UNIT II
VIBRATION MEASUREMENTS

Vibration refers to mechanical oscillations about an equilibrium point. The oscillations may be periodic such as the motion of a pendulum or random such as the movement of a tyre on a gravel road.

Vibration is occasionally "desirable". For example the motion of a tuning fork, the reed in a woodwind instrument or harmonica, or the cone of a loudspeaker is desirable vibration, necessary for the correct functioning of the various devices.

What are the Components of Vibration?
Amplitude
-Maximum value of vibration
Frequency
-Number of events or cycles per unit time
Phase
-Time relationship between vibrations of the same frequency

Characteristics of vibration
Vibration may be characterised by :
a) the frequency in Hz;
b) the amplitude of the measured parameter, which may be displacement, velocity, or acceleration.This is normally referred to as the vibration amplitude when expressed in units, but vibration level when expressed in decibels.

Units of vibration
The units of vibration depend on the vibrational parameter, as follows:
a) Acceleration, measured in g or $[m/s^2]$
b) Velocity, measured in $[m/s]$
c) Displacement, measured in $[m]$

Some effects of vibration
- Vibration can cause damage to structures and machine sub-assemblies, resulting in mis-operation, excessive wear, or even fatigue failure.
- Vibration may have adverse effects on human beings. The primary effects are task-performance interference; motion sickness; breathing and speech disturbance; and a hand-tool disease known as "white finger", where the nerves in the fingers are permanently damaged, resulting in loss of touch sensitivity.

Decibel notation applied to vibration measurement
Because of the wide range of vibration amplitudes found in engineering, it is convenient to express the measured amplitude in decibels with reference to a fixed value. Reference values which are internationally accepted are as follows:
a) for velocity, the reference is 10^{-3} m/s ;
b) for acceleration, the reference is 10^{-5} m/s^2.
Thus if the measured amplitude is A_1 and the reference amplitude is A_0, the vibration level expressed in decibels is

$$\text{vibration level} = 20 \log_{10} \frac{A_1}{A_0} \text{ dB}$$

Types of vibration

(i) Free vibration occurs when a mechanical system is set off with an initial input and then allowed to vibrate freely

Examples of this type of vibration are pulling a child back on a swing and then letting go or hitting a tuning fork and letting it ring. The mechanical system will then vibrate at one or more of its "natural frequency" and damp down to zero.

Forced vibration is when an alternating force or motion is applied to a mechanical system.
Examples of this type of vibration include a shaking washing machine due to an imbalance, transportation vibration (caused by truck engine, springs, road, etc.), or the vibration of a building during an earthquake. In forced vibration the frequency of the vibration is the frequency of the force or motion applied, with order of magnitude being dependent on the actual mechanical system.

(ii) Linear and Non-linear vibration: If the basic components of a vibrating system, namely the spring, the mass and the damper behave in a linear manner, the resulting vibrations caused are known as linear vibrations. These are governed by linear differential equations. They should obey the law of superposition.
On the otherhand, if any of the basic components of a vibratory system behave in a non-linear manner, the resulting vibration is called non-linear vibration. In this case, the governing differential equation is also non-linear. It does not follow the law of superposition.

(iii) Damped and Undamped vibrations: When a damper or damping element is attached to the vibratory system, the motion of the system will be opposed by it and the energy of the system will be dissipated in friction. This type of vibration is called damped vibration.
On the otherhand, the vibration generated by the system having no damping element is known as undamped vibration.

(iv) Deterministic and Random vibrations: If the amount of excitation (force or motion) acting on a vibratory system is completely known precisely, the resulting vibrations are called as deterministic vibrations. Contrary to it, when the amount of excitation is not completely known, the resulting vibrations are known as non-deterministic vibrations or random vibrations. Random vibration analysis is used to analyse the earthquake excitation of buildings and structures.

(v) Longitudinal, Transverse and Torsional vibration: When the particles of the body or shaft move perpendicular to the axis of the shaft, the vibrations created are known as transverse vibrations as shown in Figure 1.4(a).
If the mass of the vibratory system moves up and down parallel to the axis of the shaft, the vibrations created known as longitudinal vibrations as shown in Figure 1.4(b).
If the shaft gets alternately twisted and untwisted on account of vibratory motion of the suspended disc, such vibrations are called torsional vibrations as shown in Figure 1.4(c).
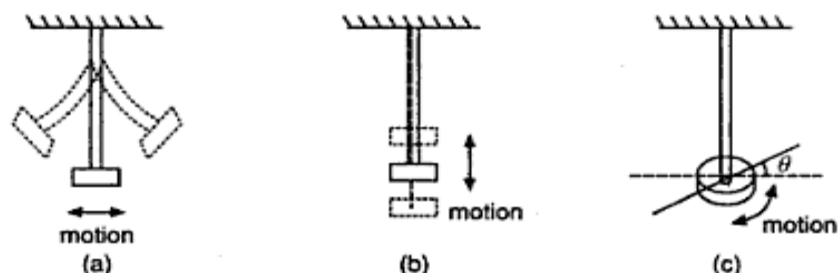

Figure 1.4 Example for (a) Transverse, (b) Longitudinal, and (c) Torsional vibrations.

Linear Variable Differential Transformer(LVDT)

LVDT's are robust equipment for measuring deflection. The LVDT (Linear Variable Differential Transformer) is an electrometric device that produces an electrical voltage proportional to the displacement of a movable Magnetic Core.

The LVDT is composed of these basic components:

A coil winding assembly

It consisting of a Primary Coil and two Secondary Coils symmetrically spaced on a tubular center.
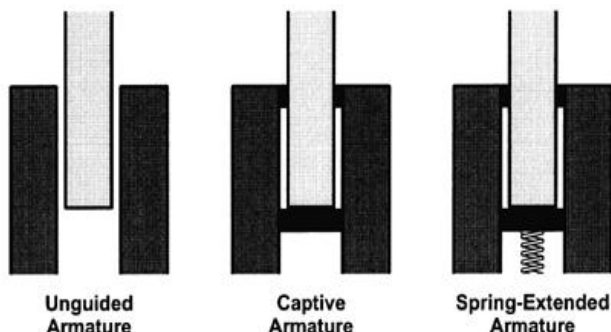
A Cylindrical Case

Which encloses and protects the Coil Winding Assembly

A rod shaped **Magnetic Core** which is free to move axially within the Coil Winding Assembly. A separate shield is used for **Electromagnetic Shielding.**
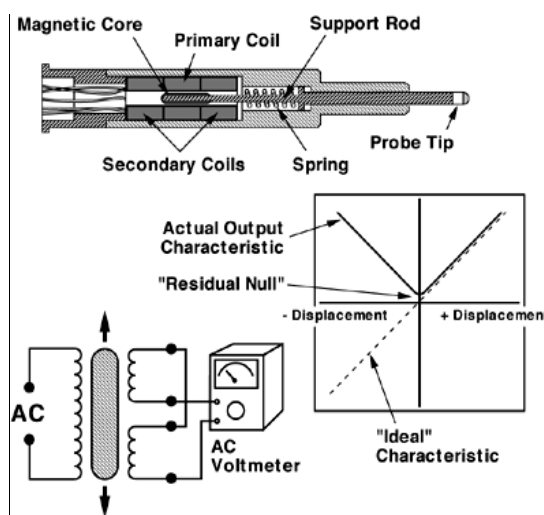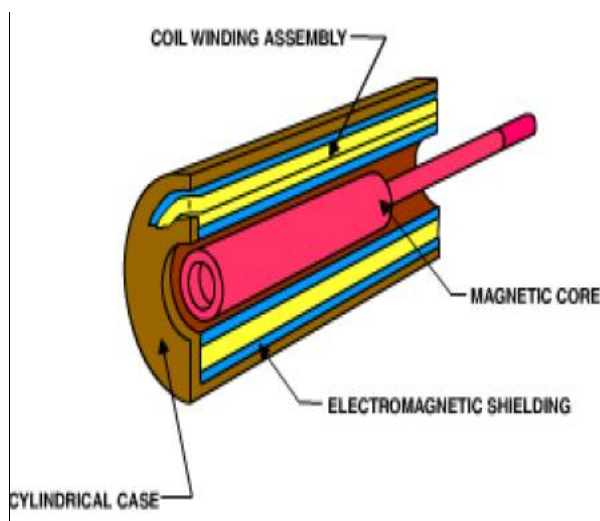
Types of LVDT's

- ► Unguided Armature
- ► Captive Armature
- ► Spring-extended Armature

3

Unguided Armature:

► There is no wear on the LVDT because no contact is made between armature and bore.
► LVDT does not restrict the resolution of measured data ("infinite resolution").
► Well-suited for short-range, high-speed applications (vibration)

Captive Armature:
► Armature is both guided and restrained by a low friction assembly
► It is Better for longer working ranges and preferred when misalignment may occur

Spring-Extended Armature:
► Like the captive armature, it has a low-friction bearing assembly
► Internal spring to continuously push the armature to its fullest possible extension
► The spring-extended armature is best suited for slow-moving applications.
► Attachment between armature and specimen is not required.

UNDERLYING PRINCIPLE AND OPERATION
Electromagnetic Induction:

– Primary Coil (RED) is connected to power source

– Secondary Coils (BLUE) are connected in parallel but with opposing polarity

– Primary coil's magnetic field (BLACK) induces a current in the secondary coils

– Ferro-Metallic core (BROWN) manipulates primary's magnetic field

– In the null position, the magnetic field generates currents of equal magnitude in both secondary coils.

