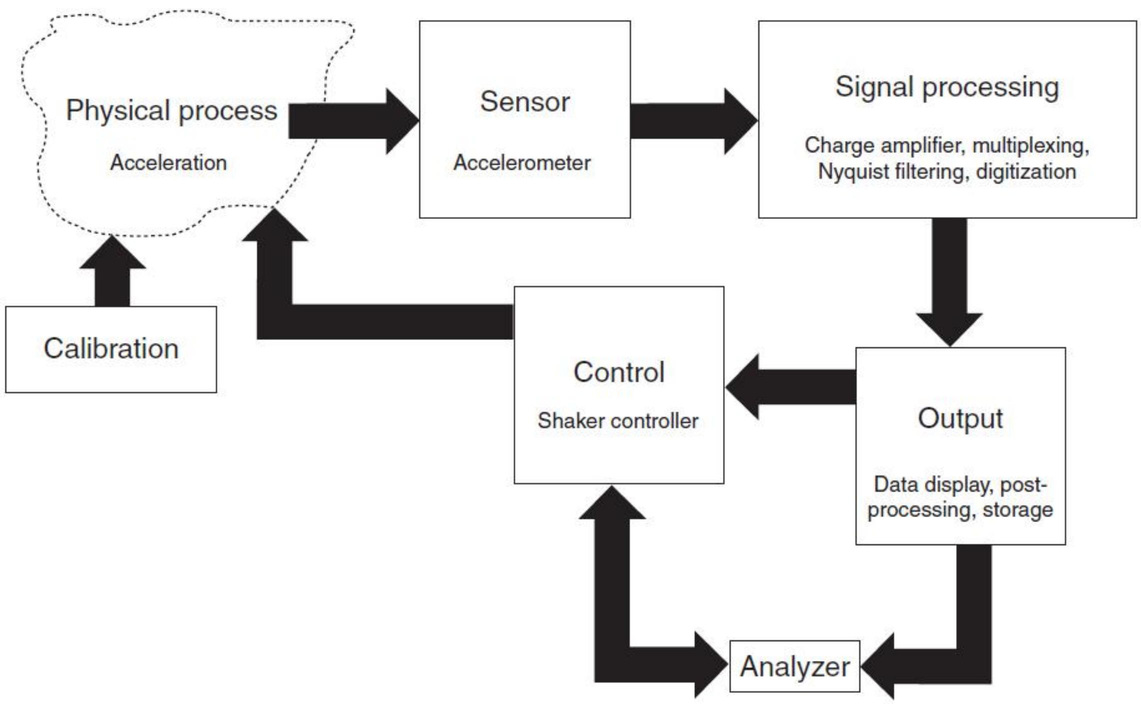
Unit-1
Sensor data acquisition systems and architectures

General measurement system

A very general schematic of a measurement system is shown in Fig. 2.1. The schematic shows the bridge between the physical process being detected (e.g., acceleration vibration of a structure) and the analyzer (the engineer



who reads and interprets output from the measurement system) as several modules. The first module is the *sensor module* , which consists of the physical element(s) that somehow interact with the system to sense the physical process and convert that information into a detectable signal form (e.g., an electrical voltage). For example, in a structural vibration application, the sensing module might consist of an accelerometer mounted to the structure; the accelerometer contains an inertial mass that moves in response to the host structure motion, and this inertial mass motion induces stress in some piezoelectric material, which causes an electric potential (voltage difference) to develop. Information from the sensing module proceeds to a *signal conditioning* *module* , which may have any of a number of functions that could be subdivided into analog functions (voltage amplification, some types of filtering, and possibly telemetry) and digital functions (timekeeping, digitization, triggering, master control). The signal conditioning module in this conception may be thought of as the 'brain' of the measurement system, as it is primarily responsible for taking raw information from the sensing module and converting it to a form suitable for display and analysis by the engineer (analyzer). In the accelerometer example, the signal conditioning module would contain a charge amplifier (the voltage differences produced by the piezoelectric effect are very small), a noise filter (to get rid of very high-frequency random processes), a Nyquist filter (tuned to the desired sampling frequency of the system), a multiplexing unit (for appropriately managing multiple accelerometer channels in simultaneous signal detection), some form of analog-to digital converter, and a controller with analog or digital trigger input/output, a buffer, and a master clock. Digital data are then sent to the *output module,* which provides an actual indication, in an appropriate form, of the measurement. The simplest module might be a digital word read-out of the measurement value on a display, although more commonly the digitized words are stored (either in RAM or on a digital storage medium) for interface with a personal computer. The most sophisticated output modules integrate post digitization data analysis (see Part I 'Sensor data interrogation and decision making' in Volume 2), usually with external software. Finally, data from the signal processing module may also interact with a *control module*, which contains some form of an active controller that interprets the output and feeds back that information to an actuator that can manipulate the physical process. This module is only present in active sensing applications; in the context of the accelerometer measurement, if part of the civil infrastructure application was to mitigate excessive levels of vibration, then some sort of control module would be present whereby acceleration signals are used as feedback to, say, hydraulic dampers, to actively reduce the acceleration. This control module is not meant to be confused with a number of activities that the signal conditioning module performs in controlling the data acquisition process such as timekeeping, filter setting, and so forth; all applications will have some sort of signal conditioning module that controls the data acquisition process, but only active sensing applications will have the additional separate control module that directs actions that explicitly affect the physical process being measured.

2.8 DATA CONVERTER INTEGRATED CIRCUITS

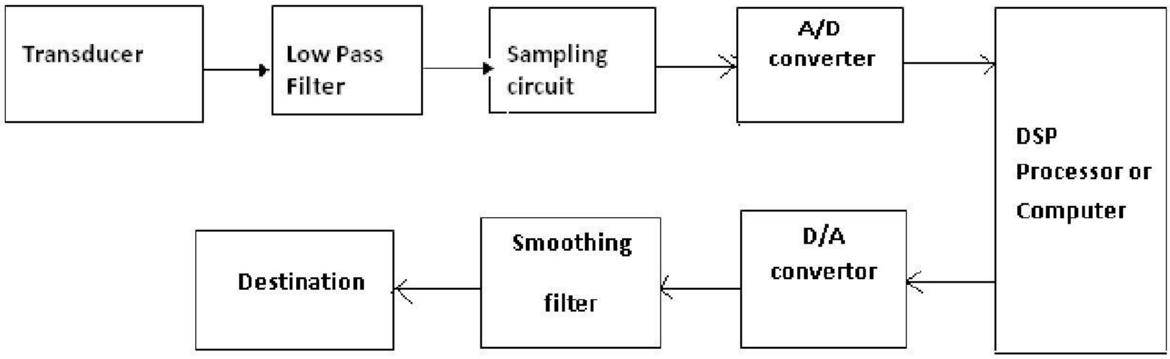


Fig 2.18: Application of A/D and D/A converters

Fig 2.15 shows the application of A/D and D/A converters. The transducer circuit will gives an analog signal. This signal is transmitted through the LPF circuit to avoid higher components, and then the signal is sampled at twice the frequency of the signal to avoid the overlapping. The output of the sampling circuit is applied to A/D converter where the **samples are converted into binary data i.e. 0's and 1's. Like this the analog data converted** into digital data.

The digital data is again reconverted back into analog by doing exact opposite operation of first half of the diagram. Then the output of the D/A convertor is transmitted through the smoothing filter to avoid the ripples.

2.9 BASIC DAC TECHNIQUES

The input of the block diagram is binary data i.e, 0 and 1,it contain 'n' number of input bits designated as **d1,d2,d3,…..dn .this input is combined with the reference voltage** called Vdd to give an analog output.

Where d1 is the MSB bit and dn is the LSB bit Vo=Vdd(d1*2-1+d2*2-2+d3*2-**3+…………………..+dn*2**-n)

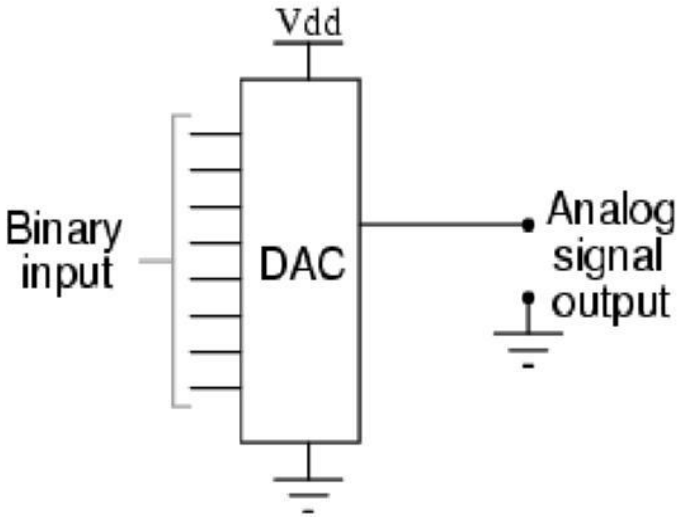


Fig 2.19: Basic DAC diagram

2.9.1 Weighted Resistor:

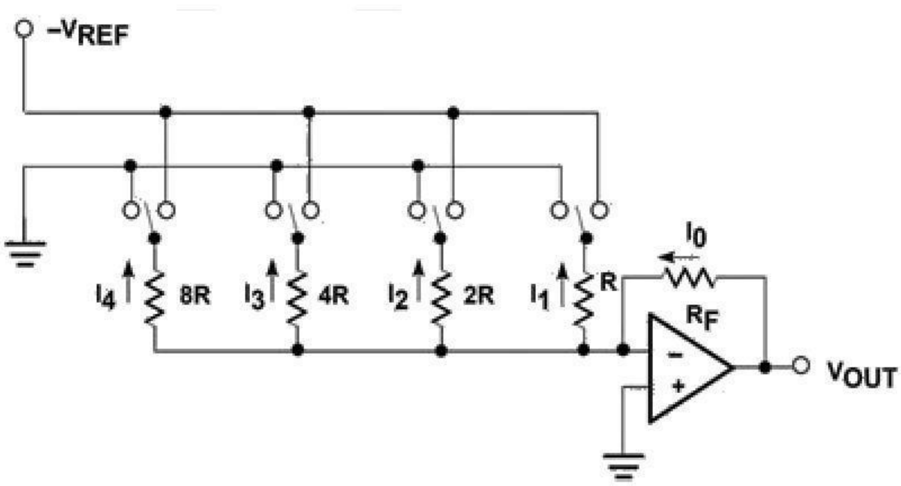


Fig: 2.20: simple 4-bit weighted resistor

Fig. 2.17 shows a simplest circuit of weighted resistor. It uses a summing inverting amplifier. It contains n- electronic switches (i.e. 4 switches) and these switches are controlled by binary input bits d1, d2, d3, d4. If the binary input bit is 1 then the switch is connected to reference voltage –VREF , if the binary input bit is 0 then the switch is connected to ground.

The output current equation is Io=I1+I2+ I3+I 4

Io= VREF (d1*2-1+d2*2-2+d3*2-3+d4*2-4)

The transfer characteristics are shown below (fig 2.13) for a 3-bit weighted resistor

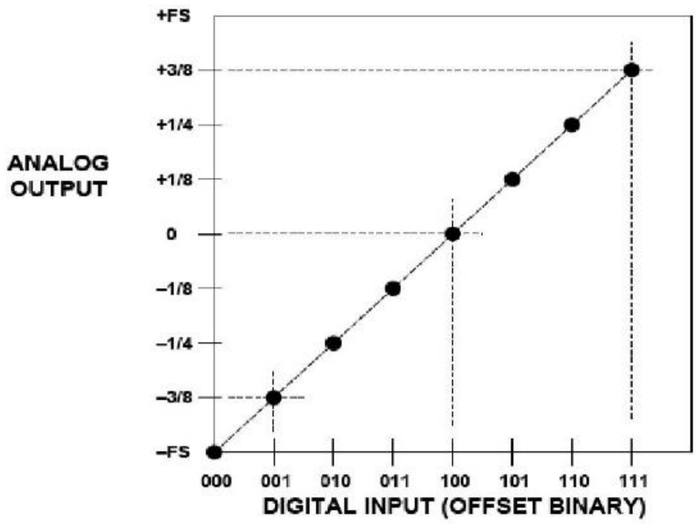


Fig 2.21: Transfer characteristics of 3-bit weighted resistor

Disadvantages of Weighted resistor D/A converter:

Wide range of resistor's are required in this circuit and it is very difficult to fabricate such a wide range of resistance values in monolithic IC. This difficulty can be eliminated using R-2R ladder network.

2.9.2 R-2R LADDER DAC

Wide range of resistors required in binary weighted resistor type DAC. This can be avoided by using R-2R ladder type DAC. The circuit of R-2R ladder network is shown in fig 2.19. The basic theory of the R-2R ladder network is that current flowing through any input resistor (2R) encounters two possible paths at the far end. The effective resistances of both paths are the same (also 2R), so the incoming current splits equally along both paths. The half-current that flows back towards lower orders of magnitude does not reach the op amp, and therefore has no effect on the output voltage. The half that takes the path towards the op amp along the ladder can affect the output. The inverting input of the op-amp is at virtual earth. Current flowing in the elements of the ladder network is therefore unaffected by switch positions.

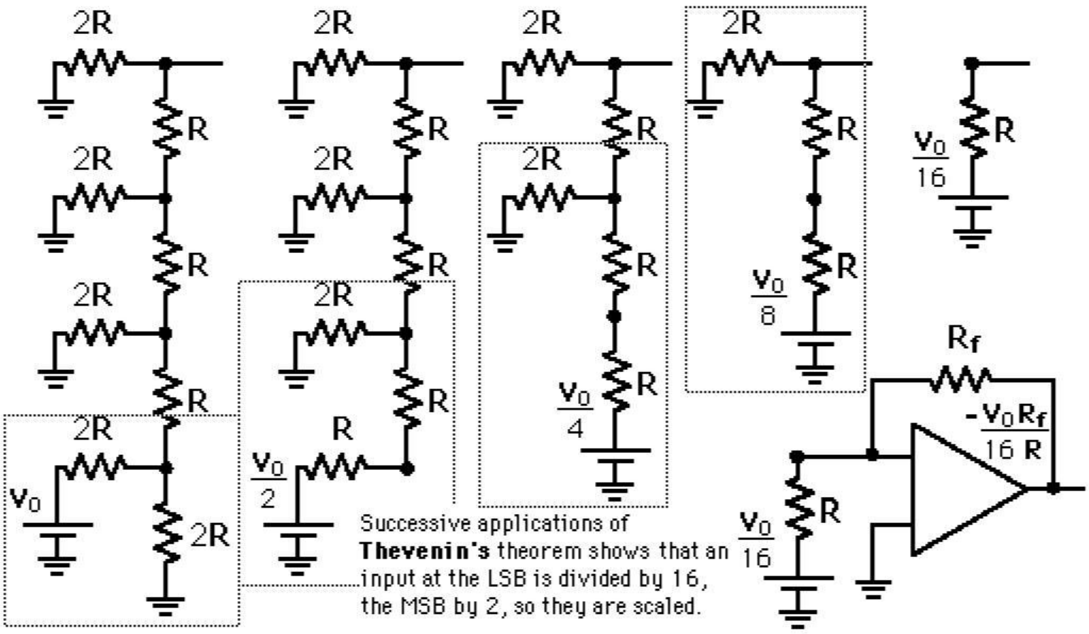


Fig 2.22: A 4-bit R-2R Ladder DAC

If we label the bits (or inputs) bit 1 to bit N the output voltage caused by connecting a particular bit to Vr with all other bits grounded is:

Vout = Vr/2N

where N is the bit number. For bit 1, Vout =Vr/2, for bit 2, Vout = Vr/4 etc.

