# Module 5

This module looks at some general issues that are important in measurements. Some of these issues are:

- ♦ **Data acquisition, data manipulation, data presentation.**
- ♦ **Case studies pertaining to the design of experimental set ups.**
- ♦ **The case studies will deal with layout, selection of instruments and design of experiments.**

In order to appreciate these issues we look at the schematic of a general measurement process shown in Figure 1. Incidentally this figure was discussed earlier in Module 1.
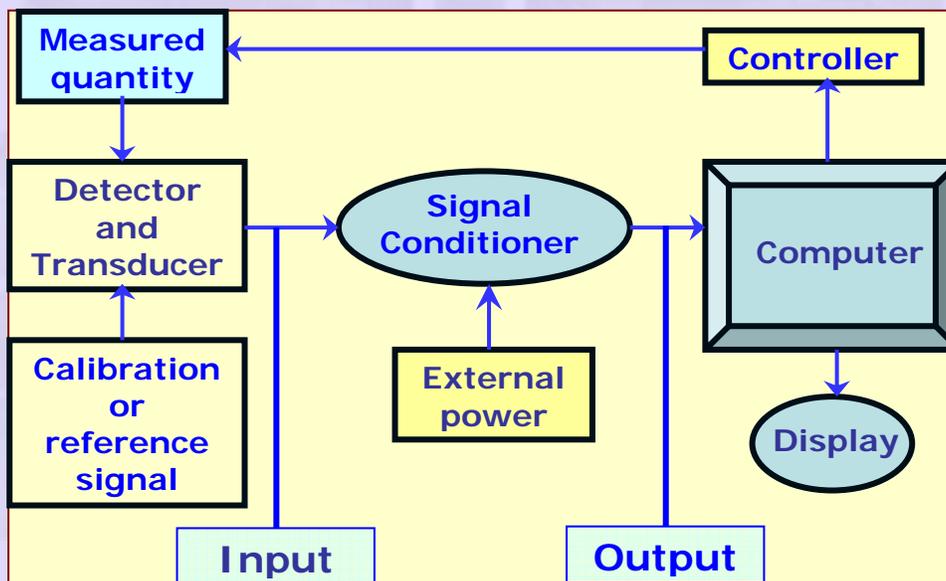
Figure 1 Schematic of a general measurement process

1

We see from this figure that the measurement process involves several steps between the measured quantity and the output that is proportional to it. In mechanical analog instruments manipulations are done using mechanical elements like gears, lever, optical magnification and use of vernier scale and such things. In the case of transducers that operate with electrical quantities these are done by suitable electrical and electronic circuits.
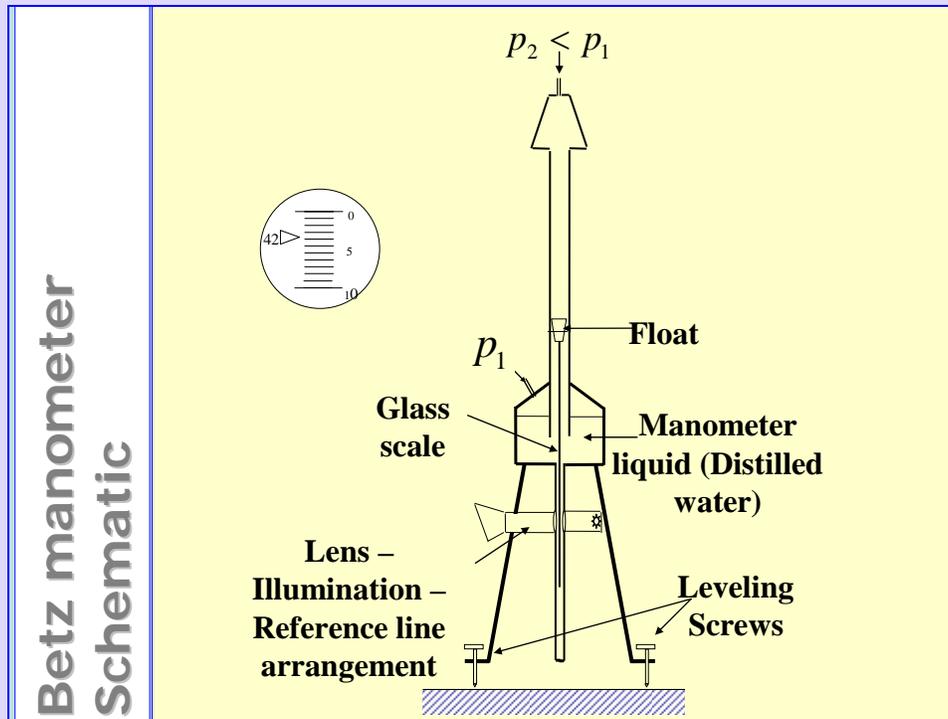
Mechanical signal conditioning examples:

We consider here a couple of cases where the measuring instrument uses purely mechanical signal conditioning. The examples considered are:

i)   Measurement of a small pressure difference

ii)   Measurement of twist in a wire

i)   Measurement of a small pressure difference

In applications such as the measurement of fluid velocity using a Pitot static tube one has to measure a very small pressure differences. It may be a few millimeters of water column. Since the precision of the velocity measurement is intimately connected with the precision of the water column measurement signal conditioning is required. We have already seen one such signal conditioning method viz. the use of the inclined tube manometer which gives amplifies the signal by the small inclination of the manometer tube. For precision measurement it is normal to employ an optical method of measurement by the use of a Betz manometer, named after the manufacturer. The schematic of a Betz manometer is shown in Figure 2.

2

Betz manometer Schematic

$p_2 < p_1$

p_1

Glass scale

Float

Manometer liquid (Distilled water)

Lens – Illumination – Reference line arrangement

Leveling Screws

Figure 2 Schematic of a Betz manometer

The instrument consists of a reservoir that holds the manometric liquid - distilled water - and communicates with a vertical manometer tube as shown in the figure. The reservoir has a tubular extension below and a glass scale attached to a float follows the position of the meniscus in the tube. The pressure difference to be measured is communicated between the top of the vertical tube and the top of the reservoir as shown. The float has scale divisions engraved on it. A light source and a lens arrangement complete the instrument. The light pointer is seen by the observer viewing through the lens. The position of the pointer against the scale divisions engraved on the glass scale are viewed with enough optical magnification to afford a measurement of the manometric height with 0.1 *mm* resolution. Note that the Betz manometer is provided with leveling screws for orienting it vertically.

3

ii) **Measurement of twist in a wire**

This example brings out how a mechanical amplification is possible using essential an optical arrangement. The arrangement is illustrated schematically in Figure 3.
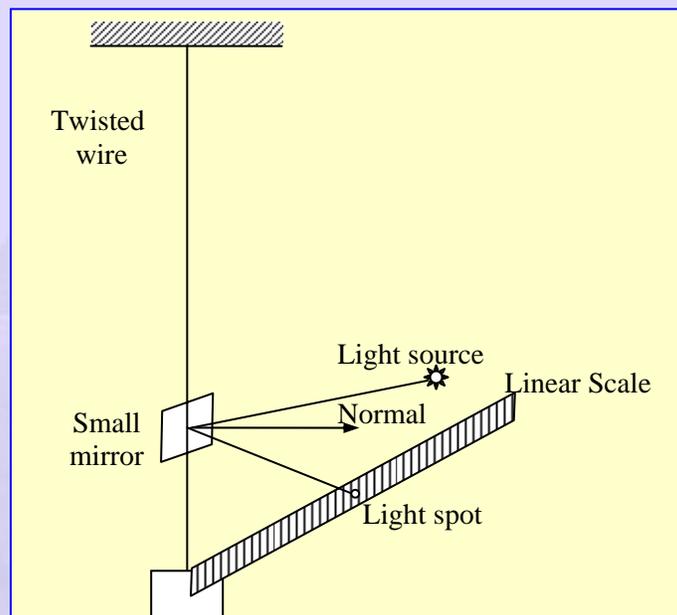
Figure 3 Measurement of twist in a wire

The intention is to measure a very small angle through which the wire has been twisted. A small plane mirror is attached rigidly to the wire. A narrow collimated beam of light is incident on the mirror as shown. If the twist is zero the reflected beam will go back along the incident direction. However when the wire has a twist the normal to the mirror will occupy a different position and the light spot will be reflected according to laws of optics. The light spot will move by a certain distance along the scale that may be directly marked in units of angle. The distance of the scale with respect to mirror provides the mechanical gain.

4

5

Electronic or electrical signal conditioning:

Following are some of the manipulations that are involved in signal conditioning:

- o Amplification – Increase voltage level
- o Amplification after Manipulation – Increase voltage level after some algebraic manipulation
- o Analog to Digital Conversion – Convert analog signal to digital signal readable by a computer
- o Communication with a computer
  - Data Storage
- o Manipulation using software and presentation of data in a user friendly form
  - Uses software such as LABVIEW, MATLAB, EXCEL and others

Signal Amplification and manipulation:

Amplifiers are analog devices that change the signal level from low levels at the transducer end to a value large enough to be measured by an indicating instrument without drawing power from the transducer. In recent times amplifiers are usually in the form of integrated chips called operational amplifiers (or Op Amp, for short) with very high open loop gain (of the order of a million). These amplifiers are very reliable and have become progressively less and less expensive. Some examples of amplifiers are given here.

