Display, recording and presentation of measurement data

The earlier chapters in this book have been essentially concerned with describing ways of producing high-quality, error-free data at the output of a measurement system. Having got the data, the next consideration is how to present it in a form where it can be readily used and analysed. This chapter therefore starts by covering the techniques available to either display measurement data for current use or record it for future use. Following this, standards of good practice for presenting data in either graphical or tabular form are covered, using either paper or a computer monitor screen as the display medium. This leads on to a discussion of mathematical regression techniques for fitting the best lines through data points on a graph. Confidence tests to assess the correctness of the line fitted are also described. Finally, correlation tests are described that determine the degree of association between two sets of data when they are both subject to random fluctuations.

11.1 Display of measurement signals

Measurement signals in the form of a varying electrical voltage can be displayed either by an *oscilloscope* or else by any of the *electrical meters* described earlier in Chapter 6. However, if signals are converted to digital form, other display options apart from meters become possible, such as electronic output displays or using a computer monitor.

11.1.1 Electronic output displays

Electronic displays enable a parameter value to be read immediately, thus allowing for any necessary response to be made immediately. The main requirement for displays is that they should be clear and unambiguous. Two common types of character format used in displays, seven-segment and 7 × 5 dot matrix, are shown in Figure 11.1. Both types of display have the advantage of being able to display alphabetic as well as numeric information, although the seven-segment format can only display a limited nine-letter subset of the full 26-letter alphabet. This allows added meaning to be given to the number displayed by including a word or letter code. It also allows a single

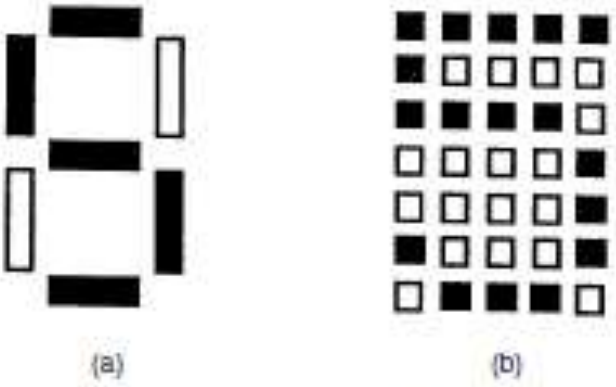


Fig. 11.1 Character formats used in electronic displays: (a) seven-segment; (b) 7 × 5 dot matrix.

display unit to send information about several parameter values, cycling through each in turn and including alphabetic information to indicate the nature of the variable currently displayed.

Electronic output units usually consist of a number of side-by-side cells, where each cell displays one character. Generally, these accept either serial or parallel digital input signals, and the input format can be either binary-coded decimal (BCD) or ASCII. Technologies used for the individual elements in the display are either light-emitting diodes (LEDs) or liquid-crystal elements.

11.1.2 Computer monitor displays

Now that computers are part of the furniture in most homes, the ability of computers to display information is widely understood and appreciated. Computers are now both cheap and highly reliable, and they provide an excellent mechanism for both displaying and storing information. As well as alphanumeric displays of industrial plant variable and status data, for which the plant operator can vary the size of font used to display the information at will, it is also relatively easy to display other information such as plant layout diagrams, process flow layouts etc. This allows not only the value of parameters that go outside control limits to be displayed, but also their location on a schematic map of the plant. Graphical displays of the behaviour of a measured variable are also possible. However, this poses a difficulty when there is a requirement to display the variable's behaviour over a long period of time since the length of the time axis is constrained by the size of the monitor's screen. To overcome this, the display resolution has to decrease as the time period of the display increases.

Touch screens are the very latest development in computer displays. Apart from having the ability to display the same sort of information as a conventional computer monitor, they also provide a command-input facility in which the operator simply has to touch the screen at points where images of keys or boxes are displayed. A full 'qwerty' keyboard is often provided as part of the display. The sensing elements behind the screen are protected by the glass and continue to function even if the glass gets scratched. Touch screens are usually totally sealed, and thus provide intrinsically safe operation in hazardous environments.