Since an R/2R ladder is a linear circuit, we can apply the principle of superposition to calculate Vout. The expected output voltage is calculated by summing the effect of all bits connected to Vr. For example, if bits 1 and 3 are connected to Vr with all other inputs grounded, the output voltage is calculated by:

Vout = (Vr/2)+(Vr/8) which reduces to Vout = 5Vr/8.

An R/2R ladder of 4 bits would have a full-scale output voltage of 1/2 +1/4 + 1/8 + 1/16 = 15Vr/16 or 0.9375 volts (if Vr=1 volt) while a 10bit R/2R ladder would have a full-scale output voltage of 0.99902 (if Vr=1 volt).

2.9.3 INVERTED R-2R LADDER DAC

In weighted resistor and R-2R ladder DAC the current flowing through the resistor is always changed because of the changing input binary bits 0 and 1. More power dissipation causes heating, which in turn cerates non-linearity in DAC. This problem can be avoided by using INVERTED R-2R LADDER DAC (fig 2.20)

In this MSB and LSB is interchanged. Here each input binary word connects the corresponding switch either to ground or to the inverting input terminal of op-amp which is also at virtual ground. When the input binary in logic 1 then it is connected to the virtual ground, when input binary is logic 0 then it is connected to the ground i.e. the current flowing through the resistor is constant.

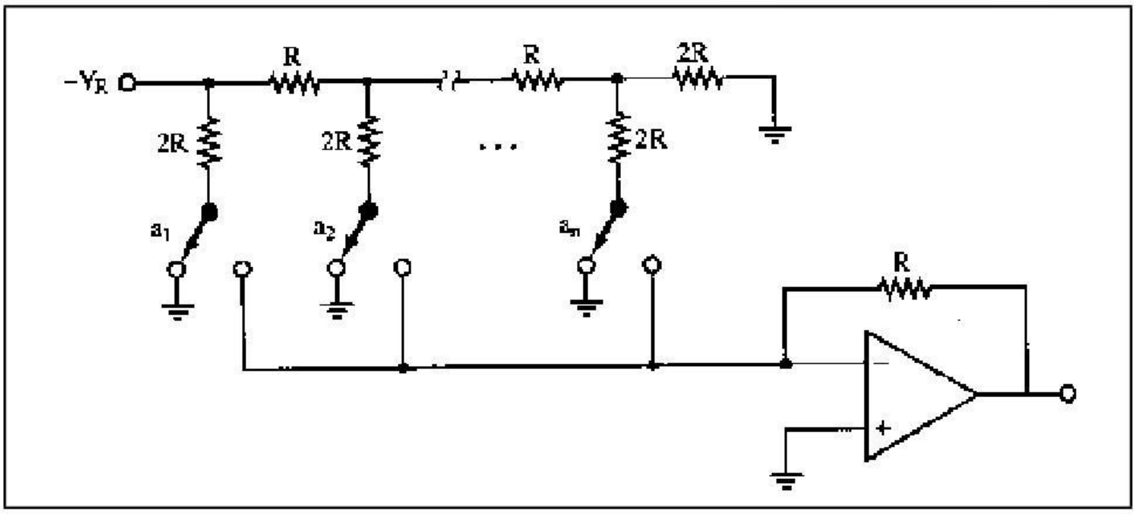


Fig 2.23: Inverted R-2R ladder

2.10 DIFFERENT TYPES OF ADC'S

It provides the function just opposite to that of a DAC. It accepts an analog input voltage Va and produces an output binary word d1, d2, **d3….dn. Where d1 is the most significant bit and** dn is the least significant bit.

ADCs are broadly classified into two groups according to their conversion techniques

1) Direct type

2) Integrating type

Direct type ADCs compares a given analog signal with the internally generated equivalent signal. This group includes

i) Flash (Comparator) type converter

ii) Successive approximation type convertor

iii) Counter type

iv) Servo or Tracking type

Integrated type ADCs perform conversion in an indirect manner by first changing the analog input signal to linear function of time or frequency and then to a digital code.

2.10.1 FLASH (COMPARATOR) TYPE CONVERTER:

A direct-conversion ADC or flash ADC has a bank of comparators sampling the input signal in parallel, each firing for their decoded voltage range. The comparator bank feeds a logic circuit that generates a code for each voltage range. Direct conversion is very fast, capable of gigahertz sampling rates, but usually has only 8 bits of resolution or fewer, since the number of comparators needed, 2N - 1, doubles with each additional bit, requiring a large, expensive circuit. ADCs of this type have a large die size, a high input capacitance, high power dissipation, and are prone to produce glitches at the output (by outputting an out-of-sequence code). Scaling to newer sub-micrometre technologies does not help as the device mismatch is the dominant design limitation. They are often used for video, wideband communications or other fast signals in optical storage.

A Flash ADC (also known as a direct conversion ADC) is a type of analog-to-digital converter that uses a linear voltage ladder with a comparator at each "rung" of the ladder to compare the input voltage to successive reference voltages. Often these reference ladders are constructed of many resistors; however modern implementations show that capacitive voltage division is also possible. The output of these comparators is generally fed into a digital encoder which converts the inputs into a binary value (the collected outputs from the comparators can be thought of as a unary value).

Also called the *parallel* A/D converter, this circuit is the simplest to understand. It is formed of a series of comparators, each one comparing the input signal to a unique reference voltage. The comparator outputs connect to the inputs of a priority encoder circuit, which then produces a binary output.

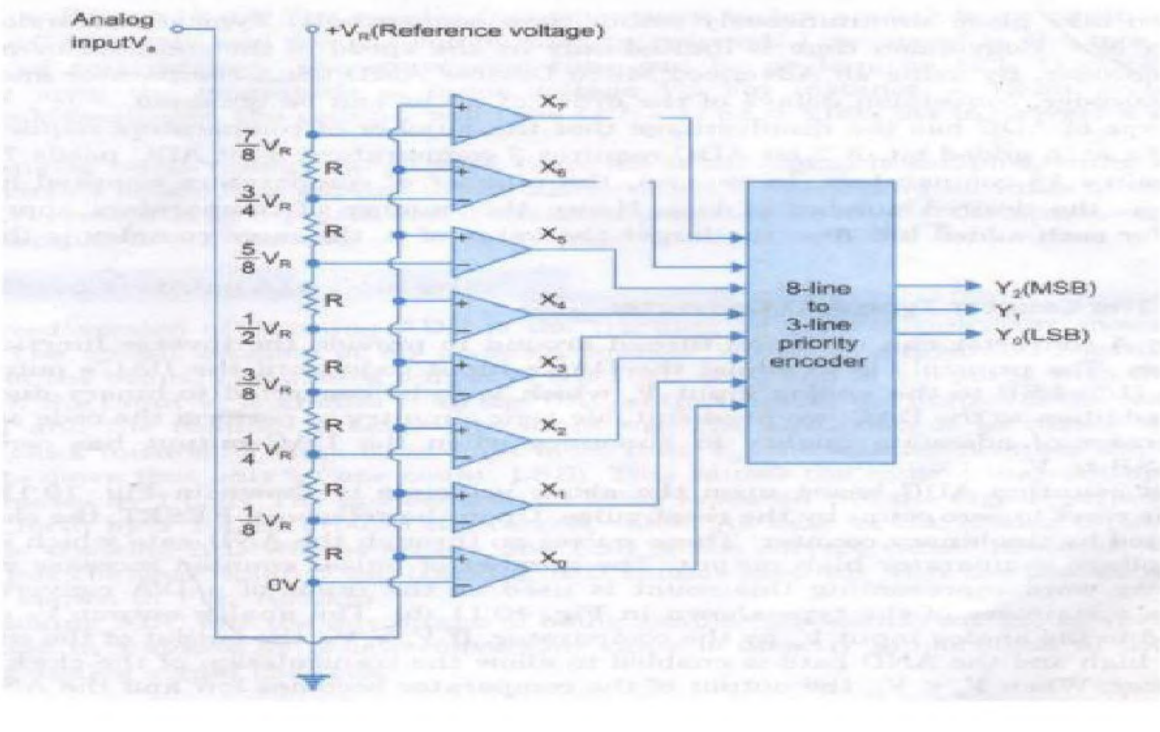


Fig 2.24: flash (parallel comparator) type ADC

VR is a stable reference voltage provided by a precision voltage regulator as part of the converter circuit, not shown in the schematic. As the analog input voltage exceeds the reference voltage at each comparator, the comparator outputs will sequentially saturate to a high state. The priority encoder generates a binary number based on the highest-order active input, ignoring all other active inputs.

2.10.2 COUNTER TYPE A/D CONVERTER

In the fig 2.22 the counter is reset to zero count by reset pulse. After releasing the reset pulse the clock pulses are counted by the binary counter. These pulses go through the AND gate which is enabled by the voltage comparator high output. The number of pulses counted increase with time.

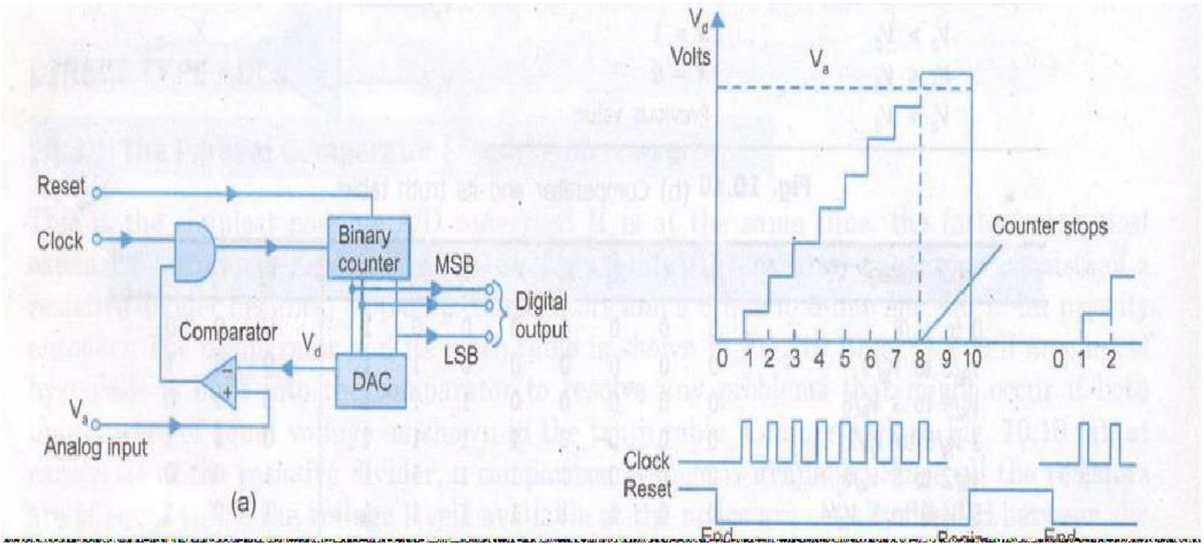


Fig 2.25: Countertype A/D converter

The binary word representing this count is used as the input of a D/A converter whose output is a stair case. The analog output Vd of DAC is compared to the analog input input Va by the comparator. If Va>Vd the output of the comparator becomes high and the AND gate is enabled to allow the transmission of the clock pulses to the counter. When Va<Vd the output of the comparator becomes low and the AND gate is disabled. This stops the counting we can get the digital data.

2.10.3 SERVO TRACKING A/D CONVERTER :

An improved version of counting ADC is the tracking or servo converter shown in fig 2.23. The circuit consists of an up/down counter with the comparator controlling the direction of the count.

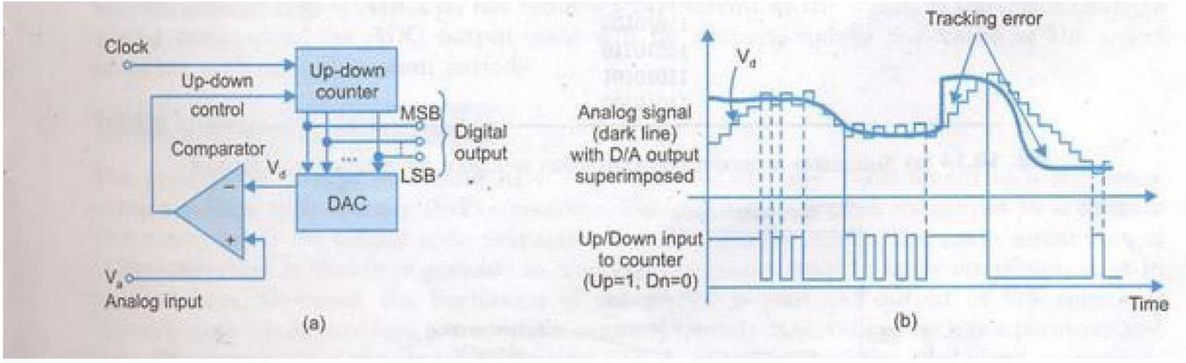


Fig: 2.26: (a) A tracking A/D converter (b) waveforms associated with a tracking A/D converter

The analog output of the DAC is Vd and is compared with the analog input Va. If the input Va is greater than the DAC output signal, the output of the comparator goes high and the counter is caused to count up. The DAC output increases with each incoming clock pulse when it becomes more than Va the counter reverses the direction and counts down.

2.10.4 SUCCESSIVE-APPROXIMATION ADC:

One method of addressing the digital ramp ADC's shortcomings is the so-called successive- approximation ADC. The only change in this design as shown in the fig 2.19 is a very special counter circuit known as a successive-approximation register.

Instead of counting up in binary sequence, this register counts by trying all values of bits starting with the most-significant bit and finishing at the least-significant bit. Throughout the count process, the register monitors the comparator's output to see if the binary count is less than or greater than the analog signal input, adjusting the bit values accordingly. The way the register counts is identical to the "trial-and-fit" method of decimal-to-binary conversion, whereby different values of bits are tried from MSB to LSB to get a binary number that equals the original decimal number. The advantage to this counting strategy is much faster results: the DAC output converges on the analog signal input in much larger steps than with the 0-to-full count sequence of a regular counter.

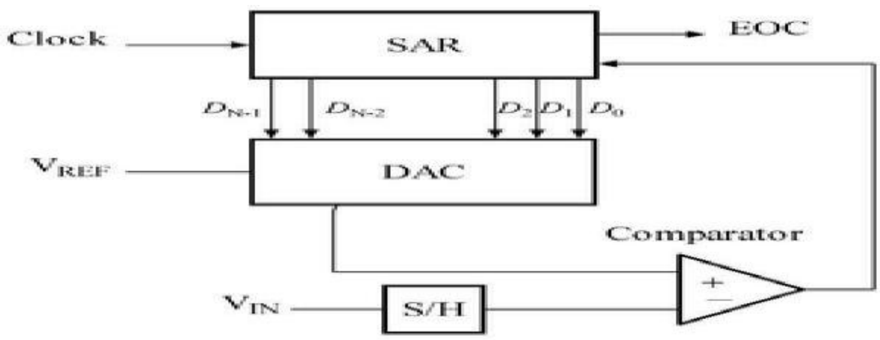


Fig: 2.27: Successive approximation ADC circuits

The successive approximation analog to digital converter circuit typically consists of four chief sub

1. A sample and hold circuit to acquire the input voltage (Vin).

2. An analog voltage comparator that compares Vin to the output of the internal DAC and outputs the result of the comparison to the successive approximation register (SAR).

3. A successive approximation register sub circuit designed to supply an approximate digital code of Vin to the internal DAC.

4. An internal reference DAC that supplies the comparator with an analog voltage equivalent of the digital code output of the SAR for comparison with Vin.

