Feedback

Analogue Servo Fundamentals Trainer

33-002

 Computer Assisted Learning

 Electricity & Electronics

 Control & Instrumentation

 Process Control

 Mechatronics

 Robotics

 Telecommunications

 Electrical Power & Machines

 Test & Measurement

Technology Training for tomorrow's world

ANALOGUE SERVO

FUNDAMENTALS TRAINER

33-002

Feedback

THE HEALTH AND SAFETY AT WORK ACT 1974

We are required under the Health and Safety at Work Act 1974, to make available to users of this equipment certain information regarding its safe use.

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.

While we provide the fullest possible user information relating to the proper use of this equipment, if there is any doubt whatsoever about any aspect, the user should contact the Product Safety Officer at Feedback Instruments Limited, Crowborough.

This equipment should not be used by inexperienced users unless they are under supervision.

We are required by European Directives to indicate on our equipment panels certain areas and warnings that require attention by the user. These have been indicated in the specified way by yellow labels with black printing, the meaning of any labels that may be fixed to the instrument are shown below:

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.

Any component may be ordered direct from Feedback or its agents by quoting the following information:

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.

CE   DECLARATION CONCERNING ELECTROMAGNETIC COMPATIBILITY

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.

COPYRIGHT NOTICE
© Feedback Instruments Limited

CONTENTS

CONTENTS

CONTENTS

NOTES

INTRODUCTION AND DESCRIPTION   **CHAPTER 1**

INTRODUCTION   The 33-002 Servo Fundamentals Trainer is intended to provide students with a sound introduction to the principles of analogue servomechanisms, and by extension to those of closed-loop systems more generally.

The 33-002 consists of 2 units:

■ Analogue Unit   33-110

■ Mechanical Unit   33-100

   which are connected as in fig 1.1, where dotted boxes represent essential additional items.

A Digital unit the 33-120 is available which allows the Mechanical unit, 33-100, to be used in conjunction with a computer. Feedback Discovery Software package 33-910 accompanies the Digital unit.
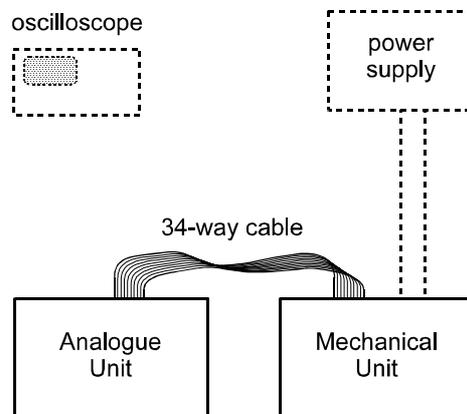
Fig 1.1 - Principal System Interconnections

INTRODUCTION AND DESCRIPTION   **CHAPTER 1**

EQUIPMENT	Qty	Designation	Description
	1	33-110	Analogue Unit
	1	33-100	Mechanical Unit, supplied with:
	1	–	34-way terminated cable
	1	–	Lead 600mm, 4mm plugs, 4-way
	14	–	Leads 200mm, 2mm plug
	6	–	Leads 400mm, 2mm plug
	3	–	Fuse 2A.

ANCILLARY EQUIPMENT

The following items of equipment are required in addition to the 33-002 trainer:

Qty Description

1 Power Supply Unit ±15V dc, 1.5A; +5V dc, 0.5A
   (eg Feedback DC Power Supply PS446 or 01-100)

1 Oscilloscope: Storage or long persistence, preferably with X-Y facility.
   (eg Feedback 1810-01229)

FAULTS

The 33-002 contains a number of switchable faults causing system malfunction and providing experience in fault finding. The faults are controlled by DIL switches on the analogue unit and the faults occur throughout the system. The relation between switch location and fault can be changed by a removable header under the unit panel. See Appendix A.

A fault is introduced by setting numbered switches to the ON (upwards) position.

Introduction and Description   **Chapter 1**

DESCRIPTION

**Mechanical Unit
33-100**

Contains a power amplifier to drive the motor from an analogue or switched input. The motor drives the output shaft through a 32:1 belt reduction. The motor shaft also carries a magnetic brake disc and an analogue speed transducer (tachogenerator). A two-phase pulse train for digital speed and direction sensing is also derived from tracks on the brake disc.

The output shaft carries analogue (potentiometer) and digital (64 location Gray code) angle transducers.

The unit contains a simple signal generator to provide low frequency test signals, sine, square and triangular waves, and requires an external power supply providing:

+15V, 0, −15V at 1.5A

+5V, 0, at 0.5A

The Feedback PS446 or 01-100 are suitable.

**Analogue Unit
33-110**

Connects to the Mechanical Unit through a 34-way ribbon cable which carries all power supplies and signals enabling the normal circuit interconnections to be made on the Analogue Unit using the 2mm patching leads provided. The unit enables a basic system as in fig 1.2 to be configured and contains facilities to introduce compensation to investigate improvement in overall system performance.
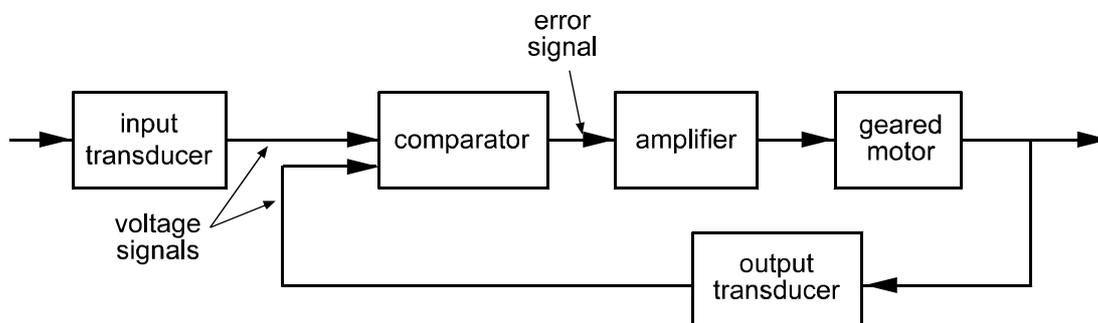
Fig 1.2 Analogue Control System

See Appendix C for details of the new numbering system and a minor change to the specification, introduced with the new numbers.

Introduction and Description   Chapter 1

33-002 SYSTEM

Analogue Unit (33-110)
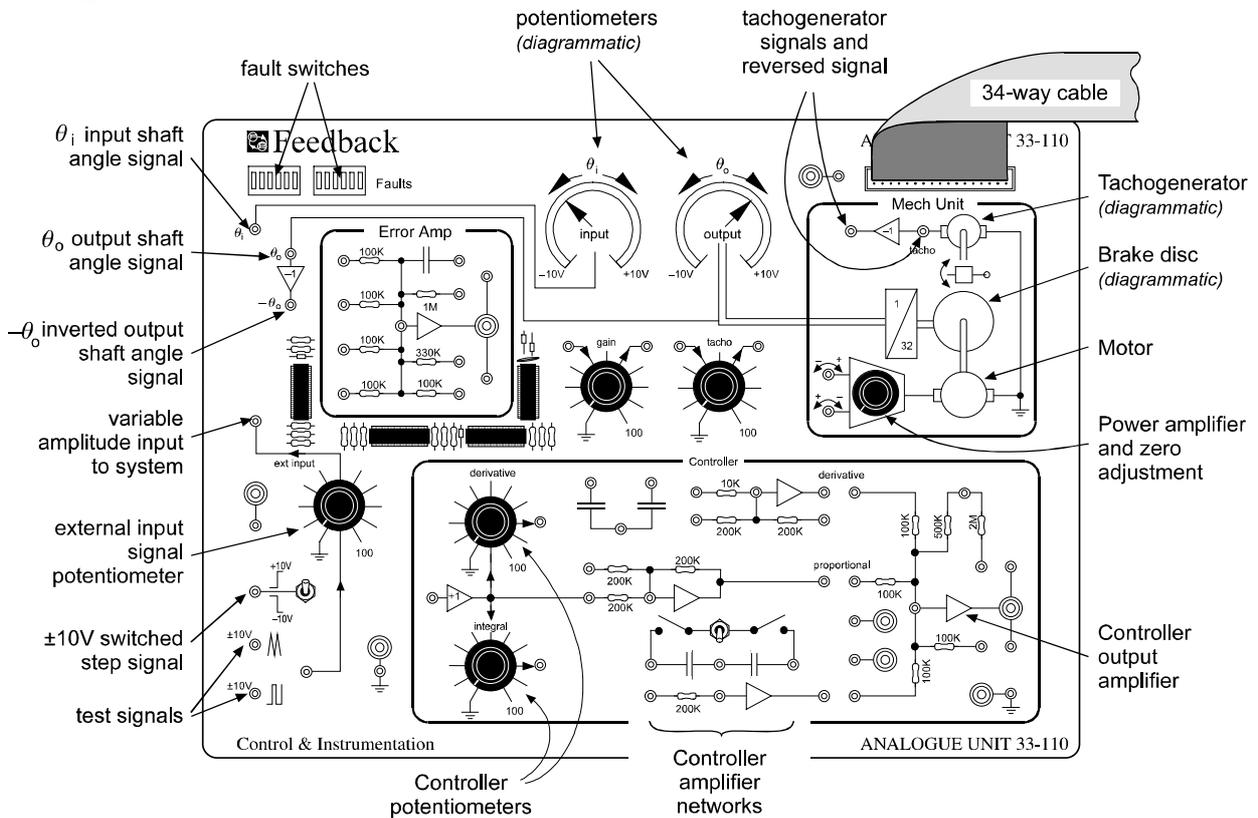
Fig 1.3 - The Analogue Unit

Fig 1.3 shows the general arrangement of the panel, interconnections are made by 2mm plug leads and there are a few 4mm sockets for conversion or oscilloscope connections.

Upper portion of panel from left to right

θ_i, θ_o These sockets give the voltage signals from the input and output shaft potentiometers. These are represented diagrammatically in the centre of the panel, the potentiometers themselves being in the Mechanical Unit.

$-\theta_o$ This socket provides a reversed output shaft signal required for certain applications.

Introduction and Description   Chapter 1

Fault switches	These enable faults to be introduced. For normal (no fault) operation all switches should be down.
Error Amplifier	This is used to combine potentiometer signals to provide the error.
Potentiometers P_1 and P_2	These provide system gain control and tachogenerator signal adjustment.
Power amplifier	This drives the motor. The two inputs drive the motor in opposite directions for a given input. The zero adjustment enables the motor to be rotated with no amplifier input.
Motor	This is in the Mechanical Unit and drives the brake disc and tachogenerator directly, and the output shaft through a 32:1 belt reduction.
Brake disc and magnet	These are in the Mechanical Unit and provide an adjustable load for the motor.
Tachogenerator	This is mounted on the motor shaft and provides a voltage proportional to motor speed; the voltage is available with reversed polarity.

Lower portion of panel from left to right

±10V step	This enables a manually switched 10V step input to be obtained.
Test signals	These sockets provide ±10V low frequency (nominally 0.1 to 10Hz) square and triangle waveforms. The frequency control and range switch are on the Mechanical Unit. A sine wave test input is available from the Mechanical Unit
External input potentiometer P_3	This can be linked to any input to provide an adjustable input to the error amplifier.
Controller	This contains operational amplifiers with associated networks to enable various compensating and control circuits to be introduced to improve the performance of a basic system.

Introduction and Description   Chapter 1

**Mechanical Unit
(33-100)**

Fig 1.4 shows the general arrangement of the panels. The unit is common to both Analogue and Digital systems. Since all signals, including supplies, for both units are available from the 34-way socket, the unit can be operated from any source of suitable signals connected to the 34-way socket.

For full details refer to Appendix B.

Power Supplies

External supplies of +15V and –15V at 1.5A and of +5V at 0.5A are required. The input sockets (4mm) are protected against accidental misconnection of supplies, though misconnection may blow a fuse.
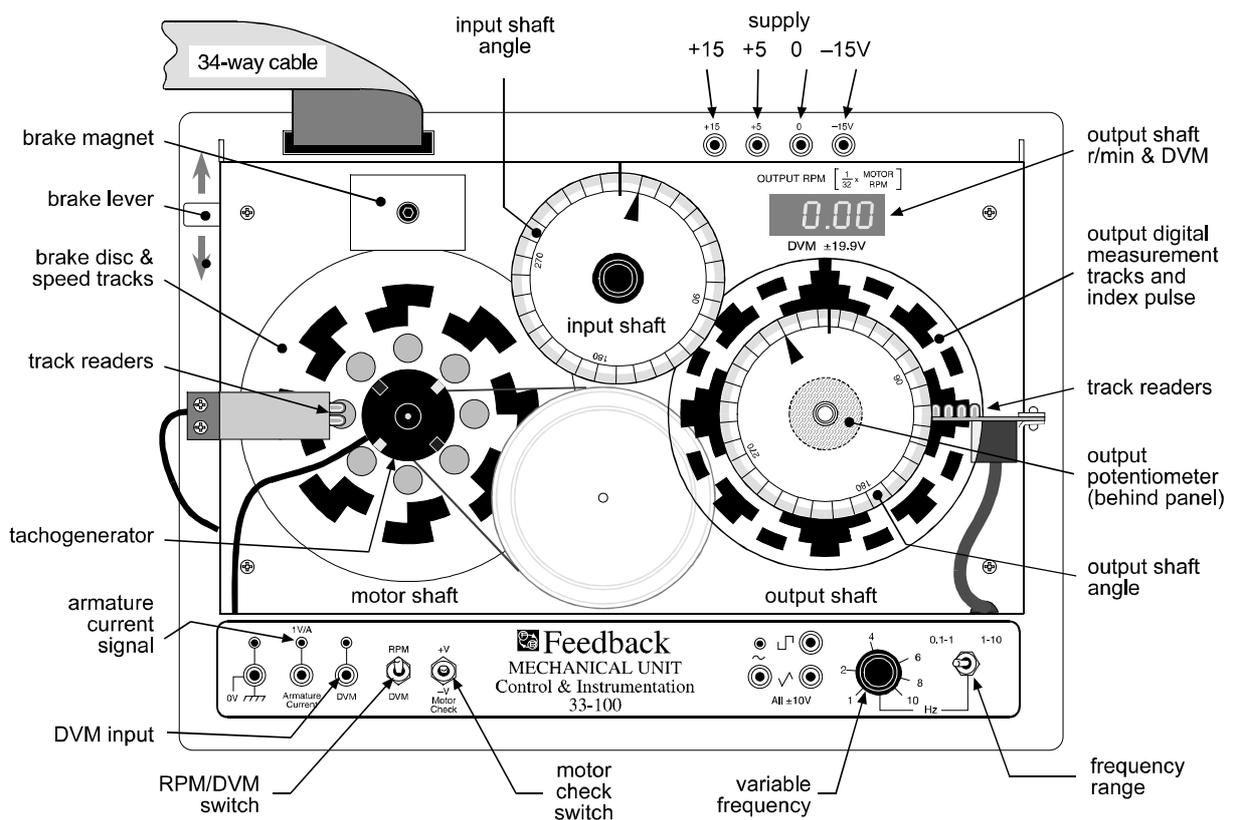
Fig 1.4 - Mechanical Unit

Introduction and Description   **Chapter 1**

Motor shaft	This carries the brake disc, together with a 2-phase speed track and tachogenerator.
Brake disc and magnet	The brake is applied by the lever projecting at the left. The lever scale is provided to enable settings to be repeated.
Speed tracks and readers	These provide two-phase, 0-5V square waves at 8 cycles per revolution. These signals are available on the 34-way socket but are not used in the Analogue system.
Motor check switch	This enables the motor to be rotated as an initial check. See initial check procedure in Chapter 2.
Armature current signal	This is a voltage waveform indicating the armature current with scale of 1V/A.
Input shaft	This carries the input potentiometer and scale and gives a signal θ_i in the range ±10V.
Test signal frequency and range switch	These control the internal oscillator to provide ±10V square, triangular and sine waveforms with nominal frequency 0.1 to 10Hz in two ranges. The square and triangular waveforms are connected to the 34-way socket.
Output shaft	This carries the output potentiometer and digital angular measurement tracks. The potentiometer provides θ_o in the range ±10V.
Digital measurement and readers	The digital tracks give 6 bit Gray code (64 locations) information and are read by infra-red readers. The 6-bit information is supplied as 0 or 5V to six pins on the 34-way socket.
Index pulse	At one pulse per revolution this provides an output shaft reference point for incremental control connected to a pin on the 34-way socket.
Output speed display	This provides a direct reading of output shaft speed in r/min in the range 00.0 to 99.9, derived from the tachogenerator. Since the reduction ratio is 32:1, a motor speed of 1000 r/min gives 31.1 r/min at the output shaft.

Introduction and Description   **Chapter 1**

**Display Facilities
Required**

Many results from the 33-002 Analogue System are presented as waveform displays on an oscilloscope, and since the responses are slow, perhaps taking 0.5 second or more, it is essential to have an oscilloscope with a long persistence screen or a storage oscilloscope.

