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Transducers Kit

Part 1 - Electro-Mechanical Transducers

TK2942-1

TRANSDUCERS KIT
TK2942

Part 1 Electro-Mechanical Transducers

Feedback Instruments Limited

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Manual: 2942-1 Ed05 072006 *Printed in England by FI Ltd, Crowborough*

Feedback Part No. 1160–0029421

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The equipment, when used in normal or prescribed applications within the parameters set for its mechanical and electrical performance, should not cause any danger or hazard to health or safety if normal engineering practices are observed and they are used in accordance with the instructions supplied.

If, in specific cases, circumstances exist in which a potential hazard may be brought about by careless or improper use, these will be pointed out and the necessary precautions emphasized.

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CAUTION -
RISK OF
DANGER

CAUTION -
RISK OF
ELECTRIC SHOCK

CAUTION -
ELECTROSTATIC
SENSITIVE DEVICE

Refer to accompanying documents

PRODUCT IMPROVEMENTS

We maintain a policy of continuous product improvement by incorporating the latest developments and components into our equipment, even up to the time of dispatch.

All major changes are incorporated into up-dated editions of our manuals and this manual was believed to be correct at the time of printing. However, some product changes which do not affect the instructional capability of the equipment, may not be included until it is necessary to incorporate other significant changes.

COMPONENT REPLACEMENT

Where components are of a 'Safety Critical' nature, i.e. all components involved with the supply or carrying of voltages at supply potential or higher, these must be replaced with components of equal international safety approval in order to maintain full equipment safety.

In order to maintain compliance with international directives, all replacement components should be identical to those originally supplied.

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1. Equipment type
2. Component value
3. Component reference
4. Equipment serial number

Components can often be replaced by alternatives available locally, however we cannot therefore guarantee continued performance either to published specification or compliance with international standards.

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Should this equipment be used outside the classroom, laboratory study area or similar such place for which it is designed and sold then Feedback Instruments Ltd hereby states that conformity with the protection requirements of the European Community Electromagnetic Compatibility Directive (89/336/EEC) may be invalidated and could lead to prosecution.

This equipment, when operated in accordance with the supplied documentation, does not cause electromagnetic disturbance outside its immediate electromagnetic environment.

Errata Sheet

Transducers Kit TK2942 Part 1

The patching area in the centre of the Instrumentation Module TK2941A has been modified to accommodate plugs with a larger body. The new layout is shown in the figure below and applies to all the patching diagrams given in this manual.

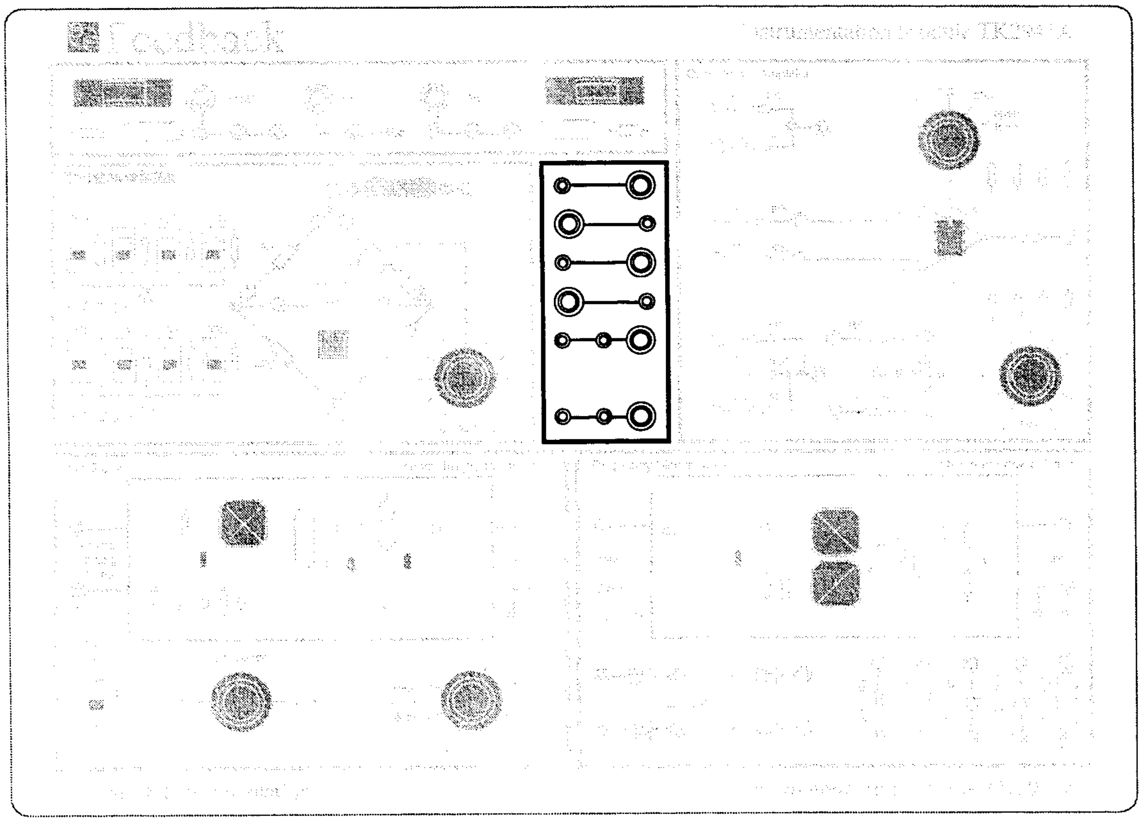

Figure Showing Modifications to the Patching Area.

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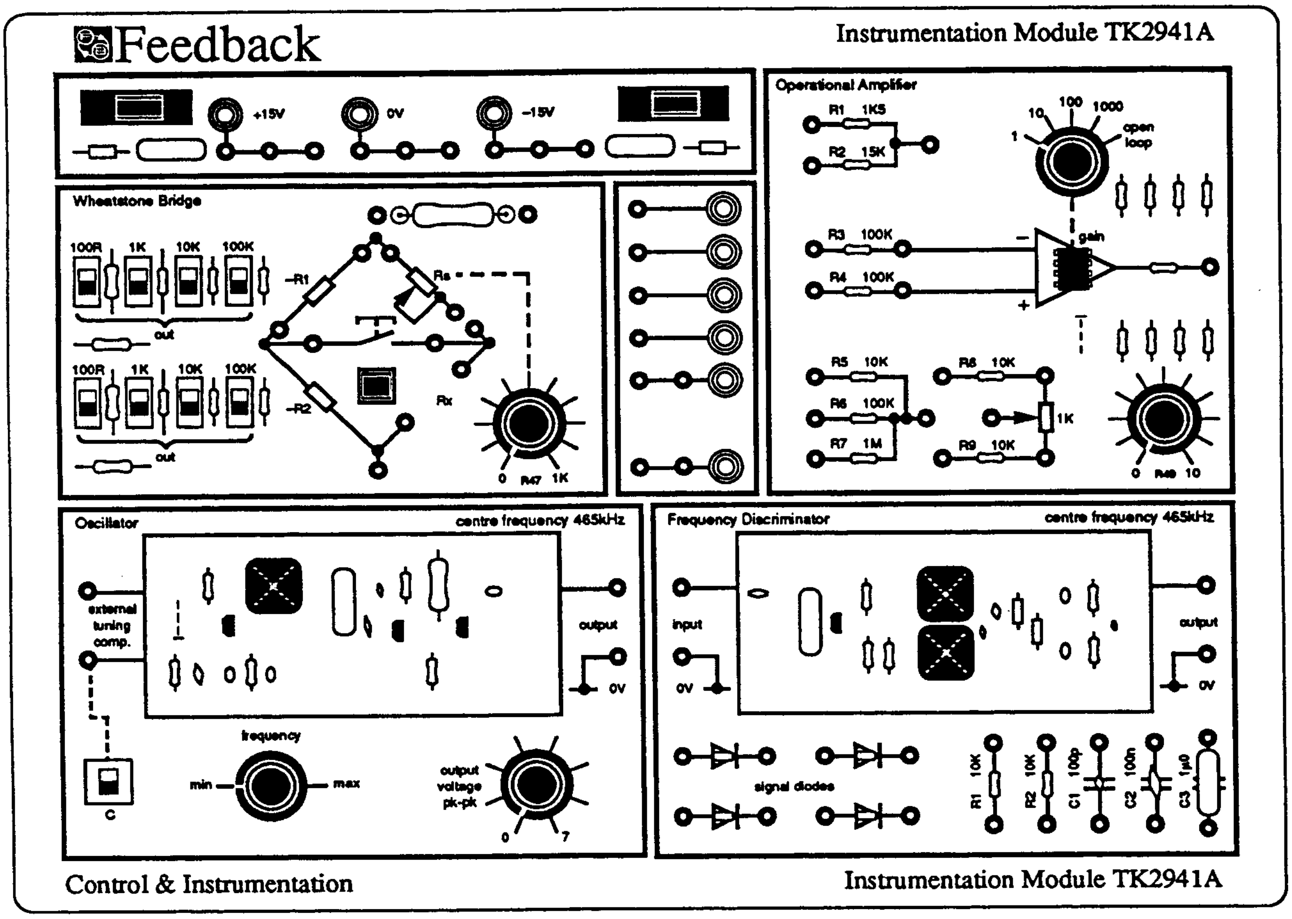


Fig 1.1 Instrumentation Module TK2941A

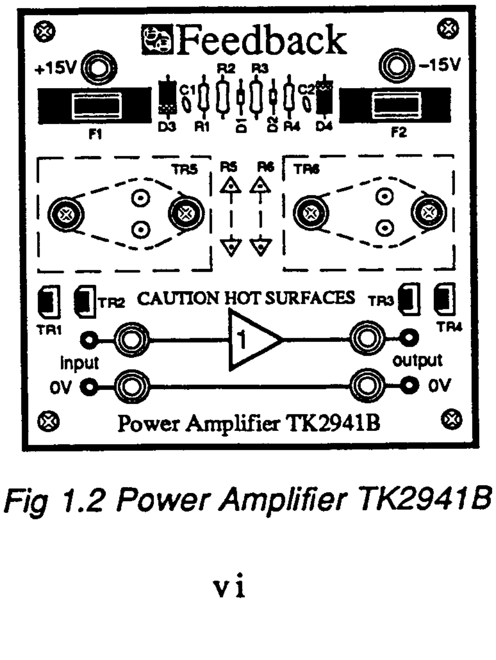


Fig 1.2 Power Amplifier TK2941B

INTRODUCTION AND DESCRIPTION

CHAPTER 1

INTRODUCTION

The TK2942 Transducers Kit consists of a Measurements Package, containing an Instrumentation Module, a Power Amplifier and a Linear Transducer Test Rig; together with three self contained transducer kits. See figs 1.1 and 1.2. The Kits are available separately for use with the Measurements Package, allowing a comprehensive transducers trainer to be built up in stages.

The Kits allow a variety of practical assignments to be carried out which investigate the electrical and physical characteristics of commonly used transducers. The basic theory of their operation is discussed together with the practical aspects of their use.

EQUIPMENT

Qty	Designation	Description
1	TK2941M	Measurements Package comprising:
1	TK294	Linear Transducer Test Rig with slide, micrometer control and sub-unit lock
1	TK2941A	Instrumentation Module
1	–	Resistor 100Ω 1W
1	–	Resistor 1kΩ 0.25W
1	–	Resistor 4.7kΩ 0.125W
1	–	Resistor 10kΩ 0.125W
1	TK2941B	Power Amplifier
1		Set of leads comprising:
12	–	Lead, 2mm plug, 150mm
6	–	Lead, 2mm plug, 300mm
5	–	Lead, 4mm plug, 420mm
8	–	Lead, taper pin – 2mm plug, 300mm
1	–	Lead, taper pin, 150mm
1	–	Resistor 10kΩ 0.125W
2	–	Fuse 160mA
2	–	Fuse 1.6mA
1	TK2941E	Electro-mechanical Transducers Kit comprising:
1	TK294E	Strain gauge
1	TK294F	Variable inductor sub-unit with sliding rod carrying ferrite slug and return spring
1	TK294G	Linear variable differential transformer (LVDT) sub-unit with ferrite slug and return spring
1	TK294H	Variable capacitor (area) sub-unit with operating rod, flexible connector and return spring.
1	TK294J	Variable capacitor (distance) sub-unit with operating rod, fixed and moving plates and return spring.
1	TK294K	Variable resistor sub-unit with operating rod and return spring

1	–	Conductance probe with flying leads.
–	–	Two parallel rods in circular supports.
1	TK2941H	Heat Transducers Kit comprising:
1	–	Heat bar with line connector, on-off switch, voltage selector, main and auxiliary heaters.
1	–	Calibration tank with lid and spring clip for mounting on heat bar
1	–	Transducer mount with spring clip for mounting on heat bar
1	–	Thermal reed relay with spring clip for mounting on heat bar
1	–	Bi-metal thermostat with spring clip for mounting on heat bar
1	–	Transducer – thermocouple and flying compensating leads. Brown sheath.
1	–	Transducer – thermistor with flying leads. White sleeve.
1	–	Transducer – platinum resistance with flying leads. Yellow sleeve.
1	–	Thermometer.
1	TK2941L	Light Transducers Kit comprising
1	–	Lamp holder to mount on Electro-mechanical transducers test rig (TK294)
1	–	Lamp 14.4V 0.1A
1	TK294	Light Transducer Box complete with:
		Optical detector assembly with photo-transistor, photodiode, photoresistor, infra-red filter and optical filter mounts.
1	–	Pack of nine optical filters.

DESCRIPTION

Measurements Package

Instrumentation Module

The Instrumentation Module TK2941A contains a Wheatstone Bridge, Operational Amplifier, Oscillator and Frequency Discriminator circuitry. The transducers are connected to the electronic circuits as required using the 2mm patching leads supplied.

SPECIFICATION

Wheatstone Bridge	Ratio arms of 100Ω, 1kΩ, 10kΩ, 100kΩ Reference – external or 1kΩ
Operational Amplifier	Type 741 op-amp. Gains ±1, 10, 100, 1000.
Oscillator	Frequency range with L/C switch at a C and no external capacitor: Output 7V pk to pk max. Facility for connection of external capacitor or inductor.
Discriminator	Centre frequency 465kHz. Unloaded output at deviation of ±5kHz os ±1V. Output resistance approx 50kΩ.

Power Amplifier

The Power Amplifier TK2941B is a unity gain power amplifier with an output capability of 4 watts.

SPECIFICATION

Power Amplifier	Voltage gain:	±1
	Output Power:	4W max.

Linear Transducer Test Rig

The Linear Transducer Test Rig TK294 comprises a platform to securely support the electro-mechanical transducers and the optical detector assembly, together with a micrometer located on a metric scale. The micrometer is replaced by a lamp holder when the optical detector assembly is in use.

SPECIFICATION

Linear Transducer Test Rig	With slide, micrometer control and sub-unit lock. Motion 11.5cm max. Scale 90mm in 1.0mm divisions

TK2941A and TK2941B require DC power supplies ±15V at 1.5A. The Feedback PS446 DC Power Supply is the recommended item.

The ±15V power supply connections are made to 4mm sockets on the top of the modules. Thorough protection is provided against reverse voltage, over-voltage and over-current.

Electro-mechanical Transducers Kit

The Electro-mechanical Transducers Kit TK2941E provides six linear displacement transducers for use with the test rig. It is the foundation kit for the TK2942 range and the other two kits should be regarded as extensions to it.

SPECIFICATION

TK294E	Strain Gauge Cantilever	R = 120Ω (2 off)	
TK294F	Variable Inductor	R L_{min} L_{max}	9Ω 23μH 81μH
TK294G	Linear Variable Differential Transformer	Primary Secondaries	R = 6.3Ω N = 140 R = 2.5Ω N = 140
TK294H	Variable Area Capacitor	C_{min} C_{max}	15pF 40pF
TK294J	Variable Distance Capacitor	C_{min} C_{max}	15pF 40pF
TK294K	Variable Resistor	10kΩ 0.5W Linear Dual track (second track spare)	
	Conductance Probe		

Heat Transducers Kit

The Heat Transducers Kit TK2941H contains a heat bar, three thermal transducers, a reed relay and a bi-metal switch together with temperature measurement accessories.

The transducers are clipped to the heat bar in a calibration tank. The temperature gradient along the bar is used to investigate the properties of the devices.

SPECIFICATION

Heat Bar	Flat bar with cast box at one end and heat sink at other. Has line connector, on-off switch, voltage selector, main and auxiliary heaters. Line voltage 100/240V 50/60Hz Main heater 50W Auxiliary heater resistance = 30Ω cold
Calibration Tank	Cylindrical tank with lid and spring clip for mounting on heat bar.
Transducer Mount	2.5" long plate with 0.125" diameter tube attached with spring clip for mounting on heat bar.
Thermal Reed Relay	1.125" long x 0.25" diameter cylinder attached to plate with spring clip for mounting on heat bar. Operating temperature = 45°C Hysteresis = 3°C Contacts normally open - 10A rating
Bi-metal Thermostat	Open structure with single normally closed contact attached to plate with spring clip for mounting on heat bar. Operating temperature = 45°C Differential = 5°C Contacts normally open - 10A rating.
Transducer Platinum Resistance	$R_0 = 100\Omega \pm 0.1\Omega$ $R_{100} = 138.5\Omega \pm 0.2\Omega$ Self-heating <0.1°C rise for 3mA, <0.3°C rise for 10mA Time constant ≈ 9s.

Light Transducers Kit

The Light Transducers Kit TK2941L comprises an optical detector assembly, four photo-electric devices and a selection of optical filters. The assembly is fitted to the test rig from the Measurements Package together with a light source. The filters may be fitted to the assembly as required.

SPECIFICATION

Lamp Holder	To mount on Test Rig. MBC lamp in holder on small plate with flying leads - 14.4V 0.1A
Optical Detector Assembly	Black box with rotating turret labelled "LIGHT TRANSDUCER BOX" Photo-transistor Photo-diode Photo-resistor
Optical Filters	2" x 2" slide mounts labelled with wavelengths. Wavelength of transmission 440, 470, 490, 520, 550, 580, 600, 690 and 700nM.

ANCILLARY EQUIPMENT

In addition to the TK2942, the following items of standard laboratory equipment will be required:

EQUIPMENT

Qty	Designation	Description	
1	–	Power Supply Unit ±15V dc, 1.5A. +5V, 1.0A (eg Feedback PS446)	
1	–	Variable Power Supply, 0-10V dc. *(Optional. Only required for Assignment 23, Continuous Temperature Control)*	
1	–	Function Generator 600kHz Sine at 10V pk to pk	
1	–	Digital Frequency Meter, 1MHz	
1	–	* AC Voltmeter	5mV to 10V
2	–	* DC Ammeter	1mA to 400mA
2	–	* DC Voltmeter	1V to 15V
1	–	* DC Milliameter	Centre Zero
1	–	Two - beam oscilloscope, X - Y operation, 15MHz	
1	–	Decade Resistance 1Ω to 100kΩ	
1	–	Decade Capacitance 0.001µF to 0.1µF	
3	–	Parallel sided beakers, 250ml	
1	–	Measuring cylinder or jug, 250ml	
1	–	Spoon	
–	–	Common Salt	
–	–	Water	

* Alternatively multimeters may be used

Practical Work

The manual associated with the Transducers Kit is provided in three separate parts for ease of handling and use. The parts, however, have their page numbers and individual assignments consecutively numbered.

Each part has its own contents list for ease of reference and the assignments are self-contained.

INSTALLATION CHECKS — CHAPTER 2

INSPECTION

Check the equipment supplied for mechanical damage.

Check that the relevant leads and accessories listed in the Equipment Section of Chapter 1 are all present.

Meaurements Package

In order to check that the Meaurements Package circuits are functioning correctly, carry out the following procedures:

Connect up the equipment as shown in fig 4.6.2.

Set the Operational Amplifier to its lowest gain (ie 1) and balance the bridge roughly with the variable dc set; using the potentiometer control on the Operational Amplifier; to give approximately 4V.

When the approximate balance point has been reached increase the gain of the amplifier to 10 and find the balance more accurately.

Assemble the TK294 and the TK294H and reconnect up the transducer and modules as shown in fig 4.14.2. Keep the leads as short as possible in order to reduce stray capacitance.

Set the position of the slider to 42.5mm at the middle of the scale, corresponding to the rod being halfway into the tubular capacitive transducer.

The lower 'external tuning comp' socket is connected to 0V and should be connected to the left-hand socket on TK294H ie the capacitor body.

Set switch SW9 to the 'C' position.

Set the micrometer to read 10mm.

Set the output voltage control on the Oscillator to mid scale. Set the gain of the Operational Amplifier to 10. Switch on the power supply. An output should be visible on the meter.

Heat Bar

Connect the Heat Bar to the appropriate mains supply and check that the length of the bar is progressively heated.

Adjust the oscillator frequency control until the sharp transition from positive to negative (or vice-versa) of the output voltage, corresponding to the steep linear central portion of the discriminator 'S-curve is found. From this point, slowly adjust the oscillator frequency control until the meter indicates exactly zero volts. **Always remove your hand when taking readings to avoid the effects of stray capacitance.** You can obtain increased sensitivity for this part of the experiment by temporarily increasing the amplifier gain. Now move the slider towards the transducer and check that the meter reading increases to a positive value.

If the equipment fails any of these checks please contact your supplier.

NOTES

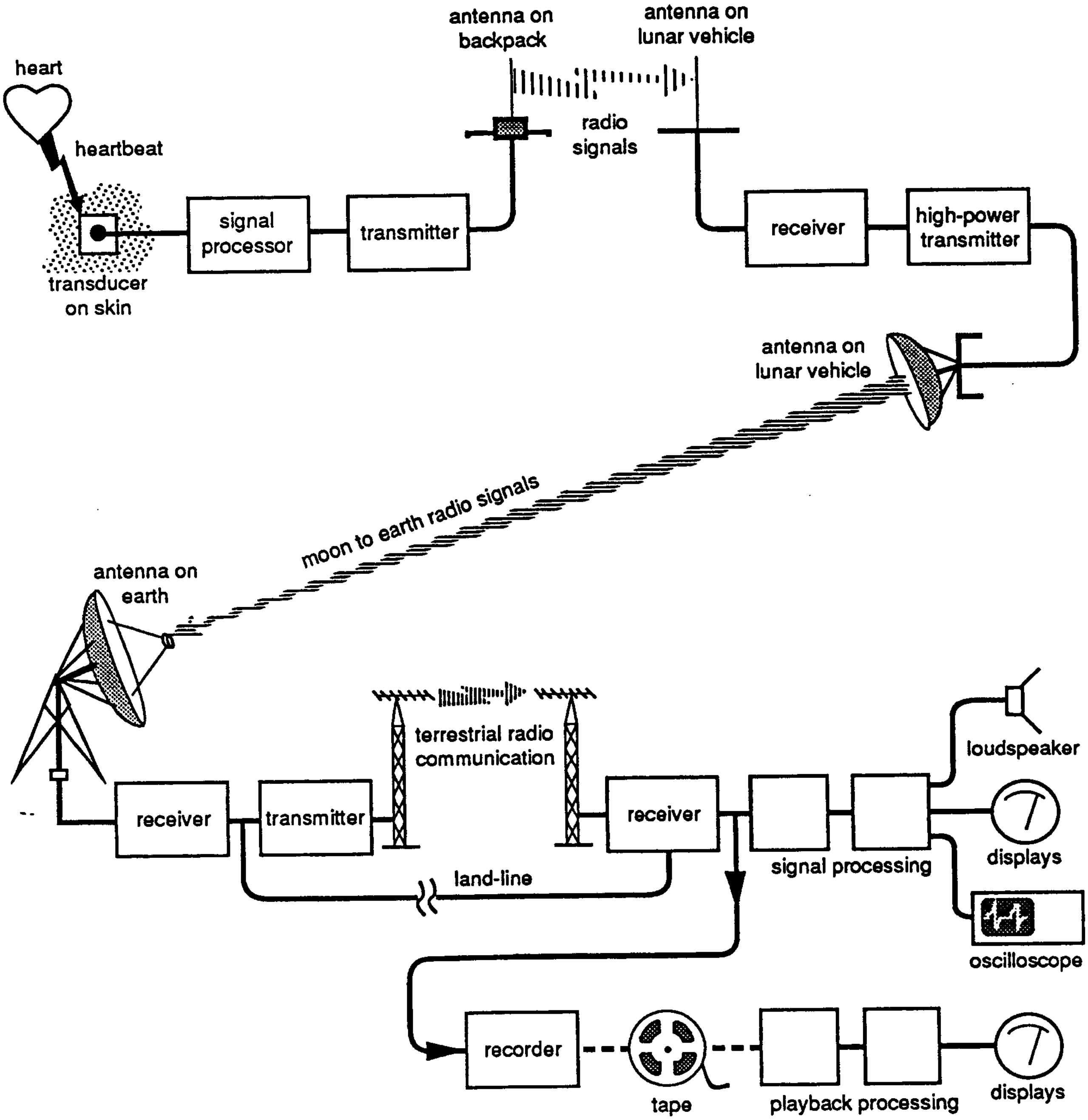


Fig 3.1. Measurement over a Long Distance

BASIC IDEAS

CHAPTER 3

MEASUREMENTS

How would you measure your own weight? This may sound a trivial question. Of course, you answer 'by using a weighing machine or scales'. But think what the scales are actually doing: they are converting the force applied to them by gravity acting on your body (your weight) into movement of a dial, so that you can instantly see what your weight is. Thus the scales convert the thing we want to measure (weight) into a form of information which we can easily use and interpret (we see the position of a calibrated dial).

The scales are a form of *TRANSDUCER*.

A transducer is a device which, in response to a particular property being measured, gives an output of a form which is easily usable.

The form of the output from a transducer may not be directly usable by our senses. In the example above the output was directly interpreted by our sense of sight. However there are many applications where the easily usable output is in the form of an electrical signal, which may be processed in some electronic way before being applied to a second transducer which converts the electrical signal into an output which can be interpreted by one of our senses. Thus a total measuring system may comprise many transducers converting energy from one form to another before presenting it as a recognisable output.

As an example of a complex measuring system, let us consider how an astronaut's heartbeat is measured when he is walking about on the moon. Fig 3.1 is a block diagram of the system. Firstly, the astronaut's heartbeats are converted into an electrical signal by a transducer attached to his skin. This electrical signal is processed and is converted into a radio signal which is transmitted, via the antenna on the astronaut's backpack, to the lunar vehicle, where it is picked up by another antenna and converted back to an electrical signal. This signal is amplified and processed in the lunar vehicle and is retransmitted at higher power, as a radio signal, back to earth. Here the radio signal is again picked up by another antenna and converted into an electrical signal again which is processed and may be retransmitted across the globe either by radio or by land-line, to the control centre where it undergoes more processing before being used to drive a display which can be interpreted by the doctors and scientists. In addition to this, the received signals may be recorded on tape to be replayed at some later time. This is summarised in fig 3.1.

At each stage where energy is converted from one form to another, a transducer of some type is used. All the antennas are types of transducers; so are the tape recorders and the displays. This helps to show how modern science depends to a large extent on transducers and their uses in measuring systems, and that transducers which convert energy forms to and from electrical signals are very important. These types of transducers are often known as *ELECTRICAL TRANSDUCERS* and it is these that we will study.

ELECTRICAL TRANSDUCERS

Electrical transducers use variations in the physical property to be measured to produce variations in one of the electrical parameters of the transducer. For instance, the parameter varied may be the resistance of an element in the transducer. Depending on the way the resistive element is connected and the method used to vary the resistance, many physical properties may be measured using resistive transducers. For example, linear displacement, strain, position, temperature, liquid level, humidity, and many more properties may be measured using variations based on the same principles of change of resistance. Other transducers may use capacitance or inductance parameters, or may use the photoelectric or the piezoelectric effects as their principle of operation. Once such an electrical parameter has been varied it is a matter of electronically detecting this, processing the signals, and applying these to another output display transducer to provide the required information in the form needed. These output devices often use the same principles as the input devices but have to work the opposite way round, i.e converting electrical variations into ones detectable by human senses.

As there are a finite number of electrical parameters which can be varied, but almost an infinite number of types of transducer using these variations, the subject of electrical transducers will be tackled from their principles of operation, rather than giving examples of the many types which could measure any particular physical property.

SIGNAL PROCESSING

As the transducer element converts changes in the measurand (the property being measured) into changes in one of its electrical parameters, some way of detecting these changes in parameter must be employed. This is done in the signal processing stages.

With transducer elements which use the principle of variation of resistance, detection can be done by applying a dc signal to the transducer, and measuring the current or voltage change. With transducer elements which use variations of their reactive properties (e.g capacitance or inductance) the signal applied must be an ac one, and changes in amplitude, frequency, phase, etc of this signal may be measured.

The output signals from the transducer (either dc or ac) may be amplified using the appropriate type of amplifier, and the ac output signals may be converted to dc signals, or vice-versa, as required to drive the display in use. Thus the signal processing forms an important and necessary part of the total transducer system.

NOTES

PART 1 - ELECTRO-MECHANICAL TRANSDUCERS CHAPTER 4

ASSIGNMENTS

The following assignments can be carried out using the TK2941M Measurements Package and the TK2941E Electro-mechanical Transducers Kit:

1 Resistance

2 The Wheatstone Bridge

3 Sensitivity of a Wheatstone Bridge

4 The Wheatstone Bridge at AC

5 The Operational Amplifier

6 Using the Operational Amplifier

7 Variable Resistivity Transducers

8 Variable Area Transducers

9 Variable Length Transducers

10 Strain Gauges

11 Measurement of Capacitance

12 Small variations in Capacitance

13 Frequency Discrimination

14 Capacitive Transducers in an FM system

15 Inductive Transducers in an FM system

16 Variable Reluctance Transducers

17 The Linear Variable Differential Transformer (LVDT)

RESISTANCE — ASSIGNMENT 1

CONTENT

Various methods of measuring resistance are investigated and compared.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	–	Power Supply, ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 100KΩ
1	–	*DC Ammeter 400mA
1	–	*DC Ammeter 1mA
1	–	*DC Voltmeter 1V
1	–	*DC Voltmeter 10V

* Alternatively two suitably ranged multimeters may be used.

PRACTICALS

1.1 Ohm's Law R = 90Ω

1.2 Ohm's Law R = 1KΩ

1.3 Ohm's Law R = 20KΩ

RESISTANCE

ASSIGNMENT 1

OBJECTIVES

When you have completed this assignment you will:

- Know how to measure resistance using Ohm's Law techniques
- Have observed that errors in measurement can occur due to meter losses.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the theory and application of Ohm's Law
- Know how to apply Ohm's Law to series and parallel dc circuits.

INTRODUCTION

The basic formula for the resistance of a specimen of any material is:

$$\text{Resistance } R = \frac{\rho l}{a}$$

where

- ρ is the resistivity of the material
- l is the length of the material
- a is the cross sectional area of the specimen.

From this it can be seen that the resistance may be varied by varying ρ, l or a. Thus, it would seem to be possible to construct transducers using the variation of these parameters to produce a change in resistance which could be detected and measured. The parameter which is varied will depend on the construction of the transducer and the transducer application, but the final measurement of the resistance could be the same regardless of the transducer or application.

Firstly we will examine resistance measurement techniques, and evolve a suitable method which can be used for future practical work.

PRACTICAL 1.1

Ohm's Law R = 90Ω

The most fundamental method of determining resistance is by measuring the current flowing through a specimen and the voltage across the specimen, and using Ohm's Law to calculate the resistance value.

There are two ways of connecting a voltmeter and an ammeter to a component to measure resistance. These are shown in fig 4.1.1 below.

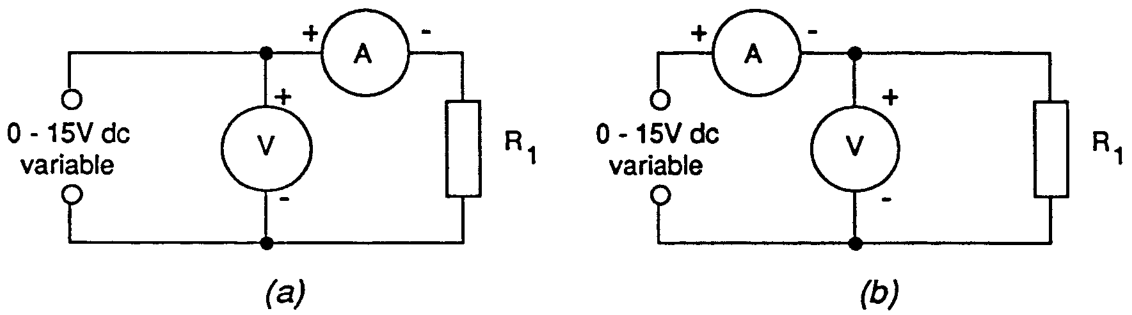


Fig 4.1.1 Methods of connecting a voltmeter and ammeter

Using a dc milliammeter and a dc voltmeter, with the 90Ω resistor on the decade box as R_1, set up the circuit of fig 4.1.1(a) as shown in fig 4.1.2.

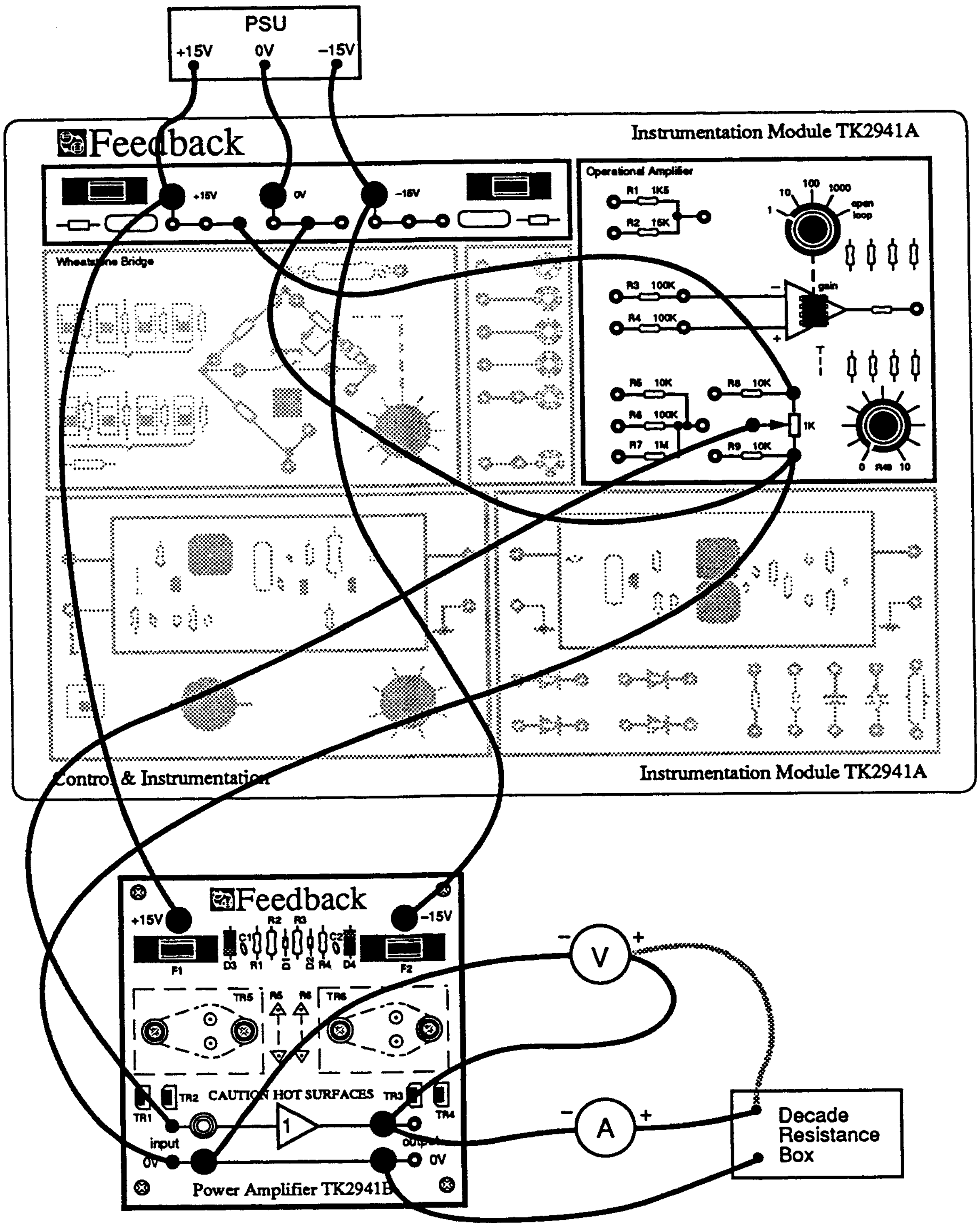

PSU
+15V
0V
-15V
Feedback
Instrumentation Module TK2941A
Operational Amplifier
Wheatstone Bridge
Control & Instrumentation
Instrumentation Module TK2941A
Feedback
+15V
-15V
CAUTION HOT SURFACES
input
0V
Power Amplifier TK2941B
V
A
Decade
Resistance
Box

Fig 4.1.2

Note Do not adjust the setting on the decade resistance box during this practical. Use 90Ω only. Damage may occur to the resistors in the box if the setting is changed with power applied.

Slowly increase the variable voltage dc output, using the 1kΩ potentiometer control on TK2941A Operational Amplifier, and set it to approximately 4 volt dc.

Read the resultant current and record the values of voltage and current in your own copy of fig 4.1.3.

	Variable Voltage (V)	Voltmeter (V)	Ammeter (mA)	Resistance (Ω)
Fig 4.1.1(a)	4.0			
Fig 4.1.1(b)	4.0			

Fig 4.1.3

Repeat the reading for two or three voltage settings between 0V and 4V.

Now, disconnect the positive side of the voltmeter from the positive side of the ammeter, and connect it to the negative side of the ammeter. This will give the circuit connection of fig 4.1.1(b) as shown by broken line connection of fig 4.1.2.

Again, read the currents and voltages indicated for several voltage settings between 0 and 4V.

Using Ohm's Law, calculate the resistance for each set of current and voltage readings.

Question 1.1 ***Calculate the average value of resistance for the circuit of fig 4.1.1(a), and also the average for the circuit of fig 4.1.1 (b).***

Question 1.2 ***Are they the same?***

Question 1.3 ***If not, what is the percentage difference between them?***

Question 1.4 ***Which circuit gives the higher resistance value?***

PRACTICAL 1.2

Ohm's Law R = 1kΩ Reduce the variable dc to zero and set the 1kΩ in circuit instead of the 90Ω resistor. Adjust the meter ranges as required.

Repeat the procedure as before using voltages between 0 and 10V dc, and again record your results.

Question 1.5 ***Calculate the two average resistance values again.***

Question 1.6 ***Are these the same?***

Question 1.7 ***If not, what is their percentage difference?***

PRACTICAL 1.3

Ohm's Law R = 20kΩ Repeat the procedure using a 20kΩ resistor.

Question 1.8 ***Are the resulting resistance values the same?***

Question 1.9 ***What is the percentage difference?***

DISCUSSION

It should be seen from the results you obtain that the calculated value of resistance depends on the circuit connection used, and that the difference between the two values is greater for a low or a high resistance value component than for one with an intermediate resistance value. Let us try and explain this.

The ammeter will have some resistance. Normally this will be of a low value, ranging from a fraction of an ohm for a 1A fsd meter, to perhaps 100Ω for a 1mA fsd meter.

The voltmeter will also have a resistance. This will generally be high in value, ranging from about 20kΩ for a 1V fsd meter to perhaps 2MΩ for a 100V fsd meter.

There is bound to be some voltage drop across the ammeter and some current flowing through the voltmeter.

Question 1.10 ***In the circuit of fig 4.1.1(a), what voltage are you actually measuring with the voltmeter?***

The current indicated on the ammeter is the actual current flowing through the resistor, but the voltage reading will not be the true voltage present across the resistor. The ammeter and the resistor form a potential divider, as shown in fig 4.1.4.

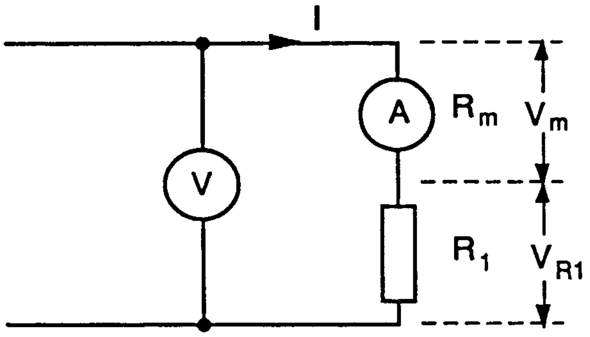


Fig 4.1.4 Potential Divider

Now $R_1 = \frac{V_{R1}}{I}$ and not $\frac{V}{I}$ as calculated

and $V_{R1} = \frac{R_1}{R_m + R_1} \times V$

Therefore, to get reasonable accuracy with this connection, R_m must be very small compared with R_1. If this is so, then R_m may be neglected.

ie $R_m \ll R_1$

$(R_m + R_1) \cong R_1$

therefore $V_{R1} = \frac{R_1}{R_1} . V = V$

and $R_1 = \frac{V_{R1}}{I} = \frac{V}{I}$ as calculated.

Thus the circuit of fig 4.1.1(a) is only accurate when the resistor measured has a value much greater than the ammeter resistance.

Now considering the circuit of fig 4.1.1(b).

Question 4.1.11 ***What current are you actually measuring with the ammeter? The current paths are shown in fig 4.1.5***

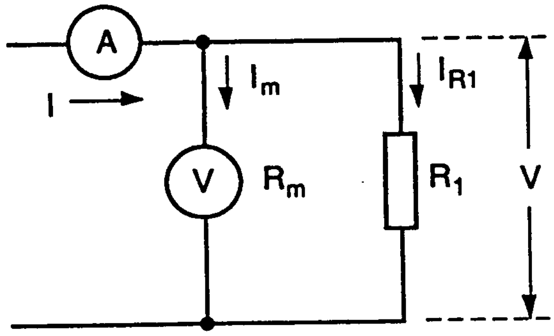


Fig 4.1.5 Current paths

Here $R_1 = \frac{V}{I_{R1}}$ and not $\frac{V}{I}$ as calculated

and $I_{R1} = \frac{R_m}{R_m + R_1} . I$

Thus to obtain accuracy, R_m must be very much greater than R_1, so that R_1 may be neglected in the above expression.

ie $R_m \gg R_1$

$(R_m + R_1) \equiv R_m$

therefore $I_{R1} = \frac{R_m}{R_m} . I = I$

and $R_1 = \frac{V}{I_{R1}} = \frac{V}{I}$ as calculated.

Thus the circuit of fig 4.1.1(b) is only accurate when the resistor measured has a value less than the voltmeter resistance.

Question 1.12 ***Which is the more correct answer for the resistance of the nominally 90Ω resistor?***

Question 1.13 ***Which is the more correct answer for the nominally 10k resistor?***

Question 1.14 ***Does it matter which form of connection is used for the intermediate value of 1kΩ?***

For low value resistances, connect the circuit as in fig 4.1.1.(b).

For high value resistances, connect the circuit as in fig 4.1.1.(a).

For intermediate values, either form of connection will do.

PRACTICAL ASPECTS

The first conclusion that may be drawn from the assignment just performed is that measurement of resistance by this method can easily give rise to substantial errors, especially if the wrong form of connection is used, or if the measuring instruments are not of reasonably good quality.

If the resistance of each of the meters is known, then this method may be used, and some calculations can be performed to obtain a correction factor which can be used to find the true value.

For example, suppose the resistance of the ammeter is Rm and the circuit is as in fig 4.1.4.

We said $R_1 = \frac{V_{R1}}{I}$ and $V_{R1} = \frac{R_1}{R_m + R_1} \cdot V$

For these, or directly from fig 4.1.4 and Ohm's Law, we can see:

$$\frac{V}{I} = R_m + R_1 \text{ ie } R_1 = \frac{V}{I} - R_3$$

If R_m is known then the true R_1 can be found.

From the assignment and from the calculations above, it should be clear that this method of measuring resistance is not very quick or convenient The main disadvantages are:

it is not a direct reading method,

it requires two meters,

it needs calculations to achieve a result.

It would be much more convenient , and much easier to use if a direct reading method could be found. By 'direct reading' is meant a method that gives an output which is directly calibrated in the quantity to be measured. For example, a method for measuring resistance which gives an output on a meter calibrated in ohms would be a direct reading method.

If in the circuit of fig 4.1.4 the resistor R_1 is very much greater than the resistance of the meter, R_m, then we can say that:

$$I \propto \frac{1}{R_1} \text{ if V is constant.}$$

Thus an ammeter used in such a circuit could be directly calibrated in ohms, and the value of R1 read directly off the scale.

This is principle of operation of most multimeters when used on their ohms ranges. The voltage V is supplied from an internal battery, and the value of the resistor under test is read directly off the relevant scale on the meter. As the current is inversely proportional to the resistance under test then a full-scale reading on the meter corresponds to zero resistance, and conversely a zero reading on the meter is given by an open circuit. If you examine the ohms scale on a multimeter you will find that it is back to front compared with the other scales. This is because of the inverse proportionality.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 1

The voltmeter used to obtain these results had a sensitivity of 20kΩ/V on a 10V fsd scale.

The ammeter used to obtain these results had an internal resistance of approximately 16.4Ω on a 50mA fsd scale and 72Ω on a 5mA fsd scale.

	Variable Voltage (V)	Voltmeter (V)	Ammeter (mA)	Resistance (Ω)
Fig 4.1.1(a)	4.0	4.0	36	111
	2.5	2.5	22	114
	2.0	2.0	18	111
	1.0	1.0	9	111
Fig 4.1.1(b)	4.0	3.4	37	92
	2.5	2.15	23	94
	2.0	1.75	19	92
	1.0	0.85	9	94

Fig E4.1.3 Typical results where R = 90Ω

Question 1.1 112Ω for fig 4.1.1(a)
93Ω for fig 4.1.1(b).

Question 1.2 No.

Question 1.3 Resistance from fig 4.1.1(a) is 20% higher than for fig 4.1.1(b).

Question 1.4 The circuit of fig 4.1.1(a) gives higher value.

Question 1.5 1.1Ω for fig 4.1.1(a)
1.02Ω for fig 4.1.1(b).

Question 1.6 No.

	Variable Voltage (V)	Voltmeter (V)	Ammeter (mA)	Resistance (Ω)
Fig 4.1.1(a)	5	5	4.6	1.09
	4	4	3.6	1.11
	3	3	2.7	1.11
Fig 4.1.1(b)	5	4.7	4.6	1.02
	4	3.2	3.6	1.03
	3	2.8	2.8	1.00

Fig E4.1.3 Typical results where R = 1kΩ

Question 1.7 8%

	Variable Voltage (V)	Voltmeter (V)	Ammeter (mA)	Resistance (Ω)
Fig 4.1.1(a)	5	5	0.24	20.8
	4	4	0.19	21.1
	3	3	0.14	21.4
Fig 4.1.1(b)	5	4.8	0.26	18.5
	4	3.9	0.21	18.6
	3	2.9	0.16	18.1

Fig E4.1.3 Typical results where R = 20kΩ

Question 1.8 No

Question 1.9 Resistance from fig 4.1.1(a) produces a value 5.5% higher than the nominal 20kΩ compared with fig 4.1.1(b) which gives a value 8% lower.

Question 1.10 In the circuit of fig 4.1.1(a) the voltmeter measures the volt drop across the load resistor plus the volt-drop across the ammeter.

Question 1.11 In the circuit of fig 4.1.1(b) the ammeter measures the current through the load resistor plus the current flowing through the voltmeter.

Question 1.12 The circuit of fig 4.1.1 (b) gives a more accurate reading.

Question 1.13 The circuit of fig 4.1.1 (a) gives the more accurate reading.

Question 1.14 No.

THE WHEATSTONE BRIDGE — ASSIGNMENT 2

CONTENT

The basic behaviour of a Wheatstone Bridge is introduced. The advantages of bridge measurement techniques over simple Ohm's Law methods are investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	–	Power Supply, ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 100kΩ
1	–	* DC Voltmeter 15V
1	–	* Centre zero dc milliammeter
1	–	Resistor – 100Ω, 1W
1	–	Resistor – 1kΩ, 1/8W
1	–	Resistor – 10kΩ, 1/8W

* Alternatively multimeters may be used.

PRACTICALS

2.1 The basic Wheatstone Bridge

THE WHEATSTONE BRIDGE — ASSIGNMENT 2

OBJECTIVES

When you have completed this assignment you will:

- Know the principle of operation of the basic Wheatstone Bridge
- Know how to measure resistances using a Wheatstone Bridge.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the theory and application of Ohm's Law
- Be familiar with the operation of series/parallel dc circuits and potential divider circuits.

INTRODUCTION

The Wheatstone Bridge

A method of determining resistance which was not direct reading has many sources of error. A direct reading method with few error sources would be of great advantage.

A way of determining resistance value which only requires one meter is shown in the circuit of fig 4.2.1.

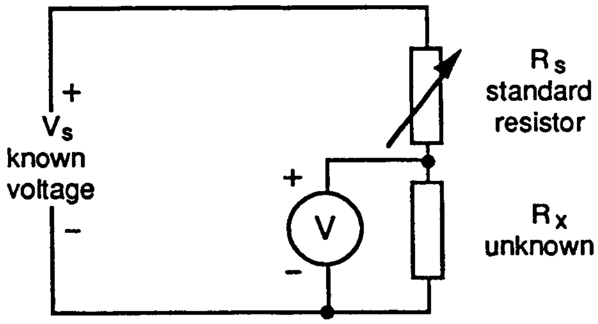


Fig 4.2.1 Basic one meter measurement

Here, the unknown resistance, R_X, is used in a potential divider circuit with a known standard resistor R_S connected across a known source voltage V_S.

By the potential divider formula:

$$V = \frac{R_x}{R_s + R_x} . V_s$$

therefore $R_x = \frac{V}{V_s - V} . R_s$

This circuit suffers from some disadvantages.

Obviously R_S, the standard resistor, must be known precisely.

The voltmeter V must have a resistance very much greater than R_X for accurate results.

The method does not lead to direct reading of the result.

When all the circuit values are known precisely, the final accuracy still depends ultimately on the accuracy of the meter indication.

It would be advantageous to find a method which does not have these drawbacks. Consider the circuit of fig 2.2.

Here, there are two voltage sources of $+V_S$ and $-V_S$ volts. R_S is a variable calibrated standard resistor and R_X is the unknown resistance.

M is a centre-zero meter.

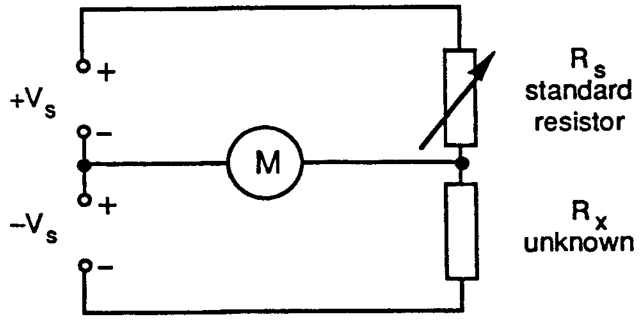


Fig 4.2.2 Centre zero reading

Question 2.1 ***In the circuit of fig 4.2.2 when will the meter read zero?***

Question 2.2 ***Assuming Rs has a calibrated scale, what will be the relationship between the resistance Rx and the indicated value of Rs?***

Question 2.3 ***Can you think of a more sensitive way of determining the zero position of the meter?***

Consider the circuit in fig 4.2.3. With the switch closed the meter needle will be at its zero position. When the switch is open any current flowing through the meter will cause the needle to move, and it is possible to detect very small movements of the needle. This method then gives a very sensitive indication of the zero position.

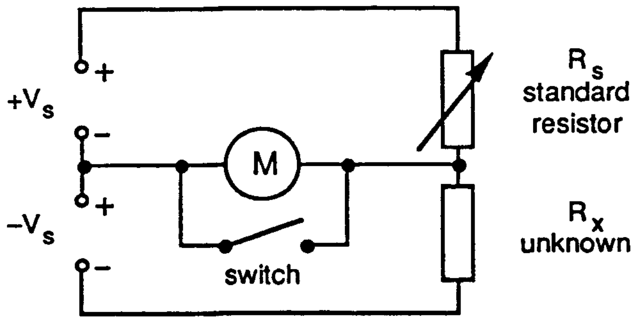


Fig 4.2.3 Sensitive zero position

Question 2.4 ***Does the accuracy of resistor measurement using the circuit of fig 4.2.3 depend on the accuracy of the meter?***

Question 2.5 ***Does the resistance of the meter affect the accuracy of measurement?***

One disadvantage with the circuit of fig 4.2.3 is that $+V_S$ must be exactly equal in magnitude and opposite in polarity of $-V_S$. This means two accurate voltage sources are needed, so some method of eliminating these would be useful.

Question 2.6 ***With a single voltage source of V volts how can you arrange it so that the meter is connected to a point of potential V/2 volts?***

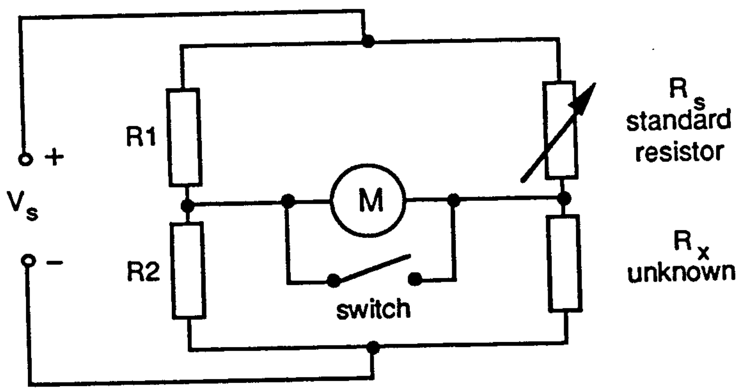


Fig 4.2.4 Centre zero but with single supply

Consider the circuit in fig 4.2.4.

With R_1 equal to R_2 the potential of the lefthand connection to the meter will be V/2 and with R_S equal to R_X the potential on the righthand end of the meter will also be V/2.

Question 2.7 ***What will the meter read when the switch is open with R_S equal to R_X?***

Question 2.8 ***Does the accuracy of the voltage source affect the measurement?***

Question 2.9 ***Does the accuracy of the voltage source affect the measurement?***

Question 2.10 ***Does the stability of the source affect the measurement?***

Question 2.11 ***Is it the absolute values of R_1 and R_2 that determine the accuracy of measurement of R_x, or is it the ratio accuracy that does so?***

R_1 and R_2 are often called the Ratio Arms of the circuit and the circuit as a whole is called a Wheatstone Bridge. It is more often drawn in the form of fig 4.2.5.

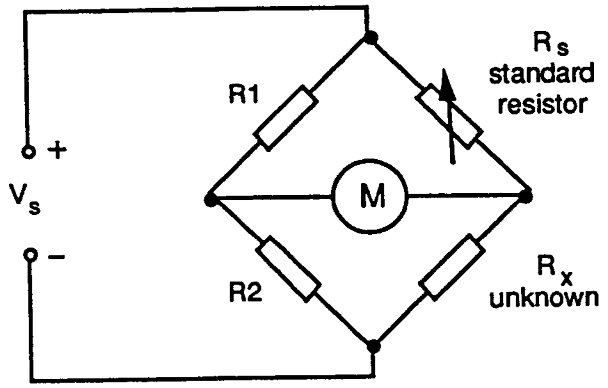


Fig 4.2.5 Circuit of Wheatstone Bridge

PRACTICAL 2.1

The Basic Wheatstone Bridge

Let us investigate the circuit. Set up your module as in fig 4.2.6. This corresponds to the circuit of fig 4.2.4 with R_1 = 10kΩ and R_2 = 10kΩ. Use the external decade box for R_S.