The successive approximation register is initialized so that the most significant bit (MSB) is equal to a digital 1. This code is fed into the DAC, which then supplies the analog equivalent of this digital code (Vref/2) into the comparator circuit for comparison with the sampled input voltage. If this analog voltage exceeds Vin the comparator causes the SAR to reset this bit; otherwise, the bit is left a 1. Then the next bit is set to 1 and the same test is done, continuing this binary search until every bit in the SAR has been tested. The resulting code is the digital approximation of the sampled input voltage and is finally output by the DAC at the end of the conversion (EOC).

Mathematically, let Vin = xVref, so x in [-1, 1] is the normalized input voltage. The objective is to approximately digitize x to an accuracy of 1/2n. The algorithm proceeds as follows:

1. Initial approximation x0 = 0.

2. ith approximation xi = xi-1 - s(xi-1 - x)/2i.

where, s(x) is the signum-**function(sgn(x)) (+1 for x ≥ 0,** -1 for x < 0). It follows using mathematical induction that |xn - **x| ≤ 1/2n.**

As shown in the above algorithm, a SAR ADC requires:

1. An input voltage source Vin.

2. A reference voltage source Vref to normalize the input.

3. A DAC to convert the ith approximation xi to a voltage.

4. A Comparator to perform the function s(xi - x) by comparing the DAC's voltage with the input voltage.

5. A Register to store the output of the comparator and apply xi-1 - s(xi-1 - x)/2i.

A successive-approximation ADC uses a comparator to reject ranges of voltages, eventually settling on a final voltage range. Successive approximation works by constantly comparing the input voltage to the output of an internal digital to analog converter (DAC, fed by the current value of the approximation) until the best approximation is achieved. At each step in this process, a binary value of the approximation is stored in a successive approximation register (SAR). The SAR uses a reference voltage (which is the largest signal the ADC is to convert) for comparisons.

For example if the input voltage is 60 V and the reference voltage is 100 V, in the 1st clock cycle, 60 V is compared to 50 V (the reference, divided by two. This is the voltage at the output of the internal DAC when the input is a '1' followed by zeros), and the voltage from the comparator is positive (or '1') (because 60 V is greater than 50 V). At this point the first binary digit (MSB) is set to a '1'. In the 2nd clock cycle the input voltage is compared to 75 V (being halfway between 100 and 50 V: This is the output of the internal DAC when its input is '11' followed by zeros) because 60 V is less than 75 V, the comparator output is now negative (or '0'). The second binary digit is therefore set to a '0'. In the 3rd clock cycle, the input voltage is compared with 62.5 V (halfway between 50 V and 75 V: This is the output of the internal DAC when its input is '101' followed by zeros). The output of the comparator is negative or '0' (because 60 V is less than 62.5 V) so the third binary digit is set to a 0. The fourth clock cycle similarly results in the fourth digit being a '1' (60 V is greater than 56.25 V, the DAC output for '1001' followed by zeros). The result of this would be in the binary form 1001. This is also called *bit-weighting conversion*, and is similar to a binary search.

The analogue value is rounded to the nearest binary value below, meaning this converter type is mid-rise (see above). Because the approximations are successive (not simultaneous), the conversion takes one clock-cycle for each bit of resolution desired. The clock frequency must be equal to the sampling frequency multiplied by the number of bits of resolution desired. For example, to sample audio at 44.1 kHz with 32 bit resolution, a clock frequency of over 1.4 MHz would be required. ADCs of this type have good resolutions and quite wide ranges. They are more complex than some other designs.

2.10.5 DUAL-SLOPE ADC

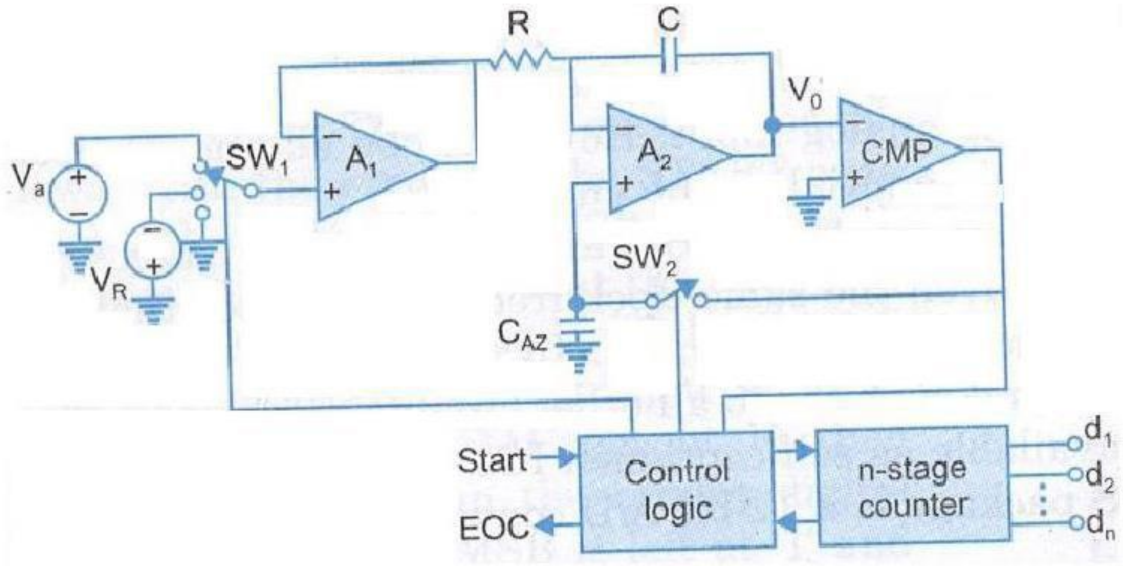


Fig 2.28: (a): Functional diagram of dual slope ADC

An integrating ADC (also **dual-slope** ADC) shown in fig 2.25 (a) applies the unknown input voltage to the input of an integrator and allows the voltage to ramp for a fixed time period (the run-up period). Then a known reference voltage of opposite polarity is applied to the integrator and is allowed to ramp until the integrator output returns to zero (the run-down period). The input voltage is computed as a function of the reference voltage, the constant run-up time period, and the measured run-down time period. The run-down time measurement is usually made in units of the converter's clock, so longer integration times allow for higher resolutions. Likewise, the speed of the converter can be improved by sacrificing resolution. Converters of this type (or variations on the concept) are used in most digital voltmeters for their linearity and flexibility.

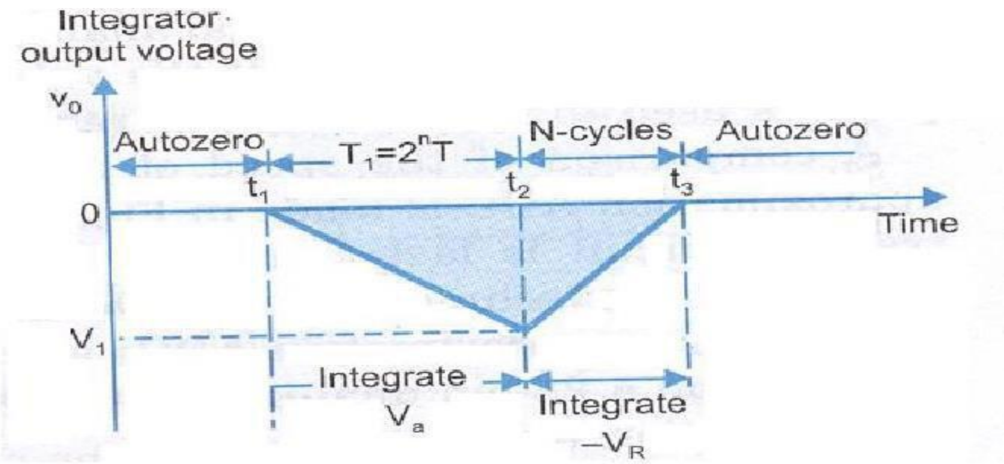


Fig 2.25 (b) o/p waveform of dual slope ADC

In operation the integrator is first zeroed (close SW2), then attached to the input (SW1 up) for a fixed time *M* counts of the clock (frequency 1/*t*). At the end of that time it is attached to the reference voltage (SW1 down) and the number of counts *N* which accumulate before the integrator reaches zero volts output and the comparator output changes are determined. The waveform of dual slope ADC is shown in fig 2.25 (b).

The equations of operation are therefore:

$$T_1 = t_2 - t_1 = \frac{2^n \ counts}{clock \ rate}$$

And

$$t_3 - t_2 = \frac{digitalcountN}{clockrate}$$

For an integrator,

$$\Delta V_O = \frac{-1}{RC} V(\Delta t)$$

The voltage Vo will be equal to V1 at the instant t2 and can be written as

$$V_1 = \frac{-1}{RC} V_a (t_2 - t_1)$$

The voltage V1 is also given by

$$V_1 = \frac{-1}{RC} (-V_R)(t_2 - t_3)$$

So,

$$V_a (t_2 - t_1) = (V_R)(t_3 - t_2)$$

Putting the values of $(t_2 - t_1) = 2^n$ and $(t_3 - t_2) = N$, we get

$$V_a (2^n) = (V_R) N$$

Or,

$$V_a = (V_R)\left(\frac{N}{2^n}\right)$$

2.11 SPECIFICATIONS FOR DAC/ADC

1. RESOLUTION: The Resolution of a converter is the smallest change in voltage which may be produced at the output of the converter.

Resolution (in volts)=(VFS)/(2n-1)= 1 LSB increment

Ex: An 8-bit D/A converter have 28-1=255 equal intervals. Hence the smallest change in output voltage is (1/255) of the full scale output range.

An 8-bit DAC is said to have: 8 bit resolution

: a resolution of 0.392 of full scale

: a resolution of 1 part in 255

Similarly the resolution of an A/D converter is defined as the smallest change in analog input for a one bit change at the output.

Ex: the input range of 8-bit A/D converter is divided into 255 intervals. So the resolution for a 10V input range is 39.22 mV = (10V/255)

2. LINEARITY: The linearity of an A/D or D/A converter is an important measure of its accuracy and tells us how close the converter output is to its ideal characteristics.

3. GLITCHES (PARTICULARLY DAC): In transition from one digital input to the next, like **0111 to 1000, it may effectively go through 1111 or 0000, which produces ―unexpected‖** voltage briefly. If can cause problems elsewhere.

4. ACCURACY: Absolute accuracy is the maximum deviation between the actual converter output and the ideal converter output.

5. MONOTONIC: A monotonic DAC is the one whose analog output increases for an increase in digital input. It is essential in control applications. If a DAC has to be monotonic, the error should de lessthan ±(1/2) LSB at each output level.

6. SETTLING TIME: The most important dynamic parameter is the settling time. It represents the time it takes for the output to settle within a specified band ± (1/2) LSB of its final value following a code change at the input. It depends upon the switching time of the logic circuitry due to internal parasitic capacitances and inductances. Its ranges from 100ns to **10µs.**

7. STABILITY: The performance of converter changes with temperature, age and power supply variations. So the stability is required.

Data acquisition systems

A *data acquisition system (DAQ)* is the integration of several components within the signal conditioning module, the sensing module, the output/ display module, and sometimes the control module that leads to stored, manipulable digital data representations of the sensor measurements. This integration is accomplished in a compact DAQ board that easily interfaces with a personal computer. A very general schematic for DAQ systems used for centralized wired-sensor configurations is shown in Fig. 2.10, where a single central controller is assumed. Analog signal considerations Analog sensor voltages are sent fi rst into a conditioning unit that could serve several purposes. One of the fi rst subcomponents in this unit is a bank of shunt circuits; the actual raw output from many sensors (e.g., piezoceramic accelerometers) is a current rather than a voltage, and a *shunt circuit* uses Ohm's law to convert this current to a voltage suitable for use with the DAQ system. DAQ systems either have separate current/voltage inputs or switches that engage shunt circuits in analog input channels when needed. Not all voltages from the sensors, however, are suitable for the voltage limitations ($V R$) of the DAQ components (such as the ADC). Thus, many analog voltage signals need either amplification or attenuation to avoid the saturation effects shown in Fig. 2.7. Amplifier gains in most modern DAQ systems are controllable individually on each channel via switch logic that engages variable resistor banks (for amplifi cation) or engage variable resistor voltage divider networks (for attenuation). The specific form of the wired connections to A central controller, or central processing unit (CPU), governs the entire DAQ process, as shown in Fig. 2.10, and its primary functions are timing control and information buffering, including often interfacing with some form of external personal computer, although these controllers can operate independent of a personal computer. The CPU's processing speed depends on its internal clock speed and the design of the various buses in the DAQ system. *Buses* are just electrical pathways through which information and commands are sent among the CPU, memory, the ADC, any other peripherals including digital input/outputs, and the personal computer. Most DAQ systems have a central bus through which many other devices/components interact through other buses. Figure 2.11 shows such a schematic. Essentially, the central bus contains three information pathways: an address lane, a data lane, and a control lane. As data are to be moved around the DAQ system, the address lane contains a digital description of the locations of the two components between which the data are to be exchanged ('Where are we going to and coming from?'), the data lane contains the data information itself ('What data are going or coming?'), and the control lane contains the status information regarding logistics and control of data movement ('How and when do we send the data?'). When data, or information, are being sent over the central bus, the control lane sends a 'busy' flag so that other information flows do not interfere, and a 'ready' flag when the process is finished

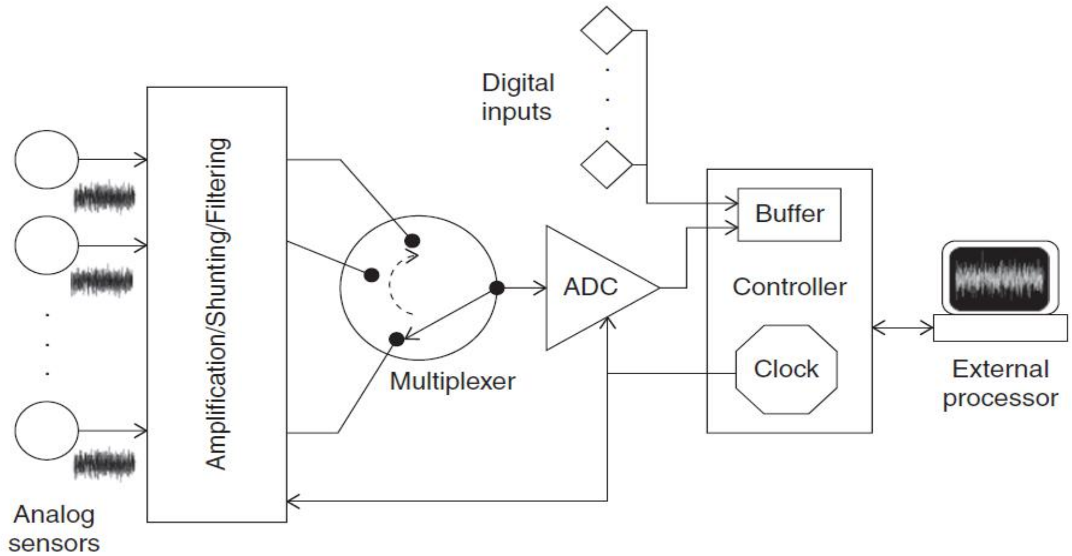


Fig: A general schematic of a conventional wired-sensor data acquisition process.