5

Gain of the amplifier is

$$G = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$$

Operational
Amplifier
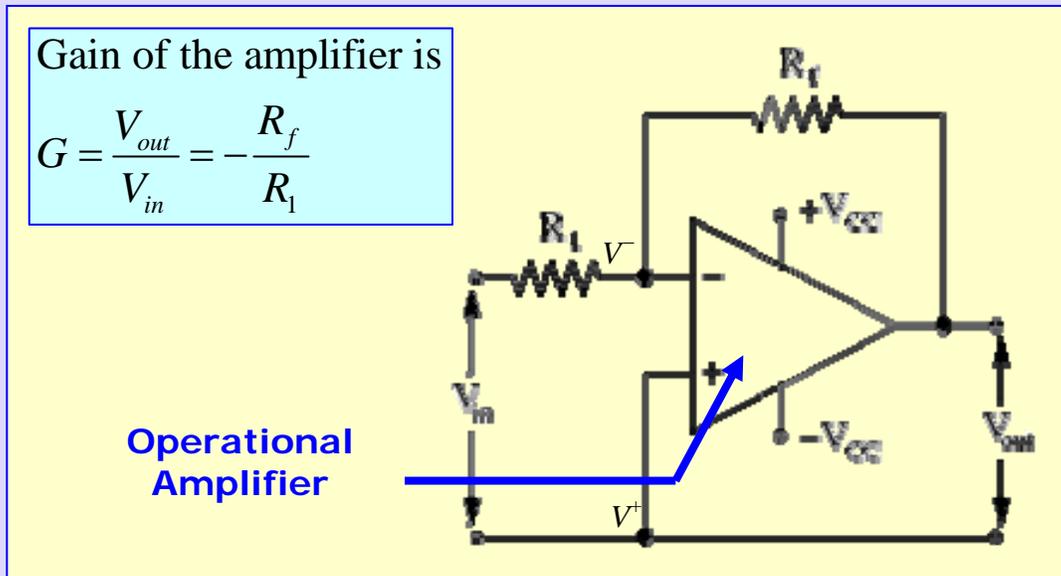
Figure 4 Basic operational amplifier circuit

Figure 4 shows the basic operational amplifier circuit. The operational amplifier has several pins for connections to be made to the external circuit. The operational amplifier is powered from an external source which provides positive and negative voltages shown as V_{cc} in the figure. Usually the voltages are $\pm$ 15 V capable of providing adequate current to run, may be, several operational amplifiers. The operational amplifier has two input terminals; inverting input shown with "–" sign in the figure and a non-inverting input shown with "+" sign in the figure. The operational amplifier is a device with a very large input impedance i.e. the impedance between the "–" and "+" terminals. In the simplest configuration the input voltage is applied across the inverting and non-inverting input terminals through a resistor R_1 and the output is available as show in the figure. A feed back resistor R_f connects the inverting input terminal and the output terminal.

6

Analysis of the operational amplifier circuit assumes that no current flows in to the operational amplifier. Hence the potential difference is zero between the "−" and "+" terminals. Thus $V^+ = V^- \approx 0$. These two terminals act as virtual ground. Consider the node "−" in Figure 2. Kirchoff's law is applied to this node to get $\dfrac{V_{in} - 0}{R_1} + \dfrac{V_{out} - 0}{R_f} = 0$. This may be rearranged to read
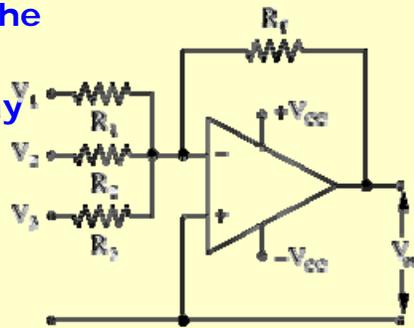
$$G = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1} \qquad\qquad\qquad\qquad \textbf{(1)}$$

In the above equation G is the voltage gain of the amplifier.

Figure 5 Summing amplifier using an operational amplifier

The reader should now be able to convince himself that the arrangement in Figure 5 will amplify the sum of all the inputs with individual gain factors determined by the respective input resistances. If all these are the same ($R_1 = R_2 = ... = R$) then the summing amplifier will amplify the sum of all the input

7

voltages with a common gain given by $G = -\dfrac{R_f}{R}$. It is clear that the summing amplifier output is also the mean of the input voltages multiplied by the common gain factor. At once it is clear, as an example, that a summing amplifier may be used with several thermocouple inputs to measure the mean temperature.

Similarly it is possible to construct a differential amplifier using both the inverting and non-inverting inputs to feed in the input signals. Figure 6 shows the arrangement. Nodal analysis may be performed as follows.

Differential Amplifier

❑ **Output is an amplified value of the voltage difference**

$$V_{out} = -\frac{R_2}{R_1}(V_1 - V_2).$$
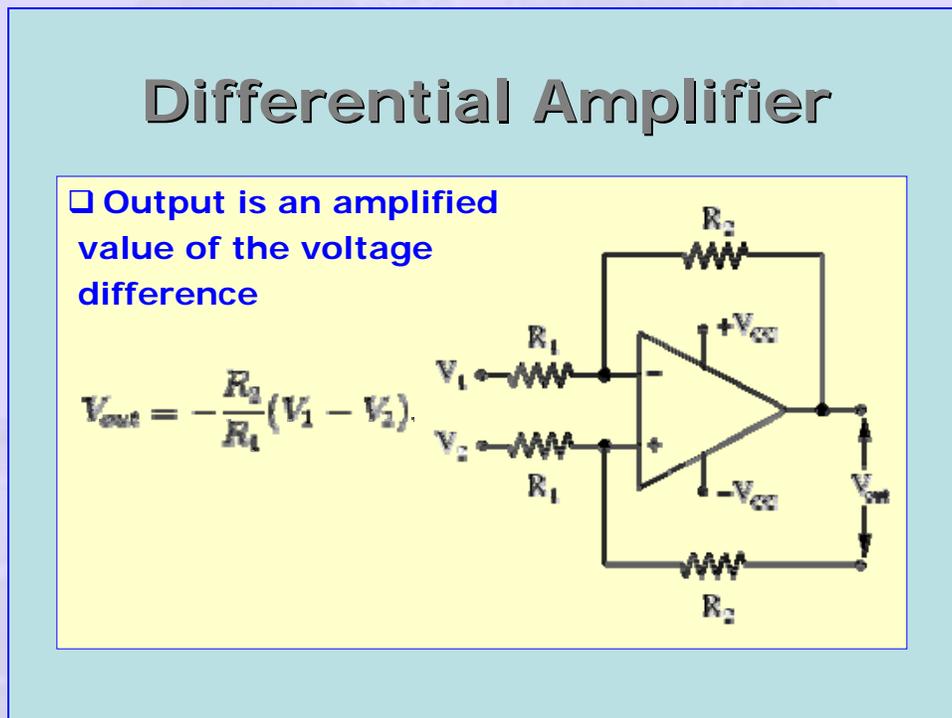
Figure 6 Differential amplifier

Again it is apparent that the output of two thermocouples may be fed in to a differential amplifier to amplify the signal that represents the temperature difference. If the two temperatures are close to each other, it is possible to use a common value of the Seebeck coefficient for the two input voltages and thus get

8

an amplified value for the temperature difference directly. The circuit is thus extremely useful in practical applications.

We note as earlier that $V^+ = V^-$. Nodal equation for the "**+**" node is written as

$$\frac{V_2 - V^+}{R_1} = \frac{V^+ - 0}{R_2} \text{ or } \frac{V_2}{R_1} = V^+ \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

Nodal equation for the "**−**" node is written as

$$\frac{V_1 - V^-}{R_1} = \frac{V^- - V_{out}}{R_2} \text{ or } \frac{V_1}{R_1} + \frac{V_{out}}{R_2} = V^- \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

The right hand sides of these two expressions are one and the same. Hence we have

$$\frac{V_1}{R_1} + \frac{V_{out}}{R_2} = \frac{V_2}{R_1} \text{ or } V_{out} = (V_2 - V_1)\frac{R_2}{R_1}$$ **(2)**

Thus the output is an amplified version of the differential voltage.

In some applications one may need the input voltage to be integrated or differentiated. These are possible using the Integrating and Differentiating amplifiers shown respectively in Figures 7 and 8.

Integrating Circuit

❑Output is an integrated version of the input

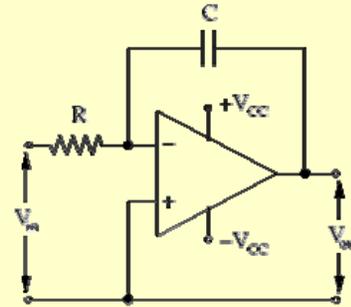$$V_{out} = -\frac{1}{RC} \int V_{in}\, dt.$$

Figure 7 Integrating amplifier

Differentiating Circuit

❑Output is derivative of the input

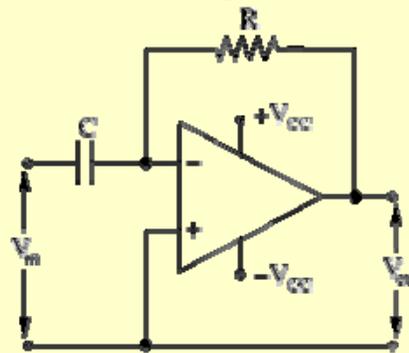$$V_{out} = -RC\frac{dV_{in}}{dt}.$$

Figure 8 Differentiating amplifier

10

Some times we require functional manipulations to be made with the signal being measured.   One such useful amplifier is the logarithmic amplifier shown schematically in Figure 9. In this amplifier the feed back resistor is replaced by a diode (or a transistor). The diode characteristics is such that the forward bias current I_f is related to the reverse bias current I_r according to the relation $I_f = I_r\left(e^{\frac{qV_b}{kT}} - 1\right)$ where q is the electronic charge, V_b is the reverse bias voltage, k is the Boltzmann constant and T is the temperature. We assume that the input voltage $V_{in} \gg I_r R$. We may replace V_{out} for V_b and perform the familiar nodal analysis to get $\dfrac{V_{in}}{R} = I_{f0} = I_r\left(e^{\frac{qV_b}{kT}} - 1\right) = I_r\left(e^{\frac{qV_{out}}{kT}} - 1\right)$.   This may be rearranged to get $e^{\frac{qV_{out}}{kT}} = 1 + \dfrac{V_{in}}{I_r R} \approx \dfrac{V_{in}}{I_r R}$. Taking natural logarithms, we then have

$$V_{out} = \frac{kT}{q} ln\left(\frac{V_{in}}{I_r R}\right) \tag{3}$$

Thus the output of the amplifier is related to the natural logarithm of the input to the amplifier.   Equation 3 shows that the output s also affected by the temperature.   In order to avoid the effect of temperature the diode may be replaced by a transistor.