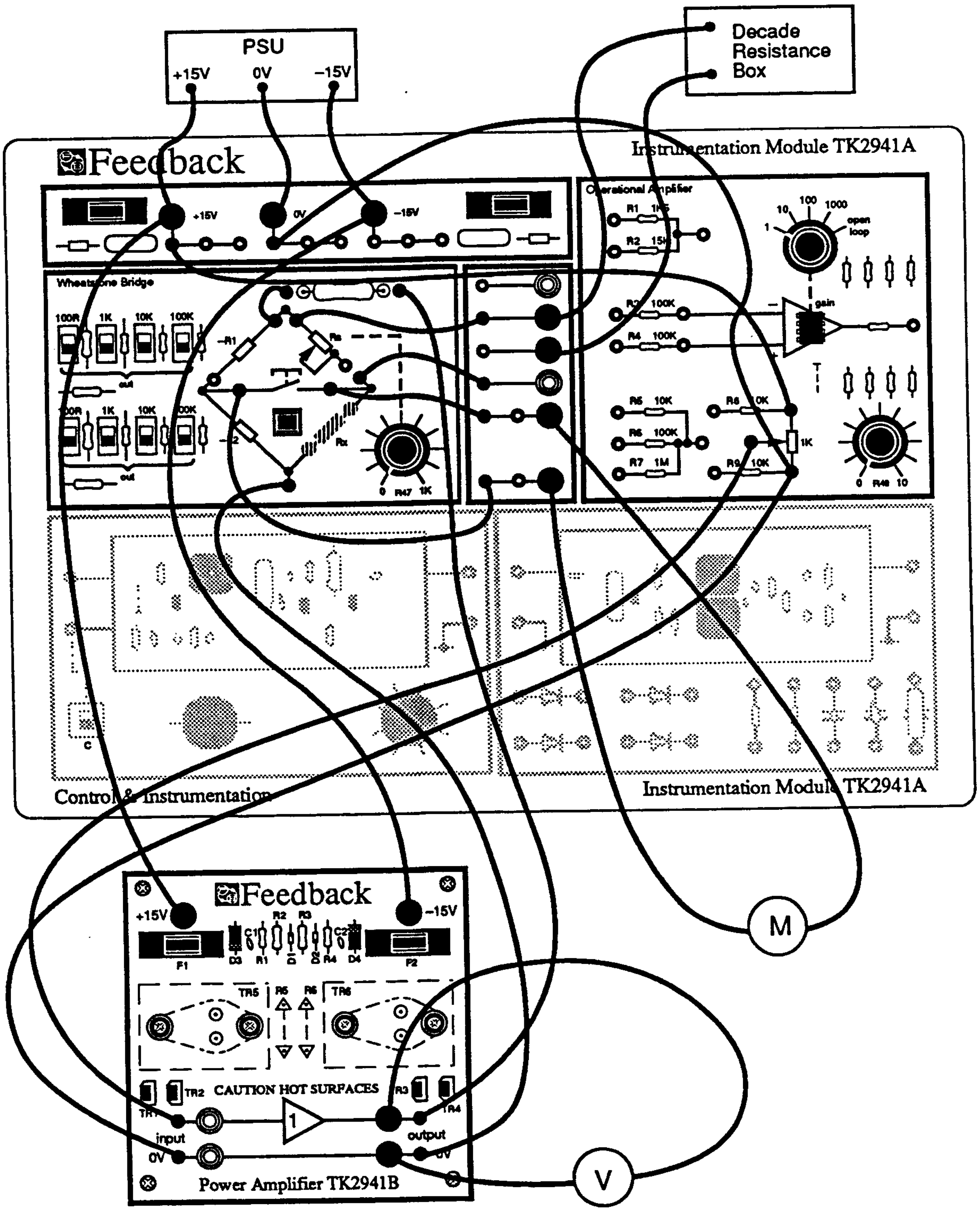


Fig 4.2.6 Wheatstone Bridge Connections

An extra 220Ω resistor is included in the module circuit in series with the Wheatstone Bridge to limit the current in event of a short circuit when connecting and using the Wheatstone Bridge.

Connect a resistor of about 100Ω across the R_X terminals.

On the Wheatstone Bridge set switches SW3 and SW7 'in'; all others 'out'.

Slowly increase the variable dc voltage, using the potentiometer on the Operational Amplifier, to give a supply V_S of 10 volts. Adjust R_S to achieve zero deflection (ie a balanced bridge condition) making use of the meter switch to obtain an accurate balance.

The recommended technique is to adjust R_S to a value such that there is minimum, ideally no, movement of the meter needle when the switch is switched in and out. The use of this method minimises any error due to the meter set-zero adjustment.

Read off the value of R_S from the resistance box.

Record your results in your own copy of fig 4.2.7.

Disconnect the 100Ω resistor and substitute a 1000Ω resistor for R_X. Repeat the balancing procedure and read the new value of R_S.

Repeat the procedure for an R_X of 10kΩ.

R_1	R_2	R_X	R_S
10kΩ	10kΩ	100Ω 1kΩ 10kΩ	
10kΩ	1kΩ	100Ω 1kΩ 10kΩ	
1kΩ	10kΩ	100Ω 1kΩ 10kΩ	

Fig 4.2.7

Question 2.12 *If the ratio arms were changed so that $R_1 = 10R_2$ what would the voltage on the junction of R_1 and R_2 be, with respect to the source voltage?*

Question 2.13 *What ratio of R_s to R_x would give a balance in this case?*

Question 2.14 *If $R_1 = R_2/10$ what would be the voltage on the R_1, R_2 junction?*

Question 2.15 *What ratio of Rs to Rx would give a balance now?*

Let us check your answers.

Change the ratio arms to $R_1 = 10k\Omega$ (SW3 'in') and $R_2 = 1k\Omega$ (SW6 'in') and repeat the measurement for $R_X = 100\Omega$, $1k\Omega$ and $10k\Omega$.

Record the results in your table.

Repeat the experiment for ratio arms of $R_1 = 1k\Omega$ (SW2 'in') and $R_2 = 10k\Omega$ (SW7 'in').

Record your results.

Question 2.16 *Does the ratio of Rs to Rx agree with that for R_1 to R_2?*

DISCUSSION

The theory for the Wheatstone Bridge is quite straightforward. Consider fig 4.2.8.

The equations for this circuit are:

$I = I_1 + I_s$

$I_1 = I_m + I_2$

$I_x = I_s + I_m$

$I = I_2 + I_x$

At balance $I_m = 0$ and the equation simplifies to:

$I_1 = I_2$

$I_s = I_x$

Also at balance $V_{R1} = V_{Rs}$ $V_{R2} = V_{Rx}$

or $I_1R_1 = I_sR_s$ $I_2R_2 = I_xR_x$

Dividing one equation by the other gives:

$\frac{I_1R_1}{I_2R_2} = \frac{I_sR_s}{I_xR_x}$ which may be simplified to give:

$$\frac{R_1}{R_2} = \frac{R_s}{R_x}$$

A more detailed analysis is given in Appendix C.

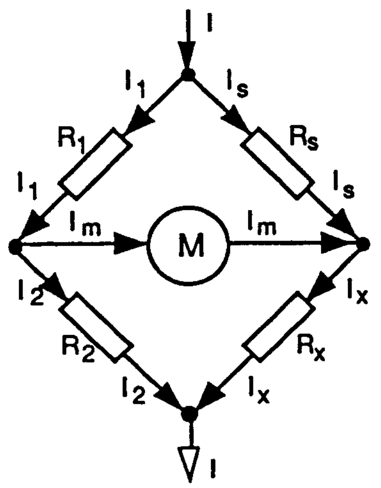


Fig 4.2.8 Circuit analysis

PRACTICAL ASPECTS

The Wheatstone Bridge circuit is the most accurate method of measuring resistance and is used very widely wherever an accurate measurement is required. It is virtually a direct reading method as the value of the calibrated standard only need by multiplied by the ratio of the ratio arms to achieve the unknown value. The ratio arms are normally arranged such that the ratios are in multiples of ten, to make calculation extremely simple.

The choice of ratio depends on several factors. Obviously the reading should be the most accurate obtainable and so the ratio should be chosen such that all the decades of the resistance standard can be used. As the method is a null one, the ratio arms should also be chosen such that the current in the detector when the bridge is slightly out of balance is maximum. This is examined in a future assignment.

When a Wheatstone Bridge is used to measure either very high, or very low resistances, there are some extra precautions which have to be taken and there are special forms of bridge which are used for these applications. These forms may be found explained in most texts on electrical measurements and will not therefore be dealt with here.

The inclusion of a switch in the detector branch of a bridge circuit is a very common way of achieving extra sensitivity. With no switch in circuit the meter is connected in circuit all the time and any static meter zero error will be present all the time as well. If the meter has a zero error, then adjusting the bridge for zero on the meter will include this error and thus the results will be wrong. If a switch is included it does not matter if there is a zero error on the meter as the bridge is adjusted so that there is no movement of the meter, when the switch is switched in and out. Not only does this method give a more accurate result but the sensitivity in determining out of balance current is increased, as very small variations can be detected.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 2

Question 2.1 The meter reads when the voltage at the junction of R_S and R_X is zero.

Question 2.2 R_X will be proportional to R_S provided that $+V_S$ is equal and opposite to $-V_S$.

Question 2.3 By switching the meter on and off. A small, but possibly barely measurable movement of the needle may be seen; thus indicating the presence of a small voltage.

Question 2.4 No. The accuracy of measurement depends upon the two voltage sources and the standard resistor.

Question 2.5 Yes. The meter resistance will affect the sensitivity of the meter, making the value of resistance more difficult to determine.

Question 2.6 By using another potential divider circuit using two resistors equal in value.

Question 2.7 Zero. If $R_S = R_X$ and $R_1 = R_2$ the voltages at the two junctions to which the meter is connected will be equal; there will therefore be no volt drop across the meter.

Question 2.8 No. The meter should however be very sensitive.

Question 2.9 No. The voltage across the meter is independent of the voltage source at balance. A low value source will cause a reduction in meter sensitivity.

Question 2.10 No.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 2

Question 2.11 The ratio R_1: R_2 determines the accuracy of measurements.

R_1	R_2	R_X	R_S
10kΩ	10kΩ	100Ω	101Ω
		1kΩ	0.994Ω
		10kΩ	10.21kΩ
10kΩ	1kΩ	100Ω	1.011kΩ
		1kΩ	9.9kΩ
		10kΩ	102.3kΩ
1kΩ	10kΩ	100Ω	10Ω
		1kΩ	99Ω
		10kΩ	1.015kΩ

Fig E4.2.7 Recorded results

Question 2.12 The voltage would be given by:

$$V_{ratio} = \frac{R_2}{R_1 + R_2}.V_s$$

if $R_1 = 10R_2$

$$V_{ratio} = \frac{R_2}{11R_2}.V_s$$

$$= 0.091V_s$$

Question 2.13 A ratio of $R_s = 10R_x$

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 2

Question 2.14 The voltage would be given by:

$$V_{ratio} = \frac{R_2}{R_1 + R_2}.V_s$$

if $R_1 = \frac{R_2}{10}$

$$V_{ratio} = \frac{10}{11}.V_s$$

$$= 0.91V_s$$

Question 2.15 A ratio of $R_s = \frac{R_x}{10}$

Question 2.16 Yes.

SENSITIVITY OF A WHEATSTONE BRIDGE — ASSIGNMENT 3

CONTENT

The techniques for improving the sensitivity of the basic Wheatstone Bridge are investigated.

EQUIPMENT

Qty	Designation	Description
1	TK2941M	Measurements Package
1	TK2941E	Electro-mechanical Transducers Kit Power Supply, ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 100kΩ
1	–	* Centre zero dc milliammeter
1	–	* DC Voltmeter 15V
1	–	Resistor - 100Ω, 1 Watt
1	–	Resistor - 1kΩ, 0.5 Watt

* Alternatively multimeters may be used.

PRACTICALS

3.1 Effect of Resistance Arms Value

3.2 Effect of Resistance Arms Ratio

3.3 Effect of Source Voltage Value

3.4 Effect of Detector Arm Resistance

SENSITIVITY OF A WHEATSTONE BRIDGE — ASSIGNMENT 3

OBJECTIVES

When you have completed this assignment you will:

- Understand the effect on the sensitivity of the bridge of varying the following parameters:
  - Resistance of the ratio arms
  - Ratios of the arms
  - Source voltage
  - Detector arm impedance

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the theory and operation of the basic Wheatstone Bridge and preferably have completed Assignment 2.

INTRODUCTION

In Assignment 2 the equation for balance for the Wheatstone Bridge circuit was found. This equation is always true, no matter what the values of R_1 and R_2 are, and no matter what the supply voltage is.

Also in Assignment 2, the factors determining the accuracy of measurement of the Wheatstone Bridge were discussed, and it was decided that the sensitivity of the detecting meter was an important factor. Obviously, the more sensitive the meter the smaller the out-of-balance current through the meter that can be measured.

Let us first define the term 'sensitivity' as related to a Wheatstone Bridge. What we are really after is a large change in meter indication for a small change of the standard resistance, so that the balance point of the bridge may be accurately determined.

The sensitivity of a bridge may be defined as the rate of change of meter current with small changes of the standard resistance about the balance setting.

For a given meter, with a given sensitivity let us try and determine if there are any properties of the bridge itself which affect the sensitivity and accuracy of measurement.

The parameters of the bridge circuit that can be varied are:

Resistance of ratio arms

Ratio of the arms

Resistance of meter

Source voltage

First let us keep the ratio of the arms constant, keep the load constant, and the source voltage constant, and find what effect the resistance of the arms has on the sensitivity of the bridge. For these tests use a 1kΩ resistor for R_X.

PRACTICAL 3.1

Effect of Resistance Arms Value

Set up the circuit as shown in fig 4.3.1.

Note No series resistor is included in the bridge connection for this circuit. To prevent damage, do not reduce the resistance values below those specified.

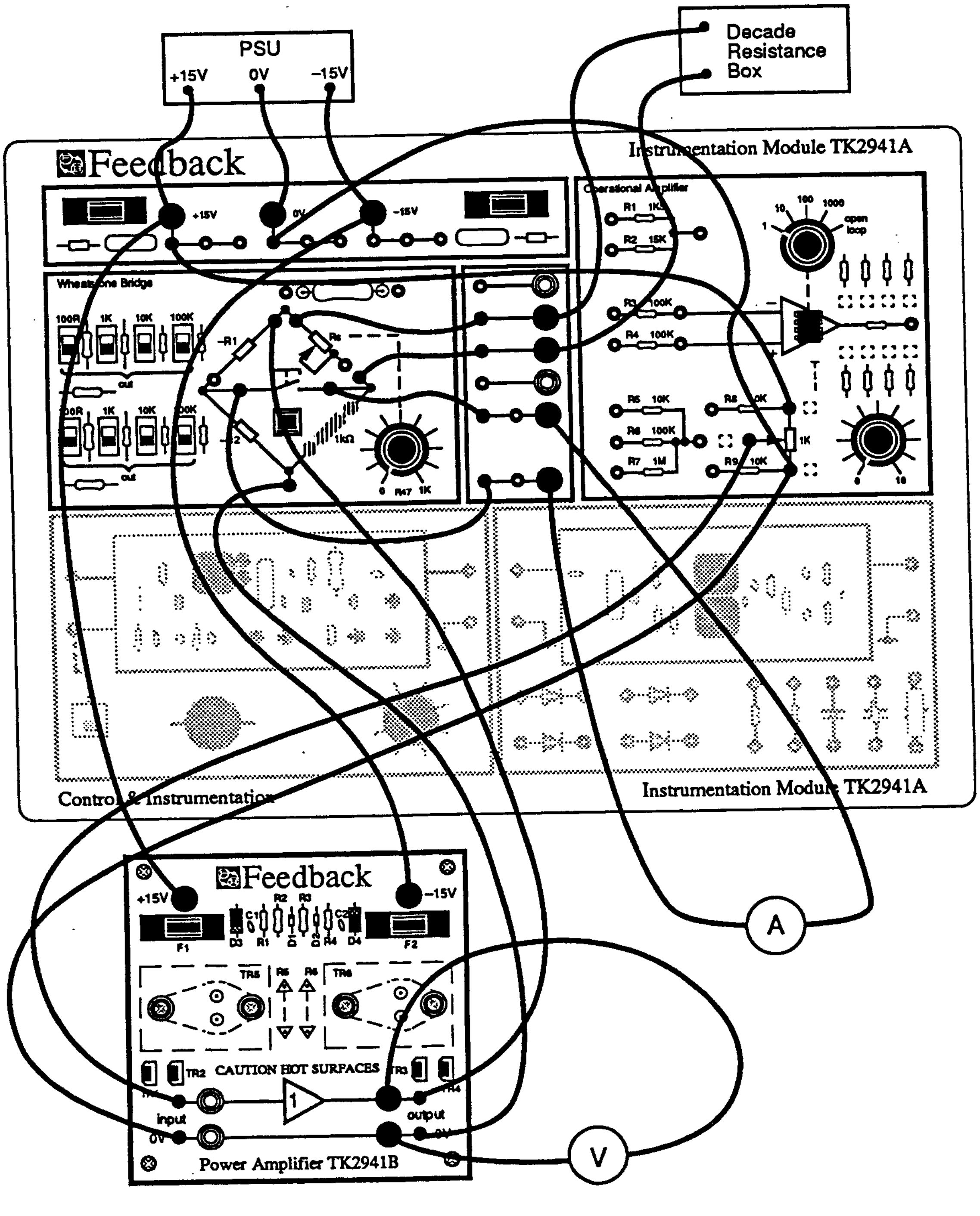


Fig 4.3.1 Wheatstone Bridge connections

On the Wheatstone Bridge set switches SW1 and SW5 'in'; and all other switches 'out'. This will set both R_1 and R_2 at 100Ω.

Ensure that the Operational Amplifier potentiometer knob controlling the dc voltage is at zero, and switch on the power supply.

Set the variable dc voltage to approximately 10V.

Balance the bridge and record the setting of R_s in your own copy of fig 4.3.2

Increase the setting of R_s by 100Ω (10%) and record the out-of-balance current flowing through the meter.

$R_1 = R_2$ (Ω)	R_s at balance (Ω)	Out of balance current (μA)
100Ω		
1kΩ		
10kΩ		
100kΩ		

Fig 4.3.2 Recorded results.

Change R_1 and R_2 to 1kΩ by setting SW2 and SW6 'in' and all other switches 'out'; repeat the balancing procedure and determine the 10% out-of-balance current as before.

Record the results in the table.

Repeat the investigation for $R_1 = R_2 = 10k\Omega$ and $R_1 = R_2 = 100k\Omega$.

Question 3.1 ***Which value of R_1 and R_2 gave the most easily found balance?***

Question 3.2 ***Which value made the balance point most difficult to find accurately?***

Question 3.3 ***Which value gave the greatest out-of-balance current for a 10% change in R_s?***

Question 3.4 ***Which gave the smallest current?***

Question 3.5 ***In your opinion which value of R_1 and R_2 gave the greatest sensitivity for the bridge?***

Question 3.6 — ***Thus, does a high value or a low value for R_1 and R_2 give greatest sensitivity?***

PRACTICAL 3.2

Effect of Resistance Arms Ratio

Next let us see what difference the ratio of R_1 to R_2 makes to the sensitivity of the bridge.

Construct a table in which to record your readings as in fig-4.3.3.

R_1 (Ω)	R_2 (Ω)	Ratio	R_S at balance (Ω)	Out of balance current (μA)
100Ω 1kΩ 10kΩ	1kΩ 10kΩ 100kΩ	1:10 1:10 1:10		
100Ω 1kΩ	10kΩ 100kΩ	1:100 1:100		
1kΩ 10kΩ 100kΩ	100Ω 1kΩ 10kΩ	10:1 10:1 10:1		
10kΩ 100kΩ	100Ω 1kΩ	100:1 100:1		

Fig 4.3.3 Recorded results.

Change R_1 to 100Ω and R_2 to 1kΩ. Balance the bridge and record the setting of R_s in your table.

Increase R_s by 10% (10Ω) and record the out-of-balance current.

Enter this in the table as well.

Repeat this procedure for R_1 = 1k and R_2 = 10k and record your results. Also repeat it for R_1 = 10kΩ and R_2 = 100kΩ (increase R_s by 10% from balance each time).

Repeat the procedure for the remaining values of R_1 and R_2 as given in fig 4.3.3.

Now compare readings for ratios of 1:100, 10:1 and 100:1 as given by the values of R_1 and R_2 in fig 4.3.3.

Sensitivity of a Wheatstone Bridge

Question 3.7 — *Within each group where R_1 and R_2 are of the same ratio, do large values for R_1 and R_2 give maximum sensitivity, or do low values?*

Question 3.8 — *Which ratio gives the greatest sensitivity?*

Question 3.9 — *Is the sensitivity obtained when the ratio is 1:1 (see fig 4.3.2) greater or less than that achieved with a 1:10 ratio?*

Question 3.10 — *Does the sensitivity for a ratio of 1:10 correspond with that for a ratio of 10:1?*

Question 3.11 — *Is the 1:100 ratio sensitivity the same as the 100:1 ratio one?*

PRACTICAL 3.3

Effect of Source Voltage Value

Now let us investigate how the source voltage (Vs) affects the sensitivity.

Construct a table as shown in fig 4.3.4.

R_1 (Ω)	R_2 (Ω)	V_S (V)	Balance (Ω)	Out of balance current (µA)
100Ω	100Ω	12 10 5		

Fig 4.3.4 Recorded results.

Reset the ratio to 1:1 with the ratio arms at $R_1 = R_2 = 100\Omega$ and balance the bridge.

Set V_S to 12V.

Increase R_s by 100Ω and record the out-of-balance current.

Now return the bridge to balance and reduce V_s to 10V.

Again increase R_s by 100Ω and record the current.

Repeat for $V_s = 5V$.

Question 3.12 ***Does the out-of-balance current change with the source voltage?***

Question 3.13 ***Does a high V_s or a low V_s give the greatest sensitivity?***

PRACTICAL 3.4

Effect of Detector Arm Resistance

The last parameter that can be varied is the detector arm resistance. The resistance of a meter is normally fixed by the physical construction of the instrument, so the only way of changing the resistance of the meter is to change the meter itself.

The detector arm resistance can be effectively increased by adding a resistor in series with the meter.

Question 3.14 ***Will this change the voltage across the detector arm?***

Check your answer by connecting a 100Ω resistor in series with the meter and measuring the voltage.

Question 3.15 ***With the voltage unchanged but with an increase in resistance what happens to the current in the detector arm?***

Question 3.16 ***Does this make the bridge more or less sensitive?***

Check your answer by connecting a 100Ω resistor in series with the meter and measuring the voltage.

SUMMARY

Let us summarise the findings:

- The lower the resistances of the arms the greater the sensitivity of the bridge.
- The lower the ratio of the arms the greater the sensitivity (1:1 is best).
- The higher the source voltage the greater the sensitivity.
- The lower the detector arm resistance the greater the sensitivity.

PRACTICAL ASPECTS

If the best accuracy is required from a Wheatstone Bridge then the sensitivity of the bridge becomes an important factor in achieving this. There are however important differences between the terms 'sensitivity' and 'accuracy' and they are not interchangeable. A measuring instrument may be sensitive without being accurate, but is unlikely to be accurate without being sensitive. As an example of this imagine a 1V fsd meter, the movement of which has an extremely good suspension with virtually negligible friction and the scale on it is particularly large (say 20cm scale length). With this length of scale each 0.1V division would be spaced at 20mm and each 0.01V division would be 2mm apart. Suppose this meter were connected to a standard voltage source of 1.000V and the reading on the meter of 0.985V. This represents an inaccuracy of 1.5%. However, suppose the source voltage was changed to 1.003V before a detectable movement of the needle was obtained. This represents a sensitivity of 2mV. This meter is thus extremely sensitive but not extremely accurate.

Consider another meter with an inferior suspension system with some friction and with a scale length of only 5cm. This gives 5mm per 0.1V division and 0.5mm per 0.01V division. Connecting this meter to the standard 1.000V source gives a reading of 0.99V on the meter, however the source has to be changed to 1.02V before any detectable change is apparent. This meter then has a poor sensitivity and because of this and because the scale divisions are so close together and difficult to read it also has poor overall accuracy even though the initial reading of 0.99V is closer to the true 1.00V than the 0.985V reading from the large meter.

What is needed is a large meter with the good suspension and thus high sensitivity of the first example, but with an improved winding to give a better accuracy. Such an instrument would have the desirable properties of accuracy and sensitivity.

With a bridge circuit you are not performing an actual measurement. The object is to detect the zero position. Thus the accuracy of the meter is not of the greatest importance providing there is a switch in the detector branch as explained before. Now the problem becomes one of comparing the current through the detector branch when the switch is open with the zero current that flows in the meter when the switch is closed. The meter used for the detector should therefore have the greatest sensitivity possible to allow small differences of current to be detected. This normally means a large meter with a very good friction-free suspension and movement.

It would seem fairly logical that if the overall sensitivity of the bridge depends on being able to detect small changes of current near to zero, then the lower the value of full scale deflection of the meter the better will be the sensitivity. Unfortunately this is not so, as meters with low full scale deflection values invariably have high resistances. The reason for this is as follows:

The fsd of a moving coil meter depends on the number of turns in the coil and on the physical disposition of those turns. When the size and disposition of the turns are not changed, the deflection of the meter is proportional to the number of turns in the coil, thus doubling the number of turns will double the deflection. However, to get twice as many turns in the same space so as to keep the physical properties of the coil the same, the area of the wire must be halved. Also doubling the number of turns will increase the length of the wire by a factor of two.

Thus as resistance is given by

$$R = \frac{\rho l}{a}$$

then if 'l' is doubled and 'a' is halved R will increase four-fold, i.e the square of the ratio of increase in turns.

As stated above, the fsd is proportional to the number of turns and thus will be proportional to the square root of the resistance of the meter. As the sensitivity of the meter goes up then so does its resistance and the sensitivity of the bridge will be reduced from the expected value because of this increase in resistance. There will be an optimum point when the total sensitivity of the bridge and detector system will be maximum. This maximum will occur when the power transferred from the bridge to the detector is maximum, as it requires power to deflect the meter needle and it takes maximum power to produce maximum deflection. This maximum occurs when the load impedance (the meter, in this case) is equal to the source impedance (the bridge). The method for determining the bridge impedance is shown in Appendix C.

From the assignment you found that the sensitivity of the bridge was increased as the values of the resistances were lowered. If you take this to its limit it would seem that maximum sensitivity would occur when the resistance values are zero. However in this state the meter would be short circuited and no current flows in it. Another disadvantage of making the resistances too low in value is that as their resistances are decreased the total current taken from the source increases. The source is commonly a battery and this large current drain can discharge it quickly. In addition to this the large currents flowing in the resistances of the bridge give rise to high power dissipations and increases in temperature in these components. These temperature increases can cause drift in the values of the resistances and thus errors in the results from the bridge. A compromise must thus be reached in this respect as well.

A mathematical analysis of the factors governing the sensitivity of a Wheatstone Bridge is contained in Appendix C, for reference. You will see that the overall sensitivity depends on a combination of all the factors discovered and that experience is needed in the choice of values to make this as high as possible.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 3

$R_1 = R_2$ (Ω)	R_s at balance (Ω)	Out of balance current (μA)
100Ω	991	155
1kΩ	996	121
10kΩ	993	38
100kΩ	990	5

Fig E4.3.2 Table of typical results.

Question 3.1 The easiest balance is obtained with R1 = R2 = 100Ω.

Question 3.2 The hardest balance is obtained with R1 = R2 = 100kΩ.

Question 3.3 The highest out-of-balance current is obtained with R1 = R2 = 100Ω.

Question 3.4 The smallest current is with R1 = R2 = 100kΩ.

Question 3.5 R1 = R2 = 100Ω.

Question 3.6 Low values for R1 and R2 give the greatest sensitivity to the bridge.

R_1 (Ω)	R_2 (Ω)	Ratio	R_s at balance (Ω)	Out of balance current (μA)
100Ω	1kΩ	1:10	100	73
1kΩ	10kΩ	1:10	99	42
10kΩ	100kΩ	1:10	99	8.5
100Ω	10kΩ	1:100	10	13
1kΩ	100kΩ	1:100	10	6
1kΩ	100Ω	10:1	10.1kΩ	90
10kΩ	1kΩ	10:1	10.1kΩ	60
100kΩ	10kΩ	10:1	10.1kΩ	11
10kΩ	100Ω	100:1	100kΩ	7
100kΩ	1kΩ	100:1	100kΩ	5

Fig E4.3.3 Table of typical results

TYPICAL RESULTS AND ANSWERS ASSIGNMENT 3

Question 3.7 Low values give maximum sensitivity.

Question 3.8 The ratio 1:10 gave the greatest sensitivity.

Question 3.9 The out-of-balance current with a 1: 1 ratio is greater than with a 1:10 ratio. Hence the sensitivity with a 1:1 ratio is greater.

Question 3.10 The sensitivity for a 10:1 ratio is less than with a 1:10 ratio. This is caused by the increased impedance of Rs when the ratio is 10:1.

Question 4.3.11 Again the sensitivity for the 1:100 ratio is slightly greater than with a 100:1 ratio.

R_1 (Ω)	R_2 (Ω)	V_s (V)	Balance (Ω)	Out of balance current (μA)
100Ω	100Ω	12	991	187
		10	991	154
		5	991	76

Fig E4.3.4 Table of typical results

Question 3.12 The out-of-balance current does vary with the source voltage.

Question 3.13 A high source voltage gives greater sensitivity.

Question 3.14 The voltage will change slightly due to the impedance of the ratio arms and the Rs/Rx arm. If the impedance of these arms is low compared to that of the meter, the voltage change is negligible.

Question 3.15 The current will drop if the meter impedance is increased.

Question 3.16 This makes the bridge less sensitive.

THE WHEATSTONE BRIDGE AT AC — ASSIGNMENT 4

CONTENT

The behaviour of a Wheatstone Bridge when supplied from an ac source is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Function Generator 10kHz Sine 20V pk-pk
1	–	Decade Resistance 1Ω to 100kΩ
1	–	*AC Voltmeter 5mV-5V
1	–	Resistor – 1kΩ, 0.5W

* Alternatively a multimeter or oscilloscope may be used.

PRACTICALS

4.1 The Wheatstone Bridge at ac

4.2 Effect of Frequency Variation

THE WHEATSTONE BRIDGE AT AC — ASSIGNMENT 4

OBJECTIVES

When you have completed this assignment you will:

- Know that the Wheatstone Bridge circuit is suitable for use with an ac source
- Understand what is meant by the term 'null'
- Appreciate the importance of correctly determining the 'null' position when using an ac detector

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the theory and operation of the basic Wheatstone Bridge and preferably have completed Assignments 2 & 3
- Be familiar with the operation of complex ac circuits and the notation used to describe them

The Wheatstone Bridge at AC — Assignment 4

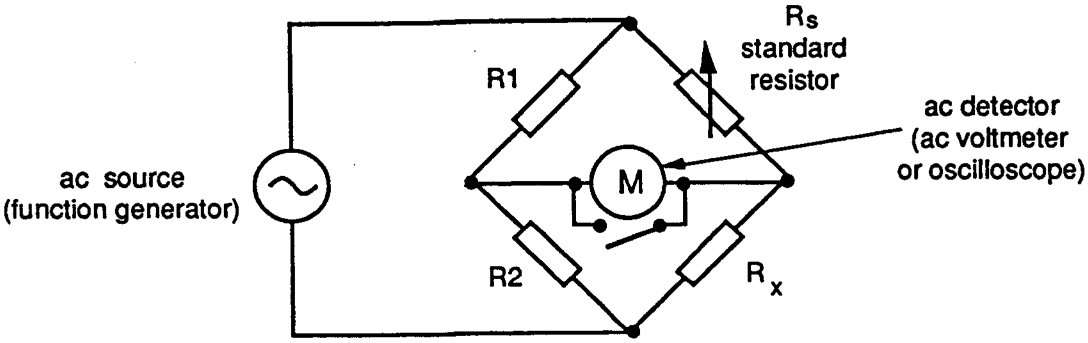


Fig 4.4.1 Wheatstone bridge connected to ac source.

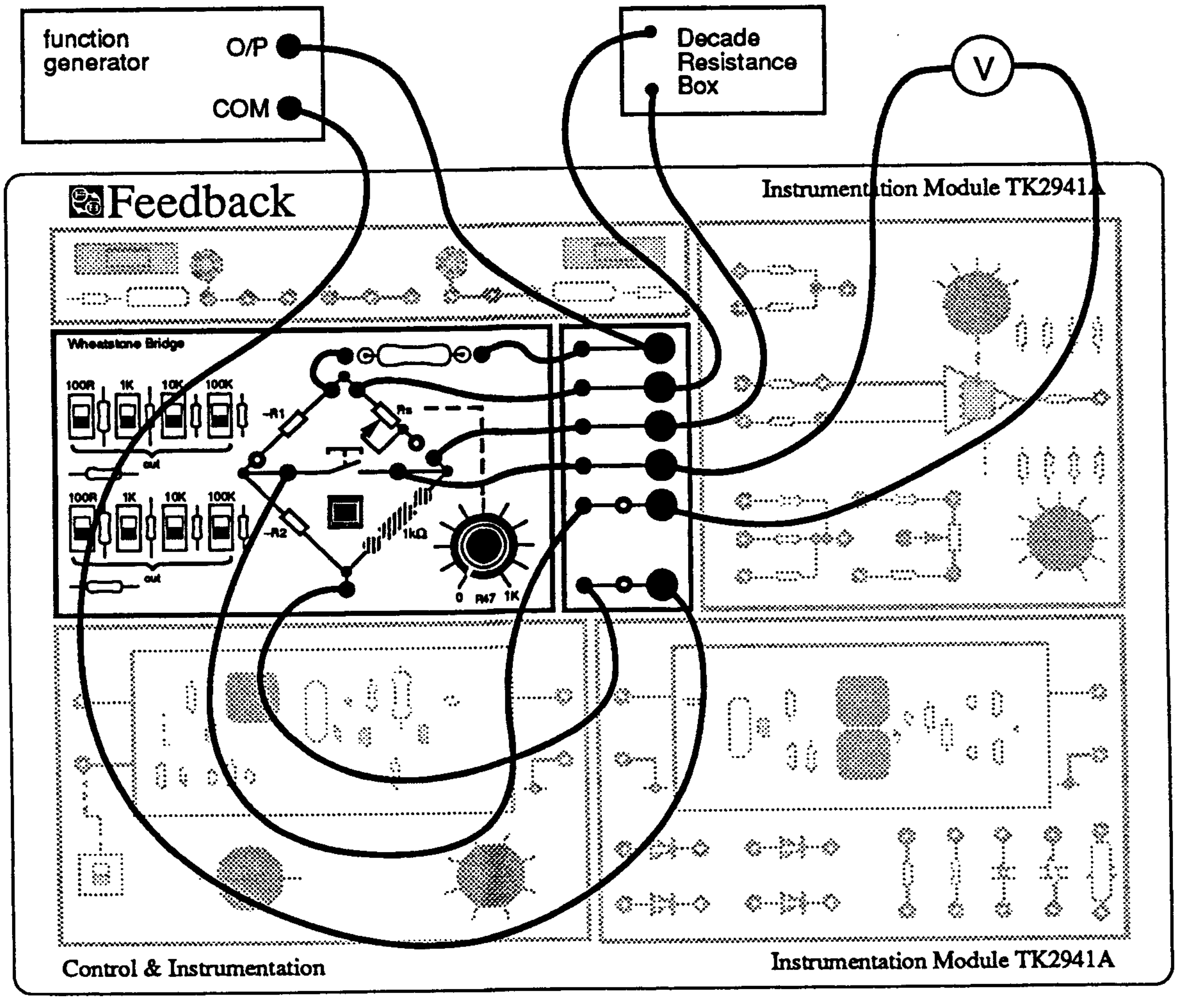


Fig 4.4.2

PRACTICAL 4.1

The Wheatstone Bridge at ac

The Wheatstone Bridge operates successfully using a dc source, let us now determine if there are any differences in its operation at ac.

Let us see if the balance equation is changed when an ac source is used. Connect up the circuit of fig 4.4.1 as shown in the connection diagram fig 4.4.2.

On the Wheatstone Bridge set switches SW2 and SW6 'in' and all other switches 'out'. This will set both R_1 and R_2 to 1kΩ.

For these tests use a 1kΩ resistor for R_X.

On the function generator set the source frequency to 1kHz and the voltage to 3V rms.

Make a table similar to fig 4.4.3 in which to record your results.

R_1 (kΩ)	R_2 (kΩ)	R_S (kΩ)	R_X (kΩ)	Out of balance voltage (mV)	$\frac{R_1}{R_2}$	$\frac{R_s}{R_x}$
1	1		1		1	
10	1		1		10	
100	1		1		100	
1	10		1		0.1	
10	10		1		1	
100	10		1		10	

Fig 4.4.3 Recorded results.

Balance the bridge and record the setting of R_s.

Increase the setting of R_s by 10% and record the out-of-balance voltage across the detector.

Repeat the procedure for other values of R_1 and R_2 as shown in fig 4.4.3.

Use your voltmeter to monitor the ac source voltage before each new ratio setting and ensure that the value is maintained constant at 3V rms throughout this assignment.

Calculate the ratios R_1/R_2 and R_s/R_x and enter them in the table.

Question 4.1 *What is the relationship between these two ratios?*

Question 4.2 *Is this the same relationship as for the dc case (see Assignment 2)?*

Question 4.3 *From your results do high values or low values of R_1 and R_2 give the greatest sensitivity of the bridge?*

Question 4.4 *What ratio of R_1 and R_2 gives the greatest sensitivity?*

Question 4.5 *Do these conditions agree with those found for the dc case?*

PRACTICAL 4.2

Effect of Frequency Variation

Let us investigate whether the frequency of the source voltage affects the balance point of the bridge.

Frequency (Hz)	R_S (Ω)
100	
200	
400	
700	
1k	
2k	
4k	
7k	
10k	

Fig 4.4.4 Frequency variation.

Make a table similar to fig 4.4.4 in which to record your results.

Set the function generator to a 100Hz sine wave at approximately 3V rms.

Set $R_1 = R_2 = 1k\Omega$ and balance the bridge.

Change the frequency of the source to 200Hz at approximately 3V rms, re-balance the bridge and record the new value of R_S.

Repeat this for frequencies of 400Hz, 700Hz, 1kHz, 2kHz, 4kHz, 7kHz, 10kHz.

Question 4.6 ***Does the balance point change with frequency?***

SUMMARY

You should find that the same conditions for balance apply for ac use as for dc use for the Wheatstone Bridge circuit and that the requirements for maximum sensitivity are also the same.

The measurements using a Wheatstone Bridge circuit are virtually frequency independent and the circuit is just as valuable at ac as at dc for measuring resistance.

PRACTICAL ASPECTS

When the Wheatstone Bridge is used with an ac source several extra points have to be considered.

Fig 4.4.5 shows a bridge with an ac source of $V_m \sin \omega t$. Z_1, Z_2, Z_s and Z_x are the arms of the bridge and because ac is used, may not be pure resistances. Z_L is the load impedance.

Now the voltage across Z_2 is given by:

$$V_{BD} = \frac{Z_2}{Z_1 + Z_2}.V_m \sin\omega t$$

and the voltage across Z_X is given by:

$$V_{CD} = \frac{Z_X}{Z_S + Z_X}.V_m \sin\omega t$$

and the voltage across the load, Z_L, is given by:

$$V_{BC} = (\frac{Z_2}{Z_1 + Z_2} - \frac{Z_X}{Z_S + Z_X}).V_m \sin\omega t$$

so the current, i_L through the load will be:

$$i_L = (\frac{Z_2}{Z_1 + Z_2} - \frac{Z_X}{Z_S + Z_X}).\frac{V_m \sin\omega t}{Z_L}$$

For balance we wish i_L to be zero

i.e $$\frac{Z_2}{Z_1 + Z_2} - \frac{Z_x}{Z_S + Z_X} = 0$$

therefore:

$$Z_2(Z_S + Z_X) = Z_X(Z_1 + Z_2)$$

$$Z_2Z_S + Z_2Z_X = Z_XZ_1 + Z_XZ_2$$

$$Z_2Z_S = Z_XZ_1$$

$$\frac{Z_1}{Z_2} = \frac{Z_S}{Z_X}$$

which is the normal form of bridge equation.

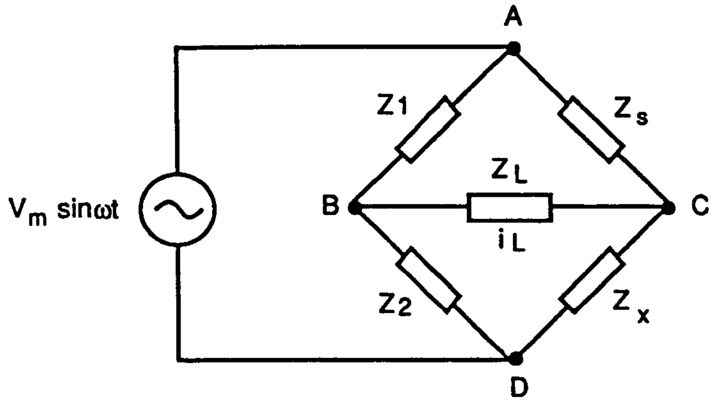


Fig 4.4.5 Bridge with ac source

From the equation for i_L above it can be seen that it is of the form

$$i_L = f(Z)\, V_m \text{ Sin } \omega t.$$

which is a sinusoidal current. Thus it must be measured with an ac meter. An ac meter does not respond to the direction of the current, only to its amplitude, so instead of adjusting the bridge to the point where the reading passes through zero, the point of null is found instead (the minimum reading of the meter).

For a true balance where:

$Z_1 = Z_s$

$Z_2 = Z_x$

$f(Z) = 0$ and $i_L = 0$, giving a true zero reading for the null point. However Z_s Z_x etc may not be pure resistances. For example, consider the situation below:

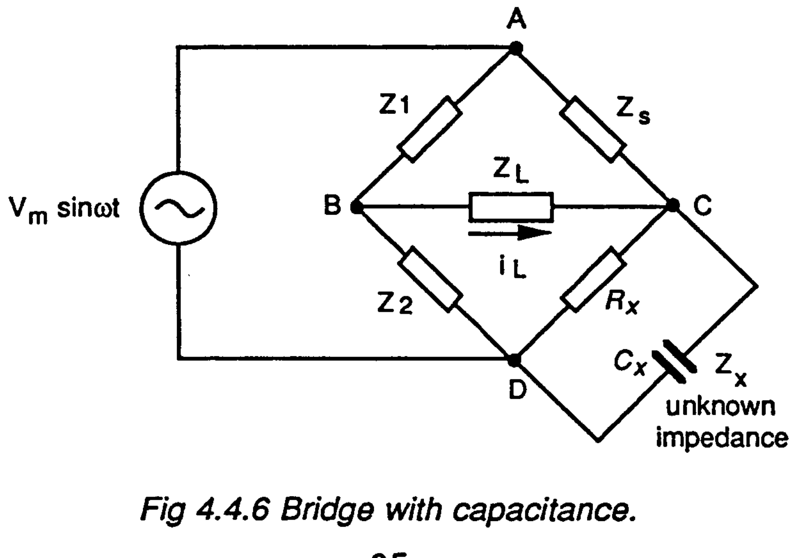


Fig 4.4.6 Bridge with capacitance.

Suppose the bridge was constructed so that the ratio arms were pure resistances and the standard was also constructed to minimise such things as stray capacitances, etc. These impedances represented in fig 4.4.6 may therefore be considered as pure resistances.

Suppose that the component to be measured is predominantly resistive, but has long leads with an appreciable stray capacitance. This is represented by the parallel capacitor shown as C_X.

Now we can say: $Z_1 = R_1$

$Z_2 = R_2$

$Z_s = R_s$

Z_x = impedance of Rx in parallel with Cx

and now for true balance

$$Z_X = \frac{Z_S Z_2}{Z_1}$$

but Z_X has a real part and an imaginary part i.e

$$\frac{1}{Z_X} = \frac{1}{R_X} + j\omega C_X$$

and for true balance both the real parts and the imaginary parts must correspond for equality. Thus it is impossible for a true zero balance to be achieved if the imaginary parts (reactive parts) are not balanced out in an ac bridge. To balance out the imaginary part e.g stray capacitance, a capacitor must be connected in parallel with the standard R_X and adjusted so that its value matches that of the strays (multiplied by the ratio of the bridge of course).

R_1 (kΩ)	R_2 (kΩ)	R_s (kΩ)	R_x (kΩ)	Out of balance voltage (mV)	$\frac{R_1}{R_2}$	$\frac{R_s}{R_x}$
1	1	1	1	74.6	1	1
10	1	10	1	21.3	10	10
100	1	100	1	2.8	100	100
1	10	0.1	1	22	0.1	0.1
10	10	1	1	76.8	1	1
100	10	10	1	24	10	10

Fig E4.4.3 Typical results.

Question 4.1

$$\frac{R_1}{R_2} = \frac{R_S}{R_X}$$

Question 4.2 This is the same relationship as for the dc case.

Question 4.3 Low values give best sensitivity. The meter used for the out-of-balance voltage readings was an ac voltmeter, and had a high input impedance. Consequently the effect of the detector loading the circuit cannot really be seen in these results.

Question 4.4 A ratio of R1/R2 = 1 gives greatest sensitivity.

Question 4.5 Yes.

Question 4.6 No: the balance point is independent of frequency.

Frequency (Hz)	R_S (kΩ)
100	1.001
200	1.001
400	1.001
700	1.001
1K	1.001
2K	1.001
4K	1.001
7K	1.001
10K	1.001

Fig E4.4.4 Typical frequency results

THE OPERATIONAL AMPLIFIER — ASSIGNMENT 5

CONTENT

The operation of the Operational Amplifier is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	–	Power Supply, ±15V dc *(eg Feedback PS446)*
2	–	DC Voltmeter 15V

* Alternatively two multimeters may be used.

PRACTICALS

5.1 The basic Op Amp

5.2 Common Mode Gain

THE OPERATIONAL AMPLIFIER — ASSIGNMENT 5

OBJECTIVES

When you have completed this assignment you will:

- Understand the operation of the basic operational amplifier.
- Know how to connect up an operational amplifier to act as a voltage amplifier.
- Understand the terms 'differential gain' and 'common mode gain'.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the operation of the potential divider circuit.

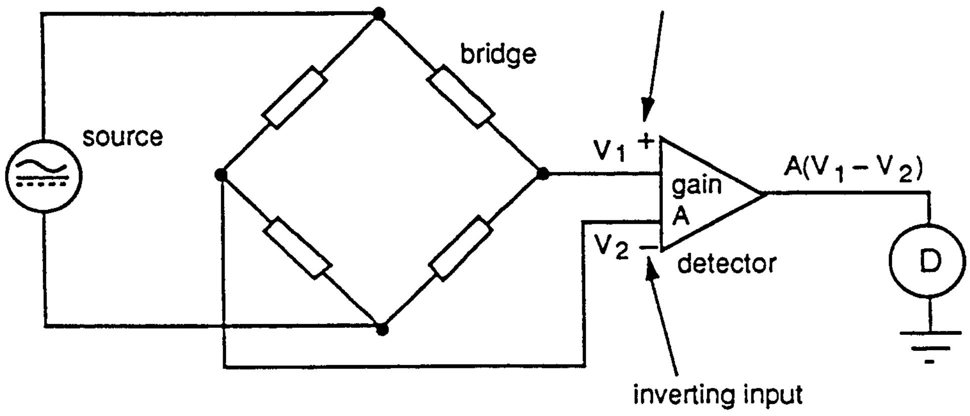


Fig 4.5.1

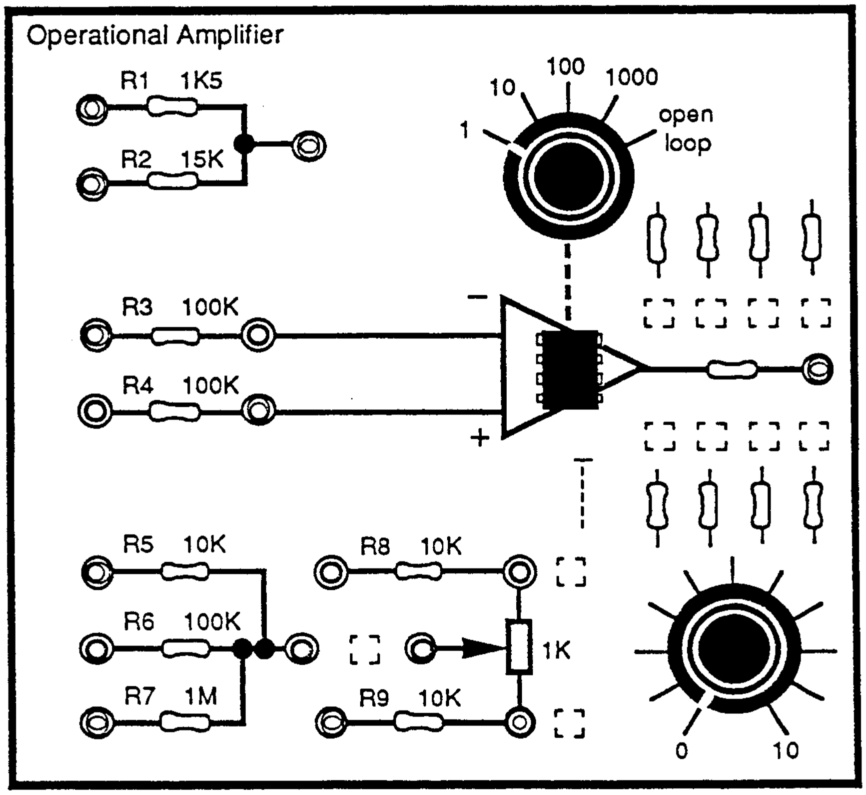


Fig 4.5.2 Operational Amplifier

INTRODUCTION

The output from a Wheatstone Bridge circuit is of the form of a voltage difference between the junction of the ratio arms and the junction of the standard and the unknown resistors. When a detector is connected between these junctions a current will flow through the detector and the magnitude of the current will depend on the amount the bridge is out of balance and on the factors governing the sensitivity.

To obtain greater sensitivity with a given bridge and detector it is possible to amplify the output voltage difference using an amplifier which has a differential input and then apply this amplified signal to the detector. The amplifier will convert small differences in input voltage into a much larger voltage across the detector, hence the sensitivity of the system will be greatly increased. This is shown in fig 4.5.1.

First let us examine the Operational Amplifier on the TK2941A Instrumentation Module, shown in fig 4.5.2

The main amplifying part of the circuit is that shown in fig 4.5.3. This comprises an integrated circuit operational amplifier with differential inputs. The gain of the amplifying stage is determined by external components and is set by the switch on the panel.

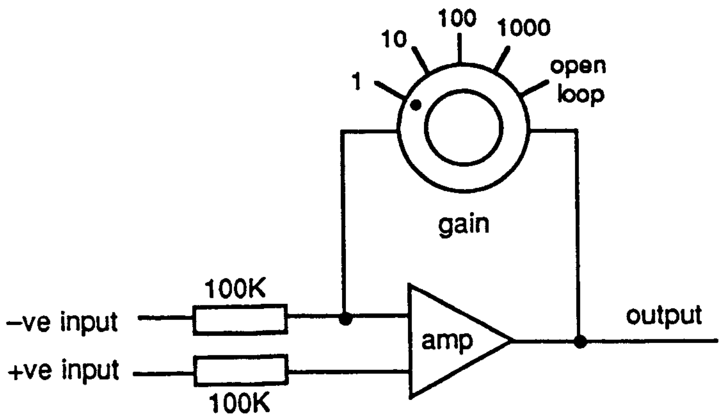


Fig 4.5.3 Main amplifier

PRACTICAL 5.1

The Basic Op Amp

Connect up the circuit as shown in fig 4.5.4.

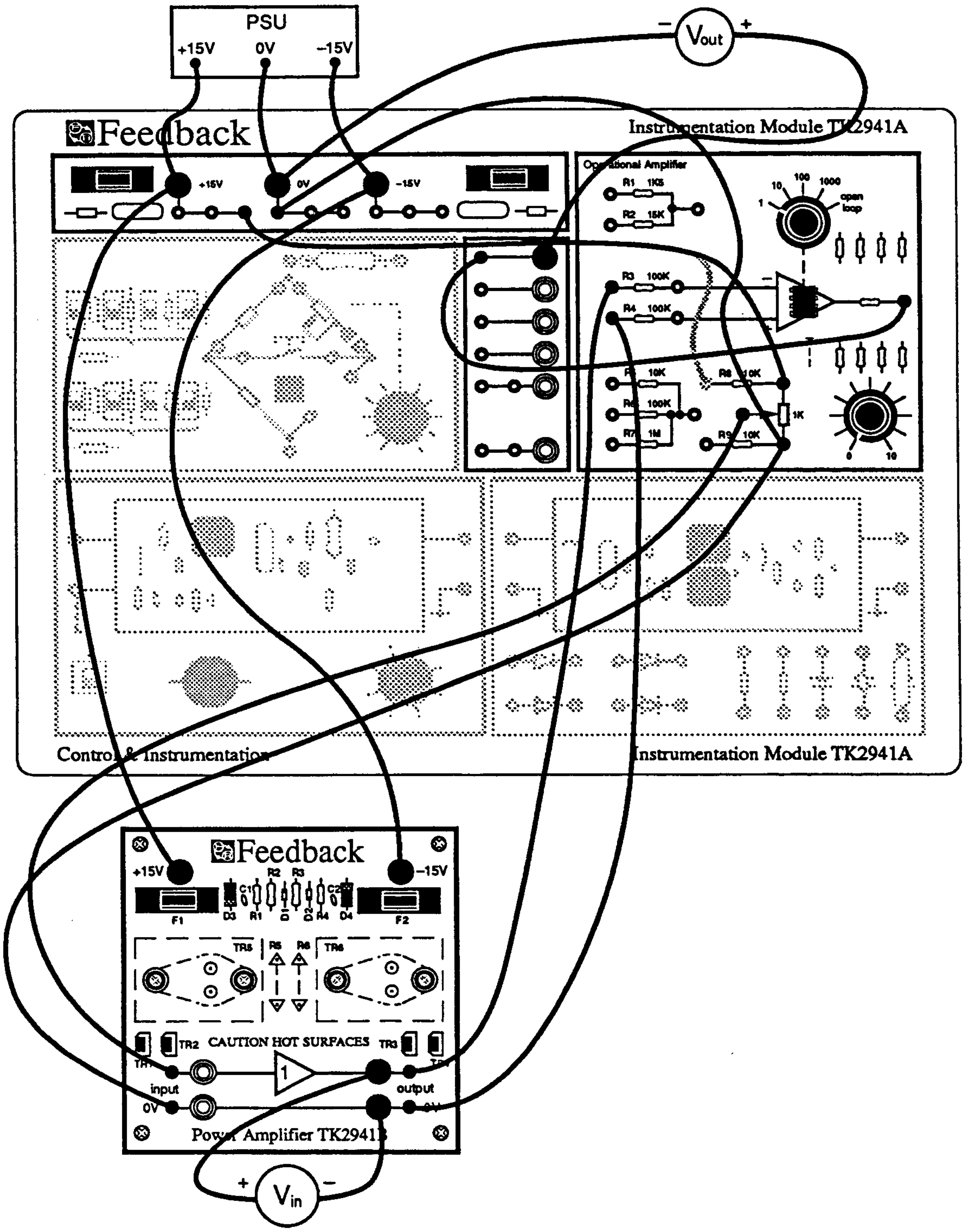


Fig 4.5.4 Connection diagram

Set the potentiometer control to zero.