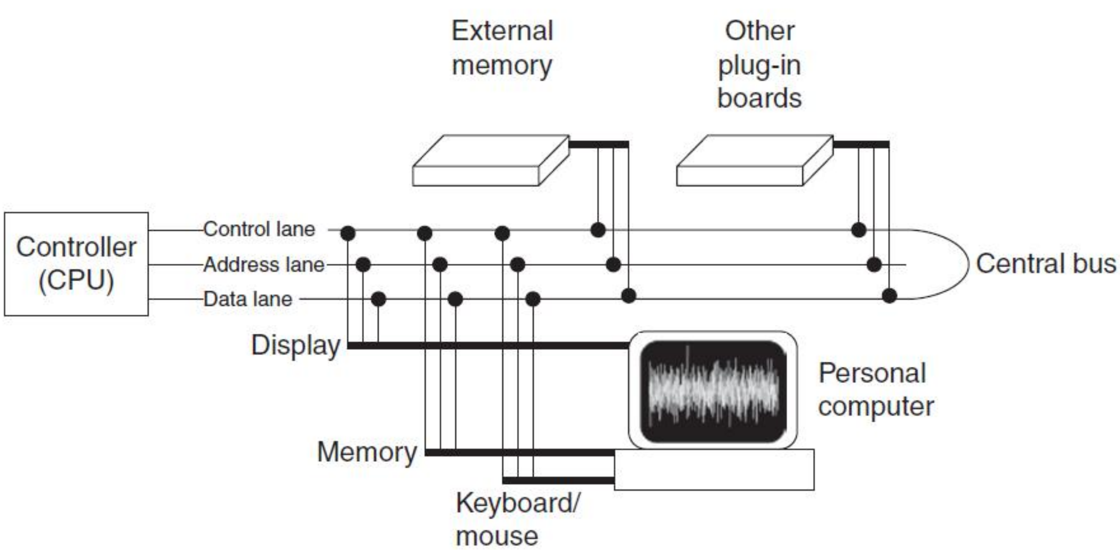


Fig: A central bus architecture showing typical connectivities.

Digital communications

Much of the multifunctionality that is required for modern DAQ systems has been integrated into compact ‘plug-and-play’ boards. Figure shows a generic schematic of such a multifunctional plug-and-play board. These boards contain several analog and digital communications, processing, and control functions. As already seen in Section 2.5.1, digital signals play a critical role in a number of CPU, control, triggering, signal processing, and A/D operations in a DAQ system. Generally speaking, digital (TTL-compatible) signals communicate with devices in serial (bit by bit) or in parallel (in words).

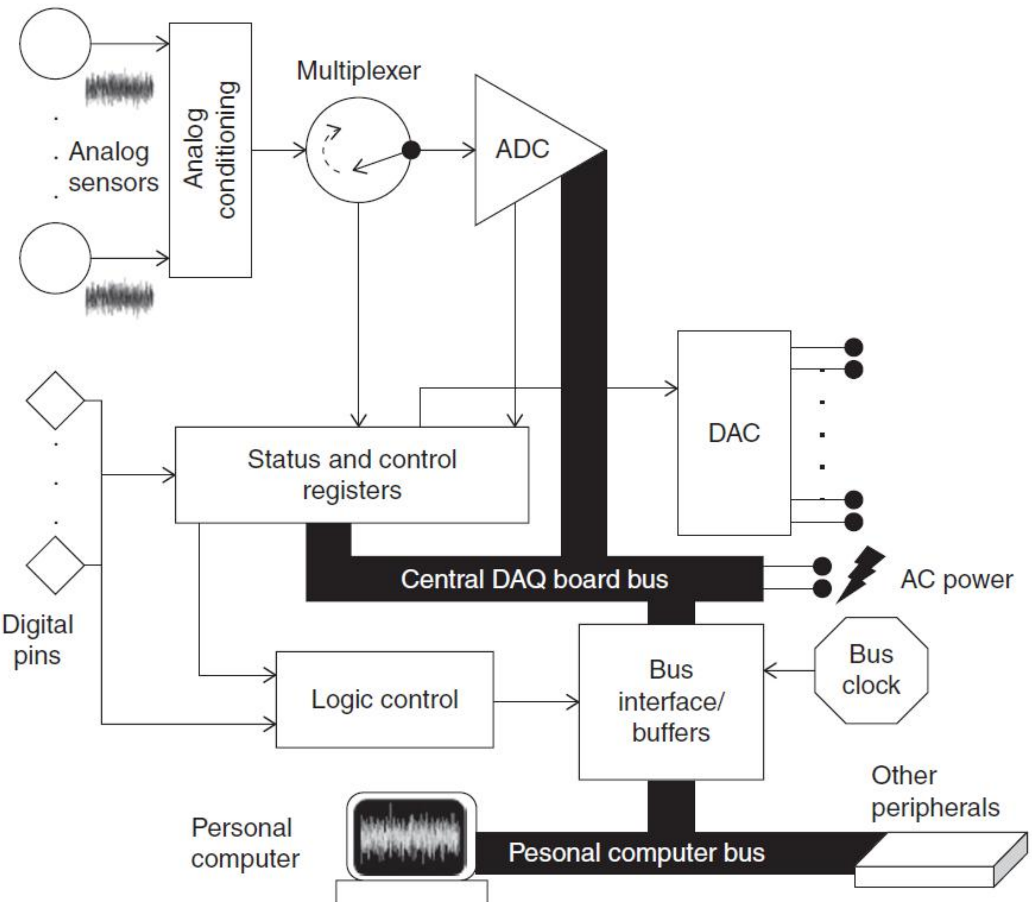


Fig: A general DAQ system plug-and-play architecture for multipurpose functionality.

Unit-II
Sensors and Sensing Technology for Structural Monitoring

Introduction

Sensors are instruments that detect the state of the system and produce the appropriate information (e.g. structural responses and environmental quantities) for health assessment of civil engineering structures.

The sensors are typically used for

(a) safety monitoring and active safety control of the structure,

(b) usage monitoring such as accumulating strain load data for condition assessment and future design,

(c) health monitoring for current state estimate and

(d) deterioration monitoring for future performance prediction and optimum maintenance strategy.

Traditional sensing techniques such as piezoelectric sensors have been extensively used in practice for many decades. Advanced sensing methods such as micro-electromechanical systems (MEMS) have become popular in civil engineering applications. Recently, emerging sensing techniques such as Fiber optic sensors have shown superior performance compared to traditional sensors. Sensors have to be robust and must operate stably and reliably. The quality of sensors should not be altered by environmental effects such as temperature, humidity and electromagnetic fields. Currently, choosing sensors is mainly a qualitative process based on the expert's judgement. Such a qualitative process has the advantage of simplicity, but it may provide ineffective solutions.

Sensor Types

Sensors are one of the most critical components of an SHM strategy, since the quality of the analysis results directly depends on the quality of the data collected. Sensing is a process that produces certain information about the state of a system by interrogating the system (Wong and Ni 2009), as illustrated in Figure 1. In the SHM of civil engineering structures, various types of sensors are often adopted for measuring different types of physical and/or chemical quantities. The key factors considered in the selection a proper type of sensor for monitoring include: type of measurand, type of output signal, type of excitation, measuring range, measuring resolution, measuring accuracy, measuring linearity, sampling rate, environmental operation limits and service life.

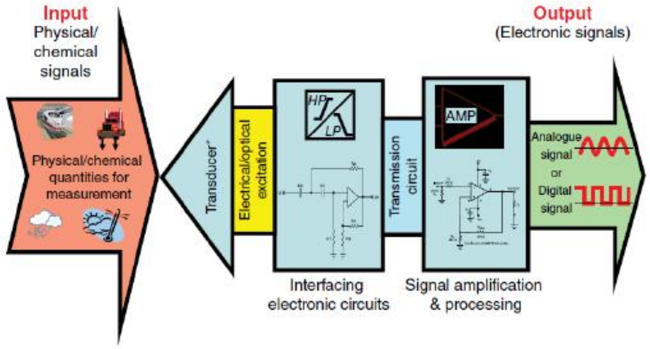


Figure 1: Schematic diagram of a typical sensory system, converting measured quantities into analogue or digital signals.

Table 2.1 Typical sensing methods for structural health monitoring.

Sensor group	Sensor type	Measurement type	Physical principle	Reliability issue
Ceramics and oxides	Piezoelectric	Strain, vibration, ultrasound	Electromechanical	Brittle fracture, disbond
	Pyroelectric	Temperature	Thermoelectric	Brittle fracture, disbond
	Ferroelectric	RFIDs, vibration, temperature	Dipole moment	Brittle fracture, disbond
Electromagnetic	MWM, Foil EC	Cracks, fatigue, corrosion	Dielectric, eddy currents	Electrical short, disbond
Micro-electro-mechanical	MEMS	Strain, vibration, force	Micromechanical motions	Fracture, wear, short
Thin/thick film	Strain/crack gauges	Strain, crack growth	Electrical resistance	Electrical short, disbond
	Thermocouples	Temperature	Electrical resistance	Oxidation, disbond
	Electrochemical	Corrosivity, chemical	Electrical resistance	Electrical short, disbond
Fibre-optic	EFPI, Bragg grating	Strain, temperature, chemical	Optical reflectance	Brittle fracture, pullout
Wireless	Passive sensor, active sensor	Strain, vibration, force	Sensing interface	Power fault, electrical short

Table 2.2 Examples of sensors used for monitoring of structural responses and operation loads.

Sensor type	Measurand	Measuring range	Measuring accuracy	Resolution	Sampling rate	Excitation / Signal type
Tri-axial servo-type accelerometer	Acceleration in three orthogonal directions	±30 g	—	1 μg	≥100 Hz	Voltage/ Analogue
Vibration type strain gauge	Strain in concrete	±4000 με	0.1% of full scale	1 με	≥20 Hz	Voltage/ Analogue
Load cell	Stress in tendon	100 kN to 10,000 kN	0.25% of full scale	—	≥20 Hz	Voltage/ Analogue
Weldable foil type strain gauge	Stress in structural steel	±3500 με	0.1% of full scale	1 με	≥100 Hz	Voltage/ Analogue
Global position system (GPS)	Displacement in in three orthogonal directions	—	Horizontal: 3 mm ±0.5 ppm Vertical: 5 mm ±1 ppm	—	≥20 Hz	Voltage/ Digital
Bi-axial tiltmeter	Rotation in μ-radian	Low gain: ±8000 μ-radian High gain: ±800 μ-radian	—	±0.1 μ-radian	≥20 Hz	Voltage/ Digital
Displacement transducer	Uni-axial displacement	±500 mm	±0.5% of full scale	1 mm	≥20 Hz	Voltage/ Analogue
Dynamic weight-in-motion station	Axle-load; Axle-speed	0.5–20 ton; 5–200 kph	±0.6%; ≥9.0%	—	≥215 Hz	Voltage/ Analogue
High definition video cameras	Image of highway traffic composition	—	—	—	—	Voltage/ Digital

Table 2.3 Examples of sensors used for monitoring of environmental factors.

Sensor type	Measurand	Measuring range	Measuring accuracy	Resolution	Sampling rate	Excitation /Signal type
Tri-axial ultrasonic type anemometer	Wind speed in three orthogonal direction	0–100 m/s	±1%RMS	0.01 m/s	≥20 Hz	Voltage/ Digital
Ambient temperature and relative humidity sensor	Ambient air temperature	−20 °C to +60 °C	0.1 °C	—	0.02 Hz	Voltage/ Analogue
	Relative humidity	0–100%	±2%	0.1%	—	Voltage/ Analogue
Temperature inside structural components	Temperature in steel/ concrete/pavement section	−40 °C to +60 °C	±0.1 °C	0.01 °C	0.02 Hz	Voltage/ Analogue
	Temperature in cable	−40 °C to +200 °C	—	—	Slow	Optical / Digital
	Strain in cable	Distributed type (in km)	±100 με	—	Slow	Optical/ Digital
Electrochemical corrosion cells for embedded steel reinforcement	Corrosion potential	−200 mV to +2000 mV	±0.2 mV	0.2 mV	Slow	Voltage/ Analogue
	Corrosion current	−2 mA to +2 mA	±200 nA	200 nA	Slow	Voltage/ Analogue
	Concrete resistivity	0 to 7 mΩ	±1 Ω	1 Ω	Slow	Voltage/ Analogue
	Linear polarisation resistance	−1 kΩ to +1 kΩ	±1 Ω	1 Ω	Slow	Voltage/ Analogue
	Concrete relativity humidity	0–100%	±2%	0.1%	Slow	Voltage/ Analogue
	Concrete temperature	−40 °C to +60 °C	±0.1 °C	0.01 °C	Slow	Voltage/ Analogue
Electrochemical gas detector	Carbon dioxide	0–5000 ppm	±5% of full scale	±1% of full scale	30 seconds per sample	Voltage/ Digital
	Oxygen	0–25 vol%				
	Chloride	0–3 ppm				
	Hydrogen chloride	0–6 ppm				
	Carbon monoxide	0–150 ppm				

Sensor Measurements in Structural Monitoring

Sensors are typically chosen according to the measurand – the quantity to be measured. Three categories of physical and chemical quantities should be considered for measuring in structural monitoring of civil engineering structures: structural responses, environmental quantities and operational quantities.

Structural Responses

The structural responses of civil structures typically include: acceleration; displacement; velocity; strain, stress or force; pressure and tilt.

Acceleration – Accelerometers are sensors that use different principles for measuring accelerations. There is a wide range of different accelerometer types available (Chen and Maung 2014, Wong and Ni 2011), as shown in Figure 2.

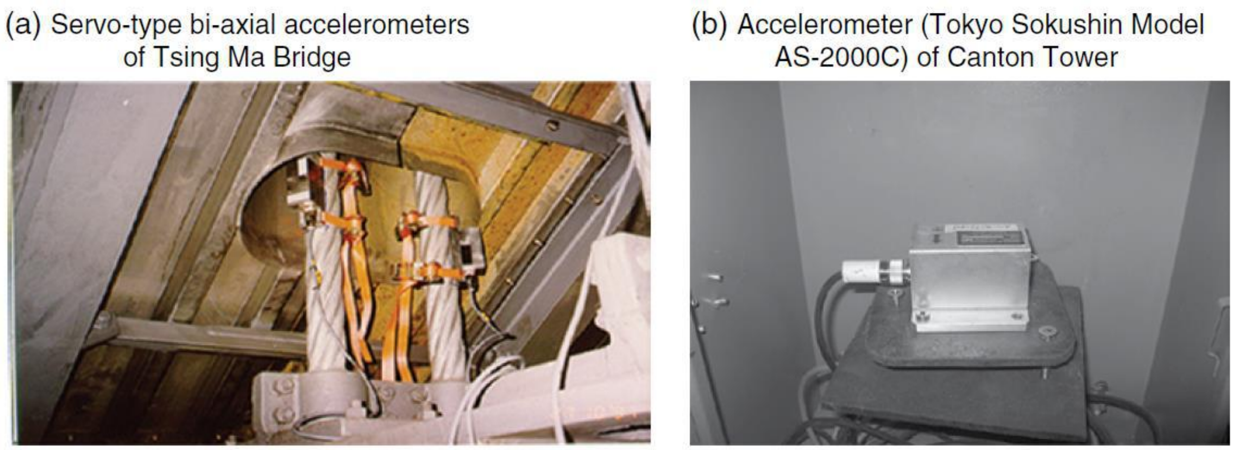


Figure Accelerometers used in vibration monitoring of civil engineering structures.

The main types of accelerometers include:

- piezoelectric accelerometer
- servo-accelerometer
- capacitive accelerometer
- strain gauge accelerometer
- MEMS (capacitive and piezo-resistive) accelerometer
- FBG (fiber Bragg grating) accelerometer
- LVDT (linear variable differential transformers) based accelerometer
- laser vibrometer.

The selection of accelerometers for civil infrastructure applications depends on cost, dynamic range, resolution, noise floor, frequency range, power consumption, cabling requirements and limitations and conditioning requirements. During the selection process, the challenging civil structure environments, such as low frequency and low-level vibrations, need to be considered.