11

12
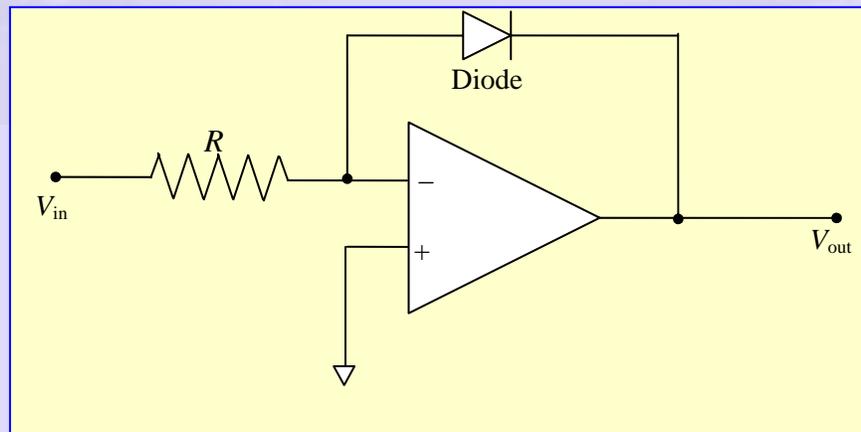
**Figure 9 Logarithmic amplifier**

One possible use for a logarithmic amplifier is in taking the ratio of two signals. This type of manipulation is done very often in radiation measurement. The schematic of such a circuit is shown in Figure 10. The signal from two channels *A* and *B* are conditioned by two logarithmic amplifiers. Subsequently the difference of these two is obtained by a differential amplifier. We thus see that the output signal is an amplified version of the logarithm of the ratio of the signals in the two channels. The gain of the differential amplifier may be adjusted such that the output is in *dB* ($dB = 20\,log\left(\dfrac{V_A}{V_B}\right)$).

13

Other concerns:

In instrumentation practice the amplifier may be used with dc or ac signals. In either case one would not like to load the transducer. This requires the amplifier to have very large (in principle infinite) input impedance. For this purpose we may use special integrated chips called instrumentation amplifiers. One way of achieving high input impedance is to use the arrangement shown in Figure 11.
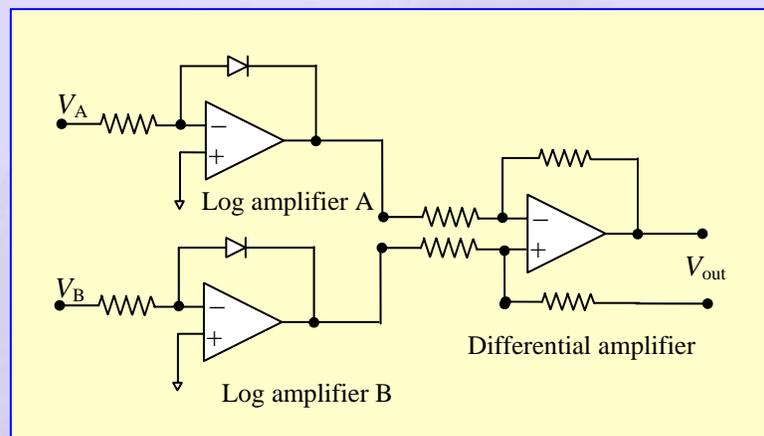

Figure 10 Schematic of a circuit for taking the ratio of two signals
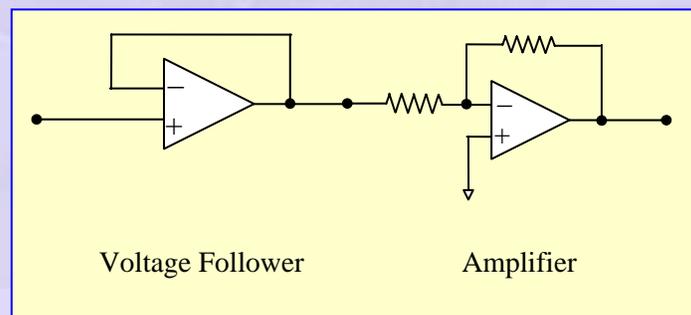
Figure 11 Schematic of an instrumentation amplifier

13

The instrumentation amplifier has two stages, the first one being a unity gain buffer amplifier called the voltage follower. This buffer helps in presenting an input impedance of ~ 1 G to the transducer. Thus the transducer is not loaded by the amplifier. This means that the current drawn from the transducer is negligibly small. Special instrumentation amplifiers with special input stage like field effect transistor are available in the form of a single package.

In many applications we operate with ac signals and hence it is necessary to know how the amplifier behaves with signals of different frequencies. An ideal ac amplifier should show gain independent of frequency. This is seldom the case and hence it is necessary to choose the amplifier based on its frequency response. Also the coupling between the signal and the input to the amplifier should be properly made keeping this in mind. It is best to refer to application notes that accompany the devices supplied by the manufacturer.

In addition to amplification one may also choose or reject some frequencies. Electronic circuits are known to be prone to noise being picked up since the laboratory space is full of electrical disturbances. For example the line frequency of ac power from the socket is typically at 50 Hz and this should be discarded by the amplifier circuit. One interposes a suitable filter section to avoid picking up such noise. There are many types of filters available. We shall look at the most elementary of these, just to understand how they function. The case being considered is a passive filter consisting of resistance – capacitance – inductance.

RC Notch Filter (Twin T):

14
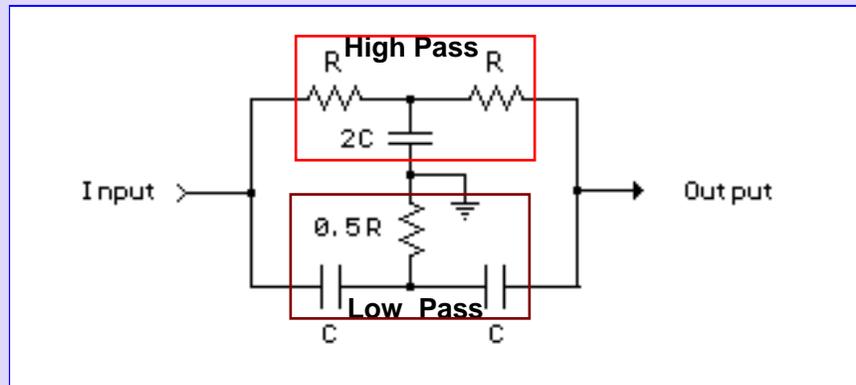
Figure 12 Notch filter

Figure 12 shows a notch filter that helps in removing an unwanted frequency in the input. It is also called a Twin T filter since it has two filters that look like the letter "T". The filter consists of resistors and capacitors arranged in the form of a network consisting of two individual filters – the 'high pass' and the 'low pass'. Before we look at the behavior of the notch filter we look at the low pass and high pass filters. These are first order filters and the analysis is as follows.
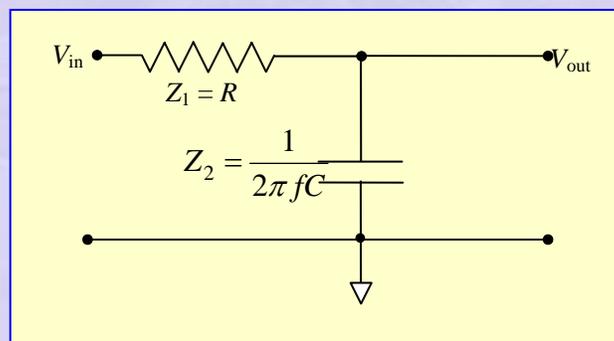
Figure 13 Low pass filter

Consider a low pass consisting of a resistor and a capacitor as shown in Figure 13. The input voltage is a sinusoidal with a frequency f and the output is also a sinusoidal at the same frequency. The impedances are

15

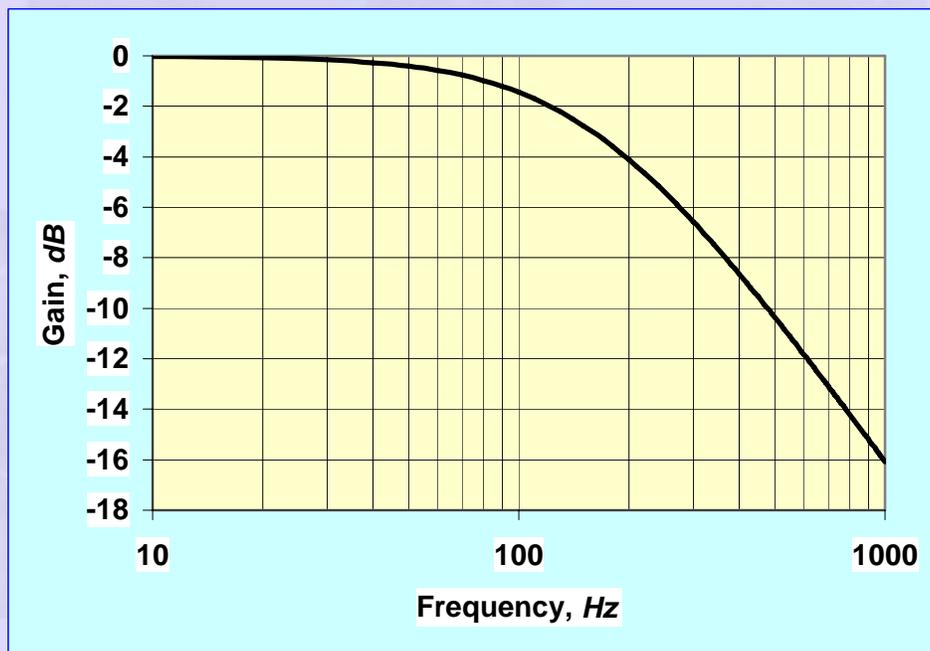$Z_1 = R$ and $Z_2 = \dfrac{j}{2\pi fC} = jX_C$ as shown in the figure. The network is a voltage divider and hence we have

$$\left|\frac{V_{out}}{V_{in}}\right| = \left|\frac{Z_2}{Z_1 + Z_2}\right| = \frac{X_C}{\sqrt{R^2 + X_C^2}} = \frac{1}{\sqrt{1 + \left(\dfrac{R}{X_C}\right)^2}} \qquad \textbf{(4)}$$

The above may be recast in *dB* units as

$$\text{Gain (or attenuation) in } dB = 20\ ln\left|\frac{V_{out}}{V_{in}}\right| = 20\,ln\frac{1}{\sqrt{1 + \left(\dfrac{R}{X_C}\right)^2}} \qquad \textbf{(5)}$$

A plot of this expression is shown in Figure 14 for a network consisting of $R = 1000\,\Omega, C = 1\,\mu F$.