11.2 Recording of measurement data

Many techniques now exist for recording measurement data in a form that permits subsequent analysis, particularly for looking at the historical behaviour of measured parameters in fault diagnosis procedures. The earliest recording instruments used were various forms of mechanical chart recorder. Whilst many of these remain in use, most modern forms of chart recorder exist in hybrid forms in which microprocessors are incorporated to improve performance. The sections below discuss these, along with other methods of recording signals including digital recorders, magnetic tape recorders, digital (storage) oscilloscopes and hard-copy devices such as dot-matrix, inkjet and laser printers.

11.2.1 Mechanical chart recorders

Mechanical chart recorders are a long-established means of making permanent records of electrical signals in a simple, cheap and reliable way, even though they have poor dynamic characteristics which means that they are unable to record signals at frequencies greater than about 30 Hz. They have particular advantages in providing a non-corruptible record that has the merit of instant 'viewability', thereby satisfying regulations in many industries that require variables to be monitored and recorded continuously with hard-copy output. ISO 9000 quality assurance procedures and ISO 14000 environmental protection systems set similar requirements, and special regulations in the defence industry go even further by requiring hard-copy output to be kept for ten years. Hence, whilst many people have been predicting the demise of chart recorders, the reality of the situation is that they are likely to be needed in many industries for many years to come. This comment applies particularly to the more modern, hybrid form of chart recorder, which contains a microprocessor to improve performance. Mechanical chart recorders are either of the galvanometric type or potentiometric type. Both of these work on the same principle of driving chart paper at a constant speed past a pen whose deflection is a function of the magnitude of the measured signal. This produces a time history of the measured signal.

Galvanometric recorders

These work on the same principle as a moving-coil meter except that the pointer draws an ink trace on paper, as illustrated in Figure 11.2, instead of merely moving against a scale. The measured signal is applied to the coil, and the angular deflection of this and its attached pointer is proportional to the magnitude of the signal applied. Inspection of Figure 11.3(a) shows that the displacement y of the pen across the chart recorder is given by $y = R \sin\theta$. This sine relationship between the input signal and the displacement y is non-linear, and results in an error of 0.7% for deflections of $\pm 10^\circ$. A more serious problem arising from the pen moving in an arc is that it is difficult to relate the magnitude of deflection with the time axis. One way of overcoming this is to print a grid on the chart paper in the form of circular arcs, as illustrated in Figure 11.3(b). Unfortunately, measurement errors often occur in reading this type of chart, as interpolation for points drawn between the curved grid lines is difficult. An alternative solution is to use heat-sensitive chart paper directed over a knife-edge, and

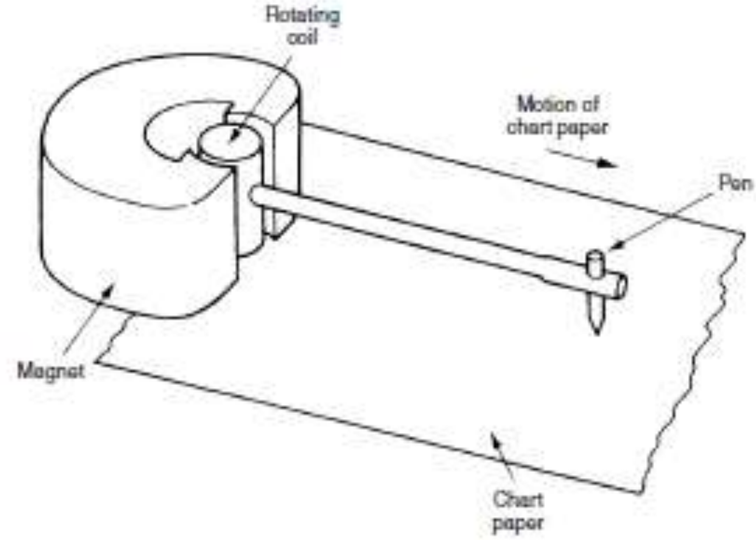
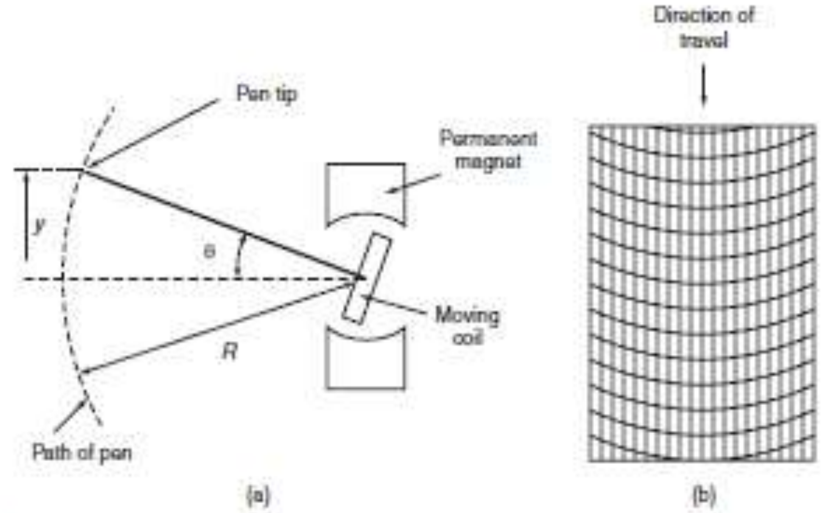