– When the core is moved, there will be more magnetic flux in one coil than the other resulting in different currents and therefore different voltages

– This variation in voltages is linearly proportional to displacement
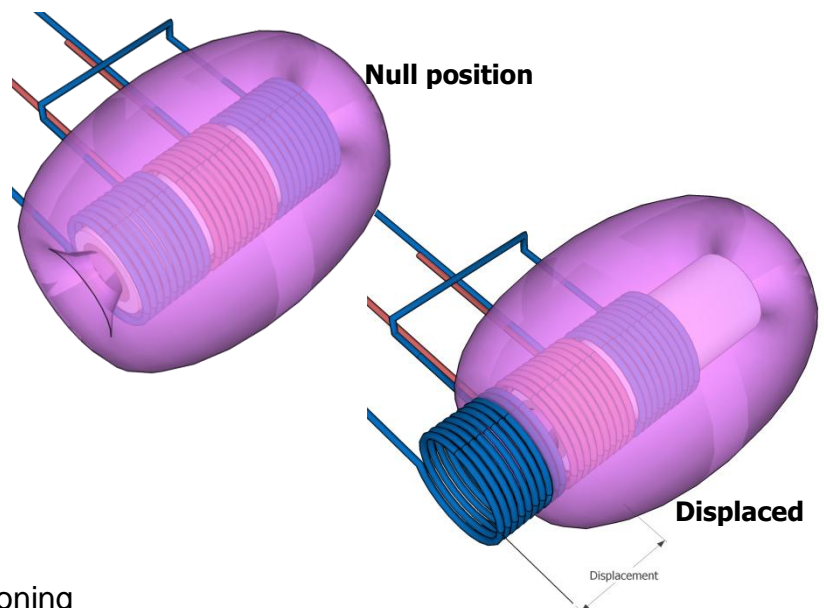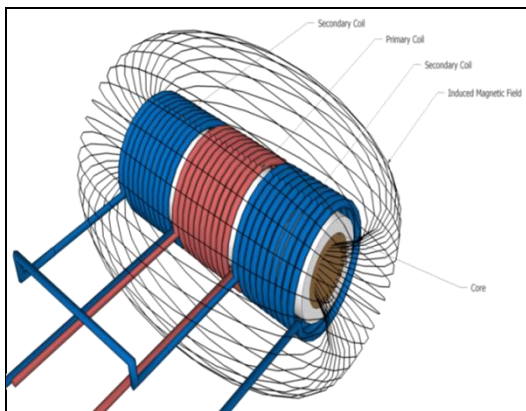
DC vs. AC Operated LVDT
– DC Operated
• Ease of installation
• Simpler data conditioning

- Operate from dry cell batteries (remote locations)
- Lower System Cost
– AC Operated
  - Smaller than DC
  - More accurate than DC
  - Operate well at high temperatures

Civil/Structural Engineering Examples

– Displacement measurement of imbedded concrete anchors tested for tensile, compression, bending strength and crack growth in concrete

– Deformation and creep of concrete wall used for retaining wall in large gas pipe installation

– Dynamic measurement of fatigue in large structural components used in suspension bridges

– Down-hole application: measuring displacement (creep) of bedrock

Applications to Structural Engineering

- LVDT's are reliable for measuring member deflection in many structural engineering experiments.

- LVDT's can measure displacement response directly in dynamic experiments.

- Mounting the LVDT to a stationary location is critical.

TRANSDUCERS

A transducer is a device that is used to convert a physical quantity into its corresponding electrical signal.

In most of the electrical systems, the input signal will not be an electrical signal, but a non-electrical signal. This will have to be converted into its corresponding electrical signal if its value is to be measured using electrical methods.

Transducers may be classified into:
1. Active Transducers
2. Passive Transducers

Active Transducers:
The active type of transducers converts one form of energy to another form without any use of energy. It directly produces electric signals without an external energy source; it does not require an external power. Active transducers convert physical quantities like temperature, pressure and speed.

Passive Transducers:
The passive type of transducers requires an external source of power to operate, apart from that supplied by any of the actuating signals, which power is controlled by one or more of

these signals. Energy is supplied through a separate voltage source. Most of the transducers nowadays are passive.

VIBRATION-MEASURING DEVICES

Vibration Transducers

(i)   The Stroboscope Method

The fixed pointer or stud, shown in Figure, is attached to the vibrating surface and is used to give an indication of the displacement only. By using the light of a stroboscope to "freeze" or "slowly move" the stud, quite high-frequency small-amplitude vibrations may be measured. The typical upper range of frequency is quoted at 500 Hz for direct measurement.
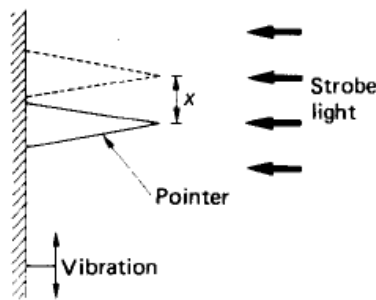

The Stroboscope Method

(ii)   The Reed Vibrometer

The variable-length reed vibrometer shown in Figure 3 is used to measure the main frequency component of the vibration. In practice the length *l* is adjusted until the maximum reed vibration occurs, when its resonant frequency is the same as the frequency of the vibrating mechanism or structure.

The length *l* is calibrated directly in Hz. A small mass may be added to the cantilever if the vibrometer is to be used for very-low frequency investigation, but the scale readings would then need to be corrected for the additional mass. The range of measurement is quoted as 5 Hz to 10kHz.
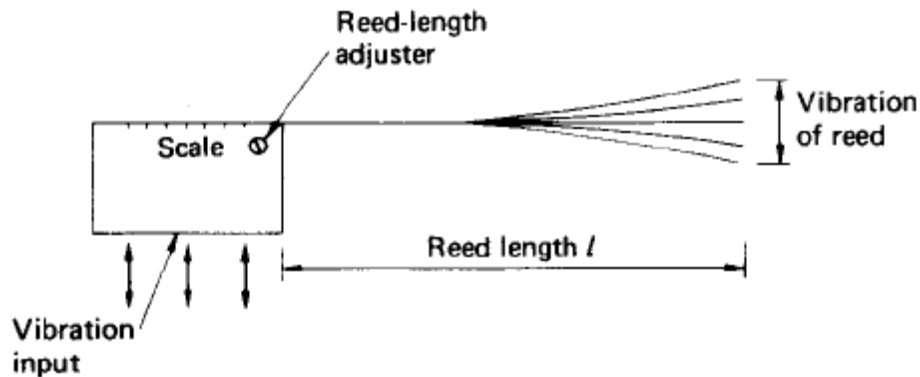
The Reed Vibrometer

(iii)   The Seismic-Mass Transducer

In instrumentation, seismic pickups are used to measure the motion of the surfaces to which they are fixed. They are sensitive to motion along one axis only, so if the motion is three dimensional, three seismic pickups are needed to determine the components of the motion along three mutually perpendicular axes.

The principal features of a seismic pickup are shown diagrammatically in Figure. The essential component is the seismic mass. This is a body of metal, suspended from a resilient support. This is a support whose deflection is proportional to the force applied to it. The inertia of the seismic mass causes it to lag behind the motion of the casing when the casing is accelerated, causing a deflection in the support. This deflection forms the input to a transducer, which produces a proportional output signal. In Figure the transducer is represented by a potentiometer,

but any suitable type of transducer may be used. The damping shown in Figure may consist only of the hysteresis of the support material, or it may be increased by filling the casing with a silicone fluid of suitable viscosity for example. By choosing suitable values for the mass, the stiffness of the support and the damping, and by using an appropriate transducer, the same basic arrangement of seismic pickup can be designed as a displacement pickup, a velocity pickup or an acceleration pickup (accelerometer). The seismic pickup is essentially a damped spring-mass system, and will have a natural frequency of vibration given by:
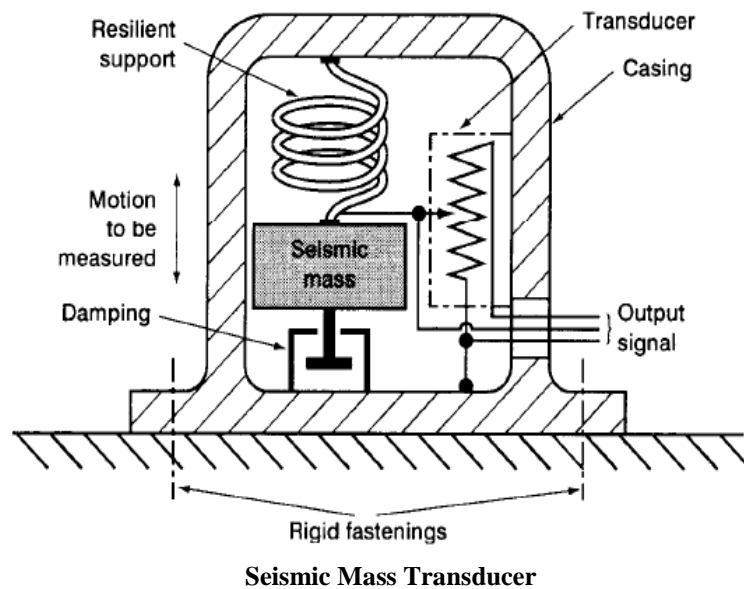
$$\omega_n = \sqrt{\frac{\lambda}{n}}$$

where

w_n is the natural angular frequency (rad/s)
l is the spring stiffness (N/m)
m is the mass (kg).

