Engineering Measurement and System Monitoring

DV9P 34
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Introduction to the Unit

What this Unit is about

This Unit is about the significance of measurement in engineering systems: the parameters which are measured, the instruments used, and how the data is used.

Outcomes

1. Verify by measurement a range of electrical and mechanical quantities.
2. Explain the principle of operation and application of sensors/transducers used in engineering systems.
3. Analyse engineering system responses and corrective actions required to allow an engineering system to operate within its normal range.

Unit structure

This Unit contains the following study sections:

<table>
<thead>
<tr>
<th>Section number</th>
<th>Section title</th>
<th>Approximate study time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1 hour</td>
</tr>
<tr>
<td>2</td>
<td>Electrical and mechanical measurements</td>
<td>14 hours</td>
</tr>
<tr>
<td>3</td>
<td>Principles of sensors and transducers</td>
<td>11 hours</td>
</tr>
<tr>
<td>4</td>
<td>Analysis of system response</td>
<td>14 hours</td>
</tr>
</tbody>
</table>

How to use these learning materials

The recommendation is that you work through the Unit in the order shown above. Feel free to support your study with other materials and resources. For some of the tasks and activities (see below) you will need to have access to suitable devices and test equipment. More details are shown in the section listing other resources required.
Symbols used in this Unit

These learning materials allow you to work on your own with tutor support. As you work through the course, you’ll encounter a series of symbols which indicate that something follows which you’re expected to do. You’ll notice that as you work through the study sections you will be asked to undertake a series of activities and self-assessed questions. An explanation of the symbols used to identify these is given below.

Activity

This symbol indicates an activity, which is normally a task you’ll be asked to carry out which should improve or consolidate your understanding of the subject in general or a particular feature of it.

The suggested responses to activities will follow directly after each activity.

Self-assessed question

This symbol is used to indicate a self-assessed question (SAQ). Most commonly, SAQs are used to check your understanding of the material that has already been covered in the sections.

This type of assessment is self contained; everything is provided within the section to enable you to check your understanding of the materials.

The process is simple:

- You are set SAQs throughout the study section.
- You respond to these, either by writing in the space provided in the assessment itself or in your notebook.
- On completion of the SAQ, you turn to the back of the section to compare the model SAQ answers to your own.
• If you’re not satisfied after checking out your responses, turn to the appropriate part of the study section and go over the topic again.

Remember — the answers to SAQs are contained within the study materials. You are not expected to ‘guess’ at these answers.

Remember that the activities and SAQs contained within your pack are intended to allow you to check your understanding and monitor your own progress throughout the course. It goes without saying that the answers to these should only be checked out after the activity or SAQ has been completed. If you refer to these answers before completing the activities, you can’t expect to get maximum benefit from your course.

Other resources required

Test equipment:

digital multimeter
0–30 V d.c. power supply
function generator
wattmeter

Transducers:

strain gauge
Bourdon tube
thermocouple
tachogenerator

Electronic components:

selection of resistors from the E24 range

Software applications:

spreadsheet
control engineering simulation
Information sources:

- product catalogues
- access to the internet
Assessment information

How you will be assessed

There will be four practical assessment tasks, one for each of the Outcomes. You will be required to carry out each activity and submit appropriate documentation.

When and where you will be assessed

Each task will follow your study of each Outcome. The practicals will be scheduled and organised by your study centre.

What you have to achieve

You must complete each task satisfactorily, including the presentation and analysis of the results you obtain.

Opportunities for reassessment

Normally, you will be given one attempt to pass an assessment with one reassessment opportunity.

Your centre will also have a policy covering ‘exceptional’ circumstances, for example if you have been ill for an extended period of time. Each case will be considered on an individual basis, and is at your centre’s discretion (usually via written application). They will decide whether to allow a third attempt. Please contact your tutor for details regarding how to apply.
Section 1:
Introduction
Introduction to this section

What this section is about
This section discusses the aims of measurement and data analysis in engineering systems.

Outcomes, aims and objectives
The aim is to provide you with relevant information about the concepts of engineering measurement by examining the properties of engineering systems which are measured, how they may be measured, and what happens to the data collected.

Approximate study time
One hour should be allocated to this section.

Other resources required
None

Assessment information for this section

How you will be assessed
There is no assessment for this section.
Engineering measurement and system monitoring

Introduction

This Unit is concerned with measurement and data analysis in engineering systems. Measurement is a key aspect for all branches of engineering. This teaching pack contains notes on measurement techniques, instruments and analytical options.

We can start by asking some basic questions:

- Why do we measure?
- What is an engineering system?
- What do we measure?
- How do we measure?
- How do we use the data we collect?

Why do we measure?

This seems a fairly obvious question to ask. We measure system performance during development and operation. When we view a TV picture, we continually observe, sometimes unconsciously, the picture quality and the volume. Of course, we as viewers do not use any special equipment to make these measurements as they are not required.

What we are doing is checking on the functionality of the TV system at its main output, that is the image on the screen. For other systems there are often equivalent observations, but there may be points in the system where parameter value measurements are required.

For example, at TV transmitter stations the power delivered to the antenna is continually monitored to ensure that it is at its optimum level to broadcast the signal to our TV receivers.

The broadcast engineers could not effectively operate the transmitter system if they had to rely on viewers’ observations, so they measure power output. If there is a problem, they can rectify it.
When we drive, the speed of the car is measured so that we can ensure that we keep within the speed limit, or do not drive too fast for the road or weather conditions. If we approach queuing traffic, we slow down. If we move out of a built-up area, we may be able to speed up. We may notice that acceleration is not as good as it can be, so when our car is in the garage, the mechanic may measure the ignition timing to identify the cause of the sluggish acceleration.