Set the gain control to 1.

Switch on the power supply.

With the variable dc input voltage to the amplifier at zero, measure the output voltage from the amplifier. Record your readings in your own copy of fig 4.5.5.

Slowly increase the variable dc voltage between the two input terminals to 1V. Record the output voltage of the amplifier.

Repeat this procedure for voltages of 2, 3 and 4V dc between the inputs.

Return the potentiometer control to zero and reverse the input connections to the amplifier.

Repeat the experiment and record the readings in your table.

Voltage between Inputs V_{in} (V)	Gain Setting	Output Voltage V_{out} (V)
0	1	
1		
2		
3		
4		
–1		
–2		
–3		
–4		

Fig 4.5.5 Recorded results

Question 5.1 ***What relationship is there between the output and input voltages?***

Question 5.2 ***What happens to the output voltage when the input voltage is inverted?***

Switch off the power supply and transfer the connection from the +15V terminal, shown shaded in fig 4.5.4, to the other end of R8.

Switch on the power supply.

Set the gain of the amplifier on the module to 10.

With the potentiometer set to give 0V input measure the output voltage. Record the reading in your own copy of a table such as in fig 4.5.6.

Input Voltage (V)	Gain Setting	Output Voltage (V)
0	10	
0.5	10	
1.0	10	
−0.5	10	
−1.0	10	

Fig 4.5.6 Recorded results

Reset the potentiometer to give 0.5V input, and measure the output voltage.

Repeat this for a setting of 1V, and for settings of 0, 0.5V and 1V with the input connections reversed.

Repeat the previous procedure with input voltages of 0, 0.05 0.1V, for a gain setting of 100.

Question 5.3 ***Does the output voltage have the same relationship to the input voltage as before?***

Question 5.4 ***How are they related?***

You should find that the voltage between the output terminal and the earth terminal is proportional to the voltage difference between the two input terminals and that the constant of proportionality is set by the gain setting of the amplifier.

You should have also discovered that reversing the two inputs causes a reversal of the polarity of the output.

Question 5.5 ***What voltage difference between the inputs gives an output voltage of zero volts?***

Question 5.6 ***If an amplifier such as this is used with a bridge in a circuit of the type of fig 4.5.1 what would be the detector reading when the bridge is balanced?***

Question 5.7 — ***If the gain of the amplifier is say 10, and the bridge is slightly out of balance such that the voltage between the amplifier inputs is 10mV, what would be the magnitude of the voltage across the detector?***

Question 5.8 — ***Does the amplifier give greater or less sensitivity to the bridge circuit?***

Thus an amplifier that is to be used with a bridge circuit must have differential inputs and the sensitivity of the bridge-amplifier circuit as a whole will be greater than that of the bridge alone by a factor of the differential gain of the amplifier.

Let us see if there are other requirements for this amplifier. Consider the circuit of fig 4.5.7(a).

This represents a possible condition for a bridge circuit.

Question 5.9 — ***Is the bridge balanced?***

Question 5.10 — ***What should the output voltage be?***

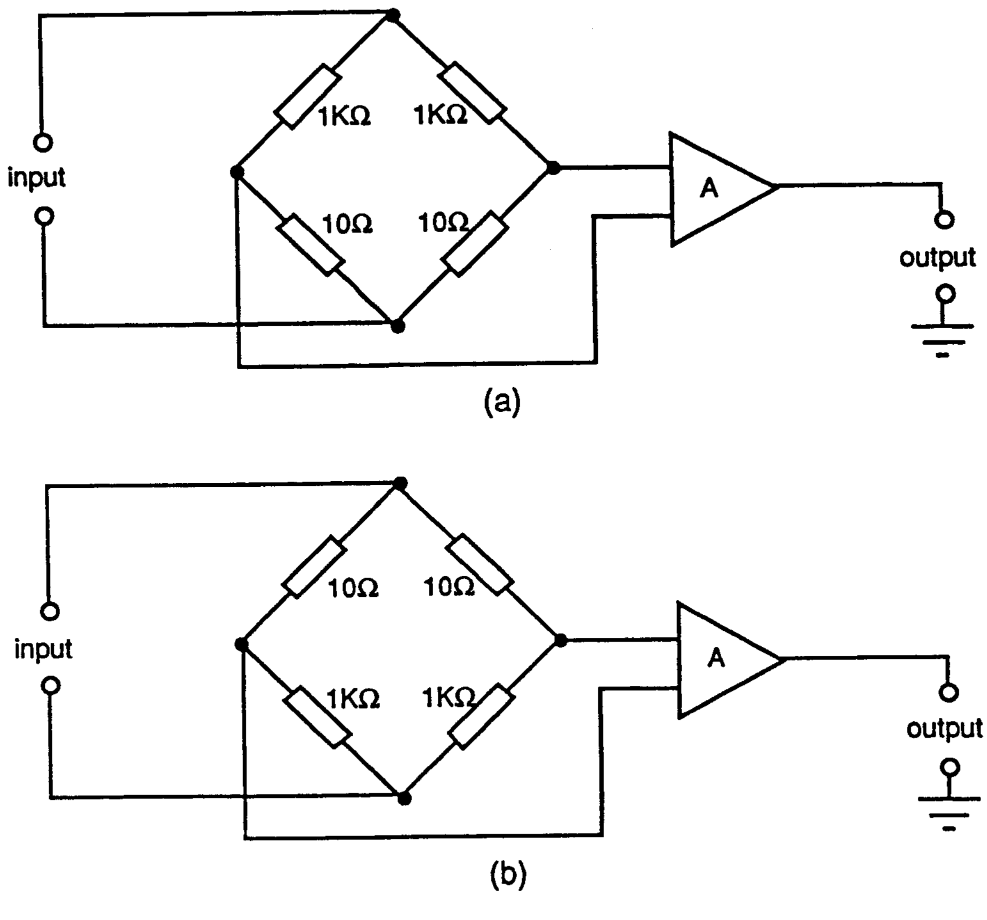


Fig 4.5.7

Question 5.11 ***Although the voltage difference between the amplifier inputs is zero, what would be the voltage between the amplifier inputs and earth if, say the input voltage to the bridge was 10 volts?***

Now consider fig 4.5.7(b).

Question 5.12 ***Is this bridge balanced?***

Question 5.13 ***What should be the output voltage?***

Question 5.14 ***What is the voltage between the amplifier inputs and earth for an input voltage of 10 volts to the bridge?***

Thus it can be seen that the amplifier output voltage must stay constant irrespective of the common voltage level on the inputs to the amplifier. Its ability to do this is expressed by the 'common mode gain' which should be low for a good amplifier.

PRACTICAL 5.2

Common Mode Gain

Let us examine our amplifier for common mode gain.

Ensure that the variable dc voltage is zero and connect up the circuit of fig 4.5.8. Set the gain of the amplifier to 1.

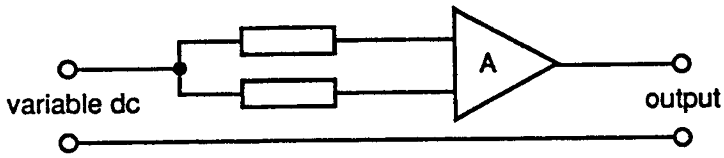


Fig 4.5.8 Common mode amplifier

Measure the output voltage and record it in your own copy a table such as fig 4.5.9.

Repeat the procedure for variable dc inputs of 2V, 4V, 6V, 8V and 10V.

Reset the variable dc voltage to zero and change the gain setting to 10. Repeat the above procedure for an input of 10V and record your results.

Take readings as before for gain settings of 100 and 1000.

Question 5.15 ***Do your output voltage readings correspond with the values expected?***

Gain Setting	Common Mode Voltage (V)	Output Voltage (V)
1	0	
	2	
	4	
	6	
	8	
10	10	
	0	
100	10	
	0	
	10	

Fig 4.5.9 Recorded results

Question 5.18 ***Does the gain setting affect the output?***

Question 5.19 ***Do you think the amplifier is good or bad as regards common mode gain?***

Because the change in output voltage is very small for large changes in common mode input voltage the amplifier is suitable for use as a bridge amplifier and errors due to the amplifier will be small. This factor is sometimes expressed the other way round, as 'common mode rejection'. This figure should be high for a good amplifier.

PRACTICAL ASPECTS

The amplifier used in a system to enhance the sensitivity of a transducer must meet several requirements. Apart from providing the required amount of amplification needed it must have excellent stability, both of gain and voltage and must introduce negligible distortion. It must have an output impedance low enough to enable the required load to be connected to it without upsetting the output of the amplifier. It should also have a wide dynamic range and a high common mode rejection ratio (low common gain).

Very often an operational amplifier type of circuit is used as the transducer amplifier. The theory of such a circuit may be found in many electronics textbooks Briefly it comprises a high gain amplifying block with differential inputs. The input impedance of the basic amplifier is as near to infinite as it can be made and the output impedance should be as close to zero as possible.

The differential gain of the basic amplifier should be extremely high, and its common mode gain as low as possible. With such an amplifier, see fig 4.5 10(a), the gain can be fixed to that required by the transducer by the connection of external input and feedback resistors as shown in fig 4.5.10(b).

For the circuit of fig 4.5 10(b) the differential gain is given by the expression:

$$V_{out} = \frac{R_f}{R_j}(V_{in2} - V_{in1})$$

ie

$$\frac{V_{out}}{V_{in2} - V_{in1}} = \frac{R_f}{R_j}$$

and thus the gain is determined by the choice of the resistors R_f and R_i.

A more detailed analysis is given in Appendix D.

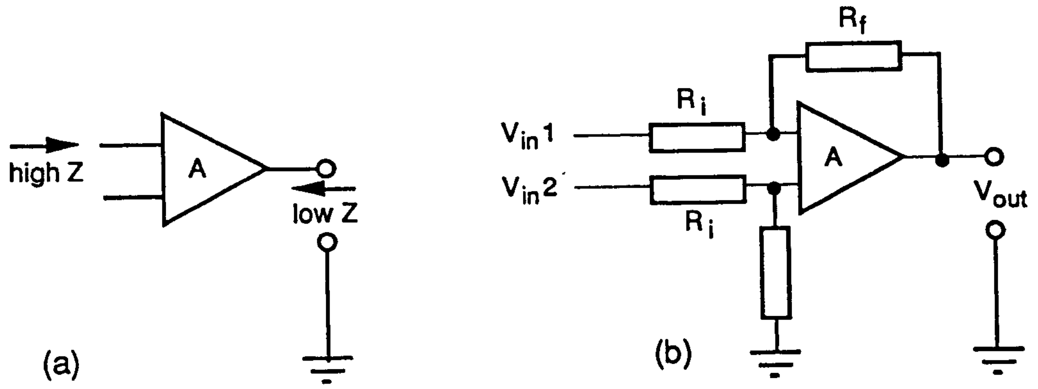


Fig 4.5.10 Differential gains

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 5

Voltage between Inputs V_{in} (V)	Gain Setting	Output Voltage V_{out} (V)
0	1	0
1	1	1
2	1	1.98
3	1	2.97
4	1	3.97
–1	1	–1
–2	1	–2
–3	1	–3
–4	1	–3.99

Fig E4.5.5 Typical results

Question 5.1 $V_{out} = V_{in}$.

Question 5.2 The output voltage is inverted when the input voltage is inverted.

Input Voltage (V)	Gain Setting	Output Voltage (V)
0	10	0
0.5	10	4.93
1.0	10	9.9
0	10	–0
–0.5	10	–5.0
–1.0	10	–9.9
0	100	0
0.05	100	4.62
0.1	100	9.02
0	100	–0
–0.05	100	–4.41
–0.1	100	–8.95

Fig E4.5.6 Typical results

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 5

Questions 5.3 and 5.4 The output and input voltages are related by the gain:
ie $V_{out} = \text{Gain} \times V_{in}$

Question 5.5 Zero volts.

Question 5.6 Zero volts.

Question 5.7 The amplifier output voltage would be 100mV.

Question 5.8 The amplifier increases the sensitivity of the bridge.

Question 5.9 Yes the bridge is balanced.

Question 5.10 Zero volts.

Question 5.11 0.1V.

Question 5.12 Yes, the bridge is balanced.

Question 5.13 Zero volts.

Question 5.14 The inputs are both at a potential of 9.9V.

Gain Setting	Common Mode Voltage (V)	Output Voltage (V)
1	0	
	2	
	4	
	6	
	8	
10	10	
	0	
100	10	
	0	
	10	

Fig 4.5.9 Typical results

Ideally the output voltage should be 0V at every setting of gain and input voltage.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 5

Questions 5.15 and 5.16

All but the 1000 times gain give no dc offset for common mode voltage at the inputs.

Question 5.17

This is of course an excellent amplifier!

The common mode error is only noticeable at a gain of 1000 times. This makes the amplifier very suitable for most balancing applications.

In cases where the offset voltage remains constant the error voltage can be balanced out on gains of 1000. This is in fact done in various assignments.

USING THE OPERATIONAL AMPLIFIER — ASSIGNMENT 6

CONTENT

The use of the operational amplifier with a Wheatstone Bridge circuit is investigated. A balancing procedure for the bridge is discussed

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	–	Power Supply, ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 10kΩ
1	–	Resistor – 4.7kΩ, 0.5W
1	–	* DC Voltmeter 10V

* Alternatively a multimeter may be used.

PRACTICAL

6.1 Effect of Operation Amplifier on Sensitivity

USING THE OPERATIONAL AMPLIFIER — ASSIGNMENT 6

OBJECTIVES

When you have completed this assignment you will:

- Know how an operational amplifier may be used to improve the sensitivity of a Wheatstone Bridge.
- Have developed a procedure for balancing the bridge.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the operation of a Wheatstone Bridge.
- Know how an operational amplifier works and understand the terms used to describe its action.

INTRODUCTION

The use of an operational amplifier with a bridge requires some simple techniques to achieve proper results and this Assignment outlines these techniques.

PRACTICAL 6.1

Effect of Operational Amplifier on Sensitivity

Connect up the circuit of fig 4.6.1 as shown in fig 4.6.2.

For the unknown resistor use one of a value around 5kΩ.

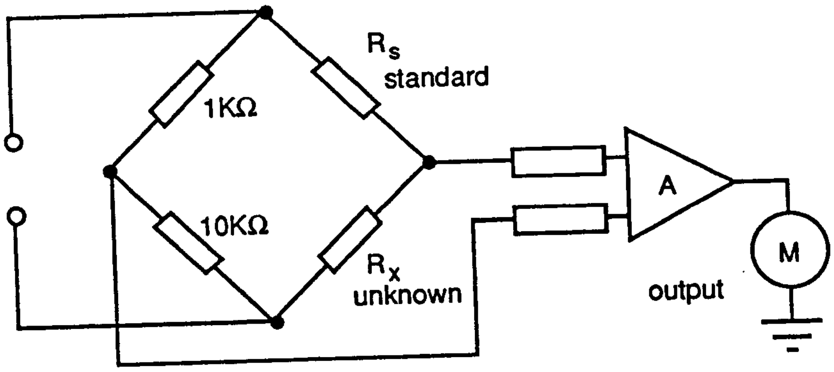


Fig 4.6.1

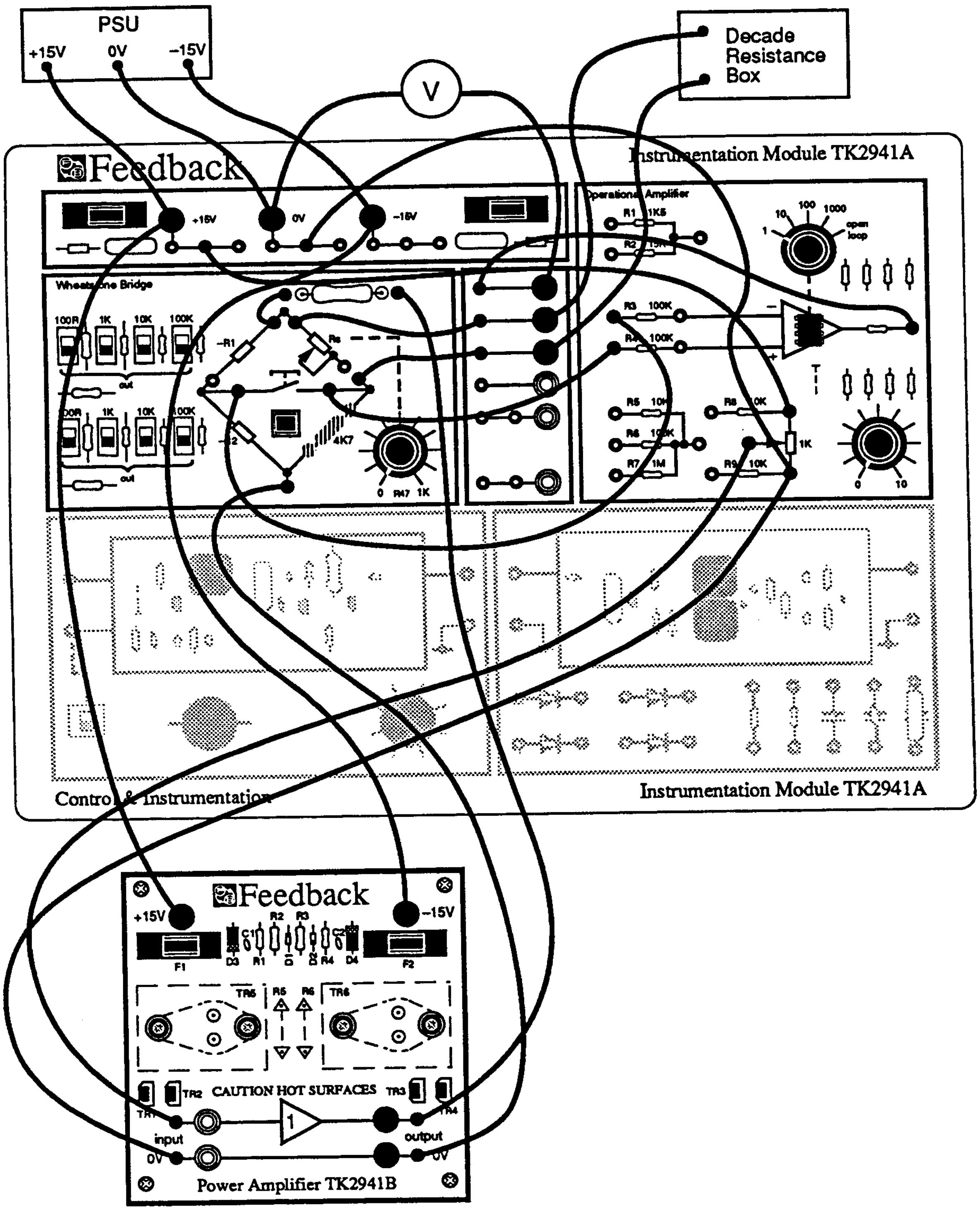

PSU
+15V
0V
-15V
V
Decade
Resistance
Box
Feedback
Instrumentation Module TK2941A
+15V
0V
-15V
Operational Amplifier
Wheatstone Bridge
100R
1K
10K
100K
out
4K7
0
R47
1K
R1
1K5
R3
100K
R4
100K
R5
R6
R7
1M
R9
10K
1K
open loop
Control & Instrumentation
Instrumentation Module TK2941A
Feedback
+15V
-15V
F1
F2
CAUTION HOT SURFACES
input
output
0V
Power Amplifier TK2941B

Fig 4.6.2

Question 6.1 ***What value of standard will this mean?***

The first step in the balancing procedure is to set the amplifier to its lowest gain (i.e 1) and balance the bridge roughly, with the variable dc set to give approximately 4V.

When the approximate balance point has been reached increase the gain of the amplifier to 10 and find the balance more accurately.

To achieve greater sensitivity still a higher gain may be selected but the adjustment of the standard becomes extremely critical.

Question 6.2 ***Record the value of the unknown found using the circuit.***

Disconnect the operational amplifier from the bridge and connect the detector directly across the bridge outputs. Balance the bridge normally.

Record the value of the unknown by this method.

Question 6.3 ***Is the value the same?***

Question 6.4 ***What difference in sensitivity does the amplifier make?***

Question 6.5 ***Is it easier to get accuracy with or without the amplifier?***

Question 6.6 ***Why is this so?***

PRACTICAL ASPECTS

We have seen that by using an amplifier we are able to increase the sensitivity of a bridge circuit and when nearing balance, the amount of current flowing in the detecting meter becomes very small. A good moving coil movement, with a centre zero needle, will give full positive or negative deflection for less than 25μA. It is very difficult with this type of instrument to detect current that is smaller than a fraction of a micro-amp. This is where the amplifier is advantageous, because it is able to detect current that is a few nano-amps in value.

However, with this great advantage do arise certain problems. The amplifier will amplify any apparent differences in the signal values at its output. If the non-inverting input is tied to the common rail, any change in supply value will produce an apparent difference in value compared to that of the inverted input. As the inverted input is the signal input, although its value has not changed, any deviation in the voltage supply will appear at the output. Because of the sensitivity of the amplifier, this deviation or error may be quite large.

To prevent the effects of variations in supply values caused by transient effects, great care has to be taken to ensure that the voltage supply to the amplifier is very carefully regulated.

Another problem is drift in the characteristics of the amplifier. If readings are to be made over an extended period then the effects of drift can be very noticeable, if the circuits are not specially stabilised. The effective reason for drift is changes in the temperature of the transistors forming the amplifier.

In early amplifiers drift was cured by chopping the signal, then amplifying the signal with an ac amplifier and then inverting the signal back to a dc value. With the latest types of I.C amplifiers it is possible to obtain amplifiers in which the gains of the transistors have been balanced. As well as this, there are also current compensation techniques that by the addition of some extra circuitry are able to produce devices with drifts of a few parts of a million per degree Centigrade change.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 6

Question 6.1 The value of standard needed for an unknown of about 50kΩ will be about 5kΩ.

Question 6.2 A typical value of unknown as measured might be 4660Ω.

Question 6.3 The balance value will be substantially the same when not using the amplifier but the resolution will be poorer, eg a 'balance' can be obtained at any value between 4600Ω and 4700Ω.

Question 6.4 With the amplifier, values can be resolved to more significant places than without it.

Question 6.5 Accuracy is more easily achieved with the amplifier.

Question 6.6 Because much smaller offset voltages can be detected.

NOTES

VARIABLE RESISTIVITY TRANSDUCERS — ASSIGNMENT 7

CONTENT

The variation in resistance resulting from the variation in the resistivity of a substance is investigated. Its use in a transducer is discussed.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Conductance probe from TK2941E Electro-mechanical Transducers Kit.
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 100kΩ
1	–	*AC Voltmeter 5mV-5V
1	–	Function Generator 10kHz Sine, 20V pk-pk
3	–	Parallel sided beakers, 250ml.
1	–	Spoon
–	–	Common salt
–	–	Water

* Alternatively a multimeter may be used.

PRACTICAL

7.1 Resistance of Salt Solution

VARIABLE RESISTIVITY TRANSDUCERS — ASSIGNMENT 7

OBJECTIVES

When you have completed this assignment you will:

- Understand the relationship between a variation in resistivity and variation in resistance
- Know how variation in resistivity may be used in a simple transducer.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand how an operational amplifier works.
- Understand the operation of a Wheatstone Bridge using ac sources.
- Understand the relationship $R = \frac{\rho l}{a}$ defining resistance values.
- Be familiar with the use of the Instrumentation Module TK2941A.

INTRODUCTION

The formula for the resistance of an object is:

$$\text{Resistance} = \frac{\text{Resistivity} \times \text{length}}{\text{cross sectional area}}$$

$$R = \frac{\rho l}{a}$$

Thus the resistance of anything is directly proportional to its resistivity. The resistivity of a material is dependent on the number of free electrons available for conduction and this in turn is dependent on several factors.

Conductors which have large numbers of free electrons and hence conduct electricity easily, have low resistances and thus low resistivities. Insulators have very high resistivities as they hardly conduct electricity at all. Semiconductors have resistivities around half-way between the two extremes.

By rearranging the formula for resistance we can obtain

$$\text{Resistivity} = \frac{\text{Resistance} \times \text{cross sectional area}}{\text{length}}$$

$$\rho = \frac{Ra}{l}$$

Now R is in ohms
a is in square meters
l is in meters

Thus the unit of resistivity is given from:

$$\rho = \frac{\Omega \times m^2}{m}$$

i.e resistivity is measured in ohm metres.

Fig 4.7.1 gives an indication of the relative resistivities of conductors, insulators and semiconductors.

Material	Resistivity range (Ωm)
conductor	10^{-8} to 10^{-6}
insulator	10^{6} to 10^{18}
semiconductor	1 to 10^{4}

Fig 4.7.1

Several factors affect the number of electrons free in any material: temperature, purity, surface condition, voltage applied, mechanical stress are a few.

In metals the number of free electrons is extremely large, so that the application of external influences such as heat or voltage, etc, does not change the number of free electrons and hence the resistivity to a great extent, for instance the resistivity of copper changes by about 0.4% per degree Celcius (between 0° and 100°C).

In insulators the number of free electrons is very low and the currents which can flow are minimal. However factors such as purity or surface condition can change the properties of the material, and hence its resistivity.

An interesting group of materials is liquids, especially solutions of salts in water. Most pure liquids are bad conductors, in particular water has a very high resistivity unless it contains slight traces of impurities. The most important liquid conductors are solutions of acids, bases and salts in water. When one of these materials goes into solution its normally electrically neutral molecules dissociate into positive and negative ions. If an electric field is applied to the solution, by dipping two electrodes into it for example, then the positive and negative ions move towards opposite electrodes. The charge carried through the solution by the ions constitutes an electric current. The current passing through the liquid will depend on the charge carried by the ions, the number of ions in the solution and the speed at which they move through the solution. The charge on the ions depends on the particular material that is in solution, and the speed of movement depends on the forces on the ions applied by an electric field for instance caused by a voltage between the electrodes.

The number of ions in solution depends on the concentration of the solution. If more of the impurity is dissolved, the concentration and hence the number of ions available in the solution is increased. This produces an increased current or a decrease in resistivity of the solution.

Transducers may be constructed which use the principle of variation of the resistivity of a material to change the resistance between the terminals of the transducer. This resistance may be measured by the methods which use Wheatstone Bridge techniques.

As an example of such a transducer, let us perform an experiment to show the variation of resistance due to varying concentration of a salt solution.

PRACTICAL 7.1

Resistance of Salt Solution

Firstly set up the circuit of fig 4.7.2 setting the function generator output to zero.

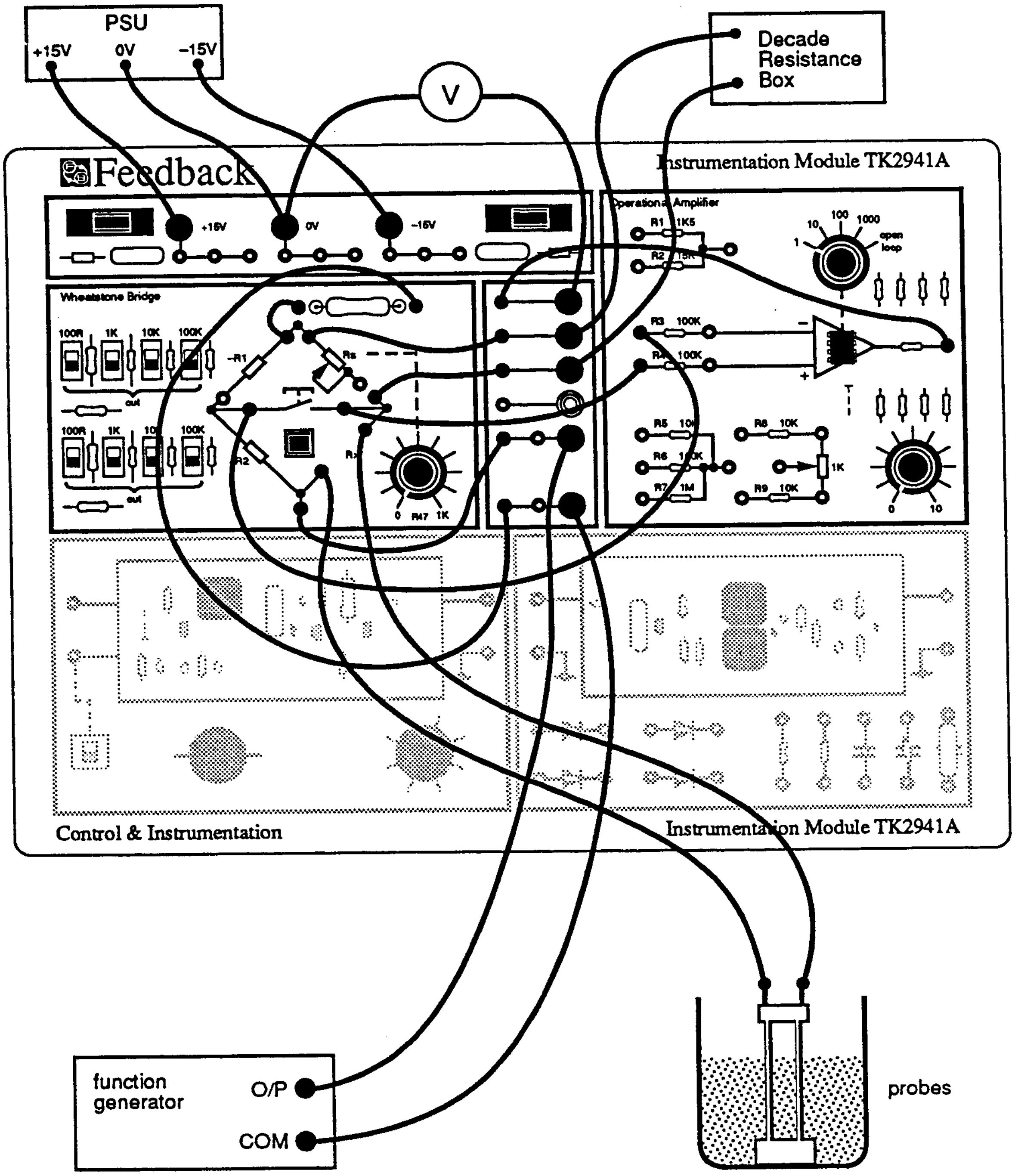


Fig 4.7.2

An earphone could be used in place of the ac meter to give an audible output.

Almost fill one beaker with tapwater. This will be the test solution. The beaker in which the probes are placed should be as narrow as possible so that the volume of water is small. It should be filled initially to a level which will allow the addition of the salt solution and which produces a resistance value of approximately 250Ω.

Almost fill a second beaker with warm water and dissolve less than one eighth of a teaspoon of salt into it. This provides a weak salt solution which may be added to the test solution in measured quantities; it is more accurate to do it this way than try to measure the minute amounts of salt needed to achieve the same concentrations in the test solution. It is important however that the quantity of salt is not exceeded.

Set R_1 and R_2, the ratio arms of the bridge, both to 1kΩ (switches 2 and 6 'in') and set the gain of the operational amplifier to 1. Increase the function generator output to give a reasonable deflection on the meter at a frequency of about 5kHz.

Measure the resistance between the probes in the uncontaminated water. Because there is approximately 5nF capacitance associated with the probes and leads, the bridge cannot be truly balanced. You should adjust the standard resistance, R_s, to produce a null reading on the detector; you could also try putting a capacitor of suitable value in parallel with R_s to achieve a better balance. Record your results in your own copy of fig 4.7.3.

salt water added (teaspoons)	resistance (Ω)	conductance (mS)
0		
2		
4		
6		
8		
10		
12		
14		

Fig 4.7.3

Remove two teaspoons of water from your test solution to the third, empty beaker and add two teaspoons of the salt solution. Measure the new resistance value and record it in the table.

Repeat the procedure above for amounts of salt water added of 4, 8, 10, 12 and 14 teaspoonsful. For each spoonful added, remove one from the test solution to keep the amount of solution constant.

To calculate the concentration of salt solution in the water for the purpose of this experiment we will define it as the number of teaspoons of test solution replaced.

Calculate the reciprocals of the resistances and record these in the conductance column.

Question 7.1 *Does the resistance measured vary with salt concentration?*

Question 7.2 *Between what values does it vary?*

Plot graphs of resistance and conductance against concentration. Use the same piece of graph paper with axes as in fig 4.7.4.

Question 7.3. *What is the relationship between the conductance and the liquid concentration?*

Question 7.4 *Therefore, what is the relationship between the resistance and the concentration?*

Question 7.5 *As the resistivity is directly proportional to the resistance, what is the relationship between the resistivity and the concentration?*

It can be seen from this experiment that it is possible to use the principle of variation of resistivity in a practical transducer.

Question 7.6 *What other effect was mentioned in the introduction to this Assignment which changes the resistivity of metals?*

Question 7.7 *Could this be put to use for a practical transducer?*

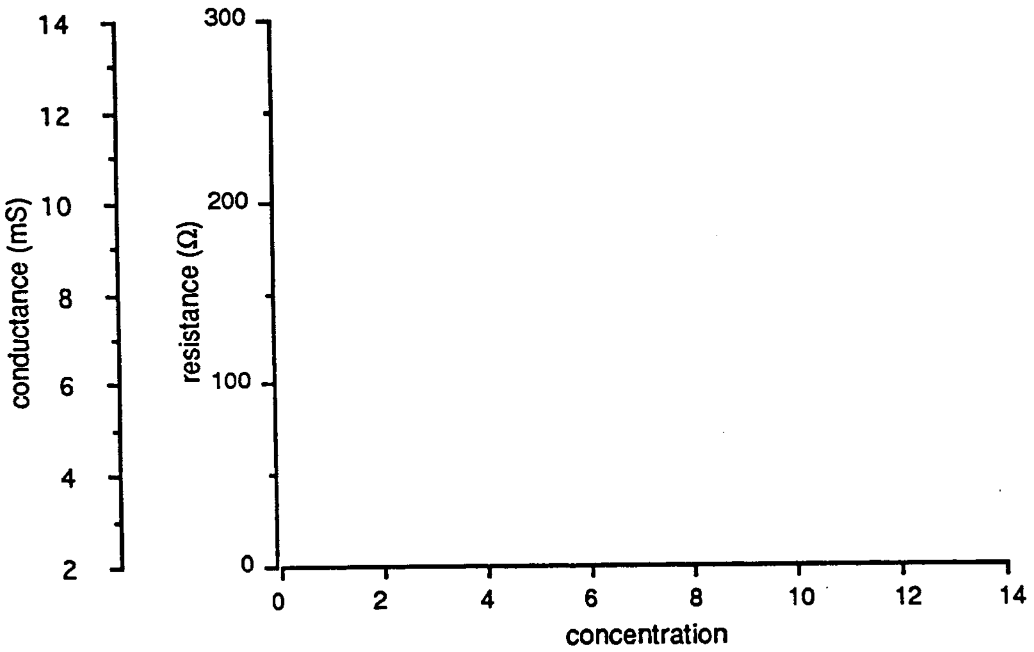


Fig 4.7.4

Resistive temperature-sensing elements are normally conductors or semiconductors which change their resistivity, and hence their resistance, as the temperature changes. Sensing elements used in practice may be metal wires or thermistors, and deposited metal films, germanium and silicon crystals, and carbon resistors are also used. Temperature transducers are dealt with in later assignments.

PRACTICAL ASPECTS

Many of the commonly used humidity sensing elements use the principle of variation of resistivity, and hence resistance to give an output which is proportional to the humidity.

The materials normally used in which the resistance change occurs are often either hygroscopic salts or carbon powder and they usually take the form of a thin film deposited on an insulating base, with metal electrodes as terminations. This is shown in fig 4.7.5.

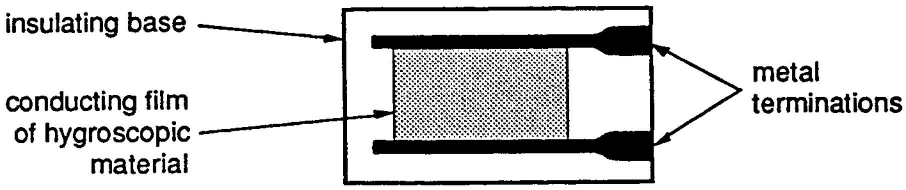


Fig 4.7.5

The hygroscopic salt film ionises in the same way as the salt solution used in this Assignment did, and the resistivity of the materials varies as a function of the amount of water vapour in the surrounding air. The best known hygroscopic salt element used is lithium chloride which is an aqueous solution of lithium chloride (LiCl) in a plastic binder.

Other variable resistivity materials used as films in this type of transducer include barium fluoride, cerium titanate and carbon.

In practical relative humidity transducers using this principle the resistance change can be from up to 25MΩ resistance at 10% relative humidity to as low as 1kΩ resistance at 100% relative humidity.

Because of the fact that the materials used in this form of transducer ionise, problems arise concerning conduction. As the ions are attracted by the electrodes and move towards them, a build-up of positive ions around the negative electrode, and of negative ions about the positive electrode occurs. In time the situation arises when these ions form a layer on and around the electrodes, and the layer produces an e.m.f in opposition to the driving current. This e.m.f builds up, and is sufficient to stop the flow of current between the electrodes.

This effect is called Polarisation.

To combat the effects of polarisation this build-up of ions must never be given time to form, thus it is normal to supply this form of transducer with an ac signal. The ions are first attracted one way, and then on the reversal of current they are attracted in the opposite direction and thus they do not concentrate themselves around the electrodes.

The variation of resistivity with temperature is used in practice for both rough and extremely accurate measurement of temperature. The table in fig 4.7.6 gives the resistivity and temperature coefficient for several materials commonly used. The negative temperature coefficient for carbon signifies that the resistance goes down with increasing temperature.

material	resistivity at 20°C (Ωm x 10–1)	temp. coeff. (per °C)
aluminium	26.9	0.0042
carbon	35,000 (at 0°C)	–0.0005
copper	16.73	0.0043
gold	23	0.0039
iron	97.1	0.0065
nickel	68.44	0.00681
palladium	108	0.00377
platinum	98.1 (at 0°C)	0.00392
silver	16.3	0.0041
tungsten	55	0.0046

Fig 4.7.6

A high value of temperature coefficient is desirable in a temperature sensing transducer of this type so that a measurable resistance change is produced, even when the range of temperature variation is small.

A high resistivity material is also of advantage so that the physical size, and the amount of material to be used in the transducer may be kept small.

For extremely accurate measurement of temperature, transducers using the variation in resistivity of a platinum wire are most commonly used. The resistance versus temperature characteristic of platinum is very accurately known, and this type of transducer may be used over the temperature range –265°C to +1050°C. An element of this type is used over the range –183°C to +630°C to define the International Temperature Scale. Platinum wire transducers are used in laboratories and in missile and space instrumentation when great accuracy is required. These elements are extremely costly.

For less critical applications, and where the temperature to be measured lies in the range –100°C to +300°C, nickel wire transducer elements are used. These are commonly used in industrial applications as the cost is much more reasonable.

Copper wire transducer elements were often used in the past; however the low resistivity of copper meant that large lengths were needed to achieve any reasonable resistance. The other types of wire elements have now made copper units virtually obsolete.

Carbon elements are used both as rough sensors in range –20°C to +200°C and in the range below –200°C where their high resistivity and negative temperature coefficient ensures a high resistance in the very low temperature range.

Semiconductor elements are now being used, to a large extent as temperature sensing transducers, and the resistivity of the materials used varies rapidly with temperature. Normally the resistivities are high, and have a negative temperature coefficient with a non-linear resistance as temperature characteristic. There are several types of semiconductor temperature transducer: the thermistor, manufactured using sintered mixtures of sulphides, elenides or oxides of nickel, manganese, copper or similar metals moulded into beads or rods and enclosed in glass. They are normally used over the range of about –75°C - 200°C although ranges outside these temperatures may be accommodated using special devices.

Germanium crystals with controlled levels of doping have negative temperature coefficients and are used for temperature measurement at extremely low temperatures e.g below 40°K (–233°C).

Silicon crystals with controlled doping can be manufactured with positive temperature coefficients above about –220°C and can be used effectively to above +250°C. Below –220°C the temperature coefficient becomes sharply negative, and thus this type can also be used for low temperature sensing as well. Later Assignments in this manual cover many of the usual temperature transducers.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 7

salt water added (teaspoons)	resistance (Ω)	conductance (mS)
0	250	4.0
2	200	5.0
4	144	7.0
6	120	8.3
8	101	10.0
10	93	10.8
12	86	11.6
14	80	12.5

Fig E4.7.3

Question 7.1 Yes.

Question 7.2 It drops from 250Ω to 80Ω typically.

Question 7.3 Conductance is directly proportional to concentration

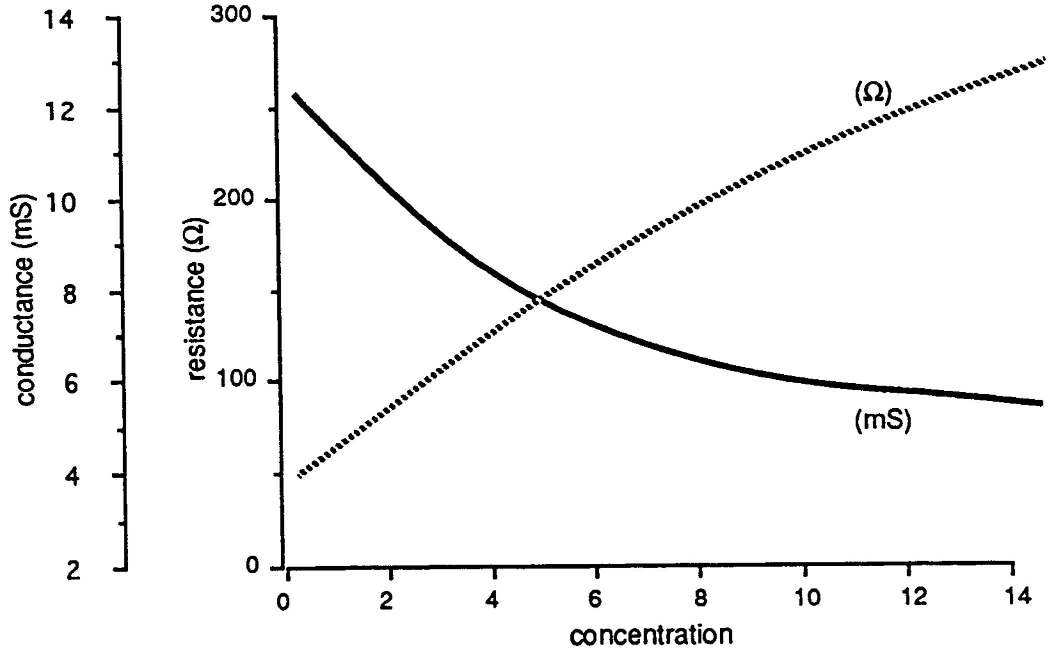


Fig 4.7.4

Question 7.4 $\text{Resistance} \propto \frac{1}{\text{concentration}}$

Question 7.5 $\rho \propto \frac{1}{\text{concentration}}$

Question 7.6 Heat.

Question 7.7 Yes, see the discussion about thermistors in the Practical Aspects section.

VARIABLE AREA TRANSDUCERS — ASSIGNMENT 8

CONTENT

The relationship between variation in cross-sectional area and variation in resistance of a material is measured; its application in a transducer is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Conductance probe from TK2941E Electro-mechanical Transducers Kit.
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 100kΩ
1	–	*AC Voltmeter 5V
1	–	Function Generator 10kHz Sine, 20V pk-pk
2	–	Parallel sided beakers - 250ml
1	–	Measuring cylinder or jug - 250ml
–	–	Water

* Alternatively a multimeter may be used.

PRACTICAL

8.1 Variation in Area

VARIABLE AREA TRANSDUCERS — ASSIGNMENT 8

OBJECTIVES

When you have completed this assignment you will:

- Have confirmed the relationship between the cross-section area and resistance of a material.
- Have observed how the relationship may be used in a variable area transducer.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Know how to use a Wheatstone Bridge and Operational Amplifier for resistance measurement.
- Understand the relationship $R = \frac{\rho l}{a}$.
- Be familiar with the use of the Instrumentation Module TK2941A.

INTRODUCTION

We know that the formula for resistance is:

$$\text{Resistance} = \frac{\rho l}{a}$$

from which it can be seen that the resistance of an object is inversely proportional to the cross-sectional area of the object.

To show the variation in resistance with area an apparatus is required which allows the cross-sectional area, a, to be changed whilst keeping ρ and l constant. The probes provided with TK2941E offer a convenient way of achieving this, as the distance between them (l) is fixed and the resistivity of the solution into which they are dipped (ρ) can also be kept constant. By varying the depth of the solution the area (a) can be altered as desired.

PRACTICAL 8.1

Variation in Area

Set up the circuit of fig 4.8.1 ensuring that the output of the function generator is zero.

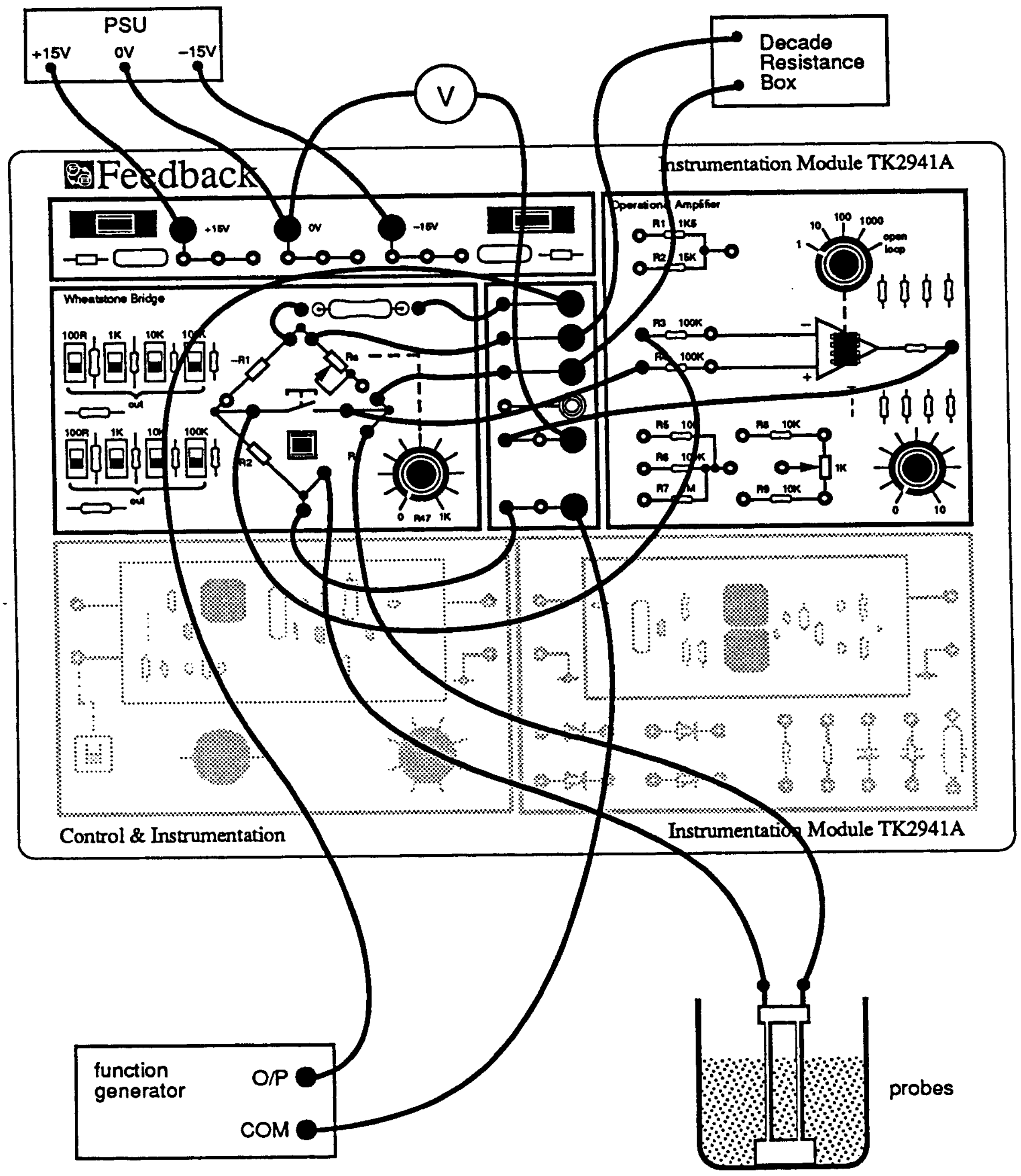


Fig 4.8.1

Set the ratio arms of the bridge both to 1kΩ and the gain of the operational amplifier to 1.

Pour enough water into the beaker to cover the base of the probes by about three or four millimetres. This will be the reference level.

Set the generator frequency to about 5kHz and increase the output to obtain a reasonable deflection on the meter.

Measure the resistance between the probes in the water. Record your result in your own copy of fig 4.8.2.

unit of water added	resistance R (Ω)	conductance (mS)
ref		
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Fig 4.8.2

Add a measured small amount of water to that in the beaker, enough water to raise the water level by 4 or 5mm should be sufficient. This measure will be used in the rest of the experiment.

Again measure the resistance between the probes, and record your result in the table.

Repeat the procedure for another measured quantity of water added, and for further measured units until the beaker is full.

Calculate the reciprocals of the resistances found and enter these in the relevant positions in the table.

Question 8.1 ***Can you see any relationship between resistance, or conductance and depth of water?***

Plot graphs of your results as indicated in fig 4.8.3.

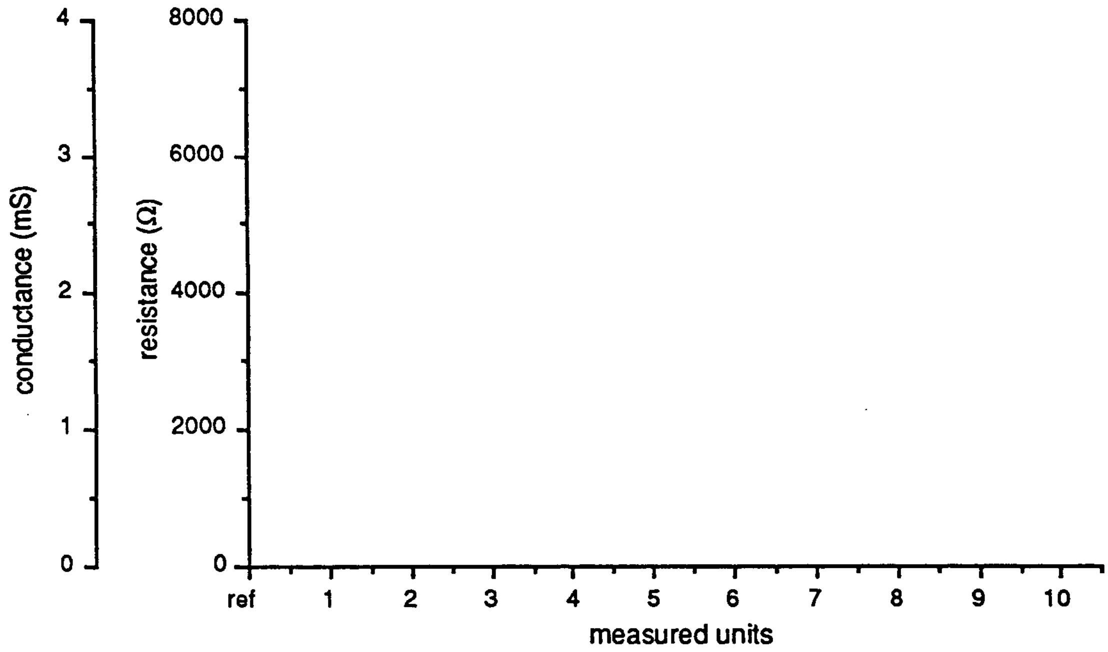


Fig 4.8.3

Question 8.2 ***How does the conductance vary with depth?***

Note The area involved is that between the section of the two probes immersed in the liquid. See fig 4.8.4

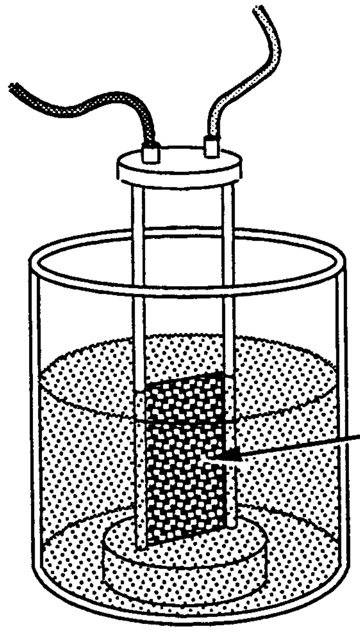


Fig 4.8.4

Question 8.3 ***How does the conductance vary with area?***

Question 8.4 ***Thus how does the resistance vary with area?***

Question 8.5 ***Does this confirm the relationship stated initially for resistance?***

PRACTICAL ASPECTS

Transducers using the principle of the variation in area causing a variation in resistance are not very common, perhaps those used for liquid level measurements being the most used. Both continuous monitoring and discrete level measuring transducers may be constructed with this principle of operation.

Similar problems as those discussed in Assignment 7 exist with respect to the ionisation and polarisation of the liquid and an alternating supply of greater than 20Hz in frequency must be used to minimise these effects.

Some level transducers of this type comprise only one electrode which is mounted close to and parallel with the side of the metallic vessel, which serves as the other electrode.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 8

units of water added	resistance (Ω)	conductance (mS)
ref	6470	0.155
1	2145	0.466
2	1266	0.790
3	910	1.10
4	699	1.43
5	577	1.765
6	480	2.08
7	420	2.38
8	370	2.705
9	333	3.000
10	404	3.29

Fig E4.8.2

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 8

Question 8.1 See fig E4.8.3.