Fig. 11.2 Simple galvanometric recorder.



(a) (b)

Fig. 11.3 Output of simple chart recorder: (a) y versus θ relationship; (b) curvilinear chart paper.

to replace the pen by a heated stylus, as illustrated in Figure 11.4. The input–output relationship is still non-linear, with the deflection y being proportional to $\tan\theta$ as shown in Figure 11.5(a), and the reading error for excursions of $\pm 10°$ is still 0.7%. However, the rectilinearly scaled chart paper now required, as shown in Figure 11.5(b), allows much easier interpolation between grid lines.

Potentiometric recorders

Potentiometric recorders have much better specifications than galvanometric recorders, with a typical inaccuracy of ±0.1% of full scale and measurement resolution of 0.2% f.s. being achievable. Such instruments employ a servo system, as shown in Figure 11.8, in which the pen is driven by a servomotor, and a potentiometer on the pen feeds back a signal proportional to pen position. This position signal is compared with the measured signal, and the difference is applied as an error signal that drives the motor. However, a consequence of this electromechanical balancing mechanism is to give the instrument a slow response time in the range 0.2–2.0 seconds. This means that potentiometric recorders are only suitable for measuring d.c. and slowly time-varying signals. In addition, this type of recorder is susceptible to commutator problems when a standard d.c. motor is used in the servo system. However, the use of brushless servo motors in many recent models overcomes this problem. Newer models also often use a non-contacting ultrasonic sensor to provide feedback on pen position in place of a

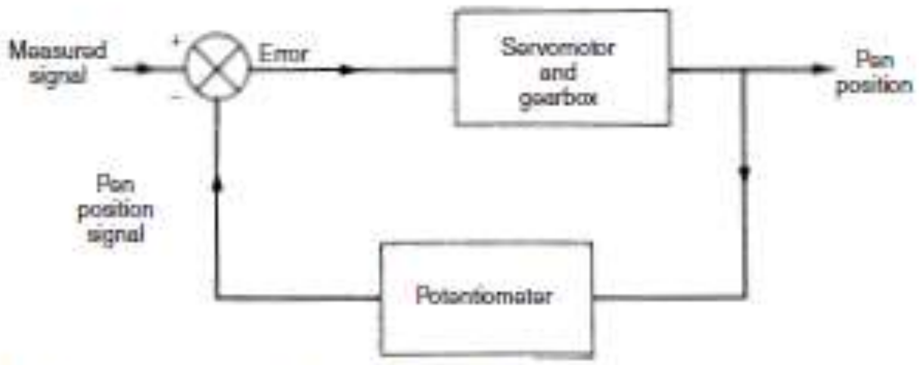


Fig. 11.8 Servo system of potentiometric chart recorder.

potentiometer. Another recent trend is to include a microprocessor controller (this is discussed under hybrid chart recorders).

Circular chart recorders

Before leaving the subject of standard mechanical chart recorders, mention must also be made of circular chart recorders. These consist of a rotating circular paper chart, as shown in Figure 11.9, which typically turns through one full revolution in 24 hours, allowing charts to be removed once per day and stored. The pen in such instruments is often driven pneumatically to record 200–1000 mbar (3–15 psi) pneumatic process signals, although versions with electrically driven pens also exist. This type of chart recorder was one of the earliest recording instruments to be used and, whilst they have now largely been superseded by other types of recorder, new ones continue to be bought for some applications. Apart from single channel versions, models recording up to six channels, with traces in six different colours, can be obtained.