Each of these examples gives some indication of why we measure: we do so to observe system performance, and to collect data about system parameters to add information to permit system analysis.

**What is an engineering system?**

You will study these in more depth in the Unit Principles of Engineering Systems, but it is worthwhile including some definitions and examples here. Many systems are easily identifiable, for example the car briefly discussed above. Our TV is perhaps less recognisable as an engineering system — where is the movement or structural features we might expect? However if we include energy conversion as an aspect of an engineering system then we can correctly define a TV receiver as being appropriate for inclusion.

Broadly speaking then, we can include products which convert energy into different forms, and/or include some form of motion or perform some work.

1.1

List some examples of your own.

**What do we measure?**

What we measure will be system dependent. The TV transmitter discussed above will have its transmitter power measured (in watts). The speed (or more correctly the velocity) of our car will be typically indicated in miles or kilometres per hour; however velocity is more properly measured in metres per second (m/s).
The following list is not comprehensive:

- pressure
- velocity
- current
- voltage
- strain.

1.2

Add to this list.

How do we measure?

For some parameters, we use dedicated instruments which are capable of measuring values directly; for some others we measure secondary effects. An example of this is temperature, which can be established by measuring the voltage produced by a thermocouple. For both of these techniques we connect in some way to the system, taking care that taking this measurement does not affect the system performance and so affect the measurement itself. Consider measuring the temperature in a furnace. If we open the door and insert a suitable device, the temperature at the time of measurement may be reduced because the door is open.

How do we use the data we collect?

This will vary between systems and applications. In some cases, for example automated speed control, we utilise the data collected from measurements to help control a system or process. In others, such as the supply of domestic energy, we record the data for later analysis.

1.3

Add your own suggestions.
Summary of this section

In this section you have been introduced to the principles of measurement in engineering systems.
Answers to SAQs

1.1 List some examples of your own.

You might have included: DVD recorders, MP3 players, washing machines.

1.2 Add to this list.

Other parameters measured include temperature, distance and acceleration.

1.3 Add your own suggestions.

Data can be used to help identify system trends or problems, to permit costs to be allocated or charges to be made.
Section 2:
Electrical and mechanical measurements
Introduction to this section

What this section is about

This section of the pack gives more detail about the measurement of electrical and mechanical properties of engineering systems. It discusses the issues associated with accuracy and reliability of measurements.

Outcomes, aims and objectives

After studying this section you should be able to verify by measurement a range of common electrical and mechanical properties associated with engineering systems.

Approximate study time

Fourteen hours should be allocated to the study of this section.

Other resources required

- Digital multimeter
- D.C. power supply
- Function generator
- Wattmeter
- Appropriate components and devices
Assessment information for this section

How you will be assessed
You will be assessed by completing a practical task involving the measurement and evaluation of a range of electrical and mechanical properties.

When and where you will be assessed
You will be assessed at the end of the study period at your study centre.

What you have to achieve
You have to make the measurements satisfactorily and complete all required documentation.

Opportunities for reassessment
If necessary, you will be reassessed on a different set of properties.
Outcome 1

Verify by measurement a range of electrical and mechanical quantities.

Introduction to measurement

Accuracy in measurement

Unfortunately, no instrument is ideal and consequently any measurement we make will be inaccurate. In order to have confidence in the data we collect, it is vital that we are able to classify and quantify errors in measurement. We must take into account all parts of the measurement process, including both instruments and any sensors or transducers which are used.

The statistical analysis of errors is outwith the scope of this Unit.

Range of measurement

Logic demands that there will be upper and lower limits to an instrument’s capability, for example the minimum and maximum pressure. Outside this range any measurements taken will be invalid.

Resolution

This is a figure which relates to the smallest change in parameter an instrument can measure. It is often expressed as a percentage of the instrument’s range.

Sensitivity

This ratio tells us how the instrument output changes as the input parameter value changes.

Drift

This is a change over time in some feature, for example sensitivity, of the instrument. Basically the figure indicates how close the instrument remains to its capability.
Environmental effects
As with all aspects of technology, care must be taken to operate instruments within their specified temperature, humidity and pressure capability. If any environmental aspect varies outside this range then the data should be classed as invalid.

Hysteresis
Hysteresis is a feature of many facets of engineering and science. For instruments, it can be thought of as a variation in the measured value due to the direction in which the measurand is changing, that is increasing or decreasing. Instruments may typically give a slightly different indication of a value according to the direction of change. Consequently hysteresis is a source of error. Figure 2.1 shows an example — ideally the hysteresis loop should be as thin as possible.

![Hysteresis Diagram](image)

Figure 2.1 Hysteresis

State three possible sources of error in measurements.

Electrical instruments and measurements
Measurements of electrical quantities are common and generally straightforward, making use of instruments which are accurate and reliable.
Parameters commonly measured are:

- voltage
- current
- power.

Voltmeters and ammeters are designed to measure voltage and current respectively, although multimeters are commonly used as they have the capability of measuring either quantity. Wattmeters are used for power measurement.

Measurement of resistance can also be used to establish the integrity of electrical circuits. Energy measurements provide information to electricity suppliers to enable them to bill customers and can also be used to help in minimising energy wastage.

In this Unit we do not need to study in detail the actual technology of instruments but it is worthwhile giving an outline of how they function and their limitations.

**Voltmeters**

When we make voltage measurements, the meter does not become part of the circuit but there will still be an inaccuracy in the reading. The cause of this error is the parallel current path introduced by the meter being placed across the measurement points. Consider the example of Figure 2.2.