Figure 14 Low pass filter frequency response

16

Consider now the high pass filter shown in Figure 15. It is obtained by simply interchanging the resistor and the capacitor in the low pass filter circuit. We can easily show that Equation 4 is replaced by]

$$\left|\frac{V_{out}}{V_{in}}\right| = \left|\frac{Z_2}{Z_1 + Z_2}\right| = \frac{R}{\sqrt{X_C^2 + R^2}} = \frac{1}{\sqrt{1 + \left(\frac{X_C}{R}\right)^2}} \qquad \text{`} \qquad (6)$$
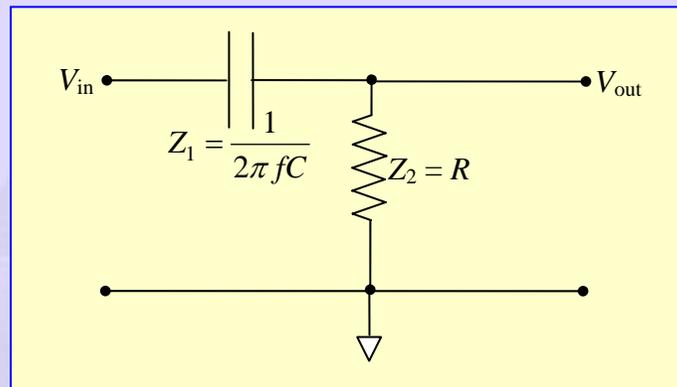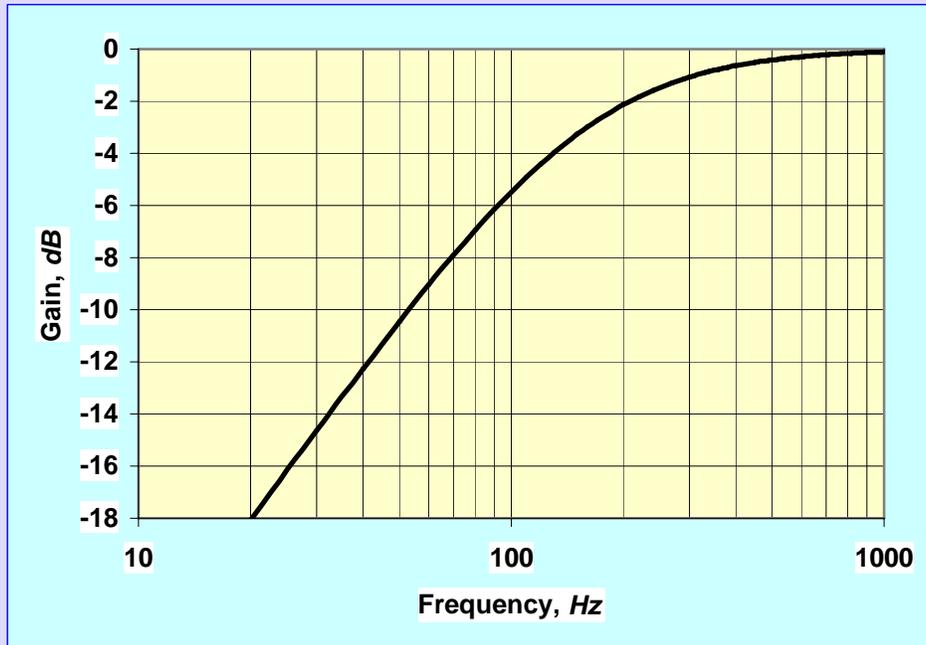
Figure 15 High pass filter

Equation 5 will be replaced by

$$\text{Gain (or attenuation) in } dB = 20 \; ln\left|\frac{V_{out}}{V_{in}}\right| = 20\,ln\frac{1}{\sqrt{1 + \left(\frac{X_C}{R}\right)^2}} \qquad (7)$$

A plot of this expression is shown in Figure 16 for a network consisting of $R = 1000\,\Omega, C = 1\,\mu F$.

Figure 16 High pass filter frequency response

We thus observe that a low pass filter passes on low frequency signal and the high pass filter passes on the high frequency components. The output in either case shows the presence of "knee" at a characteristic frequency for which the resistive impedance and the capacitive impedance are the same. This corresponds to a critical frequency given by

$f = \dfrac{1}{2\pi RC}$. In the case illustrated here this frequency is around 160 *Hz*. At this frequency the gain is 0.5 or -3 *dB*. It is thus clear that a combination of these two should give a notch filter as shown in Figure 10 with the notch frequency at 160 *Hz*. The notch filter is achieved by the arrangement shown in Figure 17.
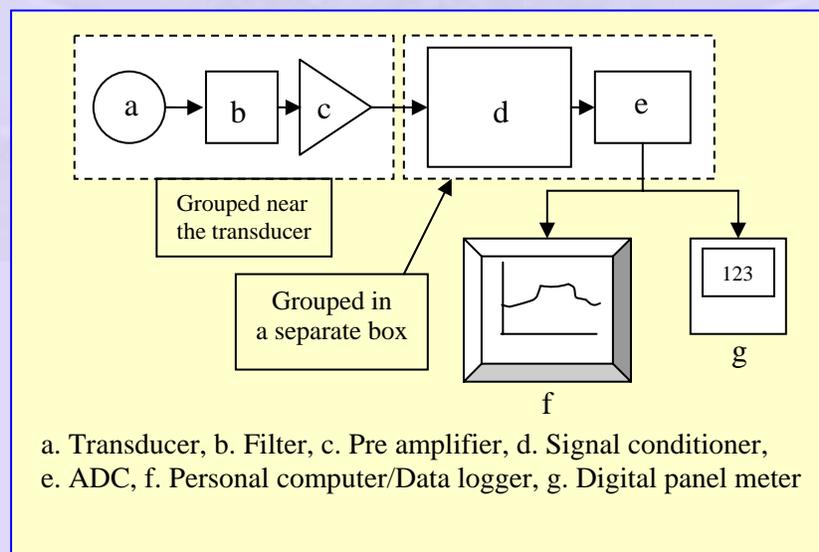
18
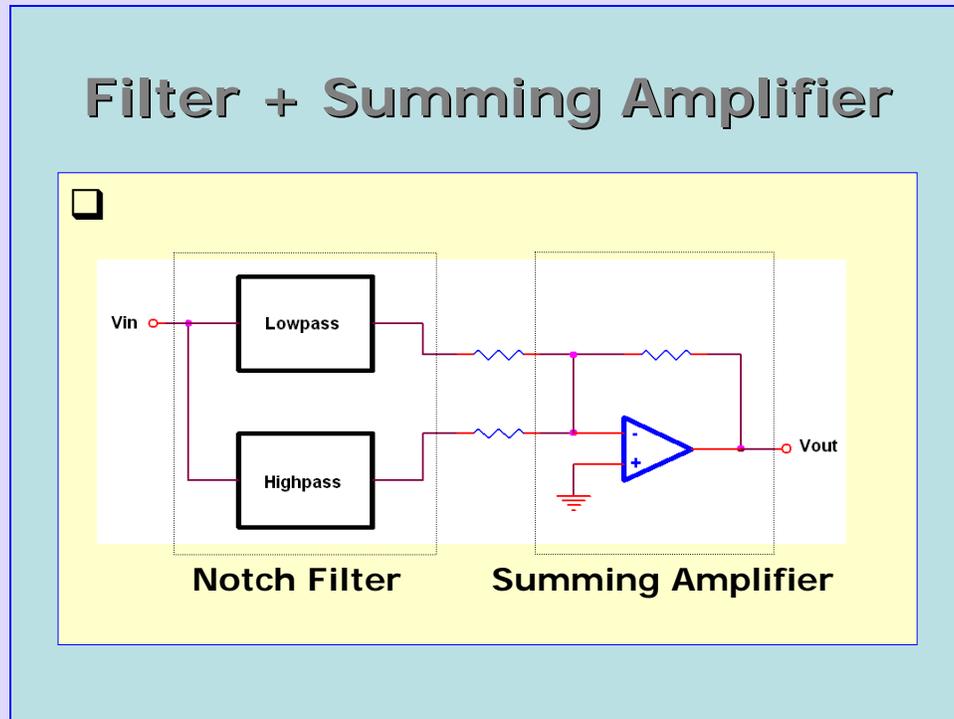
Figure 17 Notch filter followed by a summing amplifier to reject an unwanted frequency component

Characteristics of a typical notch filter are shown in Figure 18. We may now give a schematic of any measuring instrument (Figure 19). Typically it consists of a transducer followed by a pre-amplifier with possibly a suitable filter. The preamplifier is normally placed very close to the transducer so that noise pick up is avoided. All cables are either coaxial shielded cables or twisted pairs. These also help in reducing noise pick up. In modern laboratory practice it is normal to use a digital data logger or a digital computer to collect and store the data. For this purpose the signal conditioner is followed by an analog to digital converter or ADC. The signal is then communicated to a data logger or a digital computer; either a PC or a laptop computer. This requires a communication between the ADC and the computer. In case the ADC is done in a board in one of the slots of the PC the communication is through a data cable via a suitable port. Nowadays