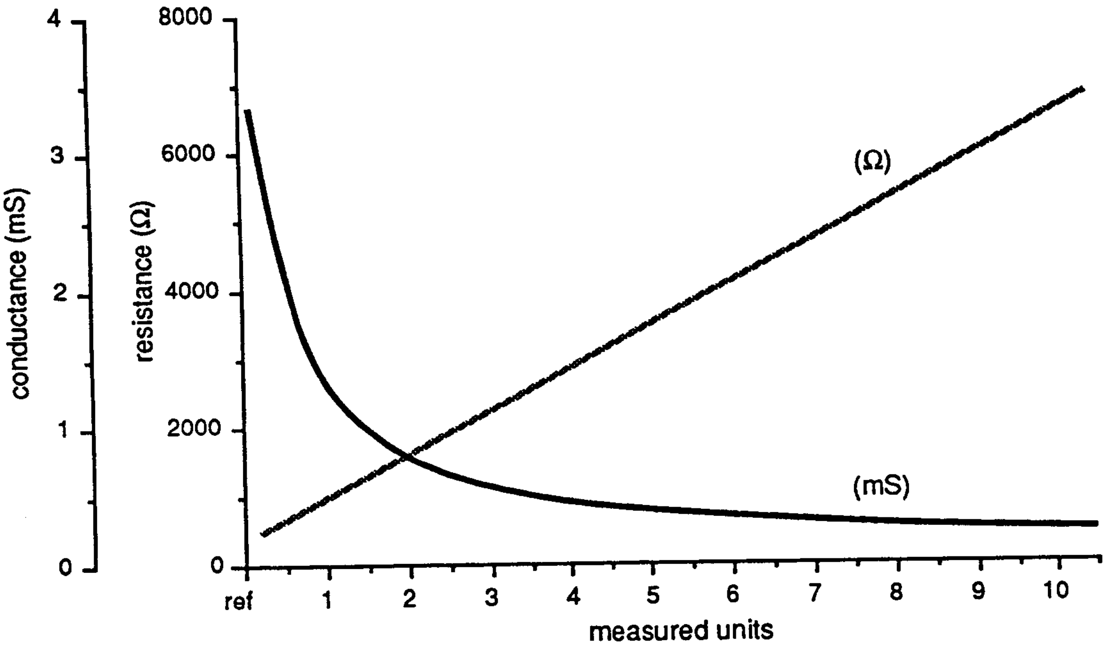


Fig E4.8.3

Question 8.2 Conductance ∝ Depth.

Question 8.3 Depth ∝ Area Thus S ∝ a.

Question 8.4 $R = \frac{1}{S}$ Thus $R \alpha \frac{1}{a}$.

Question 8.5 Yes.

NOTES

VARIABLE LENGTH TRANSDUCERS — ASSIGNMENT 9

CONTENT

A transducer element which uses variations in the length of a material to produce a variation in resistance is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	TK294	Linear Transducer Test Rig.
1	TK294K	Variable Resistor Sub-unit.
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
1	–	Decade Resistance 1Ω to 100kΩ
1	–	* DC Voltmeter 15V
1	–	Centre zero dc milliammeter

* Alternatively a multimeter may be used.

PRELIMINARY PROCEDURE

None

PRACTICALS

9.1 Resistance and Length

9.2 Direct Resistance Reading

VARIABLE LENGTH TRANSDUCERS — ASSIGNMENT 9

OBJECTIVES

When you have completed this assignment you will:

- Have confirmed the relationship between length and resistance of a material.
- Have observed how the relationship may be used in a variable length transducer.
- Have investigated a method of obtaining a direct reading of resistance value.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Know how to use a Wheatstone Bridge and Operational Amplifier for resistance measurement.
- Understand the relationship $R = \frac{\rho l}{a}$.
- Be familiar with the use of the Measurements Package TK2941M.

INTRODUCTION

We know that the resistance of an object is directly proportional to its length, as given by the formula

$$R = \frac{\rho l}{a}$$

Let us investigate the variation of resistance with length using an apparatus which allows l to be varied whilst keeping the resistivity and the cross-sectional area of the specimen constant.

Firstly, examine the Variable Resistor Sub-unit, TK294K, for use with Linear Transducer Test Rig TK294. You will see that it has three connections. Two of these connections are made directly to the resistive element, one at each end of it; the third connection is made to a sliding contact which may travel up and down the resistive element. The position of this sliding contact may be varied by pushing or pulling the threaded connecting rod.

The schematic symbol of the transducer is as shown in fig 4.9.1(a) and the TK294K in fig 4.9.1(b).

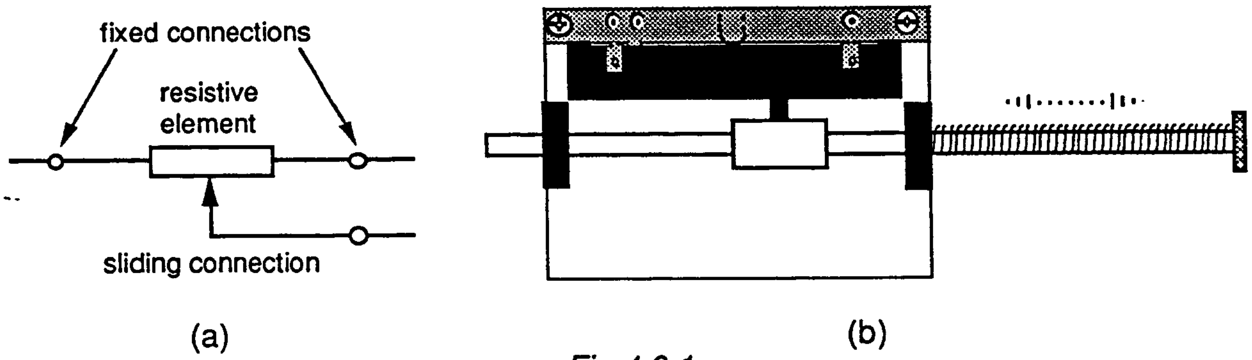


Fig 4.9.1

By using one of the fixed connections and the sliding connection a resistive element may be made whose effective length varies with the position of the slider, but whose resistivity and cross-

section remain constant. This is the situation that we desire.

Assemble the TK294K onto the TK294 by aligning the two holes in the assembly with the two pins on the sub-unit, and then dropping the sub-unit into place. The sub-unit is then secured to the assembly by tightening the finger screw.

The sub-unit includes a return spring and is operated by pressure applied to the end of the operating rod by the micrometer shaft.

PRACTICAL 9.1

Resistance and Length

Connect up the circuit of fig 4.9.2 ensuring that the operational amplifier potentiometer is at zero.

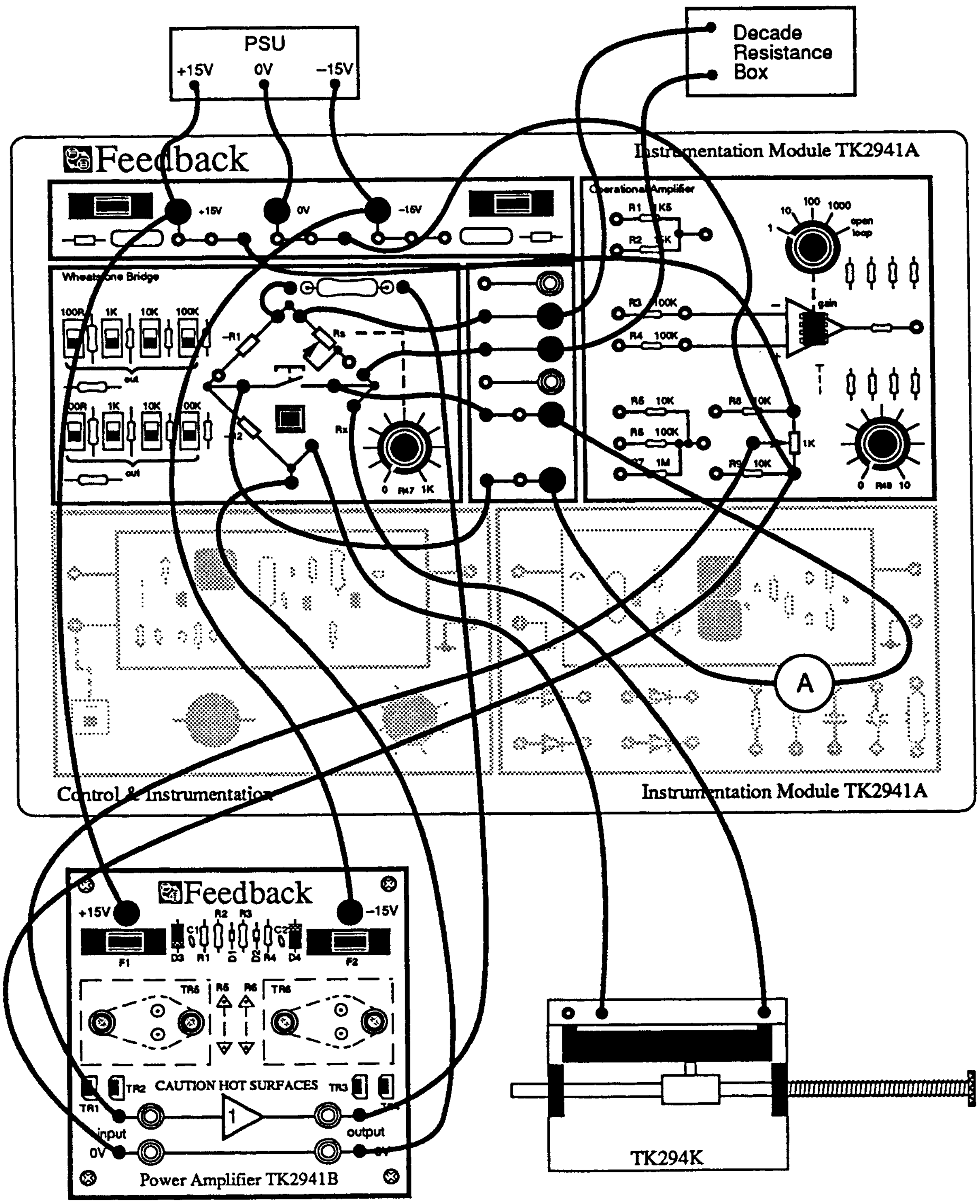


Fig 4.9.2

Position the slider of the TK294 at the 10mm point on the scale, and note this position from the scale, using the engraved line on the front face of the slider, first setting the micrometer to 10mm (see Appendix B for information on micrometer adjustment).

Set the variable dc to approximately 10 volts.

Balance the bridge in the normal manner using the adjustable standard resistor and record your results in your own copy of fig 4.9.3.

Move the slider 5mm to the left and read its position on the scale.

slider position (mm)	resistance (Ω)

Fig 4.9.3

Rebalance the bridge and record your results in the table.

Repeat the procedure for settings of the slider 5mm apart for the complete range of movement of the transducer.

Question 9.1 ***Does the resistance of the transducer change with the position of the slider?***

On a piece of linear graph paper plot a graph of position against resistance using the results you obtained.

Question 9.2 ***Can you notice any relationship between position and resistance?***

Question 9.3 ***What is this relationship?***

Question 9.4 ***Is this the relationship that you expected from the theory you know?***

Thus it can be seen that the principle of variation of the length of a resistive element can be used in transducers to give a change in resistance which may be detected.

Question 9.5 ***If this method was used in practice to measure the position of a particular mechanical part, would the bridge method of determining the resistance be a convenient one?***

Question 9.6 ***Would it be if the mechanical part was in continuous motion?***

It would be far more convenient if the method used for displaying the resistance was direct reading on a meter, calibrated directly in position perhaps, or as a voltage which could be shown on an oscilloscope or a pen recorder.

From Appendix C it can be seen that an equation for the current in the detector arm of a Wheatstone Bridge may be found when the bridge is off balance, but reasonably close to it. This equation is:

$$I = \frac{-V\delta n}{n(1+n)(R_a + R_b) + (1+n)^2 R_L}$$

where V is the supply voltage.
R_a and nR_a are the ratio arms
R_b is the standard
$(n+\delta n)\ R_b$ is the unknown
and R_L is the detector resistance

It can be seen that the current, I, is directly proportional to the out-of-balance of the bridge, signified by δn.

Thus a current meter could be calibrated for this out-of-balance and could give a direct reading of position. However this equation only holds true for a reasonably small deviation from balance and would be almost useless for the range of resistance that our transducer gives, 0-10kΩ. It would be of use though if the movement was small about a fixed point, or if the transducer resistance was only a small part of the total resistance of the unknown arm.

What is really needed is a means of measurement of resistance which gives a direct output voltage which is proportional to the resistance.

Consider the operational amplifier circuit with resistive feedback. This is fully explained in Appendix D, and the equation of operation is given by:

$$V_{out} = \frac{-R_f V_{in}}{R_{in}}$$

Now if V_{in} and R_{in} are kept constant and R_f is then varied, the output voltage will be directly proportional to R_f.

Question 9.7 — ***If V_{in} is set to -15V and R_{in} is 15kΩ what output voltage would you get with a value of R_f of 500Ω?***

Question 9.8 — ***What V_{out} would you get for R_f = 1239Ω?***

It can be seen then that the output in volts is exactly the same as the value of R_f in Kilohms.

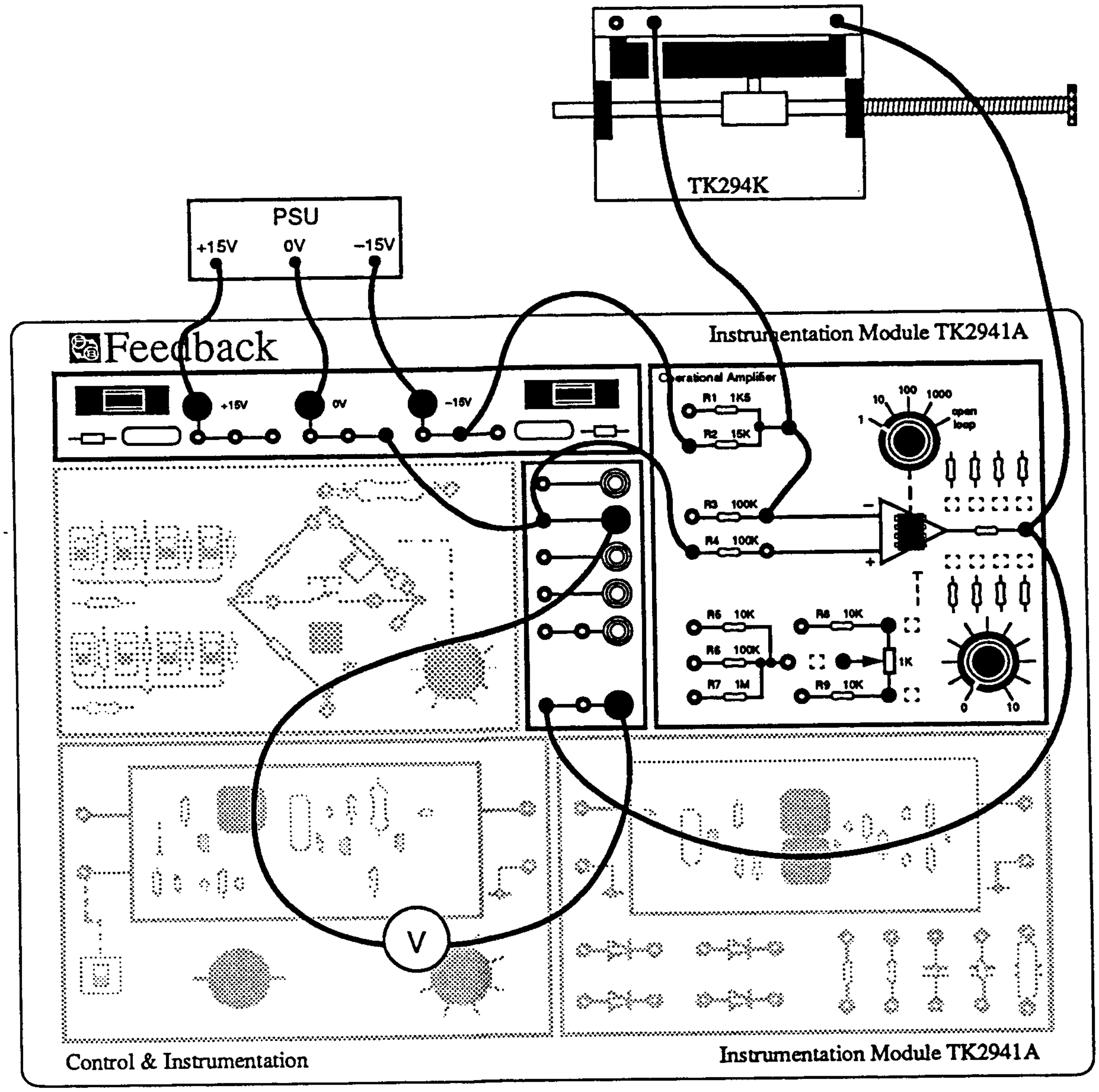
PRACTICAL 9.2

Direct Resistance Reading

Turn the variable dc to zero, switch off the power and connect up the circuit of fig 4.9.4.

Switch on the power.

Return the slider of the linear position assembly to its furthest right position, read its position from the scale and also take the meter readings.


TK294K
PSU
+15V
0V
−15V
Feedback
Instrumentation Module TK2941A
Operational Amplifier
R1 1K5
R2 15K
R3 100K
R4 100K
R5 10K
R6 100K
R7 1M
R8 10K
R9 10K
1K
10
100
1000
1
open loop
0
10
V
Control & Instrumentation
Instrumentation Module TK2941A

Figs 4.9.4

Record these readings in your own copy of fig 4.9.5.

slider position (mm)	output (V)	resistance (kΩ)	
		calculated	from graph

Fig 4.9.5

Move the slider 5mm to the left and repeat the readings.

Repeat this procedure for positions at 5mm intervals for the full travel of the transducer and record all the results in the table.

Also take readings from your graph of resistance for each slider position.

Question 9.9 ***How do the resistance values calculated from the output voltage compare with those from he graph?***

Question 9.10 ***Is the amplifier method more or less convenient than the bridge method?***

Question 9.11 ***Could the output of the amplifier be fed to an oscilloscope or a chart plot of positions?***

PRACTICAL ASPECTS

We have seen in this assignment how we can use variations of position to cause a contact slider to pass over a potentiometer track and vary its resistance linearly with position variation. The use of an operational amplifier has made possible the linear amplification of the small out of balance currents so as to allow accurate calibration of the transducer.

The simple construction of this type of transducer and its principle of operation made it one of the earliest types of transducer used with the development of electro technology. It is a transducer that is used in cars to measure the level of petrol in the tank. Coupled to a floating ball by a lever, the ball will cause the slider on the potentiometer to vary its position according to the amount of petrol in the tank. A crude moving iron meter then measures the resulting current flow to indicate how full the tank is. The meter is square law and so gives a very non-linear reading.

Potentiometers suffer from the problem that the continuous movement of the slider causes the track to wear and break down. Where movement is very slow this wearing effect can be ignored otherwise it has to be taken into consideration and may be the reason why the other types of transducer dealt with in later assignments are chosen.

Typical results are:

Question 9.1 Yes.

slider position (mm)	resistance (Ω)
10	1.0
15	975
20	2000
25	3000
30	3700
35	4670
40	5680
45	6740
50	7720
55	8870
60	10100
65	11160

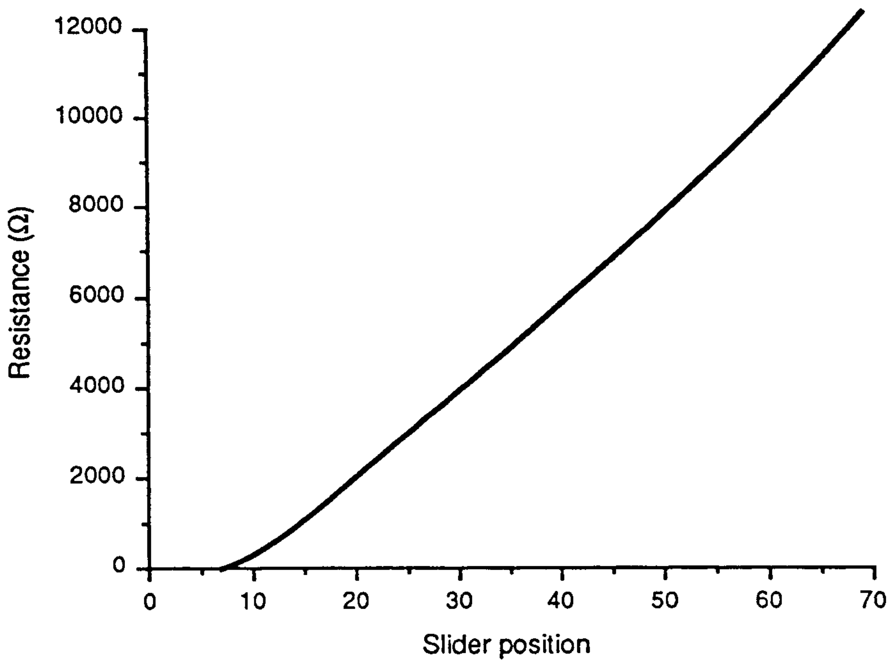


Fig E4.9.3

Questions 9.2 and 9.3 From the graph it can be seen that position and resistance are almost linearly related.

Question 9.4 A linear law was expected, as $R = \frac{\rho l}{a}$

then $R \propto l$

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 9

Question 9.5

The bridge method is not convenient because a balancing procedure is required at every position. Also an accurate resistance standard and a sensitive meter are required. This would make this technique both time-consuming and expensive.

Question 9.6

For continuous motion this technique would be impossible since the bridge could only be balanced at one position.

Question 9.7

$$V_{out} = \frac{-R_f}{R_{in}} V_{in}$$

$$V_{out} = \frac{500}{15 \times 10^3} \times 15V = 0.5V$$

where $R_f = 500\Omega$
$R_{in} = 15k\Omega$
$V_{in} = -15V$

Question 9.8

For similar calculations V_{out} is 1.239V for a feedback resistor of 1239Ω.

slider position (mm)	output (V)	resistance (kΩ)		error
		calculated	from graph	%
10	0.002	0.002	0.001	+100
15	0.975	0.975	0.975	0
20	1.853	1.853	2.0	−7.35
25	2.739	2.739	3.0	8.7
30	3.684	3.684	3.7	0.4
35	4.60	4.60	4.67	1.5
40	5.59	5.59	5.68	1.6
45	6.61	6.61	6.74	1.9
50	7.69	7.69	7.72	0.4
55	8.70	8.70	8.87	2.6
60	9.80	9.80	10.1	2.0
65	11.03	11.03	11.16	1.2

Fig E4.9.5

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 9

Question 9.9

They are generally slightly lower. The error varies between 0.4% to 8.7% on the readings taken here.

Question 9.10

The amplifier method is better partly because the readings can be taken rapidly, and partly because the standard resistor has been eliminated, the only significant parts left being the transducer, the amplifier and the display meter.

Question 9.11

The output could very easily be fed to an oscilloscope or a chart recorder. It is also possible to have the display at a remote position from the transducer and amplifier. Previously the extra resistance of the leads going to the transducer could have caused an extra error in the Wheatstone bridge circuit.

NOTES

STRAIN GAUGES — ASSIGNMENT 10

CONTENT

The application of the variable length transducer principle to strain gauge transducers is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig.
1	TK294E	Strain Gauge Sub-unit.
1	–	Power Supply,±15V, 5Vdc *(eg Feedback PS446)*
1	–	* DC Voltmeter 15V

* Alternatively a multimeter may be used.

PRACTICALS

10.1 Basic Strain Gauge

10.2 Dual Gauge System

STRAIN GAUGES — ASSIGNMENT 10

OBJECTIVES

When you have completed this assignment you will:

- Know how the change in resistance of a material, caused by a change in its physical dimension, can be used to measure the strain in the material.
- Have investigated methods using one and two strain gauges and observed the advantages of the twin-gauge system.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Know how to use a Wheatstone Bridge and Operational Amplifier for resistance measurement.
- Understood the principle of the basic variable length transducer.
- Be familiar with the use of the Measurements Package TK2941M and the Linear Transducer Test Rig TK294.

INTRODUCTION

It is possible to construct transducers which use the principle of variation in length of a resistive path to give a variation in the resistance of the transducer element. Also, variation in the cross-sectional area of a resistive element will cause a change in the resistance of the element and this principle can be applied to transducers.

In the variable length transducer investigated in Assignment 9, the length of the resistive element was effectively varied by changing the distance between the contacts. This was done by having one contact fixed and the other a variable position contact in the form of a slider which could move up and down the resistive element.

Another method of increasing the length of a resistive element is by physically stretching it. Let us see what happens when this is done and whether this method can be used as the principle of operation of a transducer.

When a rectangular bar of material is stretched by the application of a tensile force along its axis, not only will the bar increase in length, but it will also decrease in cross-sectional area. This is shown in fig 4.10.1.

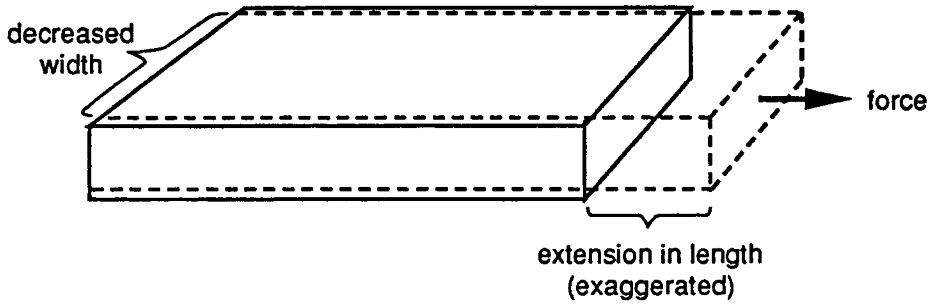


Fig 4.10.1

The amount by which the bar is elongated is related to the amount that its width and depth decrease by a factor which is known as Poisson's Ratio.

Poisson's Ratio (μ) is given by:

$$\mu = \frac{\text{lateral contraction per unit breadth}}{\text{longditudinal extension per unit length}}$$

For materials such as steel, aluminium, copper and other metals Possion's Ratio lies between about 0.25 and 0.35.

Now as resistance $= \frac{\rho l}{a}$ and as this method both increases l and decreases a, then the resistance will change with them.

There will also be a change in the resistivity ρ of the material, due to the change in physical properties as the bar is stretched. This causes a distortion of the crystal lattice of the material which changes the value of ρ.

Examine the Strain Gauge Sub-unit, TK294E, for use with the Linear Transducer Test Rig, TK294. You will see that attached to each side of the cantilever is a zig-zag conductor mounted on a red base. This conductor is very thin and narrow, but because of its zig-zag pattern, it has quite a considerable length. This enables a reasonable resistance to be obtained. You will notice that it is mounted in such a way that the conductors run lengthwise up the axis of the cantilever.

Question 10.1 ***If you push gently on the operating rod, what happens to the cantilever?***

Because the cantilever bends in an arc, it is very slightly deformed. One side of the cantilever will get very slightly longer and the other side of the beam will get slightly shorter.

Each gauge is bonded firmly to the cantilever with a special cement which will follow the movements of the beam and transmit all the changes in length of the beam to the gauge.

Question 10.2 ***Will the conductors of the gauge nearest the rod get longer or shorter as it is pushed against the spring return?***

Question 10.3 ***What else happens to the properties of the conductors of the gauge?***

Question 10.4 ***How will this change the resistance of the conductor?***

PRACTICAL 10.1

Basic Strain Gauge

Let us connect up the transducer and see if your answer is correct. Assemble the TK294E to the TK294 and connect the gauge No. 1, nearest the operating rod, (see fig 4.10.2 for details) into the circuit of fig 4.10.3.

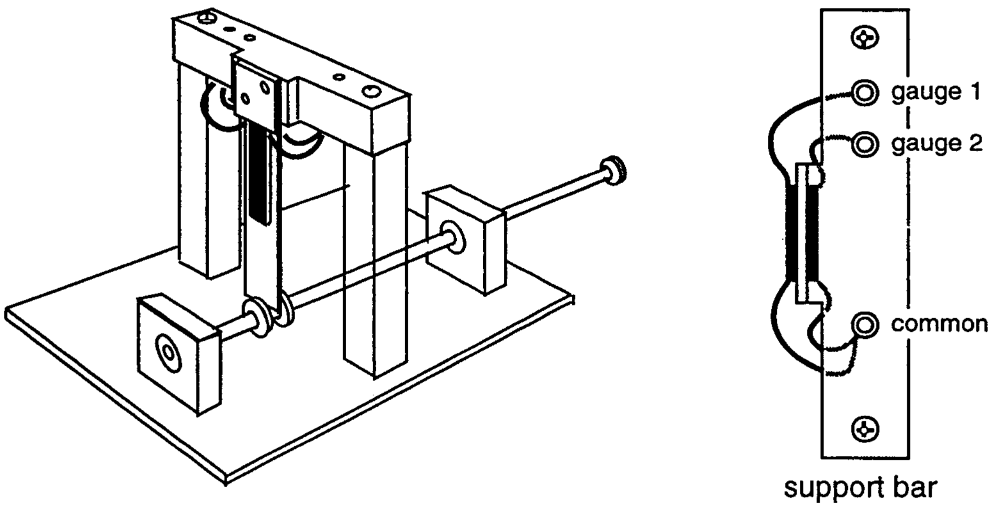


Fig 4.10.2 Strain Gauge TK294E

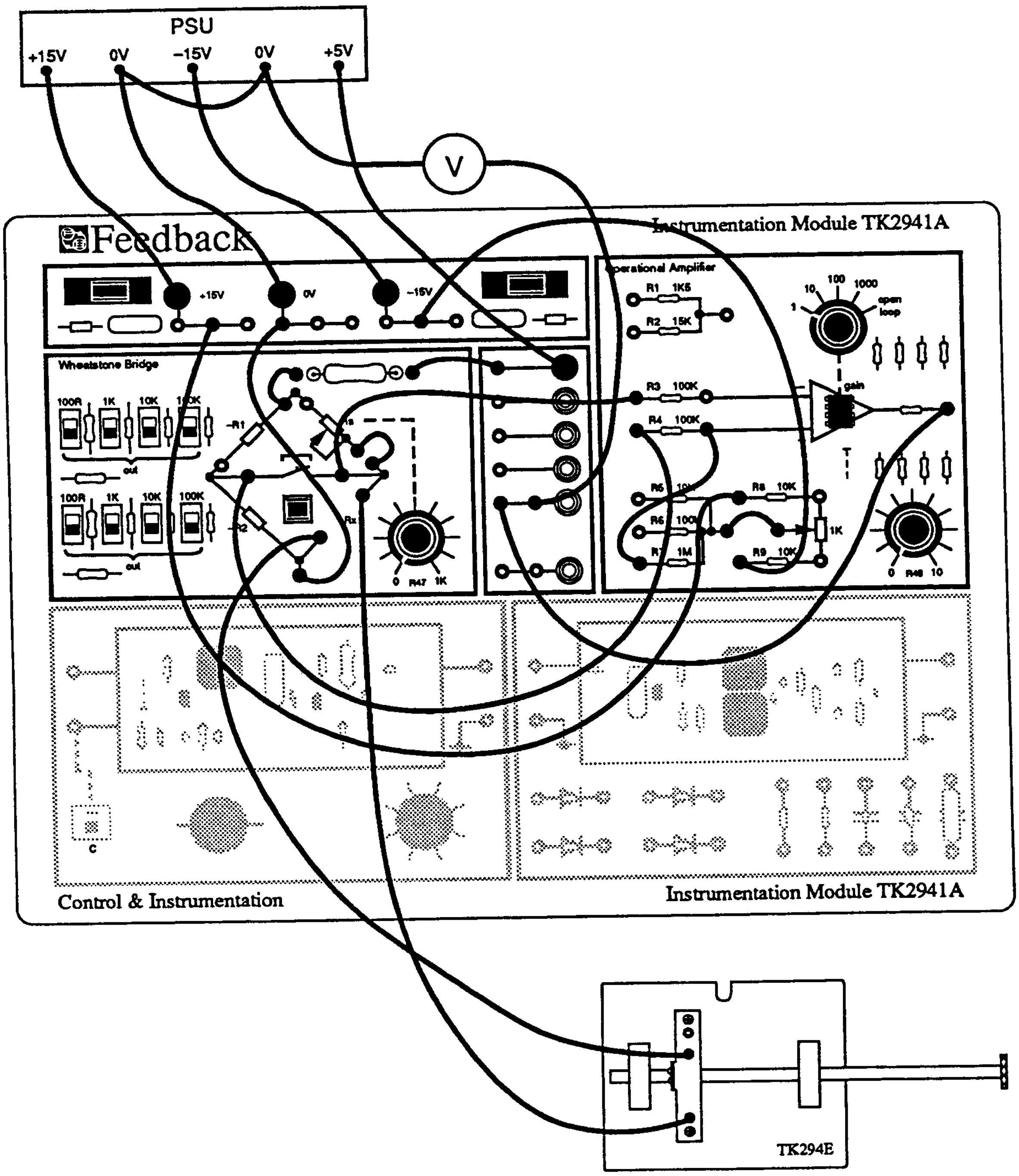

PSU
+15V
0V
-15V
0V
+5V
V
Feedback
Instrumentation Module TK2941A
Wheatstone Bridge
Operational Amplifier
Control & Instrumentation
Instrumentation Module TK2941A
TK294E

Fig 4.10.3

We are going to use this arrangement to measure the change in resistance of the gauge. In its resting state, the gauge has a resistance of about 120Ω which we could measure by balancing the bridge, as was done in Assignment 2. When we bend the beam, the actual changes in the transducer will be very small, such that its resistance will change by only about 0.2Ω. It would be very difficult to measure this change by normal bridge methods as the contact resistances of any plugs, switches or potentiometers may change by a similar small amount. However, such a small change means that the bridge is only just out of balance,and we can amplify the out of balance voltage appearing across the detector and use this to indicate on our meter.

However, it will still be necessary to obtain an amplifier output of zero for the starting condition and to do this we shall use the variable resistor R_S on the Wheatstone Bridge module to obtain a rough bridge balance; R_S is too coarse to give an accurate zero output though, so we use a different method for the fine control. This is to offset the amplifier deliberately so that it produces zero output for a small non-zero input, being the residual bridge unbalance. The potentiometer on the Operational Amplifier, R49, is used for this purpose, as shown in fig 4.10.3.

To set up the bridge and amplifier, proceed as follows:

- Set the micrometer to 10mm (see Appendix B for information on micrometer adjustment)
- Use the slide to push the gauge operating rod against its lefthand stop and note the slide scale reading (about 29mm).
- Move the slide to the right until there is just no pressure on the operating rod and again note the scale reading (say 24mm).
- Set the slide to the midway point of your two readings (26.5mm typically) and lock the slide. The strain gauge should now be in about the middle of its operating range.
- On the Wheatstone Bridge set $R_1 = R_2 = 1k\Omega$.
- Switch on the power supply.
- Select a 10V range on the meter (or the nearest available) and set a gain of 100 on the Operational Amplifier. Set the potentiometer, R49, to mid-scale and adjust R_S on the Wheatstone Bridge until the meter reads as near to zero as you can manage.

- Now adjust R49 to give an exact zero, increasing the meter sensitivity and re-adjusting R49 alternately until you have a zero setting on the most sensitive range available . Wait five minutes for the system to settle and finally reset to zero with R49.

If you followed through the above procedure carefully you should now find that small movements of the operating rod by the micrometer adjustment will cause the meter reading to change by a small amount. In fact ±1.5mm motion should cause approximately ±75mV output.

Take a set of output readings for 0.5mm steps of position, starting at 10.0mm, increasing to 12.5mm, reducing to 7.5mm and finally increasing again to 10.0mm. Record your results in your own copy of fig 4.10.4.

Micrometer setting (mm)	Output Voltage (mV)
10.0	
10.5	
11.0	
11.5	
12.0	
12.5	
12.0	
11.5	
11.0	
10.5	
10.0	
9.5	
9.0	
8.5	
8.0	
7.5	
8.0	
8.5	
9.0	
9.5	
10.0	

Fig 4.10.4

Plot your results of micrometer setting against output voltage on linear graph paper.

Question 10.5 ***Is the plot linear? If so, what is its slope in volts/mm?***

Question 10.6 ***Do the results for increasing displacement lie exactly over those for decreasing displacement?***

Question 10.7 ***In particular does the last reading for 10.00mm equal that of the initial reading for 10.0mm (i.e approximately zero output)?***

If the answer to either Question 10.6 or 10.7 was no it is probably due to the effect of small temperature changes which occurred during the time you were taking your readings. These could alter the gauge resistance and the bridge balance resistance R_S by differing amounts, since they are different types of resistor located at different places.

Question 10.8 ***Can you suggest how this difficulty could be overcome or lessened?***

In Appendix E it is shown that:

$$\frac{\delta R}{R} = G\varepsilon$$

Where δR = change in gauge resistance
G = gauge factor
R = nominal gauge resistance
ε = strain in the test material

Exercise 10.1 ***Knowing the amplifier gain and the bridge supply voltage and given that $G = 2.2$ for the gauge in use and $R = 120\Omega$, estimate the factor relating the change in output voltage to the change in strain ε (i.e volts output per unit change in strain). You may also need to refer to the equation for V_{OC} for a Wheatstone Bridge in Appendix C.***

You may have suggested in answer to Question 10.8 that if a second, similar, gauge were mounted on the other side of the test specimen and used to form the balancing arm of the bridge in place of R_S, temperature changes would affect both gauges equally, leaving the bridge balance unaffected.

Question 10.9 ***Can you see another advantage in this arrangement?***

PRACTICAL 10.2

Dual Gauge System Connect up the circuit of fig 4.10.5. Although the two gauges are nominally of equal resistance there could still be a small unbalance remaining so the offset potentiometer R49 is retained in this circuit.

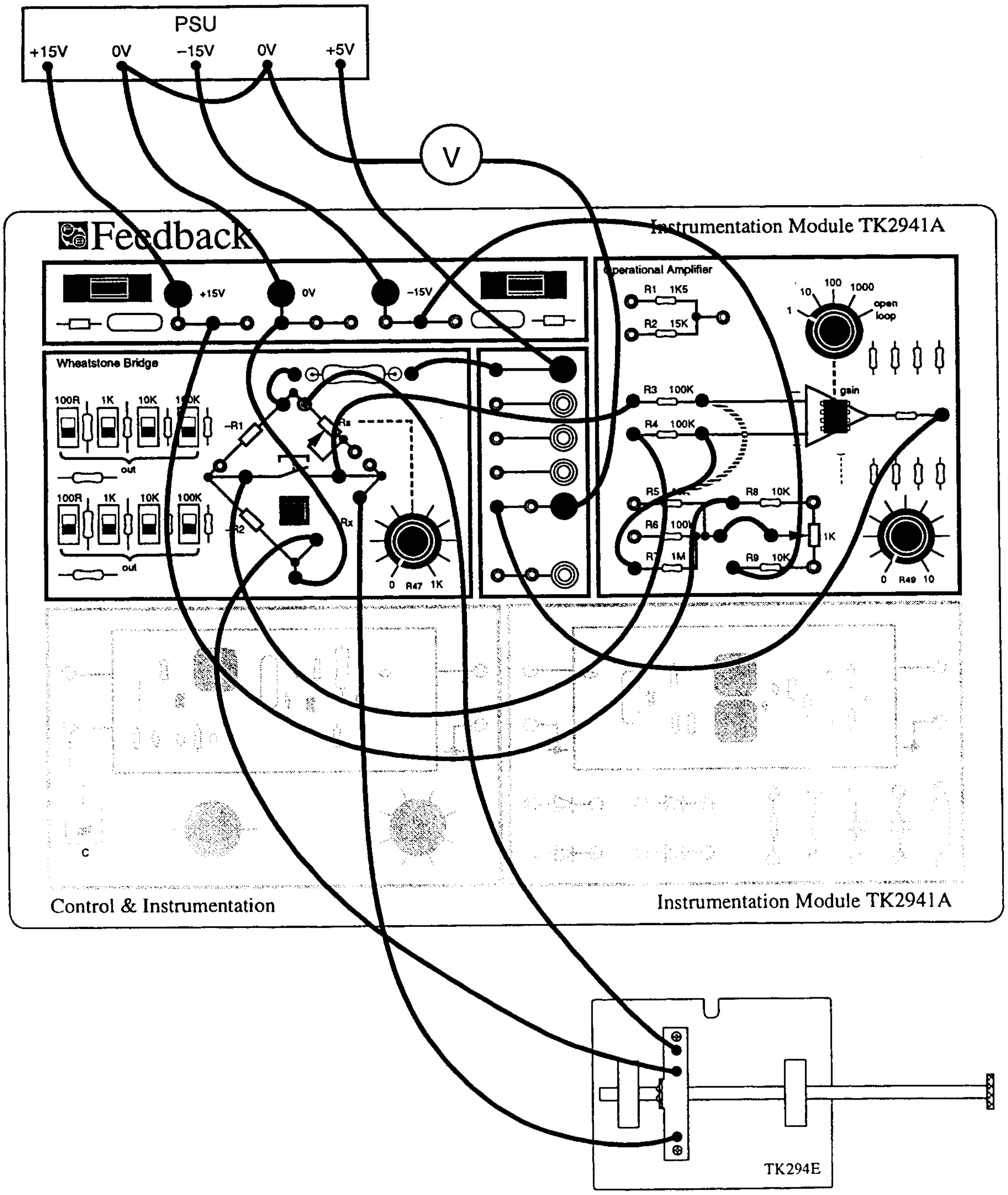


Fig 4.10.5

On the Wheatstone Bridge set $R_1 = R_2 = 1k\Omega$.

Set the operating rod to the same mid-position as was used in Practical 10.1 and then adjust R49 to give an exact zero as before. If you find balance cannot be obtained move the lead from R7 to the other input to the amplifier as shown dotted in fig 4.10.5 and try again.

Now take a set of readings of output voltage against micrometer setting as before (10.0 up to 12.5, down to 7.5 and back up to 10.0mm), and record them in a similar table.

Plot your results on the same sheet of graph paper as you used before.

Question 10.10 ***Are your new results free from thermal drift effects?***

Question 10.11 ***What is the slope of your new plot?***

You should find that the slope is about double that of your previous curve due to the added sensitivity achieved by using two gauges which are strained in opposing senses.

The amount the beam bends is proportional to the change in length of the sides of the beam in compression and tension. As the gauges are mounted with their conductors running lengthwise along the axis of the beam, the length of these conductors will also change in proportion. Do not forget that this also alters the area and the resistivity of the conductors. Any width changes in the transverse direction will not be picked up because of the direction in which the gauge is mounted. This causes a change in resistance given by the formula proved in Appendix E.

$$\frac{\delta R}{R} = \frac{\delta l}{l}(1 - 2\mu) + \frac{\delta \rho}{\rho}$$

Where l is the total length of the conductors of the strain gauge, ρ is their resistivity and R the total resistance. δ represents the small changes and μ is Poisson's Ratio.

But $\frac{\delta l}{l}$ is a measure of the strain ε in the gauge.

This is the same as the strain ε in the beam at the place where the gauge is mounted. Thus this type of transducer is called a *STRAIN GAUGE.*

The above equation is often written as:

$$\frac{\delta R}{R} = G\varepsilon$$

where G is called the *GAUGE FACTOR*, and is typically about 2.1 for certain types of gauge.

G depends upon the changes in length, area and resistivity, and this is discussed further in Appendix E.

But from the theory of the unbalanced Wheatstone Bridge (Appendix C) for small changes, $\frac{\delta R}{R}$ is proportional to meter output.

Therefore the meter output is proportional to strain which is proportional to slider position.

And it is this relationship we have proved with the graphs.

PRACTICAL ASPECTS

Although the Wheatstone Bridge is not a particularly convenient method for frequent determinations of actual resistance values, in the case of the strain gauge we are only interested in resistance changes, and once the bridge has been balanced in the resting position, it is a most simple method of obtaining a signal proportional to strain. When many gauges are used on a structure, electronic data logging equipment can be used to carry out the measurements and record the values quickly, easily and permanently for subsequent analysis.

The ideal gauge has a high factor, but most materials that exhibit high G have other characteristics which make them unsuitable for strain gauge use. Ideally the resistance change should be linear, i.e G constant. This is almost true with wire and foil gauges (see below) for small changes. It is also an advantage to have a reasonable value of resistance, so that the change in resistance with strain is appreciable, and this is achieved in a small area by the zig-zag winding of the conductor. The gauges should be protected against atmospheric conditions which can affect the conductor, and careful mounting is necessary to avoid any effects due to different expansion with temperature changes of the gauge and the object to which it is mounted. Of course temperature changes will also affect the resistance of the gauge itself.

A later assignment deals with resistance changes with temperature. This can be compensated for by having a similar gauge supplied from the same batch of gauges by the same manufacturer, mounted onto an un-stretched piece of similar material, and kept in the same vicinity as the active gauge. This *DUMMY GAUGE* as it is called, is placed in another arm of the Wheatstone Bridge e.g R_S to balance the active gauge. Thus any temperature changes will affect both the active and dummy gauges and the bridge will remain in balance.

It is often possible to use two or more gauges connected in series to give a higher output. In our beam we mounted another similar gauge on the opposite side of the beam so that one gauge was compressed and the other extended. As we connected these in opposite arms of the bridge, their effects were added together. This method can also be used to correct for strains in a direction not required. For example, if our beam was subject to direct tension as well as bending, using two gauges as above, the tension effect would cancel out. Strain gauges are designed to be sensitive in one axis only and there are methods discussed below to obtain strains in more than one direction. Strain gauges have the advantage that they can be fixed to any point on the structure where it is desired to measure the strain.

Similar methods can also be used with strain gauges to measure dynamic strains, i.e where the part is in motion. Here electronic methods of amplification and detection must be used in conjunction with the bridge. Often ac is used and the output demodulated. This is known as a carrier wave system.

Strain gauges can also be used to measure load and torque. If the force is transmitted to an elastically strained block of metal to which strain gauges are attached, or to an elastically twisted bar in the case of torque any further force will produce an output from the strain gauge. Such an arrangement is known as a *LOAD CELL*, and all the above measurement techniques can be used.

Types of Strain Gauge

The device which is used for the vast majority of strain measurements is the strain gauge. This consists essentially of a conductor whose length is great and cross-sectional area is very small. When the gauge is mounted to the surface of the object to be measured in such a way that it elongates and contracts with that surface, the deformation causes a change in resistance of the conductor. As we have seen, the ratio of the resistance is proportional to the ratio of its change in length to its original length. This then gives a direct measure of the strain on the measured surface.

Wire Strain Gauges

The first type of strain gauge to be developed was of the type known as the unbonded metal wire strain gauge. This type is not much used nowadays, but comprises a wire stretched between two terminal posts and unsupported along its length.

A more common form of wire strain gauge is shown in fig-4.10.6. This type is called the bonded wire strain gauge.

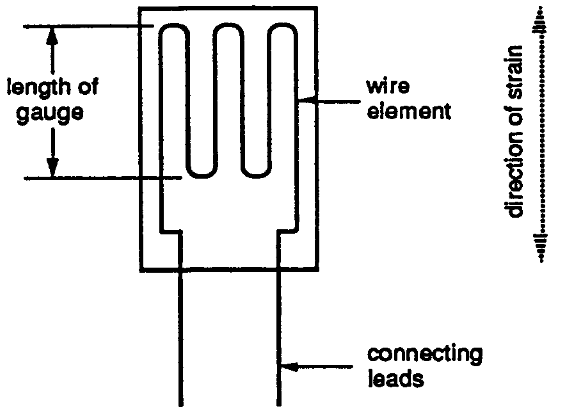


Fig 4.10.6

The thin wire filament is attached to a base material as shown in the diagram. The wire is arranged in this zig-zag pattern so as to have maximum deformation along the axis of the gauge and minimum at right-angles to this axis.

There are several factors which govern the choice of material for the resistance element of a wire strain gauge. Obviously the change in resistance with change in strain should be as large as possible, and the resistivity of the material should be high also, to enable a reasonable value of resistance to be obtained in a small area. The temperature coefficient of resistance of the material should be as low as possible to minimise errors due to temperature and the connection lead material should also be chosen carefully so that the junction between load and wire element generates the smallest possible thermoelectric potential (thermocouple effect). As well as these electrical requirements the filament must have high mechanical strength to be able to withstand the range of stresses to which it has to be subjected.

Perhaps the most commonly used material for the wire element is Constantan, a copper-nickel alloy, which has a very low temperature coefficient of resistance, between $\pm0.4 \times 10^{-4}$ per deg C between 0°C and 100°C, and an electrical resistivity of 40Ω-m at 0°C. The gauge factor of a Constantan strain gauge is normally between 1.9 and 2.1.

For special applications, for instance at high temperature, other alloys are sometimes used, for example: Nichrome or platinium-iridium, or alloys such as iron-nickel-chromium when a higher gauge factor (up to 3.5) is required. Wire diameters of around 0.025mm are often used for wire strain gauges.

The backing material which supports these very fine wires, and holds them in place, may be plastic or paper based. A common base material is nitrocellulose paper about 50μm in thickness, this being suitable for gauges to be used in the temperature range –70°C to +70°C. Polyester backed strain gauges are now very popular and various types are available which operate between –100°C and +150°C, whilst for high temperature work, polyimide backed gauges are suitable over the range –100°C to +300°C or so. Epoxy and ceramic based materials are also available for special applications.

The main requirement for the backing material is that of insulation, as it is normally very thin. It must of course insulate the parts of the wire filament from each other and also insulate the filament from the member onto which the gauge is attached. The base must also be non-hygroscopic, as absorption of water will give rise to resistance errors, and it must have sufficient strength to withstand the strains to which the gauge will be subjected. It must also be very much stronger than the conductor, so that all the strain is transmitted to the conductor without straining the backing at all.

Metal Foil Gauges

Instead of using a fine wire filament for the resistive element of the gauge, this type of strain gauge uses a very thin metal foil which is etched to give the zig-zag pattern, as before. Fig-4.10.7 shows the form of a typical metal foil strain gauge.

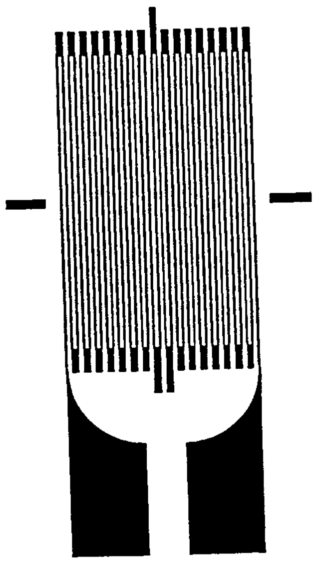


Fig 4.10.7

For a metal foil strain gauge a rolled Constantan foil between 2μm and 10μm thick is normally used. This is bonded to the backing material, which may be any of those described previously for the wire gauges and a photo etching process similar to that used in printed circuit manufacture is employed to produce the required pattern.

Foil gauges may be mass produced more easily than wire gauges, and allow a better utilisation of a given area as the cross section is rectangular which gives a better cross section/surface area ratio. The width at each end of the loop is often increased to reduce the sensitivity to transverse strain. The gauge factor is typically 5% - 10% higher than for a comparable wire gauge, which leads to smaller gauges. They can be used to measure higher strains than wire gauges, and are more robust, making them progressively more and more popular when a choice between the two types is made.

Semiconductor Strain Gauges

A silicon crystal attached to a backing can be used as a bonded strain gauge. The gauge factor is high, approaching 100, but it is ten times as sensitive to temperature changes as a wire gauge. The linearity is also very poor which makes this type of gauge only suitable for very specialised work.

Strain Gauge Rosettes

Strain gauges are made long and thin, as shown in fig 4.10.7, so that only strain in the direction of the long conductors will cause changes in resistance.

However, when the strains are known to be uniaxial, i.e when transverse strains may be neglected, it is possible to use a wide gauge. This type of gauge can dissipate more power, and may thus be used with a higher excitation voltage, giving a greater output from the bridge.

If the direction of the strain is not known, a combination of gauges as shown in fig 4.10.8 may be used. Here two of the gauges are at 45° to the third. By comparing the changes of resistance of the three gauges, both the magnitude and the direction of the strain may be deduced. The arrangement of more than one gauge on the same backing piece is known as a rosette.

Other rosette arrangements are available, two of which are shown in fig 4.10.8. The 60° rosette is another form that is commonly used when the direction of the strain is unknown.

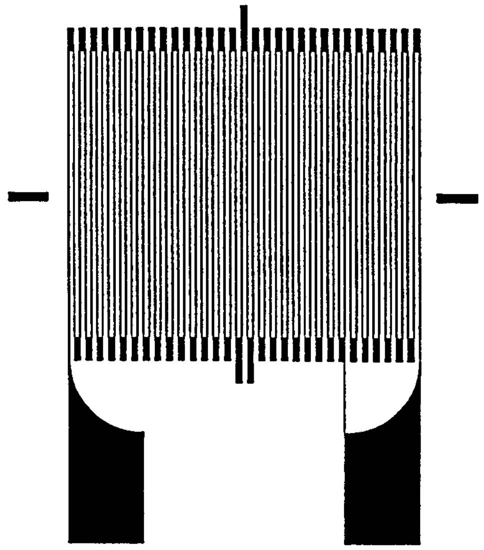


Fig 4.10.8

Strain Gauge Attachment

Strain gauges are normally attached to the member under strain by means of an adhesive cement. The surface should be prepared by thoroughly cleaning and degreasing, and roughening if necessary with fine emery paper. The gauge is then cemented in place. The type of cement used will depend on the backing material of the gauge to be used and its application conditions. There are three main types of cement: acetone based, polymerising types and ceramic based. The acetone based cements cure at room temperatures, whilst polymerising cements may be cured at or above room temperature. Those cured above room temperature are suitable for subsequent high temperature use, up to about 20°C from their initial curing temperature. Ceramic cements are flame cured and can withstand high temperatures.

The acetone based cements require little or no clamping pressure while curing, but the polymerising cements need clamping pressures between 15 x 10^3 and 600 x 10^3N. Ceramic cements need no clamping force. The surface must be thoroughly cleaned and if necessary roughened before attachment, and after drying, the gauge is often given a protective coating against atmospheric corrosion.

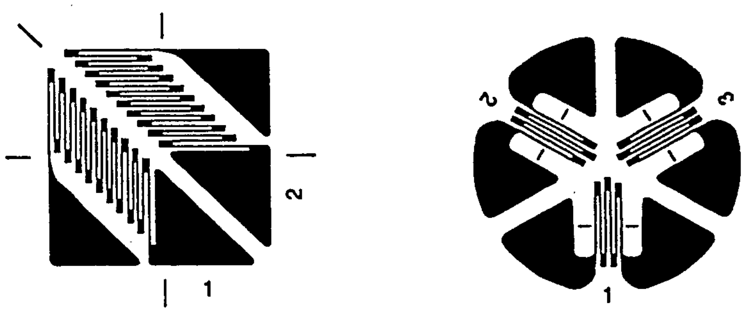


Fig 4.10.9

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 10

Question 10.1 The cantilever bends in an arc.

Question 10.2 The conductors of the gauge nearest the rod will become longer when the rod is pushed against the spring.

Question 10.3 and 10.4 The cross-sectional area reduces and the resistivity increases when the conductors are stretched, both effects contributing to an increase of resistance.