Seismic Mass Transducer

Vibration pick-ups: Seismic Instruments

The commonly used vibration pick-ups are called seismic instruments. The basic element of much vibration measuring instrument is a seismic unit which is basically a spring mass damper system mounted on a vibrating body on which measurements are to be made as shown in Figure.
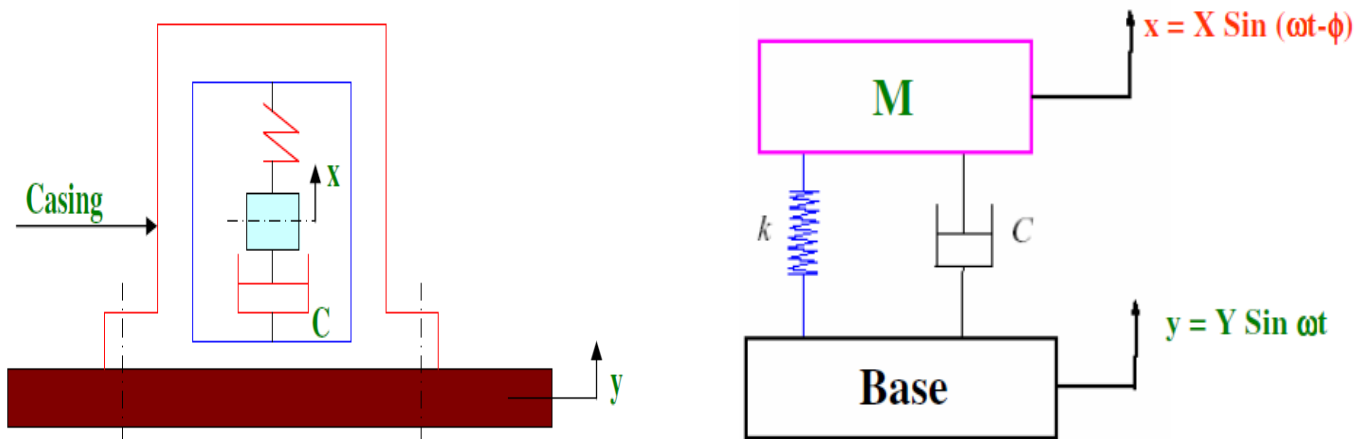
Depending on the frequency range utilized displacement, velocity or acceleration is indicated, by the relative motion of the suspended mass with respect to the case.
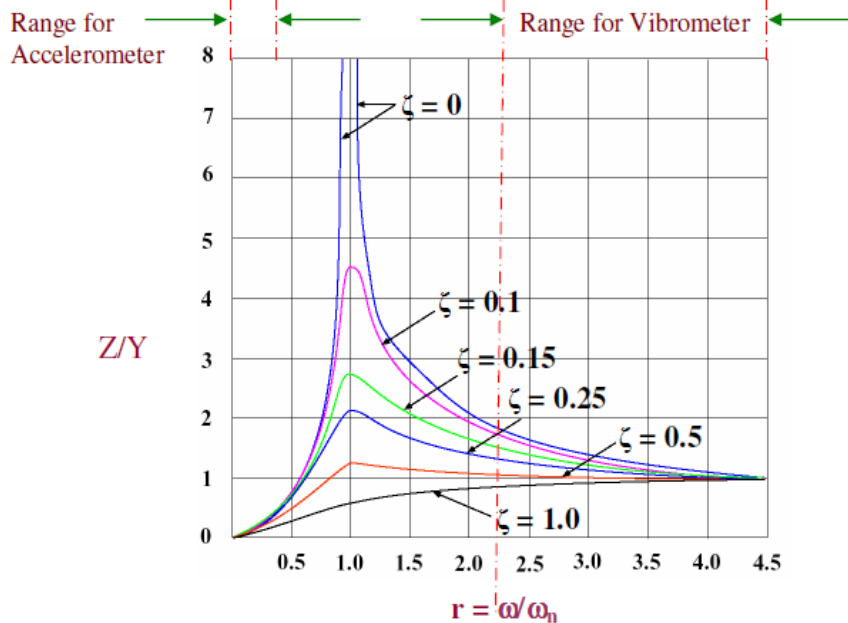
mx = - C (x-y) – K (x-y)

if Z = x-y; relative displacement the equation of motion becomes mZ + CZ + KZ = mw2Y Sin wt

$$\frac{Z}{Y} = \frac{r^2}{\sqrt{[1-r^2]^2 + [2\zeta r]^2}}$$

$$\phi = \tan^{-1}[2\zeta r/1-r^2]$$

The parameters that influence Z/Y and ϕ are: (1) frequency ratio $r = \omega/\omega_n$. (2) Damping factor ,

Above Figure also shows the range of frequencies corresponding to which a seismic instrument act as a vibrometer or an accelerometer. Type of instrument is determined by the useful range of frequencies with respect to the natural frequency (w_n) of the instrument. The relative displacement Z, may represent the displacement or acceleration depending upon w_n of the seismic unit and frequency of vibrating body,

VIBROMETER

It is an instrument with low natural frequency.
Therefore,   w >>>>> wn
                  r >>>> 1, r is very large.
                  Z/Y » 1, in particular when r > 3
                  Z/Y » 1, (independent of ξ)
                  Z=Y
Relative displacement of the seismic mass = displacement of base.

Hence the seismic mass remains stationary. It remains undisturbed in space. The supporting casing moves the vibrating body. Thus the relative displacement between the casing and the mass is the true displacement of the casing. Like wise, the relative velocity between the casing and the mass is the true velocity of casing. Usually, the relative motion Z is converted into electric voltage. The seismic mass is a magnet moving relative to the coils fixed to the case, as shown in Figure.

The voltage generated is proportional to the rate of cutting of magnetic field. Therefore the output of the instrument is proportional to the velocity of the vibrating body. Such instruments are called vibrometers. A typical instrument of this kind may have a natural frequency of 1 Hz to 5 Hz and a useful range of 10 Hz to 2000 Hz. The sensitivity of such instruments may be in the range of 20 mV/cm to 350 mV/cm. Both the displacement and acceleration are available from the velocity type transducer by means of the integrator or the differeniator provided in most signal conditioner units.
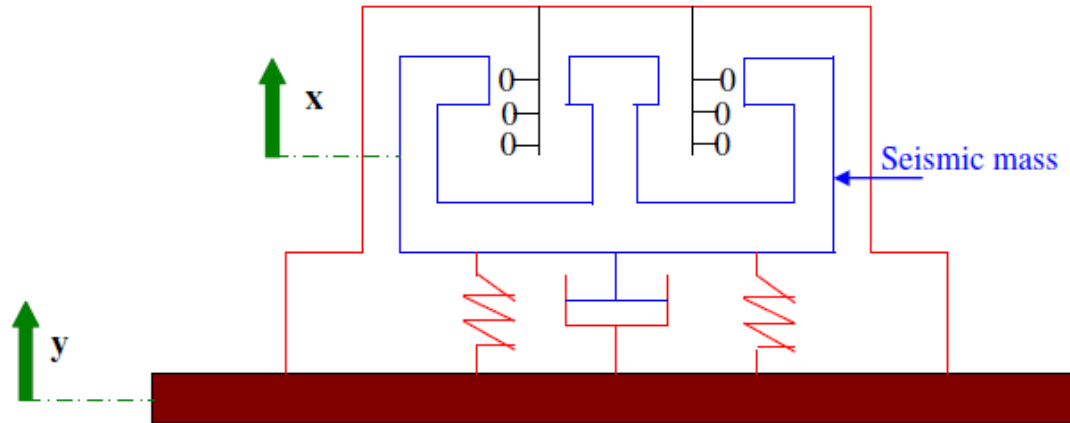
Limitation of Vibrometers

In order to have r >>>1, wn should be very small. This means that, the mass must be very large and the spring must have a very low stiffness. Therefore, a vibrometer is a springmass-damper system with a very large mass and a flexible spring. This results in bulky instrument, which is not desirable in many applications.

In practice, a vibrometer may not have a large value of r, and hence the value of Z, may not be exactly equal to Y. In such cases the true value of Y, can be computed from:

$$\frac{Z}{Y} = \frac{r^2}{\sqrt{[1-r^2]^2 + [2\,\zeta\,r]^2}}$$

Effect of the transducer on the vibrating structure

In general, the larger the mass of the vibration transducer, the greater its sensitivity. Unfortunately, the addition of the transducer's mass (m_1) to the mass (m_0) of the vibrating structure changes the resonant frequency of the vibrating system as follows:

$$\frac{f_1}{f_0} = \sqrt{\frac{m_0}{m_0 + m_1}}$$

where

        f_1 = resonant frequency of the structure with the mass added

and f_0 = resonant frequency of the structure before the transducer is added.

ACCELEROMETER

Accelerometer is electromechanical devices that measure the acceleration forces (vibration) of a structure. The forces may be static like for example that of gravity or dynamic which are cause by moving or vibrating the accelerometer.

It is an instrument with high natural frequency. When the natural frequency of the instrument is high compared to that of the vibrations to be measured, the instrument indicates acceleration
Then

$w \lll w_n$,
$r \lll 1$,

the factor $\sqrt{[r - (w/wn)2]2 + (2 \xi r)2}$ approaches unity.

$Z \longrightarrow (w/w_n)2.Y$
$\longrightarrow (1/w_n^2). w^2Y$

Hence, $Z \alpha w^2Y$, which implies that Z is proportional to the acceleration of the vibrating body. Thus in order to make $r \lll 1$, w_n should be very large. Hence K should be very large and m should be small. This means that, the instrument needs a small mass and spring of large stiffness. Therefore, the instrument will be very small in size and compact.

Due to their small size and high sensitivity accelerometers are preferred in vibration measurements. The acceleration measured can be integrated once or twice with the help of modern electrical circuits to obtain velocity and displacement of the system. Thus the difference between a vibrometer and an accelerometer is in its natural frequency. In vibrometer it is very small where as in accelerometer it is very high. The principle of construction remains same.

Different types of accelerometers
1) Capacitive Accelerometers
2) Piezoelectric
3) Piezoresistive
4) Hall Effect Accelerometers
5) Magnetoresistive Accelerometers
6) Heat Transfer Accelerometer

There are a number of types of accelerometers.
The difference between the types of accelerometers is the sensing element and the principles of their operation.

Types of Accelerometers

Capacitive Accelerometers –
The sensing element of a capacitive accelerometer consists of two parallel plate capacitors. These plates act in a differential mode. Capacitive accelerometers sense a change in electrical capacitance, with respect to acceleration, to vary the output of an energized circuit. The sensing element operates in a bridge circuit, along with two fixed capacitors. The peak voltage will be altered by these capacitors when the structure undergoes acceleration. The reading of the peak voltage is detected and then fed to a summing amplifier. From here the final output signal is found. Capacitive accelerometers are structured with a diaphragm. This diaphragm acts as a mass which undergoes flexure in the presence of acceleration. The diaphragm is sandwiched between two fixed plates. These plates share the diaphragm as a movable plate. The flexure causes a capacitance shift by altering the distance between two parallel plates, the diaphragm itself being one of the plates.

Characteristics:
- Very robust packing
- One, two or three orthogonal axes
- Measures dynamic and static acceleration
- Both analog and digital output

Uses
- Automative safety – airbags, stabilizers
- Gaming devices
- Personal navigation devices
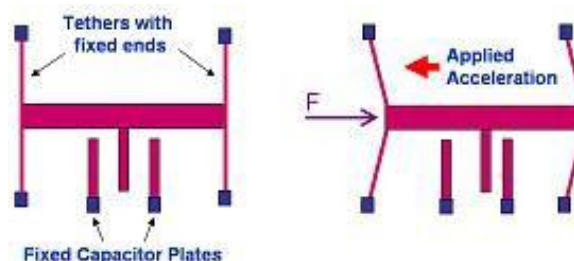
Piezoelectric –

In this type of sensor, the active element is the man made piezoelectric material. This type of accelerometer is designed to work the following way; one side of the piezoelectric material is connected to a rigid post at the sensor base, whilst on the other side a 'seismic' mass is attached. When vibration is present, a force is generated on the piezoelectric material. The force is equal to the product of the acceleration and the seismic mass. Due to the piezoelectric effect a charge output proportional to the applied force is generated.