Using a conventional double beam oscilloscope it is convenient to trigger the trace in synchronism with any test signal to obtain a repetitive display. In the 33-002 the trigger can be obtained from the square wave which is always available on the Mechanical and the Analogue Unit. If the oscilloscope has an external trigger facility this should be used so that the trace(s) remain synchronised with the Y input. The general arrangement would be as in fig 1.5(a).

Here it is assumed that the square waveform is being applied to the system and also to the EXT sync input, and a response is being displayed on Y_1. Another response could be displayed on Y_2. If the test frequency is changed the time base may require adjustment.
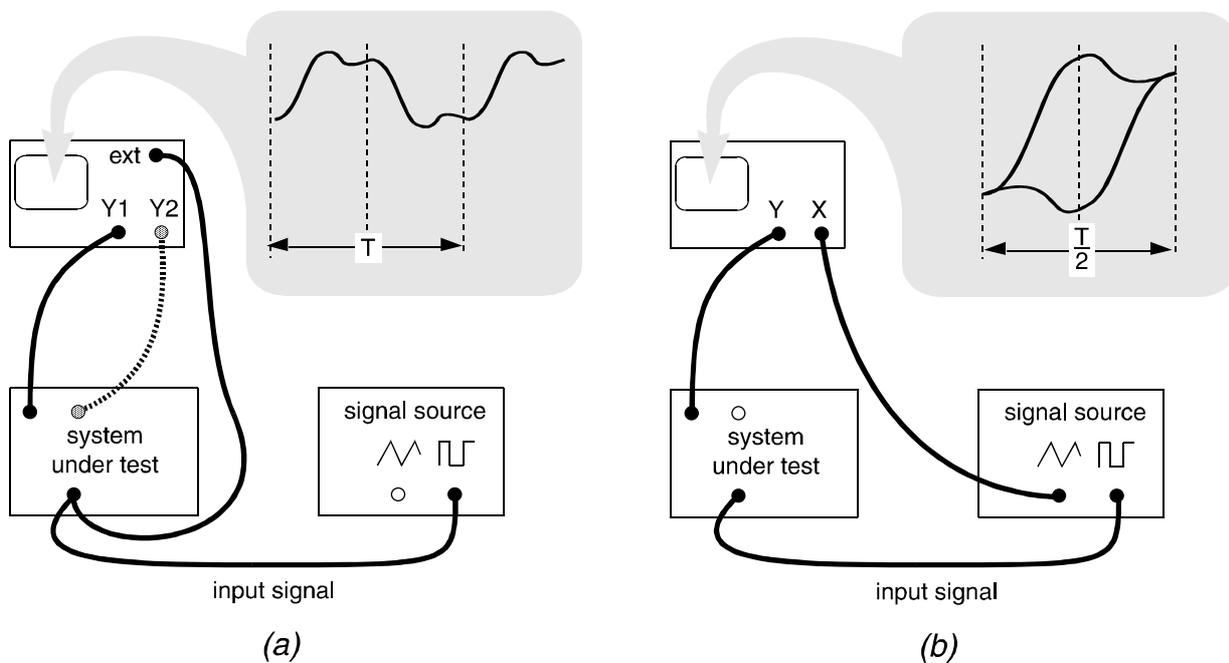
Fig 1.5 Alternative Forms of Oscilloscope Display.

If an X-Y oscilloscope is available, a very convenient form of display can be obtained as in fig 1.5(b). The X deflection is obtained from the triangle test signal waveform and hence the spot is deflected across the screen in time $\dfrac{T}{2}$, where T is the period of the square wave, and returns with a reversed scan of the same duration. Thus the display obtained is exactly as in (b), but a half cycle can be arranged to fill the screen by adjustment of the X gain. If the test frequency is changed the X deflection remains constant. Thus the display is always synchronised with the square wave and no adjustment is required.

Introduction and Description   **Chapter 1**

NOTES

INSTALLATION CHECKS

<div align="right">

CHAPTER 2

</div>
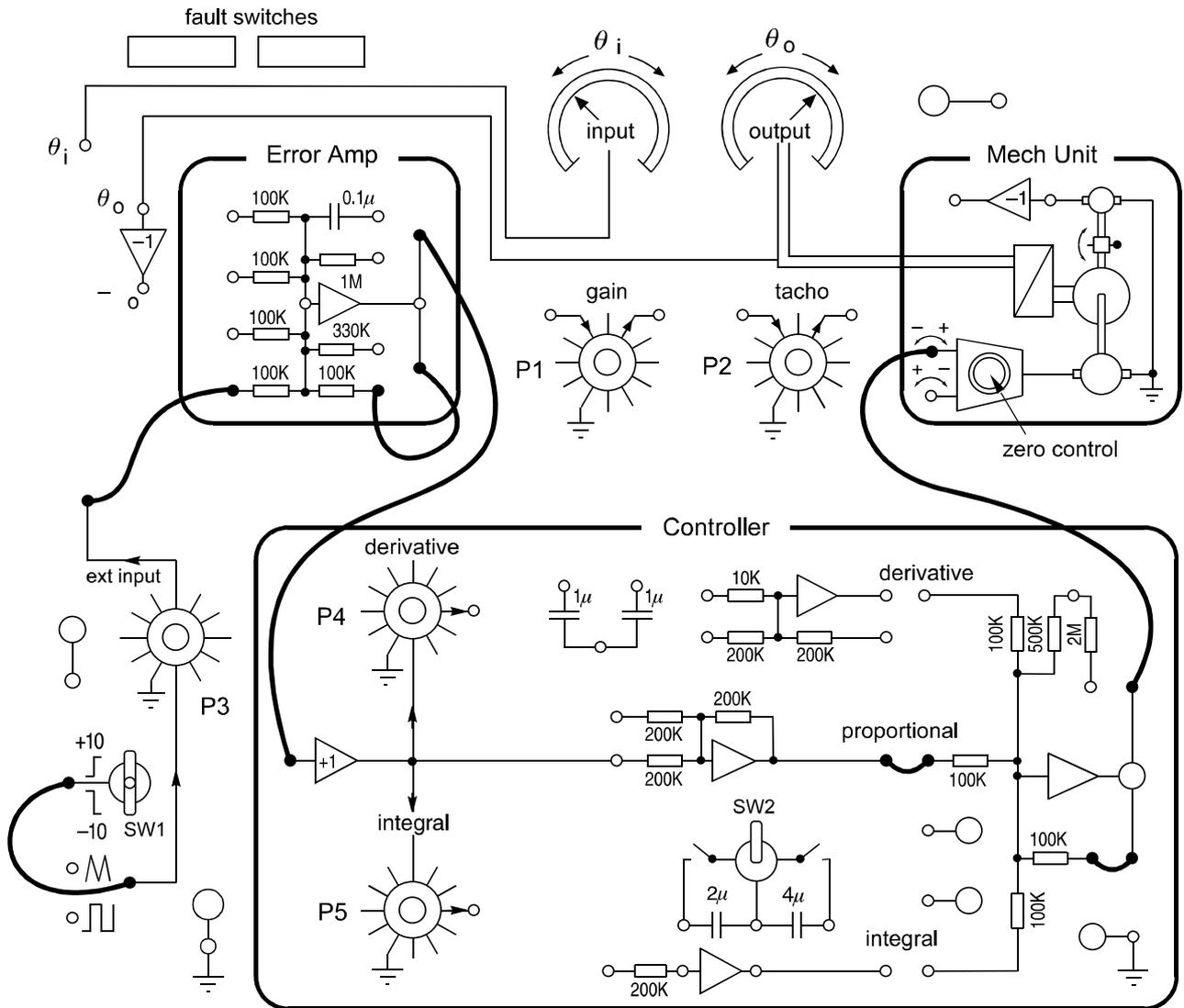
Fig 2.1 Connections for Testing the Analogue Unit.

INSTALLATION CHECKS   **CHAPTER 2**

Inspection   Check the units supplied for mechanical damage.

                          Check that the leads listed in the Equipment Section in Chapter
                          1 are all present.

                          In order to check that the equipment is operating satisfactorily,
                          the procedures on the following pages should be carried out.

Analogue System   Connect together the Analogue Unit 33-110 and the
                          Mechanical Unit 33-100 using the 34-way ribbon cable
                          supplied.

                          Connect the Mechanical Unit 33-100 to a suitable power supply
                          (Feedback Power Supply 01-100 recommended) using the
                          4mm lead provided.

                          The connections are:

Red	+15V
Orange	+5V
Black	0V
Blue	−15V

                          Ensure all of the fault switches on the Analogue Unit are off
                          (down).

                          Switch on the power supply.

                          The motor on the Mechanical Unit may revolve and the
                          speed/rpm display should light.

                          Adjust the power amplifier zero control to be found on the
   righthand side of the Analogue Unit. The motor should drive in
                          both directions, controllable by the zero knob. With the display
                          switch set to RPM the display should read the output shaft
                          speed in r/min.

                          Set the zero control so that the motor is stopped.

                          Set SW1 on the Analogue Unit to its centre position and the
                          'ext input' potentiometer, P3, fully anti-clockwise, then connect
                          up the Analogue Unit as shown in fig 2.1.

                          Switch SW1 to +10 and slowly increase P3. The motor should
                          drive and increase speed. Reset P3 fully anti-clockwise.

                          Switch SW1 to −10 and slowly increase P3. The motor should
                          drive in the opposite direction.

CLOSED-LOOP CONTROL SYSTEMS   CHAPTER 3

INTRODUCTION

What is an automatic control system?

This is a system in which we are controlling the state of a Process, say the width and thickness of strip being rolled in a steel mill. In setting up the system we need to know what the required width and thickness are, and to set up *reference* or input signals to represent these values. We are able, by means of transducers, to generate similar signals to represent the actual values at the output of the process. We can then compare the actual width and thickness of the strip produced with those required. The system must be able, if there is a difference or error, to send modifying signals to an Actuator, in this case the motor and gearing controlling the roller setting.

The closed-loop control system

The difference or *error* signal may be thought of as producing effects which move forward, from the point of comparison to the resulting action. The comparison itself depends on a signal which is *fed back* from the output of the process to be compared with the reference or input signal. The forward flow and *feedback* of signals form a loop around which information flows, fig 3.1. Such a system is therefore called a *closed-loop system.*

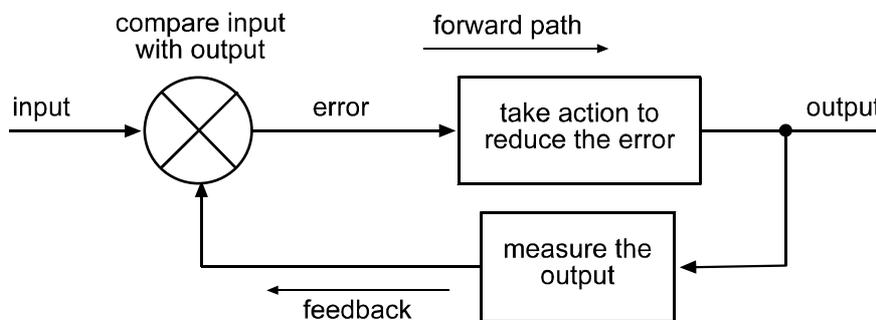*Fig 3.1. The Closed Control Loop.*

Various names are given to the signals in different industrial or other contexts, but the meanings of words in any one of the columns below are much the same:

input	output	difference
reference value	actual value	error
set value	measured value	deviation
setpoint	controlled quantity	
desired value		
demanded value		

Closed-loop Control Systems **Chapter 3**

Where the system is electrical, the state will normally be represented by signals expressed in volts; in our example it might be, for the width, a signal representing ten inches per volt. In this manual, the difference in the comparison will be called the *error* signal and the part of the system that carries out the comparison is the error channel.

There is usually a power amplifying device to drive the Actuator (which in fig 3.2 is the geared motor).

It is usual for control engineers to describe their systems in a block diagram form. The block diagram below describes the type of system we shall be using in the assignments. Here there is a comparison by the error channel of the input and output, the error is then amplified to drive a motor and gearing in the forward path so that the speed or position of the output shaft can be modified.
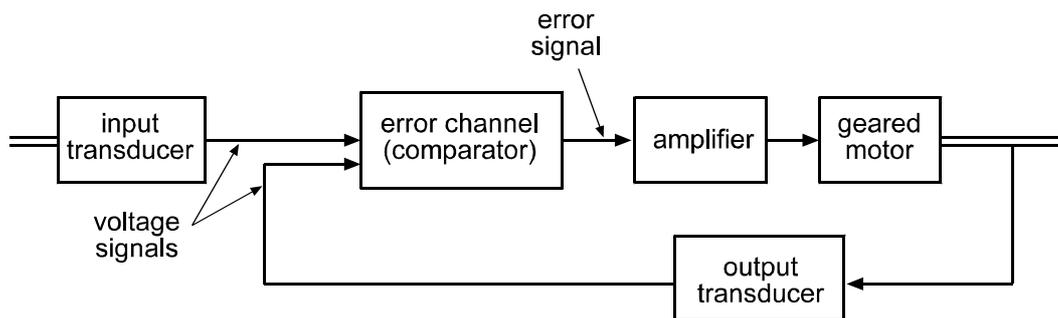
Fig 3.2. Block Diagram of an Analogue Closed-Loop System.

Analogue & Digital Systems

In the system of fig 3.2 it is assumed that the input and output are measured as voltages and lead to an error voltage which is amplified to operate the motor. This system has an analogue error channel since input and output are measured as continuous voltages.

However it is common practice to use digital techniques to generate the error signal in digital form, either by digitising the input and output by an analogue-to-digital (A/D) converter or by direct digital measurement techniques. The error signal is then processed in a computer to generate a digital signal to drive the motor. The motor may then be driven from a digital-to-analogue (D/A) converter or digitally by switching techniques.

Closed-loop Control Systems   **Chapter 3**

Thus the system may take the general form of fig 3.3.
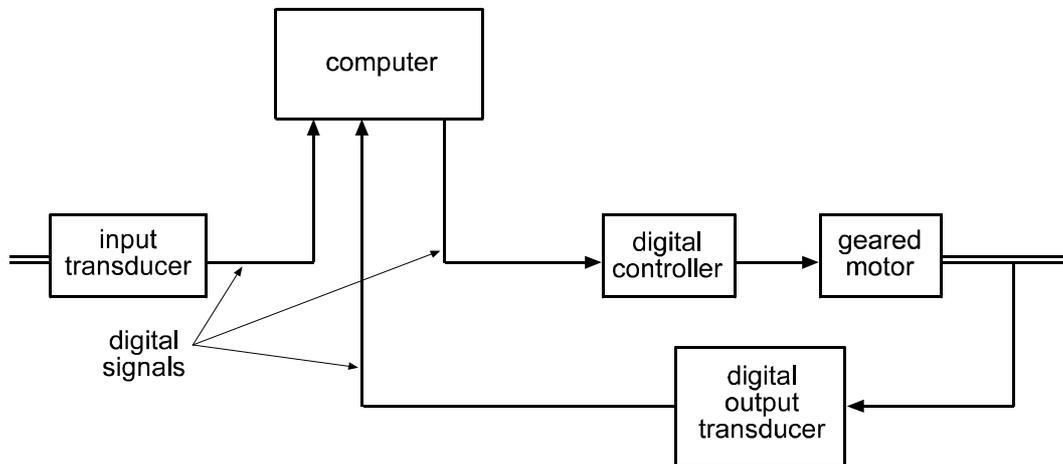
Fig 3.3. Block Diagram of a Digital Closed-Loop System.

The digitising of inputs may be within the system or in an internal computer interface. The computer-generated motor command will be digital and may be converted to analogue form in the computer interface or within the system. Alternatively the command may be used to drive the motor by a switching technique.

The Feedback Servo Fundamentals Trainer (33-002) provides facilities to investigate purely analogue systems as fig 3.2, or systems involving a range of digital techniques as fig 3.3. For the digital techniques it is necessary to use an IBM-compatible PC in which a Feedback interface unit has been installed, plus a Digital Board 33-120. The Assignments in this manual relate only to the analogue system. Assignments to investigate the digital system are provided as interactive Discovery software supplied with the 33-003 system.

NOTES

ASSIGNMENTS   **CHAPTER 4**

This chapter contains assignments which relate to the Analogue and Mechanical Units, which together form analogue control systems.

The assignments are:

1   Familiarisation

2   Operational Amplifier Characteristics

3   Motor, Tachogenerator and Brake Characteristics

4   Error Channel and Feedback Polarity

5   The Influence of Gain

6   Velocity Feedback

7   System Following Error

8   Unstable System

9   Speed Control System

10   Introduction to 3-Term Control

11   Application of 3-Term Control

12   Single Amplifier Control Circuits

13   Transient Velocity Feedback and
     Derivative Feedforward

14   Transfer Functions and Closed-loop
     Frequency Response Principles

15   Application of Frequency Response method
     to the 33-002 Control System

Assignments **Chapter 4**

NOTES

FAMILIARISATION   **ASSIGNMENT 1**

The following Practicals are included in this assignment:

1.1   Initial Mechanical and Analogue Unit check

1.2   To Display the Waveforms

1.3   To Display the Speed of Response of the Motor

FAMILIARISATION   **ASSIGNMENT 1**

FAMILIARISATION   **ASSIGNMENT 1**

CONTENT   The practicals in Assignment 1 provide some introduction to the
                     33-002 before more detailed investigations are carried out.