Displacement – Structural movements may comprise both dynamic components, caused by seismic, wind and vehicular loading, and quasi-static components, caused by thermal effects, settlement and variation of static loading. Displacements are usually relative values and require definition of a reference datum. They are typically determined with respect to an unloaded or undeformed state. **Dynamic displacements related to vibrations can be calculated from accelerations by double integration after high-pass filtering.** Measurement techniques include conventional survey techniques and advanced methods such as:

- laser and LED devices, e.g. laser Doppler vibrometers (LDVM)
- global positioning system (GPS)
- image tracking via CCD arrays
- surveying and total station
- optical marker tracking
- microwave interferometry, e.g. radar system
- pneumatic system
- contacting displacement measurements, e.g. LVDT.

Laser Doppler vibrometers are useful for bridge dynamic testing for both displacement and velocity measurements. However, LDVMs have limitations to applications for modal testing since they cannot measure multiple locations simultaneously. The global positioning system has been successfully applied for measuring displacements of large civil infrastructure, such as long span bridges, landslides and high-rise structures (Ni 2014), as shown Figure 3.

Figure 3: Global positioning system (GPS, Leica Geosystems Model 1230) used in construction monitoring of Canton Tower.

GPS can offer measurements with an accuracy of a few millimeters at sample rates as high as 20 Hz. GPS is a promising but relatively expensive sensing technology. Alternatively, displacements could be derived from other measurements, such as acceleration, velocity, strain or rotation signals.

Velocity – Velocity measurements are a common feature of seismic studies. LDVMs can measure velocity by Doppler shifting of light frequencies. They are non-contacting and can operate at both short and long ranges, but they are generally expensive and can only measure at a single point at a time. Alternatively, velocities can be measured indirectly by integrating the accelerations measured from LVDT accelerometers.

Strain – Strain gauges are widely used to measure strains in critical structural components, such as girders, rebar and concrete decks. The measured strain data can then be utilized to calculate stresses and evaluate load bearing capacity of the structure. Only differential strain can be measured without knowledge of a baseline value. Due to thermal effects, self-temperature compensating type sensors are preferred in the cases with temperature variations. Typical methods used for measuring strains include:

- Foil strain gauges or piezoelectric foil gauges
- Demountable strain gauges
- Strain transducers
- Vibrating wire gauges
- Fiber optic sensors, e.g. Fiber Bragg grating (FBG).

Electrical resistance strain gauges are cheap but often noisy. Vibrating wire strain gauges are popular because of their reliability and repeatability, as shown in Figure 4.

Figure 4: Vibrating wire strain gauges (Geokon Model GK4200) installed at the inner tube of Canton Tower.

The Fiber optic sensing method is an emerging technology; it can provide integrated, quasi-distributed or fully distributed strain measurements.

Stress or force – Direct stress measurement instruments are relatively rare. Vibrating wire stress cells are often used for measurements in tunnel linings, and in concrete box-girder bridges. A form of stress cell using elasto-magnetic effects can be used for monitoring of cable forces, such as for post-tensioning tendons and stays, main cables and hangers of suspended bridges. Load cells are mechanical devices for measuring naturally or mechanically induced loads on structures. There are several types of load cells, such as mechanical load cells (hydraulic or pneumatic), strain gauge-based load cells (shear beam, ring and pancake and bending beam) and other load cells (e.g. Fiber optic and piezo-resistant). Currently, most commonly used load cells are transducers made based on strain gauges and their principles.

Pressure – Pressure measurement technology is similar to force measurement technology, such as by using vibrating wire pressure sensors for static measurements and/or piezoelectric pressure sensors for dynamic measurements, as described in detail in Doebelin (1990). High-speed pressure on surfaces can be measured via pressure taps, a standard technology in wind tunnel testing. Static water pressure measurements are common, for example in piezometers for water level measurement (Catbas et al. 2012). Dynamic water pressure measurements are required to understand fluid–structure interactions, particularly for dams.

Tilt – Inclinometers are used to measure inclination (tilt) of structural components due to distress in the system. For example, they are often utilized to assess fixity of bridge girders at supports and to monitor long-term movements of bridge piers, abutments and girders. There are several types of inclinometers, including hydraulically and electrically based. The hydraulic inclinometers are simple, but not suitable for dynamic measurements.

Environmental Quantities

Environmental quantities, such as temperature, wind and corrosion (due to aggressive environments), should be measured during monitoring of civil engineering structures. *Temperature* – Temperature measurements are often needed in structural monitoring, since many structural responses and parameters, such as strains, displacements and frequencies, are related to temperature due to thermal effects. There are several methods for measuring temperature, including

- biomaterial temperature sensors
- electrical resistance thermometers

- thermocouple thermometers
- pyroelectric thermometers.

Other types of thermometers include fiber optic temperature sensors and infrared thermometers. Temperature sensors are often installed in other instruments, such as in vibrating wire and fiber optic strain gauges, in order to compensate for thermal effects on instrument performance.

Wind – Various types of anemometer are widely used in full-scale tests of structures, including cup-and-vane, windmill, propeller and sonic anemometers. Other types include hot wire and laser Doppler anemometers (for wind tunnels) and Doppler sonar for meteorology (Catbas et al. 2012). Cup-and-vane anemometers are the conventional standard, measuring the horizontal component of wind speed and the compass bearing. Measuring all three components of wind requires devices with propellers along three axes, or sonic anemometers, as shown in Figure 5.

Figure 5 Anemometer (R.M. Young Model 05103L) installed on Canton Tower.

Technical factors affecting the choice of an anemometer include the number of components resolved and the frequency response. Practical factors include cost, use of moving parts, susceptibility to electromagnetic interference and data output type. For long-term monitoring, reliability should be the main consideration.

Corrosion **–** Steel corrosion affects the durability, serviceability and safety of civil engineering structures, such as bridges. Corrosion is a major problem with bridge structural components, such as stay cables, tendons, steel structural members and the reinforcement in concrete structures. Corrosion measurement methods vary in complexity and size, from use of polarization resistance to time-domain reflectometry. A popular corrosion measuring method is the half-cell technique, owing to its simplicity and ease of implementation. But the method cannot be used for post-tensioned construction and often gives localized corrosion rate. Other corrosion measurement techniques include electrochemical techniques, electrical resistance probes, measurement of chloride concentration in concrete and destructive (coring) techniques.

Operational Quantities

Operational quantities include such factors as traffic volume for a bridge and mass loading of an offshore oil platform. Highway traffic loading can be measured by a weigh-in-motion system.

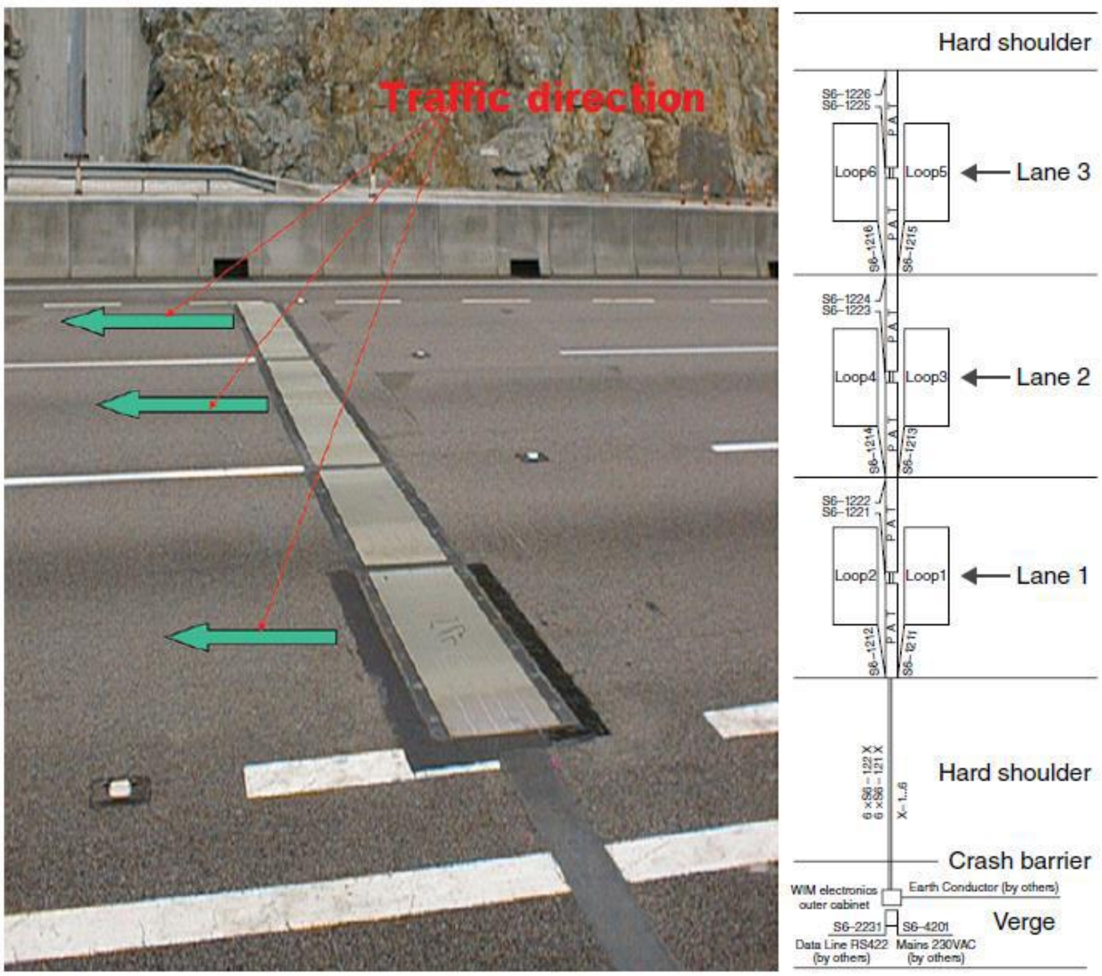


Figure 6 Deployment of weigh-in-motion (WIM) sensors on Tsing Ma Bridge.

Figure shows the implementation of dynamic weigh-in-motion stations on Tsing Ma Bridge (Ni et al. 2015). The information generated from the weigh-in-motion systems includes the vehicle arrival date and time, bound number, sequence number, lane number, vehicle speed, vehicle class, number of axles, axle weight and axle spacing.

Typical Quantities for Bridge Monitoring

The physical and chemical quantities for monitoring of civil engineering structures such as bridges depend on the structural configurations, such as structural arrangement, geometry, materials and site location. For bridges, the physical and chemical quantities for the SHM strategy can be classified into following types.

Bridge responses, including the forces in cables, the geometrical profiles in decks, towers and piers, the load or stress-histories and the accumulative fatigue damage in instrumented and key components, and the displacement and stress histories in articulated components. Table 2.4 summarizes the details of typical physical quantities for monitoring of structural responses, required monitoring sensory systems and monitoring parameters for a bridge.

- **Environmental factors**, including wind, temperature, seismic actions, humidity, ship impact, settlement, scouring, corrosion status, etc. Table 2.5 summarizes the details of typical physical and chemical quantities for monitoring of environmental factors.
- **Operational loads**, including highway traffics, railway traffics, ship impacting loads and permanent loads. Table 2.6 summarizes the details of typical physical quantities for monitoring of bridge operational loads.
- **Bridge characteristics**, including the static characteristics (e.g. static influence coefficients, creep or relaxation effects) and the dynamic characteristics (e.g. modal frequencies, mode shapes, modal damping ratios or modal mass participation factors). Table 2.7 summarizes the details of typical physical quantities for monitoring of structural characteristics.

Monitoring quantity	Monitoring sensory systems	Monitoring parameters/plots
Cable parameters	• Portable servo-type accelerometers • Load cells	• Cable frequencies, cable forces • Cable damping ratios and Scruton numbers
Tendon forces	• Load cells • Static strain gauges • Electromagnetic gauges (for unbonded tendons)	• Tendon forces • Tendon relaxation
Geometry configuration	• GPS and tiltmeters • Level sensing stations • Displacement transducers • Servo-type accelerometers • Static strain gauges	• Dynamic monitoring of deformation and stress distribution in global bridge structural system due to instant movements at monitoring locations • Load-effects (x-y plots) at key/monitoring locations
Stress/force distribution	• Dynamic strain gauges • Static strain gauges	• Stress histories at key/monitoring locations • Stress/force demand ratios at key/monitoring locations • Principal and Von-Mises stresses at key/monitoring locations • Strain/stress profiles at key/monitoring sections
Fatigue life estimation	• Dynamic strain gauges • Dynamic weigh-in-motion stations (bending-plate type)	• Fatigue life estimation due to combined effects of load-induced fatigue and distortion induced fatigue • Fatigue life estimation due to highway traffic load-effects
Articulation component responses	• Dynamic strain gauges • Displacement transducers • Bearing sensors • Buffer sensors	• Load histories in bearings • Stress demand ratios in bearing • Motion histories in movement joints • Stress and motion histories in buffers

Fiber Optic Sensors

Fiber optic sensors are becoming popular in health monitoring applications for civil infrastructure. Such sensors have many advantages, particularly because of their insensitivity to external perturbations and electromagnetic interference.

Classification of Fiber Optic Sensors

In general, an optical Fiber is a thin flexible strand of dielectric material that is protected mechanically by a polymer coating, which is further protected by a multi-layer cable structure designed to protect the Fiber from the installation environment. Since glass is inert and resistant to almost all chemicals, even at extreme temperatures, it is ideal for use in harsh environments and is particularly useful for civil engineering applications.

Since the light confined in the core of the optical Fibers does not interact with any surrounding electromagnetic field, Fiber optic sensors are immune to any electromagnetic interferences and are intrinsically safe. The Fiber optic sensing technology overcomes most of the limitations encountered in other forms of sensor and it offers several advantages:

- It is free from corrosion, having long-term stability and allowing continuous monitoring
- It is free from electromagnetic interference, avoiding undesirable noise
- It has an excellent transmission capability, allowing remote monitoring
- many measuring points can be multiplexed along a single optical Fiber, allowing fully distributed measures
- cabling and sensors are very small and light, making it possible to permanently incorporate them into the structures.

Depending on the spatial distribution of the measurand, Fiber optic sensors can be generally classified as point, integrated, quasi-distributed and distributed. In principle, Fiber optic sensors are based on measuring changes in the physical properties of the guided light. There are four main parameters of the light that can be modulated: phase, polarization state, intensity and wavelength. Thus, according to the modulated optical parameter, the sensors can be classified in four different categories: interferometric, polarimetric, intensity modulated and spectrometric.

Typical Fiber Optic Sensors in SHM

For structural monitoring of civil infrastructure, typical Fiber optic sensors include SOFO interferometric, Fabry-Perot interferometric, Fiber Bragg grating (FBG) and distributed Brillouin and Raman scattering sensors.

SOFO interferometric sensors (both static and dynamic systems) are long-base sensors, with a measurement base ranging from 200 mm to 10 m or more. The SOFO system uses low-coherence interferometry to measure the length difference between two optical Fibers installed on the structure to be monitored, as illustrated in Figure. The sensor consists of a pair of single-mode fibres placed in the structure to be monitored.

The measurement fibre is pre-tensioned and mechanically coupled to the structure at two anchorage points, in order to follow its deformations, while the reference fibre is placed loose in the same pipe. The sensors have excellent long-term stability and precision of ±2 μm independent of the measurement base. Even a change in the fibre transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity. Since the measurement of the length difference between the fibres is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors.

