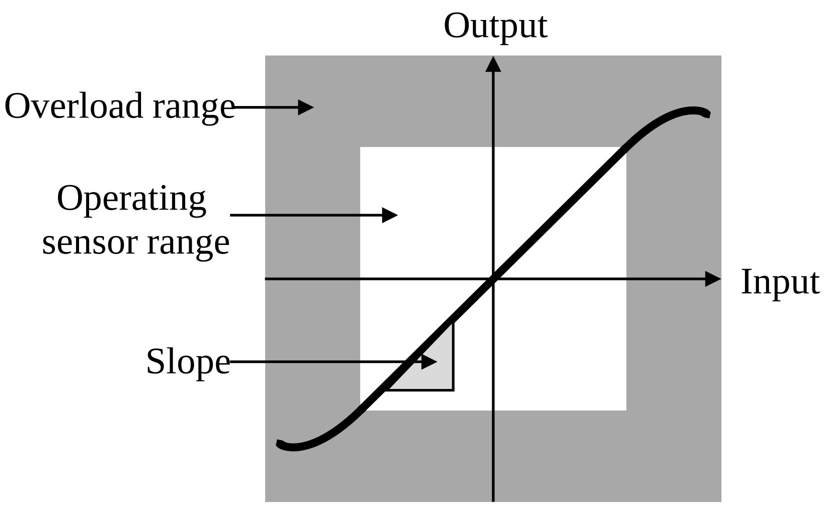
Accurate
Not Precise

Not Accurate
Not Precise

3. Fundamentals of Sensing System

Calibration

- Definition : The process to accurately measure the value of the physical quantities before using the sensor
- Single Point Calibration
  - If the output is exactly proportional to the input, a single simultaneous observation of input and output will suffice to fix the constant of proportionality



- $\text{output} = slope \times \text{input} + intercept$
- Intercept ideally has zero value, but is varied by circumstance (e.g. temperature, humidity, etc.)
- Slope and intercept values are normally provided by manufacturer.
- Slope usually has fixed value, but is varied in long-time usage

- Multipoint Point Calibration
  - Multipoint calibration works when the output is not simply proportional, and, more generally, improves the accuracy of the calibration

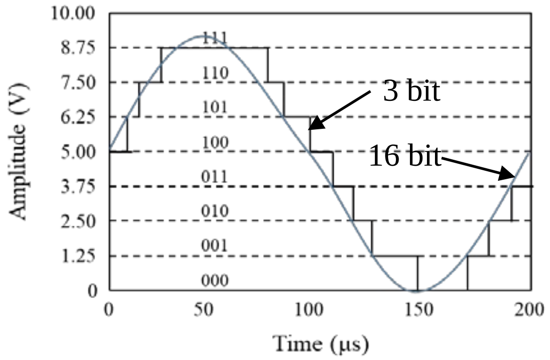
3. Fundamentals of Sensing System

Sensitivity

- Definition : The change of sensors output per unit change in the measured quantity
- A more sensitive sensor's reading changes significantly in response to smaller changes in the measured quantity
  - $\text{Sensitivity} = \frac{\text{Change in ouput}}{\text{Change in input}}$
- Sensitivity can be expressed as V/cm, V/g, V/(m/s^2), etc.

Resolution

- Definition : The smallest change it can detect in the quantity that it is measuring.
- In general, the number of bits represent the degree of resolution
- Higher bits, higher resolution (e.g. n bit device present analog signal with 2^n values)

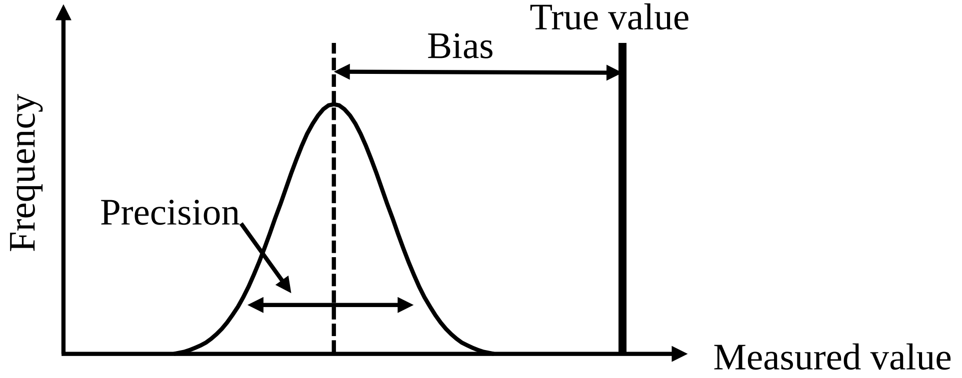


3. Fundamentals of Sensing System

Common Types of Error

- Bias Errors (also referred to as systematic errors)
  - Bias errors occur the same way each time a measurement is made
  - Example : If the scale on an sensor consistently reads 5% high, then the entire set of measurements will be biased by +5% above the true value

- Precision Errors (also referred to as random errors)
  - Precision errors are different for each successive measurement having an average value of zero
  - Example : Mechanical vibration may cause the reading of a measuring value to fluctuate about the true value, sometimes reading high and sometimes reading low



3. Fundamentals of Sensing System

Measurands

- Definition
  – Physical properties that are directly measurable with sensors

- Geometric Configuration : Displacement, Tilt and Flatness
  – Human eyesight and simple sensors can quickly measure geometric properties
  – All geometric measurements require an established reference frame with an associated coordinate system

- Kinematics : Displacement, Strain, Velocity, and Acceleration
  – Structural stiffness calculations and models often make use of displacement
  – Accelerations measurement are common due to low cost for measuring than velocities or displacements

- Kinetics: Force, Stress, Torque, Pressure
  – Indirect measurements (typically based on deformation) are more common
  – Example : Load cell for measuring a force actually measure the deformation of an internal elastic element and infers it from elastic force-deformation model

3. Fundamentals of Sensing System

Measurands

- Electromagnetic Properties: Impedance, Voltage, Current, Magnetic Flux
  - Direct measurements (typically based on voltage) are more common
  - Example : LCR meter measures impedances (resistance, capacitance, inductance) using frequency responses of voltage and current across specimen

- Chemical State: Corrosion, Dissolved Gas
  - Many experimental techniques (e.g. chromatography) can be used to measure or separate the target chemicals.
  - Example 1 : Hydrogen sulfide corrosively damage concrete sewer pipe
  - Example 2 : Dissolved gases in transformer oil are closely related to internal faults

- Others : Temperature, Moisture, etc.
  - A variety of sensors (e.g. thermometer: mercury, alcohol, bimetal, thermistor, infrared) can measure and transduce the information into an easily measured property, such as voltage, optical intensity, or direct digital readout.