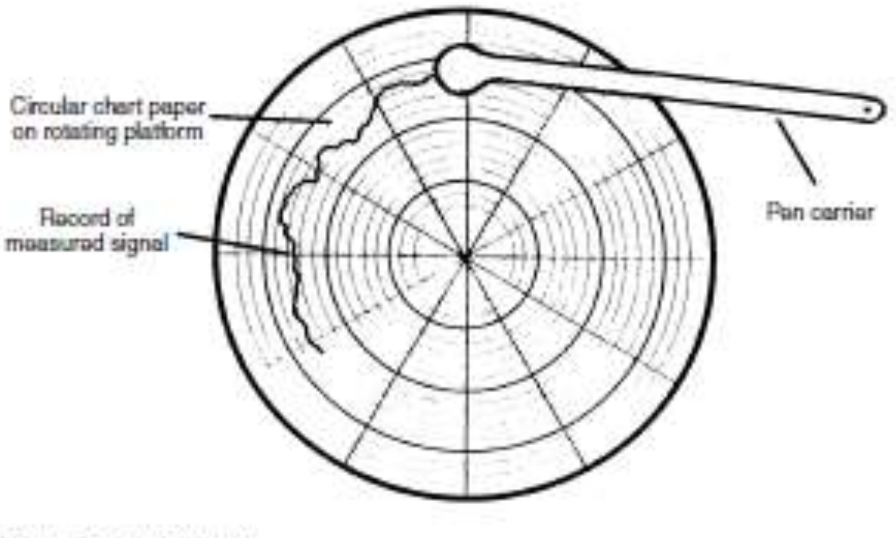


Fig. 11.9 Circular chart recorder.

11.2.2 Ultra-violet recorders

The earlier discussion about galvanometric recorders concluded that restrictions on how far the system moment of inertia and spring constants can be reduced limited the maximum bandwidth to about 100 Hz. Ultra-violet recorders work on very similar principles to standard galvanometric chart recorders, but achieve a very significant reduction in system inertia and spring constants by mounting a narrow mirror rather than a pen system on the moving coil. This mirror reflects a beam of ultra-violet light onto ultra-violet sensitive paper. It is usual to find several of these mirror-galvanometer systems mounted in parallel within one instrument to provide a multi-channel recording capability, as illustrated in Figure 11.10. This arrangement enables signals at frequencies up to 13 kHz to be recorded with a typical inaccuracy of ±2% f.s. Whilst it is possible to obtain satisfactory permanent signal recordings by this method, special precautions are necessary to protect the ultra-violet-sensitive paper from light before use and to spray a fixing lacquer on it after recording. Such instruments must also be handled with extreme care, because the mirror galvanometers and their delicate