EQUIPMENT
REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A; +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810- 01229)*

FAMILIARISATION   **ASSIGNMENT 1**

OBJECTIVES   When you have completed this assignment you will:

ν   Realise that the 33-002 equipment comprises sub-systems
    which may be combined various ways to make control
    systems.

ν   Be familiar with two of the sub-systems, the Mechanical
    Unit and the Analogue Unit.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Have some experience of using an electric motor.

ν   Have some experience of handling electronic circuits.

ν   Know how to use an oscilloscope

**PRELIMINARY
PROCEDURE**   The Power Supply should be connected by 4mm-plug leads to
                         the +15V, +5V, 0V and –15V sockets at the back of the
                         Mechanical Unit.

Familiarisation
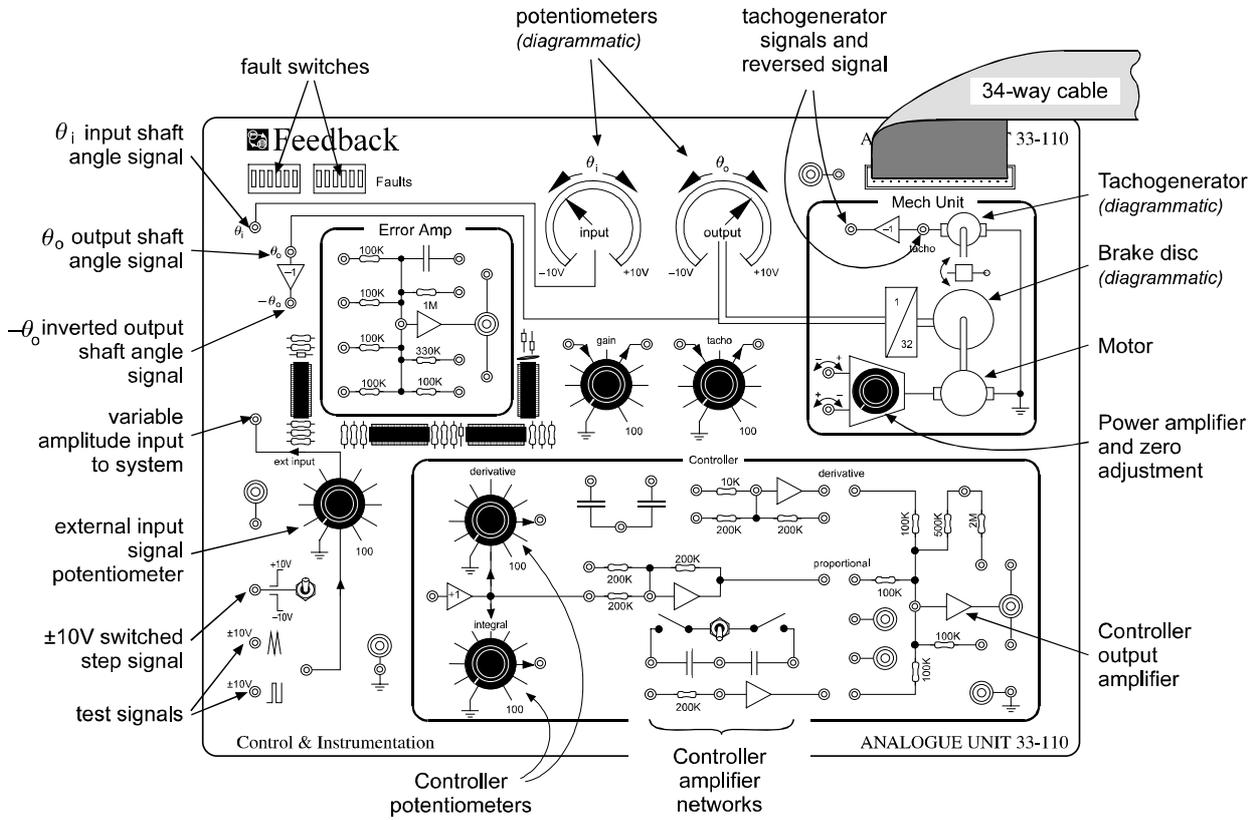
Assignment 1

Fig 4.1.1 - The Analogue Unit

Familiarisation   **Assignment 1**
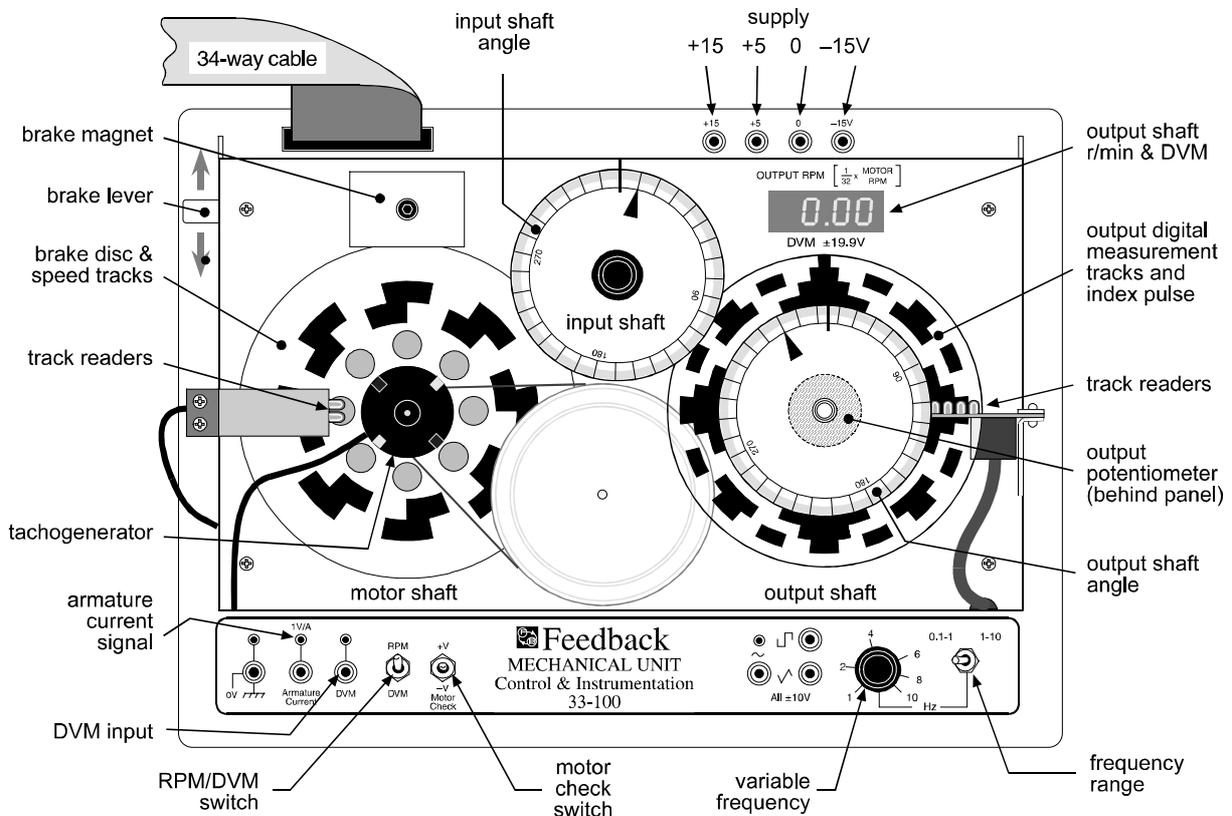
Fig 4.1.2 - The Mechanical Unit.

Initially examine the Mechanical and Analogue Units without making any connections and identify all items mentioned in figs 4.1.1 and 4.1.2. The digital facilities in the Mechanical Unit, speed and output tracks, will not be used with the Analogue Unit.

PRACTICAL 1.1

Initial Mechanical and Analogue Unit check

With the power supply switched OFF, connect its outputs to the Mechanical Unit.

Set the brake fully upwards.

The Analogue Unit should not be connected.

Switch the power supply ON.

The motor should remain stationary — there may be a slight movement when the supply is actually switched.

The output shaft speed display should show:

0.00

This indicates that the 5V supply is operating.

Hold the motor check switch to the right and the motor should run clockwise and the output speed display should indicate 15 to 25 rpm.

Hold the switch left and the motor should run anti-clockwise with approximately the same speed.

This test indicates that the ±15V supplies are operating.

Hold the check switch to one side and gradually lower the brake to maximum. The motor should slow down.

These tests indicate that Power Supply and Mechanical Unit are operating correctly.

Switch the power OFF.

Connect the Analogue Unit to the Mechanical Unit by the 34-way cable.

Raise the brake fully.

Switch the power ON.

Rotating the power amplifier zero adjustment should enable the motor to be driven in both directions up to about the same speed as before.

Zero the amplifier to stop the motor.

Overall the tests indicate that the system is working correctly.

Familiarisation **Assignment 1**

PRACTICAL 1.2

To Display the Waveforms

It is assumed that a suitable oscilloscope is available with:

EITHER

ν   A single Y channel or preferably two Y channels when used in conjunction with a time base, with …

ν   External sync input for the time base.

OR

ν   A facility for X-Y operation with X and Y both able to operate with a d.c input.

Test Waveforms

Connect the oscilloscope to the test signals using either the 4mm sockets in the Mechanical Unit or the 2mm terminals in the Analogue Unit.

Observe that the frequency may be varied between 0.1 and 1Hz or 1 and 10Hz.

System Waveforms

The system waveforms may be observed either from an externally triggered display against a timebase as shown in fig 4.1.3(a) or from an X-Y display as shown in fig 4.1.3(b). Signal source sockets are provided on the Mechanical Unit (4mm) and the Analogue Unit (2mm).
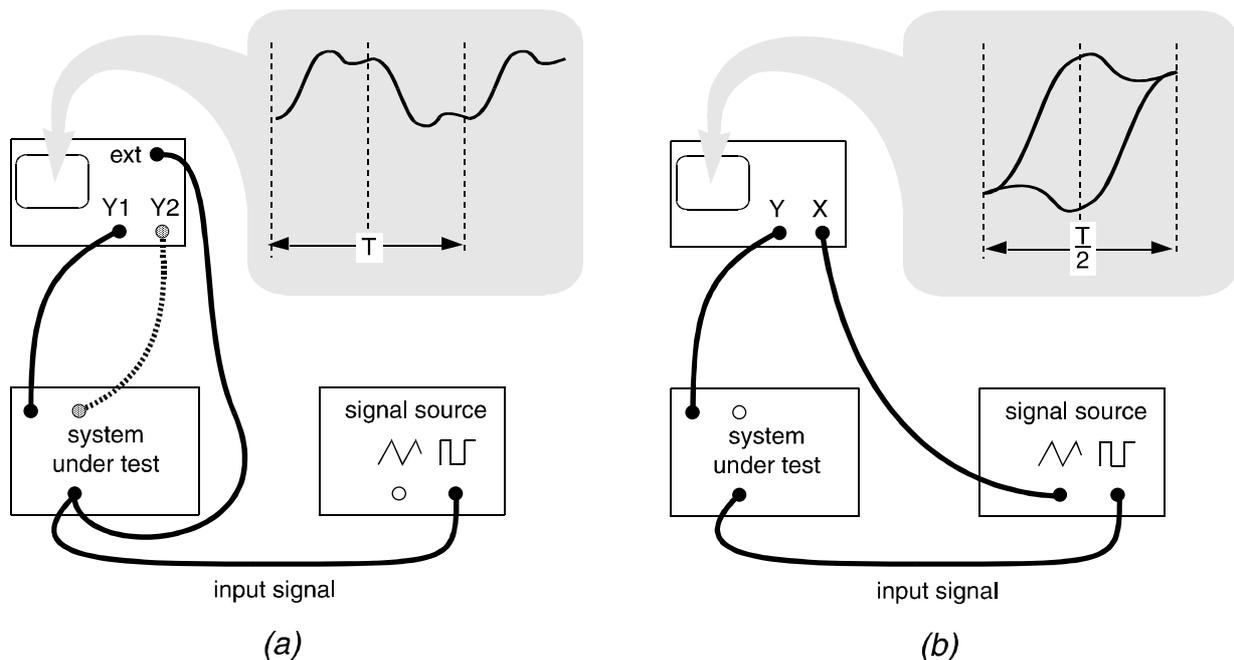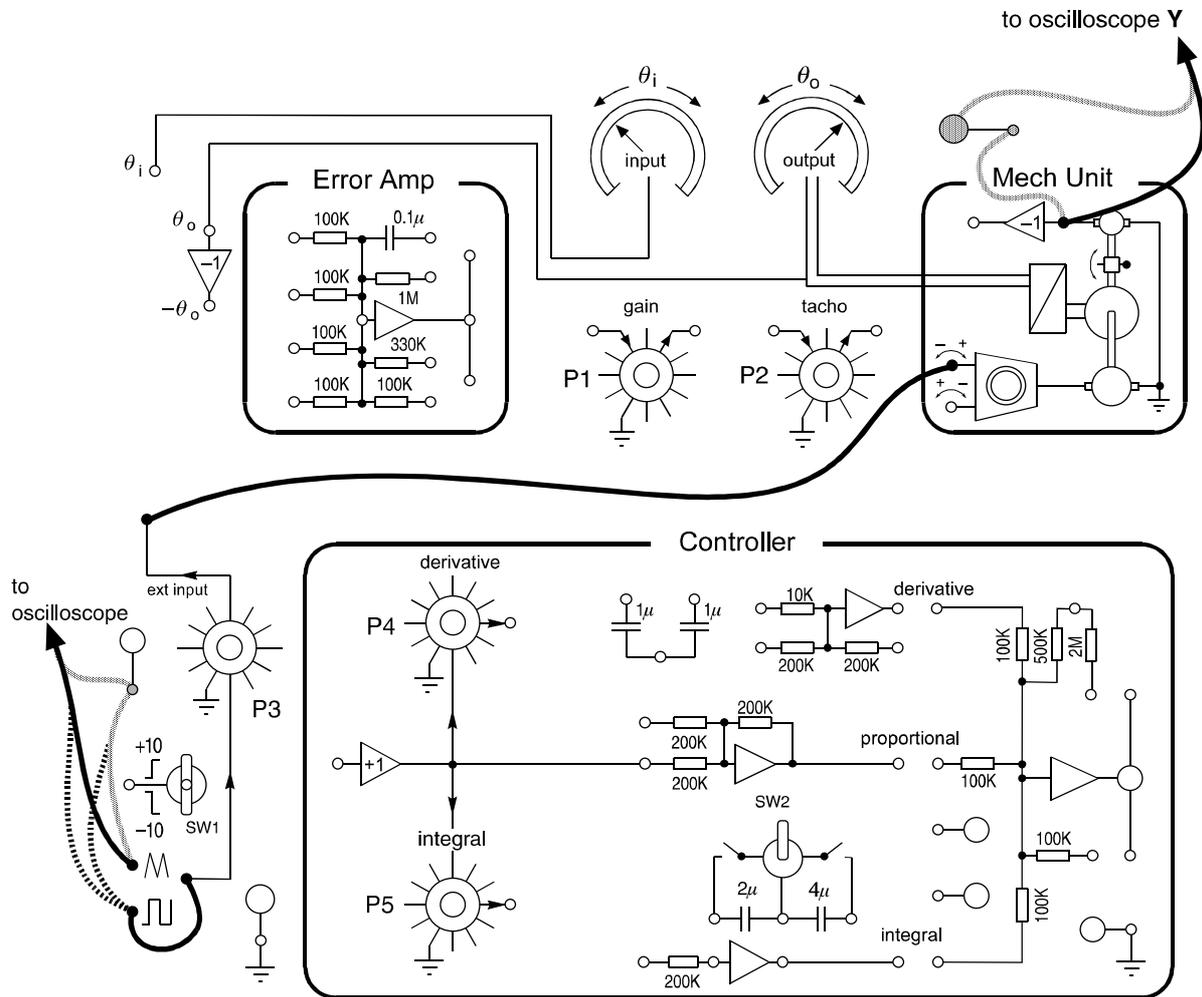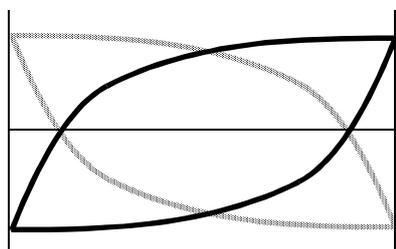

(a) *(b)*

Fig 4.1.3 - Oscilloscope Connections and Display

(a)

(b)
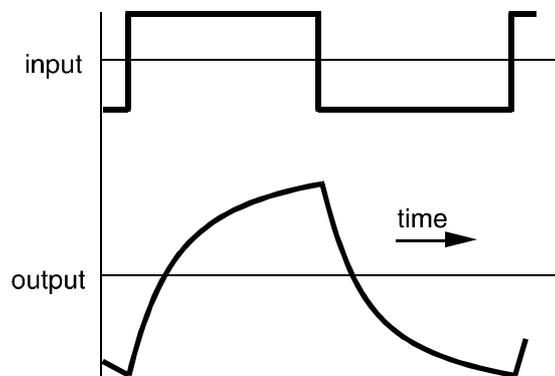
(c)

Fig 4.1.4 - Connections for Practical 1.3

Familiarisation   **Assignment 1**

PRACTICAL 1.3

To display the
Speed of Response
of the Motor   Set P_3 to zero and make the connections on the panel shown
                                    in fig 4.1.4(a).