3. Fundamentals of Sensing System

Dimensional Units of Sensing : International System of Units (SI System)

- Establishment of the SI System
  - Seven base units of SI System are listed in below left table
  - Other dimensions can be derived from these base unis by multiplication and division shown
  - A few such derived units are assigned special name shown in below right table

Quantity	Unit	
	Name	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	S
Electric current	Ampere	A
Temperature	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

Quantity	Unit		Other Unit
	Name	Symbol	
Angle	Radian	rad	$m \cdot m^{-1}$
Frequency	Hertz	Hz	s^{-1}
Force	Newton	N	$kg \cdot m \cdot s^{-2}$
Pressure, Stress	Pascal	P	N/m^2
Power	Watt	W	$N \cdot m \cdot s^{-1}$
Charge	Coulomb	C	$A \cdot s$
Voltage	Volt	V	W/A

3. Fundamentals of Sensing System

Dimensional Units of Sensing : International System of Units (SI System)

- Conversions between system of units
  - There are five systems listed in below table
  - System of units differs in their use of defined and derived units
  - In any case, whichever system is used, a consistent, compatible balance of units must be maintained

Quantity	Unit				
	SI	**CGS**	**English Engineering**	**Absolute English**	**Technical English**
Length	Meter (m)	Centimeter (cm)	Foot (ft)	Foot (ft)	Foot (ft)
Time	Second (s)	Second (s)	Second (s)	Second (s)	Second (s)
Mass	Kilogram (kg)	Gram (g)	Pound-mass (lbm)	Pound-mass (lbm)	slug
Force	Newton (N)	Dyne	Pound-force (lbf)	Poundal	Pound-force (lbf)

- Example : Determine the conversion factor between pounds-force and newtons
  - 1 lbf = 32.147 lbm·ft/s^2

$$= 32.147\ (0.453\ \text{kg})\ (12\cdot 0.0254\text{m})/\text{s}^2$$

$$= 4.448\ \text{kg}\cdot\text{m}/\text{s}^2$$

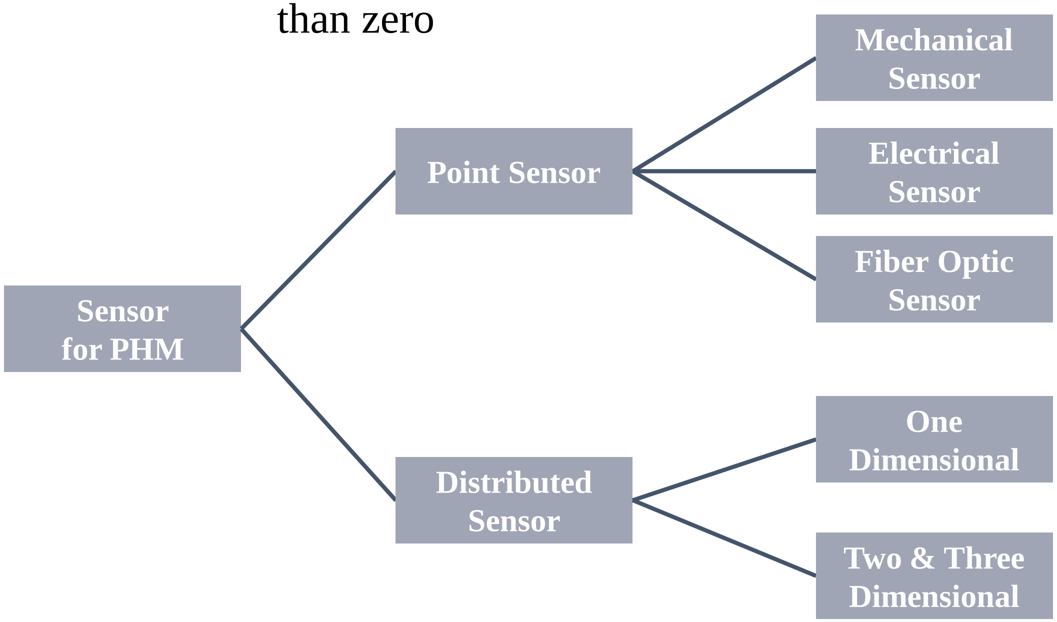
$$= 4.448\ \text{N}$$

4. Sensor Classification

Overview of Sensors

- Definition
  - A sensor is a device that detects or measures physical quantities and records, indicates or otherwise responds to these

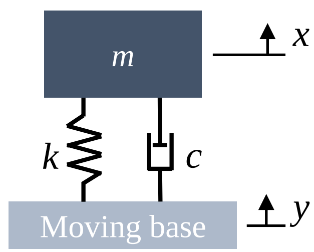
- Classification of Sensors
  - Point sensor : measure a region that is sufficiently small to be approximated as a point
  - Distributed sensor : measure over larger regions with an effective dimension greater than zero



4. Sensor Classification

Point Senor – Mechanical Sensors

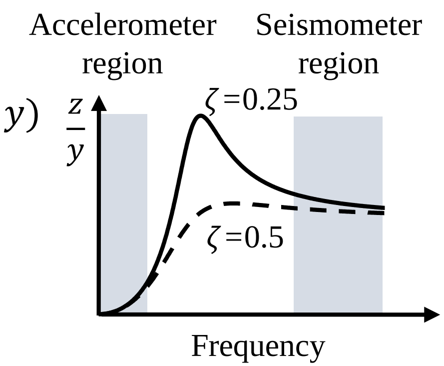
- Accelerometer
  - Purpose : measure acceleration relative to an inertial reference frame
  - Principle : measure the relative displacement of a spring-mounted proof mass w.r.t moving base



$$m\ddot{x} = -c(\dot{x} - \dot{y}) - k(x - y)$$

$$m\ddot{x} \cong -kz$$

(Light damping, $z = x - y$)



- Dial Indicator and Demec Gage
  - Dial indicator : measure relative displacement between two solid surfaces
  - Demec gage : measure two reference points that are fixed onto a structural element

4. Sensor Classification

Point Sensor – Mechanical Sensors

- Gyroscope Sensor and Microphone
  - Gyroscope sensor : measure rotation and orientation using gravity
  - Microphone : measure acoustic pressure

- Schmidt Hammer and Portable Indenter
  - Schmidt hammer : estimate the strength of a brittle material by measuring the amount of energy absorbed during a standardized hammer impact
  - Portable indenter: measure the hardness of a material from indentation (e.g. Brinell hardness testing, Vickers hardness testing)

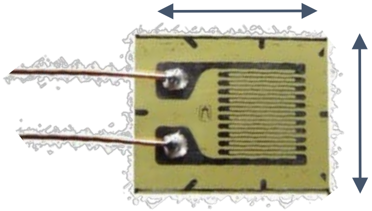
4. Sensor Classification

Point Sensor – Electrical Sensors

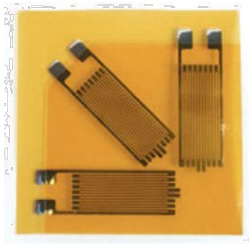
- Strain Gage
  - Purpose : measure mechanical strain on the structure
  - Principle : measure electrical resistance change of the strain gage in response to deformation (e.g., elongation, compression) called piezoelectric effect