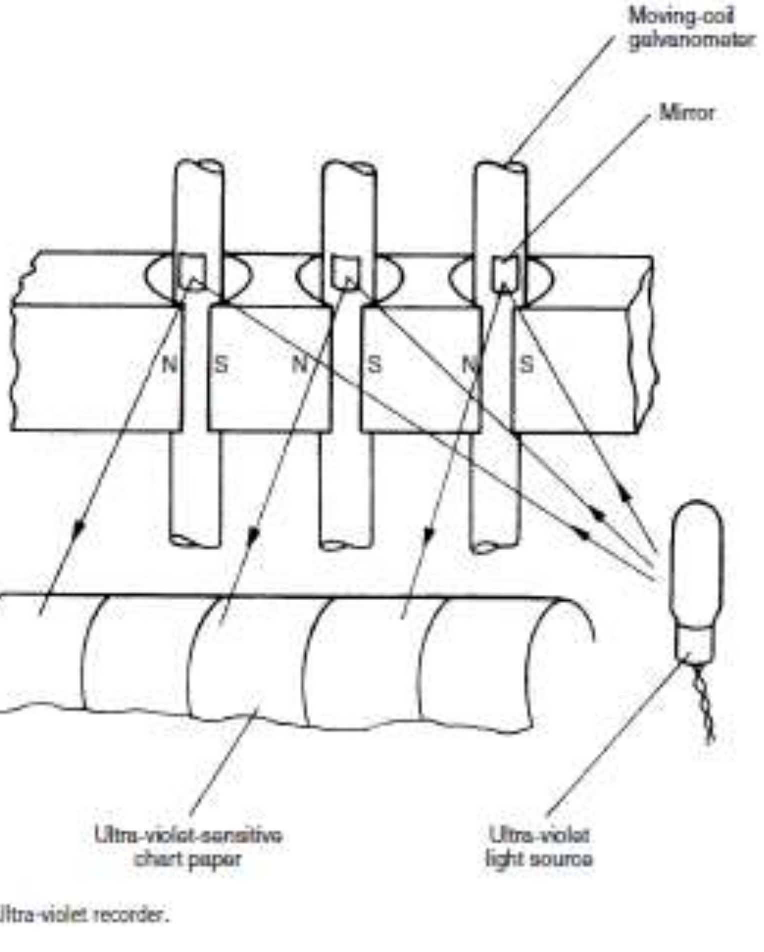


Fig. 11.10 Ultra-violet recorder.

mounting systems are easily damaged by relatively small shocks. In addition, ultra-violet recorders are significantly more expensive than standard chart recorders.

11.2.3 Fibre-optic recorders (recording oscilloscopes)

The *fibre optic recorder* uses a fibre-optic system to direct light onto light-sensitive paper. Fibre-optic recorders are similar to oscilloscopes in construction, insofar as they have an electron gun and focusing system that directs a stream of electrons onto one point on a fluorescent screen, and for this reason they are alternatively known as *recording oscilloscopes*. The screen is usually a long thin one instead of the square type found in an oscilloscope and only one set of deflection plates is provided. The signal to be recorded is applied to the deflection plates and the movement of the focused spot of electrons on the screen is proportional to the signal amplitude. A narrow strip of fibre optics in contact with the fluorescent screen transmits the motion of the spot to photosensitive paper held in close proximity to the other end of the fibre-optic strip. By driving the photosensitive paper at a constant speed past the fibre-optic strip, a time history of the measured signal is obtained. Such recorders are much more expensive than ultra-violet recorders but have an even higher bandwidth up to 1 MHz.

Whilst the construction above is the more common in fibre-optic recorders, a second type also exists that uses a conventional square screen instead of a long thin one. This has a square faceplate attached to the screen housing a square array of fibre-optics. The other side of the fibre-optic system is in contact with chart paper. The effect of this is to provide a hard copy of the typical form of display obtainable on a cathode ray oscilloscope.

11.2.4 Hybrid chart recorders

Hybrid chart recorders represent the latest generation of chart recorder and basically consist of a potentiometric chart recorder with an added microprocessor. The microprocessor provides for selection of range and chart speed, and also allows specification of alarm modes and levels to detect when measured variables go outside acceptable limits. Additional information can also be printed on charts, such as names, times and dates of variables recorded. Microprocessor-based, hybrid versions of circular chart recorders also now exist.

11.2.5 Magnetic tape recorders

Magnetic tape recorders can record analogue signals up to 80 kHz in frequency. As the speed of the tape transport can be switched between several values, signals can be recorded at high speed and replayed at a lower speed. Such time scaling of the recorded information allows a hard copy of the signal behaviour to be obtained from instruments such as ultra-violet and galvanometric recorders whose bandwidth is insufficient to allow direct signal recording. A 200 Hz signal cannot be recorded directly on a chart recorder, but if it is recorded on a magnetic tape recorder running at high speed and then replayed at a speed ten times lower, its frequency will be time scaled to 20 Hz which can be recorded on a chart recorder. Instrumentation tape recorders typically have between four and ten channels, allowing many signals to be recorded simultaneously.

The two basic types of analogue tape recording technique are direct recording and frequency-modulated recording. Direct recording offers the best data bandwidth but the accuracy of signal amplitude recording is quite poor, and this seriously limits the usefulness of this technique in most applications. The frequency-modulated technique offers better amplitude-recording accuracy, with a typical inaccuracy of ±5% at signal frequencies of 80 kHz. In consequence, this technique is very much more common than direct recording.