Micrometer setting (mm)	Output Voltage (mV)
10.0	+3
10.5	+25
11.0	+48
11.5	+64
12.0	+88
12.5	+108
12.0	+82
11.5	+62
11.0	+44
10.5	+20
10.0	−2
9.5	−23
9.0	−46
8.5	−67
8.0	−86
7.5	−105
8.0	−85
8.5	−62
9.0	−41
9.5	−19
10.0	+2

Fig E4.10.4 Single Strain Gauge

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 10

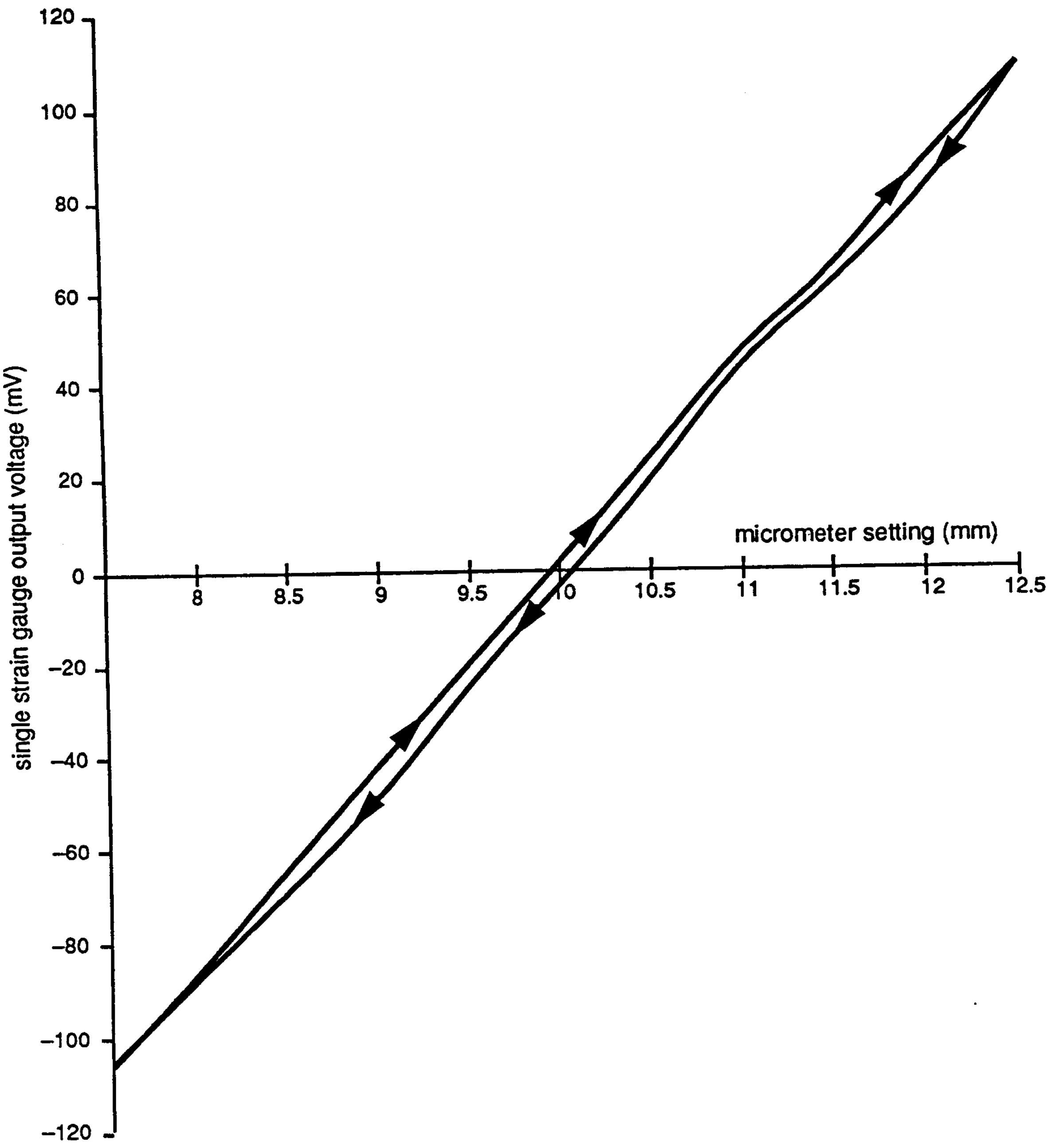


Fig E4.10.4 Single Strain Gauge

Question 10.5 The curve is linear but suffers some drift due to temperature variations. The slope is around 40mV/mm.

Question 10.6 The results for increasing and reducing displacement will probably not be exactly superimposed, due to drift.

Question 10.7 The final reading for 10.00mm will probably not be exactly the same.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 10

Question 10.8

The drift effect could be cancelled out by using a dummy gauge of similar type to the active gauge and subject to the same temperature, mounted in the opposite arm of the bridge.

Exercise 10

For the figures given the volts per unit strain can be as follows.

From Appendix C

$$\frac{V_{oc}}{V} \cong \frac{-\delta n}{(1+n)^2}$$

Where V_{oc} = change in bridge output
V = bridge voltage
n = ratio
δn = change in ratio

In this case, since the total bridge resistance across the 5V supply is 240Ω in parallel with 2000Ω, or about 214Ω, the actual bridge voltage is:

$$V = \frac{5 \times 214}{220 + 214} = 2.47$$

Also n = 1 so in δn = 1% or 0.01

$$V_{oc} = \frac{2.47 \times 0.01}{4} = 6.18\text{mV}$$

At a gain of 100 the output of the amplifier would change by 0.618.

For a gauge factor of 2.2 the percent strain = $\frac{1}{2.2}$ for a 1% change of resistance.

Therefore $\frac{1}{2.2\%}$ strain corresponds to 0.618V.

Thus $\frac{1}{220}$ per unit strain corresponds to 0.618V.

Thus the voltage per unit strain = 0.618 x 220 = 136V.

Conversely an output change of 1V represents a change in the per-unit strain of $\frac{1}{136}$ or about 0.007%.

Question 10.9 The other advantage of the twin-gauge arrangement is that it doubles the sensitivity, as explained in the assignment.

Micrometer setting (mm)	Output Voltage (mV)
10.0	+5
10.5	+440
11.0	+860
11.5	+1225
12.0	+1630
12.5	+2100
12.0	+1580
11.5	+1160
11.0	+845
10.5	+420
10.0	−7
9.5	−424
9.0	−839
8.5	−1250
8.0	−1664
7.5	−2024
8.0	−1597
8.5	−1168
9.0	−742
9.5	−325
10.0	+87

Fig E4.10.4 Dual Strain Gauge

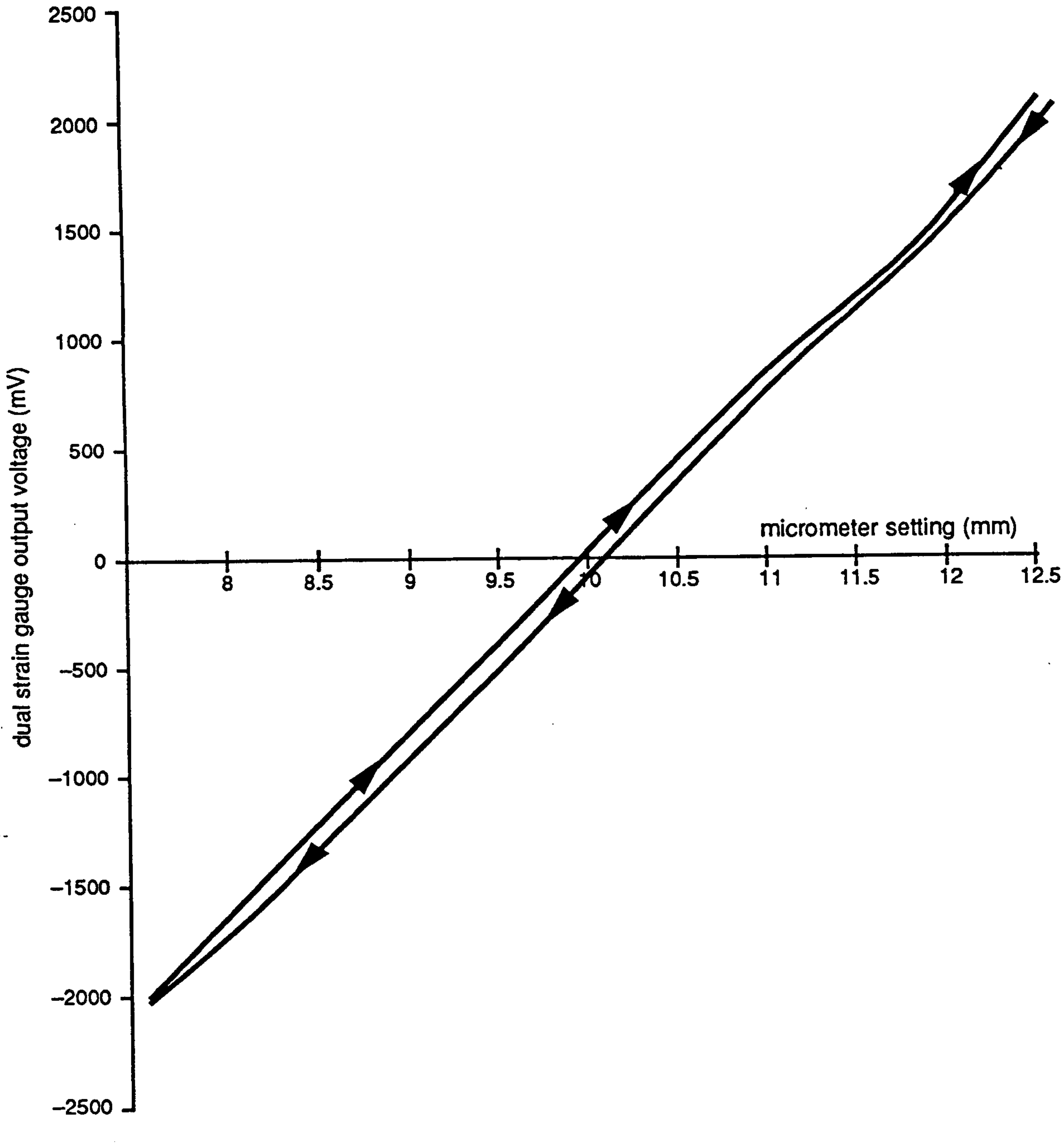


Fig E4.10.4 Dual Strain Gauge

Question 10.10

The curve for dual gauges should be free from thermal drift. The typical curve of fig E4.10.4 ends up at 0V for 10mm setting, as it should, but displays a slight hysteresis so that it does not pass through zero at 1mm on the way down from 12.5mm to 7.5mm. This is probably due to the characteristics of the cantilever metal.

Question 10.11

The slope of the dual gauge curve is typically 0.53V/mm, that is about double that for the single gauge, as expected.

NOTES

MEASUREMENT OF CAPACITANCE — ASSIGNMENT 11

CONTENT

The use of a Wheatstone Bridge to compare values of capacitance is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Function Generator 10kHz Sine, 20V pk-pk
1	–	Decade Capacitance 0.001μF to 0.1μF.
1	–	*AC Voltmeter 10V

* Alternatively a multimeter or oscilloscope may be used.

PRACTICAL

11.1 Capacitance Measurement

MEASUREMENT OF CAPACITANCE — ASSIGNMENT 11

OBJECTIVES

When you have completed this assignment you will:

- Know how to measure capacitance using a Wheatstone Bridge circuit.
- Have considered the difficulty of measuring small capacitance values.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the operation of the Wheatstone Bridge circuit.
- Be familiar with the operation of complex ac circuits and the notation used to describe them.

INTRODUCTION

Capacitance

The charge held by a two conductor system is directly proportional to the voltage between the conductors. The constant of proportionality of the equation is called the capacitance of the system.

The capacitance of a system is determined by the physical parameters of the system and is given by the equation:

$$\text{Capacitance, } C = \frac{\varepsilon_o \varepsilon_r A}{d}$$

where ε_o is the permittivity of free space

ε_r is the relative permittivity of the medium between the conductors (the dielectric)

A is the area of the conductors facing or influencing each other

d is the distance between the conductors.

It may be seen that the capacitance can be varied by varying ε_r, A or d. Thus it should be possible to construct transducers which use the variation of one or more of these parameters to vary the capacitance of the system. This variation in capacitance may be measured and thus related to the magnitude of the physical change which caused the parameter variation.

In practice, it is difficult to construct transducers which use the variation in ε_r, so we will concentrate on examining variable area and variable distance capacitive transducers in the following assignments.

Wheatstone Bridge Circuit

The method for measuring resistance using a Wheatstone Bridge uses the ratio of resistance in each of the two arms to effect a balance. This balance is obtained when the voltages at each end of the detector arm are equal and to achieve this the ratio of resistances in each side of the bridge must be equal as well.

The Wheatstone Bridge circuit may be used with an ac source as well, and the same balance conditions apply. However, at ac it is a ratio of impedances and not just resistances which cause the potential division in each side which is necessary for balance.

Consider the circuit of fig 4.11.1.

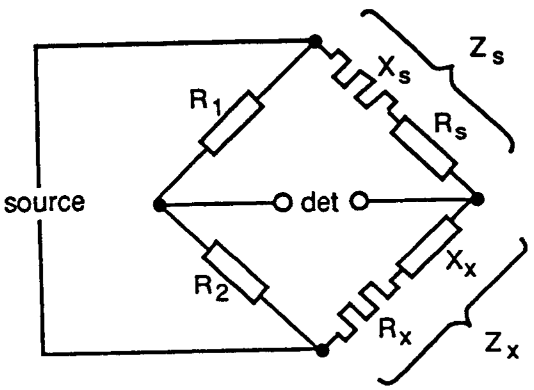


Fig 4.11.1

For this circuit:

$$\frac{R_1}{R_2} = \frac{Z_s}{Z_x}$$

Where Z_s and Z_x are the impedances of the standard and unknown arms respectively.

These impedances, of course, will be phasor quantities with both magnitude and phase angle, and it is necessary to adjust both the magnitudes and phase angles of the impedance arms to achieve balance. This means that the bridge has to be balanced for both the resistive and the reactive components.

as $\frac{R_1}{R_2} = \frac{Z_s}{Z_x}$

then $Z_x = \frac{R_2}{R_1} . Z_s$

but $Z_x = R_x + jX_x$

and $Z_s = R_x + jX_s$

so $R_x + jX_x = \frac{R_1}{R_2}(R_s + jX_s)$

equating real and imaginary parts, we get:

$$R_x = \frac{R_2}{R_1}.R_s$$

and $$X_x = \frac{R_2}{R_1}.X_s$$

These are the general equations for this type of bridge. It is often known as the resistance-ratio bridge.

Question 11.1 ***If Z_X is a pure capacitor, what form of component would the standard, Z_s, have to be to achieve balance?***

Question 11.2 ***What is the formula for Z_X, if a pure capacitor is used?***

Question 11.3 ***What do the balance equations now become?***

To see if your answers are confirmed in practice, set up the circuit of fig 4.11.2 with the output of the generator set to zero.

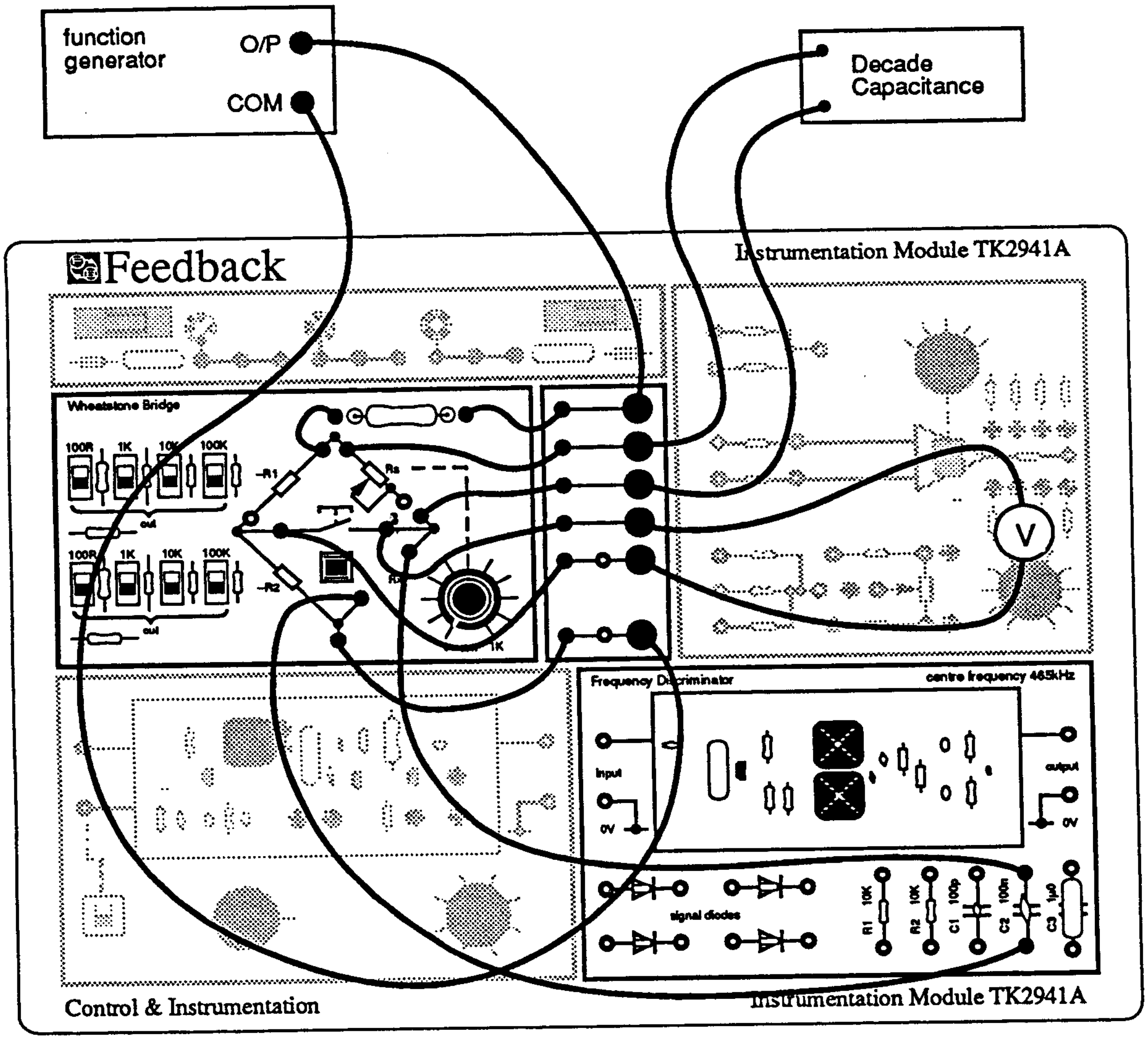


Fig 4.11.2

PRACTICAL 11.1

Capacitance Measurement

Choose a value for C_x of about 100nF. You can either use a loose capacitor, or the one in the Frequency Discriminator section as shown.

Set $R_1 = R_2 = 1k\Omega$.

Question 11.4 ***With R_1 and R_2 both set to $1k\Omega$, what value of C_s should produce balance?***

Set C_s to this value. Set the generator frequency to about 1kHz and increase the generator output until you get a reasonable reading on the detector and adjust C_s until the bridge is balanced.

Question 11.5 ***What is the balance value of C_s ?***

Question 11.6 ***Using this value in your balance equation for the bridge, what is the value of C_x?***

Question 11.7 ***Did you find it fairly easy to obtain a balance for C_x?***

Reset the generator output to zero and replace the 0.1μF nominal C_x with a 1μF C_x. This can be a separate component or may be the one on the Frequency Discriminator section.

Using the same procedure as before find the balance again. You may find that you need to change the ratio arms, R_1 or R_2, to achieve balance.

Question 11.8 ***What is the balance value of C_s this time?***

Question 11.9 ***What value is C_x now?***

Question 11.10 ***Was the balancing any more difficult?***

Reset the generator output to zero and replace the 1μF C_x with a 100pF C_x.

This again may be separate or found on the Frequency Discriminator section.

Again, using the same procedure, balance the bridge. You may need to change the ratio arms to achieve balance.

Question 11.11 ***What value of C_s gives balance?***

Question 11.12 ***What value is C_x now?***

Question 11.13 ***How does this value compare with its nominal value of 100pF?***

Question 11.14 ***Was the balance easy to obtain?***

Reset the generator output to zero and reverse C_s and C_x on the module (i.e plug the unknown into the position for C_s and the standard into that for C_x).

Increase the output of the generator again and balance the bridge once more.

Question 11.15 ***What value of standard C_s gives balance this time?***

Question 11.16 ***What value of C_x does this give?***

Question 11.17 ***How does this compare with its nominal value of 100pf?***

Question 11.18 ***How does this compare with the previous reading for this capacitor?***

Question 11.19 ***Was the balancing procedure easy or difficult?***

Question 11.20 ***What do you think is the cause of the discrepancy?***

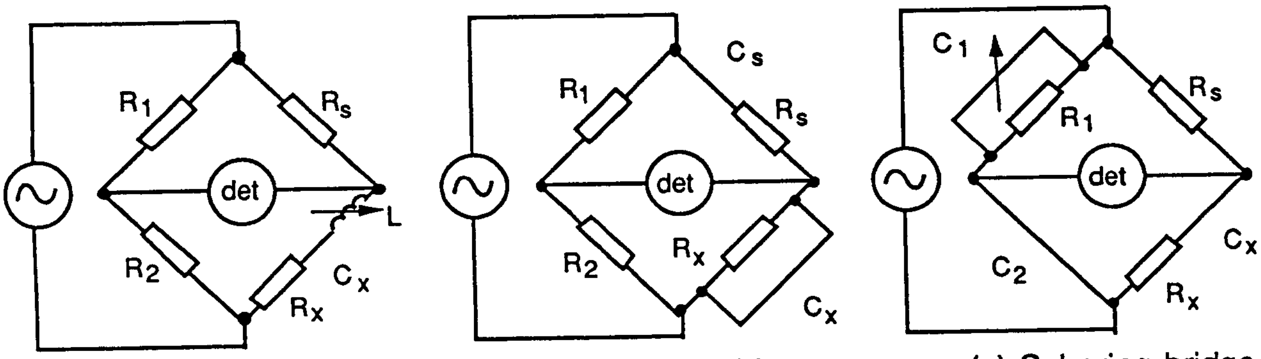
From your experimental results you should have found that this method for the measurement of capacitance is valid especially for capacitors of reasonably large value. However, in a simple bridge of the construction used in Instrumentation Module TK2941A, there will be appreciable stray capacitances which will contribute to errors which may be considerable if the capacitance to be measured is of small value. Stray capacitances and screening are discussed more fully in Appendix C.

PRACTICAL ASPECTS

We have seen in the assignment that if the Wheatstone Bridge is supplied from an ac source, and if the capacitor is placed in the unknown R_x arm then its reactance can be used as a way of measuring its capacitance if the frequency is set.

It is not necessary only to use resistors in each of the other arms of the bridge. There has developed a variety of bridges for measuring the value of capacitors. In them, the impedance of each arm is made up of various combinations of resistance, capacitance and even inductance.

A few of the most effective are shown in fig 4.11.3. Each has its own special features. Fig 4.11.3(a) is that of the resonance bridge in which the unknown capacitor is C_x is placed in one arm, together with an inductance L. The supply frequency then varied so that series resonance takes place in the LC_x circuit. In this condition the inductive and capacitive reactances cancel out and the impedance is only that of the resistance R_x. This minimum value can then be measured in terms of frequency by using a variable inductance. Taking R_x as the resistance of the inductance, then it will be balanced when



(a) (b) Wien bridge (c) Schering bridge

Fig 4.11.3

$$\frac{R_s R_2}{R_1} = R_x$$

The value of the capacitor at resonance will be:

$$C = \frac{1}{L\omega^2}$$

Another bridge that is able to give very precise measurement of capacitance, in terms of resistance and frequency, is the Wien bridge. It can also be used to measure frequency in the audio range and if a regenerative amplifier is used in the bridge, then the circuit is capable of generating very pure sine waves. In balance the value of the unknown C_x is:

$$C_x = \frac{R_1 C_s}{R_2\left(1 + \omega^2 C_s{}^2 R_s{}^2\right)}$$

The third bridge we will discuss is the Schering bridge. This bridge measures not only capacitance but at the same time the power factor of the capacitor under test. This is because the loss R_x of the unknown capacitor C_x is balanced by a capacitor of fixed value C_3. For a set ratio $\frac{R_2}{R_1}$ of the resistance arms, the value of C_x will be proportional to C_3 and will be unaffected by the effects of the loss. At balance the value of C_x will be:

$$C_x = \frac{R_1}{R_s} C_2$$

Capacitive transducers have small values of capacitance and as it is difficult to measure such small values on a bridge, in Assignment 12 we shall be showing a more usual method of carrying out these measurements.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 11

Question 11.1 A pure capacitance which has no resistive losses.

Question 11.2

$$Z_x = \frac{R_2}{R_1} Z_s = \frac{R_2}{R_1}\left(\frac{1}{j\omega C_2} + R_s\right)$$

$$\therefore Z_x = \frac{R_2}{j\omega C_2 R_1} + \frac{R_2 R_s}{R_1}$$

Question 11.3

$$R_x = \frac{R_2 R_x}{R_1} = \infty \text{ if } R_s = \infty$$

$$X_x = \frac{R_2}{\omega C_s R_1} \qquad \text{Thus } C_x = \frac{C_s R_1}{R_2}$$

Thus R_x can be neglected.

Question 11.4 100nF.

Question 11.5 108nF.

Question 11.6 $C_x = C_s \times 1$ = 108nF.

Question 11.7 Yes, the balance is fairly sharp. In a typical measurement Vs was 10V rms. The voltage at balance was 30mV p-p; at 109nF the unbalance voltage was 38mV p-p, and at 107nF was 98mV.

Questions 11.8 and 11.9

Giving $C_x = C_s \times 1$

C_x = 1.040μF

Question 11.10 The balance voltage was 4mV p-p.

The out of balance voltages for a ±1% change in C_s were 57mV and 60mV. Hence balancing was easier.

Questions 11.11, 11.12 and 11.13

C_s = 0.108μF $\qquad \frac{R_1}{R_2} = \frac{1}{1000}$

Thus Cx = 108pF

Not far from 100pF.

Question 11.14	Balance was not easy to obtain. The offset voltage at balance was 10mV p-p, and 1% change in capacitance gives no detectable change. The final decimal place was found by interpolation.
Question 11.15	0.100µF approximately.
Questions 11.16 and 11.17	100pF approximately.
Question 11.18	The previous reading was more accurate because the balancing null was sharper.
Question 11.19	Difficult because of the poor null obtained.
Question 11.20	Stray capacitance.

SMALL VARIATIONS IN CAPACITANCE — ASSIGNMENT 12

CONTENT

Methods of measuring small changes in capacitance are investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig.
1	TK294H	Variable Capacitor (Area) Sub-unit.
1	TK294J	Variable Capacitor (Distance) Sub-unit.
1	–	Digital Frequency Meter 1MHz
1	–	Power Supply,±15Vdc *(eg Feedback PS446)*

PRACTICALS

12.1 The Oscillator

12.2 Frequency Variation – Variable Area Capacitor

12.3 Frequency Variation – Variable Distance Capacitor

SMALL VARIATIONS IN CAPACITANCE — ASSIGNMENT 12

OBJECTIVES

When you have completed this assignment you will:

- Recognise the problems associated with measuring small capacitance values using Wheatstone Bridge techniques.
- Have investigated a method of measurement using variation in resonant frequency.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the Instrumentation Module TK2941A and the Linear Transducer Test Rig TK294.
- Understood complex ac circuits involving resonant frequencies and the notation used to describe them.

INTRODUCTION

It is very difficult to measure small values of capacitance using normal Wheatstone Bridge techniques, therefore some other method is needed when transducers whose operation depends on detecting small capacitances are used.

In a transducer system it is the state of the thing that has to be measured that is important. Consider a situation where the position of a connecting rod in some engine has to be measured, and a resistive transducer is being used. The resistance transducer is being used as one part of a potential divider circuit and the output voltage from this circuit is being measured and displayed on a meter. The actual resistance of the transducer is not really the important factor, what is really important is the relationship between the position of the connecting rod and the output voltage as seen on the meter.

Similarly, if a capacitive position transducer was being used for the above application, knowing the actual capacitance of the transducer is less important than knowing the relationship between the thing being measured and the output.

Thus instead of using a method which actually measures the value of the capacitance of the transducer, such as would be the case if a bridge type circuit is being used, a method which uses the capacitance of the transducer to vary the parameters of an electronic circuit, and hence vary the output from that circuit, may be more usefully employed, provided the relationship between the thing being measured and the circuit output is known, of course.

If we are to use this method with a capacitive transducer, we must find a circuit whose parameters change for change a in capacitance.

Question 12.1

Can you think of a simple circuit whose parameters change for a change in capacitance in that circuit?

Perhaps the most common such circuit is the inductance-capacitance resonant circuit, often referred to as a 'tuned circuit'.

The well-known formula for the frequency of resonance (f_r) of an LC tuned circuit is:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

hence, if C is changed, then f_r, will change also.

The resonant circuit can be used, together with an amplifying circuit, to form another type of circuit which is known as an oscillator. The oscillator produces an ac sinusoidal output at a frequency governed by the resonant frequency of the tuned circuit used in that oscillator. Hence, if the resonant frequency of the tuned circuit is changed by changing the capacitance, C, the frequency of the ac output from the oscillator will change also.

The Instrumentation Module TK2941A contains such an oscillator circuit. The two sockets on the lefthand side of the oscillator section are for the connection of the external component (the transducer). This may be either an inductor or a capacitor, the switch being switched to the appropriate position.

The external component only forms part of the oscillator's resonant circuit. Also in this circuit is a variable capacitor which is controllable by the "frequency' control. This will also change the resonant frequency of the oscillator tuned circuit and hence the frequency of the oscillator output.

Following the oscillator circuit there is a separate amplifier which is controllable by the 'output voltage pk-pk' control, to give a variable output ac voltage at the 'output' sockets.

PRACTICAL 12.1

The Oscillator

Set up the circuit of fig 4.12.1 with the output of the oscillator being connected, via the transfer sockets, to a digital frequency meter.

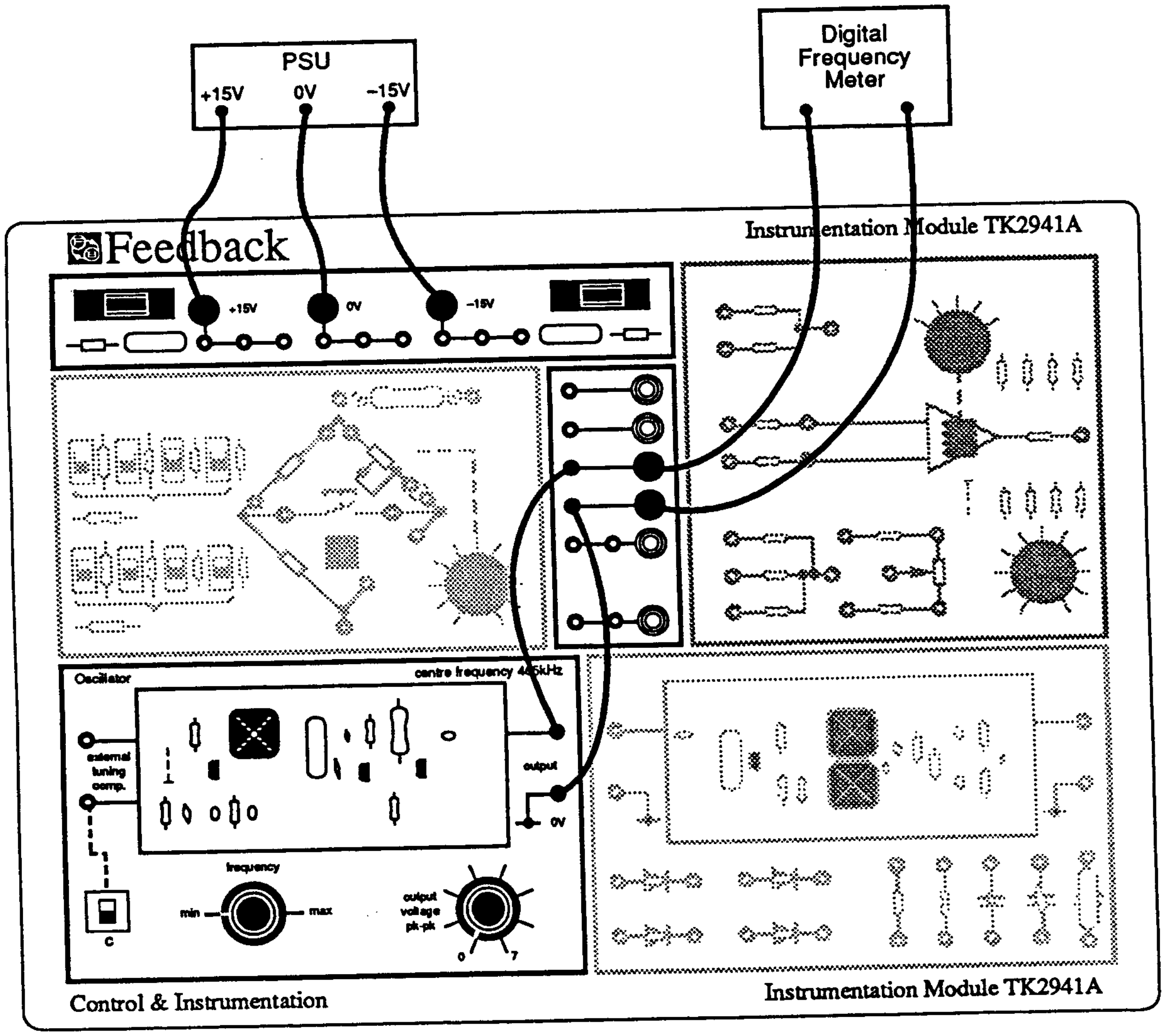


Fig 4.12.1

Set the sensitivity control on the digital frequency meter to half scale and the output voltage control on the oscillator to zero.

Set the oscillator frequency control to 'min'.

Switch on the power supply unit and increase the output voltage of the oscillator until the frequency meter gives a steady reading.

Question 12.2 ***What is the frequency of the oscillator output waveform with the control on 'min'?***

Move the control slightly clockwise.

Question 12.3 ***Does the oscillator frequency change?***

Set the oscillator frequency control to 'max'.

Question 12.4 ***What is the frequency now?***

When the frequency control is at 'min' are the vanes of the variable capacitor are meshed and its capacitance is at its maximum.

With the variable capacitor at maximum capacitance the frequency of the oscillator output is at its minimum and with the variable capacitor at minimum capacitance the frequency is maximum.

This can be seen from the following:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

thus $f_r \alpha \frac{1}{\sqrt{C}}$ and if C increases $\frac{1}{\sqrt{C}}$ becomes smaller and the frequency decreases. If C becomes smaller the frequency; increases

Consider the resonant circuit shown in fig 4.12.2.

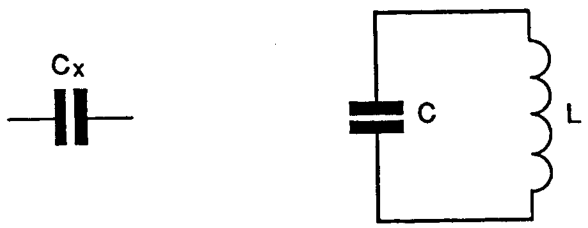


Fig 4.12.2

Question 12.5 ***How can the capacitor C_x be connected into the resonant circuit to change the frequency of resonance?***

You should be able to name two ways.

Question 12.6 ***If $C_x << C$, and the change in resonant frequency required is small, which of these two ways is most suitable?***

The form of the tuned circuit used in the oscillator is shown in fig 4.12.3, together with the values of the capacitors.

Question 12.7 ***With the variable capacitor at 50pF, what is the capacitance of C?***

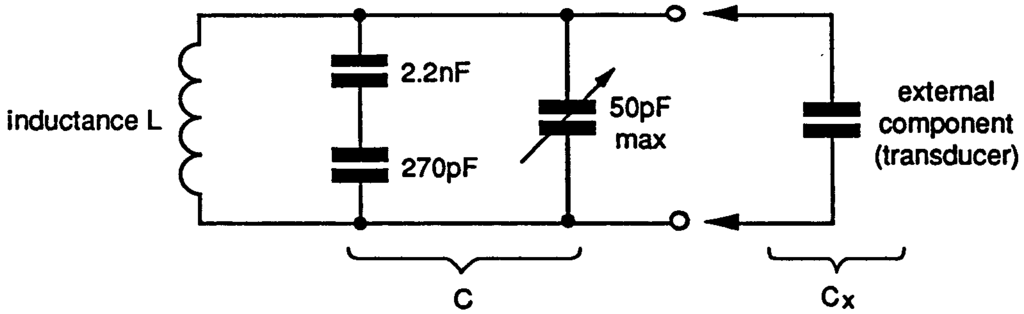


Fig 4.12.3

Thus, if C_x is considerably smaller than this value, connecting it in parallel with C, as shown in fig 4.12.3 will increase the total capacitance and lower the resonant frequency of the tuned circuit by small amounts.

Examine the tubular, variable area, capacitive transducer, TK294M, for use with the Linear Transducer Test Rig, TK294. The dimensions of this transducer are shown in fig 4.12.4.

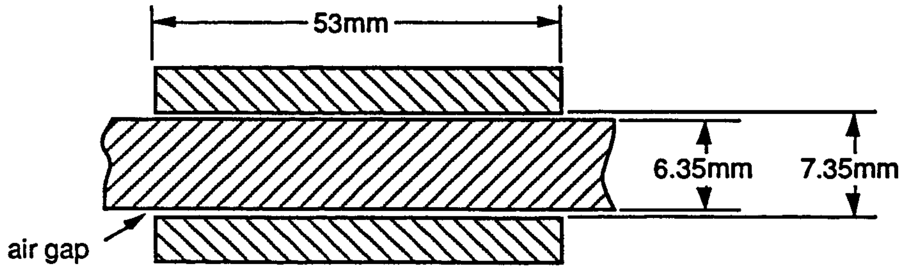


Fig 4.12.4

Question 12.8

Using the formula $C = \frac{\varepsilon_o \varepsilon_r a}{d}$

Calculate the value of the capacitance of this transducer when the inner rod is fully inserted.

$\varepsilon_o = 8.85pF/m$

and $\varepsilon_r = 1$

What is this value?

Question 12.9

Is it much smaller than the value of the rest of the capacitance across the tuned circuit?

Thus connection of this transducer across the resonant circuit of the oscillator will lower the resonant frequency of the oscillator by the required small amount.

When the switch on the Oscillator is in the 'C' position the two sockets designated 'external tuning comp' allow the capacitive transducer to be connected across the oscillator tuned circuit as desired.

PRACTICAL 12.2

Frequency Variation - Variable Area Capacitor

Assemble the TK294 and the TK294H, and make the circuit shown in fig 4.12.5

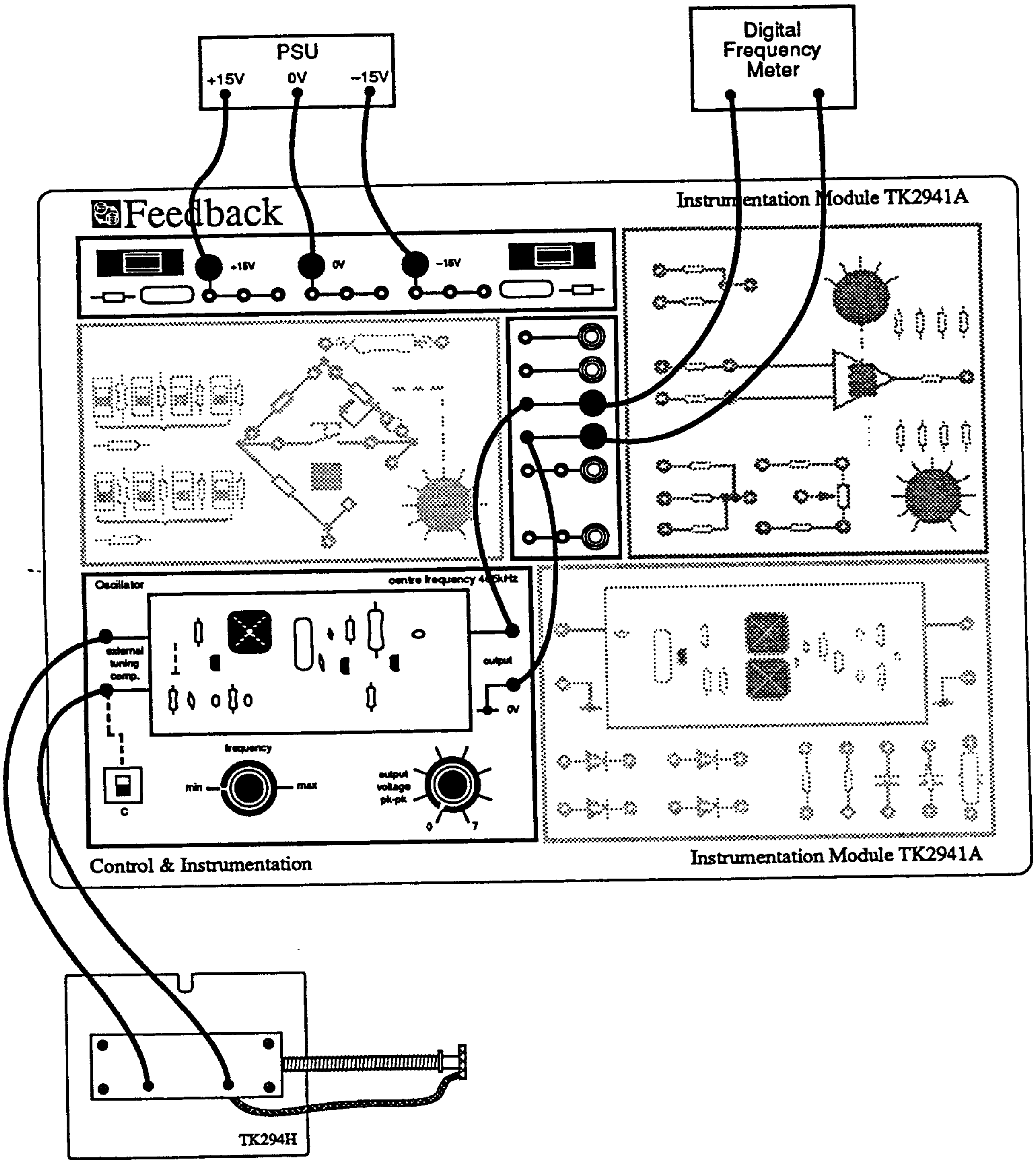


Fig 4.12.5

The lower 'external tuning comp' socket is connected to 0V and should be connected to the left hand socket on TK294H ie the capacitor body.

Set switch SW9 to the 'C' position.

Set the slider to 45mm, so that the steel rod is positioned half way through the capacitive transducer.

Set the oscillator frequency to give 465kHz at the output.

Take a set of readings of slider position and frequency of oscillation and enter them into your own copy of a table such as in fig 4.12.6.

slider position (mm)	frequency (kHz)
20	
25	
30	
35	
40	
45	
50	
55	
60	
65	
70	

Fig 4 12 6

Using your results, plot a graph of position against frequency of oscillation, on linear graph paper

Question 12.10 ***What shape is the graph?***

The formula you used for the capacitance of the transducer was:

$$C = \frac{\varepsilon_o \varepsilon_r a}{d}$$

Now εo , ε_r are constant but 'a' varies with the distance of insertion of the centre rod The area of 'a' cylinder is given by:

$a = \pi$ x diameter x length

Therefore the area is directly proportional to the length (in this case the distance of insertion of the centre rod).

Thus the transducer capacitance, C_x, must be directly proportional to the distance of insertion, x, of the centre rod.

ie $C_x = k\,x$ where k is constant

Substituting this expression into the formula for the resonant frequency gives:

$$f_r = \frac{1}{2\pi\sqrt{L(C + K_x)}}$$

where C is the internal capacitance in the oscillator.

Thus for constant L the resonant frequency is inversely proportional to the square root of the distance of insertion of the rod of the transducer provided $C_x << C$.

Thus the resonant frequency is inversely proportional to the square root of the distance of insertion of the rod of the transducer.

Question 12.11 ***Should this relationship give a straight line law as obtained in your graph?***

Question 12.12 ***Why do you think that a straight line was obtained?***

We know that the resonant frequency is given by:

$$f_r = \frac{1}{2\pi\sqrt{L(C + C_x)}}$$

and that $C_x << C$, thus the variation in f_r with variation of C_x will be a small proportion of the actual f_r If this is so, then the fact that f_r is inversely proportional to the root of C_x will not affect the shape of the curve and it will look predominantly linear (eg an arc of a circle will look very much like a straight line if the diameter is very large and the angle is very small).

This is proved formally in Appendix F where it is shown that if $C_x << C$, the change in frequency is almost linear with change in capacitance.

Thus for the variable area capacitor it is almost linear with the depth of insertion of the rod.

As we discussed previously, we could also use the principle of varying the distance between the plates of a capacitor, as a transducer and we will now examine this method.

PRACTICAL 12.3

Frequency Variation – Variable Distance Capacitor

Switch off the power supply and remove the TK294H from the TK294 and in its place substitute TK294J.

Connect this capacitor to the oscillator module in place of the other capacitor, similarly to the previous method in fig 4.12.5.

Note The lower of the 'external tuning comp' sockets is connected to 0V and should be connected to the lower socket on TK294J ie the metal chassis.

Switch on the power supply.

Set the micrometer to 12.5mm and the slider position so that the capacitor plates are roughly midway between fully open and fully closed (about 25mm on the scale) Lock the slider and set the oscillator frequency control to give approximately 465kHz Now adjust the micrometer in 05mm steps from 10mm to 15mm, or until the stop is reached, noting the frequency at each step.

Record your readings in your own copy of a table similar to fig 4.12.6.

Using your results, plot a graph of position against frequency of oscillation on the same piece of linear graph paper on which you plotted the previous results for the tubular capacitor.

Question 12.13 ***What shape is this new graph?***

PRACTICAL ASPECTS

You will have seen in this assignment that over the range used, the relation between frequency change and capacitance was linear The use of a digital frequency meter while attractive is rather an expensive solution to the problem This is because it is change in frequency that we are after and so a way has to be found to subtract from the total reading, the reading at the reference frequency Also it is a manual and time consuming method, as we have to do it separately for each frequency and refer to a calibration curve The output is seldom directly usable.

The type of system to do this directly is shown in the generalised example of fig 4.12.7 In such a system we need to set up a set sampling time, as an example 2ms, so that we have a crystal controlled oscillator that with other circuits will deliver a pulse every 2mS.

This pulse will then reset the Main and Over flow counter Every cycle input from the Oscillator/Transducer after being converted into a pulse is fed into the Main counter The counter is set such that at the reference frequency it becomes just full in the sampling time So that if the Main Counter can count up to 8192 bits, in every sample period and is preset to 3592, then at the reference frequency of 460kHz, it will be just full However, if the upper limit of oscillation is 470kHz; in every sampling period there will be an overflow of 100.

Coupling the Overflow Counter to a digital display will then give us a direct read out of either the change in capacitance or the change in the thing to be measured.

At the end of each sampling period, each part of the system is reset.

In Assignment 13 a more economical system is demonstrated, using the principle of frequency discrimination.

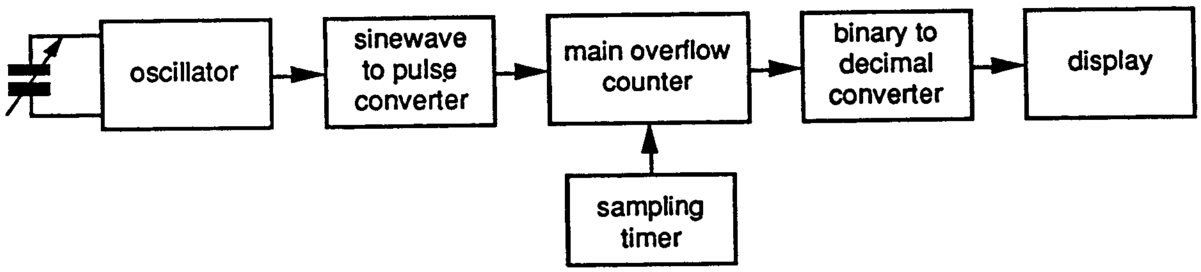


Fig 4.12.7

TYPICAL RESULTS AND ANSWERS ASSIGNMENT 12

Question 12.1 Series or parallel tuned circuits will change their tuning frequency if the capacitor is changed.

Question 12.2 470kHz approximately.

Question 12.3 The frequency increases.

Question 12.4 515kHz approximately.

Question 12.5 The capacitor C_x can be connected into the circuit in series with C or in parallel with it.

Question 12.6 If $C_x << C$ then the parallel mode is the preferred connection because changes in Cx will cause small changes to the frequency that are near to the resonant frequency of the circuit If Cx was in series it would control the resonant frequency of the circuit rather than shift it slightly.

Question 12.7 290pF.

Question 12.8

$$C = \frac{8.85 \times \pi \times 6.85 \times 53 \times 10^{-6}}{0.5 \times 10^{-3}}$$
$$= 20.2\text{pF}.$$

Question 12.9 It is 6% of the value of the rest of the capacitance in the tuned circuit.

slider position (mm)	frequency (kHz)
20	471.5
25	470.2
30	468.9
35	467.6
40	466.2
45	465.0
50	463.8
55	462.5
60	461.3
65	460.0
70	458.9

Fig E4.12.6 Variable area

Question 12.10 The graph is a straight line.

Question 12.11 In theory a curve should have been obtained.

Question 12.12 The percentage change in capacitance was only 6% Thus only a small portion of the curve has been plotted, and this curve is too near to a straight line to be detected.

micrometer setting (mm)	frequency (kHz)
10.0	453.2
10.5	454.7
11.0	454.6
11.5	458.0
12.0	462.0
12.5	464.8
13.0	466.8
13.5	468.1
14.0	469.3
14.5	470.2
15.0	470.8

Fig E4.12.6 Variable distance

Question 12.13 This graph is curved, partly because the capacitance change is much larger, and partly because:

$C \propto \frac{1}{d}$ or $C \propto \frac{1}{\text{slider position}}$

and this gives a more pronounced curve.

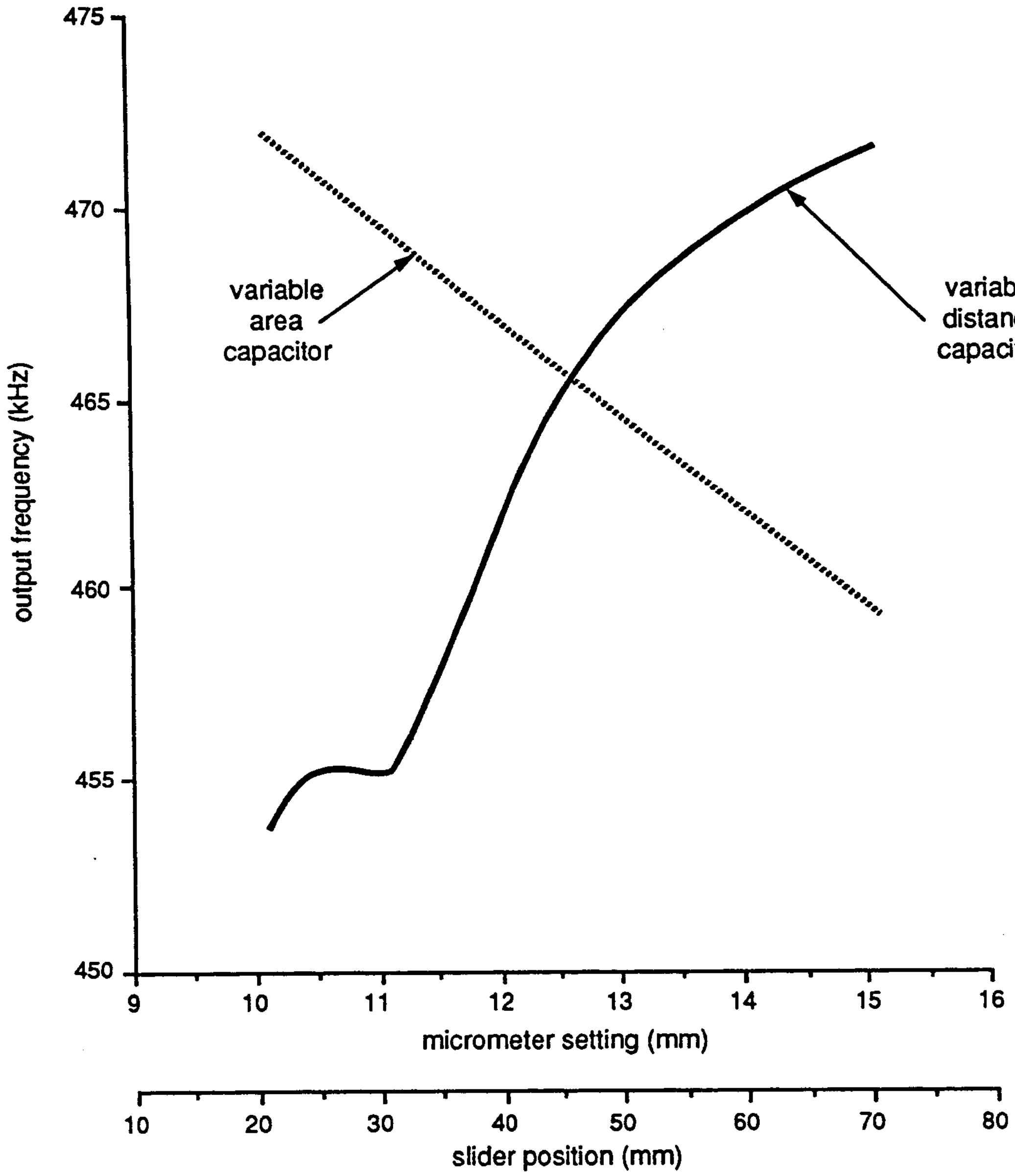


Fig E4.12.6 Plot of slider/micrometer positions against frequency

FREQUENCY DISCRIMINATION — ASSIGNMENT 13

CONTENT

The use of a frequency dicriminator to relate variations in frequency, to values of voltage is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig.
1	TK294J	Variable Capacitor (Distance) Sub-unit.
1	–	Power Supply,±15Vdc *(eg Feedback PS446)*
1	–	Function Generator Sine, 600KHz
1	–	Digital Frequency Meter 1MHz
1	–	*DC Voltmeter 10V

* Alternatively a multimeter may be used.

PRACTICALS

13.1 Frequency Discriminator

13.2 Frequency Modulated System

FREQUENCY DISCRIMINATION — ASSIGNMENT 13

OBJECTIVES

When you have completed this assignment you will:

- Recognise the characteristic output curve for a frequency discriminator circuit.
- Know how a frequency discriminator together with a capacitatively tuned oscillator may be used to form a Frequency Modulated (FM) system.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the Instrumentation Module TK2941A and the Linear Transducers Test Rig TK294.
- Understand complex ac circuits involving resonant frequencies and the notation used to describe them.
- Preferably have completed Assignment 12, Small Variations in Capacitance.

INTRODUCTION

Small changes in a small capacitance can be related to changes in the frequency of an oscillator, when the transducer capacitance is used to form part of the resonant circuit of that oscillator. The method normally uses a digital frequency meter to measure the oscillating frequency. This is a very complex and expensive measuring instrument. Also, its reading cannot be directly interpreted as transducer position without a calibration curve relating frequency to position.

It would be more economical and simpler if a circuit could be obtained which converted frequency changes into voltage changes. This could then be measured on an ordinary meter, which could be calibrated directly relating voltage to frequency.

The Instrumentation Module TK2941A contains such a circuit. It is called a 'frequency discriminator'. Let us examine the properties of the circuit.

PRACTICAL 13.1 Frequency Discriminator

Connect up the circuit of fig 4.13.1 as shown in fig 4.13.2. The amplifier is required as the output of the discriminator circuit itself is small.