Tension increased resistance

Measured resistance form circuit



Insensitive to lateral force



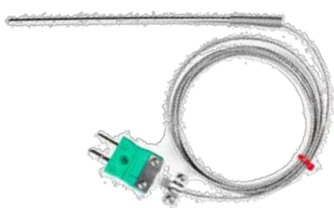
Rosette strain gage for 2D

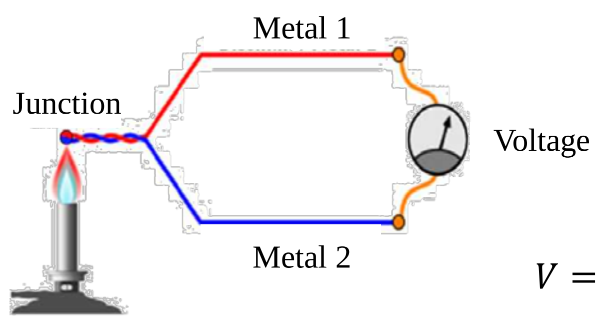
- Load Cell and Pressure Sensor
  - Load cell : measure forces and loads using piezoresistive strain gage
  - Pressure sensor : measure pressure using piezoresistive strain gage

4. Sensor Classification

Point Sensor – Electrical Sensors

- Thermocouple
  - Purpose : measure the temperature difference between two positions
  - Principle : produce a temperature-dependent voltage as a result of Seeback effect and this voltage can be interpreted to temperature





Seeback Effect

$$\nabla V = -S(T)\nabla T$$

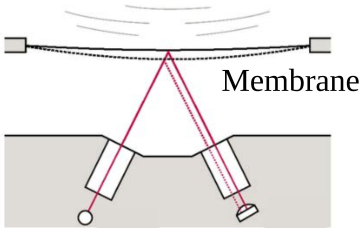
$$V = \int_{T_{ref}}^{T_{sense}} \left(S_{+}(T) - S_{-}(T)\right) dT$$

- Capacitance Sensor and Water Absorption Detector
  - Capacitance sensor : measure capacitance of conductive or dielectric material
  - Water absorption detector : measure the moisture of insulators by capacitance change

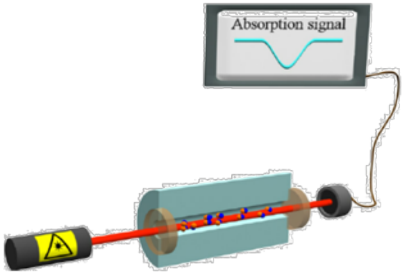
4. Sensor Classification

Point Sensor – Optic Sensors

- Optical Microphones
  - Purpose : measure the acoustic (sound) pressure
  - Principle : measure changes in light intensity reflected from an vibrating membrane fluctuating sound waves and transform these into sound signal



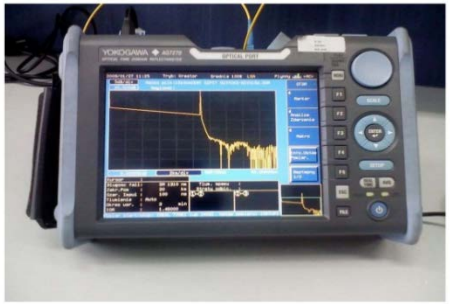
- Light Sensor and Laser-based Gas Sensor
  - Light sensor : measure the intensity or brightness of light
  - Laser-based gas sensor : defect and quantify gases from absorption of energy of light

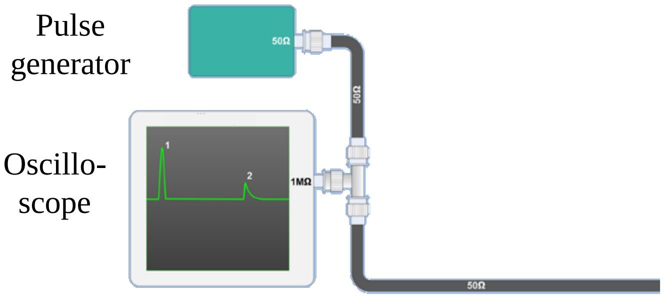


4. Sensor Classification

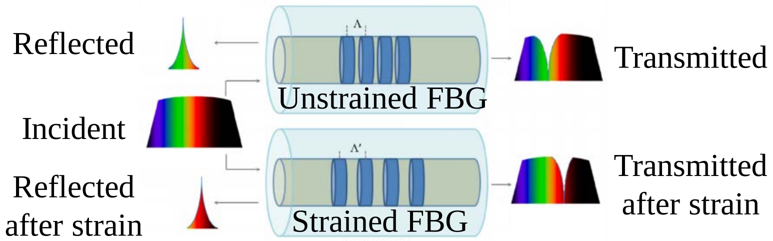
Distributed Sensor – 1D

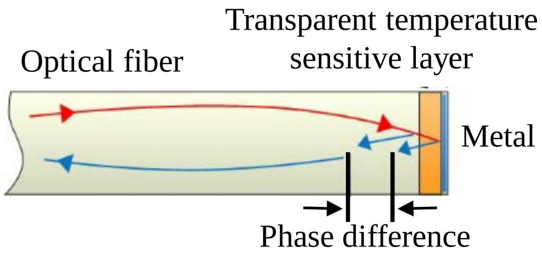
- Time Domain Reflectometry (TDR)
  - Purpose : characterize faults and these location in metallic cables
  - Principle : transmit an incident signal onto the conductor and measure the condition of reflected signal considering the impedance mismatch





- Fiber Bragg Grating (FBG) Sensor and Fiber Optic Interferometer
  - FBG sensor : measure the vibration using the reflected wavelength of light caused by bragg scattering and deformed cable (raman scattering)
  - Fiber optic interferometer : measure temperature from optical phase difference (Rayleigh)

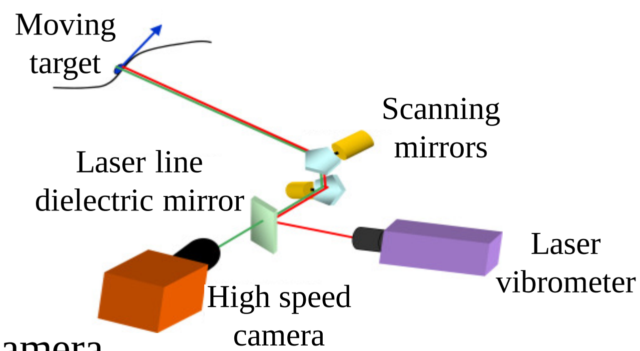




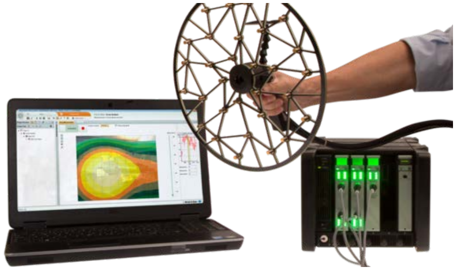
4. Sensor Classification

Distributed Sensor – 2D and 3D

- Laser Doppler Vibrometer (LDV)
  - Purpose : measure the acceleration, velocity and displacement and image these
  - Principle : the laser from the LDV is directed and the information of vibration is extracted from the Doppler shift of the reflected laser beam frequency