The charge output signal will be proportional to the acceleration of the mass, this is because the mass is always constant. A piezoelectric accelerometer can be regarded as a mechanical low-pass with a resonance peak. Its equivalent circuit is a charge source in parallel to an inner capacitor. If the seismic mass is reduced a wider operating frequency range is obtained and the resonance frequency is increased, but the lower the seismic mass the lower the sensitivity of the accelerometer therefore accelerometers with high resonance frequency are usually less sensitive. These devices offer a very wide measurement frequency range (a few Hz to 30 kHz) and are available in a range of sensitivities, weights, sizes, and shapes

Characteristics:
- Extremely wide dynamic range, low output noise, this type of sensors is suitable for shock measurement
- Excellent linearity over their dynamic range
- Wide frequency range
- Compact yet highly sensitive
- Self generating no external power required

Uses:
- Are best used to measure the AC phenomenon such as vibration or shock rather than DC phenomenon such as acceleration of gravity
- They are used in large industrial applications
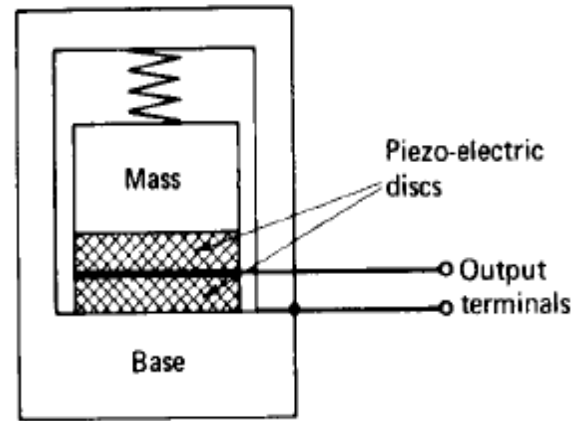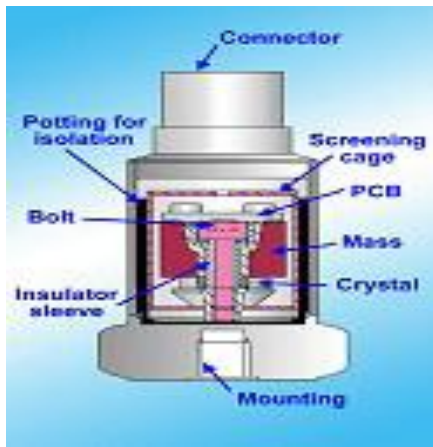
Piezoresistive – a piezoresistive accelerometer works on the same principle as the piezoelectric accelerometer i.e. of using Newton's Law of Motion, but instead of using a piezoelectric crystal the piezoresistive accelerometer uses a resistive substrate. When vibration will be present the force that is created will excite the seismic mass. This therefore will change the resistance of the etched bridge network and wheatstone bridge network will detect this change. These type of sensor have a large advantage over the piezoelectric, this is because they can measure acceleration down to zero Hertz. Piezoresistive accelerometers generally have a wide bandwidth (from a few hundred Hz to >130 kHz) and the frequency response goes down to 0 Hz (often called "DC responding") or steady state, so they can measure long-duration transients.

Characteristics:
- Measure down to 0 Hz (DC response)
- Limited dynamic range (<80 dB = 10,000:1)
- Limited high frequency range (<10 kHz)
- Often a damped frequency response (0.7% of critical)
- Sensitivity may vary with input (mV/g/V)
- Traditionally fragile (limited shock protection)
- Operates multi-conductor cable (at least 3 wires)
- Micro-machined versions are small and lightweight

Uses:
- Used for shock measurement
- Mostly used for transportation crash
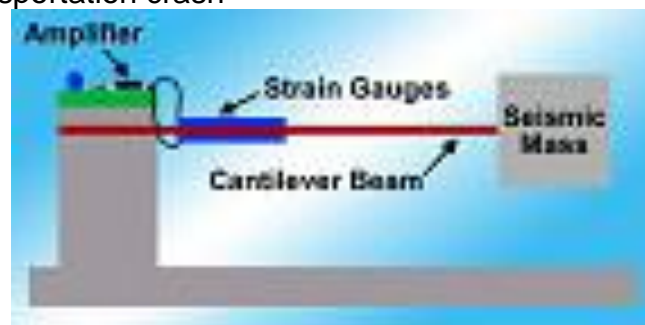
Hall Effect Accelerometers – If current flows in a conductor and a magnetic field are present, which is perpendicular to the current flow, and then the combination of current and magnetic field will generate a voltage perpendicular to both. This is called the Hall Effect. This can be used to measure magnetic field. Doing this one will have contact free measurement i.e. no wear and tear will be present.
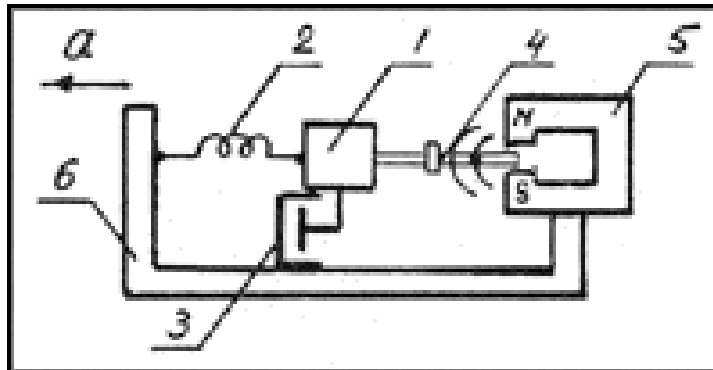
In a Hall-effect accelerometer, the Hall element is attached to a spring with a seismic mass deflecting because of the forces due to acceleration. The element moves in a non-uniform, linear-gradient-intensity magnetic field. Under these conditions, the generated transverse Hall voltage is proportional to the measured acceleration.

Characteristics:
- Immune to dust, dirt and water when appropriately packed
- Very low signal level an amplifier is required

Uses:
- Automotive valve position sensing
- Suspension
- Automotive throttle

Magnetoresistive Accelerometers - work by measuring changes in resistance due to a magnetic field. The structure and function is similar to a Hall Effect accelerometer except that instead of measuring voltage, the magneto resistive accelerometer measures resistance.
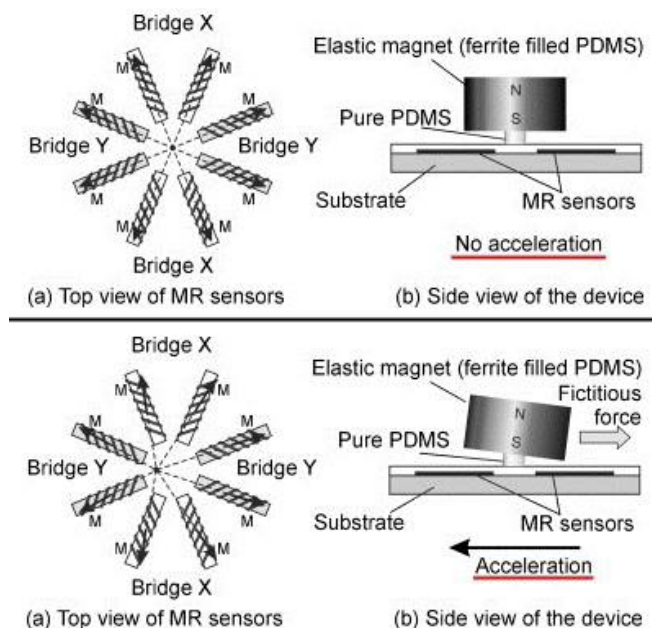
Heat Transfer Accelerometer – The heat transfer accelerometer works with the principle of convection. The device measures internal changes in heat transfer caused by acceleration. In this type of sensor the seismic mass is not solid but is a gas and because of this the device does not display particle contamination problems. The design of this accelerometer is as follows; a single heat source, centered in the silicon chip is suspended across a cavity. Equally spaced aluminum thermocouples are all located equidistantly on all four sides of the heat source. Under zero acceleration the temperature gradient is symmetrical about the heat source, so that the

temperature will be the same for all thermocouples of course causing them to output the same voltage.

If acceleration is present in any direction it will cause a disturbance in the temperature profile due to the free convection heat transfer and hence the output of the thermocouples will be different. This difference in voltage will be directly proportional to the acceleration.

Types of low-frequency accelerometer

Strain gauges may be used as the transducer system; the strain gauges can be of either the unbonded type or the bonded type. Bonded strain gauges are usually applied to a thin flexible beam or cantilever which acts as the spring supporting the seismic mass. They are connected into a bridge circuit and positioned so as to have maximum sensitivity to accelerations along the sensing axis, minimum sensitivity to transverse accelerations, and to cancel out temperature effects. Damping is usually by means of silicone oil, to give a damping ratio of 0.6 to 0.8. Other forms of transducer which may be used in accelerometers are the potentiometer, the linear variable differential transformer (LVDT), and the differential capacitor.

Servo accelerometers

Servo accelerometers (another name for them is null-balance accelerometers) are used in preference to other types of accelerometer where greater accuracy is required. In the usual form of servo accelerometer the seismic mass is attached to the casing by material which has been thinned down, by machining, to make it flexible enough to act as a hinge. The seismic mass is maintained in an almost constant position relative to the casing by an automatic control system. This controls the position of the seismic mass by adjusting the current through an electromagnet which consists of a pair of coils attached to the seismic mass, and annular permanent magnets fixed to the casing. The current through the coils is also passed through a sensing resistance, R, so that an output voltage proportional to the acceleration is obtained from the voltage drop across R. The position of the seismic mass relative to the casing is sensed by an inductive or capacitive displacement transducer, the output of which is amplified and applied to the electromagnet to provide the restoring force.