![Figure 2.2 Meter loading](image)

In this circuit $V_1 = V_2 = 5$ V as the resistors have identical values. Now, if a moving coil meter is connected across $R_2$, its range resistance, coil and coil
resistance combination will be in parallel with $R_2$. If the coil combination has a value of 50 kΩ (not untypical), then the EFFECTIVE resistance between B and C will be 10 kΩ in parallel with 50 kΩ, giving a value of 8.33 kΩ.

Consequently, the voltage indicated will NOT be 5 V, the true value, but

$$\frac{8.33 \times 10}{10 + 8.33} = 4.54 \text{ V}$$

This is an error of 9%.

The error will vary depending on the values in the circuit being tested. A way to reduce the error is to use a meter that has large resistance multipliers. The way to establish this is to refer to the $\Omega/V$ figure quoted for the instrument.

For the same circuit as above, a digital voltmeter with an input resistance of 10 MΩ will produce an effective resistance of 9.99 kΩ.

The indicated voltage will now be 4.99 V, an error of 0.2%, a far better degree of accuracy.

The $\Omega/V$ figure indicates the sensitivity of the meter; the bigger this figure is the better. Moving coil meters may have different figures depending on the range. A figure of 20 kΩ/V on the 10 V range gives a connected resistance of 200 kΩ. The sensitivity of alternating ranges is often worse than for direct ranges due to the internal components used for conversion of alternating to direct voltage.

2.2

Explain why digital meters are more accurate than analogue devices.

2.1

Investigate parameters of voltmeters.

There can be no definitive list of values as there is such a wide variety of instruments available, but the following should be considered:

- technology: moving coil; digital
• available voltage ranges
• mode: direct (d.c.) and alternating (a.c.)
• input resistance: the larger the better, 10 MΩ considered acceptable
• frequency range: 20 Hz–20 kHz.

Ammeters

When you connect an ammeter to measure a current in a circuit, the instrument itself becomes part of the circuit and therefore the circuit differs from the non-measured condition. Ohm’s law tells us therefore that there will be a change in current flowing due to this extra resistance. By definition, the meter reading must have an error. For greater accuracy, we should select an ammeter which has a low voltage drop.

A useful tip for current measurement, if you find it awkward to insert the meter into a circuit, is to:

• identify an appropriate resistor.
• measure the voltage across it.
• apply Ohm’s Law to find the current at that point.

Investigate parameters of ammeters.

As with voltmeters, there can be no definitive list of values as there is such a wide variety of instruments available, but the following should be considered:

• technology: moving coil; digital
• available current ranges
• mode: direct (d.c.) and alternating (a.c.)
• voltage drop when in circuit, a typical value being <300 mV
• frequency range: 20 Hz–20 kHz.

Wattmeters

Wattmeters are used to measure electrical power. They function by measuring both the current and voltage in a circuit as:
Power = voltage in volts × current in amps

\[ P = VI \text{ watts} \]

Wattmeters are available in both moving-coil and digital format. Care must be taken with either to ensure that neither the current nor voltage ratings are exceeded.

 så 2.3

Explain why measuring current is more difficult than measuring voltage.

A 2.3

Investigate parameters of wattmeters.

As with voltmeters and ammeters, there can be no definitive list of values as there is such a wide variety of instruments available. Remembering that wattmeters measure both current and voltage, we must ensure that the ratings for each of these is not exceeded.

The following should also be considered:

- technology: dynamometer; digital
- available power ranges
- mode: direct (d.c.) and alternating (a.c.)
- power factor range: low or high
- frequency range: 20 Hz–20 kHz.

Multimeters

Probably the most common measurement you will make will be a direct voltage using a multimeter. A multimeter is an instrument that can be readily set up to perform each of the following measurements:

- alternating voltage
- alternating current
- direct voltage
- direct current
• resistance.

Multimeters are available in both moving-coil and digital form. Nowadays the digital form is more common; this is usually referred to as a DMM. You must be able to use both types. A number of instrument manufacturers produce a range of models; all are basically the same but with some variations in their capabilities. A typical DMM is shown in Figure 2.3.

![Typical DMM front panel](image)

Figure 2.3 Typical DMM front panel

In many systems meters are permanently connected to give an indication of the state of the system. In these cases the meter scale is likely to be calibrated in the units of interest, for example velocity or pressure.

**A 2.4**

Investigate specification of analogue and digital multimeters.

**A 2.5**

Calibrate a voltmeter.

**A 2.6**

Measure the current and voltage in the following circuit for both d.c. and a.c. sources.
Refer to your tutor for evaluation of your responses to these activities.

**Mechanical instruments and measurements**

Carrying out some types of mechanical measurement can sometimes be awkward, requiring physical modifications to the part of the system from which data is required. An example of this is measuring pressure in a pneumatic system. Typically, pressure is measured by changing its effects into a displacement or force. This utilises some of the energy from the fluid and will consequently modify the pressure being measured.

Many other mechanical measurements also require conversion of the measurand into some other form, generally a voltage. The versatility of data in electrical form means that it is easy to transmit and process in engineering systems. Other transducers convert the physical influences into pneumatic or hydraulic forms.

**2.4**

Explain why mechanical measurands are often converted into voltages.

**Displacement**

The mechanical devices used aim to magnify small changes in the position of some object so that the displacement may easily be indicated. Some form of gearing or other linkage is typically used. The results are displayed locally to

![Diagram of a simple circuit](image-url)
the object. Problems exist due to hysteresis, or backlash, in gears, and the inertia of the mechanism. If the displacement data is required to be transmitted over some distance then an electrical conversion is required.