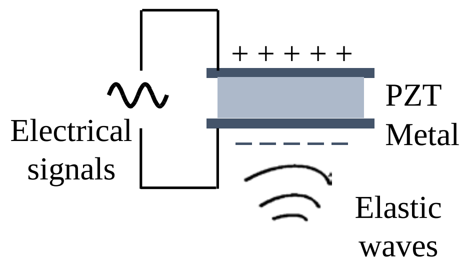
- Thermographic Camera and Acoustic Camera
  - Thermographic camera : form images using radiation for finding overheating part
  - Acoustic camera : visualize the pressure field for characterizing the location and amplitude of sound sources

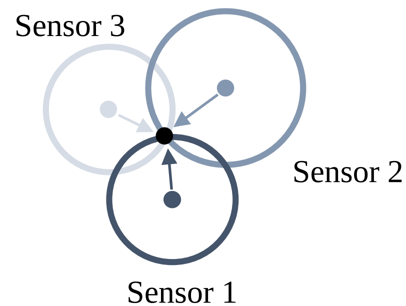


4. Sensor Classification

Distributed Sensor – 2D and 3D

- Acoustic Emission (AE) Testing and Sensor
  - Purpose : detect faintest surface movements of elastic waves released from fractures and find the location of these
  - Principle : piezoelectric effect and triangulation



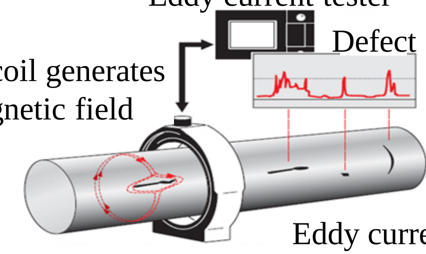


- Metal Particle Counter and Ground Penetrating Radar Testing
  - Metal particle counter : detect and count metal particles from wear
  - Ground penetrating radar testing : image the subsurface using electromagnetic radar

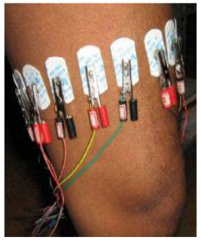
4. Sensor Classification

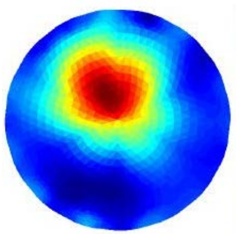
Distributed Sensor – 2D and 3D

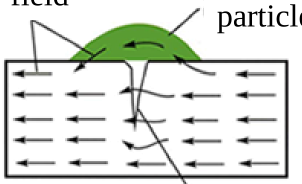
- Eddy Current Testing (ECT) and Proximity Sensor
  - ECT : detect the crack measuring disturbances in the magnetic fields by eddy current
  - Proximity sensor : detect the presence of nearby objects by emitting the magnetic field and looking for changes in the field



- Electric Impedance Tomography (EIT) and Magnetic Particle Imaging (MPI)
  - EIT : form tomographic image the conductivity, permittivity and impedance of objects
  - MPI : identify cracks and other defects in ferromagenetic material





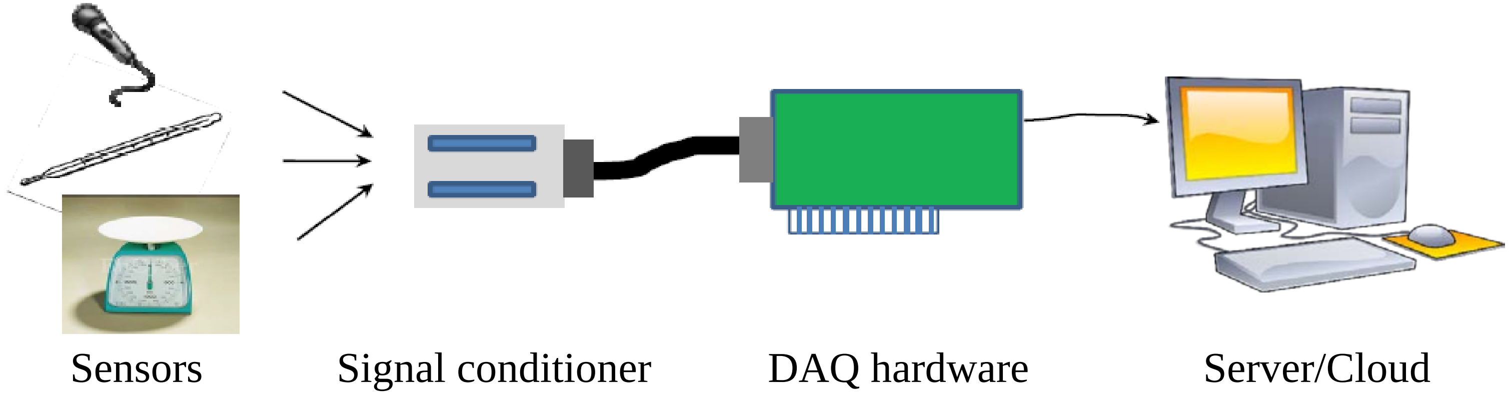


5. Data Acquisition and Sensor Networks

Data Acquisition (DAQ)

- Definition
  - The process of measuring electrical or physical phenomena such as voltage, current, temperature, pressure, or noise.

- DAQ system
  - DAQ system consists of sensor, signal conditioner, DAQ hardware, computer & software
  - Sensors : transform measured physical quantities into voltage or current
  - Signal conditioner : amplify the sensor output voltage or to filter the noise
  - DAQ hardware : convert the voltage output from a sensor or conditioner into a computer-readable digital signal



5. Data Acquisition and Sensor Networks

Data Acquisition (DAQ)