19

miniature data loggers are available that connect to the USB port of a computer.
More discussion on these follows later on.
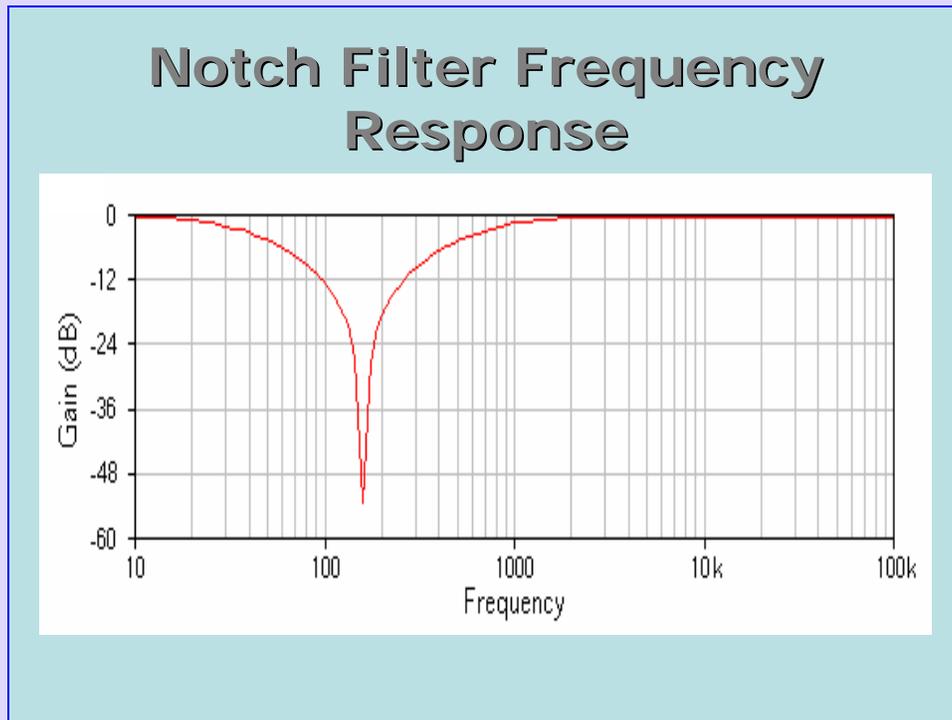
Figure 18 Frequency response of a notch filter

a. Transducer, b. Filter, c. Pre amplifier, d. Signal conditioner,
e. ADC, f. Personal computer/Data logger, g. Digital panel meter

Figure 19 Schematic of a general instrument

In order to avoid noise pick up the transducer and associated pre amplifier is mounted in a box near the point of measurement. A signal conditioner along with ADC may be grouped together near the output unit. Output unit may wither be a computer or a digital panel meter. We now look at the fundamental ideas with reference to digital voltage measurement.

Digital panel meter or Digital voltmeter:

Normally the output of a transducer is an analog signal represented by a continuous variation of output as a function of input. For example, a thermocouple produces a Seebeck voltage that is a continuous function of the junction temperature. If we want to use a digital voltmeter to measure this voltage the signal has to suitably amplified and converted to digital form. Analog to digital conversion is done in an ADC and transmitted by a cable to the DPM or the PC. The ADC converts the input voltage to a count (or number) represented in digital form using a certain number of bits. Consider an example.

Let the maximum and minimum values of the measured voltages be respectively 1 *V* and 0 *V*. Consider a four bit ADC as a simple example. Count is represented in the form

Table 1 Representation of count by a 4 bit ADC

Digit	4 bit representation

0	0 0 0 0
1	0 0 0 1
2	0 0 1 0
14	1 1 1 0
15	1 1 1 1

There are thus 16 levels including 0 and the maximum. Note that the least bit represents 2^0 and highest bit represents 2^3. The total number of levels is given by 2^4 = 16. Each of these numbers represents a voltage between 0 and 1 *V.* The resolution of the 4 bit digital voltmeter is the Range divided by the total number of intervals between the maximum and minimum count. Thus the resolution of a 4 bit digital voltmeter is

$$\text{Resolution} = \frac{1V - 0V}{15 - 0} = \frac{1}{15} \approx 0.067 \ V/count \qquad \textbf{(8)}$$

We may generalize the above to the case of *n* bit ADC. The number of levels is given by 2^n and the resolution by $\frac{Range}{2^n - 1}$. If *n* is large the denominator may be approximated by 2^n itself. A 10 bit ADC gives a maximum count of $2^{10} = 1024$. The resolution is calculated as $\text{Resolution} = \frac{1}{2^{10} - 1} \approx \frac{1}{2^{10}} = 0.000977$. If the full scale is 1 V the resolution is very close to a *mV.* In case we make the full scale exactly equal to 1.023 V the resolution will in deed be exactly equal to 1 *mV.* The instrument is referred to as a 3 digit meter. For example a 3 digit meter will have a maximum of 1 *V* with a resolution of a *mV.*

Example 1

22

A T type thermocouple is to be used in an experimental set up. The maximum temperature that will be measured is about 400°C. The experimenter wants to choose a proper digital voltmeter with a resolution of 0.25°C. You are required to help him.

Table of response of T type thermocouple shows that, the output of the thermocouple is 20.872 *mV*, when the measuring junction is at a temperature of 400°C and the reference junction is at ice point. We shall assume, for the present that the experimenter has an ice point reference available in his set up. Normally voltmeters have range of 1, 3, 10 *V* etc. The voltmeter appropriate to the present application may be chosen as one that has a range of 3 *V*.

We know that the Seebeck coefficient of T type thermocouple is about 40 *V/°C*. The experimenter desires a resolution of 0.2°C. This corresponds to a Seebeck voltage resolution of $0.25 \times 40 = 10\,\mu V = 10^{-2}\,mV$. Thus the output of the thermocouple is to be measured with 10 V resolution and is of the form $\mathrm{xx.xx}\,mV$. We shall assume that a good amplifier with a gain of 143.7 is available to amplify the thermocouple output. The maximum output after amplification will be $20.87 \times 143.7\,mV = 20.87 \times 0.1437V = 3.000\,V$. We may choose a digital voltmeter with a range of 3.000 *V*.

The resolution of the voltmeter is thus 0.001 *V* or 1 *mV*. The number count of the digital voltmeter may now be worked out:

$$\text{Number count} = \frac{\text{Range}}{\text{Resolution}} = \frac{3.000}{0.001} = 3000$$

24

The number of digits of the voltmeter is simply the logarithm to base 10 of the number count. Thus

$$\text{Number of digits} = \log(3000) = 3.4771 \approx 3.5$$

Thus a $3\frac{1}{2}$ voltmeter with a range of 3 *V* is required for measuring temperature using a T type thermocouple.

Let us look at the number of bits required. The number count for $n = 11$ is 2048 while it is 4096 for $n = 12$. The desired number count is 3000 which may be represented by a binary digit with 12 bits. The maximum count is less than the maximum possible value of 4096.

Data loggers and data acquisition boards:

These are available from various manufacturers like Hewlett Packard, National Instruments and others. The data loggers operate as stand alone or as attachment to a computer. These are supplied with appropriate software with user friendly features. For example, National Instruments supplies a general purpose software called LABVIEW that may be used for creating virtual instruments based on add on cards that reside in the slots available in a PC.

Recently DAQ have become available that are connected to a PC through the USB port. A example is shown in Figure 20.

25

Figure 20 National Instruments USB compatible Data Acquisition Module

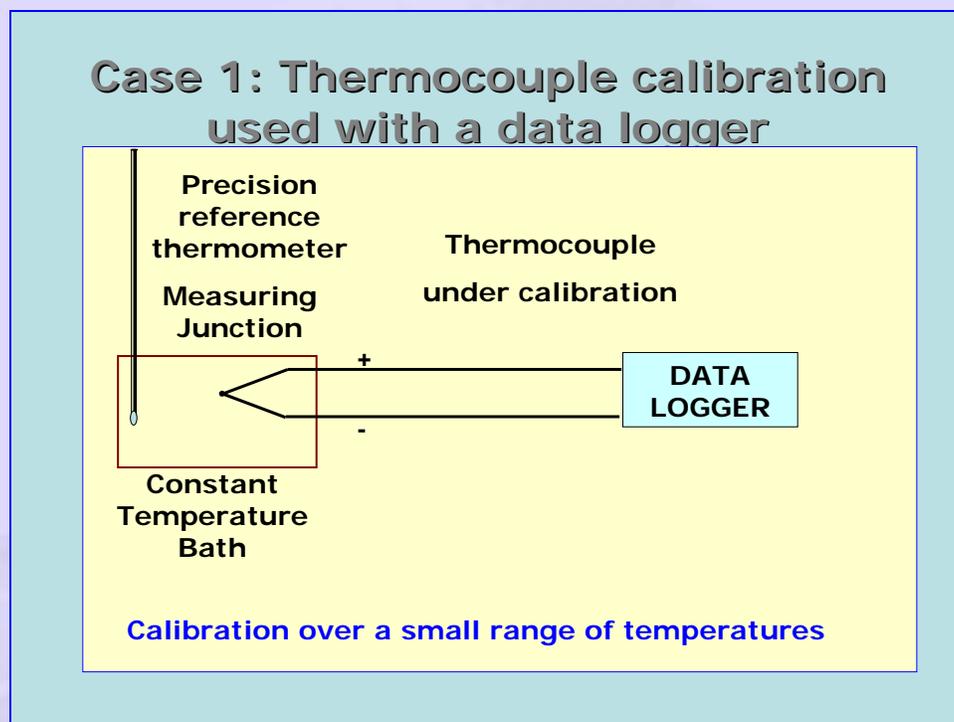The NI module is capable of the following:

- o USB Based DAQ from National Instruments
- o 4 Channels of 24 bit thermocouple input
- o Internal cold junction sensor
- o Compatible with J, K, R, S, T, N, E and B thermocouple types
- o Plug and play connectivity with USB
- o Bus powered
- o Windows 2000/XP, MAC OS X, Linux
- o Software supplied by NI

Most important advantage of the module is the USB connectivity that is quick and does not require opening the PC cover! It has a 24 bit ADC giving a sensitivity of ~ 0.1 $\mu V/V$.