**Force**

Force can be measured using coil springs, beams and cantilevers made from elastic materials which will deflect in proportion to any applied force. As with displacement measurement, the deflection can be displayed locally in a relatively easy manner.

The piezoelectric effect produces a proportional e.m.f. if a force is applied to a crystal cut in an appropriate fashion (see Figure 2.4).

![Piezo crystal diagram](image)

**Figure 2.4 Outline of piezo crystal**

Piezo crystals need to be carefully machined and synthetic crystals can have high temperature limitations.

**Pressure**

Pressure gauges are common and widely used. You may be familiar with a barometer, which is used to measure atmospheric pressure. Domestic versions often have scales which indicate possible changes in weather.
For engineering use, the fluid whose pressure is to be measured is generally present in a thin metal enclosure either in tube or bellows form. Changes in fluid pressure will cause the enclosure to change shape or size. Indicators can be directly coupled to the enclosure and so show the pressure value.

Pressure can also be measured using electrical instruments based on changes in inductance or capacitance.

**Velocity**

Velocity measurement in a single direction is a parameter that many of us are familiar with, although we typically refer to it as speed. The speedometer in a car is measuring the velocity and displaying the result directly in m.p.h. or k.p.h.

How accurate do we need this to be? For road safety reasons we have a moral and legal obligation to ensure that we drive according to speed limits and road conditions. We need therefore to rely on the ‘speedo’ being accurate and reliable.

Other common velocity measurements are the speed of ships and aircraft. As ships are relatively slow moving compared to aircraft, we may assume that the need for accuracy may not be so great.

The velocity of a car is generally achieved by a cable linkage from the gear box. Rotational velocity here is converted into an electrical signal of proportional value and scaled appropriately by the speedometer.

Non-contact methods of velocity measurement are also common, examples being found in safety cameras and the equipment police use to deter speeding motorists.

Within engineering systems, electromagnetic effects and optical methods can be utilised to measure rotational velocity.

Airspeed can be established by the link between the air flowing and the energy this contains being converted into a pressure differential. Bernoulli’s equation is applied to establish the velocity:
\[ v = \sqrt{\frac{2(p_1 - p_2)}{\rho}} \]

\( p_1 \) and \( p_2 \) are the reference and applied pressures

\( \rho \) is the fluid density

\( v \) is the velocity.

Figure 2.5 shows a schematic of a Pitot–static tube used for establishing airspeed. The difference between the stagnation pressure and static pressure establishes the airspeed displayed on the aircraft's instrument.

**Flow**

Measurement of fluid flow is a key parameter in many engineering systems and processes. Domestically, our gas and water supplies depend heavily on such measurements to help ensure efficient treatment and transmission.

**2.5**

State two disadvantages of making displacement measurements by purely mechanical means.
Summary of this section

In this section you have studied the techniques used to measure some of the common electrical and mechanical properties of engineering systems and the factors to be taken into consideration when evaluating data. You have had the opportunity to make a number of these measurements.
Answers to SAQs

2.1
State three possible sources of error in measurements.
The following can cause errors: hysteresis, excess humidity, poor sensitivity.

2.2
Explain why digital meters are more accurate than analogue devices.
Commonly digital meters have a higher input resistance on their voltage ranges and this has less of a loading effect on the circuit being measured. Their displays are also not subject to the possibility of a different interpretation due to being viewed at an angle.

2.3
Explain why measuring current is more difficult than measuring voltage.
Voltages can be measured without making changes to the circuit. In some circumstances current can only be measured by inserting an ammeter into the circuit, although current clamps can be used for certain measurements.

2.4
Explain why mechanical measurands are often converted into voltages.
A signal in the form of a voltage is easy to manipulate or display.

2.5
State two disadvantages of making displacement measurements by purely mechanical means.
Backlash and inertia can cause inaccuracies in such measurements.
Section 3:
Principles of sensors and transducers
Introduction to this section

What this section is about

This section discusses the types of transducers and sensors used as part of the data collection process in engineering systems.

Outcomes, aims and objectives

After studying this section you should be able to explain the principle of operation of these sensors and transducers and their application in engineering systems.

Approximate study time

You should spend approximately 11 hours studying this section.

Other resources required

A selection of sensors and transducers and appropriate test equipment
Assessment information for this section

How you will be assessed

You will be assessed by completing a practical task involving the calibration of one electrical and one mechanical transducer.

When and where you will be assessed

You will be assessed at your study centre when you have completed studying this section.

What you have to achieve

You have to calibrate the transducers satisfactorily and complete all required documentation.

Opportunities for reassessment

If necessary, you will be required to calibrate a different selection of transducers.
Outcome 2

Explain the principle of operation and application of sensors/transducers used in engineering systems.

Introduction

At the heart of measurement of common physical parameters such as force and pressure are sensors and transducers. These devices respond to the parameters by producing an output which is related to the measurand. Examples of these are strain gauges and Bourdon tubes. Details of some of these devices are given in Table 3.1.

<table>
<thead>
<tr>
<th>Sensor/transducer</th>
<th>Measurand</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain gauge</td>
<td>Strain</td>
<td>Change in resistance</td>
</tr>
<tr>
<td>Bourdon tube</td>
<td>Pressure</td>
<td>Scale display</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>Temperature</td>
<td>Voltage</td>
</tr>
<tr>
<td>Tachogenerator</td>
<td>Velocity</td>
<td>Voltage</td>
</tr>
<tr>
<td>Thermistor</td>
<td>Temperature</td>
<td>Resistance change</td>
</tr>
<tr>
<td>Pitot tube</td>
<td>Flow</td>
<td>Pressure</td>
</tr>
<tr>
<td>Load cell</td>
<td>Force</td>
<td>Voltage</td>
</tr>
<tr>
<td>Manometer</td>
<td>Pressure</td>
<td>Displacement</td>
</tr>
</tbody>
</table>

Table 3.1 Sensors, measurands and outputs

The above table shows some examples of the types of sensor used in engineering systems. The final column shows what form the output takes. You will notice that many are electrical in nature and in fact this conversion into electrical energy is common in both the measurement of electrical and mechanical properties.
Selection of sensors and transducers

Some of the factors affecting the accuracy and reliability of data were discussed in the previous section. Here we will look at other issues to be considered when selecting or specifying devices.