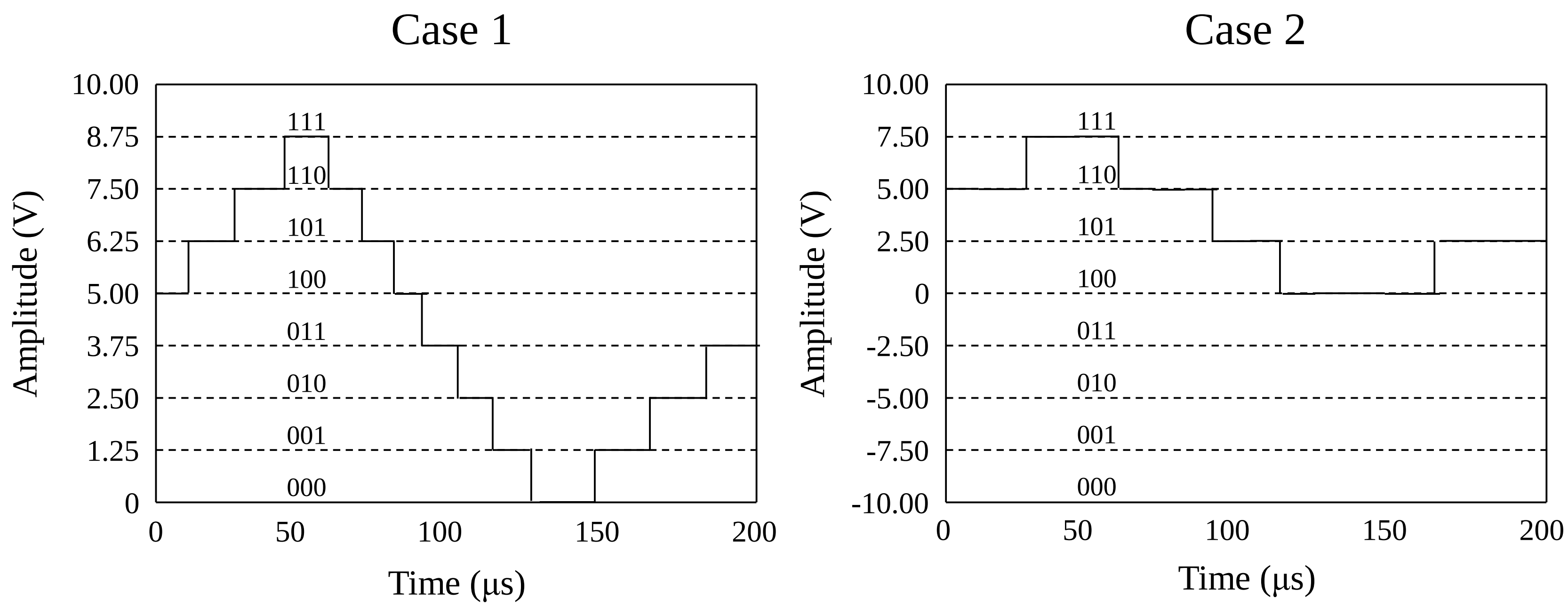
- Functions of DAQ Hardware
  - Analog input : measure analog signals (e.g. oscilloscope)
  - Analog output : analog signal generation and output (e.g. function generator)
  - Digital input : measure digital signals
  - Digital output : digital signal generation and output
  - Counter input : measure frequency, cycle, number of digital pulse
  - Counter output : digital pulse generation and output function

- Analog-to-Digital Converter (ADC)
  - Since computers recognize digital signals, analog signals must be converted to digital signals.
  - Resolution of ADC : A measure of how precisely an analog value is decomposed when the ADC converts an analog signal to a digital signal
  - The higher the number of bits, the better the resolution
  - The better the resolution, the more accurately converted to a digital value
  - Ex) If analog input range 0 ~ 10V,
    1 bit ADC: divide into two values (e.g. 0V or 5V)
    n bit ADC: divide into 2^n values

5. Data Acquisition and Sensor Networks

Data Acquisition (DAQ)

- Analog-to-Digital Converter (ADC)
  - To collect the signal with the maximum resolution, the ADC's range of use is properly set according to the range of the input signal.
  - Ex) Resolution difference according to input range of ADC
    case1: 0 ~ 10 V analog input, 3 bit ADC
    case2: -10 ~ 10 V analog input, 3 bit ADC



5. Data Acquisition and Sensor Networks

Sensor Networks

- Definition
  - Distributed networks of small and lightweight sensors to monitor engineered system

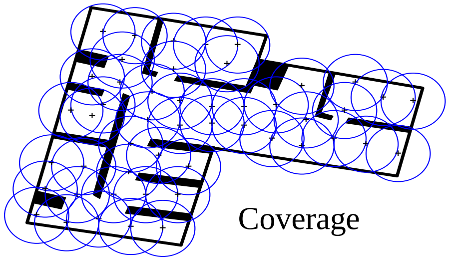
- Components in Sensor Networks
  - Assembly of distributed or localized sensors
  - Central point of information clustering
  - Set of computing resources at the central point to handle data correlation and data mining

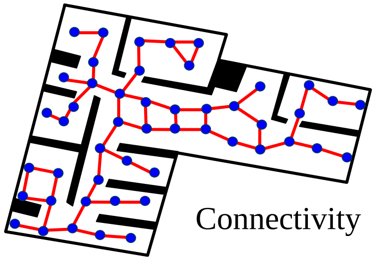
- Networked vs Individual Sensors
  - Extended range of sensing : Cover a wider area of operation
  - Redundancy : Multiple nodes close to each other increase fault tolerance
  - Improved accuracy : Sensor nodes collaborate and combine their data to increase the accuracy
  - Extended functionality : Sensor nodes can not only perform sensing functionality, but also provide forwarding service

5. Data Acquisition and Sensor Networks

Sensor Networks

- Sensor Placement
  - Placement of sensors to monitor fault indicators and signatures accurately and robustly in a critical military or industrial system constitutes an essential function of PHM
  - A good sensor placement should consider both coverage and connectivity (C&C)





  - How to place the least number of sensors in a field to achieve desired C&C properties?

Step 1: Partition the sensing field

Step 2: Place sensors in a single-row region

Step 3: Place sensors in a multi-row region

Step 4: Optimize the location and number of sensors considering C&C

5. Data Acquisition and Sensor Networks

Wireless Sensor Networks (WSN)

- Definition
  - Wireless network consisting of spatially distributed autonomous device using sensors to monitor physical or environmental conditions

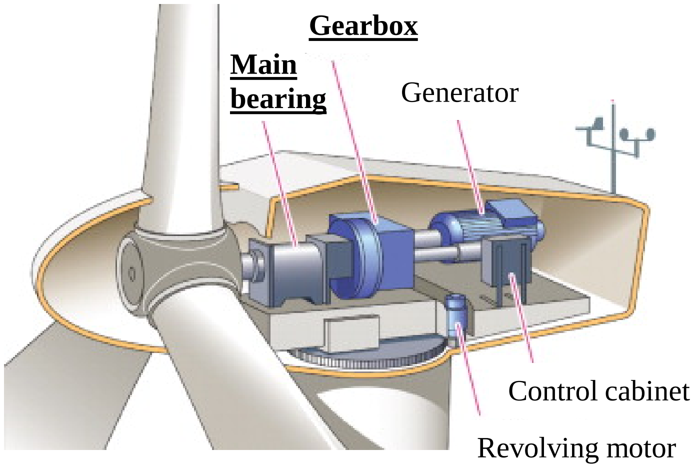
- Characteristics of WSN
  - Robust in harsh and hostile environments where wired sensors can't be deployed
  - Scalable and dense WSN construction for PHM
  - Low cost and computational power
  - Ability to cope with sensor nodes failure (→Resilience)
  - Power consumption constraints for sensor nodes (→Energy Harvesting)