Case 1: Thermocouple calibration using a data logger

In the laboratory it was necessary to measure several temperatures in an experimental set up and log the data continuously during the experiment runs. It was decided to calibrate each of the thermocouples used over a narrow range of temperatures over which the experiments were run. Typical arrangement for the calibration is shown in Figure 21.

Case 1: Thermocouple calibration used with a data logger

Precision reference thermometer

Thermocouple under calibration

Measuring Junction

+

-

DATA LOGGER

Constant Temperature Bath

Calibration over a small range of temperatures

Figure 21 Thermocouple calibration arrangements using a data logger

The thermocouple to be calibrated and a high precision reference thermometer were immersed in a constant temperature bath. Simultaneous readings are taken of both the thermocouple output as measured by the data logger and the reading of the precision thermometer. It was found that the thermocouple response within the range of interest was represented very well by a linear

27

relation and this was written directly in to the data logger. Figure 22 shows the mean calibration line for a set of 11 thermocouples that were calibrated in the experiment.
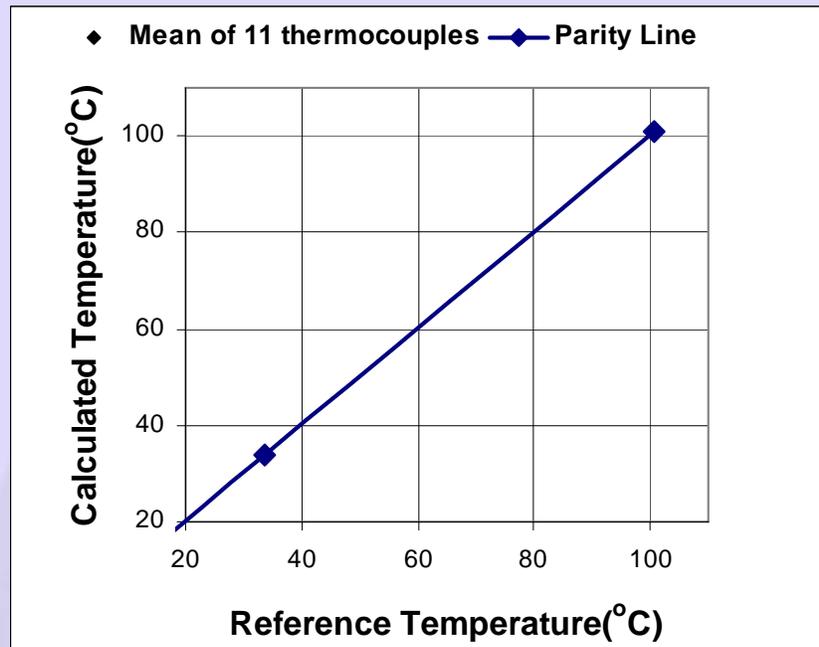
Figure 22 Parity plot showing the relationship between the calculated and reference temperatures

The formula that represents the relation between the thermocouple output V with the temperature T is $T=25253 \times V+40.718$. The graphic set up of the data logger (supplied by Agilent) is shown by the entries in the GUI as shown in Figure 23 for various thermocouple channels identified by channel numbers.

Data Logger Graphic Set Up
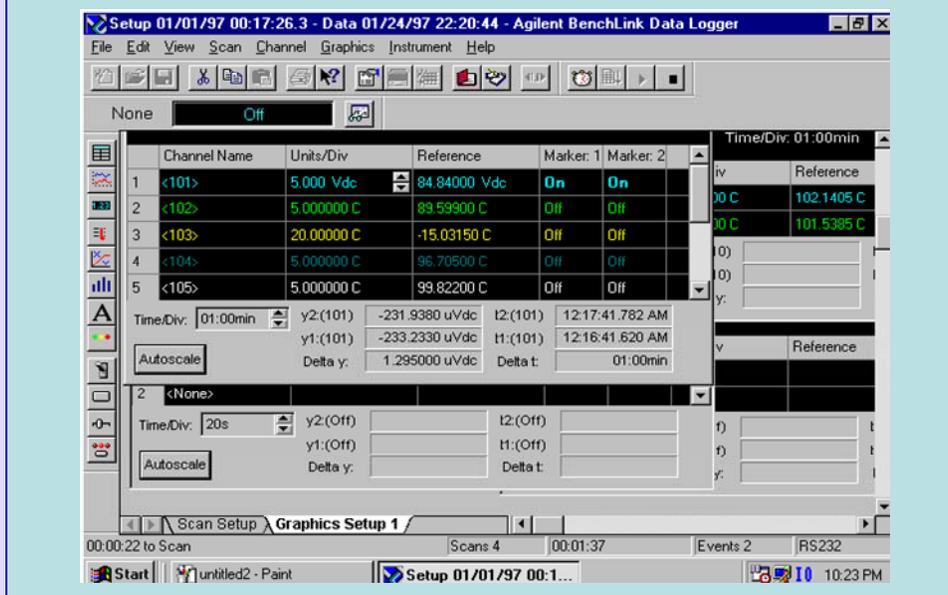
Figure 23 Data logger graphic set up

Data Logger Scan Set Up
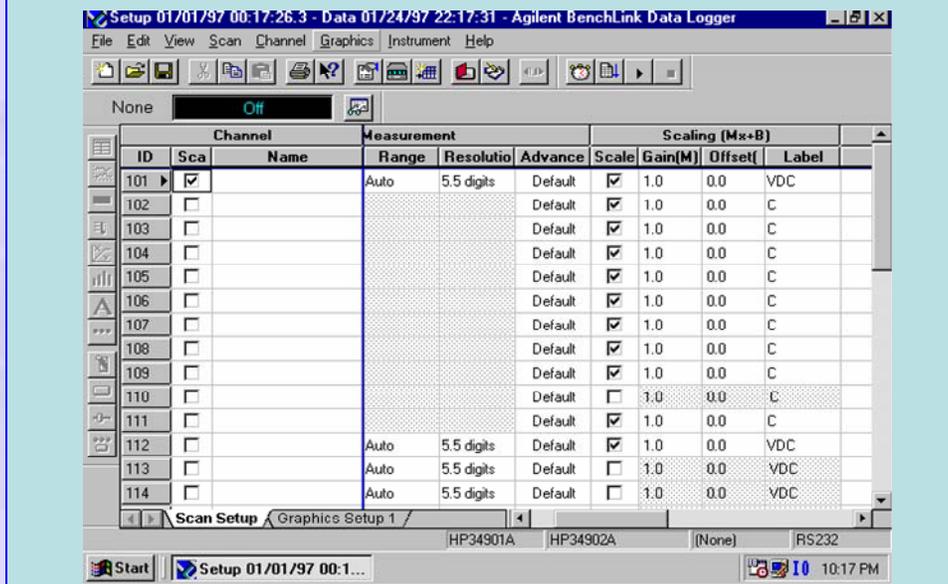
Figure 24 Data logger scan set up

29

Various channels in the data logger are set up for scanning the various channels as shown in Figure 24.   Note that the output of the channels are scanned electronically and stored in respective memory locations. Since the scanning is very fast, for the experiments that are being performed here the measurements are basically simultaneous! The desired resolution may be entered for each channel. The default value is $5\frac{1}{2}$ digits or 5.5 as entered. This corresponds to a number count of 300000 and hence a resolution of 3   *V/V*.

We also note that the formula for conversion of voltage to temperature is written as indicated in Figure 25. For the linear relation the slope goes in as the Gain and the intercept in to its own cell. In the case shown the slope as well as the intercepts are different for the individual thermocouples and are individually entered in to each of the channels.

Figure 25 Entry of conversion formulae
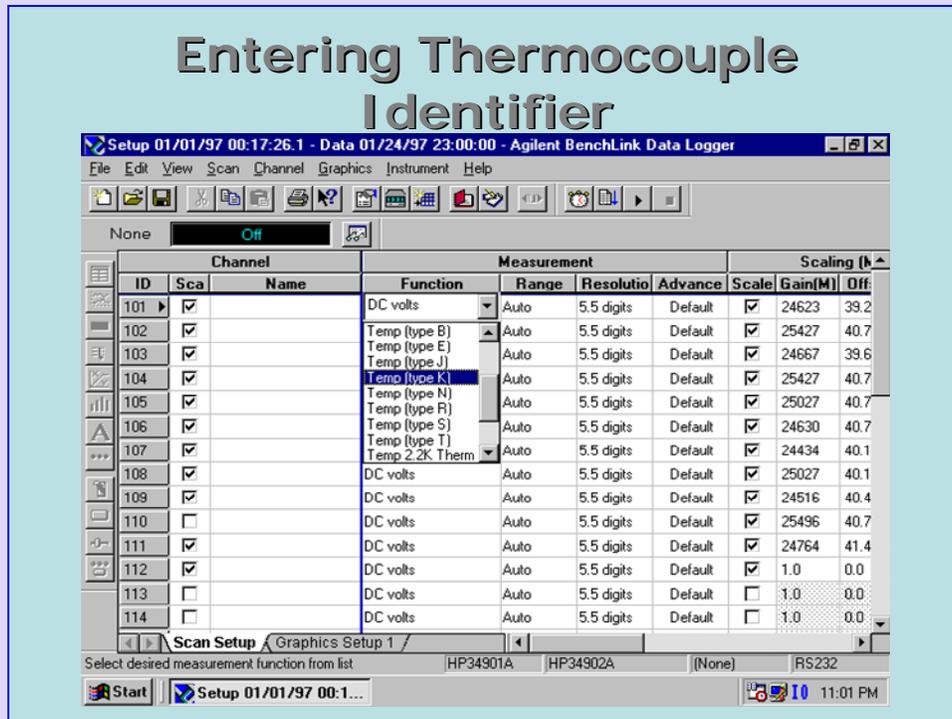
Figure 26 Entry of thermocouple type

Figure 26 shows how to select the thermocouple type using the scroll bar under "Function".