Range

The limits of measurement are indicated by the range of the device. This will be specified in terms of the indicated parameter, for example 10–40 p.s.i.

Size

It seems fairly obvious that the size of a sensor will be an influencing factor, but it is worth stating that any device which cannot be mounted, inserted, or otherwise fixed to the system will be unsuitable. Fixing methods will vary, for example strain gauges are often secured with adhesive, whereas a tachogenerator must be coupled into a rotating shaft.

Signal conditioning

Most often associated with transducers which produce an electrical signal, signal conditioning requirements may be as straightforward as voltage amplification. For some systems mathematical tasks such as integration or differentiation may be needed. This signal conditioning may be carried out by electronic circuits or by computer programs.

Response time

For many engineering systems parameter changes take place over a distinct period of time. Where measurements are being used to help control the system, it is vital that these are made in a shorter timescale. A familiar example would be a heating system in which a mass of water has its temperature raised by an electric heater. As the input energy increases the temperature, the sensor must be able to identify the target temperature and deliver this information in time for the heater to turn off before an excess of energy is delivered, otherwise there is a risk of over temperature.
Linearity

The relationship between output and input is a key parameter for sensors and transducers. Ideally there should be a straight line relationship so that equivalent changes in input produce the same order of change in output no matter where within the sensor's range these occur.

Cost

It is unrealistic to expect that transducer or sensor selection will not be subject to the cost constraints of other parts of the systems. When taking cost into account, system designers and operators should be aware not only of the initial price but also cost of ownership factors such as service costs, availability of spares, and reliability.

Calibration

We calibrate an instrument or sensor to establish the accuracy of the measurements it produces. Ideal devices will give an exact value for the measurand in all circumstances. Practical instruments and sensors will not, of course, be able to do this, however it is possible for us to take into account inaccuracies due to ageing, etc.

This process often generates a calibration table or calibration graph. An example of each is shown below. These allow us to identify the worst case accuracy of the device. The largest error (0.4%) is shown in the third measurement column at the value 30 and it is this which will be used to classify the accuracy of the device.
<table>
<thead>
<tr>
<th>Value</th>
<th>1st measurement</th>
<th>2nd measurement</th>
<th>3rd measurement</th>
<th>Average</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>−0.06</td>
<td>−0.05</td>
<td>−0.04</td>
<td>−0.05</td>
<td>−0.05</td>
</tr>
<tr>
<td>10.00</td>
<td>9.80</td>
<td>9.81</td>
<td>9.83</td>
<td>9.81</td>
<td>−0.19</td>
</tr>
<tr>
<td>20.00</td>
<td>19.70</td>
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<td>30.00</td>
<td>29.70</td>
<td>29.68</td>
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<td>39.72</td>
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</tr>
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<td>50.00</td>
<td>49.80</td>
<td>49.82</td>
<td>49.83</td>
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</tr>
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<td>60.02</td>
<td>60.15</td>
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<td>0.06</td>
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<td>70.15</td>
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<td>70.20</td>
<td>70.17</td>
<td>0.17</td>
</tr>
<tr>
<td>80.00</td>
<td>80.20</td>
<td>80.22</td>
<td>80.12</td>
<td>80.18</td>
<td>0.18</td>
</tr>
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<td>90.00</td>
<td>90.20</td>
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<td>90.15</td>
<td>90.17</td>
<td>0.17</td>
</tr>
<tr>
<td>100.00</td>
<td>100.10</td>
<td>100.12</td>
<td>100.11</td>
<td>100.11</td>
<td>0.11</td>
</tr>
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<td>90.00</td>
<td>90.25</td>
<td>90.20</td>
<td>90.22</td>
<td>90.22</td>
<td>0.22</td>
</tr>
<tr>
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<td>80.20</td>
<td>80.21</td>
<td>80.21</td>
<td>80.21</td>
<td>0.21</td>
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<tr>
<td>70.00</td>
<td>70.23</td>
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<td>0.12</td>
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<td>49.89</td>
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<td>−0.11</td>
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<td>40.00</td>
<td>39.80</td>
<td>39.82</td>
<td>39.84</td>
<td>39.82</td>
<td>−0.18</td>
</tr>
<tr>
<td>30.00</td>
<td>29.75</td>
<td>29.78</td>
<td>29.76</td>
<td>29.76</td>
<td>−0.24</td>
</tr>
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<td>20.00</td>
<td>19.80</td>
<td>19.82</td>
<td>19.81</td>
<td>19.81</td>
<td>−0.19</td>
</tr>
<tr>
<td>10.00</td>
<td>9.85</td>
<td>9.87</td>
<td>9.87</td>
<td>9.86</td>
<td>−0.14</td>
</tr>
<tr>
<td>0.00</td>
<td>−0.05</td>
<td>−0.04</td>
<td>−0.04</td>
<td>−0.04</td>
<td>−0.04</td>
</tr>
</tbody>
</table>

Table 3.2 Calibration table (data shown in percentages)
Explain the significance of calibration in measuring instruments.