Servo accelerometers have the following advantages over other types of accelerometer:
1. Because the mechanical spring is replaced by an electrical 'spring', linearity is improved and hysteresis eliminated.
2. Damping can be built into the characteristics of the electrical circuit and can therefore be made less sensitive to temperature change.
3. By introducing an offset current from an external source through the electromagnet coils, the Servo accelerometer can be used as an acceleration controller.
4. Similarly, by means of offset currents, the static and dynamic performance of the Accelerometer can be checked out before the start of expensive tests on a vehicle.

The calibration of accelerometers

- Accelerometers for the measurement of steady or slowly varying accelerations may be calibrated up to an acceleration of +1 g (the standard value of *g* is 9.80665 m/s^2) by using the earth's gravitational attraction.
- The accelerometer is mounted on a tilting table from which the angle q between the sensing axis and the vertical can be measured. At q = 0 the force of gravity on the seismic mass is the same as the inertia force due to an acceleration of 9.8 m/s^2. At any other angle of q the corresponding acceleration is 9.8cosθ m/s^2.
- For accurate calibration the true value of *g* at the location where the calibration is taking place should be used. The standard value, given above, is approximately correct for temperate latitudes, but *g* varies from 9.832 m/s^2 at the poles to 9.780 m/s^2 at the equator.

- Some steady-state accelerometers have provision for applying known forces to the seismic mass along the sensing axis, by means of weights, so that if the value of the seismic mass is known, the accelerometer can be calibrated for accelerations greater than g by applying the equivalent of the inertia force.
- If the construction of the accelerometer does not permit this it may be mounted on a turntable so that its sensing axis is radial; the turntable is then run at known angular velocities of w rad/s, so that known centripetal accelerations of w2r m/s2 are applied, where r is the radius in meters to the center of the seismic mass.
- Piezoelectric accelerometers cannot usually be calibrated by means of static loadings because their charge leaks away, although if the piezoelectric material is quartz the time constant of the leakage may be several days due to its high electrical insulation.
- It is usual, however, to calibrate piezoelectric accelerometers by shaking them with simple harmonic motion along the sensing axis, by means of an electro-mechanical exciter.

For a secondary calibration, the accelerometer to be calibrated is mounted 'back-to-back' with one which has already been calibrated to act as a transfer standard, and the same simple harmonic motion is applied by the exciter to both. The acceleration applied to the accelerometer to be calibrated is then read from the one which has been previously calibrated.

Comparison of Vibration-Measuring Systems

| Transducer	Parameter	Signal conditioner	Frequency range	Remarks
Capacitive Inductive	Displacement	Amplitude modulation with bridge circuits	0-0.1 f_c f_c = carrier frequency	Usually relative displacement only
Electro-magnetic	Velocity	May need an amplifier	15 to 1000Hz	Poor low frequency response
Piezo-electric	Acceleration	Charge amplifier	0-0.3 f_n (f_n, the natural frequency, is typically 22 kHz)	Wide range of measurement. Typical ±10000g

VIBRATION ANALYZER

Vibration Analyzer functions include route data collection, onsite measurement, time waveform analysis (oscilloscope), FFT spectrum analysis, demodulated spectrum analysis, coast-up and run-down analysis, and rotor balancing.
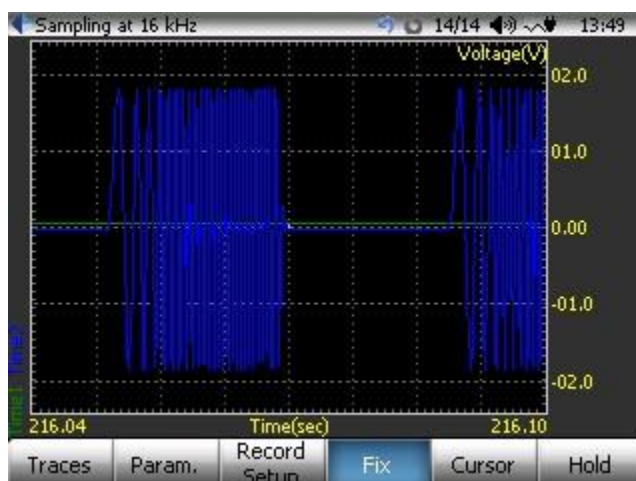
SEISMOGRAPHS

► **Seismology** = the study of seismic waves.
► **Seismogram** = the record of ground motion that is produced by a seismograph.
► **Seismograph** = an instrument that records vibrations of the Earth, especially earthquakes.
Seismograph generally refers to the *seismometer* and a recording device as a single unit.
Seismographs are instruments for recording seismic waves from earthquakes. Seismographs amplify, record, and display the seismic waves. Recordings are called seismograms
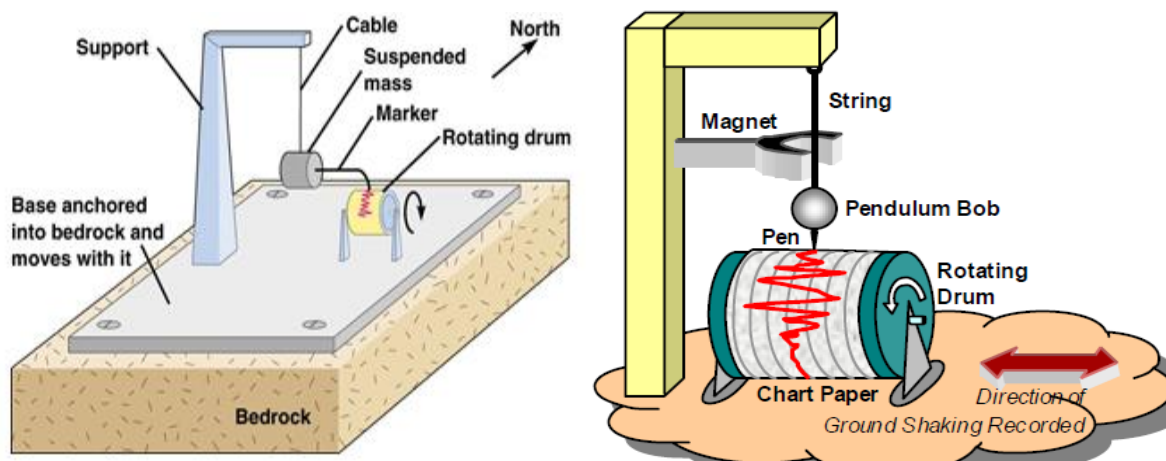
When the ground moves, the mass tends to remain stationary because of its inertia, but the support (frame) moves with the Earth.

Measuring Instruments
The instrument that measures earthquake shaking, a *seismograph*, has three components
- the *sensor*
- the *recorder* and
- the *timer*.

The principle on which it works is simple and is explicitly reflected in the early seismograph – a pen attached at the tip of an oscillating simple pendulum (a mass hung by a string from a support) marks on a chart paper that is held on a drum rotating at a constant speed. A magnet around the string provides required damping to control the amplitude of oscillations. The pendulum mass, string, magnet and support together constitute the *sensor*; the drum, pen and chart paper constitutes the *recorder*; and the motor that rotates the drum at constant speed forms the *timer*.

One such instrument is required in each of the two orthogonal horizontal directions. Of course, for measuring vertical oscillations, the *string* pendulum is replaced with a *spring* pendulum oscillating about a fulcrum. Some instruments do not have a timer device (*i.e.,* the drum holding the chart paper does not rotate). Such instruments provide only the maximum extent (or scope) of motion during the earthquake; for this reason they are called *seismoscopes*. The analog instruments have evolved over time, but today, *digital instruments* using modern computer technology are more commonly used. The digital instrument records the ground motion on the memory of the microprocessor that is in-built in the instrument.

CATHODE-RAY OSCILLOSCOPE

INTRODUCTION:

The cathode-ray oscilloscope (CRO) is a common laboratory instrument that provides accurate time and amplitude measurements of voltage signals over a wide range of frequencies. Its reliability, stability, and ease of operation make it suitable as a general purpose laboratory instrument. The heart of the CRO is a cathode-ray tube shown schematically in Figure.
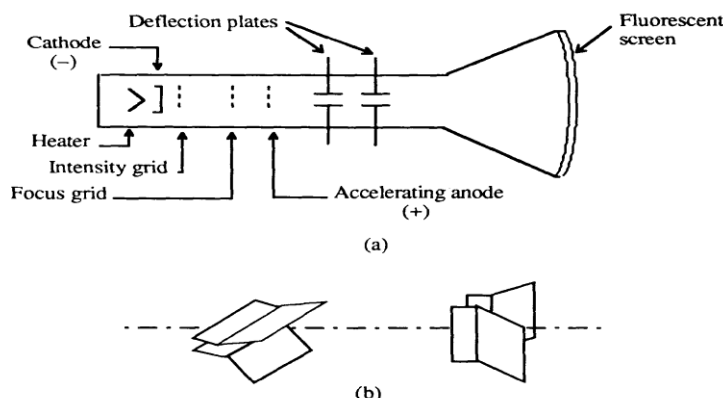

Figure 1. Cathode-ray tube: (a) schematic, (b) detail of the deflection plates.

The cathode ray is a beam of electrons which are emitted by the heated cathode (negative electrode) and accelerated toward the fluorescent screen. The assembly of the cathode, intensity grid, focus grid, and accelerating anode (positive electrode) is called an *electron gun*. Its purpose is to generate the electron beam and control its intensity and focus. Between the electron gun and the fluorescent screen are two pair of metal plates - one oriented to provide horizontal deflection of the beam and one pair oriented ot give vertical deflection to the beam. These plates are thus referred to as the *horizontal* and *vertical deflection plates*. The combination of these two deflections allows the beam to reach any portion of the fluorescent screen. Wherever the electron beam hits the screen, the phosphor is excited and light is emitted from that point. This conversion of electron energy into light allows us to write with points or lines of light on an otherwise darkened screen.

In the most common use of the oscilloscope the signal to be studied is first amplified and then applied to the vertical (deflection) plates to deflect the beam vertically and at the same time a voltage that increases linearly with time is applied to the horizontal (deflection) plates thus causing the beam to be deflected horizontally at a uniform (constant> rate. The signal applied to the vertical plates is thus displayed on the screen as a function of time. The horizontal axis serves as a uniform time scale.