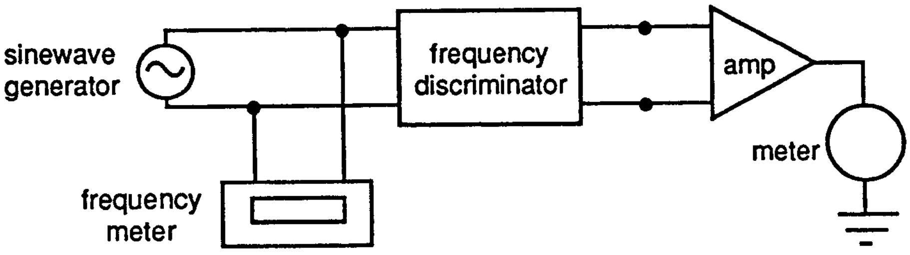


Fig 4.13.1

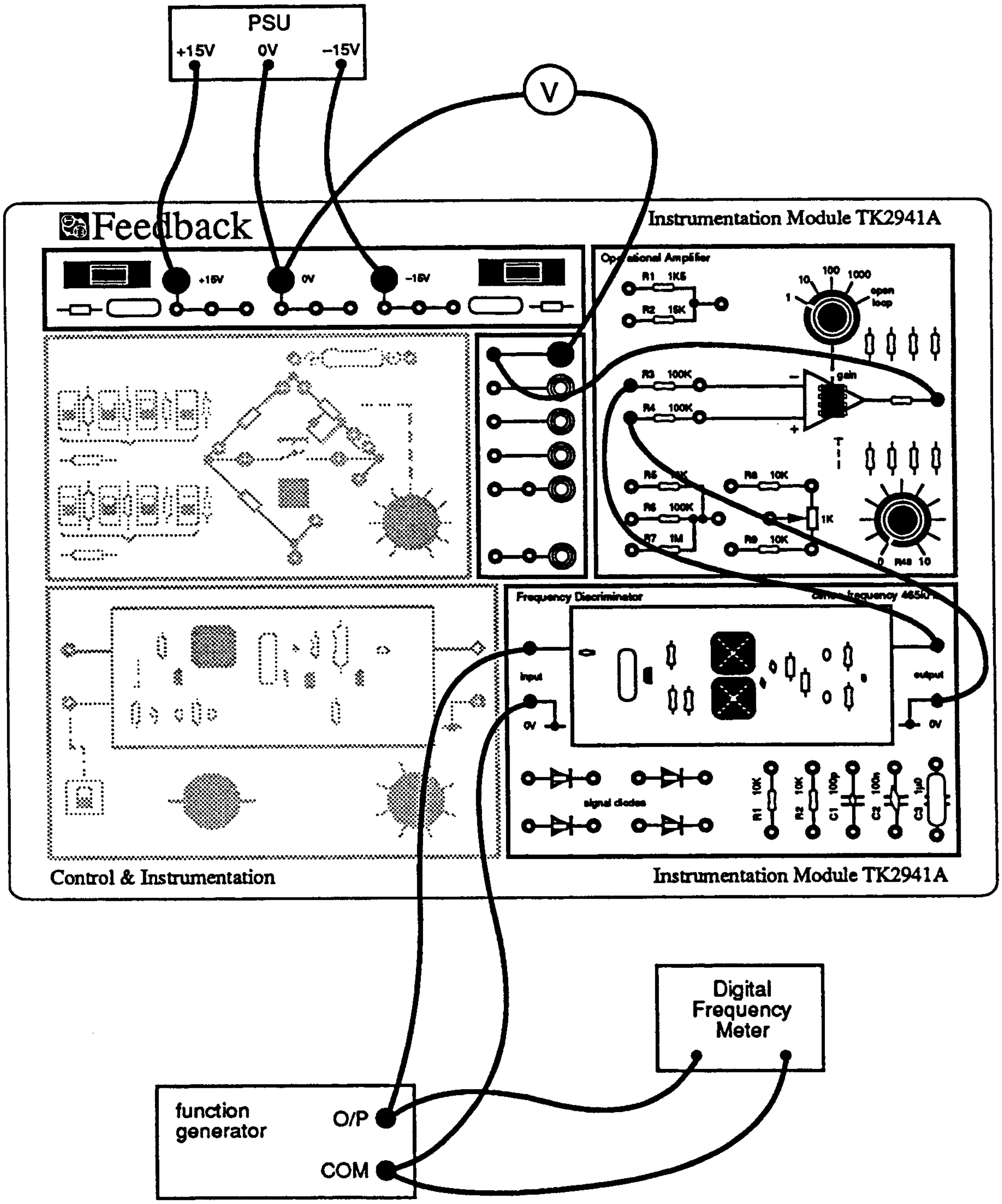

PSU
+15V
0V
-15V
V
Feedback
Instrumentation Module TK2941A
+15V
0V
-15V
Operational Amplifier
Frequency Discriminator
input
output
0V
signal diodes
Control & Instrumentation
Instrumentation Module TK2941A
Digital Frequency Meter
function generator
O/P
COM

Fig 4.13.2

Set the output of the function generator to 7 volts peak-to-peak at a frequency of 400kHz. Inputs higher than this may cause the circuit to limit. Adjust the sensitivity control on the digital frequency meter until a steady frequency reading is obtained. Set the gain of the amplifier switch to 10 and switch on the power supply.

Set the frequency to exactly 400kHz, as read on the digital frequency meter, and take a reading of the output voltage from the amplifier, as indicated on the meter. Repeat this procedure for frequencies at 10kHz intervals up to about 540kHz. Also carefully note the frequencies for which the output is (a) zero (b) maximum positive and (c) maximum negative.

Record your readings in your own copy of a table as in fig 4.13.3 .

Plot a graph on linear graph paper of output against frequency.

frequency (KHz)	output (V)
400	
410	
420	
430	
440	
450	
460	
470	
480	
490	
500	
510	
520	
530	
540	

Fig 4.13.3

Question 13.1 ***What shape of curve do you obtain?***

Question 13.2 ***Over which part of the curve does the output voltage change fastest with changing frequency?***

PRACTICAL 13.2

Frequency Modulated System

Let us examine this part of the curve more closely. Switch off and disconnect the function generator from the discriminator. Connect the Oscillator 'output' to Frequency Discriminator 'input' and Operational Amplifier as shown in fig 4.13.4. Retain the meter on the amplifier output. Make sure the oscillator switch is in the C position and connect the TK294 with variable distance capacitor, TK294J, to the oscillator 'external tuning comp' sockets.

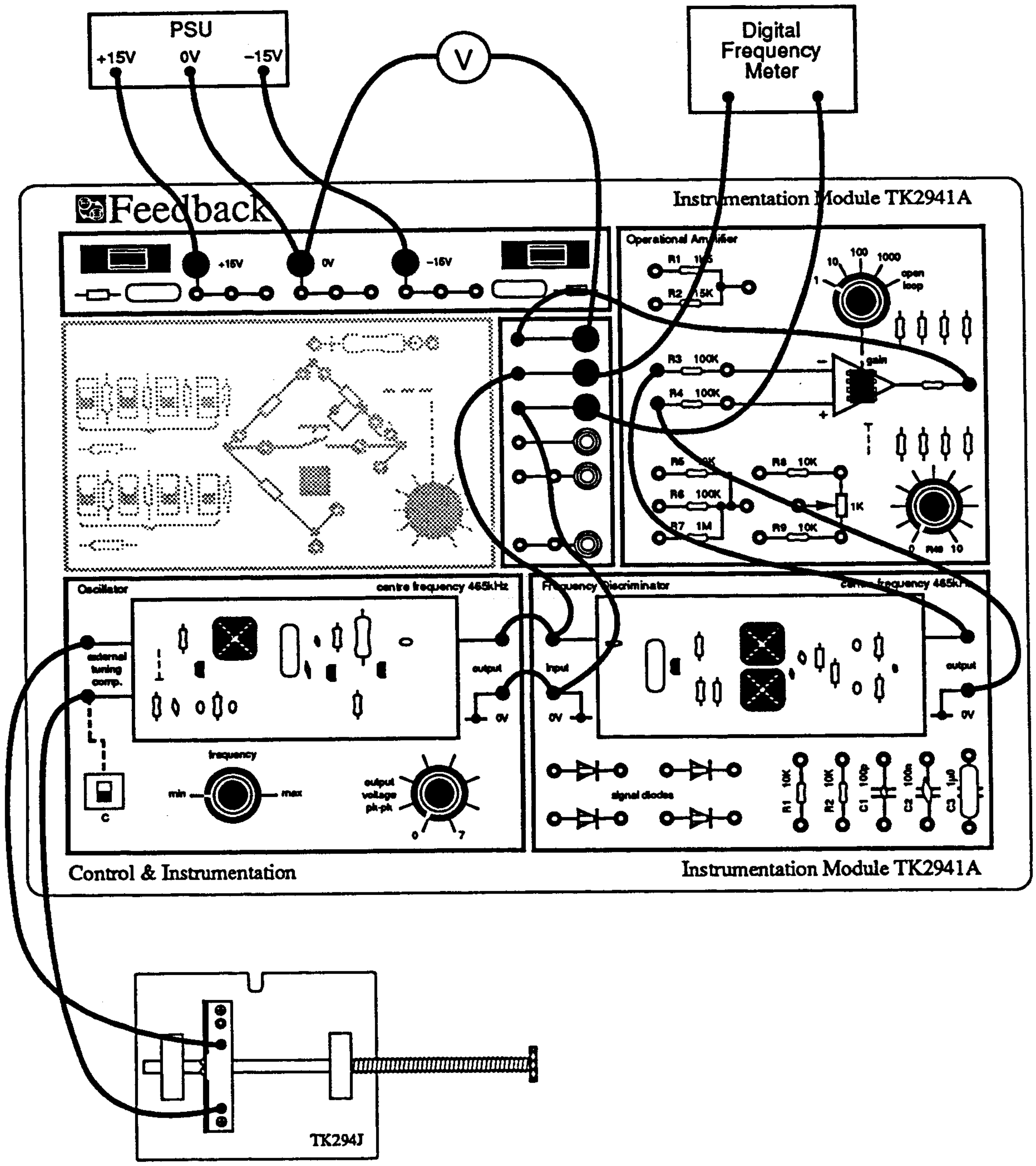


Fig 4.13.4

Note The lower of the 'external tuning comp' sockets is connected to 0V and should be connected to the lower socket on TK294J ie the metal chassis.

Set the oscillator output to '7' and the frequency control to mid-position between 'min' and 'max'. Now carefully set the slider until the meter reads zero, and then lock it in place. Note the frequency at which this occurs.

Now vary the oscillator frequency control from minimum to maximum, noting the output voltage at intervals of about 0.5V and the corresponding frequencies.

Note also the frequencies at which the maximum voltages occur.

Always remove your hand from the module when taking a reading, to avoid the effect of stray capacitance. Do not adjust the amplitude control as this will affect the results. The reason for this precaution will be explained later.

Record your readings in your own copy of a table as in fig 4.13.5.

output (V)	frequency (KHz)

Fig 4.13.5

Plot another graph of output against frequency on linear graph paper, for the centre section of the characteristic as recorded in fig 4.13.5.

Question 13.3 ***What shape is the curve, predominantly?***

The frequency at which the output voltage is zero is called the **CENTRE FREQUENCY.**

Question 13.4 ***If the transducer/oscillator system of the previous assignment gave an output frequency within the centre section of the 'S' curve of the discriminator, how would the amplifier output correspond to the transducer position?***

PRACTICAL ASPECTS

If your answer to the last question (13.4) was 'linearly' you have appreciated the application of the frequency discriminator with a capacitive transducer/oscillator system to form a *FREQUENCY MODULATED* (FM) System. This is fully explored in Assignment 14 and also for inductive transducers in later assignments.

There are several different frequency discriminator circuits which have the same characteristics as we have explored, and details of these can be found in many standard texts on electronic and radio circuits. Another application for this type of circuit is in FM (VHF) radio reception. Here the frequency modulated radio input signal is converted (by a super-heterodyne circuit) to a centre frequency of 10.7MHz. This FM signal is then applied to a discriminator which produces an audio frequency output voltage corresponding to the modulations of the input signal from the transmitter. The frequency change is necessary as it is very difficult to make discriminators with a centre frequency in the radio frequency range.

The choice of centre frequency of the discriminator for transducer systems is of course dependent on the centre frequency of the oscillator to which the transducer is attached. This depends upon the actual values of L and C but these must be high in relation to the changes in the variable produced by the transducer. This change is dependent upon the physical dimensions of the transducer.

Some discriminator circuits are also sensitive to variations in the amplitude of the input signal which will appear as a shift in the output. This can sometimes be overcome by amplifying the input signal and limiting it to a set value, whatever the actual input. Since the discriminator is sensitive to frequency changes, this will eliminate the error if the input is above a certain threshold level. Other discriminator circuits are self limiting and are said to have a large AM rejection.

The discriminator circuit used in the Instrumentation Module, TK2941A, is a Foster Seeley type circuit.

The 'S' shaped discriminator characteristics are often plotted with the aid of a sweep generator. If a FEEDBACK function generator type SFG606 or SFG611 are available, this may be explored.

frequency (KHz)	output (V)
400	+0.4
410	+0.5
420	+0.6
430	+0.9
440	+1.3
450	+2.2
460	+2.6
465	0
470	–3.1
480	–3.0
490	–2.4
500	–2.0
510	–1.7
520	–1.6
530	–1.4
540	–1.2
550	–1.0
extra readings at max output	
457	+2.9
474	–3.3

Fig E4.13.3

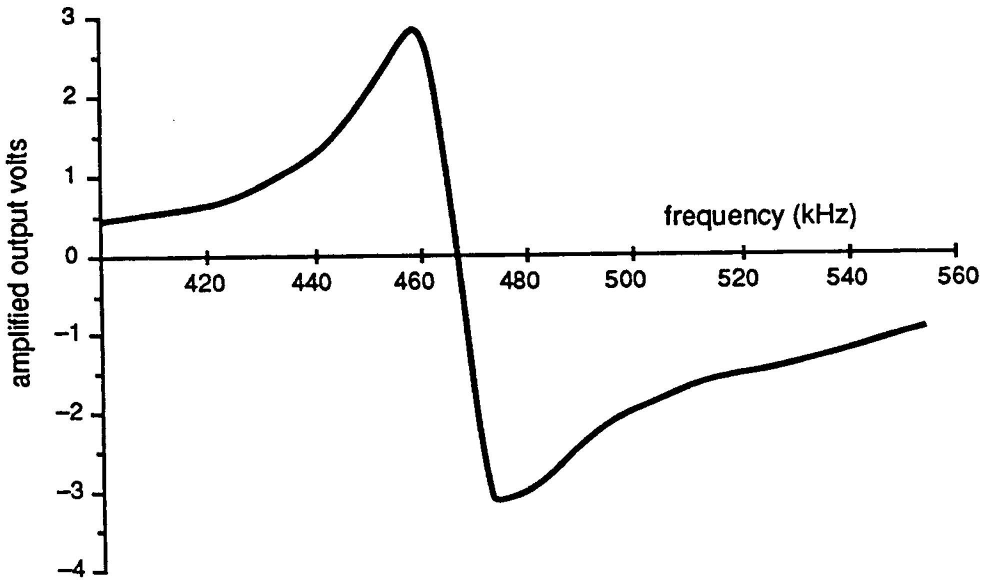


Fig E4.13.3

Question 13.1 The curve is S-shaped.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 13

Question 13.2

The output changes fastest with frequency over the steep central sections.

output (V)	frequency (KHz)
1.8	444.8
2.5	451.0
3.1 (max)	456.9
2.5	465.5
2.0	461.5
1.45	462.4
1.1	462.9
0.45	463.7
0	464.5
–0.5	465.0
–1.0	465.7
–1.5	466.3
–2.0	467.2
–2.5	468.2
–3.0	468.8
–3.4 (max)	473.5
–3.0	480.5
–2.9	482.4

Fig E4.13.5

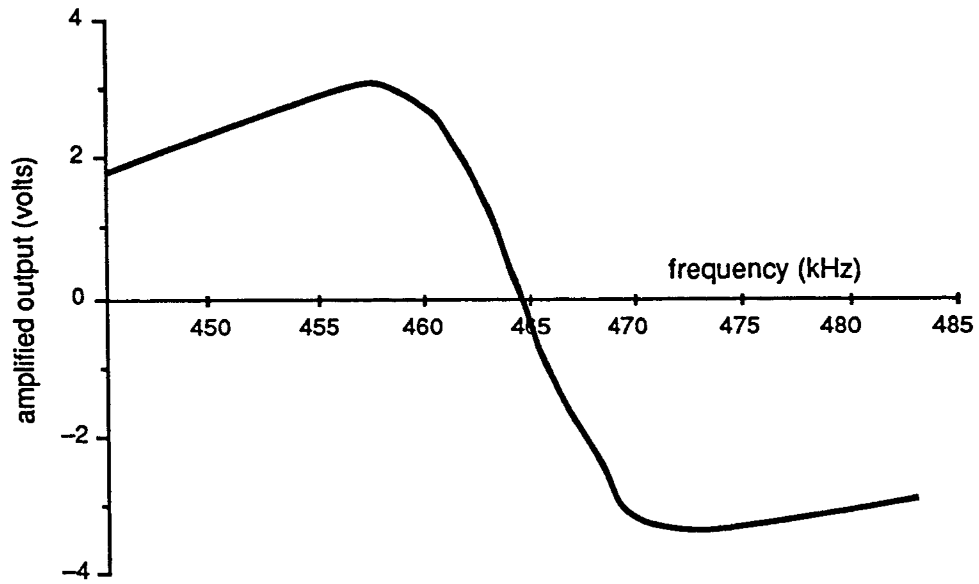


Fig E4.13.5

Question 13.3

The curve is S-shaped with the centre section between +2 and –2 volts predominantly linear.

Question 13.4

A linear relationship would result.

NOTES

CAPACITIVE TRANSDUCERS IN AN FM SYSTEM — ASSIGNMENT 14

CONTENT

A Frequency Modulated (FM) system is used to calibrate a capacitive transducer.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig.
1	TK294H	Variable Capacitor (Area) Sub-unit.
1	TK294J	Variable Capacitor (Distance) Sub-unit.
1	–	Power Supply,±15Vdc *(eg Feedback PS446)*
1	–	Digital Frequency Meter 1MHz
1	–	*DC Voltmeter 10V

* Alternatively a multimeter may be used.

PRACTICALS

14.1 Variable Area Capacitor

14.2 Variable Distance Capacitor

CAPACITIVE TRANSDUCERS IN AN FM SYSTEM — ASSIGNMENT 14

OBJECTIVES

When you have completed this assignment you will:

- Know how a capacitive transducer can be used with frequency discrimination circuitry to form a complete system.
- Realise the complexities involved in designing and implementing a practical system.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the Instrumentation Module TK2941A and the Linear Transducers Test Rig TK294.
- Understand the basic operation of a capacitively tuned oscillator.
- Understand the basic operation of a frequency discriminator.
- Preferably have completed Assignment 13, Frequency Discrimination.

Capacitive Transducers in an FM System

Assignment 14

INTRODUCTION

A capacitive transducer may be used to vary the frequency of an oscillator and that frequency variation may be fed to the input of a frequency discriminator and converted to a voltage variation at its output.

PRACTICAL 14.1

Variable Area Capacitor

Let us now assemble a complete system using the Linear Transducers Test Rig TK294 with a capacitive transducer assembly, together with the Oscillator, the Frequency Discriminator , the Operational Amplifier and a meter.

The block diagram of such a system is shown in fig 4.14.1.

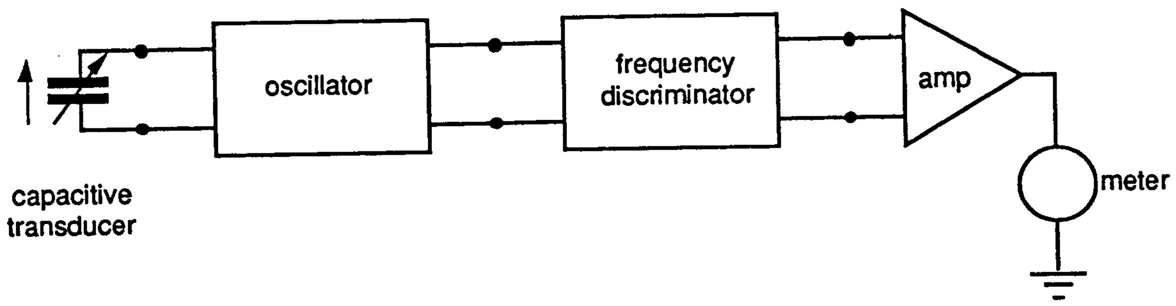


Fig 4.14.1

This corresponds to the circuit shown in fig 4.14 2.

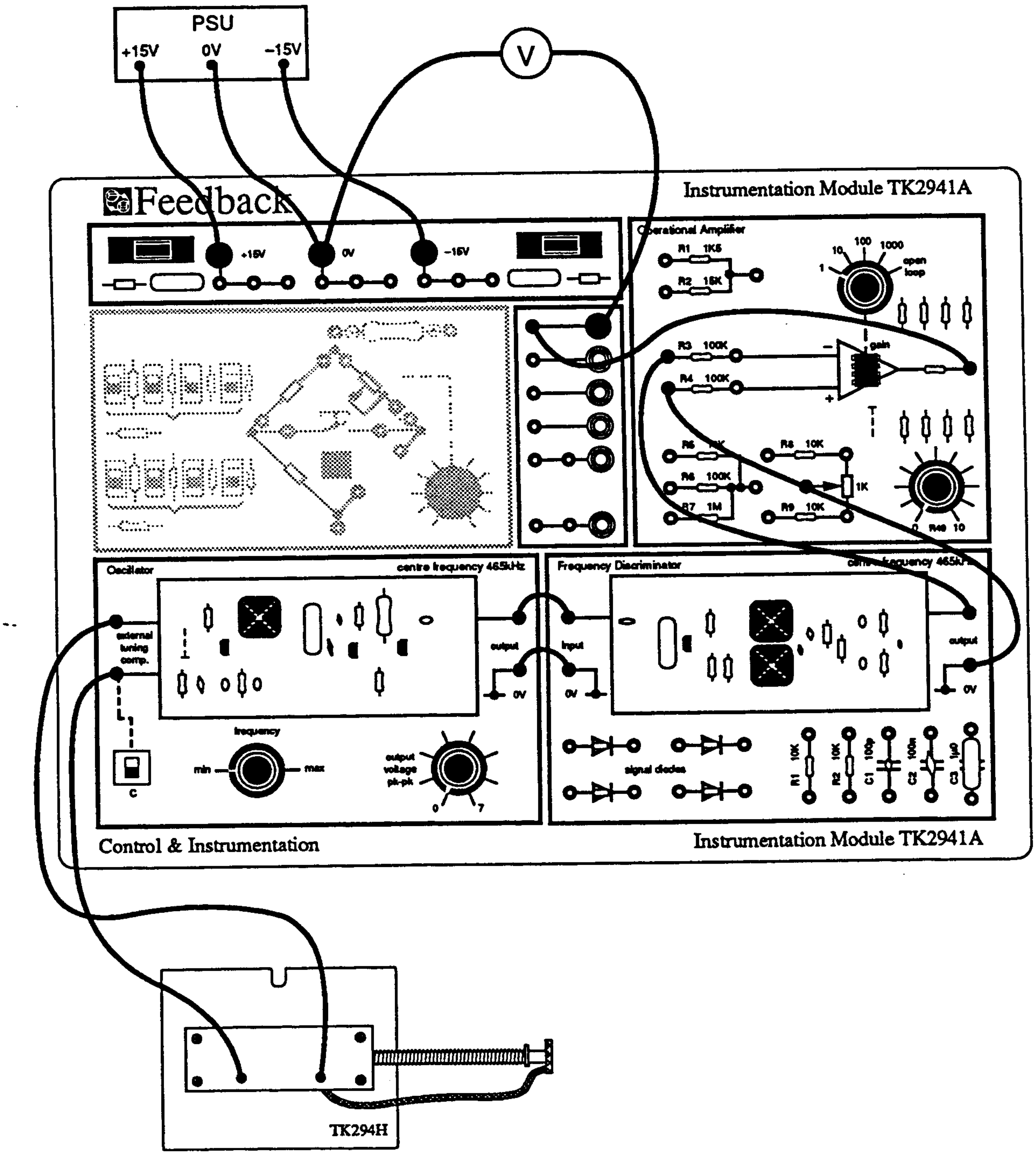

PSU
+15V
0V
-15V
V
Feedback
Instrumentation Module TK2941A
Operational Amplifier
Oscillator
centre frequency 465kHz
Frequency Discriminator
external tuning comp.
output
input
0V
frequency
min
max
output voltage pk-pk
signal diodes
Control & Instrumentation
Instrumentation Module TK2941A
TK294H

Fig 4.14.2

Assemble the TK294 and the TK294H and connect up the transducer and modules as shown in fig 4.14.2. Keep the leads as short as possible in order to reduce stray capacitance.

Set the position of the slider to 42.5mm at the middle of the scale, corresponding to the rod being halfway into the tubular capacitive transducer.

The lower 'external tuning comp' socket is connected to 0V and should be connected to the left-hand socket on TK294H ie the capacitor body.

Set switch SW9 to the 'C' position.

Set the micrometer to read 10mm.

Set the output voltage control on the Oscillator to mid scale. Set the gain of the Operational Amplifier to 10. Switch on the power supply. An output should be visible on the meter.

Adjust the oscillator frequency control until the sharp transition from positive to negative (or vice-versa) of the output voltage, corresponding to the steep linear central portion of the discriminator 'S-curve is found. From this point, slowly adjust the oscillator frequency control until the meter indicates exactly zero volts. **Always remove your hand when taking readings to avoid the effects of stray capacitance.** You can obtain increased sensitivity for this part of the experiment by temporarily increasing the amplifier gain. Now move the slider towards the transducer until either the rod is fully home or the meter reaches a positive maximum and adjust the oscillator 'output' control until this reading is some convenient figure (e.g approximately 3V). Do not adjust the oscillator frequency control, as the system is now arranged to vary about the discriminator centre frequency.

Now record in your own copy of fig 4.14.3, the output voltage for slide positions from 20mm to 65mm at 5mm intervals, leaving the micrometer setting at 10mm throughout.

slider position (mm)	output voltage (V)
20	
25	
30	
35	
40	
45	
50	
55	
60	
65	

Fig 4.14.3

Using these results, plot a graph of output against slider position, on linear graph paper.

Question 14.1 — ***What shape is the graph, over the central section?***

Question 14.2 — ***Does this part of the graph enable you to easily relate the output voltage to the position of the transducer?***

Question 14.3 — ***How can the system be modified so that it directly reads transducer position?***

This modification can be a purely mechanical one, with no changes to the electronics at all. As it stands, the meter is calibrated in volts.

Question 14.4 — ***What units would the meter have to be calibrated in to make it directly read position?***

Question 14.5 — ***Would the scale be a linear one?***

Question 14.6 — ***If the variations in transducer position were quite fast, what instrument would be more suitable for displaying the motion, as the meter has too high an inertia to show changes?***

PRACTICAL 14.2

Variable Distance Capacitor

Before we discuss these results, let us examine the other capacitive transducer in the same system. Switch off the power supply and remove the TK294H from the TK294. In its place, substitute the variable distance capacitance transducer, TK294J.

Connect this capacitor to the oscillator module in place of the other capacitor.

The lower of the 'external tuning comp' sockets is connected to 0V and should be connected to the lower socket on TK294J ie the metal chassis.

Set the capacitor plates to about mid-separation (12.5mm on micrometer and about 30mm on the slide scale).

Adjust the oscillator frequency control as before until the central portion of the 'S-curve is found. Then finally adjust, with increased amplifier gain if necessary, for zero output voltage.

The system is now at the same centre frequency as the other capacitive system. Adjust the micrometer until the meter indicates a positive maximum and adjust the oscillator output amplitude control until this reading is a convenient figure (approximately 3V). Do not adjust the oscillator frequency.

Now record in your own copy of fig 4.14.4 the output voltage for micrometer settings between 10mm and 15mm at 0.5mm intervals leaving the slide position unchanged.

output voltage (V)	micrometer setting (mm)
	10.00
	10.50
	11.00
	11.50
	12.00
	12.50
	13.00
	13.50
	14.00
	14.50
	15.00

Fig 4.14.4

Using these results, plot another graph of output voltage against slider position.

Question 14.7 — ***What shape is the graph over the central section?***

Question 14.8 — ***Why do we always concentrate on the central section?***

Question 14.9 — ***Is the graph for the variable distance capacitor similar to that for the variable area capacitor?***

If not, why not? Remember the formula $C = \frac{\varepsilon_o \varepsilon_r d}{d}$

PRACTICAL ASPECTS

We have constructed a measuring system where a variation in capacitance at the input produces a variable dc voltage at the output. This is shown in the block diagram of fig 4.14.5. You have plotted graphs of the output voltage against position of the input transducer. You should have found that these graphs were not linear, or only approximately so over a small, central position. Why is this so?

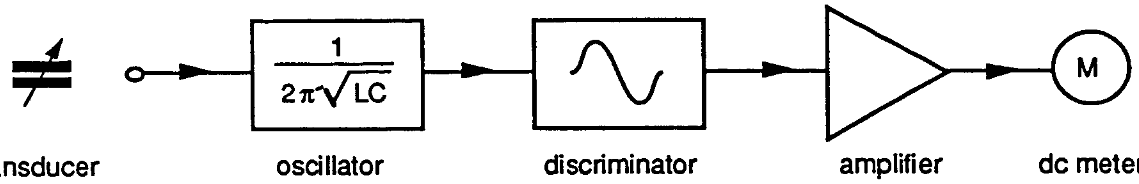


Fig 4.14.5

The system is composed of five separate parts; transducer, oscillator, discriminator, amplifier and meter. Each of these parts could introduce its own error into the system, Remember the formula for the capacitance of one of the transducers.

C is directly proportional to 'a', the area of overlap of the plates, and inversely proportional to 'd', the distance between them. So the variable area capacitor gives a linear output and the variable distance capacitor an inverse output. This is explained in Assignment 11. In Assignment 12 these capacitors were connected to an oscillator and it was noted how the frequency varied with position of the input transducer. The graphs were not completely linear, although if the changes were small, a reasonable linear approximation could be made. Appendix F shows why this is so. Losses, stray capacitances and fringing at the edges of the plates were neglected.

The frequency of operation is usually chosen to give a high output impedance, but at such frequencies, the insulation resistance must be high to avoid shunting the capacitor. If the external humidity is changing, or stray electric fields are present, this may be difficult to keep constant. Screened cable is generally used to connect the transducer to the oscillator.

The discriminator, has an S-shaped characteristic as discovered in Assignment 13. Only the centre portion of this curve is approximately linear. The amplifier and meter, have linear characteristics.

So by the time we have assembled a complete system, we have an overall characteristic which contains all the individual characteristics of the components, and it is not surprising that it is not exactly linear. By careful design of all the components, and by making all variations of small magnitude, the system could possibly be made more linear, but this would be an expensive process and the resulting system may be so restrictive as to be practically useless.

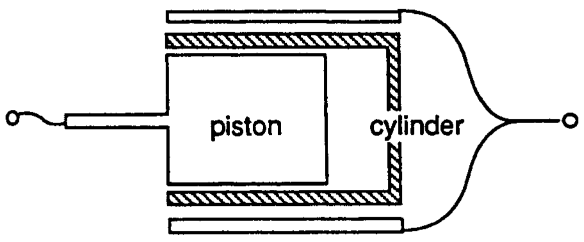
However, the fact that the characteristic is non-linear does not prevent us from making satisfactory use of the system. Once we have constructed a calibration curve, we can relate any output voltage to a precise position of the input transducer. This principle is common to many systems where a non-linear characteristic is obtained. This system is a good example of the many stages it may be necessary to employ to convert an easily produced variation, in this case, capacitance, into something which we can more easily handle, measure, operate upon, transmit or record, in this case a dc voltage. Subsequent data logging or processing equipment can easily take account of the non-linear characteristics.

The system has infinite resolution and is continuously operating, which is especially useful if the object to be measured is in continuous motion, as an individual reading does not have to be taken at each position. The frequency of movement is limited only by the frequency of operation of the system, as well as mechanical considerations.

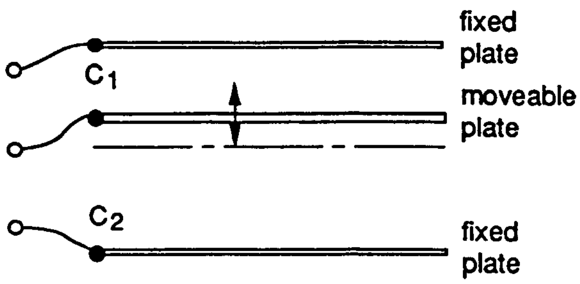
The principle of variation in capacitance can be used to measure many physical quantities. If the object to be measured can be used as one plate of the capacitor, the system becomes even more attractive. The absence of connecting wires is often a great asset, especially if movement is involved. We have seen how variations to the area of overlap and distance between plates can be used, and some transducers utilise a variation in the dielectric constant of the material between the plates. Let us see how these principles are used in some specific ways.

Linear Displacement

The assignments in this part of the manual are directly related to measurement of linear displacement. Almost any linear moving part could have a capacitive transducer attached to it, similar to those used in our assignments. The method can be employed if the moving part is in an insulating case, for example a piston moving in a cylinder. By making the piston one plate of our capacitor, and putting our other plate around the cylinder, we have a variable area capacitor as shown in fig 4.14.6(a).



(a) variable area



(b) differential

Fig 4.14.6

Sometimes a differential capacitor can be constructed. Here the moving plate is placed between two fixed plates, as shown in fig 4.14.6(b). The displacement increases one gap and decreases the other. Either the difference or the ratio between the two capacitors may be measured, but a special circuit may be required.

Angular Displacement

A logical derivative of the methods used in our assignments is to use them to measure angular displacement. All this requires, are two specially shaped plates, one fixed and one attached to the moving part. By using multi-plate capacitors it is possible to increase the sensitivity. The characteristics can be modified by altering the shapes of the plates. A range of 360° can be obtained. The arrangement for a typical tuning capacitor used in radios is shown in fig 4.14.7. The range is 180°.

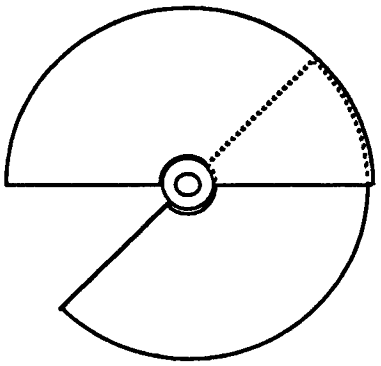


Fig 4.14.7

Level

If the substance is conducting, be it solid, eutectic or molten, the variable area method can be used with the substance itself as one plate of the capacitor. The other plate is a metal rod, covered in insulating material, to act as the dielectric, placed inside the container, as in fig 4.14.8. The capacitance varies as the level of the substance alters the area of overlap between the plates.

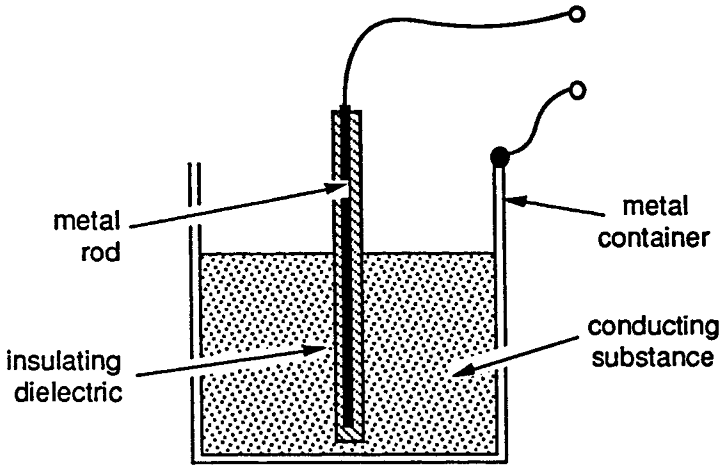


Fig 4.14.8

If the conductivity of a liquid is high enough, its surface can be used as one electrode of the capacitor. The other electrode is a fixed plate suspended above the surface of the liquid and parallel to it as shown in fig 4.14.8. The capacitance varies as the level of the liquid alters the distance between the plates. Such a system could be used to measure the level of molten metal in a furnace.

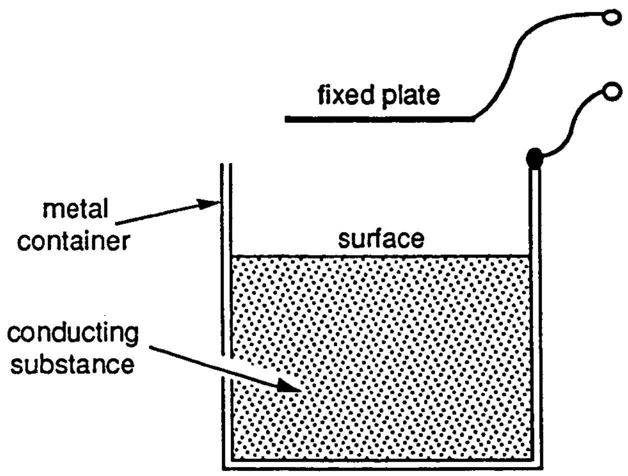


Fig 4.14.9

Thickness

By inserting a dielectric material between the plates of a capacitor, then clamping the plates to either side of the material, a thickness gauge can be made, detecting the variation in distance between the plates. The minimum thickness which can be measured is determined by the breakdown voltage of the insulating material.

Alternatively, the distance between the plates can be kept constant and the additional insulating material brought between them, thus forming a composite dielectric. The output is far from linear but is sometimes used for continuous monitoring, for example in paper making. Having the plates either side of the continuously moving paper roll enables us to measure its thickness.

Pressure

Two methods are possible here. The first is a purely mechanical conversion of pressure into linear motion by a pair of bellows. As mentioned earlier, many variables are often converted into linear displacement, which can then be measured by one of the capacitance methods already described.

The second method makes use of the property that dielectric constants of some materials vary with pressure. If two narrowly spaced electrodes are inserted in the substance, pressure variations will cause the dielectric constant to alter. This method has been satisfactorily used for the measurement of pressure in benzene.

Composition of Materials, Humidity and Temperature

These are all effects which can be detected by variations of the permittivity of the material when used as a dielectric. In the case of a liquid, it is a simple matter to contain a cell between the plates of the capacitor and include it in a flow pipeline.

slider position (mm)	output voltage (V)
20	−3.65
25	−2.92
30	−1.93
35	−0.89
40	0.08
45	1.07
50	1.93
55	2.67
60	3.31
65	3.67

Fig E4.14.3

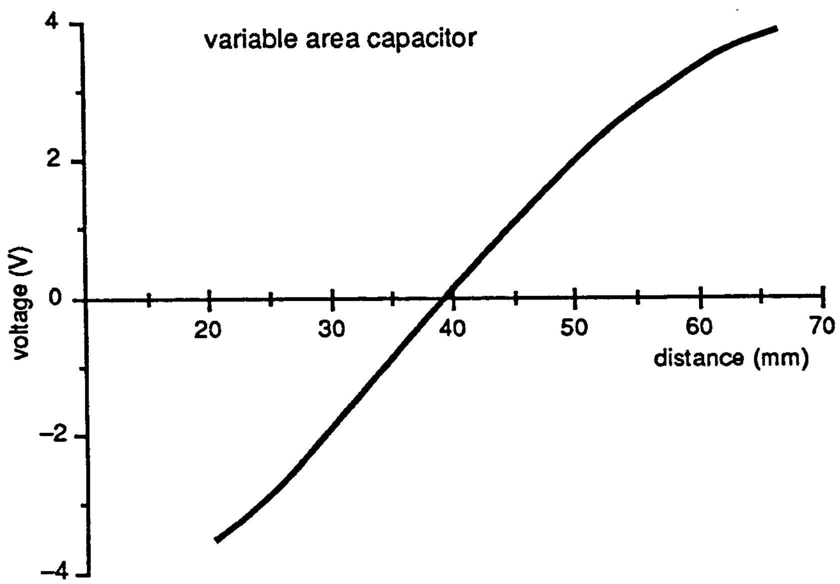


Fig E4.14.3

Question 14.1 The graph should be approximately linear over a large proportion of the central section, typically between 30mm and 50mm.

Question 14.2 Yes, this part enables us to relate directly output voltage to position.

Question 14.3 We can make the output meter read position.

Question 14.4 It would have to be calibrated in millimeters.

Question 14.5 The scale would be linear over the central section but slightly; cramped at the two ends.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 14

Question 14.6

If the changes were fast, an oscilloscope would be a more suitable output device than a meter. Alternatively, a data logging system and recorder could be used.

output voltage (V)	micrometer setting (mm)
–1.20	10.00
–1.01	10.50
–0.77	11.00
–0.47	11.50
–0.11	12.00
0.38	12.50
1.01	13.00
1.77	13.50
2.62	14.00
2.92	14.50
3.02	15.00

Fig E4.14.4

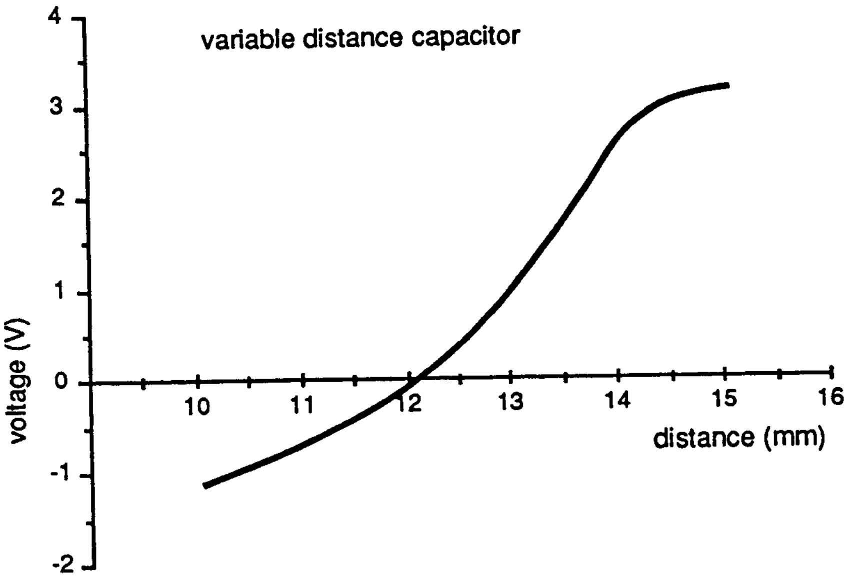


Fig E4.14.4

Question 14.7

The graph has a definite curve over the central section, from about 12.25mm upwards. It is almost certainly hyperbolic.

Question 14.8

We concentrate on the central section as outside this range, non-linearities begin to take effect, especially in the discriminator, where we are then no longer operating on the straight central position of the S-curve.

Question 14.9

No. The variable distance capacitor graph was hyperbolic whereas the variable area capacitor was linear.

This bears out the formula for the capacitance $C = \frac{\varepsilon_o \varepsilon_r a}{d}$ that C is directly proportional to the area overlap of the plates and inversely proportioned to the distance between them. This is reflected in the graphs. For small changes the change in oscillator frequency is directly proportional to the change in capacitance. This is proved in Appendix F to which you are referred. The only other thing that affects the graph is the discriminator characteristic, which you have measured to be linear over the central section.

INDUCTIVE TRANSDUCERS IN AN FM SYSTEM — ASSIGNMENT 15

CONTENT

A complete measuring system using a variable inductance transducer is constructed and tested.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducers Test Rig.
1	TK294F	Variable Inductor.
1	–	Power Supply,±15Vdc *(eg Feedback PS446)*
1	–	Digital Frequency Meter 1MHz
1	–	* DC Voltmeter 10V

* Alternatively a multimeter may be used.

PRACTICAL

15.1 Variable Inductance Transducer

INDUCTIVE TRANSDUCERS IN AN FM SYSTEM — ASSIGNMENT 15

OBJECTIVES

When you have completed this assignment you will:

- Know a position or movement measurement system can be constructed using an inductive transducer in a Frequency Modulation System.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the Instrumentation Module TK2941A and the Linear Transducers Test Rig TK294.
- Understand the basic operation of an oscillator, the frequency of which is controlled by the variation in value of a reactive component.
- Understand the basic operation of a frequency discriminator.
- Preferably have completed Assignment 14, Capacitive Transducers in an FM system.

INTRODUCTION

Electromagnetic Induction Principles

Michael Faraday was one of the early scientists to study the relationship between magnetism and electricity and Faraday's Laws can be summarised thus:

- An emf is induced in an electric circuit whenever there is a change in the magnetic flux linking with the circuit. The magnitude of the induced emf is directly proportional to the rate of change of flux linkages.

Lenz's Law details the direction of this induced emf, it being such as to oppose the change which produces it.

These laws may be summarised by the equation:

$$e = -\frac{N d\Phi}{dt}$$

where e = instantaneous value of induced emf (volts)
N = number of turns
$d\Phi$ = change of value of flux (webers) in dt seconds; the negative sign ensures compliance with Lenz's law.

Thus we can vary the induced emf by varying N or $\frac{d\Phi}{dt}$, and form the basis of another type of transducer. Changing N is a physical dimensional change which is difficult to perform; it is however used in variable transformers. It is easier to change e by changing $\frac{d\Phi}{dt}$

From basic definitions for a magnetic circuit, $B = \mu_o \mu_r H$

where μ_o = permeability of free space ($4\pi \times 10^{-7}$)
μ_r = relative permeability of material at that point
and H = magnetic field strength or mmf per unit length

$$= \frac{NI}{L} \text{ ampere turns/metre}$$

where I is the current in amperes through the coil of N turns and L is the length of the magnetic circuit in metres

and $B = \text{flux density} = \frac{\Phi}{a}$

where a is the cross sectional area in square metres of the circuit with the flux of Φ Wb.

Thus $\frac{\Phi}{a} = \frac{\mu_o \mu_r NI}{e}$

or $\Phi = \frac{NI\mu_o \mu_r a}{l}$

$= \frac{NI}{S}$ where $S = \frac{l}{\mu_o \mu_r a}$ = reluctance

and NI = ampere-turns or magneto-motive force (mmf)

These equations are true for a uniform closed circuit. If it is composed of different materials or has varying dimensions, the reluctance of the various parts must be added together before the formulae are applied.

If we choose to make our transducer by variation of $\frac{d\Phi}{dt}$, this can be done by varying either the mmf or the reluctance with time.

Variation of the mmf means variation of N or I. Changing N is difficult, as discussed before, and a change in I is an electrical change, not a physical one. Most transducers of this type use variations in the reluctance of the magnetic paths. This implies a variation of either l, μ_r or a with time.

Self Inductance

If Faraday's laws are applied to a single coil, the emf is induced in the same circuit as that in which the current is changing. This property is known as *SELF INDUCTANCE (L)*. By Lenz's Law, the induced emf opposes the change of current.

If we substitute $\Phi = \frac{NI}{S}$ (flux = mmf/reluctance) into our

expression for induced emf $e = \frac{-nd\Phi}{dt}$ we have

$e = \frac{-nd}{dt}\frac{(NI)}{S}$ and if I is changing, this becomes

$e = \frac{-N^2}{S}.\frac{dI}{dt}$. This is written as $e = -L.\frac{dI}{dt}$.

L is the self inductance (or more commonly just inductance) of the coil. This gives us the definition of the unit of inductance.

A circuit is said to have an Inductance of 1 Henry if an emf of 1 volt is induced in the circuit when the current changes at the rate of 1 ampere per second.

Thus we have an expression for the coil inductance.

$$L = \frac{N^2}{S} \text{ or } L = N^2 \mu_o \mu_r \frac{a}{l}$$

From this formula it can be seen that the inductance can be varied by varying the parameters of this equation, i.e the number of turns or the reluctance, N, μ_r, a or l. As discussed variations in N are not practical. Nor is a variation of a, as this is a physical dimensional change varying the cross sectional area enclosed by the turns, which would mean varying the diameter of the coil. Practically it is either μ_r or l (or both) which are varied.

This variation in inductance may be detected and related to the magnitude of the physical change which caused the parameter variation. We then have a variable inductance transducer.

Mutual Inductance

When an emf is induced into a circuit by a change of flux that is produced by a current changing in an adjacent circuit, the property is called *MUTUAL INDUCTANCE (M).*

Consider this circuit:

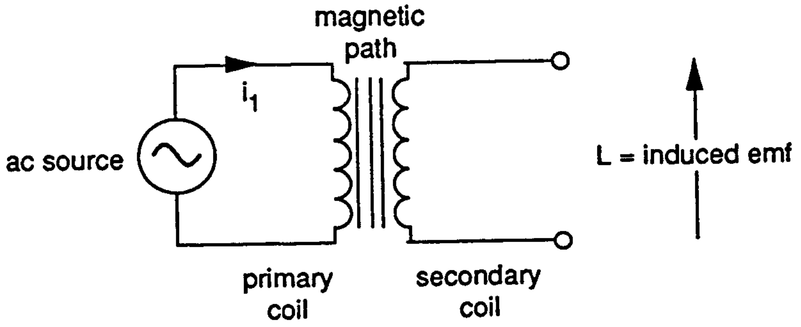


Fig 4.15.1

An ac source generates an alternating current in the primary coil. This produces an alternating flux in the magnetic path which induces an alternating emf in the secondary coil. If the secondary circuit were closed, an alternating current would flow in it. This is the principle of the transformer.

If N_1 and N_2 = number of turns on primary and secondary coils respectively

μ = permeability of magnetic path

l and a are the length and cross sectional area of the magnetic path, then the flux produced by the primary coil,

$$\Phi = \frac{N_1 \mu a i}{l}$$

where i is the instantaneous value of the primary current.

This can be written as $\Phi = \frac{N_1}{S} i$

where S is the reluctance.

If i is changing with time, Φ will also change, so we can write

$$\frac{d\Phi}{dt} = \frac{N_1}{S} \cdot \frac{di}{dt}$$

Now the instantaneous value of induced emf in the secondary is given by:

$$e_2 = -N_2 \cdot \frac{d\Phi}{dt}$$

Thus $$e_2 = \frac{N_1 N_2}{S} \cdot \frac{di}{dt}$$

The negative sign shows there is 180° phase difference. Thus we can vary the value of secondary emf by varying the parameters of this equation, and use this as the principle of a transducer; di/dt signifies that the current must be changing to obtain a secondary emf at all. We could vary the way that this is changed, but this is an electrical change. As discussed, it is not practical to vary N_1 or N_2 so we can vary the reluctance S-=-l/μa. It is difficult to vary a, so again this allows us to vary μ or l (or both) to give us a mutual inductance or transformer-type transducer.

If a sinusoidal voltage is applied to the primary, the current will be sinusoidal but 90° out of phase with it. This implies a sinusoidal flux, in phase with the current but 90° out of phase with the applied voltage.

If we replace $i = I_{max} \sin \omega t$ in the above expression, we can deduce the well known transformer equation for secondary emf (RMS value).

$$E = 4.44\, f\, N_2\, \Phi_{max}$$

The proof of this is in many standard textbooks.

This implies that the secondary emf is proportional to the frequency as well as the number of turns and the maximum flux. In practice, as the frequency increases, the reactance of the primary increases, so for the same applied voltage the current and hence the flux Φ_{max} decreases. There are other factors which govern the choice of operating frequency. If it is too low, the core may saturate. If it is too high, normal ac meters cannot be used to measure the secondary voltage.

If the primary current has any other form, we can still use the expression we have deduced.

Other methods

The change of flux required to induce an emf can also be caused by relative movement between the coil and a magnetic field. This can be used to indicate motion. A common example is the permanent magnet tacho-generator, for speed measurements. Such devices can be applied to both rotary and linear measurements.

Measurements of variations in the value of inductance

One method of detecting a change in the value of inductance is to use a Wheatstone Bridge circuit at ac. This is similar to the method discussed in Assignment 11 and the balance equations become, for fig 4.15.2.

$$R_x = \frac{R_2}{R_1} = R_s$$

$$L_x = \frac{R_2}{R_1} = L_s$$

Thus to balance the bridge with an unknown inductor L_x R_x, a standard inductance L_S and a standard resistance R_S are needed. Standard inductors are not easy to manufacture, so this method is very seldom used. It also suffers from the usual disadvantages of bridge measurements.

Alternatively, one of the forms of ac bridges discussed in the Practical Aspects of Assignment 11 could be used.

However, there are much better methods available for detecting changes of self inductance. The one we will use is an extension of the system built up in Assignments 12, 13 and 14. The inductance varies the frequency of an oscillator, whose output is passed through an F.M discriminator to a detector.

The frequency discriminator module contains a circuit for converting these frequency variations into voltage variations.

These voltage variations are then amplified and indicated on the meter.

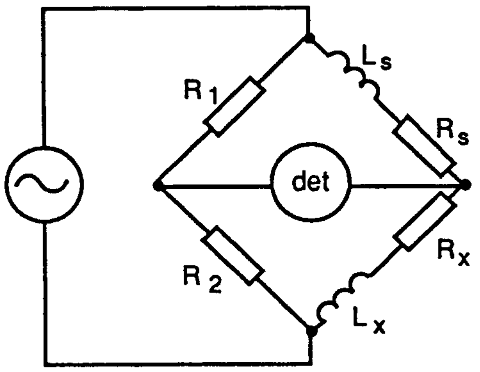


Fig 4.15.2

A capacitive transducer can be used with an oscillator, a frequency discriminator and an amplifier to form a complete FM system. Movement of the capacitive transducer varies the frequency of the oscillator and this frequency change is accompanied by a change in output from the discriminator, which can be measured and related to the transducer position.

Question 15.1 ***What component other than a capacitor could be used to vary the frequency of the oscillator?***

Let us consider the block diagram of fig 4.15.3.

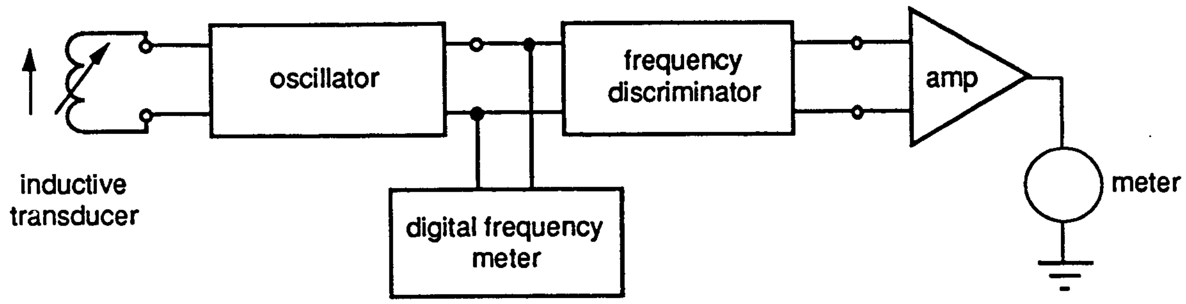


Fig 4.15.3

This corresponds to the circuit shown in fig 4.15.4.