11.2.6 Digital recorders

For some time, the only technique available for recording signals at frequencies higher than 80 kHz has been to use a digital processor. As the signals to be recorded are usually in analogue form, a prerequisite for this is an analogue-to-digital (A–D) converter board to sample the analogue signals and convert them to digital form. The relevant aspects of computer hardware necessary to achieve this were covered in Chapter 9. Correct choice of the sampling interval is always necessary to ensure that an accurate digital record of the signal is obtained and problems of aliasing etc. are not encountered, as explained in Chapter 5. Some prior analogue signal conditioning may also be required in some circumstances, again as mentioned in Chapter 5.

Until a few years ago, the process of recording data digitally was carried out by standard computer equipment equipped with the necessary analogue interface boards etc., and the process was known as *data-logging*. More recently, purpose-designed digital recorders have become available for this purpose. These are usually multi-channel, and are available from many suppliers. Typically, a 10-bit A–D converter is used, which gives a 0.1% measurement resolution. Alternatively, a 12-bit converter gives 0.025% resolution. Specifications typically quoted for digital recorders are frequency response of 25 kHz, maximum sampling frequency of 200 MHz and data storage up to 4000 data points per channel.

When there is a requirement to view recorded data, for instance to look at the behaviour of parameters in a production process immediately before a fault has occurred in the process, it is usually necessary to use the digital recorder in conjunction with a chart recorder*, applying speed scaling as appropriate to allow for the difference in frequency-response capability between a digital recorder and a chart recorder. However, in these circumstances, it is only necessary to use the chart recorder to display the process parameters for the time period of interest. This saves a large amount of paper compared with the alternative of running the chart recorder continuously if a digital recorder is not used as the main data-capture mechanism.

As an alternative to chart recorders when hard-copy records are required, numerical data can be readily output from digital recorders onto alphanumeric digital printers in the form of dot-matrix, inkjet or laser printing devices. However, when there are trends in data, the graphical display of the time history of a variable provided by a chart recorder shows up the trends much more readily.

11.3 Presentation of data

The two formats available for presenting data on paper are tabular and graphical ones and the relative merits of these are compared below. In some circumstances, it is clearly best to use only one or other of these two alternatives alone. However, in many data collection exercises, part of the measurements and calculations are expressed in tabular form and part graphically, so making best use of the merits of each technique. Very similar arguments apply to the relative merits of graphical and tabular presentations if a computer screen is used for the presentation instead of paper.

11.3.1 Tabular data presentation

A tabular presentation allows data values to be recorded in a precise way that exactly maintains the accuracy to which the data values were measured. In other words, the data values are written down exactly as measured. Besides recording the raw data values as measured, tables often also contain further values calculated from the raw data. An example of a tabular data presentation is given in Table 11.1. This records the results of an experiment to determine the strain induced in a bar of material that is subjected to a range of stresses. Data were obtained by applying a sequence of forces to the end of the bar and using an extensometer to measure the change in length. Values of the stress and strain in the bar are calculated from these measurements and are also included in the table. The final row, which is of crucial importance in any tabular presentation, is the estimate of possible error in each calculated result.

A table of measurements and calculations should conform to several rules as illustrated in Table 11.1:

(i) The table should have a title that explains what data are being presented within the table.

Table 11.1 Sample tabular presentation of data

Table of measured applied forces and extensometer readings and calculations of stress and strain

	Force applied (KN)	Extensometer reading (divisions)	Stress (N/m^2)	Strain
	0	0	0	0
	2	4.0	15.5	19.8×10^{-5}
	4	5.8	31.0	28.6×10^{-5}
	6	7.4	46.5	36.6×10^{-5}
	8	9.0	62.0	44.4×10^{-5}
	10	10.6	77.5	52.4×10^{-5}
	12	12.2	93.0	60.2×10^{-5}
	14	13.7	108.5	67.6×10^{-5}
Possible error in measurements (%)	±0.2	±0.2	±1.5	$\pm 1.0 \times 10^{-5}$

(ii) Each column of figures in the table should refer to the measurements or calculations associated with one quantity only.
(iii) Each column of figures should be headed by a title that identifies the data values contained in the column.
(iv) The units in which quantities in each column are measured should be stated at the top of the column.
(v) All headings and columns should be separated by bold horizontal (and sometimes vertical) lines.
(vi) The errors associated with each data value quoted in the table should be given. The form shown in Table 11.1 is a suitable way to do this when the error level is the same for all data values in a particular column. However, if error levels vary, then it is preferable to write the error boundaries alongside each entry in the table.