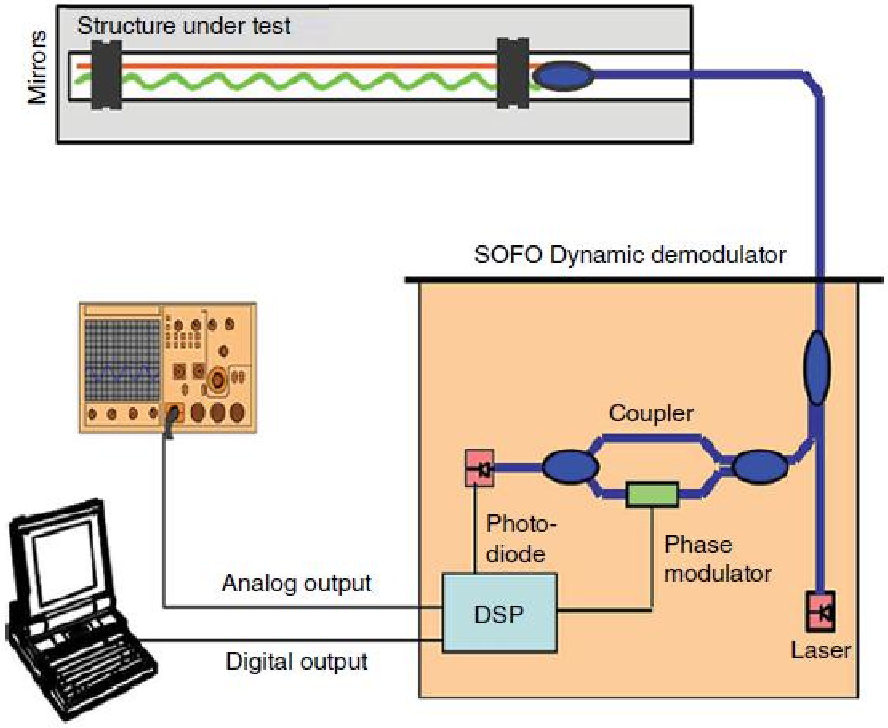


Figure: Setup of SOFO interferometric sensor system (Courtesy of Smartec).

Fabry-Pérot interferometric sensors – Fabry-Perot (FP) cavities (both passive and active) have been successfully used in sensing applications exploiting measurand-induced changes in one of their cavity parameters. The cavity can be active, for instance integrating a fibre laser sensor, or passive. An extrinsic Fabry-Perot interferometer (EFPI) consists of a capillary glass tube containing two partially mirrored optical fibres facing each other, but leaving an air cavity of a few micrometers between them, as illustrated in Figure.

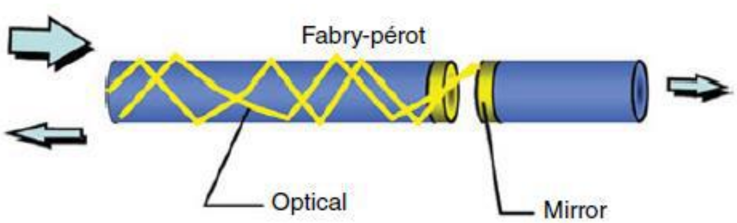
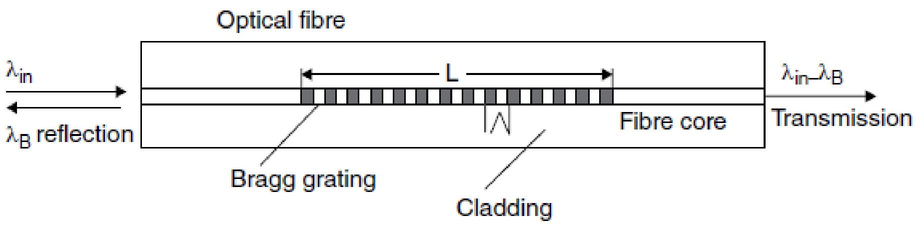


Figure: Functional principle of Fabry-Pérot sensors (Courtesy of Roctest).

When light is launched into one of the fibres, a back-reflected interference signal is obtained from the two mirrors. This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fibre spacing. Since the two fibres are attached to the capillary tube near its two extremities (with a typical spacing of 10 mm), the gap change will correspond to the average strain variation between the two attachment points. Many sensors based on this principle are currently available for monitoring of civil infrastructure, including piezometers, strain gauges, temperature sensors, pressure sensors and displacement sensors.

Fibre Bragg grating (FBG) sensors – Bragg gratings are periodic alterations in the index of refraction of the fibre core, produced by adequately exposing the fibre to intense ultraviolet light in the region of 244–248 nm, as illustrated in Figure.



The produced gratings typically have a length of about 10 mm. Light at the wavelength corresponding to the grating period will be reflected, while all other wavelengths will pass through the grating undisturbed. The grating period (length) changes with temperature and strain, thus both parameters can be measured through the spectrum of the reflected light. Light traveling down the Bragg grating core that leads to a resonance condition is a special case of the Bragg equation, given by

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

where λB is the Bragg wavelength, n_{eff} is the effective refraction index of the fibre core and P is the period of the index modulation. As a consequence of the coupling between the forward and backward propagating modes, a portion of the illuminated light is reflected by the grating while the remainder is transmitted. Both n_{eff} and P depend on temperature and strain, thus the Bragg wavelength is sensitive to both strain and temperature. One of the most significant features of an FBG sensor is its self-referencing capability. It means that no recalibration and/or re-initialization are needed for this kind of sensor, since the measurands are encoded into the wavelength, which is an absolute parameter. The main benefit with FBG sensors is their multiplexing potential, with several gratings in the same fibre at different locations and tuned to reflect different wavelengths. Accuracy of the order of 1 με and 0.1 °C can be achieved with the best demodulators.

Distributed Brillouin and Raman scattering sensors – Brillouin and Raman scattering effects give completely different spectral characteristics, because they are associated with different dynamic inhomogeneities in the silica fibres.

The Brillouin scattering is a backward process, while the Raman scattering is backward and forward process. If an intense light at a known wavelength is shone into a fibre, a very small amount of the light is scattered back from every location along the fibre itself. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are higher and lower than the original signal (called the Raman and Brillouin components). Distributed fibre optic sensors measure physical parameters, in particular strain and temperature, along their whole length. They allow the measurements of thousands of points from a single readout unit. The shifted components contain information on the local properties of the fibre, in particular its strain and temperature. Systems based on Raman scattering typically exhibit temperature accuracy of the order of ±0.1 °C and a spatial resolution of 1 m over a measurement range up to 8 km (Catbas et al. 2012). The best Brillouin scattering systems offer a temperature accuracy of ±0.1 °C, a strain accuracy of ±20 με and a measurement range of 30 km, with a spatial resolution of 1 m.

Fibre Optic Sensors for Structural Monitoring

Fibre optic sensors can be used for monitoring many physical or chemical quantities of civil structures.

Crack monitoring – The current state of many critical concrete structures can be assessed through the detection and monitoring of cracking in concrete. For example, in concrete bridge decks, crack openings beyond 0.15–0.2 mm will allow excessive penetration of water and chloride ions into the concrete cover, leading to reinforcement corrosion. So far, many optical crack sensors have been developed, such as sensing based on fibre breakage and point sensors, but they may be limited in their applications. Distributed fibre optic sensors can overcome the limitations on the basis of the measurement of the intensity loss due to deformation. They do not require prior knowledge of the crack locations, which is a major advantage over existing crack monitoring techniques (Casas and Cruz 2003). Furthermore, several cracks in concrete can be detected, located and monitored with a single fibre.

Strain monitoring – The commonly used fibre optic sensors for strain sensing include Fabry–Perot sensors and FBG sensors. The Fabry-Perot sensing technique has very good accuracy with a maximum resolution of ±0.01 με. However, a new calibration is needed every time when the readings are stopped. The FBG technique has less precision with a resolution around ±10 με for standard equipment, but the FBG technique has the advantage of reading absolute values, and thus they are unaffected by interrupted measurements. Many small instruments using FBG sensors have been developed to be embedded into concrete and to monitor the strain. In structural integrity assessment, the strain of the concrete may not be as useful as the strain of the reinforcing bars in the tensioned region of the cross-section. When there are cracks appearing in this region, the concrete releases some stress and the rebar is more strained (Casas and Cruz 2003). Thus, it should be more useful to measure the strain on the reinforcing bars.

Temperature monitoring – FBG sensors have a main limitation of dual sensitivity to temperature and strain. This creates a problem for sensors used for strain monitoring, since temperature variations along the fibre can lead to abnormal strain readings. To tackle the problem, reference gratings are used. Such reference gratings are in thermal contact with the structure, but do not respond to local strain changes. Thus, compensation can be achieved by subtracting the shift of the reference gratings from the shift of the sensing gratings. Many fibre optic sensors are available for temperature monitoring. However, these sensors cannot be embedded, unless a box is used to isolate the sensor from any structural strain.

Corrosion monitoring – Fibre optic sensors were developed to directly monitor the corrosion of the steel reinforcing bars in concrete structures. Some of these sensors are based on the Bragg grating technology which is also used for strain and temperature sensors. The measurements from corrosion monitoring can be read by the same optical system that is used for other types of sensors, such as corrosion, strain and temperature sensors (Casas and Cruz 2003). Fibre optic sensors for corrosion monitoring are based on the concept that the corrosion of reinforcing bars generates an expansive layer of corrosion products at the interface of rebar and the surrounding concrete. Thus, corrosion can be measured from the expansion of the corroded reinforcing bar.

Monitoring of other quantities – Since FBG sensors have many advantages such as low self-weight, multiple measuring points, superior performance and better reliability, they can also be used for monitoring other quantities (Casas and Cruz 2003), including inclination of structural components, vibration of the structure by measuring acceleration, force by using FBG load cells, ice detection on pavements and traffic conditions on bridges.

Wireless Sensors

Wireless sensors are gaining popularity for monitoring of large civil engineering structures because they are inexpensive and easy to install. Wireless sensors have the ability to collect data in place of traditional cabled sensors, but they do not function as exact replacements. Strictly speaking, wireless sensors are not sensors, but rather are autonomous data acquisition nodes to which traditional sensors (e.g. strain gages or accelerometers) can be attached. Wireless sensors are considered as a platform where mobile computing and wireless communication elements converge with the sensing transducer. Currently, there are a large number of different academic and commercial wireless sensors, as shown in Figures (a) and (b).

(a) Commercial wireless accelerometer (BeanDevice® AX-3D Xrange, Courtesy of Beanair).

(b) Academic wireless sensing prototype (after Ni et al. 2011).

Figure:Wireless sensors for structural monitoring.

Components of Wireless Sensors

Wireless sensors are generally divided into two groups: passive sensors and active sensors. Passive sensors measure a specific physical or chemical quantity by responding passively to the state of the system to be monitored. Passive wireless sensors consist of three functional subsystems: sensing interface, computational core and wireless transceiver. Active sensors, by contrast, generate signals in a controlled manner, and then they sense the response of the system to those signals. An additional subsystem, (an actuation interface) is added in the active sensors to generate the signal (Lynch and Loh 2006), as illustrated in Figure 2.13. Without wires, wireless sensors require internally stored power for operation. Several power sources can be used in wireless sensing systems, such as conventional batteries, radio frequency identification (RFID), ambient energy sources, such as solar, vibration and thermal. Wireless sensors contain an interface to which sensing transducers can be connected. The sensing interface is largely responsible for converting the analog output of sensors into a digital representation. Once measurement data has been collected by the sensing interface, the computing core undertakes the local data processing and computational tasks. Then, the computational demands on the central data processing resources are reduced. In order to accomplish these tasks, the computational core is provided by a microcontroller that can store measurement data in random access memory and data interrogation programs in read only memory. In order to have the capability to interact with other wireless sensors and to transfer data to remote data repositories, a wireless transceiver is necessary for both the transmission and reception of data (Lynch and Loh 2006). Finally, an actuation interface provides a wireless sensor with the capability of interacting directly with the physical system. The core element of the actuation interface is the digital-to-analogue converter (DAC), which converts digital data generated by the microcontroller into a continuous analogue voltage output.

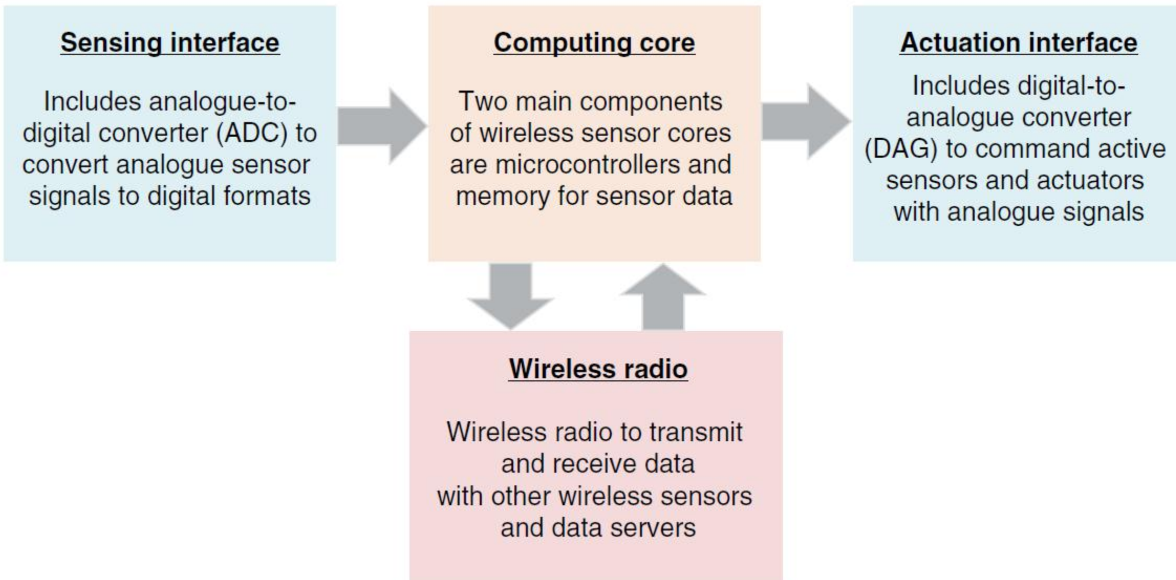


Figure 2.13 Functional subsystem and block diagrams of wireless sensors

Field Deployment in Civil Infrastructure

The academic wireless sensing prototype shown in Figure is an integrated wireless monitoring system that supports real-time data acquisition for structural monitoring. This prototype wireless monitoring system was adopted for exploring the feasibility of wireless sensing technologies in the ambient vibration monitoring of the Canton Tower (Ni et al. 2011) and in-construction monitoring of a high-rise building (New Headquarters of Shenzhen Stock Exchange).This system incorporates an integrated hardware and software design to implement a simple star topology wireless sensor network. The wireless sensing units are responsible for acquiring sensor output signals, analyzing data and transferring data to the base station for storage and further data analysis. The wireless sensing unit consists of three functional modules: sensing interface, computational core and wireless transceiver. The sensing interface converts analogue sensor signals into a digital format as used in the computational core. The main component of the sensor signal digitization module is a 4-channel, 16-bit analogue-to-digital (A/D) converter (Texas Instruments ADS8341).