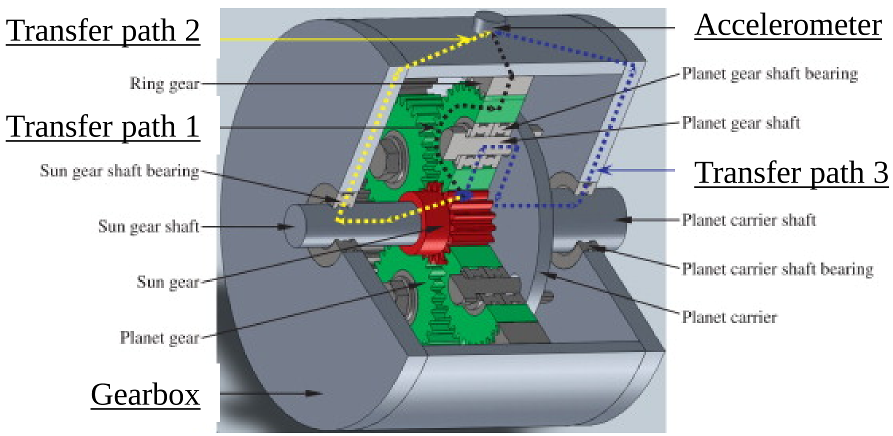
- Applications of WSN
  - Structural health monitoring
  - Internet of Things (IoT)
  - Cyber Physics System (CPS)
  - Smart factory

6. Case Study: Wind Turbine Main Bearing & Gearbox

Sensor Type – Accelerometer, Tachometer, Thermometer, Particle sensor, …

- Characteristics
  - Need to consider load transfer paths for locating sensors
- Standard
  - IEC 61400-25, ISO 10816-21, …
  - Specify the measurement target, location, type, method, …



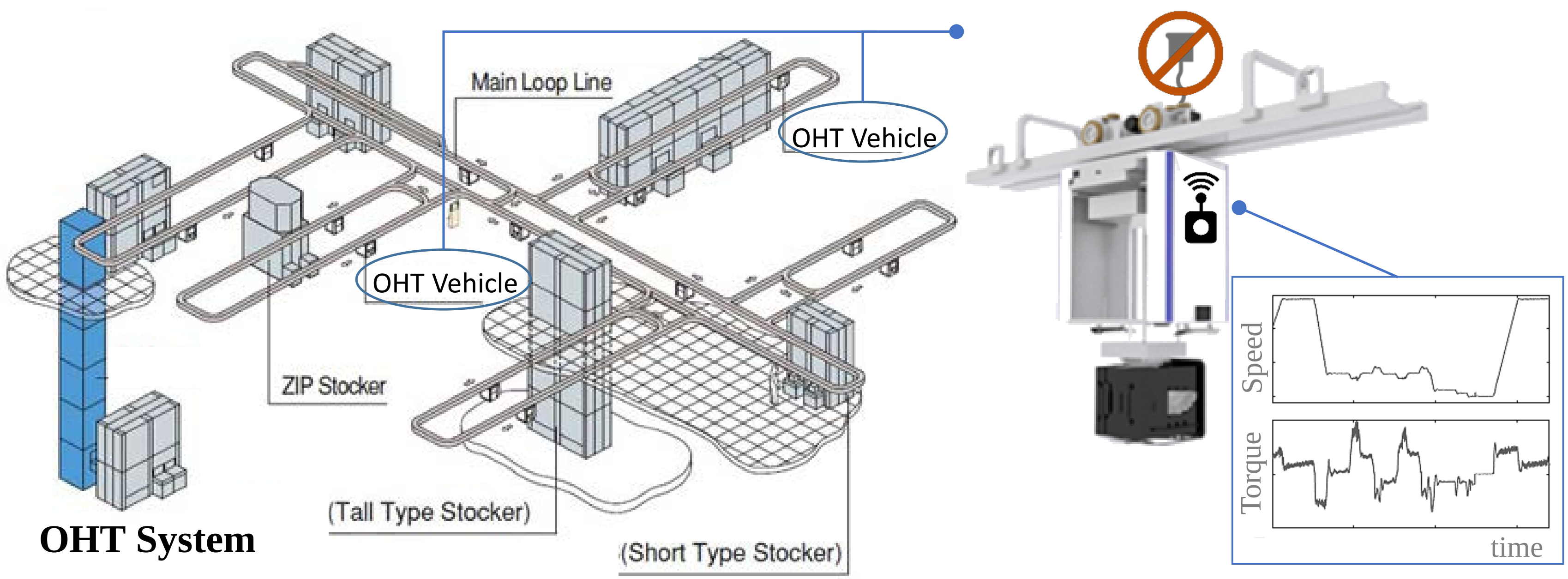


Target	Location	Type
Gearbox	Input bearing axial, radial	Acceleration
	Output bearing axial, radial	Acceleration
	Oil cleanliness	Particle count
Main bearing	Axial, radial	Acceleration
	Rotational	RPM

6. Case Study: Overhead Transport (OHT)

Sensor Type – Current sensor and Encoder embedded in a servo drive

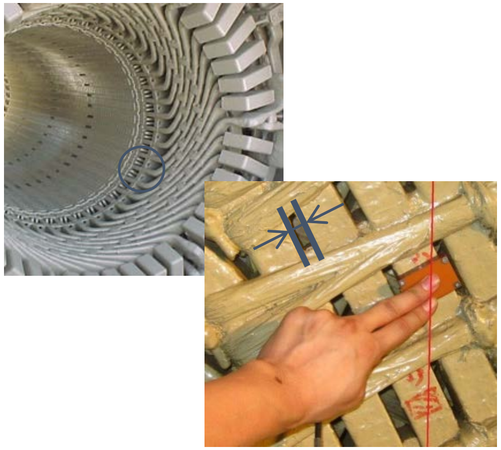
- Characteristics
  - Hard to install health-relevant sensors (e.g., accelerometer)
  - Complicated operating conditions (e.g., straight, stepped, branch, …)
- Acquire control signals originally measured for feedback control purpose
  - Command torque calculated by current
  - Speed calculated by encoder
  - One wireless DAQ per OHT vehicle



6. Case Study: Power Generator

Sensor Type – Wet Bar Detector (Water Absorption Detector)

- Measuring the capacitance of the ground wall insulation
- Estimating the extent of water penetration indirectly; WET insulation ⇨ HIGH capacitance
- Non-destructive to the stator bar
- Measurement procedure:
  - Clean the bars to assure proper contact before the test
  - Attach the probe to bars within three-inch of the bar armor
  - Measure the capacitance on given points