The linear deflection or sweep of the beam horizontally is accomplished by use of a *sweep generator* that is incorporated in the oscilloscope circuitry. The voltage output of such a generator is that of a saw tooth wave as shown in Fig. 2. Application of one cycle of this voltage difference, which increases linearly with time, to the horizontal plates causes the beam to be deflected linearly with time across the tube face. When the voltage suddenly falls to zero, as at points (a) (b) (c), etc...., the end of each sweep - the beam flies back to its initial position. The horizontal deflection of the beam is repeated periodically, the frequency of this periodicity is adjustable by external controls.
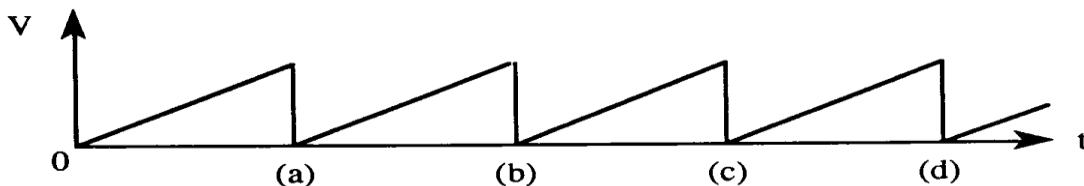
Figure. 2. Voltage difference V between horizontal plates as a function of time t.

To obtain steady traces on the tube face, an internal number of cycles of the unknown signal that is applied to the vertical plates must be associated with each cycle of the sweep generator. Thus, with such a matching of synchronization of the two deflections, the pattern on the tube face repeats itself and hence appears to remain stationary. The persistence of vision in the human eye and of the glow of the fluorescent screen aids in producing a stationary pattern. In addition, the electron beam is cut off (blanked) during flyback so that the retrace sweep is not observed.

CRO Operation:

A simplified block diagram of a typical oscilloscope is shown in Fig. 3. In general, the instrument is operated in the following manner. The signal to be displayed is amplified by the vertical amplifier and applied to the verical deflection plates of the CRT. A portion of the signal in the vertical amplifier is applied to the **sweep trigger** as a triggering signal. The sweep trigger then generates a pulse coincident with a selected point in the cycle of the triggering signal. This pulse turns on the sweep generator, initiating the sawtooth wave form. The sawtooth wave is amplified by the horizontal amplifier and applied to the horizontal deflection plates. Usually, additional provisions signal are made for appliying an external triggering signal or utilizing the 60 Hz line for triggering. Also the sweep generator may be bypassed and an external signal applied directly to the horizontal amplifier.

CRO Controls

The controls available on most oscilloscopes provide a wide range of operating conditions and thus make the instrument especially versatile. Since many of these controls are common to most oscilloscopes a brief description of them follows.
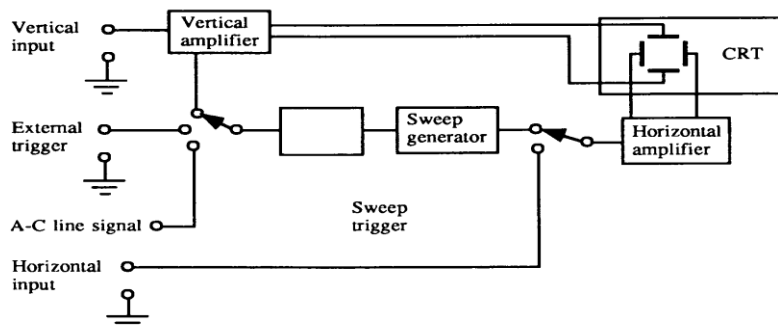

Figure 3. Block diagram of a typical oscilloscope.

CATHODE-RAY TUBE

Power and Scale Illumination: Turns instrument on and controls illumination of the graticule.

Focus: Focus the spot or trace on the screen.

Intensity: Regulates the brightness of the spot or trace.

VERTICAL AMPLIFIER SECTION

Position: Controls vertical positioning of oscilloscope display.

Sensitivity: Selects the sensitivity of the vertical amplifier in calibrated steps.

Variable Sensitivity: Provides a continuous range of sensitivities between the calibrated steps. Normally the sensitivity is calibrated only when the variable knob is in the fully clockwise position.

AC-DC-GND: Selects desired coupling (ac or dc) for incoming signal applied to vertical amplifier, or grounds the amplifier input. Selecting dc couples the input directly to the amplifier; selecting ac send the signal through a capacitor before going to the amplifier thus blocking any constant component.

HORIZONTAL-SWEEP SECTION

Sweep time/cm: Selects desired sweep rate from calibrated steps or admits external signal to horizontal amplifier.

Sweep time/cm Variable: Provides continuously variable sweep rates. Calibrated position is fully clockwise.

Position: Controls horizontal position of trace on screen.

Horizontal Variable: Controls the attenuation (reduction) of signal applied to horizontal aplifier through Ext. Horiz. connector.

TRIGGER

The trigger selects the timing of the beginning of the horizontal sweep.

Slope: Selects whether triggering occurs on an increasing (+) or decreasing (-) portion of trigger signal.

Coupling: Selects whether triggering occurs at a specific dc or ac level.

Source: Selects the source of the triggering signal.

> **INT** - (internal) - from signal on vertical amplifier
> **EXT** - (external) - from an external signal inserted at the **EXT. TRIG. INPUT.**
> **LINE** - 60 cycle triger

Level: Selects the voltage point on the triggering signal at which sweep is triggered. It also allows automatic (auto) triggering of allows sweep to run free (free run).

CONNECTIONS FOR THE OSCILLOSCOPE

<u>Vertical Input:</u> A pair of jacks for connecting the signal under study to the Y (or vertical) amplifier. The lower jack is grounded to the case.

<u>Horizontal Input:</u> A pair of jacks for connecting an external signal to the horizontal amplifier. The lower terminal is graounted to the case of the oscilloscope.

<u>External Tigger Input:</u> Input connector for external trigger signal.

<u>Cal. Out:</u> Provides amplitude calibrated square waves of 25 and 500 millivolts for use in calibrating the gain of the amplifiers.

Accuracy of the vertical deflection is $\pm$ 3%. Sensitivity is variable.

Horizontal sweep should be accurate to within 3%. Range of sweep is variable.

Operating Instructions: Before plugging the oscilloscope into a wall receptacle, set the controls as follows:

(a) Power switch at off
(b) Intensity fully counter clockwise
(c) Vertical centering in the center of range
(d) Horizontal centering in the center of range
(e) Vertical at 0.2
(f) Sweep times 1

Plug line cord into a standard ac wall recepticle (nominally 118 V). Turn power on. Do not advance the Intensity Control. Allow the scope to warm up for approximately two minutes, then turn the Intensity Control until the beam is visible on the screen.

USES OF CRO

a) Voltmeter
b) Display of waveforms
c) Measurement of short time intervals
d) Measurement of frequency
e) Display of phase relationship
f) Comparison of frequencies

X-Y recorder/X-Y Plotter
► An X–Y plotter is a plotter that operates in two axes of motion ("X" and "Y") in order to draw continuous vector graphics.
► The term was used to differentiate it from standard plotters which had control only of the "y" axis, the "x" axis being continuously fed to provide a plot of some variable with time.

A strip chart recorder records the variations of a quantity with respect to time while a X-Y recorder is an instrument which gives a graphic record of the relationship between two variables.
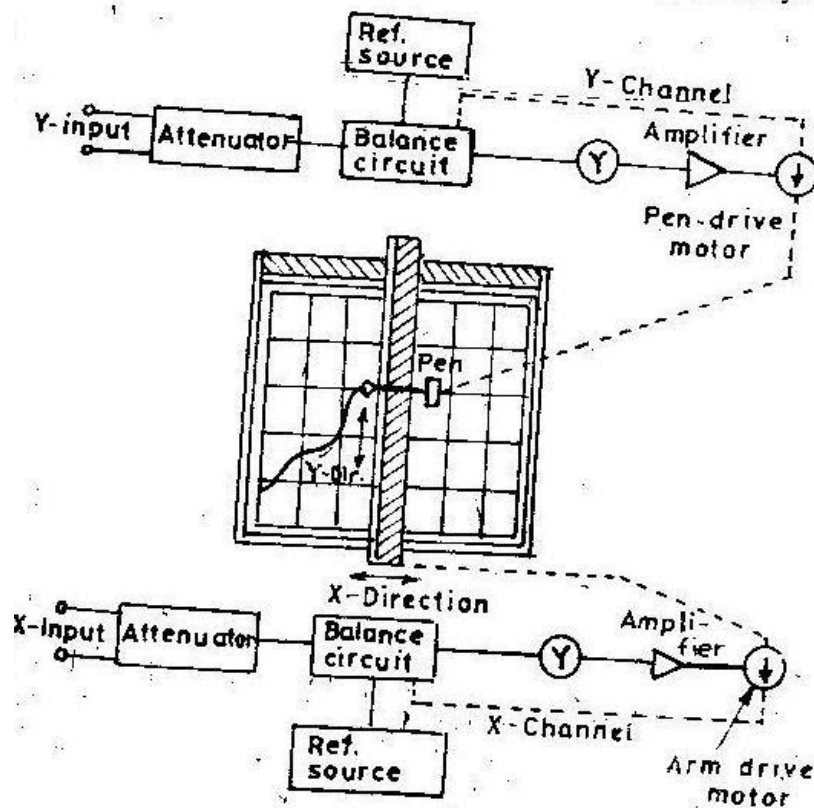
In strip recorders, usually self-balancing potentiometers are used. These self-balancing potentiometers plot the emf as a function of time. In X-Y recorders, an emf is plotted as a function of another emf. This is done by having one self-balancing potentiometer control the position of the rolls. while another self-balancing potentiometer controls the position of the recording pen.

In some X-Y recorders, one self-balancing potentiometer circuit moves a recording pen in the X direction while another self-balancing potentiometer circuit moves the recording pen in the Y direction at right angles to the X direction, while the paper remains stationary.

There are many variations of X-Y recorders. The emf, used for operation of X-Y recorders, may not necessarily measure only voltages. The measured emf may be the output of a transducer that may measure displacement force, pressure, strain, light intensity or any other physical quantity. Thus with the help of X-Y recorders and appropriate transducers, a physical quantity may be plotted against another physical quantity.

Hence an X-Y recorder consists of a pair of servo-systems, driving a recording pen in two axes through a proper sliding pen and moving arm arrangement, with reference to a stationary paper chart. Attenuators are used to bring the input signals to the levels acceptable by the recorder.