**Electrical sensors and transducers**

Electrical transducers may have mechanical, thermal, chemical, mass, or electromagnetic as their measurand. These may change resistive, capacitive, or inductive properties of the transducer, or in fact may directly produce a voltage.

**LVDT**

Linear variable differential transformers are used to measure movement or displacement. These operate by producing a.c. voltages from a pair of secondary windings as a sensing rod fixed to the magnetic core moves linearly between the windings. The primary winding of the transformer is supplied from a stable source. As the core moves, the difference in the voltages produced by the two secondary windings is proportional to its displacement.
Strain gauge

The strain gauge can be considered as an electromechanical transducer used for measuring strain in a structure. The principle of operation of bonded gauges is as follows. A thin piece of conductive material is formed into a pattern so as to create a resistance. This is secured, typically through adhesive bonding, onto the surface of the structure such as a bridge support. Forces applied to this structure will cause the gauge to change length and diameter, and hence its resistance. This change in resistance is used to indicate the deformation of the structure. Strain gauges will typically form part of a bridge circuit designed to produce a voltage output which is directly related to this change in resistance.
Thermocouples

The operation of thermocouples relies on the electric current which flows in the junction of two dissimilar metals when a pair of their junctions are at different temperatures, one of these being used as a reference. This is due to the Seebeck effect. The resulting electromotive force (e.m.f.) can be readily calibrated to measure temperature at the location of the measurement junction.

Thermocouples are available in different materials and classifications to suit the wide range of temperatures which we may require to measure. The following table and graph give information about some of the types available and their temperature/e.m.f. relationship.
Table 3.3 Some types of thermocouple

<table>
<thead>
<tr>
<th>Type</th>
<th>Metal/alloy 1</th>
<th>Metal/alloy 2</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>Iron</td>
<td>Copper–nickel</td>
<td>Cheap and common</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High e.m.f. output</td>
</tr>
<tr>
<td>K</td>
<td>Nickel–chromium</td>
<td>Nickel–aluminium</td>
<td>Wider temperature range</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>than type J</td>
</tr>
<tr>
<td>N</td>
<td>Nickel–chromium–silicon</td>
<td>Nickel–silicon</td>
<td>Reliable at high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>temperatures</td>
</tr>
<tr>
<td>R</td>
<td>Platinum–rhodium</td>
<td>Platinum</td>
<td>Relatively expensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High temperature applications</td>
</tr>
</tbody>
</table>

The graph below gives an indication of the ranges of e.m.f. and temperature over which these devices operate. Note the linearity of the responses over most of the range.

The measuring junction will typically have little mass in order for it to respond quickly to changes in temperature. Additionally, any connecting cable used between the thermocouple and indication equipment must not introduce any errors. These thermocouple compensating cables are colour coded to match the correct device.
3.2
Find some more examples of thermocouple types.

3.3
Explain why it is important that the reference junction is kept at a controlled temperature.

Thermistors
These transducers are constructed with materials which produce a large change in resistance for a relatively small change in temperature. Most have a negative temperature coefficient (ntc); this means that the resistance will fall as temperature increases.

Resistance changes exponentially:

\[ R = Ae^{\frac{b}{T}} \]

where \( A \) and \( B \) are constants for the material from which the thermistor is made.

The change in resistance is normally converted into a voltage. The fact that we must pass current through the thermistor to do this means that we have introduced a source of error as the \( I^2R \) power will raise the temperature of the thermistor and so alter its resistance.

Bridge circuits
Transducers and sensors which produce a change in resistance are typically used in a bridge circuit. This consists of an arrangement of resistances supplied from a stable voltage source (see Figure 3.6). For the bridge to be balanced, the ratio of resistances in each branch must be balanced. Any change in resistance will produce a potential difference between the two junctions. The values of resistance are designed so that the small changes in resistance from the sensor will result in an improvement in resolution of the measurement.
In the above diagram, resistance $R_2$ represents the transducer, for example a strain gauge bonded to some part of a structure subject to a stress which deforms the strain gauge. $R_4$ will normally be located physically close to $R_2$ so as to compensate for any temperature variations. $R_4$ will not be subject to stress.

As $R_1$ varies, so the galvanometer G will indicate a current between X and Y. $R_3$ is adjusted to balance the bridge. It is straightforward to establish $R_1$ using:

$$R_2 = \frac{R_1 R_4}{R_3}$$

**Hall effect sensors**

These semiconductor-based devices work on the principle that a current flowing in a magnetic field will generate a voltage. In this type of sensor a constant current flows in the device and the voltage developed is proportional to the external magnetic field.

Hall effect sensors are commonly used as proximity detectors, sensing the presence of a piece of magnetic material as it changes the magnetic field strength. They have the advantage of being immune to the contact bounce of mechanical switches and can be sealed to allow use in contaminated locations.

**Mechanical sensors and transducers**

The range of mechanical parameters is wide, as indicated above. There have been a great number of developments within this area and the range of devices is also wide. If we refer back to the physical features which we require...
to measure, we see that in many cases the method of measurement and devices selected will be influenced by factors such as environment and time as well as accuracy and repeatability.

- Spring
- Diaphragm
- Bourdon gauge
- Venturi tube
- Mass flowmeters
Summary of this section

In this section you have studied the principles of operation and applications of sensors/transducers commonly used in engineering systems. You have had the opportunity to calibrate some of the devices.
Answers to SAQs

3.1
Explain the significance of calibration in measuring instruments.
Calibration of an instrument or sensor helps ensure accuracy in the measurements made by relating the data obtained to the capability of the device.