The 16-bit A/D resolution is sufficient for most applications in civil engineering. The highest sampling rate supported by this A/D converter is 100 kHz. The digitised sensor data is then transferred to the computational core through a high speed serial peripheral interface (SPI) port. Embedded software was developed for the ATmega128 microcontroller to allow the microcontroller to effectively coordinate the various hardware components in the wireless sensing unit. An extensive algorithmic library has also been embedded in the computational core to perform data processing tasks, such as modal analysis and damage detection, on the sensor node itself. The wireless sensing unit is designed to be operable with two different wireless transceivers: 900 MHz MaxStream 9XCite and 2.4 GHz MaxStream 24XStream. Pin-to-pin compatibility between these two wireless transceivers makes it possible for the two modules to share the same hardware connection in the wireless unit. This dual-transceiver support offers the wireless sensing unit the opportunity to be used in different regions around the world. This support also allows the sensing unit to have more flexibility in terms of data transfer rate, communication range and power consumption. For example, although the 9XCite transceiver requires less power consumption, it can only be used in the region where the 900 MHz band is for free public usage. For this reason, the 24XStream transceiver operating on the open 2.4 GHz was employed in the applications of structural monitoring of the Canton Tower and the high-rise building. Through the associated wireless transceiver, the base station can communicate with the wireless sensing units that are spatially distributed throughout the structure.

Unit-III
Commonly used sensors for civil infrastructures and their associated algorithms

Introduction

While there is a wide array of different sensing technologies that are widely used throughout the civil and aerospace industries for health monitoring purposes, this chapter focuses on four general types of measurements that are widely used as part of health monitoring systems: displacement, strain, acceleration, and environmental parameters. For each of these measurement types, two or three different types of traditional sensors that are commonly used in practice are then described. Although additional sensors could be included in this list, only those sensors that were found to be the most commonly used in the literature for monitoring civil structures with a focus on bridges have been included here. Furthermore, the inclusion of sensor types in this list of 'traditional' technologies does not indicate that there are no longer innovations or advancements in each of these types of sensors. In each of these areas, new advancements continue to be made as the sensors are made smaller, less expensive, and more robust and the algorithms associated with them are improved.

Displacement

One sensing modality that is commonly used in monitoring bridges, dams, and other large civil structures is relative displacement measurement. While these measurements are not commonly used for health monitoring of aerospace structures, they can prove useful in monitoring civil infrastructure because of the much larger scales and geometric changes that can occur during a civil structure's lifecycle. While technologies such as the global positioning system (GPS) offer the capability to measure global changes in position, traditional displacement measurements are typically made using linear variable differential transformers (LVDTs) or potentiometers, which are connected to two locations on or at the boundary of the structure of interest in order to measure relative displacements.

Linear variable differential transformers

LVDTs are a type of two-part inductive sensor in which a ferromagnetic armature moves within an outer transformer consisting of one primary and two secondary coils. The secondary coils are located on either side of the primary coil and are wound in opposite directions. The primary coil is excited with an alternating current (AC) excitation and the magnetic flux that is developed is coupled to the secondary windings through the ferromagnetic core. Due to the opposite windings of the two secondary coils, when the core is positioned in the magnetic center of the transformer the two secondary coils cancel one another and no voltage is measured at the output. However, when the core moves away from this central position the amount of induced flux that is coupled into the two secondary coils becomes unequal, which creates a voltage differential in the circuit. While the core remains within the operating range of the LVDT, the amount of output voltage is linearly related to the displacement of the core. LVDTs are attractive for measuring displacement for several reasons. Because there is no mechanical contact between the sensing elements, there are no frictional forces to distort the readings and the sensors are highly robust because there are no mechanical connections that could suffer fatigue failures. This lack of mechanical connection also means that the minimum resolution of the sensor is based solely upon the noise in the signal conditioning and data acquisition systems, and consequently high resolutions can be achieved. However, because the sensor relies on this lack of contact between the core and the body, transverse motion must be minimized to avoid internal rubbing. Another possible drawback to the use of LVDTs is that the sensor's operating range is limited by the size of the sensor itself, since the core must remain within the coils for the system to operate correctly.

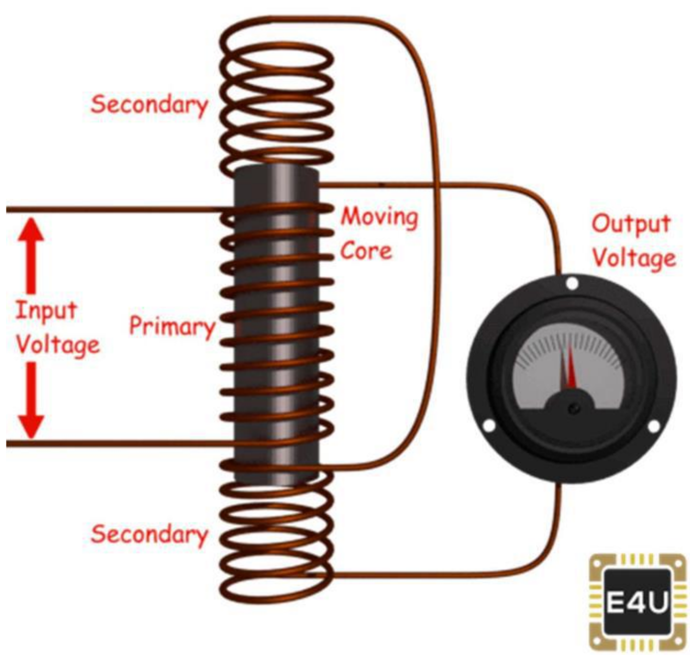


Figure: *Linear variable differential transformers*

Potentiometers

Potentiometers come in many shapes and sizes but are typically predicated on relating changes in resistance to changes in rotational or linear position. This change in resistance is typically accomplished by moving a pot wiper along a length of wire causing a linear change in the resistance between the excitation source and the wiper. As previously stated, although there are many forms of potentiometers, one of the most common is a string potentiometer in which a measuring cable is wound around a spool. The spool has a torsional spring to maintain tension in the measurement wire and the length of string that has come out of the sensor can be calculated using the rotational potentiometer on which the spool is mounted. One reason why string potentiometer can be attractive for measuring displacements is because, unlike LVDTs, they can measure displacements that are significantly larger than the sensor itself because the measurement wire is wound around the spool. This allows them to be relatively lightweight while still being able to measure ranges of over 50 meters. However, because of their mechanical connections most string potentiometers have limits on their frequency range, lifetime, and accuracy. Furthermore, while it is not typically an issue on large civil structures, the tension in the cable can affect the measurement for smaller structures that are more sensitive to external loads.

Strain

Strain measurements are used for a variety of health monitoring techniques because they are a direct measurement of the structure's relative deformation under the applied load. While these measurements can provide valuable information about a given component, they are also related to the, often unknown, load that the structure is undergoing. Despite this fact, both piezoresistive and vibrating-wire strain gauges are often used in monitoring systems for large civil structures.

Piezoresistive

Resistive strain gauges are utilized widely on both aerospace and civil structures. These simple sensors are bonded to the structure of interest so that the deformation of the structure causes the sensor to elongate or contract as well. Deformations of less than approximately 2% can be related to the resistance of the gage through the equation:

$$R = R_0 \left(1 + S_e \varepsilon\right)$$

where R is the resistance of the deformed gage, R_0 is the resistance of the gage with no stress applied, S_e is the gage factor of the conductor (approximately 2 for many metals) and ε is the strain across the gauge. These changes in resistance are typically converted to an absolute voltage using a Wheatstone bridge circuit.

While piezoresistive strain gauges are small and consequently have relatively negligible mass loading effects on the structure, their response is dominated by localized effects such as stress concentrations. For large structures this means that strain gauges should be restricted to monitoring ‘hot spots’ where damage is expected to occur or on critical components because large areas will require extensive numbers of sensors for global monitoring. Dense instrumentation with piezoresistive strain gauges can be problematic because good installation is essential to obtain high quality measurements from a strain gage and installation is a labor-intensive process that is best performed by those with the expertise. Piezoresistive strain gage measurements can also be affected by changes in temperature, and it can be difficult to detect slowly varying strains using them due to sensor drift

Vibrating-wire

Vibrating-wire strain gauges are an alternative type of strain gage that is commonly used on large civil structures such as bridges but are not extensively used in the aerospace industry. Vibrating-wire strain gauges are based on the principle that if a wire is pinned at both ends and put under tension, the natural frequency of the vibration of its first mode is:

$$f = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

where l is the length of the wire, T is the tension in the wire, and m is the mass per unit length of the wire. By bonding the locations at which the wire is fixed to the structure of interest, the strain across the length of the wire can be determined by monitoring the natural frequency of the wire. Vibrating-wire strain gauges are typically much larger than piezoresistive strain gauges and are often between 50 and 250 mm in length. The gauges themselves are often attached by welding them directly to the structure of interest or, in the case of concrete, can be directly embedded in the material. In the case of strain gauges on concrete, the relatively large size of vibrating wire strain gauges is advantageous because it averages the strain over a sufficient distance to average out much of the local inhomogeneities that are inherent in the concrete. While these gauges are sensitive to temperature, like piezoresistive strain gauges, when they are carefully installed and used at room temperature, they have been found to be very stable and exhibit drift of less than one micro strain over several months.

Acceleration

Acceleration measurements are among the most commonly used measurements in health monitoring of both civil and aerospace structures. Because of their widespread use in health monitoring applications, three different types of accelerometers are described in this section: force-balance, capacitive, and piezoelectric accelerometers.

Force-balance

A force-balance, or servo, accelerometer utilizes an active feedback control system to control the position of the proof mass, and the feedback required to keep the mass stationary is used to calculate the acceleration that the system is undergoing. The system works as follows. When the sensor housing is accelerated, the proof mass inside the sensor attempts to remain stationary with respect to the inertial frame of reference. This causes the proof mass to move away from its nominal position in the sensor housing. This relative motion is detected using a displacement sensor (often capacitive), which produces an error signal in the control system. This causes current to flow through the force generating element that balances the force due to the acceleration. Then, by relating the current to the applied force, the acceleration can be calculated using the known proof mass and properties of the forcing system.

Force-balance accelerometers can be attractive for monitoring civil structures because they are very sensitive and have very good resolution at low frequency. Furthermore, they are relatively insensitive to thermal effects and have relatively low nonlinearities. However, the major drawback of force balance accelerometers is the control mechanism itself, which makes the sensor more expensive than other accelerometers and limits the bandwidth of the sensor to relatively low frequencies.

Capacitive

A capacitive accelerometer utilizes the displacement of a proof mass with respect to the housing of the accelerometer in order to determine the acceleration that the sensor is experiencing. In a capacitive accelerometer, the motions of the proof mass are relatively small (less than 20 μ m) so the proof mass is typically suspended between two plates, one of which is above it and one of which is below it. The two capacitors that are formed between the mass and the top and bottom plates are then utilized in a differential mode so that small drifts and interferences can be compensated for in the measurement . Capacitive accelerometers are advantageous for monitoring large structures because they are able to acquire measurements across a wide frequency range including static acceleration while generally having superior stability, sensitivity, and resolution to piezoresistive accelerometers. However, they are somewhat susceptible to temperature and humidity variations and are relatively fragile compared to piezoelectric accelerometers.

Piezoelectric

Piezoelectric accelerometers are highly utilized in both the civil and aerospace industries. These accelerometers are based upon the piezoelectric effect in which certain crystalline materials generate an electric change that is proportional to the net force acting on the piezoelectric material. Piezoelectric accelerometers typically utilize one of three different configurations, namely the shear mode, flexural mode, or compression mode configurations, to measure the applied acceleration. In a shear mode accelerometer, the piezoelectric material is sandwiched between a rigid post and a cylindrical proof mass as shown in Figure,

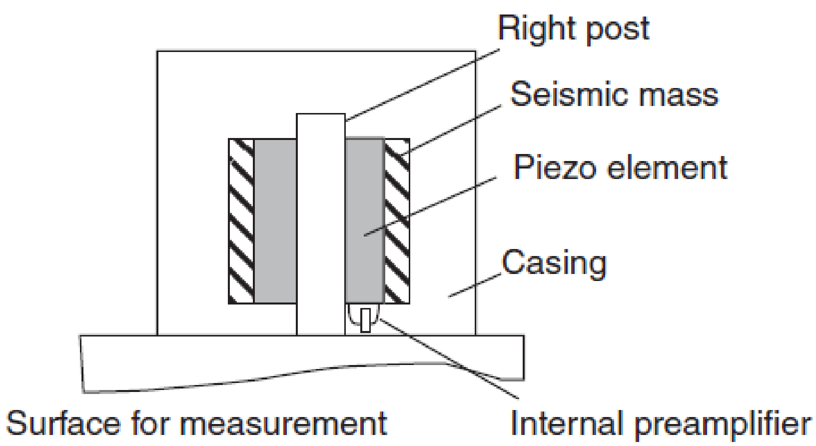


Fig: Diagram of a shear mode piezoelectric accelerometer

so that as the proof mass moves relative to the rigid post in the sensing direction, it generates a shear stress in the piezoelectric material. In flexural mode accelerometers, a beam shaped crystal is used that is supported on a fulcrum so that accelerations directly induce strains in the piezoelectric beam. This type of piezoelectric accelerometer is best suited for low-frequency, low-amplitude applications.

Compression mode accelerometers use tensile and compressive loads to generate forces in the piezoelectric material. While early designs preloaded the piezoelectric material against the base of the sensor, it was found that this approach made the accelerometer very sensitive to base strains and temperature variations. Therefore, new designs isolate the crystal by either placing it at the top of the sensor or isolating it using a washer.

Environment

Because most civil infrastructures operate in widely varying environments the preponderance of health monitoring systems typically include several types of traditional sensors to measure the current environmental conditions. While these measurements may not be used to directly calculate the health of the structure, they are essential for monitoring the loads on the structure and for the data-normalization process that is a necessary part of detecting changes in the sensor's measurements due to damage from changes due to variations in the structure's environment.

Anemometers

For large civil structures such as buildings and bridges, wind speed can be of particular interest as it can significantly excite the structure. This is even more critical for bridges in which improper design can lead to aerodynamic self-excitation, as was the case with the famous Tacoma Narrows Bridge. Lastly, anemometers are also of great interest in wind turbines since the entire operation of the structure is based on wind speed and these measurements can be used to help normalize the response of the structure. While a variety of different types of anemometers exist, perhaps the most widely used is the cup anemometer, which typically consists of three or four cups mounted on the end of horizontal arms that are fixed to a common vertical shaft. The cup anemometer is a drag-driven device that turns because the drag on the smooth back surface of the cup is less than that on the open face of the cup. This imbalance in drag results in rotational speed of the cups being proportional to the average wind speed.

Thermocouples and resistive thermometers

For large and relatively flexible structures such as bridges or even buildings, temperature changes can have a large effect on the response characteristics of the structure and can easily mask changes in the structure due to damage or result in false indications of damage. For example, Alampalli (1998) found that freezing in the supports of a bridge caused changes in the natural frequencies of the structure that were more than ten times more significant than the changes in the natural frequencies due to damage. However, perhaps even more interesting was Farrar *et al* .'s (1997) fi nding that the fi rst mode of the Alamosa Canyon bridge varied by approximately 5% throughout a single day, and that rather than being correlated with the overall ambient temperature of the structure this change was correlated with the temperature gradient across the bridge deck. This influence of temperature gradients has resulted in the widespread application of temperature sensors including thermocouples and resistance thermometers with as many as 388 temperature sensors being installed on a single bridge. Resistance thermometers utilize the principle that the resistance of metals increases with temperature. Platinum is typically utilized for resistance thermometers because it has the highest possible coefficient of resistivity, which is indicative of its high purity, and the slight changes in its resistance with temperature can be measured using a Wheatstone bridge. Thermocouples, on the other hand, use the fact that if two different metal wires are connected, the voltage that is produced in the vicinity of their connection is dependent on the temperature difference between the connectors and other parts of those wires. A wide variety of different thermocouples are produced utilizing a range of different alloys depending on the specific temperature range in which the sensor will be operating.