11.3.2 Graphical presentation of data

Presentation of data in graphical form involves some compromise in the accuracy to which the data are recorded, as the exact values of measurements are lost. However, graphical presentation has important advantages over tabular presentation.

(i) Graphs provide a pictorial representation of results that is more readily comprehended than a set of tabular results.
(ii) Graphs are particularly useful for expressing the quantitative significance of results and showing whether a linear relationship exists between two variables. Figure 11.12 shows a graph drawn from the stress and strain values given in the Table 11.1. Construction of the graph involves first of all marking the points corresponding to the stress and strain values. The next step is to draw some lines through these data points that best represents the relationship between the two variables. This line will normally be either a straight one or a smooth curve. The data points will not usually lie exactly on this line but instead will lie on either side of it. The magnitude of the excursions of the data points from the line drawn will depend on the magnitude of the random measurement errors associated with the data.
(iii) Graphs can sometimes show up a data point that is clearly outside the straight line or curve that seems to fit the rest of the data points. Such a data point is probably due either to a human mistake in reading an instrument or else to a momentary malfunction in the measuring instrument itself. If the graph shows such a data point where a human mistake or instrument malfunction is suspected, the proper course of action is to repeat that particular measurement and then discard the original data point if the mistake or malfunction is confirmed.

Like tables, the proper representation of data in graphical form has to conform to certain rules:

(i) The graph should have a title or caption that explains what data are being presented in the graph.
(ii) Both axes of the graph should be labelled to express clearly what variable is associated with each axis and to define the units in which the variables are expressed.

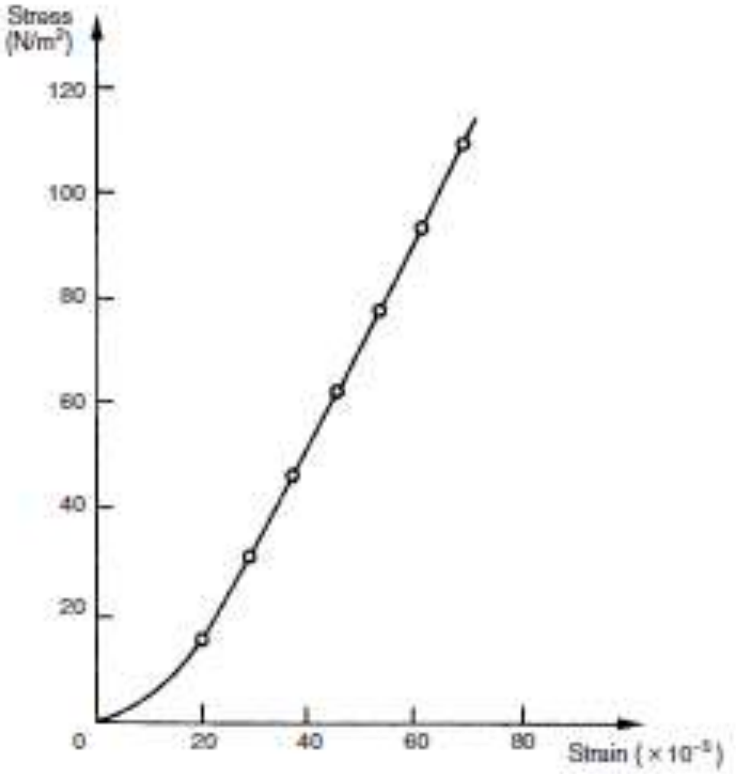


Fig. 11.12 Sample graphical presentation of data: graph of stress against strain.

(iii) The number of points marked along each axis should be kept reasonably small – about five divisions is often a suitable number.

(iv) No attempt should be made to draw the graph outside the boundaries corresponding to the maximum and minimum data values measured, i.e. in Figure 11.12, the graph stops at a point corresponding to the highest measured stress value of 108.5.