3.2
Find some more examples of thermocouple types.
Type T: copper–constantin with a temperature range of 0–370 °C

3.3
Explain why it is important that the reference junction is kept at a controlled temperature.
If the temperature at this junction varied, the resulting differential voltage would not be accurate.
Section 4:

Analysis of system response
Introduction to this section

What this section is about

In this section the emphasis is on how engineering systems respond to changes, how these changes are measured, and how the system’s response is evaluated.

Outcomes, aims and objectives

After studying this section you should be able to identify how a system response can be evaluated and what corrective actions are required to return the system to normal operation through the use of feedback. You will also be able to compare an electrical and a mechanical system.

Approximate study time

You should allocate 14 hours to this section.

Other resources required

- An electrical system consisting of resistance, capacitance and inductance, and a suitable power supply
- A mechanical system consisting of a spring, a mass, and a damper
- Alternatively, software capable of simulating the above systems
Assessment information for this section

How you will be assessed
You will be assessed by completing a practical task involving the simulation of one electrical and one mechanical system.

When and where you will be assessed
You will be assessed at your study centre when you have completed studying this section.

What you have to achieve
You have to evaluate each system satisfactorily and complete all required documentation.

Opportunities for reassessment
If necessary, you will be required to evaluate a different set of systems.
Outcome 3

Analyse engineering system responses and corrective actions required to allow an engineering system to operate within its normal range.

Control principles

Automatic control of systems relies on the accuracy of measurement of the variables which indicate the condition of the system. It uses this information to help keep the process or system operating within the specified limits.

List some examples of other control systems.

Feedback

Accurate information about the condition of its output is crucial for control of a system. In a closed loop system the data is fed back and compared with the set point or target of the system.

Error is the term used for the result of the comparison and it is this error which is used as the input to the control element.

The diagram below (Figure 4.1) shows the general arrangement for control systems.
Control solution

This is the term used to describe mathematically the actions of the control element. It is an equation which shows how the error is processed so as to bring the system’s output to match the set point. Transfer function is a more general term used to show the actions of the parts of the system.

The corrective action of the element will depend on the system, for example on a ship or aircraft it may be a change in direction to take into account the effects of tidal or wind conditions. If the temperature is too low in a building then the heating system will be turned on until the temperature is correct.

Add some more examples.

From your study of associated Units, you will recall that although many different engineering systems exist, there are sufficient common features in many types to allow their analysis to be easily adapted to match shared characteristics and so modify standard control solutions.
The graph in Figure 4.2 is typical of the response of many systems to a step change in the input or set point, or some disturbance such as a fall in the available power.

The general mathematics involved for systems is identifiable for both mechanical and electrical systems as both commonly have energy storage elements in them, for example springs and capacitors.

Analysis of such systems can be performed by physical means or by utilising suitable software to perform simulations. It will not prove possible to investigate systems which are too complex, but we can compare the actions of simple mechanical and electrical systems. Carried out carefully, we should be able to identify the similarities in response of the two types.
When the switch closes, current will flow from the source and we can write a differential equation which describes the system action as follows:

\[ L \frac{d^2i}{dt^2} + R \frac{di}{dt} + \frac{i}{C} = \frac{dv}{dt} \]

Figure 4.4 Spring–mass–damper system

The spring–mass–damper system shown above has the following differential equation:

\[ M \frac{d^2x}{dt^2} + D \frac{dx}{dt} + \frac{x}{S} = \frac{dF}{dt} \]

where  
- \( M \) is the mass (kg)  
- \( D \) is the damper resistance (Ns/m)  
- \( S \) is the spring constant (m/N)  
- \( x \) is the displacement (m)  
- \( F \) is the applied force (N)

Inspection of the two differential equations shows that their format is identical.

**4.3**

Which element in the mechanical system performs a similar function to the capacitor in the RLC circuit?
4.4 Which element in the electrical system performs a similar function to the damper in the spring–mass–damper system?

4.1 Build and test (or simulate using appropriate software) an RLC circuit.

4.2 Build and test (or simulate using appropriate software) a spring–mass–damper circuit.

4.3 Compare the two sets of results.

4.1–4.3 Refer to your tutor for evaluation of your responses to these activities.
Summary of this section

In this section you have studied how electrical and mechanical systems respond to changes, and how the measurements made can be used to evaluate the system response and be used to provide effective corrective action to bring the system back into its normal operational range.
Answers to SAQs

4.1 List some examples of other control systems.
Speed control, position control, temperature control

4.2 Add some more examples.
Other corrective actions include a fan being operated to help keep a PC cool, or the volume of petrol being adjusted in a fuel injection unit.

4.3 Which element in the mechanical system performs a similar function to the capacitor in the RLC circuit?
Inspection of the two differential equations shows that the spring is the equivalent of the capacitor.

4.4 Which element in the electrical system performs a similar function to the damper in the spring–mass–damper system?
Inspection of the two differential equations shows that the resistance is the equivalent of the damper.
## Conversion factors of common measurands