                                    Connect the oscilloscope to the system using the selected
                                    method of display.

                                    If the oscilloscope input has a 4mm plug use the transfer
                                    socket as shown dotted.

                                    This arrangement enables the square wave test signal to be
                                    applied to the power amplifier when P_3 is adjusted.

                                    Set the test frequency to about 0.2Hz.

                                    Set P_3 to about 30.

                                    The motor should rotate in both directions, giving speed
                                    displays as in fig 4.1.4 (b), using an X-Y connection; or against
                                    a time base as in (c).

                                    Note that the X-Y connection may give either of the two
                                    displays shown in fig 4.1.4(b) depending on the oscilloscope in
                                    use.

                                    Examine the effect of increasing or decreasing the test
                                    frequency between 0.1 and 1Hz.

SUMMARY   This assignment has provided a general look at the basic
                                    features of the Analogue and Mechanical Units of the 33-002
                                    equipment.

PRACTICAL
ASPECTS   The last practical shows that there is a delay in the motor
                                    response to an input, which is due to the mechanical inertia of
                                    the armature. All motors exhibit this general characteristic,
                                    which has very important consequences for control system
                                    design. Special armature design can reduce the inertia greatly
                                    for small motors.

Familiarisation   **Assignment 1**

NOTES

OPERATIONAL AMPLIFIER CHARACTERISTICS   **ASSIGNMENT 2**

The following Practicals are included in this assignment:

2.1   Scaling, Summation and Virtual Earth

2.2   Addition of AC Signals

OPERATIONAL AMPLIFIER CHARACTERISTICS **ASSIGNMENT 2**

CONTENT

The characteristics of an operational amplifier are investigated and its application to analogue signal scaling and summation is examined.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A; +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810- 01229)*

OPERATIONAL AMPLIFIER CHARACTERISTICS   ASSIGNMENT 2

OBJECTIVES   When you have completed this assignment you will know:

ν   That an operational amplifier is a d.c amplifier providing a very high negative gain.

ν   That an operational amplifier is invariably used with feedback, the nature of which almost completely determines the amplifier's behaviour.

ν   That operational amplifiers may be used to provide scaling of analogue signals and/or summation of several such signals.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Have completed Assignment 1, Familiarisation.

ν   Understand the general function of an amplifier.

**PRELIMINARY
PROCEDURE**   The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.

Operational Amplifier Characteristics   **Assignment 2**

INTRODUCTION   In the general diagram of a control system, fig 3.1 in Chapter 3, the signals – commonly voltages – are compared to produce a difference or error signal to operate the motor.

This process can be carried out very conveniently by an amplifier circuit termed an **operational amplifier** since the circuit can carry out precise mathematical **operations** on voltages. The general arrangement of an operational amplifier is given in fig 4.2.1(a).
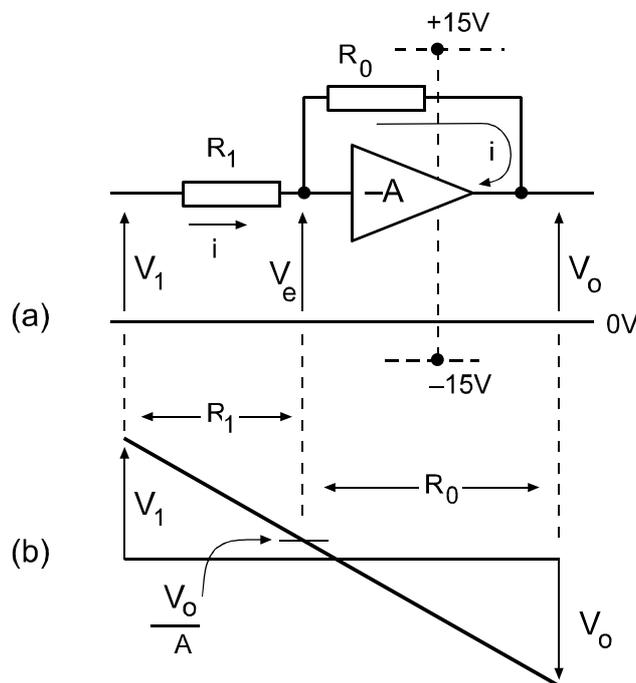

Fig 4.2.1 - Operational Amplifier Circuits

The amplifier has negative gain. That is, (if the resistors are ignored) a positive V_e gives a negative V_o and vice versa. In symbols:

$$V_o = -AV_e$$

If V_1 is considered to move positive, V_e tends to move positive and hence V_o to move negative as illustrated in fig 4.2.1 (b).

The essential principle of the circuit is that the same current i must flow in both R_1 and R_0 since the amplifier has an almost infinitely high input impedance and thus draws virtually no current. This means that if V_1 is applied, V_o will automatically take such a value that the current i is drawn off through R_0 and into the amplifier.

Operational Amplifier Characteristics   **Assignment 2**

Thus V_e will have a small positive value

$$V_e = \frac{V_o}{A}$$

where V_o is the magnitude of the output. The overall situation is illustrated in fig 4.2.1(b), where the sloping line represents the voltage to ground moving along R_1 and R_o from V_1 to V_o.

Scaling

If A is very large, the order of 10^4 to 10^6, the voltage V_e is quite negligible compared with V_1 and V_o, and can be considered as zero. Hence

$$i = \frac{V_1}{R_1}. \quad \text{Also } i = \frac{-V_o}{R_o}.$$

$$\therefore V_o = -V_1 \frac{R_o}{R_1},$$

where V_o is reversed in sign with respect to V_1, but multiplied by a ratio determined **only** by R_o and R_i. This process of multiplication by a constant is termed **scaling** and is a very important concept.

In operation as V_1 varies then V_o varies correspondingly, depending on the ratio R_o/R_1. If V_1 is reversed then V_o changes sign but the voltage distribution along R_1 and R_o remains a sloping straight line pivoting about the amplifier input point with V_e effectively zero. Thus the overall behaviour is similar to a 'see-saw' and the diagram is sometimes termed the **see-saw** diagram.
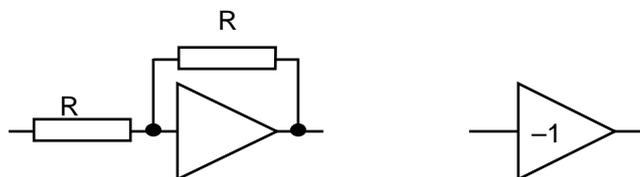
Inverter

Fig 4.2.2 - Inverter

If $R_o = R_1$, then the scaling factor becomes −1 and we have a 'sign reverser' or inverter used to change the sign of a voltage. There are two examples in the Analogue Unit, one associated with the tachogenerator (top right) and another with the output shaft angle θ_o (top left).

Operational Amplifier Characteristics

Note two levels of simplification of the circuit diagram which are commonly applied:

ν The earth line is not shown, since no, or very few, connections are made to it from the feedback network.

ν An inverter may be simply shown as an amplifier symbol with '−1' written inside it.

Virtual Earth Point

Since the signal V_e at the resistor junction and the amplifier input is substantially zero, this point is called a **virtual earth point**, and enables the overall circuit to give an output which is the sum of several inputs. This is a very important and useful property of operational amplifier circuits.
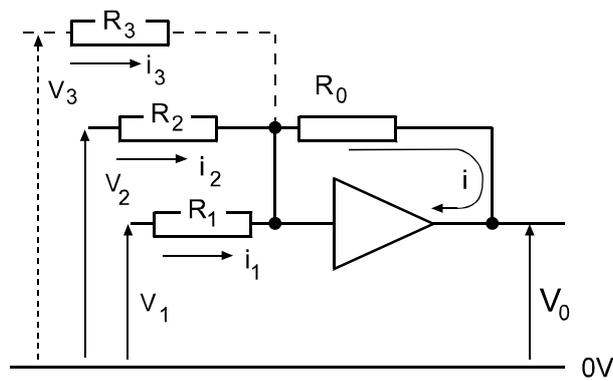

Fig 4.2.3 - Summing Amplifier

Summing

If two separate inputs are applied as in fig 4.2.3, the output V_o will take such a value that the current drawn through R_o exactly equals the sum of the input currents i_1 and i_2, that is

since $i_o = i_1 + i_2$,

$$\therefore V_o = -V_1 \frac{R_o}{R_1} - V_2 \frac{R_o}{R_2}$$

$$= -\left(V_1 \frac{R_o}{R_1} + V_2 \frac{R_o}{R_2} \right),$$

showing that the output is the **sum** of V_1 and V_2 (with reversed sign) each with a scaling factor. If all resistors are equal then:

$$V_o = -(V_1 + V_2),$$

giving direct addition.

Since the virtual earth point or **summing junction** is substantially at zero potential more resistors can be added, such as R_3 shown dotted. Each such resistor R_n will make a further contribution $V_n \dfrac{R_0}{R_n}$ to the current in R_o, so that

$$V_o = - V_1 \frac{R_o}{R_1} - V_2 \frac{R_o}{R_2} - V_3 \frac{R_o}{R_3} - \cdots$$

$$= - \left(V_1 \frac{R_o}{R_1} + V_2 \frac{R_o}{R_2} + V_3 \frac{R_o}{R_3} - \cdots \right).$$

This can be expressed alternatively as

$$V_o = - R_o \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots \right)$$

showing that various voltages can be adjusted in relative proportion by the input resistances R_1… before being added, while R_o acts as a common 'gain control' to alter the scale of the result of the summation.

This introduction has summarised important properties of operational amplifiers which are used in the 33-002 and analogue control systems generally.

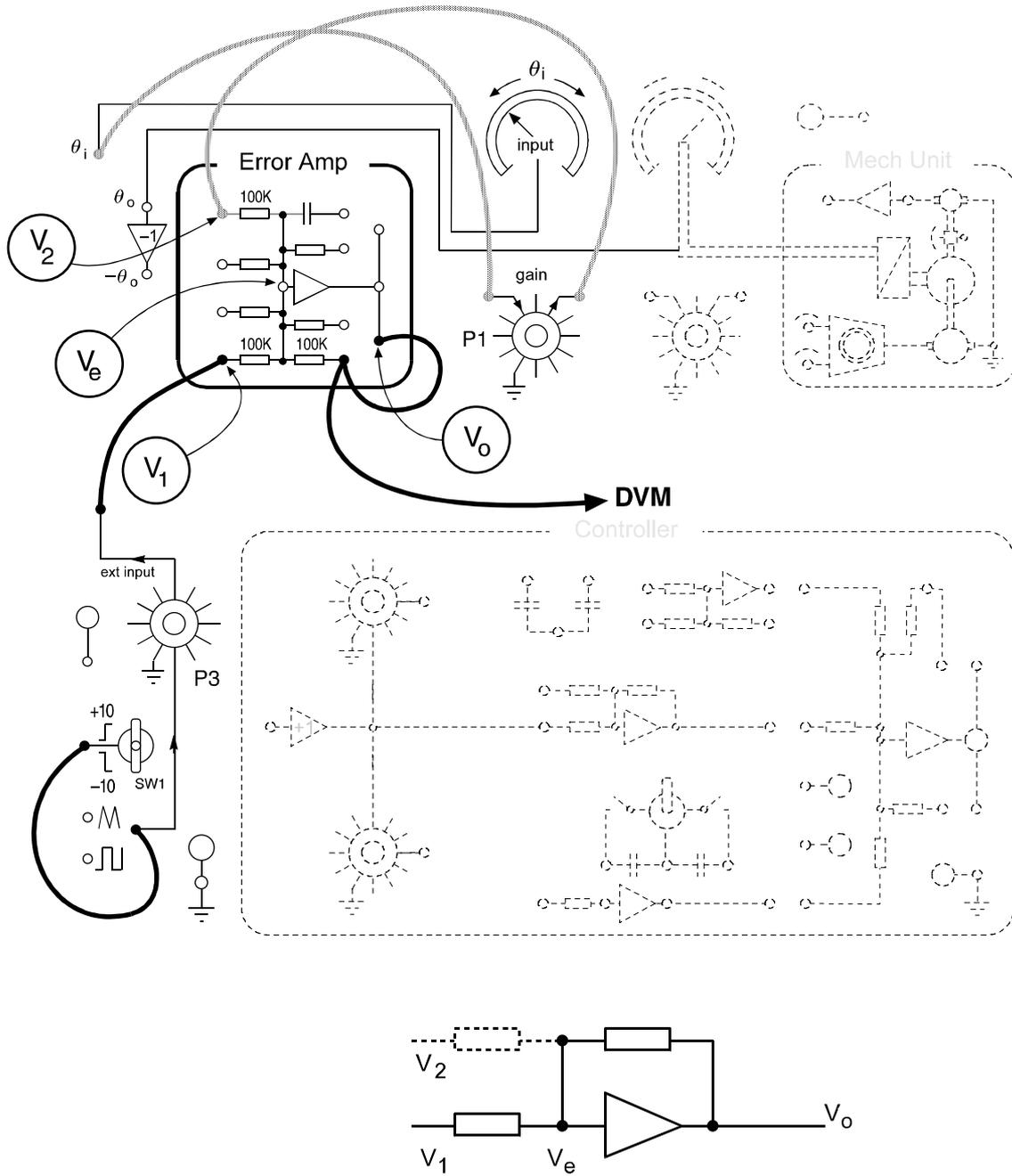# Operational Amplifier Characteristics

Assignment 2

Fig 4.2.4 - Connections for Practical 2.1

Operational Amplifier Characteristics   **Assignment 2**

PRACTICAL 2.1

**Scaling, Summation
and Virtual Earth**

The error signal amplifier a1 in the 33-002 is an operational amplifier with a selection of input resistors R_1 . . . R_4, all of 100kΩ, and feedback resistors of 100kΩ, 330kΩ, 1MΩ.

With power OFF connect the Error Amp as shown in fig 4.2.4, ignoring for the moment the connections shown as shadow lines, and set P_3 to zero. Connect the DVM to the output of the Error Amp.

Switch the power ON.

The voltmeter should read zero.

Set SW1 to +10V and turn up P_3 to 100.

The voltmeter should indicate approximately −10V.

Connect the voltmeter to measure V_e; the voltage should be substantially zero.

Vary P_3 from 0-100 and note that any change in V_e represents the input signal required to drive the amplifier.

Reconfigure the feedback resistor to 330K and set P_3 to give $V_1 = 3V$.

V_o should now be approximately −10V since $R_o/R_l = 3.3$.

Increase V_1 to 10V and the amplifier output will **limit** (refuse to change further) at about − 12 to − 13V.

These tests have demonstrated the general performance of an operational amplifier.

To investigate summation it is convenient to have two adjustable dc signals. A separate signal can be obtained from the input potentiometer on the Mechanical Unit which is internally connected between ±10V and can provide a variable voltage at the θ_i socket.

Set the gain potentiometer, P_1, and P_3 to zero. Reconfigure the feedback resistor R_o to 100K and add the connections shown as shadow lines fig 4.2.4.

Check that rotating the input potentiometer in the Mechanical Unit gives up to about ±10V at the θ_i socket.

Operational Amplifier Characteristics   Assignment 2

Set V_1 to +5V and V_o should be –5V.

Set V_2 to +5V and V_o should be –10V, that is:

$$V_o = -\,(V_1 + V_2)$$

Check that various combinations of V_1 and V_2, some with opposite polarities, give the expected value of V_o. Note that nominal ±10V is regarded as the maximum working output of the amplifier.