This figure shows a block diagram of a typical X-Y recorder. A signal enters each of the two channels. The signals are attenuated to the inherent full scale range of the recorder; the signal then passes to a balance circuit where it is compared with an internal reference voltage. The error signal the difference between the input signal voltage and the reference voltage is fed to a chopper which converts d.c signal to an a.c signal. The signal is then amplified in order to actuate a servometer which is used to balance the system and hold it in balance as the value of the quantity being recorder changes. The action described above takes place in both axed simultaneously. Thus we get a record of one variable with respect to another.

The use of X-Y recorders in laboratories greatly simplifies and expedites many measurements and tests. A few examples are being given below

1. Speed torque characteristics of motors
2. lift Drag wind tunnel tests
3. Plotting of characteristics of vaccum tubes, zener diodes rectifiers and transistors etc
4. Regulation curves of power supplies
5. Plotting stress-strain curves, hysteresis curves and vibrations amplitude against swept frequency
6. Electrical characteristics of materials such as resistance versus and temperature plotting the output from
7. electronic calculators and computers

CHART RECORDER

A **chart recorder** is an electromechanical device that records an electrical or mechanical input trend onto a piece of paper (the chart). Chart recorders may record several inputs using different color pens and may record onto strip charts or circular charts. Chart recorders may be entirely mechanical with clockwork mechanisms or electro-mechanical with an electrical clockwork mechanism for driving the chart (with mechanical or pressure inputs) or entirely electronic with no mechanical components at all (a virtual chart recorder).

They are built in three primary formats. Strip chart recorders have a long strip of paper that is ejected out the side of the recorder. Circular chart recorders have a rotating disc of paper that must be replaced more often, but are more compact and amenable to being enclosed behind glass. Roll chart recorders are similar to strip chart recorders except that the recorded data is stored on a round roll, and the unit is usually fully enclosed.

Chart recorders pre-dated electronic data loggers which have replaced them in many applications.

Origins

A patent for a 'Pressure Indicator and Recorder' was issued to William Henry Bristol, on September 18, 1888.[1] Bristol went on to form the Bristol Manufacturing Company in 1889. The Bristol Company was acquired by Emerson Electric Company in March 2006, and continues to manufacture a number of different electro-mechanical chart recorders, as well as other instrumentation, measurement, and control products.
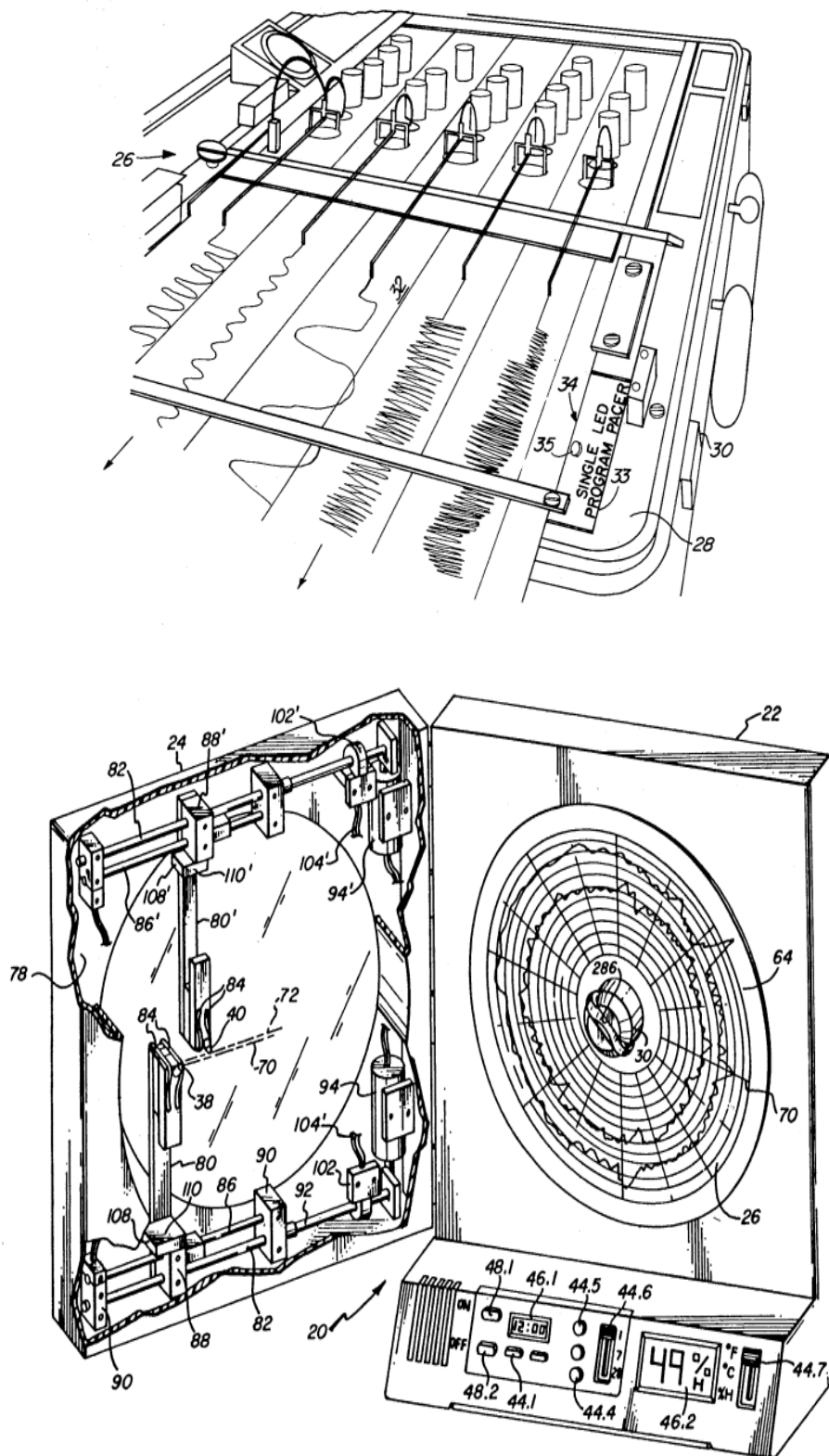
The first chart recorder for environmental monitoring was designed by American inventor J.C. Stevens while working for Leupold & Stevens in Portland, Oregon and was issued a patent for this design in 1915.[2] Chart recorders are still used in applications where instant visual feedback is required or where users do not have the need, opportunity or technical ability to download and view data on a computer or where no electrical power is available (such as in hazardous zones on an oil rig or in remote ecological studies). However, dataloggers' decreasing cost and power

requirements allow them to increasingly replace chart recorders, even in situations where battery power is the only option.

Chart drive

The paper chart is driven past the pen at a steady rate by a clockwork or electrical drive mechanism. One common method is to use a miniature synchronous motor which turns at a constant speed related to the power frequency; a gear-train is used to propel the paper. Industrial strip-chart recorders may have two-speed gear trains that allow a higher speed to be used for initial adjustments of a process or to follow process upsets. Medical and scientific recorders allow a wide range of accurately-controlled speeds to be set.

An "X-Y" recorder drives the chart depending on the value of another process signal. For example, a universal testing machine may plot the tension force on a specimen against its length. Depending on the particular recorder, either the paper chart is moved or else the pen carriage has two axes of motion.

Marking mechanisms

Many mechanisms have been adopted for marking paper. In the telegraphic siphon recorder of 1858 a fine capillary tube is connected to an ink reservoir and is deflected by the process signal. In modern strip chart recorders a disposable cartridge combining both a fiber-tipped pen and ink reservoir has been used. Other types of recorder use a heated stylus and thermally sensitive paper, or an electric spark that makes a visible spot on aluminized paper. One form of sensitive and high-speed recorder used beams of ultraviolet light reflected off mirror galvanometers, directed at light-sensitive paper.

The earliest instruments derived power to move the pen directly from the sensed process signal, which limited their senstivity and speed of response. Instruments with pneumatic, mechanical, or electromechanical amplifiers decoupled pen movement from process measurement, greatly increasing the senstivity of the instrument and the flexibility of the recorder. Directly-driven pens often moved in the arc of a circle, making the scale difficult to read; pre-printed charts have curvilinear scales printed on them that compensated for the path of the marking pen.[3]

Potentiometric (servo) instruments

Analog chart recorders using a galvanometer movement to directly drive the pen have limited sensitivity. In a potentiometric type of recorder, the direct drive of the marking pen is replaced with a servomechanism where energy to move the pen is supplied by an amplifier. The motor-operated pen is arranged to move the sliding contact of a potentiometer to feed back the pen position to an error amplifier. The amplifier drives the motor in such a direct as to reduce the error between desired and actual pen position to zero. With a suitable signal processing amplifer, such instruments can record a wide range of process signals. However, the inertia of the servo system limits the speed of response, making these instruments most useful for signals changing over the span of a second or more.[4]

Digital chart recorders

A modern chart recorder is an embedded computer system with an analog to digital converter, a microcontroller, and a hard-copy printing device; such instruments allow great flexibility in signal

processing, variable chart speed on process upsets, and can also communicate their measurments to remote points.

DIGITAL DATA ACQUISITION SYSTEM

Components	Description
Data acquisition hardware	At the heart of any data acquisition system lies the data acquisition hardware. The main function of this hardware is to convert analog signals to digital signals, and to convert digital signals to analog signals.
Sensors and actuators (transducers)	Sensors and actuators can both be *transducers*. A transducer is a device that converts input energy of one form into output energy of another form. For example, a microphone is a sensor that converts sound energy (in the form of pressure) into electrical energy, while a loudspeaker is an actuator that converts electrical energy into sound energy.
Signal conditioning hardware	Sensor signals are often incompatible with data acquisition hardware. To overcome this incompatibility, the signal must be conditioned. For example, you might need to condition an input signal by amplifying it or by removing unwanted frequency components. Output signals might need conditioning as well. However, only input signal conditioning is discussed in this chapter.
Computer	The computer provides a processor, a system clock, a bus to transfer data, and memory and disk space to store data.
Software	Data acquisition software allows you to exchange information between the computer and the hardware. For example, typical software allows you to configure the sampling rate of your board, and acquire a predefined amount of data.