Prevalence of commonly used sensors in SHM systems

To determine which sensors are most commonly used in health monitoring installations, a literature review was performed to identify some instances of installed health monitoring systems and the types of sensors that are used within them. Some of the installed instrumentation and the number of gauges of each type are listed in Table 3.1. As an illustration of the complexity of some of these systems, Fig. 3.2 shows an instrumentation diagram for the Stonecutters Bridge in Hong Kong.

Table 3.1 Health monitoring systems found installed in the literature with the type and number of sensors installed

Structure	Percent 'traditional' sensors	Displacement	Strain	Acceleration	Wind speed	Temperature
Vanke Center (Teng *et al.*, 2011)	43%	0	154	14	0	0
Shenzhen Bay Stadium (Teng *et al.*, 2011)	95%	0	108	8	2	102
24-story steel frame building (Celebi *et al.*, 2004)	100%	0	0	30	0	0
UCLA Louis Factor Building (Skolnik *et al.*, 2006)	100%	0	0	72	0	0
Humber Bridge (Brownjohn, 2007)	59%	6	0	16	13	2
Samcheonpo Bridge (Koh *et al.*, 2009)	77%	4	0	44	2	5
Sunrise Bridge (Catbas *et al.*, 2010)	83%	0	94	40	0	0
Namhae Bridge (Koh *et al.*, 2009)	87%	4	54	18	2	0
Stonecutters Bridge (Wong and Ni, 2009)	89%	34	836	58	24	388
Tsing Ma Bridge (Wong and Ni, 2009)	91%	2	110	19	6	115
Shenzhen Western Corridor (Wong and Ni, 2009)	92%	4	212	44	8	118
Seohae Bridge (Koh *et al.*, 2009)	94%	10	94	36	2	14
Yongjong Bridge (Koh *et al.*, 2009)	94%	4	297	52	4	33

(*Continued*)

Table 3.1 Continued

Structure	Percent 'traditional' sensors	Displacement	Strain	Acceleration	Wind speed	Temperature
Gwangan Bridge (Koh *et al.*, 2009)	95%	5	4	20	4	70
Øresund Bridge (Peeters, 2009)	96%	0	19	66	2	14
Kap Shui Mun Bridge (Wong and Ni, 2009)	96%	2	30	3	2	224
Little Mystic Span of Tobin Memorial Bridge (Brenner *et al.*, 2010)	97%	0	96	6	1	6
Ting Kau Bridge (Wong and Ni, 2009)	97%	2	88	45	7	83
Fairview Road On-Ramp Overcrossing (Fen *et al.*, 2006)	98%	1	19	21	0	3
Kings Stormwater Channel Bridge (Guan *et al.*, 2006)	99%	4	20	63	0	1
Jamboree Road Bridge (Fen *et al.*, 2006)	100%	1	0	14	0	0
Neka Railway Bridge (Ataei *et al.*, 2005)	100%	20	42	27	0	0
New Cape Girardeau Bridge (Celebi, 2006)	100%	0	0	84	0	0
CX-100 SMART Rotor (Adams *et al.*, 2011, Berg *et al.*, 2011)	48%	0	21	24	0	0

Note: The total percent of installed sensors that have been deemed 'traditional' is listed in the second column while the remaining columns have the number of traditional sensors of each type that were installed on each structure.

Associated algorithms

Despite the widespread use of the above sensors as part of health monitoring systems, none of those sensors, or any other sensor for that matter, can directly measure damage (Worden *et al.*, 2007). Instead, these sensors measure the response of the structure to its operational and environmental input and then the health of the structure must then be inferred using a damage feature that is obtained from the acquired data. Each sensor type, however, has specific characteristics that can lend itself to a specific type of data feature or damage identification algorithm. Therefore, this portion of this topic briefly describes how each of the traditional types of sensors can be utilized as part of a health monitoring system and what unique capabilities they lend to the performance of the system. Because of their extensive use in damage identification methodologies, algorithms created primarily for acceleration measurements will be described in greater detail than those for other sensing modalities. Emphasis is placed on identifying the underlying commonalities of the algorithms and data source from which each of the damage features were obtained.

Displacement sensors

Displacement sensors are most commonly utilized to monitor large bulk changes in a structure and, therefore, have typically been used as part of straightforward algorithms to assist in monitoring the health of the structure. For instance, in a bridge they may be used to measure the maximum deflection at certain spans (Guan *et al.*, 2007), and then simple level crossing or peak holding methodologies can be used to detect anomalous events. Similar measurements of peak displacements can also be useful for monitoring inter-story drift in buildings during earthquakes, but are difficult to make in real-world structures where long distances must be spanned and there are numerous partition walls (Skolnik *et al.*, 2008). While this is a measurement of the transient geometry of the structure, displacement sensors are also commonly used to monitor the geometry of the structure due to changes that occur over longer time scales, such as those due to temperature and material creep (Wong and Ni, 2009). Another way in which displacement sensors have been used is to directly monitor cracks and crack opening displacements (Issa *et al.*,2005). Because of the long-term stability of most displacement sensors such as LVDTs and potentiometers, crack opening displacements can be measured directly to determine the long-term degradation of the structure (Lovejoy, 2007). Furthermore, because these measurements are relatively insensitive to temperature changes, they can be used in conjunction with temperature measurements to differentiate crack opening displacements due to temperature changes from those due to operational loading such as traffic on a bridge (Wang, 2009). The relative stability of these measurements also allows them to be used on large civil structures to estimate average moduli, which may then be tracked using more statistically rigorous methods such as bootstrapping to identify significant changes in the structure (Lloyd *et al* ., 2003).

Strain gauges

Strain gauges have received fairly broad attention because they are relatively inexpensive and can provide good engineering insight into the local behavior of the structure (Yu and Ou, 2006). This is one reason why they have been used widely to monitor fatigue in fixed-wing aircraft. In this application, strain gauges are commonly used to measure fatigue critical loads due to external forces like gust and buffeting as well as abrupt maneuvers. However, in order to fully utilize these measurements, because the strain gauges are so highly influenced by the local behavior of the structure, their location must be chosen carefully to either monitor hot spots where damage is likely to occur or to monitor the dominant fatigue loads acting on the structure (Buderath, 2009). The same need to place strain gauges in critical locations is also present in civil structures to ensure that the measurements can be used effectively in algorithms such as strain-based mode-shape algorithms (Kiremidjian *et al* ., 1997). In addition to damage identification methodologies derived from dynamic strain measurements such as those mentioned above, a damage identification methodology has recently been developed by Jang *et al* . (2008), who utilized static strain measurements to detect and locate damage on a simple truss system even when the strain in the damage truss member was not directly measured. Strain gauges may be most useful for the monitoring of loads in a component or substructure, particularly when that structure has well defined load paths that can be directly measured using a relatively small number of sensors. One example of this in the aerospace industry is monitoring of landing gear loads and fatigue using strain gauges mounted on the gear that can be used to infer the ground loads imparted on the gear (Schmidt and Sartor, 2009). The operational environment of prestressed concrete pressure vessels that are used in nuclear power plants is also evaluated using vibrating-wire strain gauges in conjunction with thermocouples to ensure that the operating conditions are within safe ranges and the plant is functioning as expected (Smith, 1996). Therefore, while strain gauges are usually not used in order to monitor entire civil structures, they can be successfully utilized as part of a full monitoring system because of the physical insight they provide into loads in specific components.

Accelerometers

Accelerometers have been the most widely used type of sensor for damage identification and health monitoring algorithms because of their ease of use, robustness, relatively low cost, and ability to detect changes in both local and global properties. This widespread use is due in part to their ability to measure relatively small motions over a wide frequency band. Good broadband performance is important in health monitoring because, in general, low-frequency responses are more global in nature while high frequency responses contain more localized information about the structure and may, therefore, be more sensitive to damage (Friswell, 2007). Furthermore, accelerometers are generally robust, easy to install, and relatively inexpensive. This combination of factors has led to the development of an extremely wide variety of different algorithms that utilize acceleration measurements to monitor the health of structures. A summary of a small subset of these methods that were found in the literature and showed promising results on an experimental structure are listed in Table. Also listed in that table is the main data source from which each method’s damage feature and the level of damage identification that it provided was calculated. The level of damage identification provided by the algorithm refers to the levels of (1) determination that damage is present, (2) determination of the geometric location of the damage, and (3) quantification of the severity of the damage (Rytter, 1993).

Table 3.2 Accelerometer based damage identification algorithms, the intrinsic damage feature they utilize, the structure on which they were demonstrated, and the level of damage identification that they provide

Method	Damage feature source	Structure investigated	Level 1: detection	Level 2: location	Level 3: quantification
Decreased natural frequencies (Brinker *et al.*, 1995)	Natural frequencies	Multi-pile offshore platform	X		
Compensated changes in natural frequency (De Roeck *et al.*, 2000)	Natural frequencies	Z24 Bridge	X		
Changes in modal curvature (Abdel Wahab and De Roeck, 1999) (Gul, 2009)	Mode shapes	Z24 Bridge	X	X	
Modal strain energy method (Farrar and Doebling, 1999)	Mode shapes	I-40 Rio Grande Bridge	X	X	
Transfer function pole migration (Lynch, 2005)[a] (Swarts and Lynch, 2008)[b]	Modal properties	IASC-ASCE experimental Benchmark[a], Z24 Bridge[b]	X		
Minimum rank model updating (Doebling, 1996)	Modal properties	NASA 8-Bay cantilevered truss	X	X	
Bayesian FE model updating (Ching and Beck, 2004)[a] (Skolnik *et al.*, 2006)[b]	Modal properties	IASC-ASCE experimental Benchmark[a], UCLA factor building[b]	X	X	X
Direct stiffness calculation (Maeck and De Roeck, 2003)	Modal Properties	Z24 Bridge	X	X	X
FE model updating (Teughels and De Roeck, 2004)	Modal Properties	Z24 Bridge	X	X	X
Damage locating vector (Gao *et al.*, 2004)	Modal properties	Experimental small-scale truss	X	X	
Operating shape local curvature (Sampai *et al.*, 1999)	FRFs	Experimental bridge structure	X	X	
Interpolation damage detection method (Limongelli, 2010)	FRFs	I-40 Rio Grande Bridge	X	X	
FRF PCA for neural networks (Ni *et al.*, 2006)	FRFs	Scale building model	X	X	
Linear and nonlinear frequency domain ARX models (Adams and Farrar, 2002)	Frequency domain input–output models	Unistrut frame structure	X		X
Transmissibility functions (Johnson *et al.*, 2004)	FRFs	Unistrut frame structure, rotorcraft fuselage	X	X	
Embedded sensitivity functions (Yang *et al.*, 2008)	FRFs	Metallic composite panel	X	X	X
Two-tier AR and ARX models (Lu *et al.*, 2008)	Response time histories	Two-story RC frame structure	X		
ARX model parameters (Gul and Catbas, 2011)	Response time histories	Z24 Bridge	X	X	X
Optimized neural-wavelets (Taha, 2010)	Response time histories	IASC-ASCE experimental Benchmark	X		X

Note: The superscript letters denote which reference refers to which structure.
FRF: frequency response function; RC: reinforced concrete.

Environmental measurements

Environmental measurements are not typically used for health monitoring of a structure directly, but recent experience has shown that they are an important part of any health monitoring system because environmental changes can have a large influence on the behavior of the structure being monitored. This is a vast and quickly expanding area of research and only a brief overview of some methodologies is given here. The interested reader is encouraged to read Sohn's (2007) excellent review on the topic for more information.

One example of the use of temperature measurements for compensating for environmental changes was already described in which De Roeck *et al.* (2000) utilized an ARX model to eliminate temperature effects from the changes in the natural frequencies of the Z24 Bridge so that the effects of damage could be detected. Sohn *et al.* (1999) took a similar approach to the problem by using a linear model to predict changes in both the first and second natural frequencies of the I-40 Rio Grande Bridge. Temperature compensation methods also apply principal component analysis to vibration features such as natural frequencies directly (Yan *et al* ., 2005a) or after they have been clustered (Yan *et al* ., 2005b). Both of these methods showed promise in compensating for the temperature variations observed on the Z24 Bridge.

Examples of continuous monitoring systems

In large part because of the decreasing costs, increasing reliability, and advanced algorithms designed for many of the aforementioned sensing technologies, continuous health monitoring systems have begun to be developed and deployed for civil infrastructure. One example of such a system for a building has been implemented on the Burj Khalifa Tower in Dubai, which is the tallest manmade structure in the world (Abdelrazaq, 2012). This system utilizes the building's existing network for the transmission of data and monitors the structure using modal properties estimated using time, frequency, or time–frequency techniques (Kwon *et al* ., 2010). A system has also been deployed on the Guangzhou New TV Tower and has recorded the building's vibrations during several types of dynamic events such as earthquakes and typhoons (Ni, 2010). However, the preponderance of vibration monitoring systems that have currently been deployed is on bridges, not buildings (Brownjohn *et al* .,2011). One example of such a system is the Stonecutters Bridge in Hong Kong (Wong, 2010), which has over 1500 sensors on it. As was shown in Table 3.1, 388 of these sensors were temperature measurements. One reason for this large number of temperature measurements is that they can be used as part of correlation models to help account for changes in the modal frequencies of the bridge due to changes in the environment (Ni, 2010). However, the majority of the sensors on the Stonecutters Bridge are strain sensors. The large number of strain sensors was likely influenced by the successful use of strain sensors on the Tsing Ma Bridge to monitor the performance of the bridge deck under operational loading, detect the (see Table 3.1), many of the monitoring methodologies rely on accelerometer readings to monitor key aspects of the bridge's performance. For instance, the accelerometer readings are utilized for the operational modal analysis of the bridge including its deck, towers, and cables (Peeters *et al* ., 2003). If the influence of environmental variations on the modal parameters of the bridge are properly accounted for, changes in the bridge's modes of vibration that are dominated by the motion of the deck and tower can be used to monitor the overall health of the bridge while cable modes can be used to monitor the tension in any supporting cables (Peeters et al., 2003). The Bill Emerson Memorial Bridge also relies on accelerometers in its monitoring system (Celebi, 2006). This monitoring system has been utilized to assess the performance of the bridge against design parameters and has been utilized to analyze the response of the bridge to several earthquakes (Celebi, 2006).

Despite these examples of deployed health monitoring systems, the industry has still been relatively resistant to the deployment of health monitoring systems and new technologies (Brownjohn *et al* ., 2011). While there are many reasons for this slow transition from research to practice, one reason for this is that these systems are currently relatively expensive to install and deploy. For example, the system on the Bill Emerson Memorial Bridge reportedly cost approximately $1.3 million dollars or over $15 000 per channel (Spencer *et al.* , 2011). As advances continue to be made in both traditional and novel sensor technologies and data acquisition systems, these costs will be reduced and continuous monitoring systems for civil infrastructure will likely become far more prevalent presence of local damage using a strain energy formulation, and assess the fatigue life of the bridge using the daily stress spectra and modeled stress concentration factors (Ni, 2010). Several other noteworthy examples of continuous monitoring systems include the O resund Bridge and the Bill Emerson Memorial Bridge. many of the monitoring methodologies rely on accelerometer readings to monitor key aspects of the bridge's performance. For instance, the accelerometer readings are utilized for the operational modal analysis of the bridge including its deck, towers, and cables (Peeters *et al* ., 2003). If the infl uence of environmental variations on the modal parameters of the bridge are properly accounted for, changes in the bridge's modes of vibration that are dominated by the motion of the deck and tower can be used to monitor the overall health of the bridge while cable modes can be used to monitor the tension in any supporting cables (Peeters et al.,2003). The Bill Emerson Memorial Bridge also relies on accelerometers in its monitoring system (Celebi, 2006). This monitoring system has been utilized to assess the performance of the bridge against design parameters and has been utilized to analyze the response of the bridge to several earthquakes (Celebi, 2006).

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