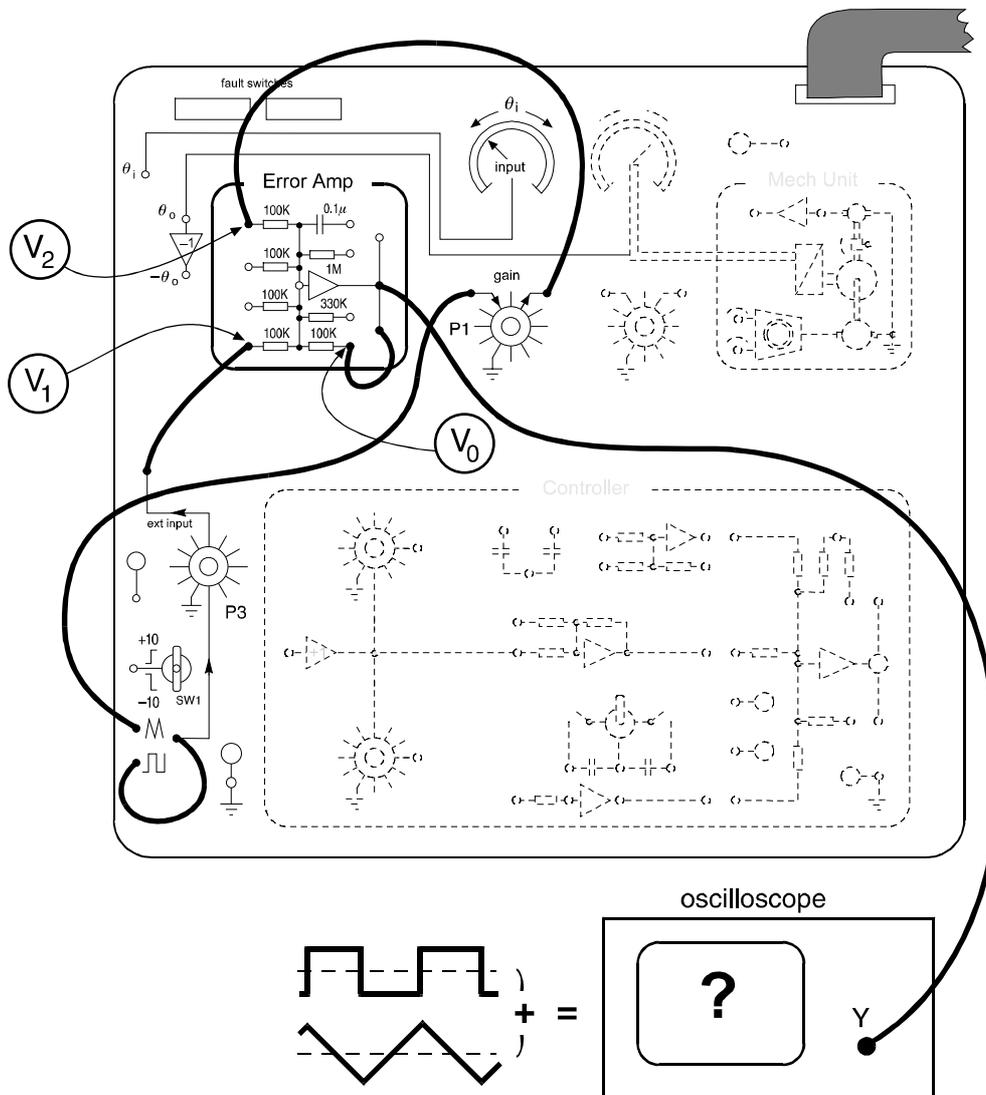These results have demonstrated the use of an operational amplifier as a summer.

Fig 4.2.5 - Connections for Practical 2.2

Operational Amplifier Characteristics   **Assignment 2**

PRACTICAL 2.2

**Addition of
a.c Signals**

The previous practical used d.c signals but the same amplifier principles apply with a.c signals. Two a.c signals are available from the test signal generator in the Mechanical Unit, at the sockets below P_3.

Set P_1 and P_3 to zero and make the connections shown in fig 4.2.5.

Set the frequency to 10Hz and arrange to display the output V_o.

If P_1 and P_3 are adjusted separately, in turn, the individual waveforms will be displayed.

Then set P_1 and P_3 to 50 and decide whether the displayed V_o is correct for the addition of both signals.

Slightly increase P_1 and P_3 and note that the waveform peaks limit as the amplifier is being momentarily overloaded.

The results indicate that it is very important to consider the full range of possible output when a.c signals are being added.

Operational Amplifier Characteristics   **Assignment 2**

SUMMARY

An operational amplifier is a d.c amplifier having a gain which is very large and negative.

An operational amplifier is always used with external components which apply feedback around the amplifier. These almost entirely determine the amplifier's behaviour.

If the gain is sufficiently high (which it usually is) the amplifier's input terminal will always be kept at nearly zero potential, which is called a **virtual earth**.

It is possible to apply several inputs, each via a separate resistor. The amplifier with these resistors and the feedback resistor connected to the virtual earth forms a **summing amplifier**. Because of this the input terminal of the amplifier is also referred to as a **summing junction**.

PRACTICAL ASPECTS

It has been assumed that the gain of the amplifier is so high that its input voltage V_e is always reduced to zero by the feedback process. In practice, unbalance between components in the amplifier may cause its output to go to zero for some non-zero value of V_e. This will have the same effect as adding a spurious input to a perfect amplifier, so that the output will be offset. A **zero adjustment** is often provided where this effect is likely to be serious.

**MOTOR, TACHOGENERATOR AND BRAKE
CHARACTERISTICS**   **ASSIGNMENT 3**

The following Practicals are included in this assignment:

3.1   Steady-State Characteristics

3.2   Steady-State Characteristics – Brake Load

3.3   Transient Response of Motor

3.4   Motor Time Constant

**MOTOR, TACHOGENERATOR AND BRAKE
CHARACTERISTICS**   **ASSIGNMENT 3**

CONTENT   The steady and transient characteristics of the motor are
examined, and the dependence of brake torque on setting and
speed is investigated.

**EQUIPMENT
REQUIRED**

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A; +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810- 01229)*

**MOTOR, TACHOGENERATOR AND BRAKE
CHARACTERISTICS**   **ASSIGNMENT 3**

OBJECTIVES   When you have completed this assignment you will know:

ν   That the steady speed of the motor is ideally proportional to
the applied voltage, less an amount proportional to load
torque.

ν   That a d.c tachogenerator provides a signal representing
speed, independent of motor loading.

ν   That the response of the motor to a change of input is not
immediate, but may be expressed as a time constant.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Have completed Assignment 1, Familiarisation.

ν   Understand simple applications of operational amplifiers,
preferably through completing Assignment 2, Operational
Amplifier Characteristics.

**PRELIMINARY
PROCEDURE**   The Analogue Unit and Mechanical Unit should be connected
together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to
the +15V, +5V, 0V and −15V sockets at the back of the
Mechanical Unit.

Motor, Tachogenerator and Brake
Characteristics   **Assignment 3**

INTRODUCTION   The motor and tachogenerator were used in Practical 1.3 to display the speed response characteristics as part of the general familiarisation in Assignment 1. In the present assignment a more detailed and wider investigation is carried out.

The motor is a permanent magnet type and can be represented in idealised form as in fig 4.3.1(a), where R_a is the armature resistance and T_1, T_2 are the actual motor terminals.

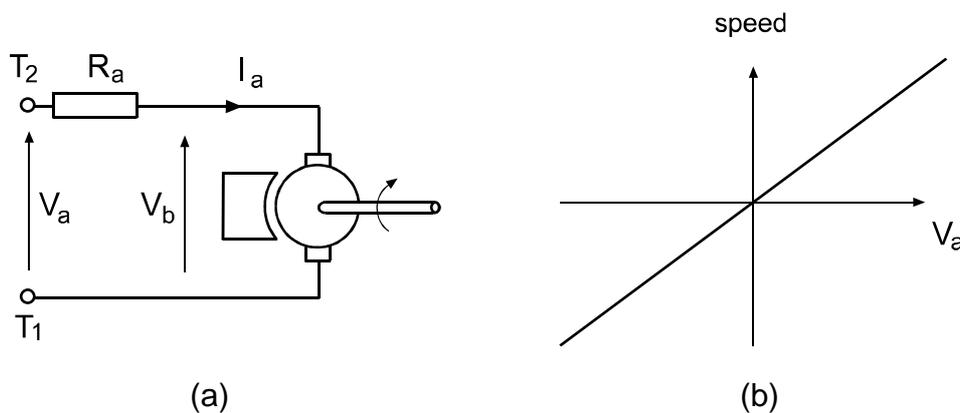(a)   (b)

Fig 4.3.1 - Representation of a Motor in terms of an Ideal Motor.

If the motor is stationary and a voltage V_a is applied, a current I_a flows which causes the motor to rotate. As the motor rotates a back emf V_b is generated. As the motor speeds up — remember the general characteristics obtained in Practical 1.3 — the back emf increases and I_a falls. In an ideal (loss free) motor, the armature current falls to substantially zero and V_b approximately equals V_a. Thus if V_a is varied slowly in either polarity, the motor speed is proportional to V_a, and a plot of motor speed against V_a would have the form of fig 4.3.1(b).

In the 33-100 the armature voltage V_a is provided by a power amplifier. A power amplifier is necessary, because although the voltages in the error channel may be of the same order as V_a, the motor current may be up to 1A, while the error channel operates with currents of less than 1mA and could not drive the motor directly. The amplifier has two input sockets, enabling the motor rotation direction to be reversed for a given input.

The tachogenerator is a small permanent magnet machine and hence when rotated produces an emf proportional to speed which can be used as a measure of the rotation speed.

The magnetic brake consists of a permanent magnet which can be swung over an aluminium disc. When the disc is rotated eddy currents circulate in the area of the disc within the magnet gap, and these react with the magnet field to produce a torque which opposes rotation. This gives an adjustable torque speed relation of the form of fig 4.3.2, and provides a very convenient load for the motor.
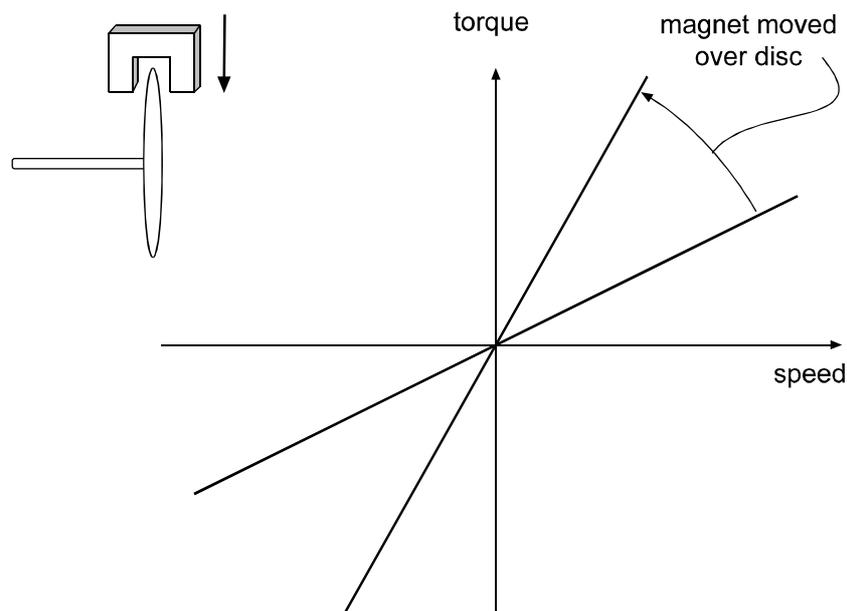
Fig 4.3.2 - Characteristic of Magnetic Brake

The overall characteristics of a motor may be considered from two aspects, both of which can be related to the idealised representation of fig 4.3.1(a). These aspects are:

ν   Steady-state, which are concerned with constant or very slowly changing operating conditions, and

ν   Transient, corresponding with sudden changes.

Both are important in control system applications.

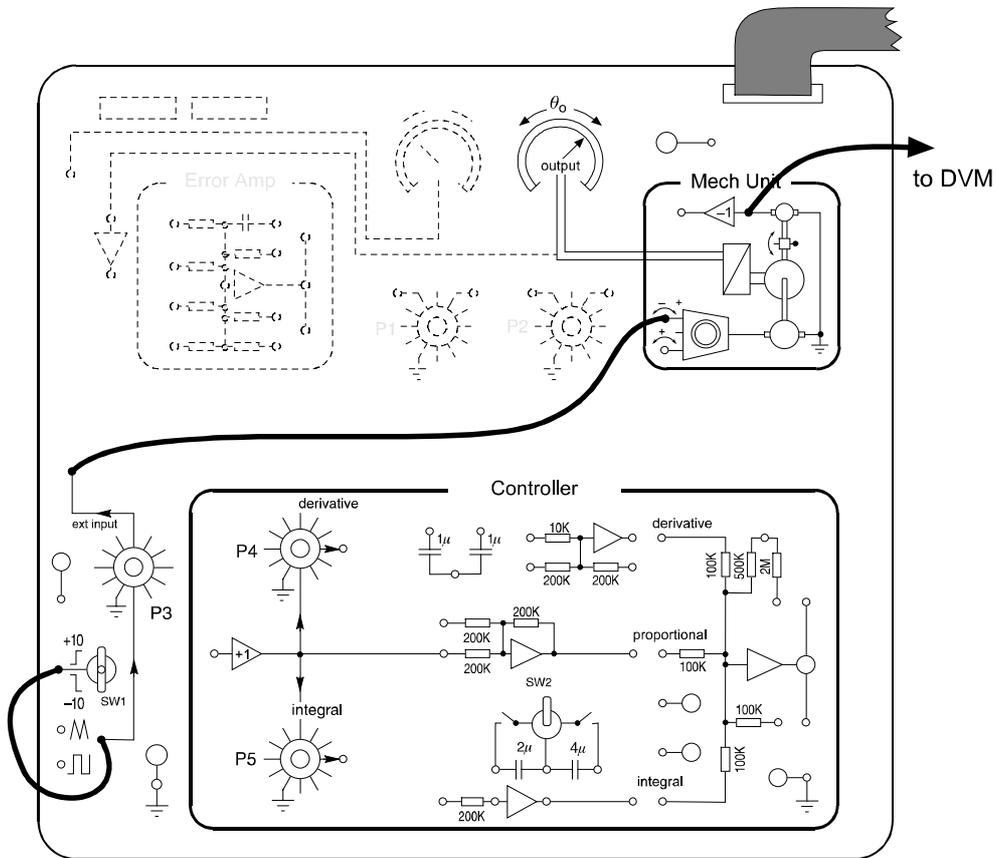## Motor, Tachogenerator and Brake
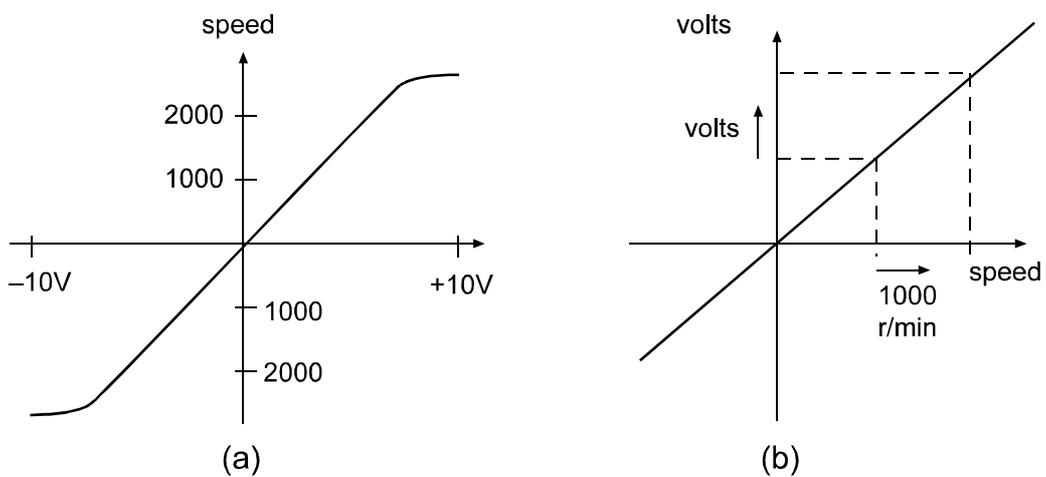## Characteristics

Fig 4.3.3 - Connections for Practical 3.1

Fig 4.3.4 - Characteristics of Motor (a) and Tachogenerator (b)

**Motor, Tachogenerator and Brake
Characteristics**   **Assignment 3**

PRACTICAL 3.1

**Steady-State
Characteristics**

In this practical the motor is operated in a range of steady-state conditions.

Arrange the system as shown in fig 4.3.3, where P_3 enables a voltage in the range ±10V to be applied to the power amplifier.

Use the DVM on the 33-100 for voltage measurements. For each measurement set up the required steady state then switch between DVM and RPM.

By setting SW1 and varying P_3, make a plot of motor speed against amplifier input, in the range ±10V, scaling the vertical axis in units of 1000 r/min. The plot should have the general shape of fig 4.3.4(a).

Note   Since the reduction to the output shaft is 32:1, the motor speed is calculated by multiplying the r/min readng by 32. eg a reading of 31.25 = a motor speed of 1000 r/min.

Initially the motor speed increases substantially linearly with the voltage to the amplifier because the motor back emf V_b, see fig 4.3.1(a), approximately equals the amplifier output, but finally the amplifier limits before the full ±10V input is reached.

Tachogenerator

The tachogenerator provides a voltage proportional to speed, which is required for various aspects of control system operation.

Plot the tachogenerator characteristics by setting the motor speed to various values by P_3 and measuring the generated voltage. The plot should be a straight line with the general form of fig 4.3.4(b).