Output

$$\boxed{C} = \varepsilon_r \varepsilon_0 \frac{A}{t}$$

- **Capacitance [pF]**

ε_r: Relative static permittivity
$\boldsymbol{\varepsilon_{water}}$: 80.4
$\boldsymbol{\varepsilon_{mica}}$: 5.6 - 6.0

ε_0: Electric constant
(~ 8.854x10-12 F/m)

A: Area of tester

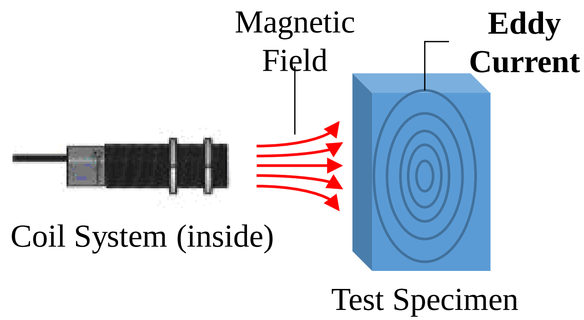
t : Thickness of insulation

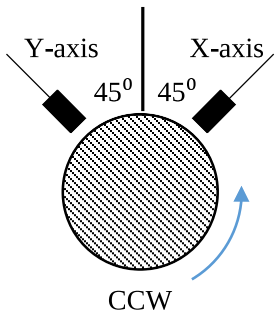
- **Irregular measurement:** Once every 2 or 3 years;

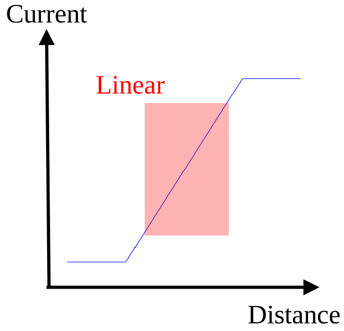
6. Case Study: Steam Turbine Rotor

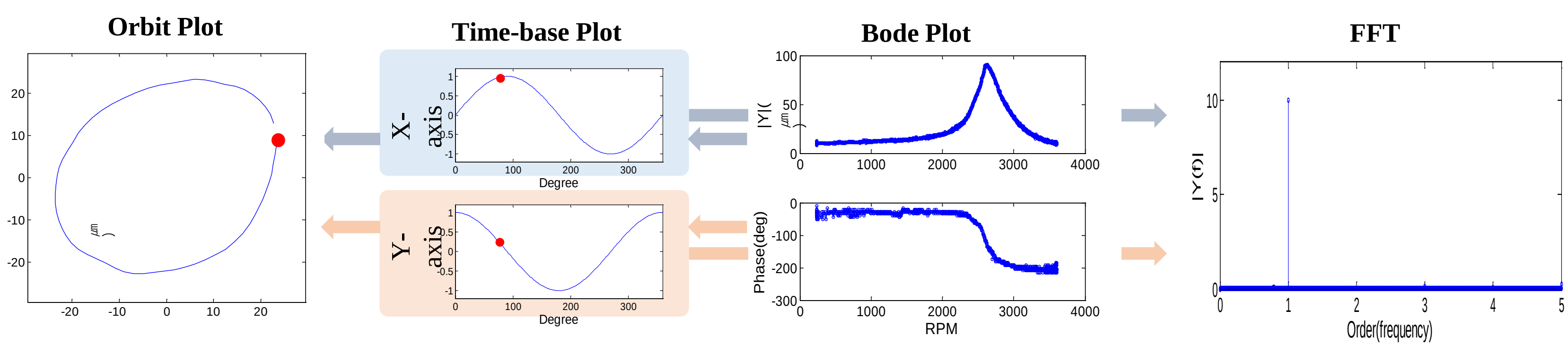
Sensor Type – Proximitor Sensor

- Characteristics
  - Gap measurement sensor using eddy current variation
  - 0.1 μm unit resolution & high accuracy
  - AC & DC measurement
- Data Acquiring Method
  - 2 sensors in 90 deg. to sense each axis behavior
  - Max / Min value limited by linear correlation of voltage and displacement
- Acquired Data
  - Two raw signals from a position



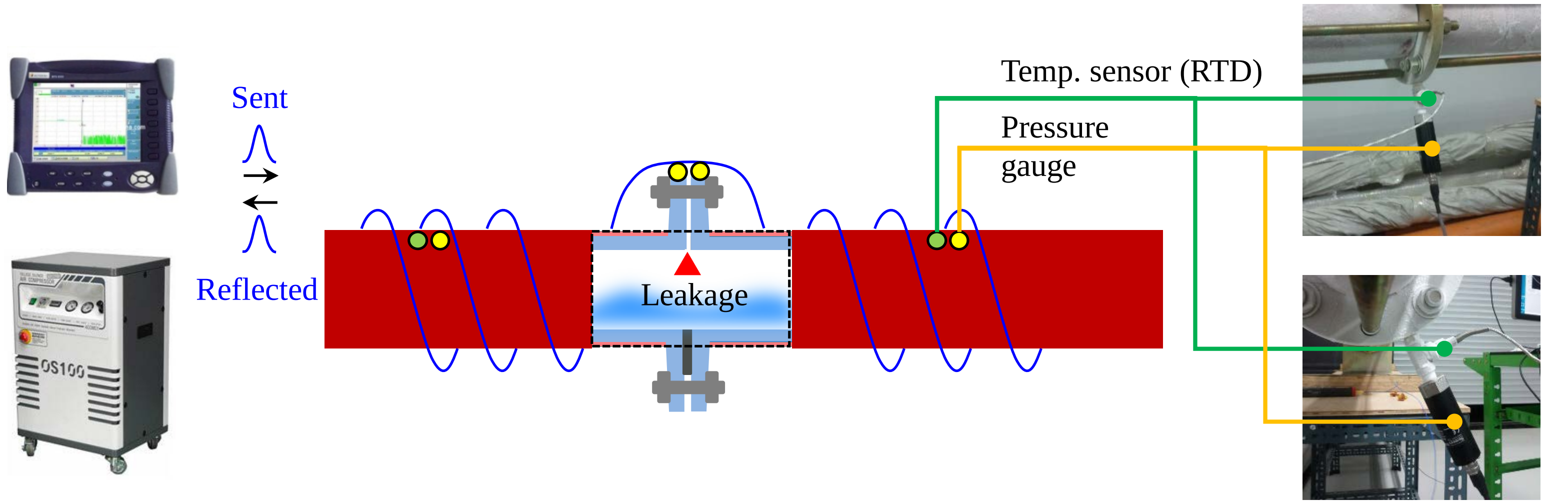






6. Case Study: Smart LNG Plants

Sensor Type – OTDR Test Equipment



OTDR Test Setting

- OTDR : MTS8000 (JDS Uniphase Corporation)
- Optical Fiber : Single mode bare (Helically Installed)
- Fiber Length : 1134m
- Point Sensors : 3 pressure gauges, 5 RTDs
- Inner flow : Dry ice (approx. -45°C)