Case 2 Calibration of a sheathed thermocouple

In an experiment it was necessary to measure the temperature between the room temperature and a maximum of about $100°C$. The thermocouple had to a sheathed thermocouple with a stainless steel sheath since the application involved a corrosive environment.

31
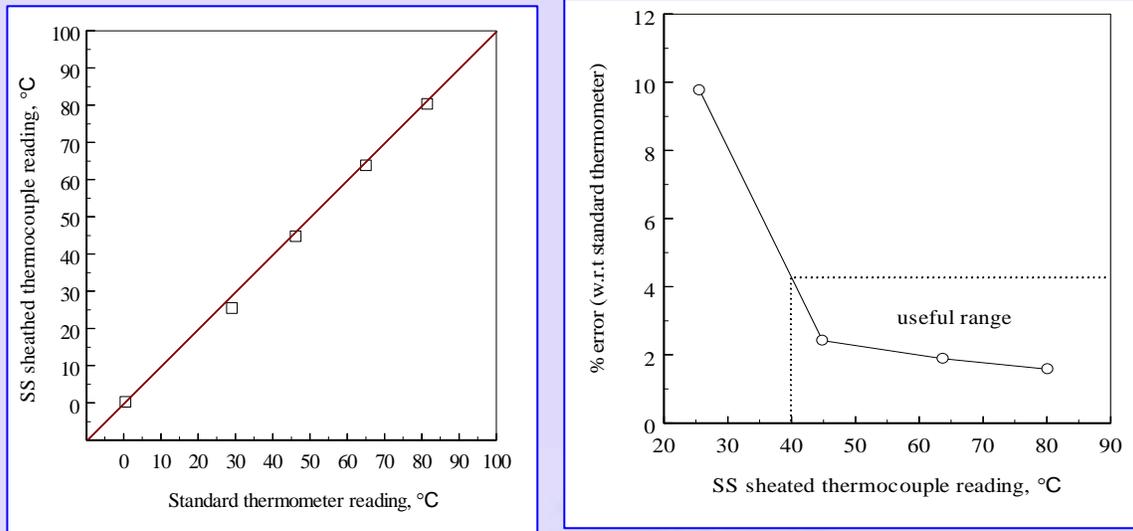
Figure 26 Sheathed thermocouple calibration data

(a) Parity plot (b) Error magnitude plot

The calibration data shown plotted in Figure 26 indicates that the sheathed thermocouple is not susceptible to any systematic errors. It is also seen that the absolute error is within 2.5% in the range indicated as 'useful range' of the sheathed thermocouple.

Use of current loop:

In most industrial applications transducers are far away from the control room where the display of the measured quantities is made. It is difficult to transmit voltages over long distances and one way of circumventing this problem is to transmit the output in the form of a current. It is common practice to represent the zero of the transducer by a current of 4 *mA* and the full scale as 20 *mA*. The transmitted signal is thus in the analog current form.

32

An example of a pressure sensor with 4 – 20 *mA* transmitter is shown in Figure 26. The power supply usually is 24 *V* DC. The power supply is designed so that it will be able to maintain a maximum current of 20 *mA* in the loop. The signal from the pressure transducer is amplified and converted to a current in the transmitter. The current output is converted to a voltage at the display end by terminating it in a drop resistor, 500   in the case illustrated in Figure 27. In the figure the pressure of 10 *mm* water will correspond to a current of 20 *mA* and a potential difference across the load resistor of 10 *V*. The current transmitter requires at least 8 *V* to operate properly. If the current loop is very long there will be the line resistance which will drop voltage. Finally the voltage drops across the drop resistor. The power supply voltage should be more than all these put together.
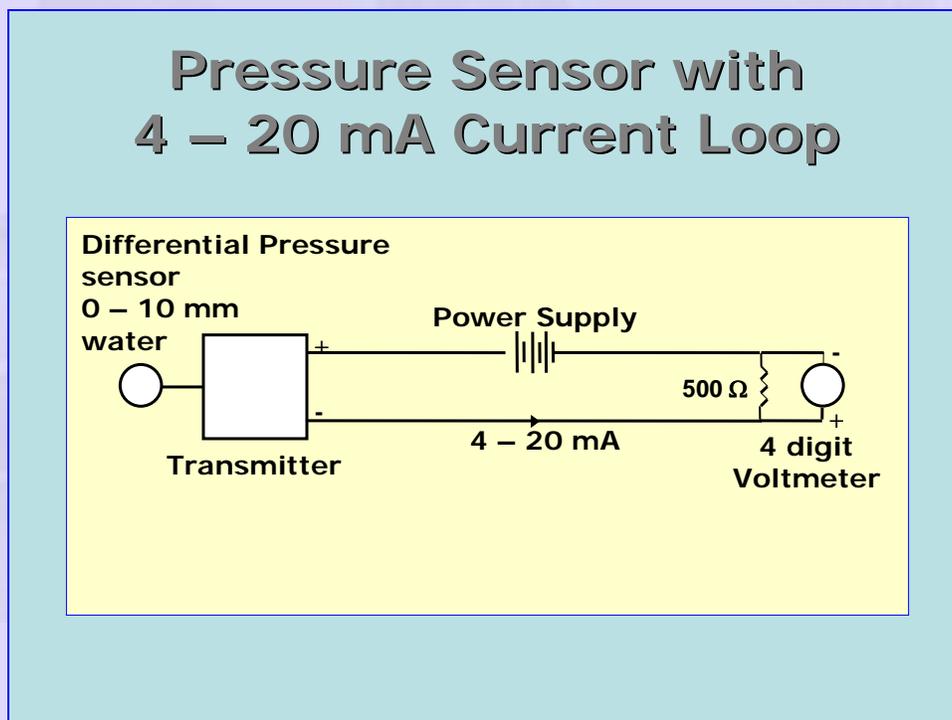
Figure 27 Pressure sensor with 4 – 20 *mA* Current Loop

Example 2

In a wind tunnel the maximum velocity of air at $25°C$ and 1 atmosphere pressure is expected to be 10 m/s. The minimum velocity is expected to be 2 m/s. A Pitot static tube is to be used for the measurement of velocity. Prescribe a suitable pressure measuring instrument for this purpose.

For the purpose of the design we assume that the coefficient of discharge of the Pitot static tube is 1.

The pressure and temperature of flowing air are:

$$p = 1.013 \times 10^5 \ Pa, \ T = 25°C = 298 \ K$$

The gas constant for air is taken as

$$R_g = 287 \ J/kg \ K$$

The density of air may be calculated as

$$\rho = \frac{p}{R_g T} = \frac{1.013 \times 10^5}{287 \times 298} = 1.184 \ kg/m^3$$

Maximum and minimum velocities of air are specified as $V_{max} = 10 m/s, \ V_{min} = 0.5 \ m/s$.

The maximum and minimum dynamic pressures to be measured are calculated as

$$\Delta p_{max} = \frac{\rho V_{max}^2}{2} = \frac{1.184 \times 10^2}{2} = 59.222 Pa$$

$$\Delta p_{min} = \frac{\rho V_{min}^2}{2} = \frac{1.184 \times 2^2}{2} = 2.368 \ Pa$$

With distilled water as the manometer liquid, the corresponding manometer column heights are

$$h_{max} = \frac{\Delta p_{max}}{\rho_m g} = \frac{59.222}{1000 \times 9.81} = 6.043 \, mm \, water$$

$$h_{min} = \frac{\Delta p_{min}}{\rho_m g} = \frac{2.368}{1000 \times 9.81} = 0.242 \, mm \, water$$

Thus we require a very sensitive manometer for this purpose.

Alternative 1:

One may use a Betz manometer for this purpose. Betz manometer can resolve pressure changes as small as 0.01 mm of water column. In that case the h will be rounded to 2 significant digits after the decimal point.

Alternative 2:

A differential pressure transducer based pressure transmitter may be used for this purpose. A suitable range for the transducer would be a differential pressure range of 0 – 10 $mm\ water$. The corresponding current outputs will be 4 – 20 mA. We convert the maximum and minimum values of pressure difference to current as

$$I_{max} = 4 + \frac{h_{max}(20-4)}{10} = 4 + \frac{6.043 \times 16}{10} = 13.669 \, mA$$

$$I_{min} = 4 + \frac{h_{min}(20-4)}{10} = 4 + \frac{0.242 \times 16}{10} = 4.387 \, mA$$

Assume that a digital panel meter would be used to measure the corresponding voltages by dropping the current across a resistor of 500 . The corresponding voltage readings indicated by the DPM are

$$V_{max} = I_{max}R = 13.669 \times 10^{-3} \times 500 = 6.835 \, V$$

$$V_{max} = I_{max}R = 4.387 \times 10^{-3} \times 500 = 2.194 \, V$$

35

36

We require a digital panel meter that is capable of reading up to 10 *V* with *mV* resolution. Appropriate instrument would be a 4 digit voltmeter.

The appropriate instrumentation for this option is shown in Figure 27.