An important parameter in the use of tachogenerators is the tachogenerator factor in volts per 1000 r/min.

Determine the tachogenerator factor by measuring the change in generated volts for a speed change of 1000 r/min.

The factor should be approximately 2.5V per 1000 r/min.
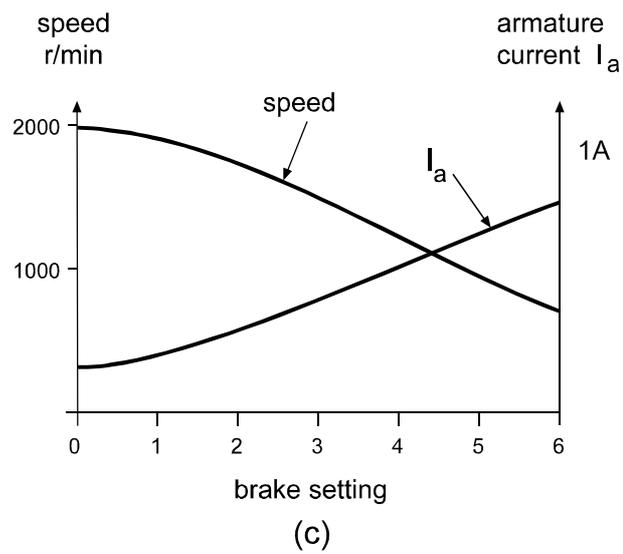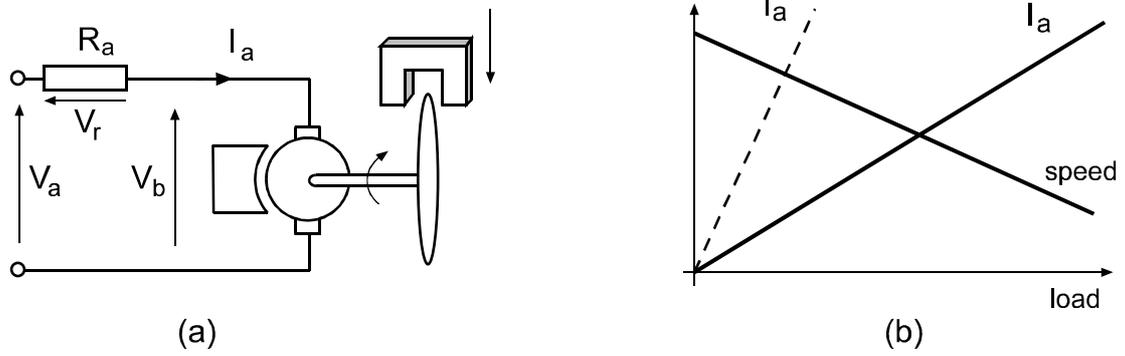
Motor, Tachogenerator and Brake
Characteristics

(a)

(b)

(c)

Fig 4.3.5 - Motor Characteristics Related to Load

**Motor, Tachogenerator and Brake
Characteristics**

Assignment 3

PRACTICAL 3.2

**Steady-State
Characteristics
— Brake Load**

Considering the idealised motor shown in fig 4.3.5(a), when the motor is unloaded the back emf V_b substantially equals the applied voltage V_a, the armature current being very small.

When the motor is loaded the speed falls, the back emf falls, and the armature current increases and the voltage drop in the armature resistance V_r ($= I_a R_a$) added to V_b matches V_a, that is:

$$V_a = V_r + V_b$$

$$= I_a R_a + V_b$$

Hence, if the motor is loaded so that the speed falls, the armature current increases, the general characteristic being as the solid lines in fig 4.3.5(b). If the armature resistance is low, which is the situation for a normal motor, the current increases greatly, as shown dotted, for a small change in speed. The proper operating range of the motor would be up to a load corresponding with a few percent drop in speed, perhaps to the point when the dotted current line crosses the speed line.

By adjusting P_3 set the motor speed to 2000 r/min (62.5 r/min at output), with the brake fully upwards. Connect the DVM to the Armature Current (1volt/amp) output on the Mechanical Unit.

Set the brake to each of its six positions in turn and for each setting record and plot the speed and armature current. The plot should have the general form of fig 4.3.5(c).

Initially the brake has little effect, but then the speed falls sharply and the armature current increases. With greater loading the back emf would become small and the current would be limited by the armature resistance.

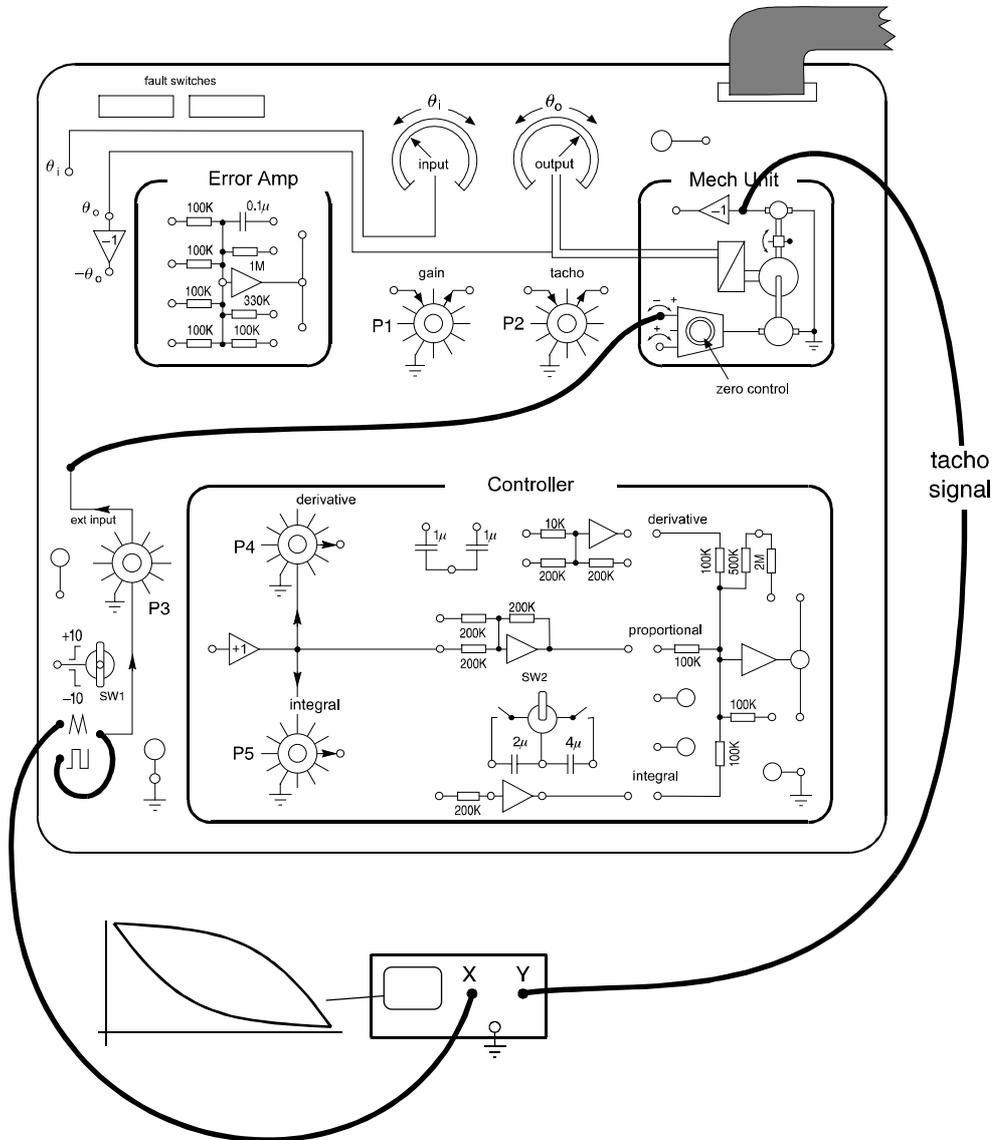## Motor, Tachogenerator and Brake Characteristics

Assignment 3

Fig 4.3.6 - Connections for Practical 3.3

**Motor, Tachogenerator and Brake
Characteristics**

Assignment 3

PRACTICAL 3.3

**Transient Response
of Motor**

The motor cannot change speed instantly due to the inertia of the armature and any additional rotating load (the brake disc in the 33-002). This effect was shown in Practical 1.3 in the familiarisation assignment, and has very important consequences for control system design.
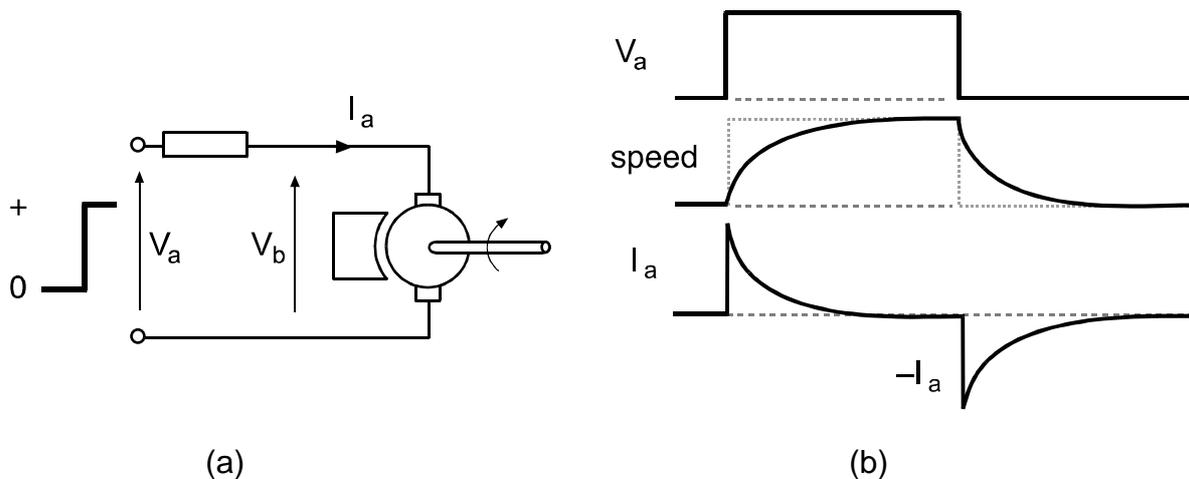

(a)

(b)

Fig 4.3.7 - Transient Characteristics of Motor

If V_a for an ideal motor has a step form as in fig 4.3.7(a), initially a large current will flow, limited only by the armature resistance. As the motor rotates and speeds up the back emf increases and the current is reduced to nearly zero in an ideal motor. This is shown in the left portion of fig 4.3.7 (b). If V_a is suddenly reduced to zero the back emf still exists, since the motor continues to rotate, and drives a current in the reverse direction dissipating energy and slowing the motor. This is illustrated in the right-hand portion of (b).

The 33-001 motor shows a speed characteristic approximating to fig 4.3.7(b), but the power amplifier is arranged to limit the maximum armature current which does not show the ideal pulse characteristic.

Connect the system as shown in fig 4.3.6, which enables the motor to be driven from the test square-wave, and allows the speed to be displayed on the Y axis of an oscilloscope. It is convenient to use an X-Y display.

Set P_3 to zero and the test signal frequency to 0.2Hz.

Motor, Tachogenerator and Brake
Characteristics

Assignment 3

Set the power amplifier zero adjustment to run the motor at maximum speed in one direction.

Turn up P_3 and the square-wave signal will speed up and slow down the motor.

Adjust P_3 until the motor is stationary for one half cycle. This corresponds with V_a in fig 4.3.7(b).

The oscilloscope will now display the speed corresponding with V_a in (b).

PRACTICAL 3.4

Motor Time
Constant

The delay in response of a motor is of great importance in control system design and is expressed as the *time-constant.* This is the time that would be required for the motor speed to change between any steady values if the initial rate of speed change was maintained. This is the dotted line in fig 4.3.8(a), while the actual speed response is shown as a solid line.

(a)   (b)

Fig 4.3.8

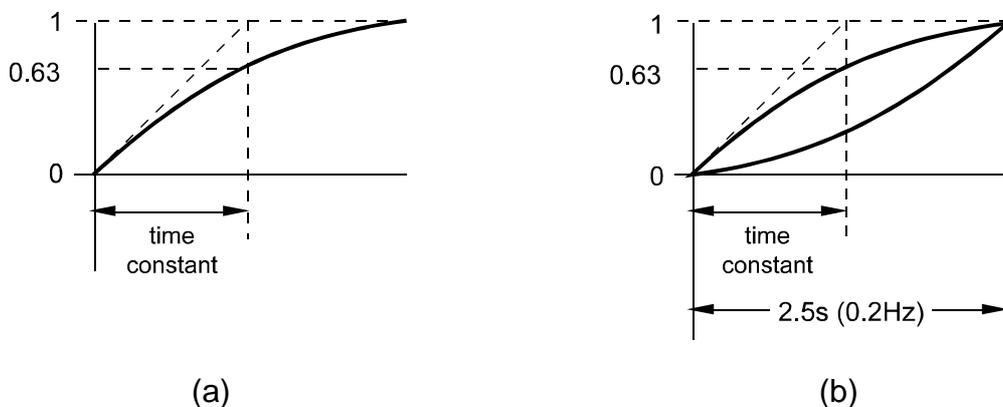It can be shown that the speed changes by 0.63 of the final change during the time constant. The time constant can be measured from a display of the speed against time.

Using the speed adjustment of Practical 3.3 and square wave frequency of 0.2Hz, the time across the trace is 2.5s.

Estimate the time constant by considering the initial slope and maximum speed. The value should be in the region of 0.5s.

Motor, Tachogenerator and Brake
Characteristics   **Assignment 3**

SUMMARY   The motor, with no load, runs at a speed almost proportional to the applied voltage.

The armature current increases with increasing load torque, causing a volt drop in the armature resistance. This effectively reduces the applied voltage, causing a drop in speed.

The magnetic brake provides a torque proportional to speed and dependent also on the overlap between the magnet and the disc.

If the applied voltage is suddenly changed, the motor does not respond instantly. Its time constant is defined as the time it would take to reach its final speed if the inital acceleration were maintained.

PRACTICAL
ASPECTS   The slowing up process associated with reverse current, shown in fig 4.3.7(b), assumes that the reverse current can be returned through the source of V_a. If this is not so the motor takes a much longer time to slow down.

If the armature resistance is low, as for a normal motor, the initial armature current may be very large (dangerously so). Thus some starting equipment (a starter) is used to limit the current while the motor is being run up to speed. This applies especially with large motors.

4 - 3 - 14

NOTES

ERROR CHANNEL AND FEEDBACK POLARITY   **ASSIGNMENT 4**

The following Practicals are included in this assignment:

4.1   Feedback Polarity

4.2   Input and Output Rotation Directions

ERROR CHANNEL AND FEEDBACK POLARITY　　　　　　**ASSIGNMENT 4**

CONTENT　　　　　The importance is shown of ensuring that feedback is negative. Care over polarities is also shown to be needed to ensure correct responses to input signals.

**EQUIPMENT
REQUIRED**

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A; +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810- 01229)*

ERROR CHANNEL AND FEEDBACK POLARITY **ASSIGNMENT 4**

OBJECTIVES   When you have completed this assignment you will know:

ν   That the polarity of the feedback in a closed-loop system must be negative for the system to work correctly.

ν   That in a typical system there are several places where the polarity of the feedback can be changed.

ν   That care must be taken over polarities in order to ensure that when the setting (or demanded value) is changed, then the output (actual or measured value) changes in the appropriate direction.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Be familiar with the equipment and preferably have completed Assignment 1, Familiarisation.

ν   Understand the behaviour of a simple operational amplifier circuit.