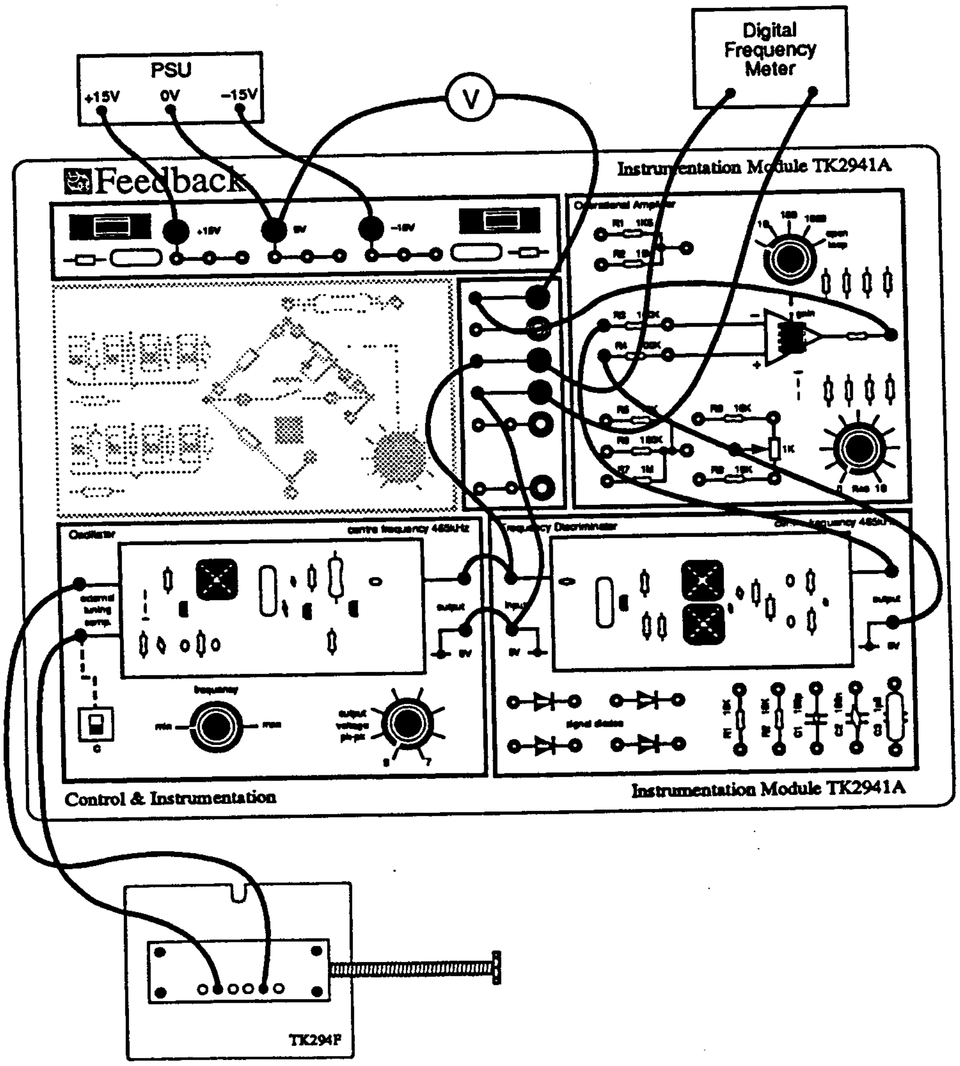


Fig 4.15.4

Here the inductive transducer becomes part of the tuned circuit of the oscillator, and varying the inductance by varying the position of the transducer will vary the frequency of oscillation.

The frequency discriminator module contains a circuit for converting these frequency variations into voltage variations. If you have not already examined the operation of this circuit, it is recommended you carry out Assignment 13.

These voltage variations are then amplified and indicated on the meter.

Examine the single-coil variable inductance transducer for use with the Linear Transducers Test Rig, TK294. Its dimensions are indicated in fig 4.15.5.

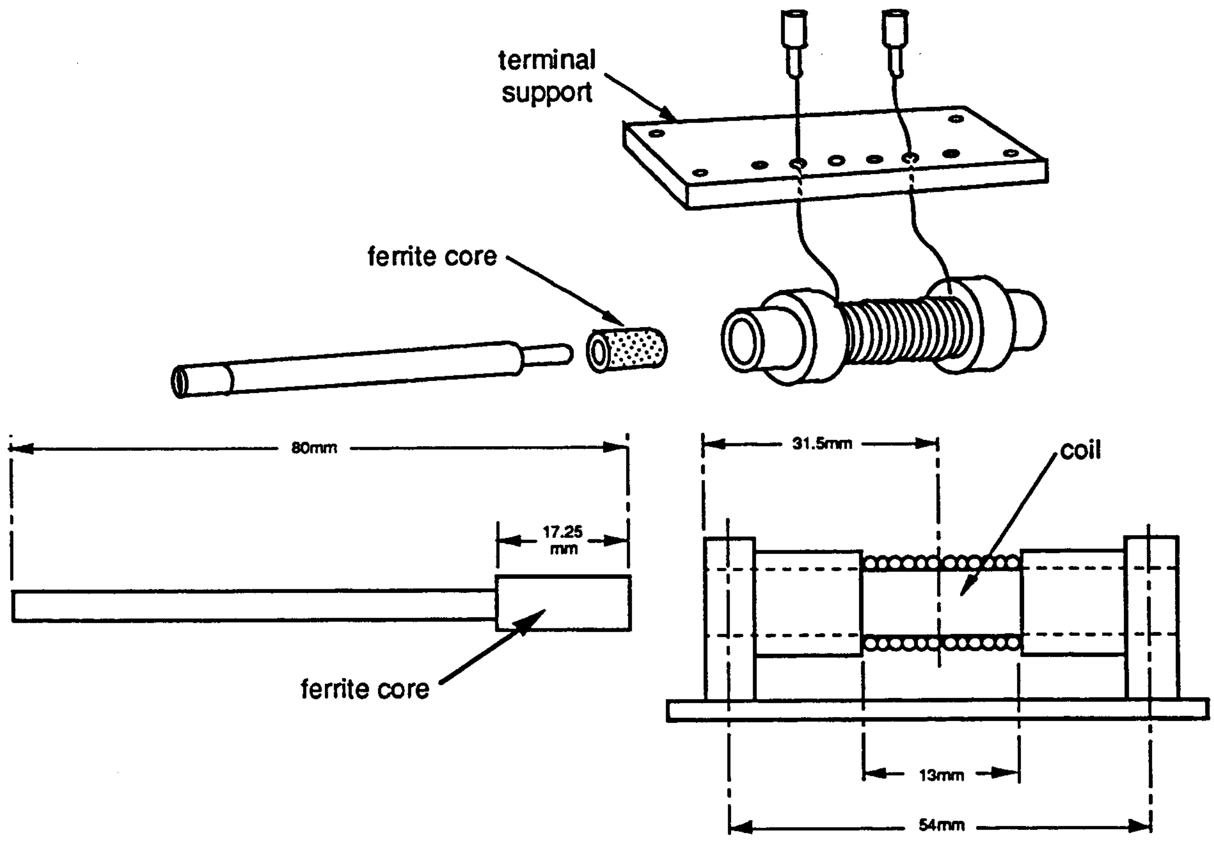


Fig 4.15.5

You will see that it consists of a single coil wound around an insulating former. Into it can slide a core of a ferrite material with a relative permeability μ_r. The value of μ_r is given by the slope of the B/H curve of the ferrite material. Since the value of H changes as we push the core into the coil, so the value of μ_r may change if the B/H curve is not linear. A typical value for μ_r is of the order of 350. The core is attached to a rod which fits on to the slider of the Linear Transducers Test Rig, TK294, enabling the position of the core inside the coil to be measured.

Question 15.2 ***What property of the coil are we varying when we move the core in and out of the coil?***

Question 15.3 ***What physical variables are affected by this movement?***

We are in fact changing the self inductance (L) of the coil by altering the reluctance of the magnetic path, by varying the proportion of core material in the path.

Question 4.15.4 ***Does the self inductance increase or decrease as the core is inserted?***

Question 4.15.5 ***Remembering that the formula for the frequency of oscillation of the tuned circuit to which this inductor is connected is*** $f = \dfrac{1}{2\pi\sqrt{LC}}$***, does this frequency increase or decrease as the core is inserted?***

PRACTICAL 15.1

Variable Inductance Transducer

Let us see if you are correct. Assemble the Linear Transducers Test Rig, TK294, and the Variable Inductor TK294F and connect up the transducer and modules as shown in fig 4.15.4. Keep the wires between the transducer and oscillator as short as possible in order to avoid pick-up, and always remove your hand when taking readings.

Make sure the switch on the Oscillator is set to the 'L' position and set the output amplitude control to mid-scale. Set the Operational Amplifier gain to 10, the micrometer to 0mm and the slide index to 55mm. Lock the slide.

Switch on the power supply. An output should be visible on the meter.

Now adjust the oscillator frequency until the meter reads zero. This should correspond to a frequency of about 465kHz, the frequency discriminator centre frequency. Move the slide index to 50mm and lock it. The meter should now read negatively.

Adjust the oscillator output amplitude until the meter reads a convenient voltage (e.g –2.5V, –4.0V).

Move the core inwards in 1mm increments, using the micrometer, and read the voltage at each stage. Take an extra set of readings of position each time the voltage passes through zero.

Record your results in your own copy of fig 4.15.5.

Continue taking readings until the core has travelled through the coil and the voltmeter reading is steady again at a negative maximum. It is good practice to take the complete set of readings as quickly as possible and going in one direction only.

If you have done Assignment 14, Capacitive Transducers in an FM System, you will notice that the method given above is slightly different to the method employed there. Here we take readings at intervals on the position scale. Previously we took readings at intervals on the voltage scale. This was in order because the values of capacitors were chosen to give readings on the centre portion of the discriminator characteristic. As you will see when you plot the graphs for this assignment, manufacturing tolerances make it more difficult to achieve this for the inductance transducer over the whole of its position range. We thus operate on a position scale so that there will be no ambiguity when the non-linear part of the discriminator characteristic is encountered.

position (mm)	amplified output voltage (V)	position (mm)	amplified output voltage (V)

Fig 4.15.4

Exercise 15.1 — *Using your results, plot two graphs of output voltage and oscillator frequency to a base of position. Use linear graph paper. Plot one graph for the complete travel of the core in and out of the coil and another on twice the position scale for the portion where the core is being inserted into the coil.*

Question 15.6 — *What shape are the graphs, especially over the central section of your second graph? Mark on this graph what you consider to be the limits of the 'linear' sections. Do you think that the voltmeter could be directly calibrated to read position?*

Question 15.7 — *What happens at either end and in the middle of the first graph? What can you say about the values of the inductance relative to the position of the core at these points?*

Exercise 15.2 — *Calculate the distance between the core positions at the two points where the first complete output voltage graph crosses zero and calculate the mid-position between these points. How does this compare with the turning point at the centre of your graph and what can you say about the position of the core at this point?*

Question 15.8 — *Does the 'linear' section of the frequency graph occupy a greater or lesser positional spread than that of the output voltage graph? Why is this so?*

PRACTICAL ASPECTS

We have constructed a measuring system where a variation in inductance at the input produces a variable dc voltage at the output. This is shown in the block diagram of fig 4.15.6. You have plotted graphs of output voltage and oscillator frequency against position of the input transducer. You should have found that the graphs were not linear, or only approximately so over a small portion. Why is this so?

The system is composed of five parts, as in fig 4.15.6, transducer, oscillator, discriminator, amplifier and meter. Each of these parts could introduce its own error into the system. This is very similar to the system we had in Assignment 14; in fact the last four elements are the same. The capacitive transducers of that assignment are replaced by the variable inductor in this assignment. If you have not already done Assignments 12, 13 and 14, it would be worthwhile at least to read through them, especially the Practical Aspects and especially that of Assignment 14. Much of the comment in Assignment 14 is also applicable to this assignment and will not be repeated here.

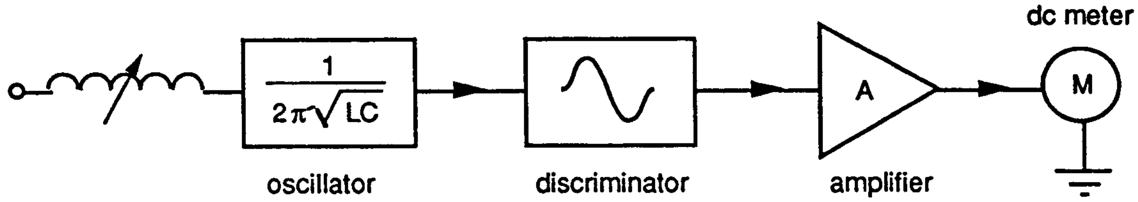


Fig 4.15.6

The only component different in this assignment is the transducer itself. The relative permeability of the core material may vary with the depth of insertion into the coil. It is difficult to derive formulae relating the core position to inductance, as strictly speaking the theory is only true for a closed magnetic circuit and here we are putting the core material into the leakage paths of the coil. This could also affect the results. There may be losses; hysteresis loss, eddy current loss and copper loss in the coil resistance. The coil may have self capacitance between its windings. Stray magnetic fields may be present; these can be minimised by surrounding the transducer with a magnetic screen, with provision for movement of the core operating rod. The magnetic field strength is not constant along the axis of the coil. It is a standard proof in many textbooks that it is linear only in the centre of the coil and diminishes at the ends.

All these effects combine to make the resulting variation of inductance with core insertion non-linear. The theory of small changes for the oscillator frequency determining components may only be valid over a limited range. When this is applied to the discriminator this further modifies the characteristic; but if we restrict operation to the central section, reasonable linearity can be obtained.

However, once we have constructed the calibration curve, which may be linear over the small central section, we can use this with our transducer system over a wider range as long as we can get repeatable results. This is the same principle as explained in Assignment 14. The voltmeter could be calibrated in position units, and this would only result in an uneven scale outside the central section.

At either end of the complete characteristic the curves reach a maximum value. This is when the core is completely out of the coil, the inductance is at its minimum and the resulting oscillator frequency is a maximum. A similar effect occurs when the coil is centrally placed inside the coil. Here we have maximum inductance corresponding to minimum oscillator frequency. You should have found that your frequency/position graph passed through its minimum position at this point and was reasonably linear over a large proportion of movement in the mid-sections of its movement either side of the centre.

When this is applied to the discriminator to produce the output voltage characteristic, the non-linear characteristics of the discriminator affect the overall graph. The range of the discriminator is not as wide as the variation of inductance and the discriminator S curve is distinctly non-linear at low and high frequencies. The exact proportion is dependent upon the setting of the centre frequency and your particular graphs may show more or less of this variation near the extremes of the maximum and minimum inductance values. This depends upon the exact values of the components in your particular kit and their tolerances.

This has the overall effect of narrowing the acceptable linear section of the characteristics, but as explained this is not a significant disadvantage as there are the two ways of taking this into account.

Let us now see how this is used to measure various physical quantities. The assignments you have carried out are directly related to the measurement of linear displacement. Almost any moving part could have the core of an inductive transducer attached to it, similar to that used in our assignment. This method is useful if the object is moving. The maximum frequency is determined by the frequency of the oscillator used and the core losses. Many other quantities, e.g level, pressure, are often converted into linear displacement so that they can be measured by this type of transducer. An alternative type of inductive transducer for linear displacement will be introduced to you in the next two assignments, dealing with mutual Inductance.

Transducers can also be made which make use of the variation of relative permeability. Pressure, stress and temperature can affect the value of μ_r of different materials in the core of a transducer.

Air-cored inductors can operate at much higher frequencies than ferromagnetic-cored inductors but the inductance changes only by small amounts and can be difficult to detect. Also they are usually multi-winding devices requiring movement of one winding relative to another. This puts constraints on the method of connection.

Another common method is to employ a coil wound around an iron core with a variable air gap of some description. We can obtain an expression relating the change in inductance to the change in gap width. Such transducers are often used for measuring the thickness of ferromagnetic materials or insulating materials with a ferromagnetic backing, by inserting them in the air gap and detecting the change in reluctance. Such relationships are non-linear, but are often used for comparative measurements. Results depend upon the value of μ_r for the test piece and calibration is required with a known thickness of the same material.

If the transducer can be designed to provide two outputs, one being an increase of inductance, the other a decrease, we have a differential transducer. If the succeeding instrumentation can measure the difference between them, stray effects of magnetic field, temperature, supply voltage, etc tend to cancel out giving a more accurate reading. An example would be to have two coils in adjacent arms of a Bridge Circuit. This method can also be used with other transducers. In the next two assignments you will see a way of applying this principle to a mutual inductance type transducer — the Linear Variable Difference Transformer (LVDT).

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 15

Question 15.1 An inductor is the alternative component to a capacitor for varying the frequency of the oscillator.

Question 15.2 We are varying the reluctance of the magnetic path as the core moves in and out of the coil.

Question 15.3 This affects the length of the magnetic path and its permeability.

Question 15.4 The self inductance increases as the core is inserted.

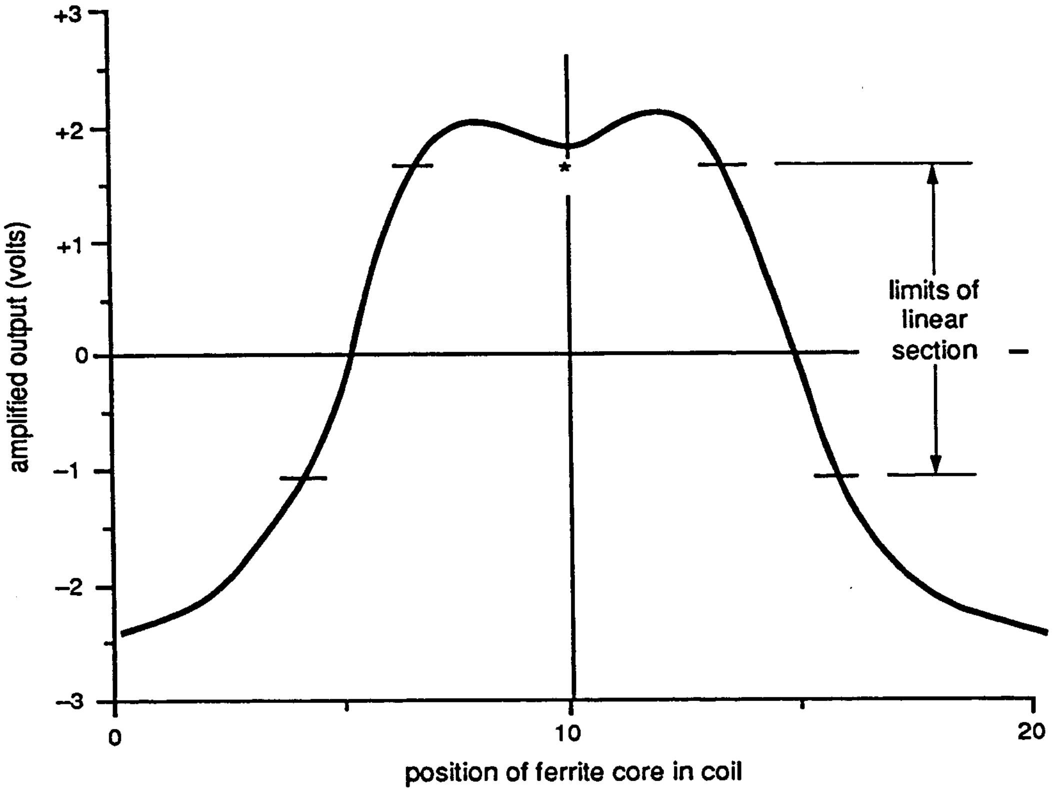
Question 15.5 The oscillator frequency decreases.

Exercise 15.1 Typical values are:

position (mm)	amplified output voltage (V)	position (mm)	amplified output voltage (V)
0	–2.5	11	+1.9
1	–2.4	12	+2.0
2	–2.2	13	+1.7
3	–1.8	14	+0.7
4	–1.2	14.65	0
5	–0.2	15	–0.5
5.1	0	16	–1.5
6	+1.2	17	–2.0
7	+1.8	18	–2.3
8	+1.9	19	–2.4
9	+1.8	20	–2.5
10	+1.7		

Fig E4.15.4

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 15



* This 'hump' may not be exactly the same on all graphs. It depends on how far over the discriminator characteristics we travel, which is dependent upon the setting of the centre frequency.

Question 15.6

The graphs are irregular in shape, but almost linear over the central sections as marked. The output voltage graph is characterised by the non-linear part of the discriminator curve. The voltmeter could be calibrated directly in position over the central linear section.

Question 15.7

At either end and in the middle, the graphs flatten out. At the ends the core is fully out of the coil and the inductance is a minimum. Thus the oscillator frequency is a maximum. In the centre, the core is in the centre of the coil and the inductance is a maximum. These represent the limiting values of inductance and frequency.

Exercise 15.2

The two null occur at 5.1mm and 14.65mm when the core is actually displaced about the centre. Halfway between these is

$$\frac{5.1 + 14.65}{2} = 9.87.$$

This coincides with the centre turning point as measured. Here the core is in the centre of the coil.

Question 15.8

The linear section of the frequency graph occupies a lesser proportional spread than that of the output voltage graph as it is affected by the non-linear section of the discriminator characteristic.

VARIABLE RELUCTANCE TRANSDUCERS — ASSIGNMENT 16

CONTENT

The behaviour of a mutual inductance type transducer with a single secondary winding, when the reluctance of the magnetic path is varied, is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducers Test Rig.
1	TK294G	Linear Variable Difference Transformer (LVDT) Sub-unit.
1	–	Power Supply,±15Vdc *(eg Feedback PS446)*
1	–	Two-beam oscilloscope 15MHz.

PRACTICALS

16.1 Mutual Inductance

VARIABLE RELUCTANCE TRANSDUCERS — ASSIGNMENT 16

OBJECTIVES

When you have completed this assignment you will:

- Understand the basic principles of operation of a Linear Variable Difference Transformer (LVDT).

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the Instrumentation Module TK2941A and the Linear Transducers Test Rig TK294.
- Understand the principles involved in self and mutual inductance.
- Preferably have completed Assignment 15, Inductive Transducers in an FM system.

INTRODUCTION

It can be seen in previous assignments how the self inductance of a coil could be varied by changing the reluctance of the magnetic path. Let us now examine how we can vary the mutual inductance between two coils.

The equation for the instantaneous value of induced emf in a secondary coil is:

$$e = \frac{N_1 N_2}{S} \frac{di}{dt}$$

where $\frac{di}{dt}$ represents the changing primary current.

The reluctance and more specifically μ_r and l are the only parameters easily variable.

l is the length of the magnetic path between two coils and could be varied by moving one of the coils as in fig 4.16.1.

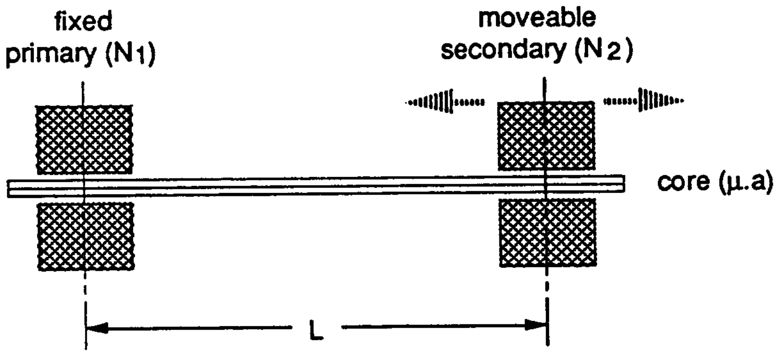


Fig 4.16.1

Question 16.1

Can you see the principal (mechanical) disadvantage of this arrangement?

With such an arrangement the connecting wires to the secondary would have to be moved. If we had to move it often or fast, this would put a strain on the wires. It may not be even practically possible to move the connections. It would be better if the coil were stationary and μ_r were changed.

We could vary the reluctance of a magnetic circuit by sliding a core into a coil. What happens if we have two coils?

As we vary the depth of insertion of the core, we vary the apparent value of reluctance which varies the induced emf. See fig 4.16.2.

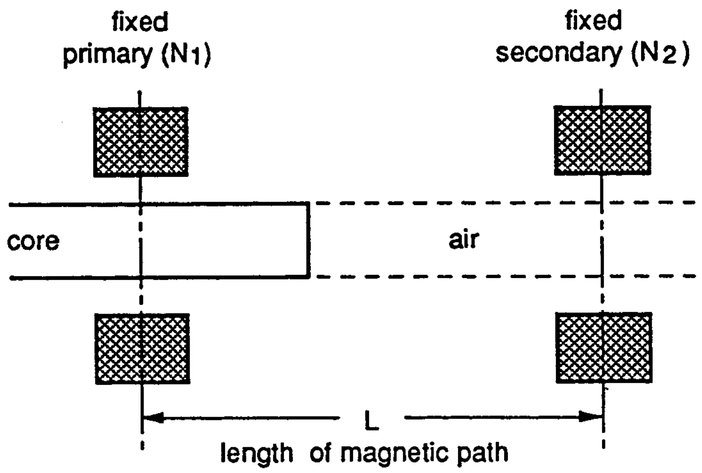


Fig 4.16.2

Examine the TK294G, which is a mutual inductance transducer. Its dimensions are indicated in fig 4.16.3.

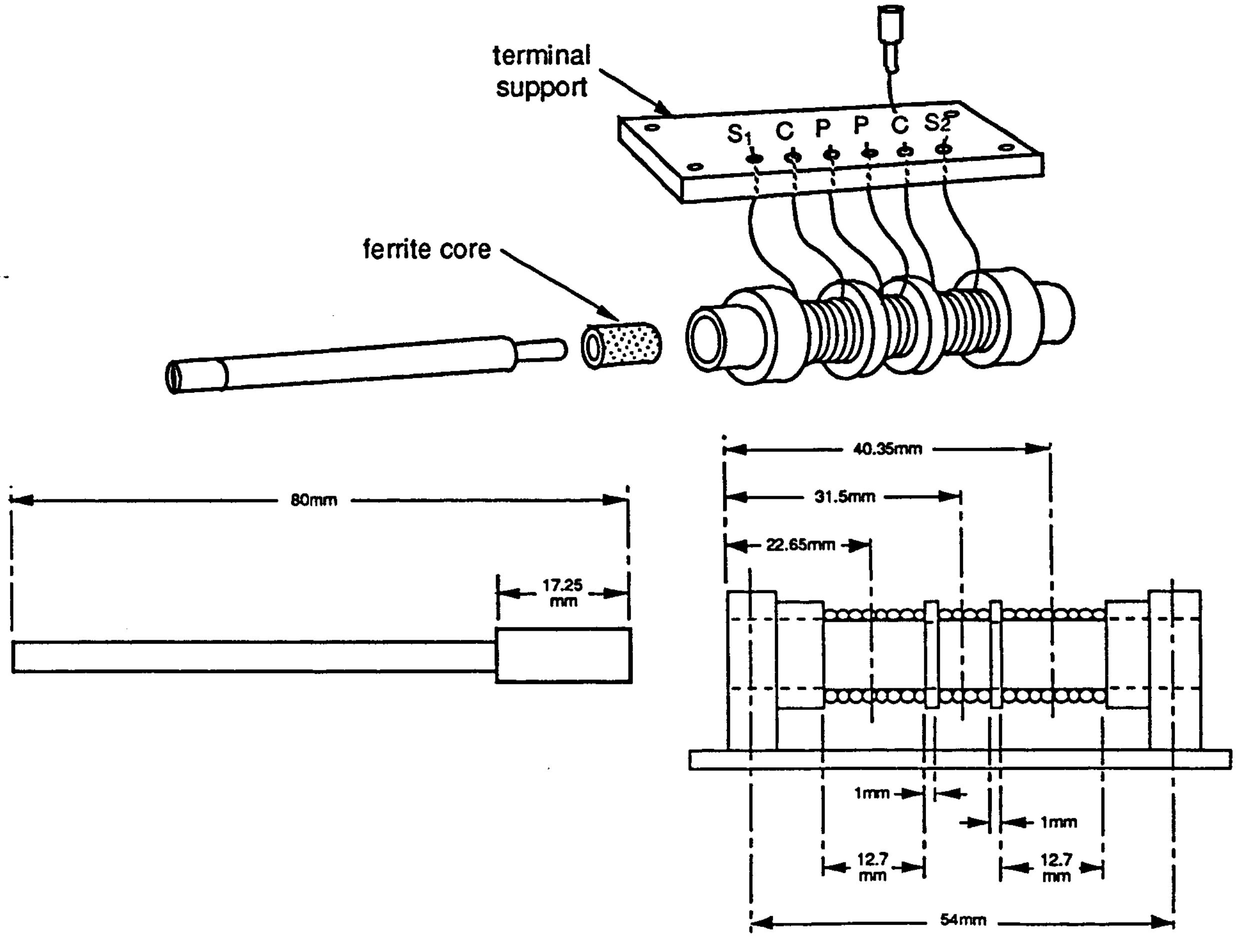


Fig 4.16.3

You will see that there are three separate pairs of terminals connected to three separate coils. A ferromagnetic core 17mm long can slide into the coils. The relative permeability μ_r of the core may vary with the current in the coil, as explained in Assignment 15. The core may be moved by the slider of the Linear Transducers Test Rig, enabling its position to be measured.

By using two of the coils adjacent to each other we can obtain a system similar to that described above. If we energise one of the coils (the primary) with an ac source, an emf will be induced into the other coil (the secondary). This is shown diagramatically in fig 4.16.4 and corresponds to the circuit shown in fig 4.16.5.

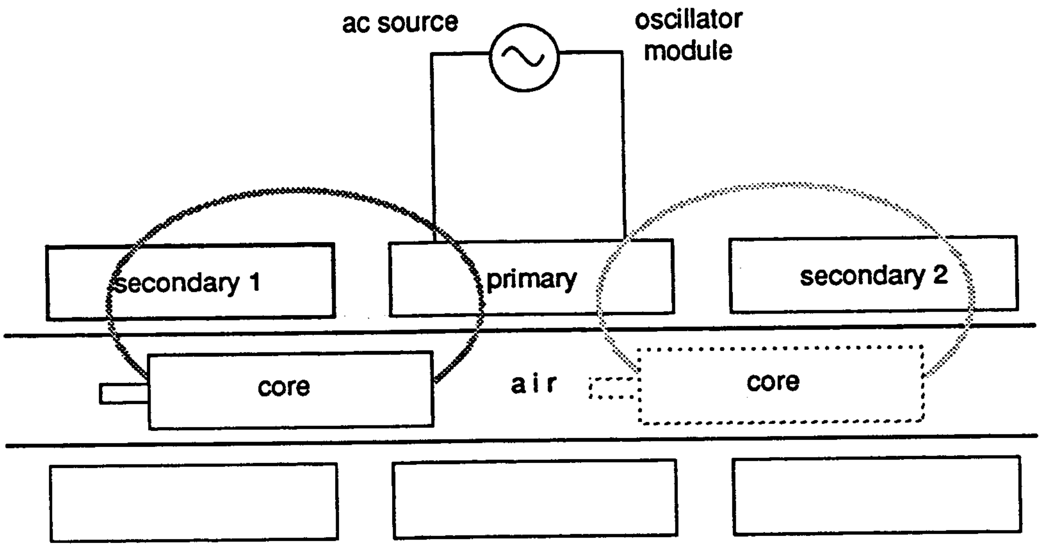


Fig 4.16.4

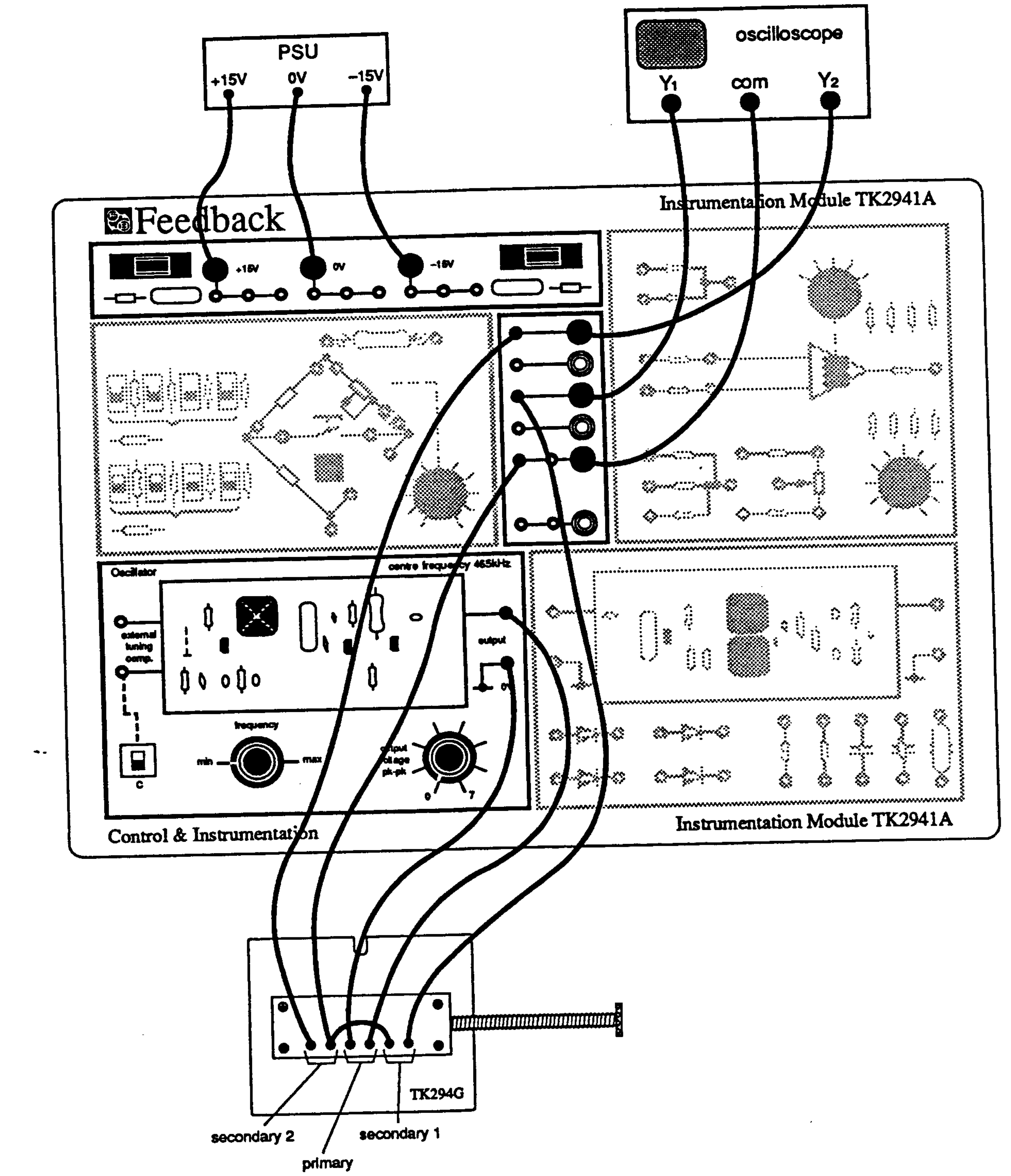


Fig 4.16.5

In fact we will investigate what happens in both secondaries as the core moves through its complete range. We would expect to find similar results.

PRACTICAL 16.1

Mutual Inductance

Assemble the TK294G onto TK294 and connect it to the Oscillator and oscilloscope as shown in fig 4.16.5. Make sure the switch on the oscillator module is in the 'C' position and nothing is connected to the 'external tuning comp' sockets. Set the frequency control to max and the output amplitude control to mid-scale and switch on the power supply. Withdraw the core completely from the transducer.

Set the Y_1 and Y_2 sensitivities on the oscilloscope.initially to 2-volts/div and set the timebase to 1µs/div. Adjust the trigger level control until a stationary display is obtained. You should see two waveforms which should be very nearly sinusoidal, almost equal in amplitude and of opposite phase. If the phases are the same, reverse the connections to one of the secondaries to produce two out-of-phase waveforms.

Move the slider so that the core moves through the body of the transducer.

Question 16.2 ***What happens to the waveforms?***

Question 16.3 ***Do they both have their maximum values at the same time?***

Set the core position so that the largest of the maximum values is displayed, then adjust the output amplitude control on the oscillator so that this just completely fills the screen in the Y direction. Observe that the waveform is not distorted.

We are going to measure the peak-to-peak amplitude of these waveforms using the oscilloscope. It is now set to its maximum point. You may find it easier to read peak-to-peak values if you reduce the oscilloscope timebase setting to say 100µs/div.

Question 16.4 ***Why do we use an oscilloscope and not an ac meter?***

The impedances of the two oscilloscope channels may affect the two secondaries differently and cause unwanted variations in the output amplitudes.

To avoid this effect measure the two outputs using one channel only, by connecting the oscilloscope lead to each secondary in turn at each micrometer setting.

With the micrometer set to the 0mm position set the slider at the 55mm position on the scale. Using the micrometer move the core through the coils at 1mm steps, recording the output of secondary 1 and secondary 2 at each step, to a final setting of 25mm on the micrometer.

Record your readings in your own copy of a table as in fig 4.16.6.

position (mm)	sec 1 output divs pk/pk	sec 2 output divs pk/pk	algebraic sum (divs)	position (mm)	sec 1 output divs pk/pk	sec 2 output divs pk/pk	algebraic sum (divs)

Fig 4.16.6

As we have seen that secondary 2 is out of phase with secondary 1, record all its values as negative. Ignore the last column for the moment.

From your readings, plot a graph of output to a base of slider position, on linear graph paper. Mark the output zero line in the centre of the paper and plot secondary one output positive above this line and secondary two output negative below this line.

Question 16.5 ***What shape are the two graphs? Are they similar? What effect does the length of the core have on the slope?***

Question 16.6 ***Where is the core when the output is a maximum?***

Question 16.7 ***Is the section on either side of the peak linear?***

Question 16.8 ***How could we obtain a single output for the whole of the core travel?***

Exercise 16.1 ***In the last column of your table, add together the outputs of the two secondaries, taking the negative sign into account. Plot the resultant on the same graph sheet as your original graph.***

Question 16.9 ***At what point does the curve pass through zero?***

Question 16.10 ***Where is the core at this point?***

Question 16.11 ***Is the graph linear on either side of zero?***

Question 16.12 ***What electrical connections are necessary to achieve this result?***

PRACTICAL ASPECTS

Many of the questions in this assignment are answered in Assignment 17. It is inconvenient to use an oscilloscope to measure the output, so a better method will be devised. The method of this assignment has little practical use on its own, but is the basic principle of operation of the LVDT.

TYPICAL RESULTS AND ANSWERS ASSIGNMENT 16

Question 16.1 The disadvantage of the arrangement suggested is that the connections would have moved. This is explained in the text.

Question 16.2 Both waveforms reach two, different amplitude, maximums with the larger amplitude occurring when the core is nearest to the primary coil.

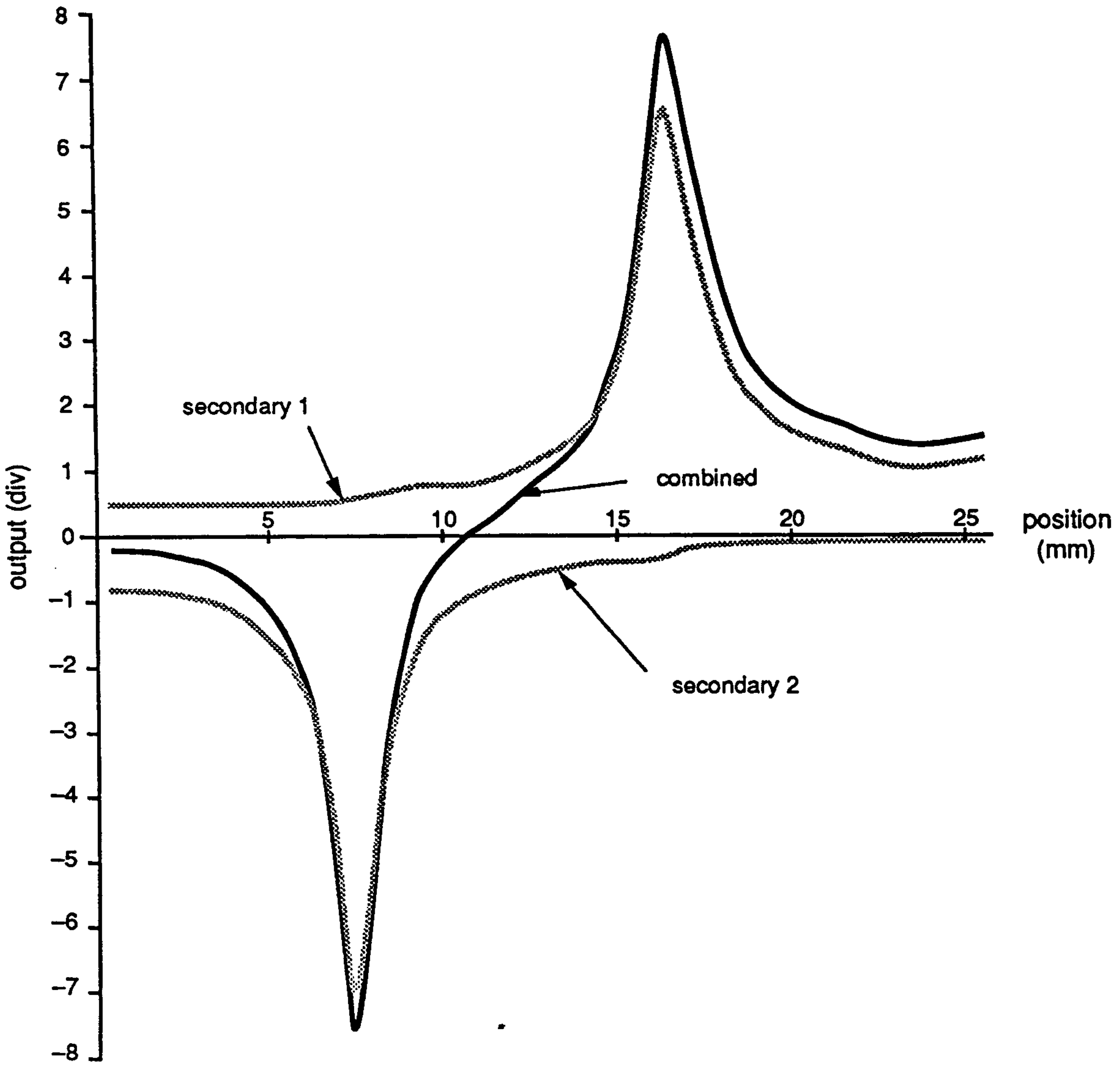
Question 16.3 No, secondary 1 peaks before secondary 2. This corresponds to the core traversing through the coils.

Question 16.4 We must use an oscilloscope, as an ac meter would not respond to this high frequency.

position (mm)	sec 1 output divs pk/pk	sec 2 output divs pk/pk	algebraic sum (divs)	position (mm)	sec 1 output divs pk/pk	sec 2 output divs pk/pk	algebraic sum (divs)
0	0.3	–0.9	–0.6	13	1.1	–0.6	0.5
1	0.3	–0.9	–0.6	14	1.65	–0.5	1.15
2	0.3	–1.0	–0.7	15	2.9	–0.5	2.4
3	0.3	–1.1	–0.8	16	6.5	–0.5	6.0
4	0.3	–1.4	–1.1	17	4.1	–0.2	3.9
5	0.3	–1.9	–1.6	18	2.3	–0.2	2.1
6	0.3	–3.1	–2.8	19	1.65	–0.2	1.45
7	0.4	–7.2	–6.8	20	1.3	–0.2	1.1
8	0.5	–3.3	–2.8	21	1.2	–0.2	1.0
9	0.6	–1.7	–1.1	22	1.0	–0.2	0.8
10	0.6	–1.1	–0.5	23	0.9	–0.2	0.7
11	0.7	–0.9	–0.2	24	0.9	–0.2	0.7
12	0.9	–0.7	0.2	25	1.0	–0.2	0.8

Fig E4.16.6

TYPICAL RESULTS AND ANSWERS ASSIGNMENT 16



Question 16.5 The secondary 2 output peaks fairly rapidly as the core is pushed into the coil but tails away less sharply due to the length of the core. The graph from secondary 1 is similar, but reversed.

Question 16.6 When an output is a maximum, the core is fully linking the primary and that secondary coil.

Question 16.7 Neither side of the peak is really linear.

Question 16.8 If we add the two outputs we obtain a combined characteristic.

Exercise 16.1 The results are given in the table, fig E4.16.6, above and the graph is plotted.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 16

Question 16.9 The curve passes through zero at 11.5mm.

Question 16.10 The core is symmetrical about the primary, linking equally with each secondary.

Question 16.11 The graph is not quite linear but it is better than before. By careful design of the core and coils it could possibly be made more so.

Question 16.12 To achieve this result, the coils must be connected in series opposition.

THE LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT) — ASSIGNMENT 17

CONTENT

The behaviour of a mutual inductance type transducer with two secondaries connected in various configurations is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducers Test Rig.
1	TK294G	Linear Variable Difference Transformer (LVDT) Sub-unit.
1	–	Power Supply,±15Vdc *(eg Feedback PS446)*
1	–	Two-beam oscilloscope 15MHz.
1	–	*DC Voltmeter 10V

* Alternatively a multimeter may be used.

PRACTICALS

17.1 LVDT AC Output

17.2 LVDT DC Output

THE LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)

ASSIGNMENT 17

OBJECTIVES

When you have completed this assignment you will:

- Know what is meant by the *Linearity and Range* of a mutual inductive type transformer.
- Have studied how a dc voltage output may be obtained from a mutual inductance type transducer operated with an FM system.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the Instrumentation Module TK2941A and the Linear Transducers Test Rig TK294.
- Understand the basic operation of a variable reluctance type transducer with an FM system.
- Preferably have completed Assignment 16, Variable Reluctance Transducer.

The Linear Variable Differential Transformer (LVDT) **Assignment 17**

INTRODUCTION

A pair of coils can be used as a mutual inductance or transformer type transducer by monitoring the secondary emf when the primary is supplied from an ac source and the reluctance of the magnetic path is varied. Because of the peaked shape of the output curve from a single secondary, there is very little direct use for a transducer of this type.

However, if we had two secondaries giving opposing outputs equally centred about the primary, the graphs could be added together algebraically to give a more useful characteristic. Let us see if this works in practice.

PRACTICAL 17.1

LVDT AC output

Connect up the circuit of fig 4.17.1 as shown in fig 4.17.2. Carefully check that the terminals of the transducer are wired up correctly.

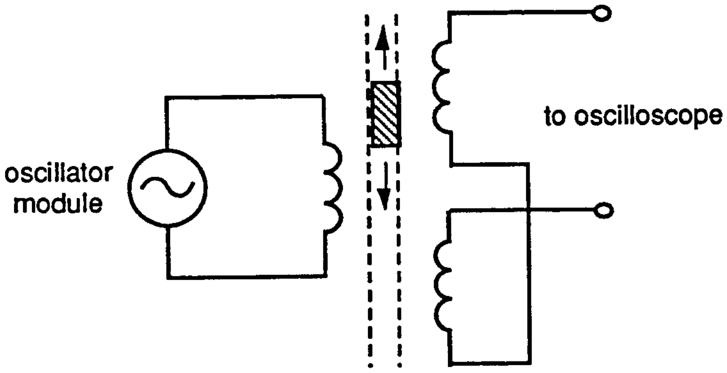


Fig 4.17.1

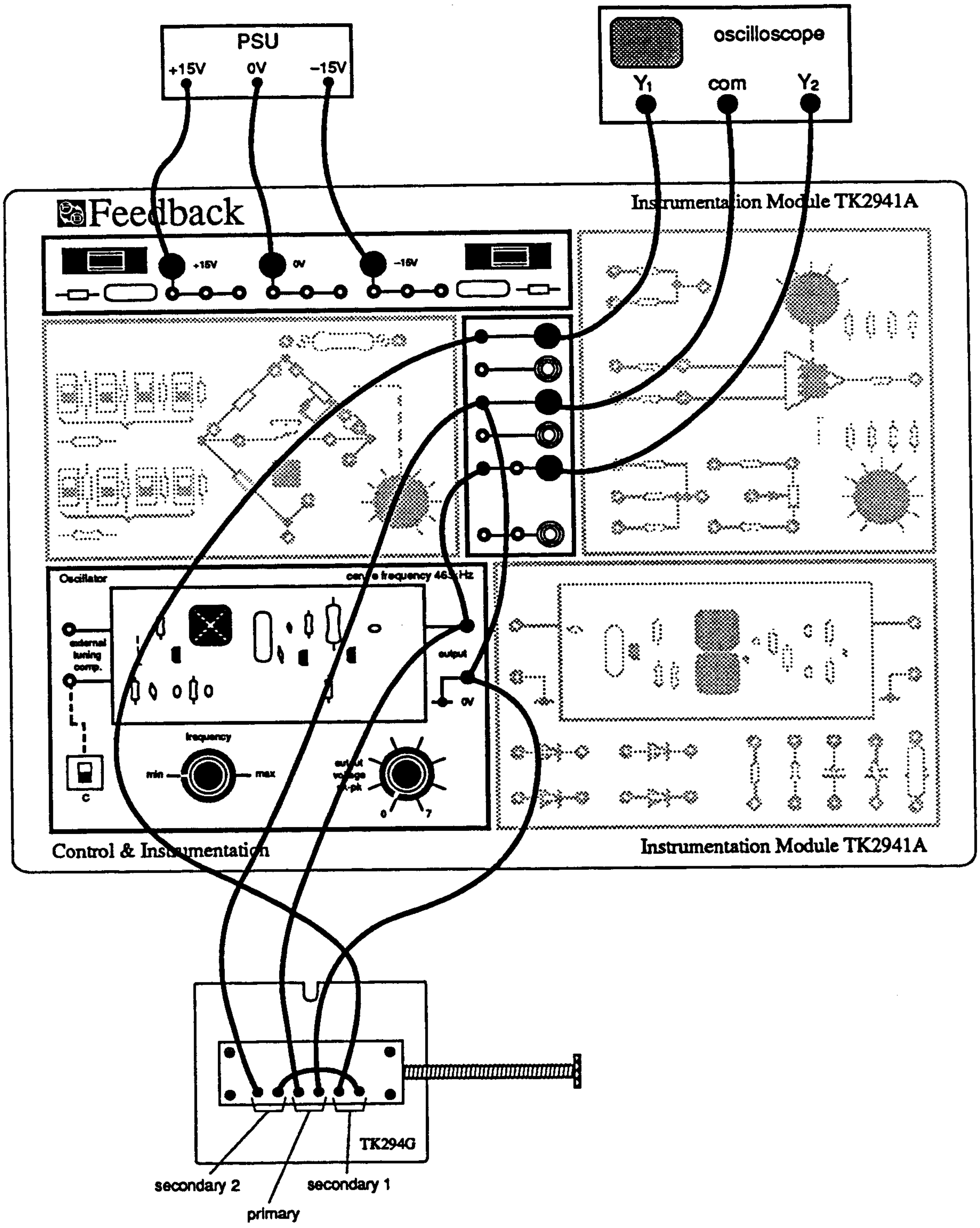


Fig 4.17.2

Make sure that the switch on the oscillator is set to the 'C' position and the frequency control set to 'max'. Set the output amplitude control to '7' and switch on the power supply.

With the oscilloscope connected as shown, set the timebase to 1μs/div and the vertical sensitivities to 2V/div to display a few cycles of the output waveform and the oscillator waveform. The trigger is derived from the latter and its control should be set to Y2. By pressing the rod against the return spring, move the ferrite core through the body of the transducer. Observe the secondary output waveform on the oscilloscope. It should go through a maximum shifting phase and then a second maximum, reduce almost to zero, change phase and go through two further maximums again shifting phase. Observe particularly the phase change at the zero position. It should be 180°. Adjust the oscilloscope amplitude control to obtain as large a display as possible.

Reduce the oscilloscope timebase setting to say, 100μs/div so that it is easier to read the number of divisions peak-to-peak of the waveform. Set the micrometer to the 0mm position and the slider index to the 55mm position on the scale.

Using the micrometer move the core through the coils in 1mm steps, recording the output at each step, to a final setting of 25mm on the micrometer.

Record you readings in your own copy of a table as in fig 4.17.3. Ignore the third column for the moment. When the output passes through the null position, as you have noted, there was an 180° phase change. Record the position where this happens, and all subsequent readings as negative.

Using your results, plot a graph of output against position for the whole range of movement.

position (mm)	output ac (volts pk-pk)	output (dc volts)	position (mm)	output ac (volts pk-pk)	output (dc volts)

Fig 4.17.3

Question 17.1 *What shape is your graph, especially over the central section?*

Exercise 17.1 *Draw in what you consider to be the best straight line approximation to the central section. It will most likely pass through the zero null point.*

Measure the maximum distance of your curve from this straight line, in the vertical (i.e output voltage) direction. Express this as a percentage of the total output voltage range between the two peaks. Call this x%.

The figure you have just calculated is the *LINEARITY* of the transducer. It should be as small as possible for a good transducer.

The Linear Variable Differential Transformer (LVDT) **Assignment 17**

Question 17.2 ***Between which positions is the output within this linearity figure? This represents the RANGE of the transducer. Express this as a figure of ±ymm about the null point.***

You now have two figures for the specification of this transducer. We can say that the output linearity is x% over a range of ±ymm about the central position.

However, the output is an ac voltage which has to be measured on an oscilloscope.

Question 17.3 ***Would a dc voltage output be more convenient?***

The answer should be, of course, yes. As well as being easier to measure it could be used as a direct input to a signal processing or control system.

Question 17.4 ***What basic component do we need to convert the ac voltage into a dc voltage?***

Question 17.5 ***How can we take account of the change in phase as the output voltage passes through zero?***

The circuit of fig 4.17.4 provides the answers to both these questions. The circuit is a differential rectifier, and a detailed description of its operation can be found in many standard electronics textbooks. It gives both positive and negative dc outputs. An amplifier is sometimes necessary as the output may be quite low. This process may be sometimes called demodulation.

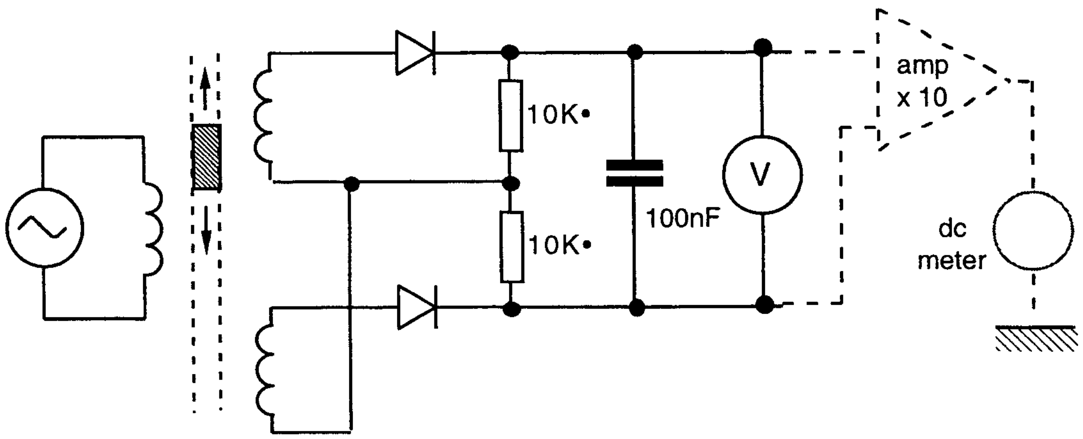


Fig 4.17.4

The Linear Variable Differential Transformer (LVDT) **Assignment 17**

PRACTICAL 17.2

LVDT DC Output

Switch off the power supply and connect up the circuit of fig 4.17.4 as shown in fig 4.17.5. Carefully check that the terminals on the transducer are wired up correctly.