Example 3

In a certain experiment is desired to measure the torque by the use of four strain gauges in a full bridge arrangement. Gauges in opposite arms of the bridge experience tension and compression respectively as shown in the figure. The shaft on which the strain gauge bridge is attached is made of steel and is of 6 mm diameter. The torque is expected to be any value between 1 and 8 N m. Discuss this case from the signal conditioning angle. Suggest suitable components in the measurement scheme.
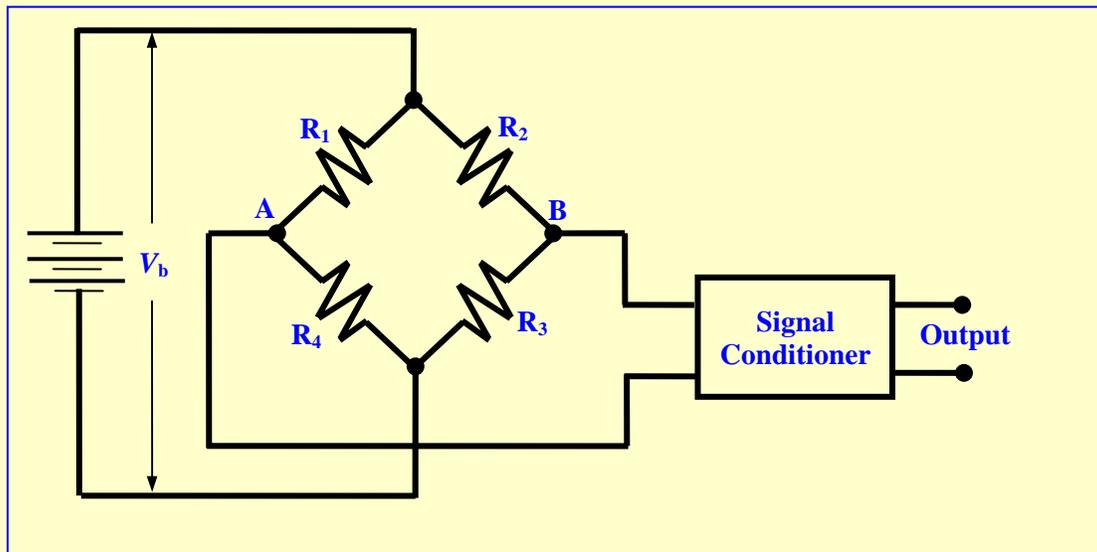
We shall assume that all the strain gauges are identical and have an unstrained resistance of 120 Ω. The gauges R_1 and R_3 are mounted on the shaft such that these sense the tensile stress (tensile principal stress) while gauges R_2 and R_4 are mounted on the shaft such that these sense the compressive stress (tensile principal stress). We know from earlier discussion that when the shaft experiences pure torsion the magnitudes of these stresses are equal and given by $\sigma = \dfrac{TR}{J}$, where the symbols have the usual meanings. The resistances R_1 and

R_3 increase by δR while resistances R_2 and R_4 decrease by δR. Let us represent the values of all strain gauges as R when there is no strain. We may easily obtain the potentials at A and B by using Ohm's law:

$$V_A = V_b \frac{R + \delta R}{(R + \delta R) + (R - \delta R)} = V_b \frac{R + \delta R}{2R}$$

$$V_B = V_b \frac{R - \delta R}{(R - \delta R) + (R + \delta R)} = V_b \frac{R - \delta R}{2R}$$

The output of the bridge is thus given by

$$V_o = V_A - V_B = V_b \frac{R + \delta R}{2R} - V_b \frac{R - \delta R}{2R} = V_b \frac{\delta R}{R}$$

We shall calculate the output when the impressed torque on the shaft has the upper limit of $T = 8$ N m. We also have $R = 0.003$ m and $J = \frac{\pi R^4}{2} = \frac{\pi \times 0.003^4}{2} = 1.27 \times 10^{-10} m^4$. The corresponding principal stress magnitude is given by

$$\sigma = \frac{TR}{J} = \frac{8 \times 0.003}{1.27 \times 10^{-10}} = 2.36 \times 10^8 \ Pa$$

With Young's modulus of steel taken as $E = 200$ GPa, the corresponding longitudinal strain may be calculated as $\varepsilon = \frac{\sigma}{E} = \frac{2.36 \times 10^8}{200 \times 10^9} = 1.18 \times 10^{-3}$. Taking the Poisson ratio of steel as $\nu = 0.3$, the gage resistance change may be calculated as

$$\frac{\delta R}{R} = \varepsilon(1 + 2\nu) = 1.18 \times 10^{-3}(1 + 2 \times 0.3) = 0.001886$$

(Refer to Module 2 for more details)

If we assume that the supply voltage is $V_b = 10$ V, the output of the bridge will be

$$V_o = V_b \frac{\delta R}{R} = 3 \times 0.001886 = 0.004527 V \ or \ 4.527 mV$$

The calculations may be repeated for the lower limit of torque to get the lowest gauge output as 0.566 *mV*.

Thus the output signal is very weak and needs to be amplified before being recorded. If the shaft is rotating, the signal needs to be taken out either through slip rings with brush contacts or using a high frequency transmitter mounted on the shaft. In the latter case the output should be boosted with a preamplifier and modulated with a carrier.   The signal is to be received by a receiver, demodulated and amplified again before being measured by a voltage measuring instrument.   If the voltage is measured by a digital meter the signal must be converted to the digital form using an ADC. The schematic of the transmitter and receiver electronics will be as shown in the following figure.
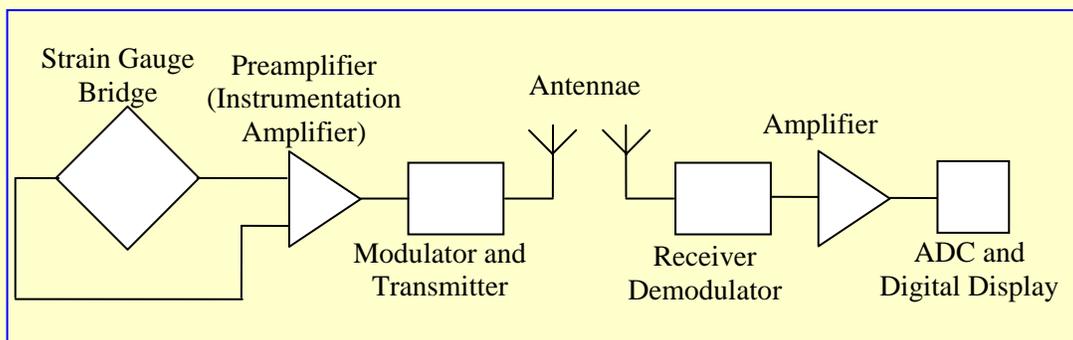
Finally the signal may be measured by a digital voltmeter. We may assume an overall gain of 2000 such that the signal is in the range 1.132- 9.054 *V*. This will require a digital voltmeter having a range of 0 – 10 V and a resolution of 0.0001 *V*. A 4 digit voltmeter is suitable for this purpose.

Software:

Most modern measurements involve the coupling of the experimental set up to a computer via suitable sensors and connecting lines. The connection between the sensor and the computer must be two way so that control information can go from the computer to the sensor and the data from the sensor to the computer. The computer uses suitable software to scan the information available on various channels (example was given earlier with respect to a data logger) and store or save the data in the computer in a file. Software also helps in creating a virtual instrument on the monitor of the computer. A typical example is shown as Figure 28. The data is presented in real time in graphical form. Output of each channel is shown graphically with different user selected colors.   This data is also available in the form of a file for manipulation using any of the programs like MATLAB, EXCEL etc.
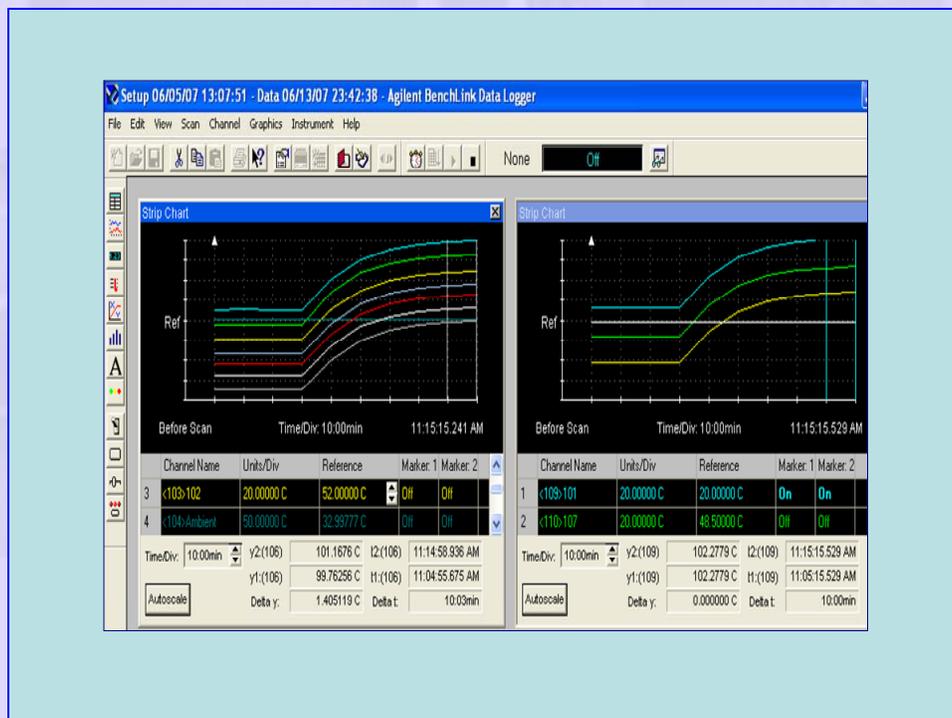
Figure 28 Typical 'real time' output

41

In the case of LABVIEW software provided by National Instruments the virtual instrument is "hard wired" in the form of software in the computer. The input signals in various channels are manipulated by the software that the hard wiring represents and the output is displayed in a user friendly format. Signal manipulation by software is an important development in instrumentation. The software deals with digital form of signal and hence any mathematical manipulation is possible using suitable software. Many of these are also possible with additional software like MATLAB, MATHCAD and EXCEL. The reader should consult web resources available from the suppliers of the above software for more details.