PRELIMINARY
PROCEDURE   The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.
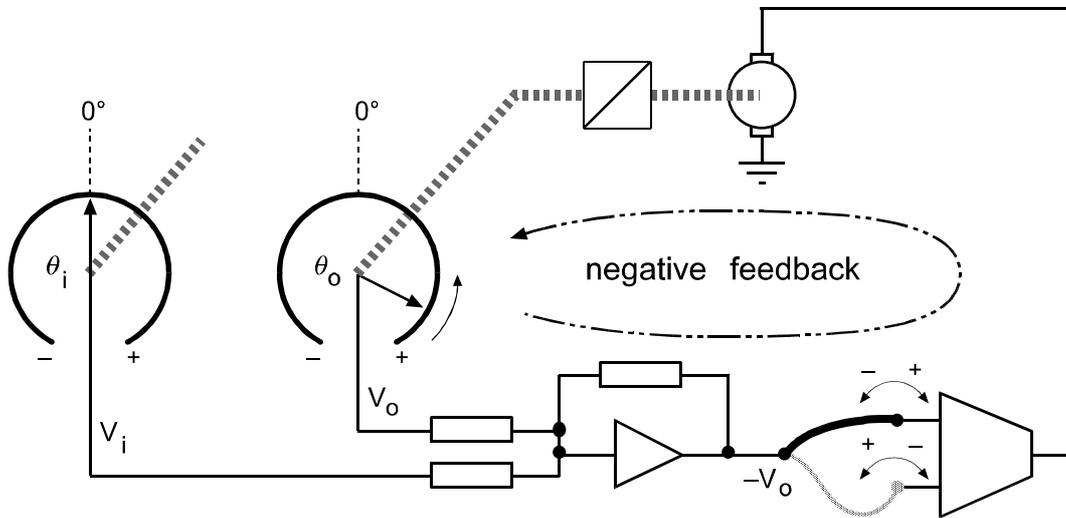
Fig 4.4.1 - Closed-Loop Control System

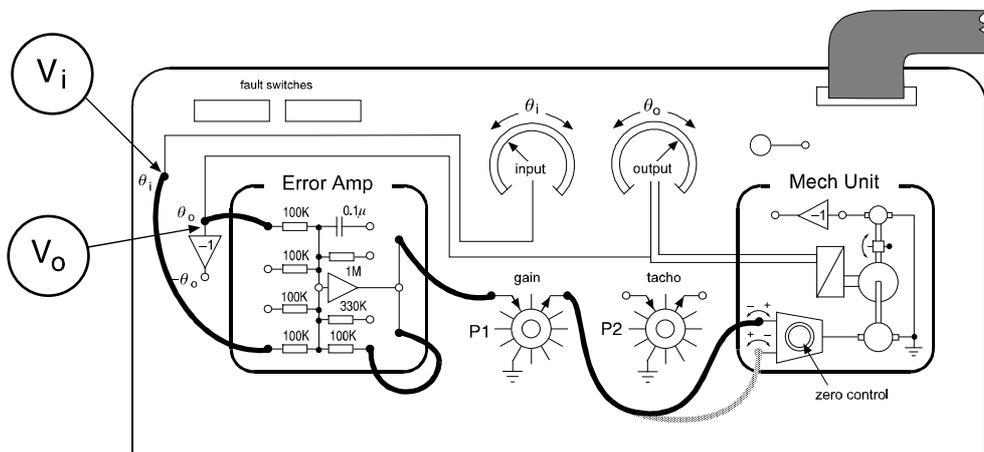*Fig 4.4.2 - Connections for Practical 4.1*

Error Channel and Feedback Polarity   **Assignment 4**

INTRODUCTION

A control system with input and output shafts, such as the 33-002, requires some method of measuring the input and output shaft angles and determining the difference or **error** between them. The error must then produce a voltage, or may be measured directly as a voltage, suitable to drive the power amplifier.

A very convenient method to measure the shaft angles electrically is to attach a potentiometer to each shaft, as in fig 4.4.1. The signals V_i and V_o can then be combined in an operational amplifier to produce an error signal to operate the power amplifier.

PRACTICAL 4.1

Feedback Polarity

Make the connections shown in fig 4.4.2, ignoring for the moment the connection shown as a shadow line, which gives the circuit of fig 4.4.1, setting P_1 to zero before connecting to the power amplifier.

Switch on the power supply.

Set the input potentiometer to 0°. Use the power amplifier zero adjustment to rotate the output shaft to set 0° on the scale horizontal to the right. Check that this condition gives a positive V_o value. Is the value what you might expect?. Measure the maximum voltages from the potentiometer.

Slowly increase P_1 to 100 and the output shaft should rotate anti-clockwise and finally align vertically with the input.

Note that the output potentiometer, error amplifier, power amplifier, motor and drive to the output shaft form a *loop*, and the system is arranged to have **negative** feedback round the loop, which **reduces** the error. This is the usual operating condition.

Set P_1 to zero, keeping θ_i at zero. Plug P_1 output to the lower power amplifier input, as shown shaded in fig 4.4.1. Use the zero control to set the 0° on the output scale horizontal to the right.

Slowly turn P_1 until the motor just rotates and the output shaft will rotate clockwise and stop vertically downwards.

The system now has **positive** feedback round the loop and increases the error.

The motor stops because the slider arm of the potentiometer has moved into the gap between the ends of the track and V_O becomes zero.

Turn P1 to 100 and use the power amplifier zero adjustment to move the output shaft and the system will probably go into a sustained oscillation.

The oscillation occurs because if the slider moves slightly to the left the signal V_O becomes –10V, which drives the slider to the right, and then V_O changes to +10, driving the slider to the left, and the whole process repeats.

Error Signal Polarity   For correct system operation it is **essential** that the error signal rotate the motor in the appropriate direction to **reduce** the error — this is **negative** feedback. If the error signal rotates the motor to **increase** the error, this is **positive** feedback and the system is useless.

An outline of the 33-100 is represented in fig 4.4.1, where it is assumed that the input shaft (θ_i) is set to 0° so that the input signal V_i is zero. The output shaft (θ_o) is assumed to the right of 0°, giving a positive V_o. The two potentiometer signals are added in an operational amplifier. With V_i at zero, the amplifier output will be $-V_o$. For the system to operate correctly this signal must rotate the output shaft **anti-clockwise** and the amplifier must be connected to the upper power amplifier socket. This will provide negative feedback.

4 - 4 - 7
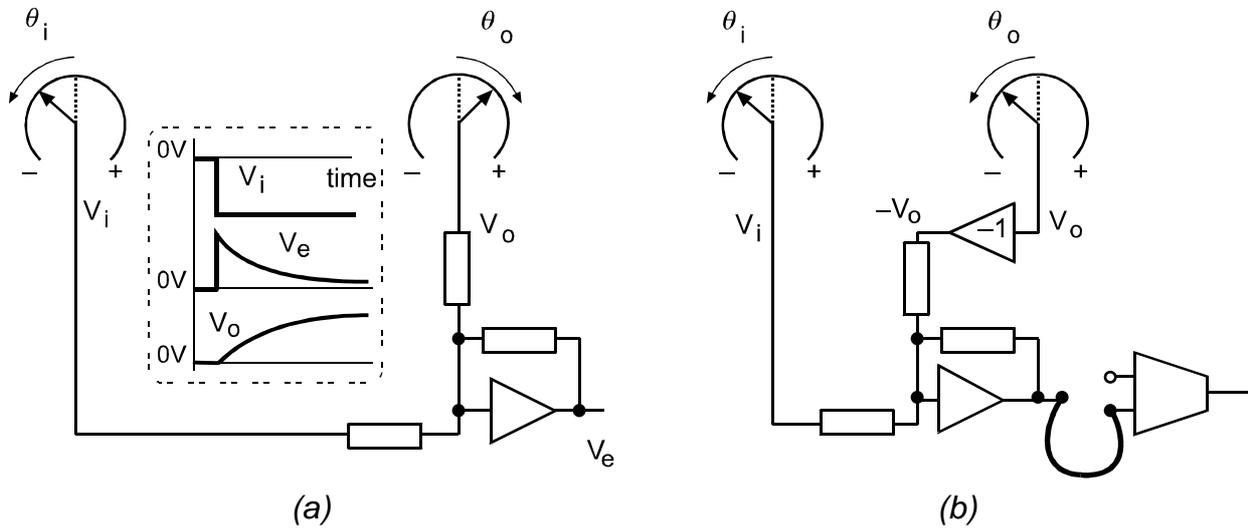
NOTES

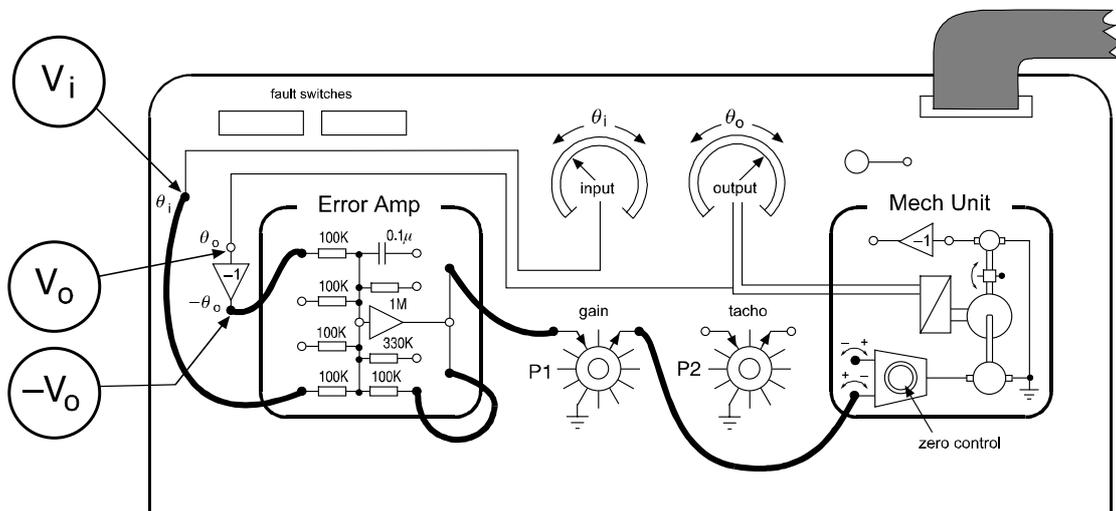*Fig 4.4.3 - Circuits for Practical 4.2*

Fig 4.4.4 - Connections for Practical 4.2

Error Channel and Feedback Polarity   **Assignment 4**

PRACTICAL 4.2

Input and Output

Rotation Directions

The previous Practical has shown that it is essential to have **negative** feedback round the loop for the system to operate properly. In addition, there are other considerations concerning relative rotation directions of shafts.

Arrange the system as shown in fig 4.4.2, using the solid connections. Set the input (θ_i) to 0°. Use the power amplifier zero adjustment with P_1 set to 100 to align θ_o to 0°.

Rotate the input (θ_i) slowly between ±90° and note that the output is controlled, but rotates in the **opposite** direction.

The results show that the system is following, but with reversed shaft rotation. The reasons can be seen from fig 4.4.3(a), representing the potentiometers and error amplifier. If θ_i is rotated anti-clockwise V_i is **negative**, hence the error signal V_e will increase **positive**, eventually causing V_o to increase and V_e to fall to zero.

To make the shafts rotate in the same direction, various changes could be made, such as:

(i) reverse the supply polarity to the input potentiometer
or
(ii) introduce a gain of −1 in the V_i line

Either would cause V_i to reverse in direction, hence V_e would reverse and the output shaft move in the opposite direction.

Check that (i) or (ii) above would make the output shaft follow in the same direction as the input motion by considering voltages as shown in fig 4.4.3(a).

It is possible to consider introducing either (i) or (ii) into the output potentiometer circuit. However, any **one** change will **reverse** the feedback polarity to give **positive** feedback, corresponding with the oscillatory situation of Practical 4.1, and the system will not operate properly.

However, introducing **two** changes will cause the feedback to remain negative.

This can be arranged as in fig 4.4.3(b), where a gain of −1 is introduced in the V_o line and the input socket on the power amplifier is reversed.

Assume that V_i is negative, as in fig 4.4.3(b), and check by considering voltages and motor rotation that the output shaft would now align with the input.

Arrange the system of fig 4.4.4, which corresponds with fig 4.4.3(b), and check that the output shaft does follow the input shaft rotation.

SUMMARY

This assignment has shown that detailed consideration of signal polarity and motor rotation direction are essential to obtain the correct operation of a control system.

PRACTICAL ASPECTS

It is very important to consider whether any alteration proposed to a system may introduce an unexpected polarity change. This may happen with some redesign of the electronic circuitry, such as introducing an additional operational amplifier for some reason. Also a change in the mechanical system may have the same effect. If a single belt reduction is replaced with a single spur gear pair, a rotational reversal between mechanical input and output shafts will occur, giving a polarity reversal. This can be compensated for by introducing an electrical phase reversal at some point in the loop.

Potentiometers, as used in the Mechanical Unit, give a very simple and convenient method to provide an electrical signal from a shaft rotation. They have the disadvantage that a simple potentiometer cannot provide a signal for a shaft rotating for more than one revolution. This is possible however using more complicated potentiometers.

Error accuracy

An ideal potentiometer would provide a voltage from the slider which varies **linearly** with rotation giving the heavy line in Fig 4.4.5, and if set at mid-track would give exactly 0V.
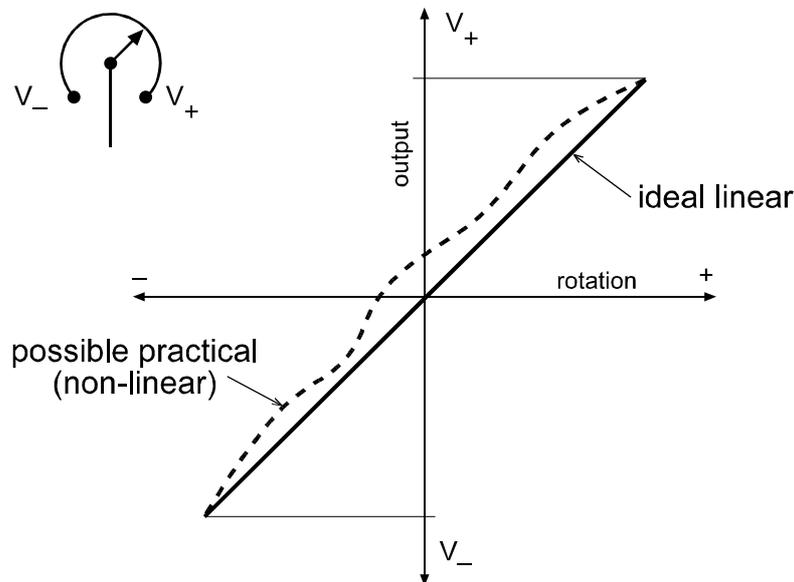

Fig 4.4.5 - Potentiometer Characteristics

Practical potentiometers have a volts/rotation characteristic as shown dotted departing from the ideal. The extent of the departure **non-linearity** depends on the individual potentiometer but is reduced by more expensive construction methods.

The effect of the non-linearity is that if two potentiometers are set to the **same** angle the voltages will be slightly different, the difference varying with the angle. The control system will always rotate the output shaft and potentiometer to give **zero** error. The effect is that the output shaft does not **exactly** follow the input shaft but has a **misalignment** error depending on the shaft angle. The error may vary from less than a degree to several degrees depending on the potentiometers used. The misalignment can always be set to zero at some point (commonly 0°)

For rotations exceeding one revolution it is usual to employ **synchros**, which are energised by a.c. These enable an a.c error signal to be obtained, with the facility for continuous rotation. Then either the system must operate with an a.c motor or the error signal must be converted to d.c for a d.c motor system. Synchros are more expensive than potentiometers, but are very accurate.

NOTES

THE INFLUENCE OF GAIN   **ASSIGNMENT 5**

The following Practical is included in this assignment:

5.1   Step Response

THE INFLUENCE OF GAIN   **ASSIGNMENT 5**

4 - 5 - 2

CONTENT   The influence is examined of the gain on the transient
                            response of a position servo.

EQUIPMENT
REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A; +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810- 01229)*

THE INFLUENCE OF GAIN   **ASSIGNMENT 5**

OBJECTIVES   When you have completed this assignment you will know that
                      varying the gain in a closed-loop system:

    ν   Affects the speed and accuracy of response.

    ν   Affects the stability of the system.

KNOWLEDGE LEVEL   Before you start this assignment you should:

    ν   Be familiar with the equipment and associated test
          equipment.

    ν   Understand the meaning and purpose of closed-loop
          control.

    ν   Preferably have completed Assignment 4, Error Channel
          and Feedback Polarity.

**PRELIMINARY
PROCEDURE**   The Analogue Unit and Mechanical Unit should be connected
                      together by the 34-way ribbon cable.

                      The Power Supply should be connected by 4mm-plug leads to
                      the +15V, +5V, 0V and −15V sockets at the back of the
                      Mechanical Unit.