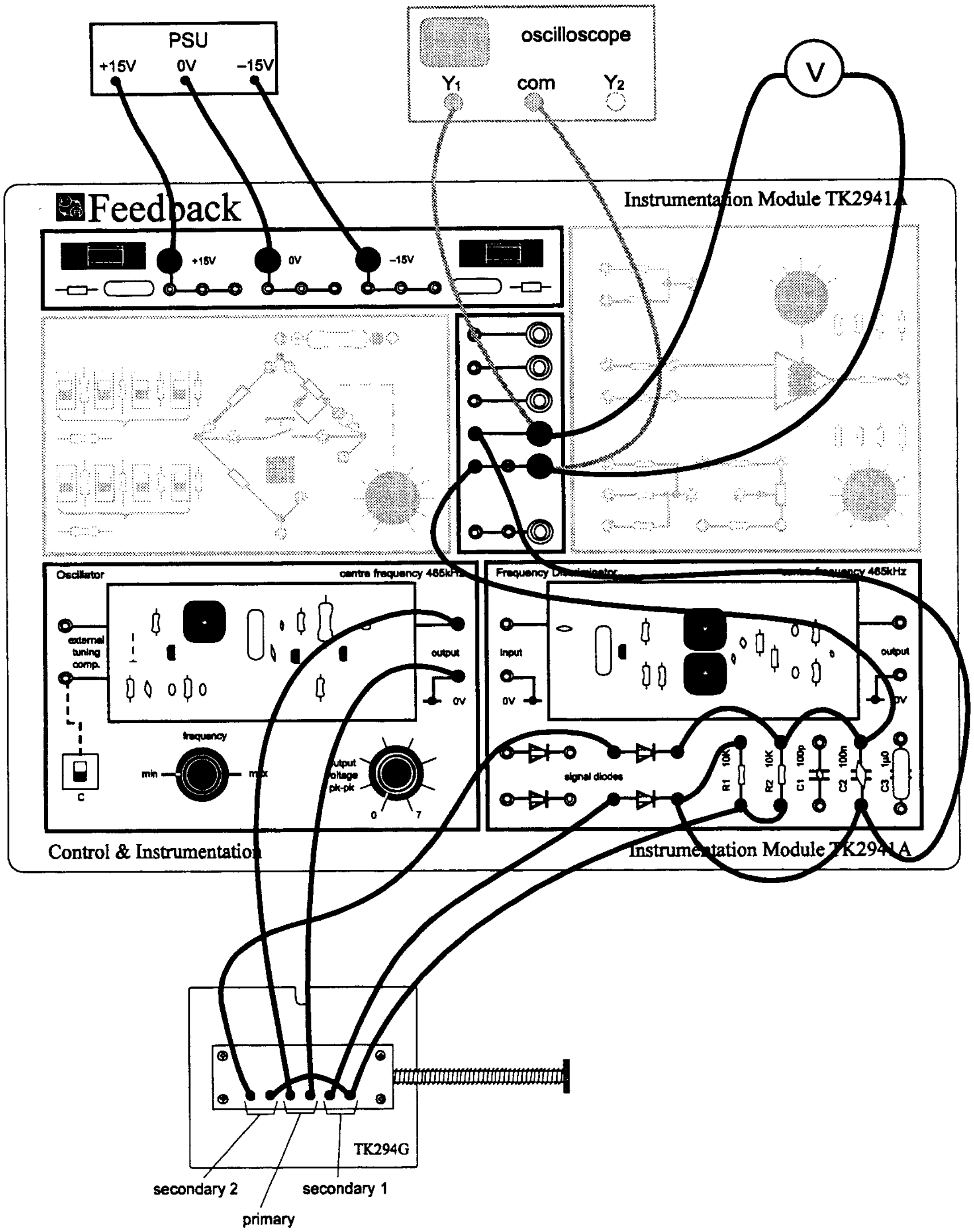


Fig 4.17.5

Make sure that the switch on the oscillator module is still in the 'C' position and the frequency control set to 'max'. Set the output amplitude control to '7' and switch on the power supply.

Connect your oscilloscope across the rectifier output terminals, set the timebase as before to 1μs/div and the Y gain to 20mV/div and dc coupled. Temporarily remove the two connections from each of the two 100nF, C2, sockets while still keeping the patching leads joined together ie remove the capacitor from the circuit. Note the rectification provided by the diodes alone.

Replace the connections, this time across the 100pF capacitor, C1. Note that this value of capacitance does not provide adequate smoothing and that the dc waveform has a large ripple.

Set the Y gain to 0.5V/div. Change the connections again to place the 1μF capacitor, C3 in circuit. Observe the waveform whilst very rapidly moving the core.

Question 17.6 ***Would this capacitor be suitable for smoothing the output voltage if the core were in continuous motion?***

Replace the correct 100nF capacitor and withdraw the core from the coils. Take a set of readings of dc output voltage and position at 1mm intervals as you move the core through the two secondary coils as before.

Record your readings in the third column in your table. Record the position where the output voltage is zero.

Using your results, plot a graph of output against position for the whole range of movement. Draw it on the same sheet of graph paper as you did the ac graph. We are going to perform the same operations on it.

Question 17.7 ***What shape is your graph, especially over the central section? Is it the same shape as the ac graph?***

Exercise 17.2 ***Draw in what you consider to be the best straight line approximation to the central section. It will most likely pass through the zero null point.***

Measure the maximum distance of your curve from this straight line, in the vertical (i.e output voltage) direction. Express this as a percentage of the total output voltage range between the two peaks. Call this x%. As before, this is the linearity (dc) of the transducer combined now with the detector system.

Question 17.8 ***Between what positions is the output within this linearity figure? Express this range as a figure of ±ymm about the zero null point. Is this greater or less than the ac range?***

PRACTICAL ASPECTS

You should have found that both your graphs had an S-shape over the whole range, starting from near zero, then increasing to a maximum as the core provided maximum coupling between the primary and secondary 1, then decreasing through zero as the voltage in secondary 2 is built up to its maximum and finally decreasing to near zero as the core moved out of the coils. The centre section should have been predominantly linear in both cases, any departures being due to any electrical or magnetic unbalance between the two coils. The shape of the individual characteristics of the two coils, as explored in Assignment 16 also affects the shape of the resultant characteristic. This depends upon the relative lengths of the core and coils. In addition harmonic voltages may be introduced.

Also we have assumed that the flux is constant. This implies a constant current in the primary. In practice this may not be the case. As the coupling between the primary and secondary is varied by the movement of the core, the self inductance of the primary will vary. This will vary the current in the primary and hence the flux. Also the driving circuit must be carefully designed so that the primary does not form a resonant circuit with the output stage of the oscillator. Whilst this has the advantage of increased output, any slight changes in the coupling will cause large changes in the current, if the Q-factor is high. This happens to a certain extent in this kit. Only by very careful design and choice of excitation parameters can these effects be minimised.

However, in practice, things may not be too bad. You should have found linearities better than 4% over a range of about ±3mm about the central position. This is where the core is centrally displaced about the primary coil, and the individual voltages from each secondary cancel out.

These two figures are used as part of the specification of the transducer. We also need to know the primary excitation requirements (voltage and frequency), the physical dimensions of the transducer and its method of coupling, the environmental conditions under which these outputs hold, the resolution (which is infinite in this case), the frequency response and damping factor (limited by the moving system), and finally the price and delivery. All these factors which we need to know about for our transducer are discussed in Appendix A.

You should also have found that although the ac and dc curves had the same form, they were of a slightly different shape and the gradient of the linear portion was different.

This is due to the rectification circuit employed. Since current is only passing during one half cycle, this will set up a pulsing unidirectional flux in the magnetic circuit. This may affect the characteristics of the primary as explained before. This causes the dc curve to be different from the ac curve, but in fact the linearity is better and the range is similar.

Therefore since a high frequency ac voltage is difficult to measure, and of little use to subsequent signal processing systems, conversion to dc provides a much better output which is of better linearity although possibly over a slightly smaller range. The demodulator could be integral with the transducer.

The transducer has a differential output which, as discussed in Assignment 15, can help to minimise the effects of errors due to temperature, stray magnetic fields and so on. If the external influence affects one coil so as to increase the output, the increase in the other coil will be in the opposite direction and so the two will tend to cancel out. Several LVDT's may be joined in series to give a greater output. Other advantages of the LVDT are that the output is electrically isolated from the input and the electrical parts are stationary, resulting in low wear and long life. By using a high excitation frequency, effects due to temperature and stray magnetic fields can be made insignificant, although the transducers are enclosed in a screening case. Excitation may be either from a constant voltage source as in our assignment, or preferably a constant current source, which ensures that the flux in the primary is constant, regardless of frequency. Well designed LVDT's have linearities typically better than 0.1% but over very small ranges, usually less than ±3mm.

The LVDT is one of the most widely used transducers, since many variables are converted to linear displacement to enable them to be more easily measured. They are used to transduce motions of bellows, diaphragms, bourdon tubes, flow meters, floats, micrometer screws, bimetallic strips, wedges, strains, torsion bars, levers, or any similar motion, into an electrical signal. This electrical signal then goes to the signal processing system where it may be recorded or transmitted or amplified and used to operate indicators, motors or controllers. Typical uses are indicated below. There are also applications where two LVDT's can be used by balancing the outputs against one another, for example in measuring thickness or differential pressure. For measuring complex shapes many LVDT's may be scanned alternately by a data logging system.

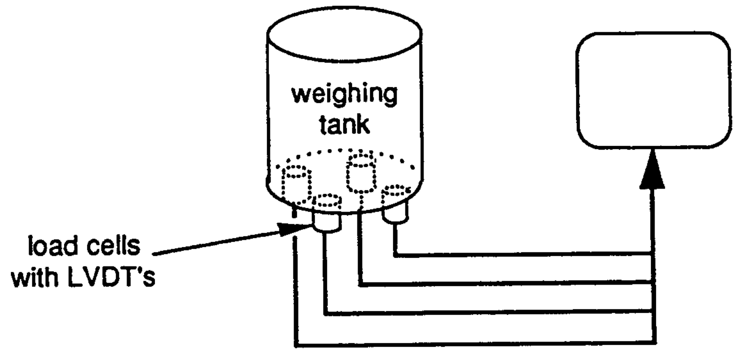


Fig 4.17.6

Four LVDT's are summed by the signal processor for increased sensitivity and output. They are all excited in parallel

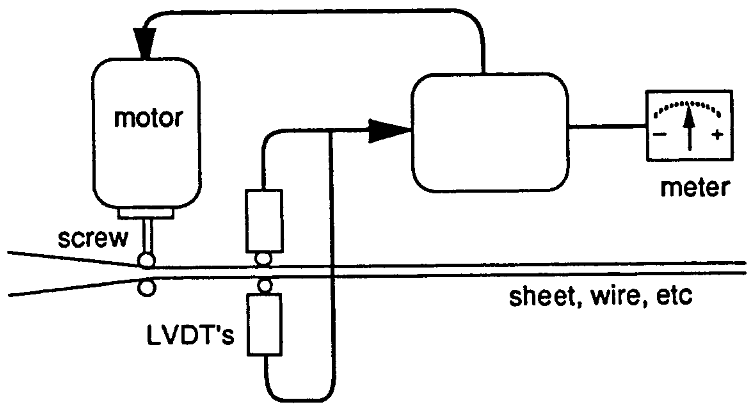


Fig 4.17.7

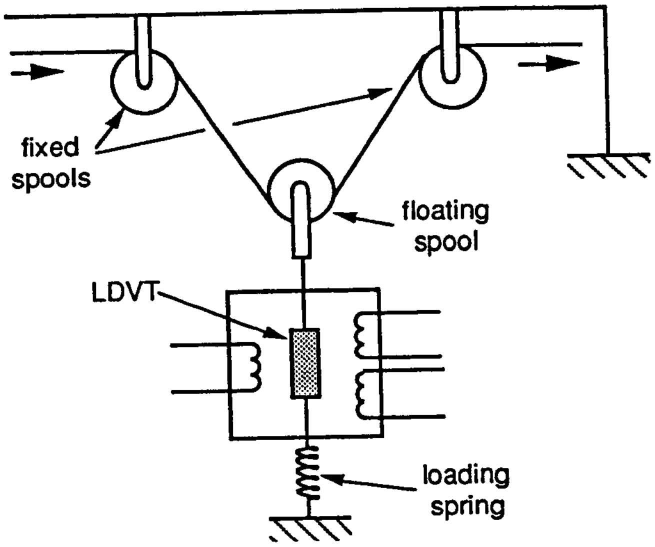


Fig 4.17.8

TYPICAL RESULTS AND ANSWERS

position (mm)	output ac (volts pk-pk)	output (dc volts)	position (mm)	output ac (volts pk-pk)	output (dc volts)
0	3.6	0.70	13	–6.6	–0.23
1	4.0	0.81	14	–8.4	–0.44
2	4.4	0.89	15	–8.4	–0.60
3	4.9	0.91	16	–7.7	–0.70
4	5.4	0.87	17	–7.0	–0.80
5	5.8	0.81	18	–6.5	–0.90
6	6.3	0.73	19	–6.0	–1.00
7	6.8	0.63	20	–5.5	–1.06
8	7.4	0.49	21	–5.0	–1.08
9	7.4	0.30	22	–4.6	–1.04
10	6.4	0.12	23	–4.1	–0.94
11	2.9	0.01	24	–3.8	–0.80
(11.52)	(280mV)	(0.00)	25	–3.6	–0.67
12	–2.5	–0.07			

Fig E4.17.3

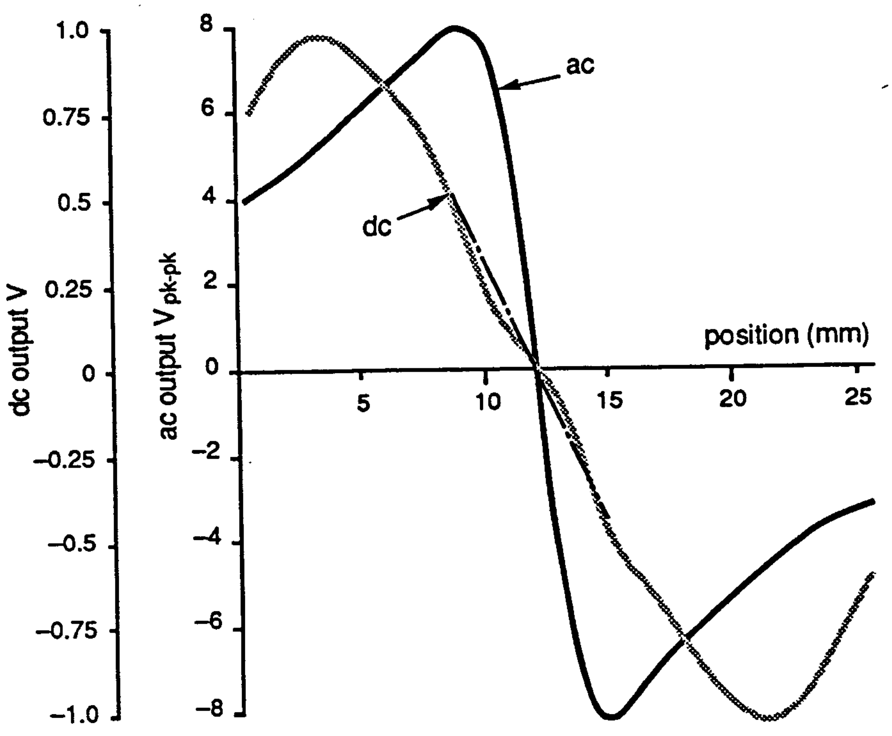


Fig E4.17.3

TYPICAL RESULTS AND ANSWERS ASSIGNMENT 17

Question 17.1 The curve is S-shaped with the centre section reasonably linear.

Exercise 17.1 See Fig E4.17.3 graph.

Question 17.2 Linearity x % should be small, no greater than about 4%.

The range over which this linearity holds is typically ±1.5mm about the central position.

Question 17.3 A dc output would be more convenient, as explained.

Question 17.4 A rectifier (diode) is required.

Question 17.5 Use a differential rectifier circuit as explained.

Question 17.6 The larger capacitor would not be suitable as the output could not follow fast changes of position.

Question 17.7 The graph is S-shaped with the centre section reasonably linear. It is unlikely to be the same as the ac graph for the reasons given in the assignment.

Exercise 17.2 See Fig E4.17.3 graph.

Linearity is typically about 3%. This is better than the ac curve linearity.

Question 17.8 The range over which this linearity holds is typically ±3mm about the central position.

TRANSDUCER CHARACTERISTICS

APPENDIX A

When choosing a transducer, if the input physical quantity is known, the type may be chosen to suit a particular signal processing system. Ideally a transducer should have no effect on the quantity it is to measure although it always requires some energy to move the transducer. The overall transfer function must be known, as the electrical output must correspond as closely as possible to the original physical variable. The following parameters must therefore be considered.

Range

This is the limit of movement of the physical input over which the electrical output stays within a specified amount. Overloading may be possible if the range is exceeded but it will not usually follow the normal law of the transducer. Mechanical stops are sometimes fitted to prevent movement beyond the limits.

Sensitivity

The ratio of electrical output to unit input eg 1V per mm movement. Alternatively it may be given as the total output for inputs within the specified range, eg 0-10volts.

Cross Sensitivity and Environment

The transducer may be subject to other physical variables, eg temperature, pressure, humidity, vibration or movement in another axis to that in which it is desired to measure. A good transducer should have minimum response to these.

Accuracy and Repeatability

These refer to the ability of a transducer to give the same electrical output for the same input at different times.

Linearity

The graph of electrical output/physical input may deviate from a straight line over the specified range. This deviation may be expressed as a percentage of full scale output, or the deviation from the best straight line passing through zero and full scale. There may also be a zero error. As explained in the Assignments, this may not be a serious problem since a calibration chart may be provided. Several other definitions of linearity are possible.

Hysteresis

If there is difference between calibration curves plotted for increasing and decreasing physical inputs, the transducer is said to possess hysteresis. This is caused by lags in the response of the mechanical system, eg stresses or backlash. Some of these may be unpredictable in service. It may be possible to construct an average best curve through the mean of the two curves.

Resolution

This refers to the smallest input change which will produce a change in the output. For example, the resolution of a potentiometer type transducer is limited by the jumps between the turns of wire. Other transducers may have infinite resolution which is then only limited by noise in the electrical or mechanical systems.

Frequency Response

If the transducer is being used to measure moving objects, a good frequency response implies the ability of the electrical output to follow these movements faithfully. Above a certain frequency, the response deteriorates.

Natural Frequency and Damping

An undamped system will oscillate at its natural frequency, so damping is often provided to decrease the amplitude of the oscillations which may occur following a change in input.

Electrical and Mechanical

The electrical characteristics, eg impedance, insulation, resistance are important. The transducer may need an external supply. Mechanically it may have to be light in weight, or a certain size, or have a corrosion free case.

Commercial

It is no use specifying a certain make of transducer for an immediate project if delivery cannot be made for some time. The price is also an important factor.

Conclusions

The choice of transducer type for a particular application is determined by one or more of the following:

- The electrical requirements of the signal processing system.
- The environment in which the transducer will work.
- The accuracy required.
- The length of service.
- Price and delivery.

HOW TO READ A MICROMETER

APPENDIX B

In many of the assignments you need to move parts of transducers by known or measurable amounts. This is achieved in the Linear Transducers Test Rig by a combination of a preset slide with a locking screw for coarse adjustment and a micrometer head for fine adjustment.

The slide scale is marked in 1mm divisions from 0 to 90mm while the linear scale of the micrometer is marked in 0.5mm divisions with major divisions every 5mm. For ease of reading the calibration marks at 0.5, 1.5, 2.5mm, etc are on the lower side of the scale line as shown in fig B1.

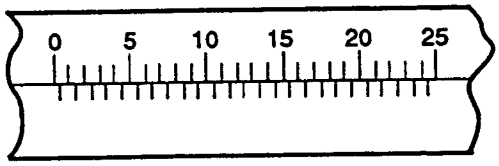


Fig B1

The range of the micrometer is 25mm, giving a total motion range of 90 + 25 = 115mm.

The micrometer barrel has 50 divisions round its circumference and the thread is arranged so that one full turn advances the head by 0.5mm. Thus *two* full turns are needed to advance it by 1.0mm and each division on the barrel corresponds to $\frac{0.5}{50}$mm = 0.01mm.

Fig B2 shows this diagrammatically.

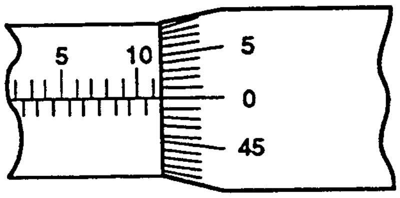
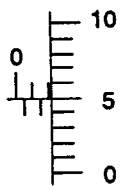
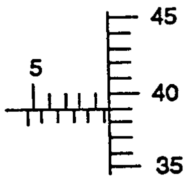
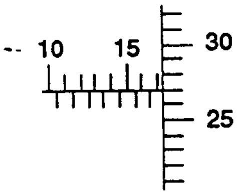
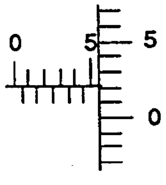


Fig B2

In fig B2 the 0 division on the barrel is aligned with the linear scale line and the edge of the barrel lies exactly over the 0.5mm calibration between 11 and 12, that is it reads 11.5mm. When the barrel is at some other setting, say 15, then you must decide whether the edge of the barrel is to the left or to the right of a 0.5mm mark. If to the left, the reading will be the next lower 1.0mm reading plus 0.15mm. If to the right it will be the next lower 1.0mm reading plus 0.5mm plus 0.15. Fig B3 shows several examples in large scale.

		linear		barrel		total
	reading =	2.0	+	0.05	=	2.05mm
	reading =	9.5	+	0.39	=	9.89mm
	reading =	17.0	+	0.27	=	17.27mm
	reading =	5.5	+	0.02(5)	=	5.25(5)mm

bracketed (5) is estimated

Fig B3

ANALYSIS OF A WHEATSTONE BRIDGE

APPENDIX C

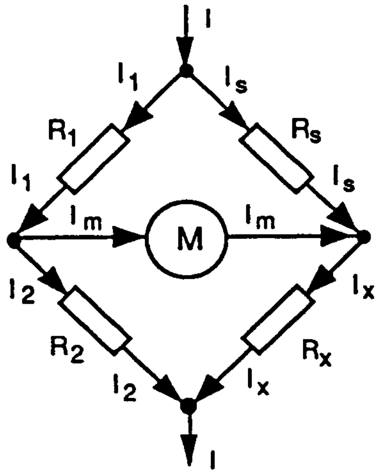


Fig C1

Using Kirchoff's Law of currents:

$$I = I_1 + I_s$$
$$I_1 = I_m + I_2$$
$$I_x = I_s + I_m$$
$$I_2 + I_x = I$$

At balance Im = 0 thus these equations are simplified to:

$$I_1 = I_2$$
$$I_s = I_x$$

also at balance, by the potential divider theory:

$$V_{R1} = V_{RS} \text{ and } V_{R2} = V_{Rx}$$

$$\therefore \quad I_1R_1 = I_SR_S \text{ and } I_2R_2 = I_xR_x$$

dividing one equation by the other gives:

$$\frac{I_1R_1}{I_2R_2} = \frac{I_sR_s}{I_xR_x}$$

or

$$\frac{R_1}{R_2} = \frac{R_s}{R_x}$$

This is the balance condition of a Wheatstone Bridge.

When the bridge is off balance there will be a finite current flowing through the meter (I_m in fig C1). The analysis of the off-balance Wheatstone Bridge is more complex but consider the bridge in fig C2.

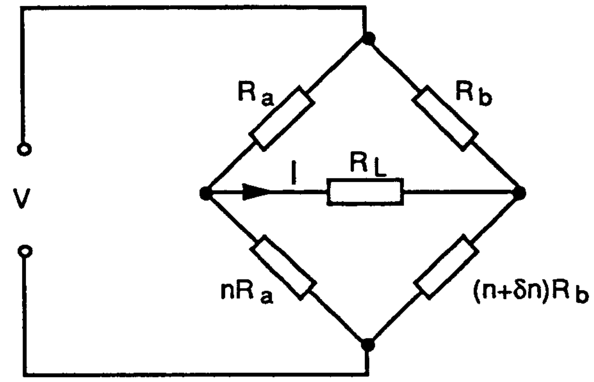


Fig C2

We wish to find the current I in the load (which may be a meter or an amplifier, etc) which is represented by the resistor R_L.

The resistors R_a and nR_a are the ratio arms of the bridge, with a ratio of n and the resistor R_b is the standard.

The unknown resistor is $(n+\delta n)\ R_b$ signifying that it is not the value that would balance the bridge as it differs from the balancing value by δnR_b.

To find the current I we can use Thévenin's Theorem.

The resistance of the bridge with the source shorted may be found, as the circuit reduces to fig C3.

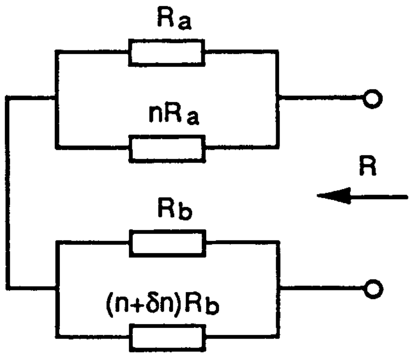


Fig C3

$$\text{ie} \quad R = \frac{R_a . nR_a}{R_a + nR_a} + \frac{R_b(n+\delta n)R_b}{R_b + (n+\delta n)R_b}$$

$$\therefore \quad R = R_a\left(\frac{n}{1+n}\right) + R_b\left(\frac{n+\delta n}{1+n+\delta n}\right)$$

The open circuit voltage may be found by using the potential divider theory.

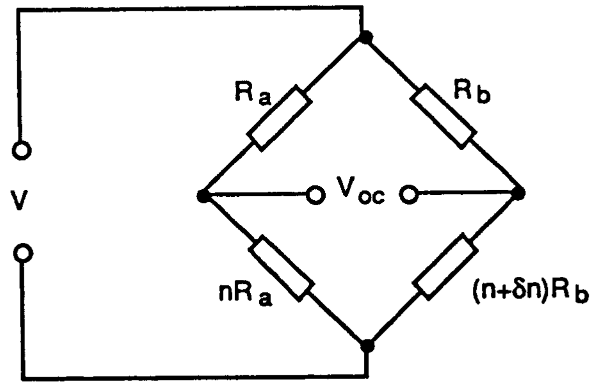


Fig C4

Voltage across resistor nR_a is given by:

$$V_{nRa} = \frac{nR_a}{R_a + nR_a} . V$$

Voltage across resistor $(n + \delta n) R_b$ is given by:

$$V_{(n+\delta n) R_b} = \frac{(n+\delta n)R_b . V}{R_b + (n+\delta n)R_b}$$

$$\text{and} \quad V_{oc} = V_{nRa} - V_{(n+\delta n) R_b}$$

$$\therefore \quad V_{oc} = \left(\frac{n}{1+n} - \frac{n+\delta n}{1+n+\delta n}\right)V$$

Thus, using Thévenin's Theorem:

$$I = \frac{V_{oc}}{R + R_L}$$

$$I = \frac{\left(\frac{n}{1+n} - \frac{n+\delta n}{1+n+\delta n}\right)V}{R_a\left(\frac{n}{1+n}\right) + R_b\left(\frac{n+\delta n}{1+n+\delta n}\right) + R_L}$$

This is a rather complicated expression and is very unwieldy. It can be simplified.

Let $\left(\frac{n}{1+n} - \frac{n+\delta n}{1+n+\delta n} = \delta m\right)$

$$\therefore \quad \frac{n+\delta n}{1+n+\delta n} = \frac{n}{1+n} - \delta m$$

Thus: $$I = \frac{V\delta m}{R_a\left(\frac{n}{1+n}\right) + R_b\left(\frac{n}{1+n} - \delta m\right) + R_L}$$

Now $$\delta m = \frac{n}{1+n} - \frac{n+\delta n}{1+n+\delta n}$$

$$\therefore \quad \delta m = \frac{n(1+n+\delta n) - (1+n)(n+\delta n)}{(1+n)(1+n+\delta n)}$$

$$\therefore \quad \delta m = \frac{-\delta n}{(1+n)(1+n+\delta n)}$$

Now if $\delta n \ll n$, which is the case when the bridge is close to balance, then:

$$\delta m \approx \frac{-\delta n}{(1+n)^2}$$

Thus the expression for the current becomes:

$$I = \frac{\dfrac{-V\delta n}{(1+n)^2}}{R_a\left(\dfrac{n}{1+n}\right) + R_b\left(\dfrac{n}{1+n} + \dfrac{\delta n}{(1+n)^2}\right) + R_L}$$

$$= \frac{-V\delta n}{R_a n(1+n) + R_b[n(1+n) + \delta n] + R_L(1+n)^2}$$

again, if $\delta n \ll n$ this reduces to:

$$I = \frac{-V\delta n}{R_a n(1+n) + R_b n(1+n) + R_L(1+n)^2}$$

$$\therefore \quad I = \frac{-V\delta n}{n(1+n)(R_a + R_b) + (1+n)^2 R_L}$$

This is the equation for current, for an off balance Wheatstone Bridge.

Reactive Strays

When the Wheatstone Bridge circuit is used at ac it is probable that there may be present some reactive strays, for example the unknown may have an appreciable stray capacitance. These reactive strays will give rise to errors, as the balance point of the bridge will be changed, if they are not balanced out by a similar reactance in the opposite arm.

Consider the circuit in fig C5.

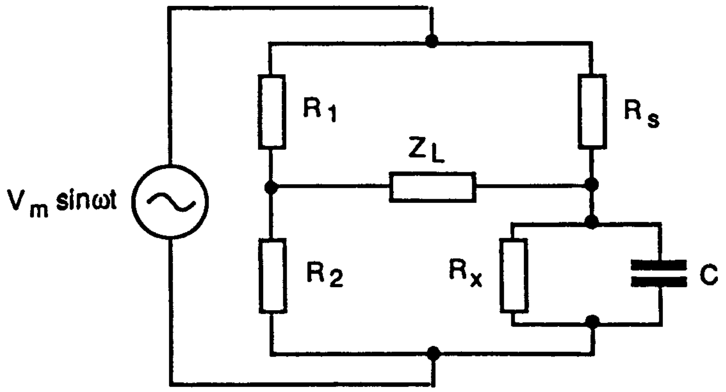


Fig C5

Here the capacitance C represents the stray capacitance of the unknown R_X, which cannot be balanced out by the pure resistance of the standard R_S.

The voltage across R_S is given by:

$$R_s = V_m \sin\omega t \frac{R_s}{R_s + R_x // Z_c}$$

and the voltage across R_1 is:

$$V_{R_1} = V_m \sin\omega t \frac{R_1}{R_1 + R_2}$$

Thus the voltage across the load will be given by:

$$V_{Z_L} = V_{R_s} - V_{R_1}$$

$$\therefore \quad V_{Z_L} = V_m \sin\omega t \left(\frac{R_s}{R_s + R_x // Z_c} - \frac{R_1}{R_1 + R_2} \right)$$

SIMPLE OPERATIONAL AMPLIFIER THEORY

APPENDIX D

The operational amplifier has three main requirements, which are:

- Infinite gain.
- Infinite input impedance.
- Zero output impedance.

An amplifier which has these properties may be connected in circuit with two resistors to achieve any desirable gain requirement.

Consider the circuit of fig D1.

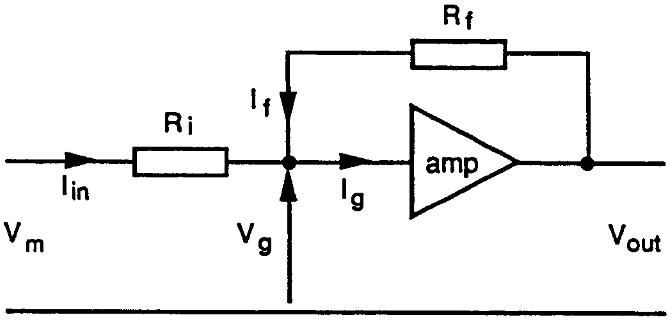


Fig D1

The amplifier has the above characteristics

R_i is the input resistor

R_f is the feedback resistor

From fig D1 and using Kirchoff's Laws

$I_g = I_f + I_{in}$

But if the amplifier has infinite input impedance then $I_g = 0$.

$\therefore \quad I_f = -I_{in}$

Also, from fig D1

$V_{out} = V_g \times$ (amplifier gain)

But if the amplifier gain is, or approaches, infinity, then $V_g = 0$.

Thus the junction of Rf and Ri is virtually at zero, and is often known as a virtual earth.

Thus we have:

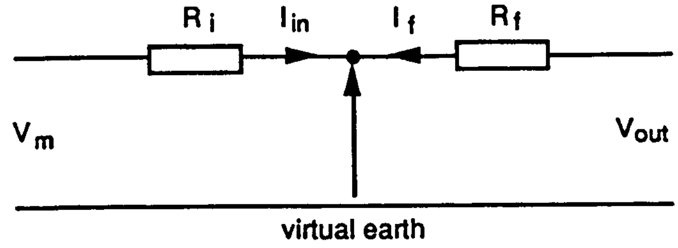


Fig D2

where: $I_{in} = \frac{V_{in}}{R_i}$

and $I_f = \frac{V_{out}}{R_f}$

but $I_{in} = I_f$

$\therefore \quad \frac{V_{in}}{R_i} = \frac{-V_{out}}{R_f}$

$\therefore \quad V_{out} = \frac{R_f}{R_i} V_{in}$

This is the equation for an operational amplifier with an ideal amplifier.

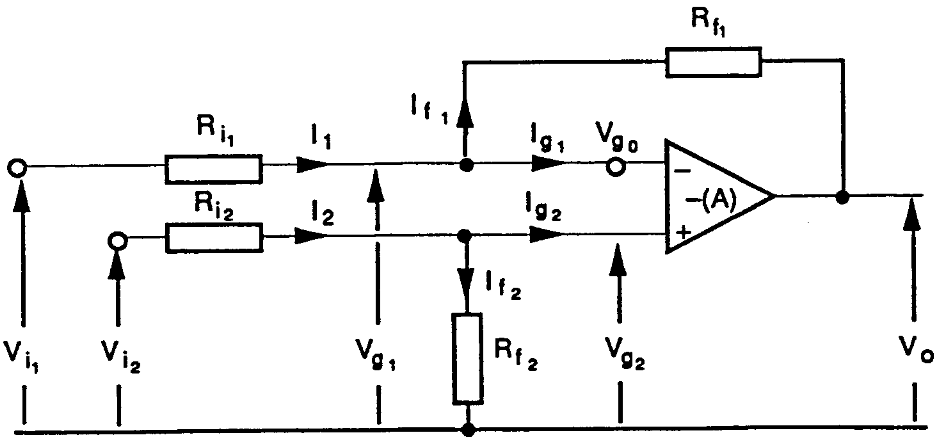


Fig D3

STRAIN GAUGE THEORY

APPENDIX E

As discussed in Assignment 10, the strain gauge consists essentially of a length of fine wire about 0.025in diameter. When this is physically stretched, the length L changes by δl, the cross sectional area 'a' changes by δa and the resistivity 'ρ will also change by $\delta\rho$, due to the physical properties of the wire being changed as the crystal lattice is distorted.

If the diameter of the wire is 'd', the area 'a' is given by:

$$a = \frac{\pi}{4}.d^2$$

To produce the change δa, the diameter changes δd and the new area is:

$$(a + \delta a) = \frac{\pi}{4}(d + \delta d)^2$$

$$= \frac{\pi}{4}\left(d^2 + 2d.\delta d + (\delta d)^2\right)$$

Throughout this appendix we can ignore terms like (δd^2), where one small quantity is multiplied by another small quantity, as the result will be of a magnitude so small as to be insignificant.

$$\therefore \quad a + \delta a = \frac{\pi}{4}\left(d^2 + 2d.\delta d\right)$$

Subtracting the original area $\left(a = \frac{\pi}{4}.d^2\right)$ from each side:

$$\delta a = \frac{\pi}{4}.2d.\delta d$$

Dividing through by the original area,

Equation 1

$$\frac{\delta a}{a} = \frac{2.\delta d}{d}$$

This tells us how the diameter (transverse dimension) change is related to the area change. It is also related to the length change by Poisson's Ratio:

$$\mu = \frac{\text{lateral strain}}{\text{longitudinal strain}} = \frac{\delta d}{d} = \frac{\delta l}{l}$$

Note that as δl and δd change in opposite directions, μ will be a negative number.

Substituting from Equation 1

Equation 2

$$\frac{\delta a}{a} = 2\mu . \frac{\delta l}{l}$$

Now the resistance of the wire in its unstretched state is given by:

$$R = \frac{\rho l}{a}$$

and if the strain produces a resistance change δR, the new resistance is

$$(R + \delta R) = \frac{(\rho + \delta l)(l + \delta l)}{(a + \delta a)}$$

$$= \frac{\rho l + l\delta\rho + \rho\delta l + \delta l . \delta\rho}{a + \delta a}$$

As explained, we can ignore the term δl.δp and now divide by the original resistance R = ρl/a.

$$1 + \frac{\delta R}{R} = \frac{1 + \frac{\delta\rho}{\rho} + \frac{\delta l}{l}}{1 + \frac{\delta a}{a}}$$

Multiply the top and bottom of the right hand side by

$$\left(1 - \frac{\delta a}{a}\right)$$

and ignore second order terms,

$$1 + \frac{\delta R}{R} = 1 + \frac{\delta\rho}{\rho} + \frac{\delta l}{l} - \frac{\delta a}{a}$$

substituting from Equation 2

Equation 3

$$\frac{\delta R}{R} = \frac{\delta l}{l}(1-2\mu) + \frac{\delta \rho}{\rho}$$

Thus it can be seen that the change in resistance is not only dependent on the change in length, but also on Poisson's Ratio and the change in resistivity of the material. Of course, $\delta l/l$ is the strain ε in the material, so Equation 3 is often written as:

$$\frac{\delta R}{R} = G\varepsilon$$

where G is called the Gauge Factor of the gauge:

$$\therefore \quad G = 1 - 2\mu + \frac{\delta l/\rho}{\varepsilon}$$

Equation 4

or $\quad G = 1 - 2\mu + m$

where $m = \frac{\delta l/\rho}{\varepsilon}$.which is approximately constant for small strains.

Typically, in practice it is found that for values of μ about –0.3, G is about 2.1 for certain materials thus m is about 0.5.

ie $\quad G = 1.2\mu + m$

or $\quad 2.1 = 1 + 0.6 + 0.5$

Thus for a specified change of resistance, about 48% is due to the change in length about 28% is due to the change in width and Poisson's ratio.

Beam Deflection Calculation

Fig E1 shows the strain gauge beam, with the gauge mounted, being deflected at its end by an amount Y.

The surface strain generated by the bending of the beam at a given point on the beam is proportional to the distance of that point from the free end. Since the gauge is of finite length the parts further from the free end are strained more than the nearer parts. But because the relationship is linear we can say that the effective strain is the average strain occurring at the gauge centre line, shown in fig E1 as distant x from the free end.

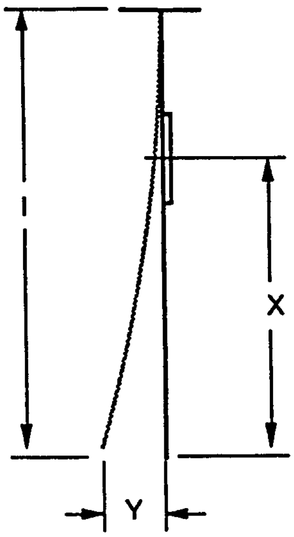


Fig E1 Strain gauge beam deflection

From the theory of simple bending for a fixed-end beam of rectangular cross-section it can be shown that the strain for deflection Y = 1mm is given by the equation:

$$\text{Strain/mm} = \frac{1.5\,X\,t \times 10^{-3}}{l^3}$$

where l = beam length (m)
X = distance from free end (m)
t = beam thickness (m)

For the beam used in the experiments the corresponding figures are:

$l = 47 \times 10^{-3}$; $c = 30 \times 10^{-3}$; $t = \times 10^{-3}$

Substituting these in the above equation gives:

Strain/mm deflection = 304×10^{-6}/mm

For a gauge factor of 2.2 this means that the relative resistance change is given by:

$$\frac{\delta R}{R} = 2.2 \times 304 \times 10^{-6} = 670 \times 10^{-6}/\text{mm}$$

FREQUENCY CHANGES IN A TUNED CIRCUIT — APPENDIX F

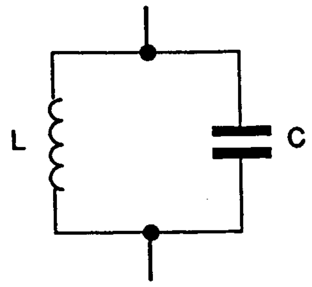


Fig F1

The resonant frequency of the circuit of fig F1 is given by:

$$\omega_o = \frac{1}{\sqrt{LC}}$$

If either component changes by a small amount, the resonant frequency will change. Suppose that C changes by δd, although the same theory will be true if L changes by δL.

New angular frequency

$$\omega = \frac{1}{\sqrt{L(C - \delta C)}}$$

$$\therefore \quad \text{Change } \omega - \omega_o \quad \delta\omega = \frac{1}{\sqrt{L(C-\delta C)}} - \frac{1}{\sqrt{LC}}$$

$$\therefore \quad \delta\omega = \frac{1}{\sqrt{LC}}\left(\frac{1}{\sqrt{1-\delta C/C}}\right) - 1$$

$$\therefore \quad \frac{\delta\omega}{\omega_o} = (1-x)^{-\frac{1}{2}} - 1 \qquad \text{where } x = \frac{\delta C}{C}$$

From the expansion series for (1 + x)n

$$(1 = x)^n + 1 + nx = \frac{n(n-1)x^2}{2!} + \frac{n(n-1)(n-2)x^3}{3!} + \ldots$$

$$(1-x)^{-\frac{1}{2}} = 1 + \frac{1}{2}x + \frac{\left(-\frac{1}{2}\right)\left(-\frac{3}{2}\right)x^2}{2} + \frac{\left(-\frac{1}{2}\right)\left(-\frac{3}{2}\right)\left(-\frac{5}{2}\right)(-x)^3}{6}$$
$$+ \frac{\left(-\frac{1}{2}\right)\left(-\frac{3}{2}\right)\left(-\frac{5}{2}\right)\left(-\frac{7}{2}\right)(-x)^4}{24} + \ldots$$

$$\therefore \quad \frac{\delta\omega}{\omega_0} = \frac{1}{2}x + \frac{3}{8}x^2 + \frac{5}{16}x^3 + \frac{35}{128}x^4 + \ldots$$

Let us see if it is possible to ignore terms in x^2 and above.

We will construct a table for different values of x.

x	$\frac{1}{2}x$	$\frac{3}{8}x^2$	$\frac{5}{16}x^3$	error in ignoring powers	
				±	%
0.1	0.05	0.00375	0.0003125	0.5406	8.13
0.05	0.025	0.0009375	0.000039	0.0259265	3.91
0.02	0.01	0.00015	0.00000025	0.0101525	1.53
0.01	0.005	0.0000375	0.0000003	0.0050378	0.756

The error becomes less than 1% when x is about 0.01 ie the ratio of C to δC is 100:1.

The circuitry and transducer dimensions have been chosen such that small changes of this magnitude are produced by both capacitance transducers.

So we can say that:

$$\frac{\delta\omega}{\omega_0} = \frac{1}{2}\frac{\delta C}{C}$$

With the inductive transducer, the μ_r of the core is very large. This means that variations of the position of the core will cause linear change in frequency.

If no heat were lost from the surface of the bar (eg because of perfect lagging), when steady conditions had been reached the temperature gradient would be constant; the temperature would fall steadily with increasing distance along the bar. In the case of an unlagged bar a portion of heat is lost from the surface, so that, proceeding from the heated end, progressively smaller quantities of heat are conducted along the bar. The value of the temperature gradient therefore becomes smaller. With reference to fig G1.

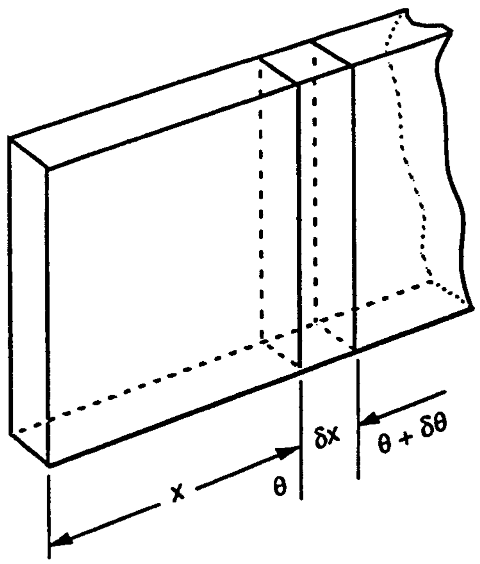


Fig G1

Let A = The cross-sectional area of the bar, assumed constant.

x = Distance along the bar.

θ = Temperature of the bar at distance x.

Q = Heat flow at distance x, ie the quantity of heat passing along the bar per second.

K = Thermal conductivity of the bar material, assumed constant.
(Where K is defined as the heat flow per unit cross-sectional area, per unit negative temperature gradient).

Considering the small length of the bar between x and x + δx, the temperature gradient is $\delta\theta \div \delta x$ and the heat flow per unit cross-sectional area is $Q \div A$ (approximately, since we are ignoring heat losses). So, allowing δx to become small (and thus removing the effect, of the heat losses) we can write the temperature gradient as $\theta \div x$. Therefore:

$$K = -\frac{Q \div A}{d\theta \div dx}$$

$$Q = -KA\frac{d\theta}{dx}$$

Suppose now that the flow alters from Q at distance x, to Q + δQ at distance x + δx. Provided δq and δx are small, then:

$$\delta Q = (dQ \div dx)\,\delta x$$

Equation 1

$$= -KA\frac{d^2\theta}{dx^2}\,\delta x$$

Now consider the losses from the bar by heat flow from the surface to the surroundings. Surface emissivity E is defined as the heat flow per unit surface area, per unit temperature difference between the surface and its surroundings. In the conditions of the experiments we may assume with sufficient accuracy that E is constant (as implied by Newton's proportional law of cooling). We again consider the small element of the bar between x and x + δx.

Let p = The surface perimeter of the section.

θ_a = The temperature of the surroundings.

Then the heat flow emitted from the surface element = $E(\theta - \theta_a)p\delta x$.

But this is equal to $-\delta Q$, so that, from Equation 1:

$$E(\theta - \theta_a)p\delta x = -KA\frac{d^2\theta}{dx^2}\,\delta x$$

Now, by dividing δx and re-arranging, we have:

$$\frac{E_p}{KA}(\theta - \theta_a) = \frac{d^2\theta}{dx^2}$$

Equation 2

or $$u^2(\theta - \theta_a) = \frac{d^2\theta}{dx^2}$$

where $u^2 = Ep/KA$.

A solution to Equation 2 is:

Equation 3

$$(\theta - \theta_a) = ae^{ux} + be^{-ux}$$

Where a and b are constants.

Equation 3 must be true no matter how long the bar is. If the bar is long enough, θ will approach θ_a as x increases. In the limit as x tends to infinity, the left-hand side of Equation 3 and e^{-ux} both tend to zero, while e^{ux} becomes large. The equation therefore becomes:

$$0 = ae^{ux} + 0$$

and $\therefore\ a = 0$.

If θ_o is the temperature at $x = 0$, it follows that:

$$\theta_o - \theta_a = 0 + be^{-uo} = b$$

$$\therefore\quad \theta - \theta_a = (\theta_o - \theta_a)\, e^{-ux}$$

This shows that the temperature along the bar decreases exponentially toward θ_a.

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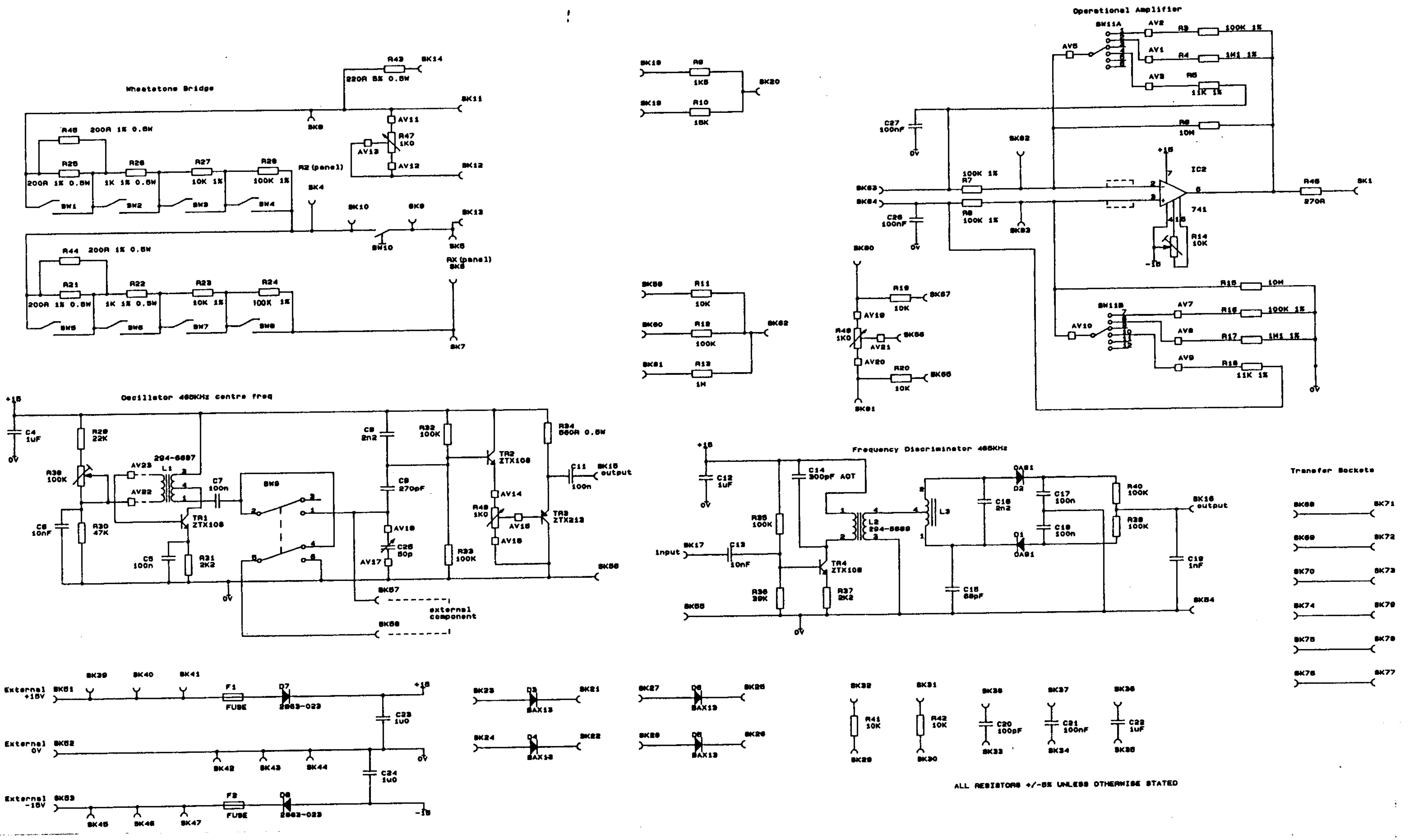

Fig H1 Instrumentation Module TK2941A (Drg No 2-2941A-14209 iss 3)

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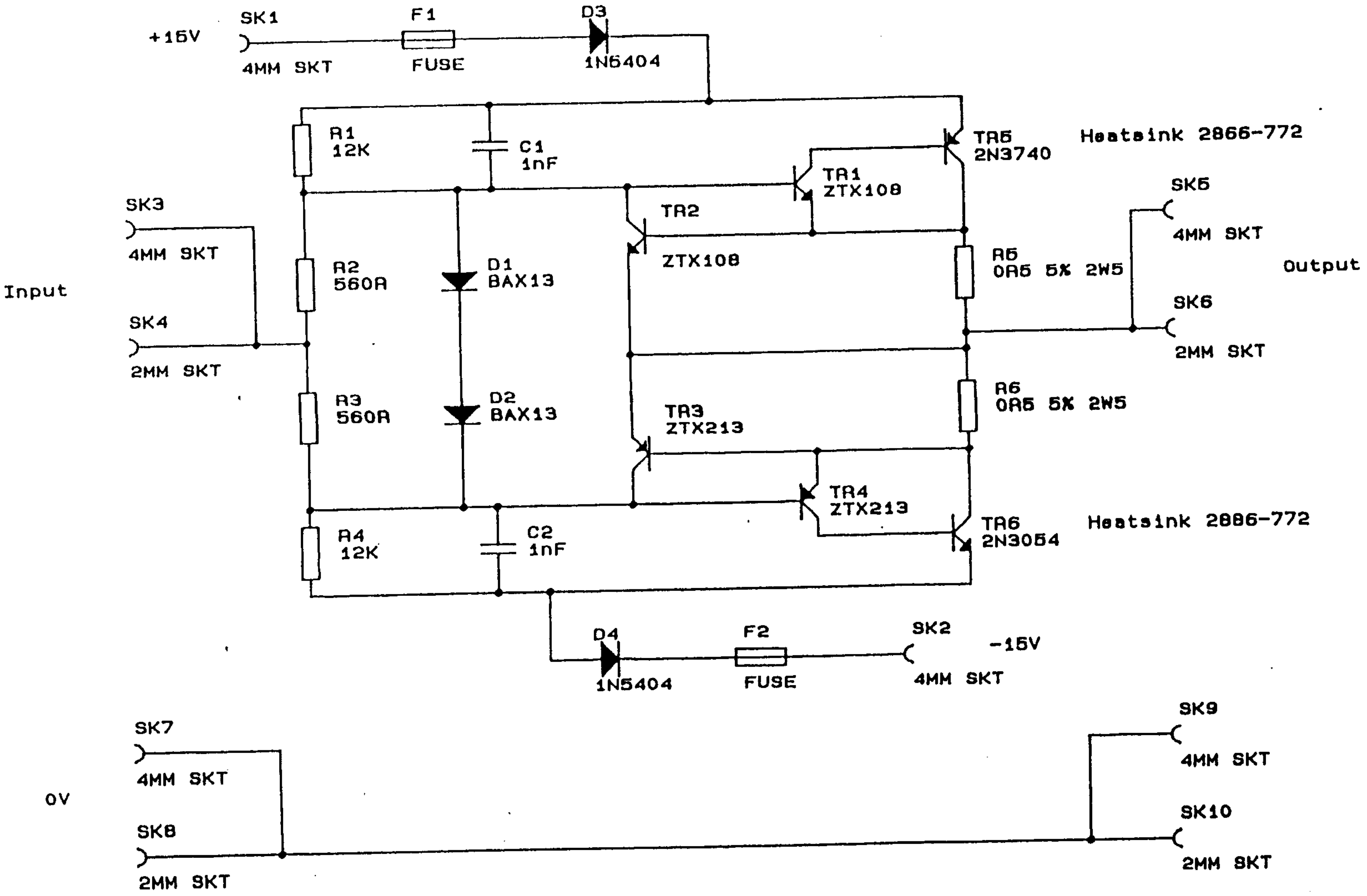

Resistors 5% 0W25 unless stated.

Fig H2 Power Amplifier TK2941B (Drg No 2-2941B-14411 iss 1)

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