The data acquisition components, and their relationship to each other, are shown below.
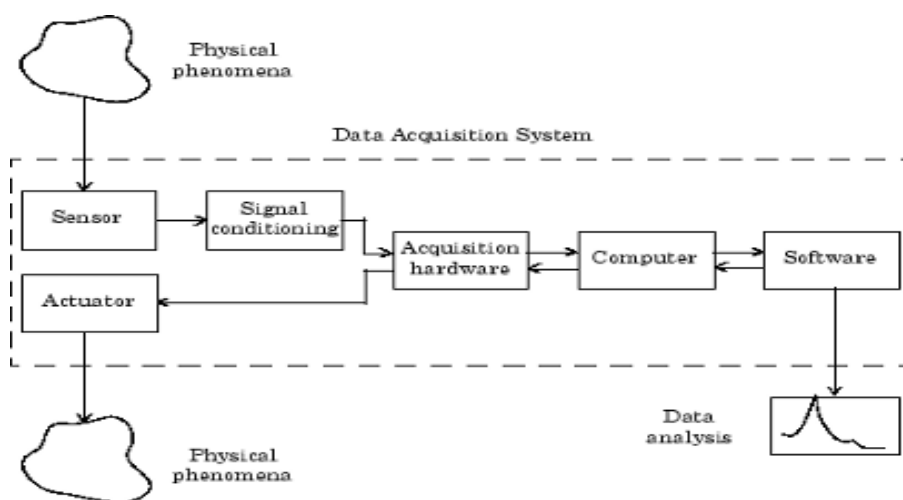
The figure depicts the two important features of a data acquisition system:

- Signals are input to a sensor, conditioned, converted into bits that a computer can read, and analyzed to extract meaningful information.

- Data from a computer is converted into an analog signal and output to an actuator.

(I) Data Acquisition Hardware

Data acquisition hardware is either internal and installed directly into an expansion slot inside your computer, or external and connected to your computer through an external cable, which is typically a USB cable.

At the simplest level, data acquisition hardware is characterized by the *subsystems* it possesses. A subsystem is a component of your data acquisition hardware that performs a specialized task. Common subsystems include

     a) Analog input
     b) Analog output
     c) Digital input/output
     d) Counter/timer

Hardware devices that consist of multiple subsystems, such as the one depicted below, are called *multifunction boards*.
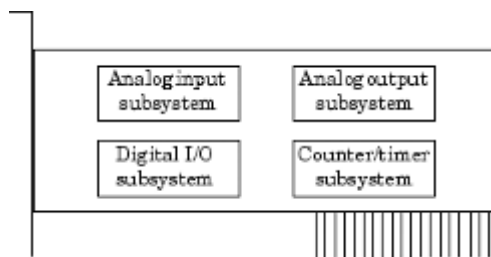
(a) Analog Input Subsystems

Analog input subsystems convert real-world analog input signals from a sensor into bits that can be read by your computer. Perhaps the most important of all the subsystems commonly available, they are typically multichannel devices offering 12 or 16 bits of resolution.

Analog input subsystems are also referred to as AI subsystems, A/D converters, or ADCs. Analog input subsystems are discussed in detail beginning in Analog Input Subsystems.

(b) Analog Output Subsystems

Analog output subsystems convert digital data stored on your computer to a real-world analog signal. These subsystems perform the inverse conversion of analog input subsystems. Typical acquisition boards offer two output channels with 12 bits of resolution, with special hardware available to support multiple channel analog output operations.

Analog output subsystems are also referred to as AO subsystems, D/A converters, or DACs.

(c) Digital Input/Output Subsystems

Digital input/output (DIO) subsystems are designed to input and output digital values (logic levels) to and from hardware. These values are typically handled either as single bits or *lines*, or as a *port*, which typically consists of eight lines.

While most popular data acquisition cards include some digital I/O capability, it is usually limited to simple operations, and special dedicated hardware is often necessary for performing advanced digital I/O operations.

(d) Counter/Timer Subsystems

Counter/timer (C/T) subsystems are used for event counting, frequency and period measurement, and pulse train generation. Use the session-based interface to work with the counter/timer subsystems.

(II) Sensors

A sensor converts the physical phenomena of interest into a signal that is input into your data acquisition hardware. There are two main types of sensors based on the output they produce: digital sensors and analog sensors.

Digital sensors produce an output signal that is a digital representation of the input signal, and has discrete values of magnitude measured at discrete times. A digital sensor must output logic levels that are compatible with the digital receiver. Some standard logic levels include transistor-transistor logic (TTL) and emitter-coupled logic (ECL). Examples of digital sensors include switches and position encoders.

Analog sensors produce an output signal that is directly proportional to the input signal, and is continuous in both magnitude and in time. Most physical variables such as temperature, pressure, and acceleration are continuous in nature and are readily measured with an analog sensor. For example, the temperature of an automobile cooling system and the acceleration produced by a child on a swing all vary continuously.

The sensor you use depends on the phenomena you are measuring. Some common analog sensors and the physical variables they measure are listed below.

Common Analog Sensors

Sensor	Physical Variable
Accelerometer	Acceleration
Microphone	Pressure
Pressure gauge	Pressure
Resistive temperature device (RTD)	Temperature
Strain gauge	Force
Thermocouple	Temperature

When choosing the best analog sensor to use, you must match the characteristics of the physical variable you are measuring with the characteristics of the sensor. The two most important sensor characteristics are:

- The sensor output
- The sensor bandwidth

Sensor Output

The output from a sensor can be an analog signal or a digital signal, and the output variable is usually a voltage although some sensors output current.

Current Signals. Current is often used to transmit signals in noisy environments because it is much less affected by environmental noise. The full scale range of the current signal is often either 4-20 mA or 0-20 mA. A 4-20 mA signal has the advantage that even at minimum signal value, there should be a detectable current flowing. The absence of this indicates a wiring problem.

Voltage Signals. The most commonly interfaced signal is a voltage signal. For example, thermocouples, strain gauges, and accelerometers all produce voltage signals. There are three major aspects of a voltage signal that you need to consider:

- **Amplitude**
- **Frequency**
- **Duration**

Sensor Bandwidth

In a real-world data acquisition experiment, the physical phenomena you are measuring has expected limits. For example, the temperature of your automobile's cooling system varies continuously between its low limit and high limit. The temperature limits, as well as how rapidly the temperature varies between the limits, depends on several factors including your driving habits, the weather, and the condition of the cooling system. The expected limits might be readily approximated, but there are an infinite number of possible temperatures that you can measure at a given time. As explained in Quantization, these unlimited possibilities are mapped to a finite set of values by your data acquisition hardware.

The *bandwidth* is given by the range of frequencies present in the signal being measured. You can also think of bandwidth as being related to the rate of change of the signal. A slowly varying signal has a low bandwidth, while a rapidly varying signal has a high bandwidth. To properly measure the physical phenomena of interest, the sensor bandwidth must be compatible with the measurement bandwidth.

(III) <u>Signal Conditioning</u>

Sensor signals are often incompatible with data acquisition hardware. To overcome this incompatibility, the sensor signal must be conditioned. The type of signal conditioning required depends on the sensor you are using. For example, a signal might have a small amplitude and require amplification, or it might contain unwanted frequency components and require filtering. Common ways to condition signals include

- Amplification
- Filtering
- Electrical isolation
- Multiplexing
- Excitation source

Amplification

Low-level – less than around 100 millivolts – usually need to be amplified. High-level signals might also require amplification depending on the input range of the analog input subsystem.

For example, the output signal from a thermocouple is small and must be amplified before it is digitized. Signal amplification allows you to reduce noise and to make use of the full range of your hardware thereby increasing the resolution of the measurement.

Filtering

Filtering removes unwanted noise from the signal of interest. A noise filter is used on slowly varying signals such as temperature to attenuate higher frequency signals that can reduce the accuracy of your measurement.

Rapidly varying signals such as vibration often require a different type of filter known as an antialiasing filter. An antialiasing filter removes undesirable higher frequencies that might lead to erroneous measurements.

Electrical Isolation

If the signal of interest contains high-voltage transients that could damage the computer, then the sensor signals should be electrically isolated from the computer for safety purposes.

Multiplexing

A common technique for measuring several signals with a single measuring device is multiplexing.

Excitation Source

Some sensors require an excitation source to operate. For example, strain gauges, and resistive temperature devices (RTDs) require external voltage or current excitation. Signal conditioning modules for these sensors usually provide the necessary excitation. RTD measurements are usually made with a current source that converts the variation in resistance to a measurable voltage.

(IV)The Computer

The computer provides a processor, a system clock, a bus to transfer data, and memory and disk space to store data.

(V) Software

Regardless of the hardware you are using, you must send information to the hardware and receive information from the hardware. You send configuration information to the hardware such as the sampling rate, and receive information from the hardware such as data, status messages, and error messages. You might also need to supply the hardware with information so that you can integrate it with other hardware and with computer resources. This information exchange is accomplished with software.

There are two kinds of software:

- Driver software
- Application software
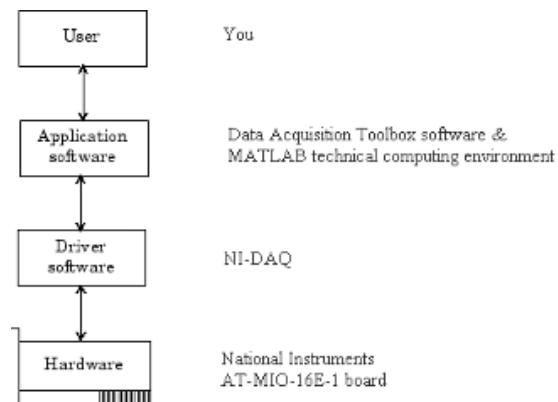
Driver Software

For data acquisition device, there is associated driver software that you must use. Driver software allows you to access and control the capabilities of your hardware. Among other things, basic driver software allows you to

- Bring data on to and get data off of the board
- Control the rate at which data is acquired
- Integrate the data acquisition hardware with computer resources such as processor interrupts, DMA, and memory
- Integrate the data acquisition hardware with signal conditioning hardware
- Access multiple subsystems on a given data acquisition board
- Access multiple data acquisition boards

Application Software

Application software provides a convenient front end to the driver software. Basic application software allows you to

- Report relevant information such as the number of samples acquired
- Generate events
- Manage the data stored in computer memory
- Condition a signal
- Plot acquired data