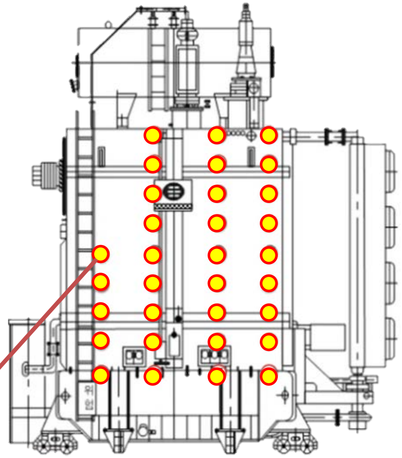
Test bed for OTDR verification test

6. Case Study: Power Transformer (1)

Sensor Type – Accelerometer

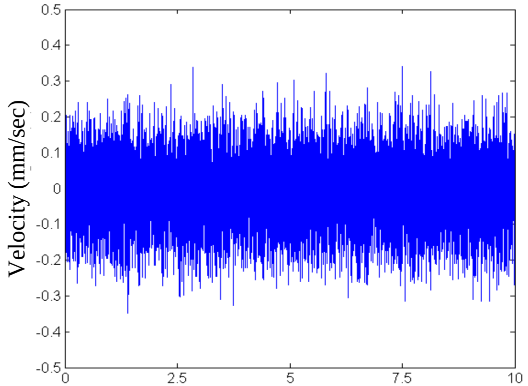
- Power Transformer
  - Single phase
  - Shell type
  - About 1000 MVA
  - Oil-filled

- Accelerometer
  - Charge-type
  - Magnet mount

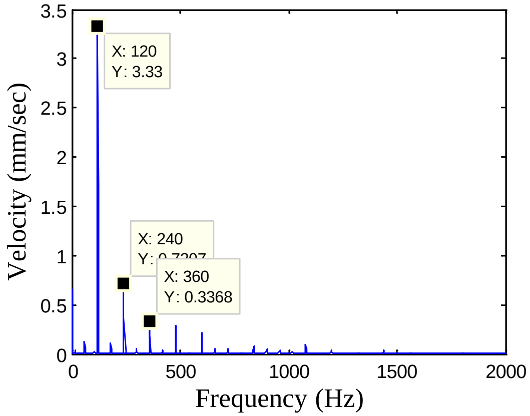


Data Acquisition

Time-domain signal



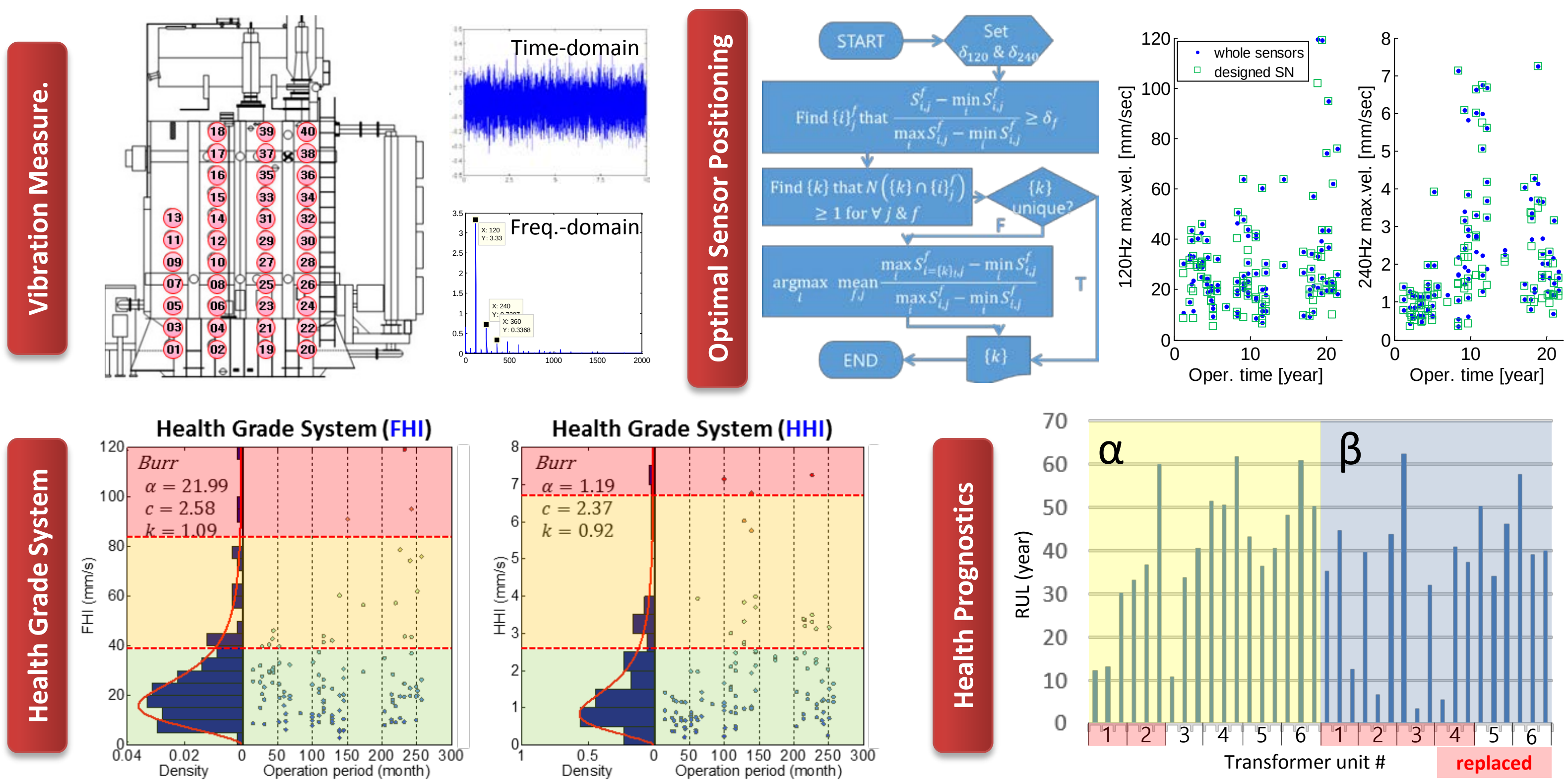
Frequency-domain signal



- Impossible to install sensors inside
- Detecting propagated vibration through oil
- 36~112 sensors/transformer
- Signals at every 1.25Hz (0~2kHz)

6. Case Study: Power Transformer (2)

Health diagnostics and prognostics of power transformers against mechanical faults



Optimal sensor positioning, Health grade system, Remaining useful life prediction

THANK YOU
FOR LISTENING

System Health & Risk Management

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