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Conversion factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area (A)</strong></td>
<td></td>
</tr>
<tr>
<td>m²</td>
<td>foot²</td>
</tr>
<tr>
<td>foot²</td>
<td>m²</td>
</tr>
<tr>
<td><strong>Density (ρ)</strong></td>
<td></td>
</tr>
<tr>
<td>kg/m³</td>
<td>lbm/foot³</td>
</tr>
<tr>
<td>lbm/foot³</td>
<td>kg/m³</td>
</tr>
<tr>
<td><strong>Energy (work)</strong></td>
<td></td>
</tr>
<tr>
<td>joule</td>
<td>foot lbf</td>
</tr>
<tr>
<td>foot lbf</td>
<td>joule</td>
</tr>
<tr>
<td><strong>Flow rate (Q)</strong></td>
<td></td>
</tr>
<tr>
<td>m³/s</td>
<td>(US)gallon/minute</td>
</tr>
<tr>
<td>(US)gallon/minute</td>
<td>m³/s</td>
</tr>
<tr>
<td><strong>Force (F)</strong></td>
<td></td>
</tr>
<tr>
<td>newton</td>
<td>lbf</td>
</tr>
<tr>
<td>lbf</td>
<td>newton</td>
</tr>
<tr>
<td><strong>Length (L)</strong></td>
<td></td>
</tr>
<tr>
<td>metre</td>
<td>foot</td>
</tr>
<tr>
<td>foot</td>
<td>metre</td>
</tr>
<tr>
<td><strong>Mass (M)</strong></td>
<td></td>
</tr>
<tr>
<td>kg</td>
<td>lbm</td>
</tr>
<tr>
<td>lbm</td>
<td>kg</td>
</tr>
<tr>
<td><strong>Moment of inertia (I)</strong></td>
<td></td>
</tr>
<tr>
<td>kgm²</td>
<td>lbm foot²</td>
</tr>
<tr>
<td>lbm foot²</td>
<td>kgm²</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td></td>
</tr>
<tr>
<td>watt</td>
<td>horsepower</td>
</tr>
<tr>
<td>Measurand</td>
<td>Conversion Factor</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Horsepower (hp)</td>
<td>1.34 × 10^{-3}</td>
</tr>
<tr>
<td>Pressure (P)</td>
<td>pascal → lbm/foot^2: 47.88</td>
</tr>
<tr>
<td></td>
<td>lbm/foot^2 → pascal: 6.8948 × 10^3</td>
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<tr>
<td>Thermal capacity (Hv)</td>
<td>joule/kg → Btu/lbm °F: 4187</td>
</tr>
<tr>
<td></td>
<td>Btu/lbm °F → joule/kg: 2.388 × 10^{-4}</td>
</tr>
<tr>
<td>Torque</td>
<td>newton metre → lbf foot: 1.356</td>
</tr>
<tr>
<td></td>
<td>lbf foot → newton metre: 0.7375</td>
</tr>
<tr>
<td>Velocity (v)</td>
<td>m.p.h. → k.p.h.: 1.609344</td>
</tr>
<tr>
<td></td>
<td>k.p.h. → m.p.h.: 0.6214</td>
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</table>
## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>Closeness to the actual value of a measuring instrument’s indicated value</td>
</tr>
<tr>
<td><strong>Ammeter</strong></td>
<td>An instrument for measuring electrical current</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>The process by which an instrument’s accuracy is established</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Actions by which a system’s output is kept as close as possible to the target value</td>
</tr>
<tr>
<td><strong>Displacement</strong></td>
<td>The change in position of some part of a system</td>
</tr>
<tr>
<td><strong>DMM (digital multimeter)</strong></td>
<td>A multimeter which uses electronic circuitry to establish the measured value of voltage, current or resistance</td>
</tr>
<tr>
<td><strong>Drift</strong></td>
<td>An unwanted change over time in a parameter</td>
</tr>
<tr>
<td><strong>Engineering system</strong></td>
<td>A product or process which utilises energy and engineering principles to perform a range of actions</td>
</tr>
<tr>
<td><strong>Error</strong></td>
<td>The difference between an actual parameter value and that indicated on the measuring instrument</td>
</tr>
<tr>
<td><strong>Feedback</strong></td>
<td>A sample of the system output used to indicate the performance of the system</td>
</tr>
<tr>
<td><strong>Gauge</strong></td>
<td>An instrument for measuring some quantity</td>
</tr>
<tr>
<td><strong>Hysteresis</strong></td>
<td>The lag in a change in parameter with respect to the effect which causes the change</td>
</tr>
<tr>
<td><strong>Instrument</strong></td>
<td>A device for measuring a system parameter</td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
<td>How close a sensor or instrument performance is to a straight line</td>
</tr>
<tr>
<td><strong>Measurand</strong></td>
<td>The system parameter being measured</td>
</tr>
<tr>
<td><strong>Meter</strong></td>
<td>A device that measures and displays a quantity such as voltage, pressure or other measurands</td>
</tr>
<tr>
<td><strong>Multimeter</strong></td>
<td>A meter which can measure voltage, current or electrical resistance</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>The difference between the lower and upper limit of the measuring capability of a device</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>The smallest change in device output, effectively the smallest quantity that can be accurately displayed</td>
</tr>
<tr>
<td><strong>Response</strong></td>
<td>How a system output changes when related to changes in input</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>A measure of the performance of a device indicated by the ratio of a change in output divided by the input change which caused it</td>
</tr>
<tr>
<td><strong>Sensor</strong></td>
<td>A device which converts the condition of a parameter into a useable signal.</td>
</tr>
<tr>
<td><strong>Signal conditioning</strong></td>
<td>The process by which the output of a sensor or transducer is modified into a more useable form of data; a typical example is the amplification of a small voltage.</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Transducer</strong></td>
<td>A device that converts one form of energy into another; usually the output is a voltage which directly represents the condition of the input.</td>
</tr>
<tr>
<td><strong>Transfer function</strong></td>
<td>The transfer function of a system, or part of a system, specifies the magnitude and timing relationship between its output and input.</td>
</tr>
<tr>
<td><strong>Voltmeter</strong></td>
<td>An instrument for measuring voltage</td>
</tr>
<tr>
<td><strong>Wattmeter</strong></td>
<td>An instrument for measuring (electrical) power</td>
</tr>
</tbody>
</table>