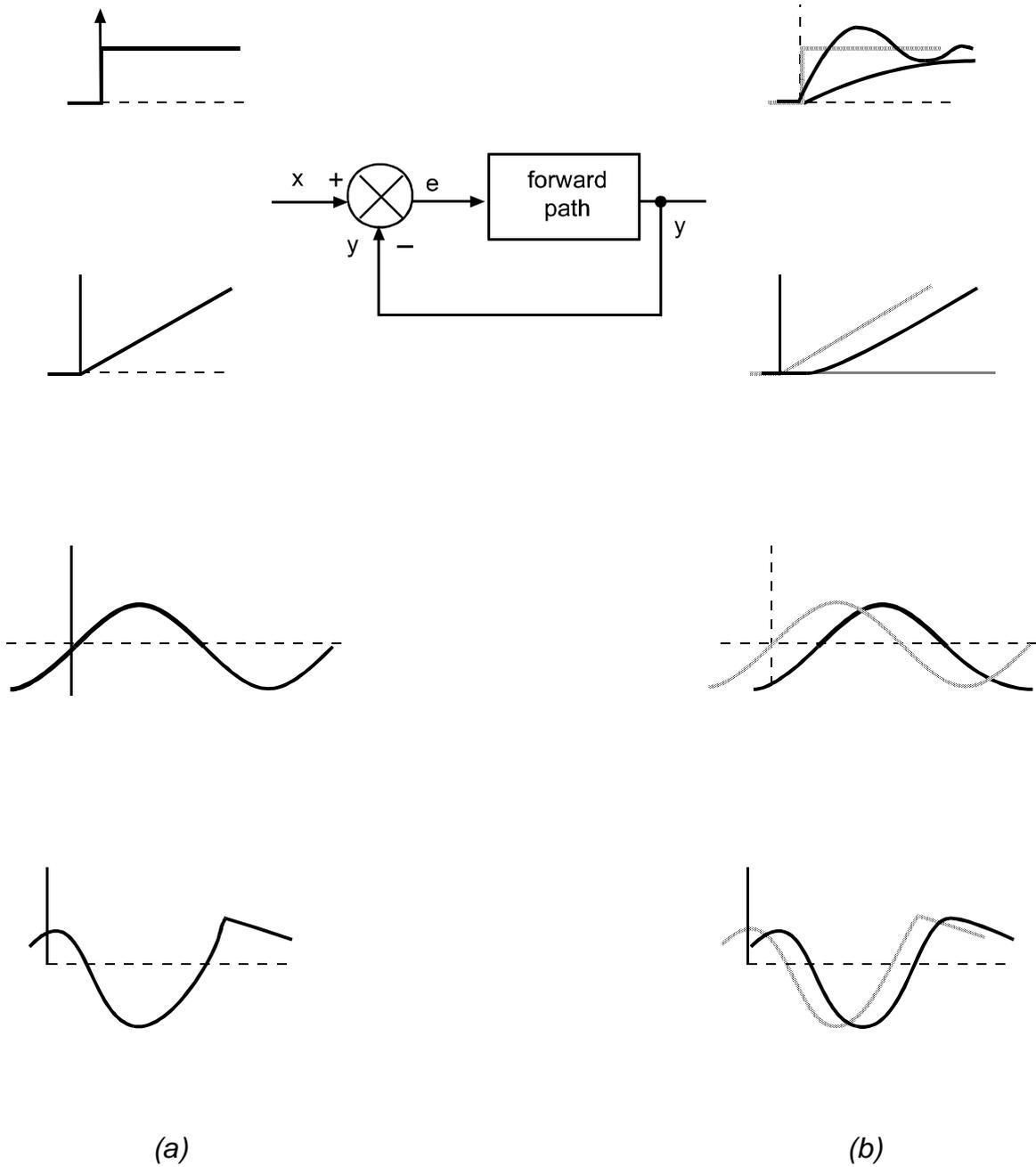**The Influence of Gain**   **Assignment 5**

(a)   *(b)*

Fig 4.5.1 - A general system with (a) Test Signals and (b) Typical Responses

The Influence of Gain   **Assignment 5**

INTRODUCTION

Previous assignments have investigated the characteristics of portions of the system and the present assignment is concerned with the performance of the complete system.

A general system has the form shown in fig 4.5.1, where an input x and an output y are compared to give an error e with the relation

$$e = x - y$$

The process of comparison is represented by a conventional symbol as in the diagram, where the input and output may not necessarily be voltage signals. For a purely electrical system the comparator may be an operational amplifier. The error operates the forward path, which includes everything between the error and the final output y. Thus the forward path may contain a facility to convert the error to a voltage, followed by a gain and a power amplifier driving a motor, and then some reduction gear to operate the output shaft.

The design and performance characteristics of systems are often considered in terms of the response to a step or ramp input (a), with possible responses shown at (b) where the input is shown in shadow. The response to a sinusoidal input, the frequency response, (amplitude and phase), also has a very important application in control system design, but requires significant mathematical background theory and appropriate test equipment.

An introduction to sinusoidal testing is provided in Assignments 14 & 15.

In application the system will probably operate from a generalised input as at (a) bottom, which is not practical as a design input, so that the simple inputs above are used for design purposes.

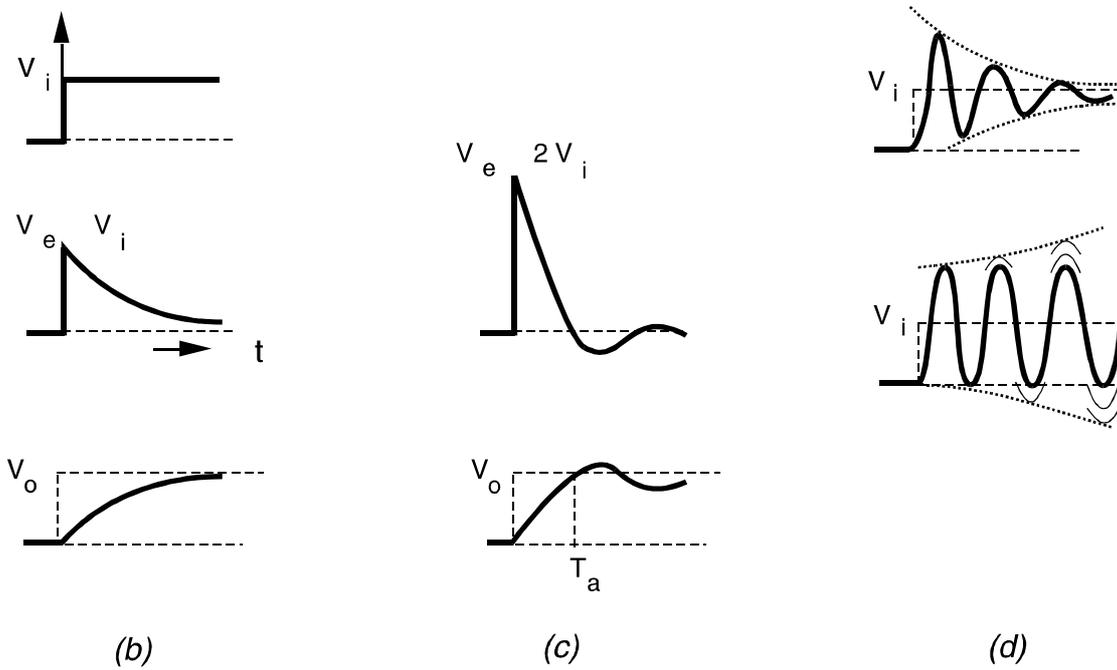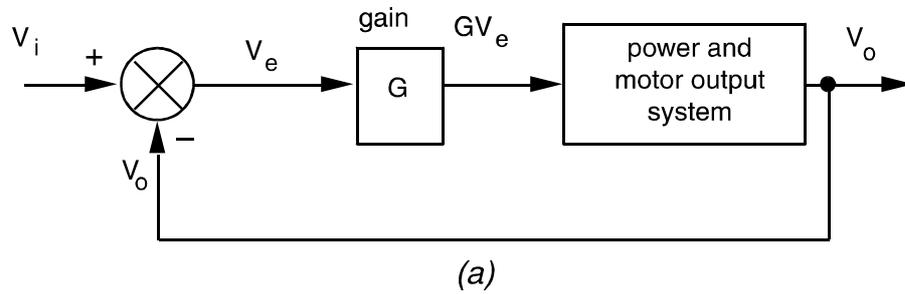**The Influence of Gain**   **Assignment 5**

(a)

(b)   *(c)*   *(d)*

Fig 4.5.2 - Effect of Varying Gain on Step Response

The Influence of Gain   **Assignment 5**

Step Response

The step response of a system gives useful information about the general system characteristics and is often required to meet some requirements in the system performance specification. To generate the step response a very simple input is required, and for these reasons much consideration is given to the step response.

For a given system the form of the step response is greatly affected by the system gain. The gain essentially determines how much power is applied to move the output for a given error. For an electrical system, such as the 33-002, the gain determines the voltage applied to the motor for a given error.

A purely electrical system may be represented as in fig 4.5.2(a), where the input (V_I), output (V_o) and error (V_e) are all voltages and the forward path gain (G) is shown separately, the voltage applied to the power amplifier being GV_e.

If a step V_i is applied, the initial value of the error is equal to V_i as in (b), since V_o is zero. If the gain is 1 the power amplifier input is initially V_i and as the motor rotates the output gradually aligns with the input, with the motor slowing up as the error decreases. If the gain is 2, the initial input to the power amplifier is $2V_i$, causing the motor to move faster and although the error decreases, the motor may overshoot the required final position due to the delay in the motor. This delay may be investigated in Assignment 3. When the motor finally stops the error is reversed in sense, so that the motor reverses and the system aligns or may undershoot, but will finally settle. This is shown in (c). The gain values refer to relative gains associated with the comparator. The overall effective gain depends on many factors, including the reduction ratio in the output system.

If the gain is increased further, the system may take several oscillations to settle, as at (d). If there are two delays in the system the result may be a steady oscillation at the output, or even an increasing oscillation. Systems with the characteristics of (d) are useless for control purposes.

An additional effect that must be considered is the magnitude of the input signal. In the hypothetical example described above, doubling the gain speeds up the response. However, if V_i increases the power amplifier drive ($2V_i$) also increases and the amplifier may limit and the motor may not be able to move fast enough to give the response at (c) for an increased V_i.
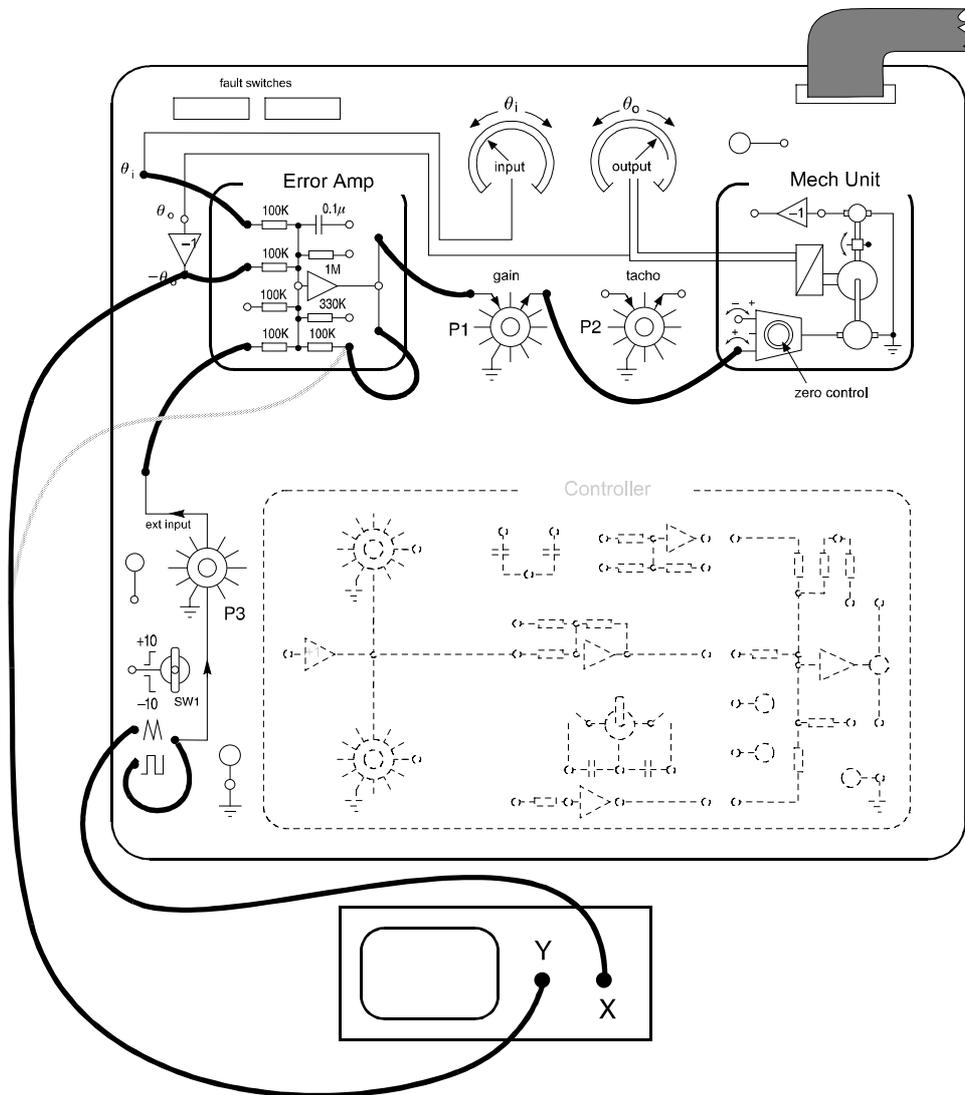
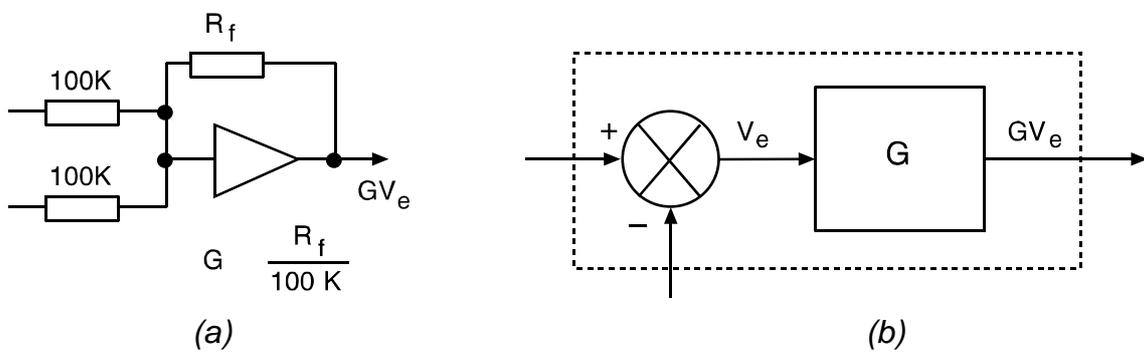## The Influence of Gain

Fig 4.5.3 - Connections for Practical 5.1

(a) *(b)*

Fig 4.5.4 - The Error Channel

The Influence of Gain   **Assignment 5**

PRACTICAL 5.1

Step Response   In this practical the 33-002 step response is investigated to show the effect of variation of forward path gain. It is convenient to arrange increasing gain by increasing the feedback resistor in the error operational amplifier as in fig 4.5.4(a). This corresponds with the comparator and forward path gain for fig 4.5.2, being a single unit as shown in fig 4.5.4(b), and it is only possible to observe GV_e, the output of the operational amplifier. If, for example, R_f is 330kΩ, then $G = 3.3$.

Arrange the system with the solid connections of fig 4.5.3, with the error amplifier feedback resistor 100kΩ, giving $G = 1$.

Set the test signal frequency to about 0.1Hz and adjust P_3 to provide a square wave input of ±5V (approx 50%).

Set P_1 to zero and arrange an X-Y display.

Turn up P_1 until the motor just rotates and the system will give a response similar to Fig 4.5.2(b).

Then increase P_1 until the system just overshoots and estimate the time to alignment T_a. It is useful to examine the output of the error amplifier which passes through zero at T_a.

Finally set P_1 to 100 and note the reduced T_a since the motor moves faster but gives increased overshoot.

When the gain is increased further, it is useful to examine the error amplifier output, which is GV_e, to check that the forward path is not being overloaded. The initial value of the error depends on the total change of input, so that a ±5V input gives an initial error (V_e) of 10V.

Set the amplifier feedback resistor to 330kΩ giving $G = 3.3$. Connect the Y input to the error amplifier output and with P_1 at 100 adjust P_3 until the peak amplifier error (GV_e) is about 10V.

The response should have the general form of the top of fig 4.5.2(d). The time to alignment is much reduced but the response is too oscillatory for a practical system.

Set the feedback resistor to 1MΩ giving $G = 10$, and repeat the test, adjusting P_3 to limit the peak error to 10V.

The Influence of Gain **Assignment 5**

The response is now more oscillatory, but the time to initial alignment will be reduced from the value with G = 3.3 and can again be estimated.

In the last two tests, the input has been reduced to prevent the signals exceeding ±10V. However, if the input is increased to say ±5V, then the theoretical initial output of the error amplifier with G = 10, would be 50V. If the amplifier could give 50V and the power amplifier accept an input of 50V and drive the motor correspondingly fast, the system response would retain the same form.

In practice the error amplifier cannot provide outputs much exceeding ±10V and hence limits; thus the motor runs at maximum speed until the error is sufficiently reduced that the amplifier ceases to limit. The result of the limiting is that the response takes longer as the input is increased.

With G = 10, adjust P_3 to give ±5V. Observe that the error limits and that the response takes longer, and the oscillation takes longer to die away.

These general results illustrate a fundamental problem for simple control systems, that increasing the gain to give a faster response leads to more marked oscillation, and no advantage may be gained.

SUMMARY Testing of closed-loop systems is most conveniently done with special simple test signals. The most usual is a step signal.

The response to a step input is sluggish if the gain is low.

Increasing the gain causes a faster response, but if too much gain is applied the response may overshoot and take several oscillations before settling. Further increase in gain may cause sustained oscillations to build up.

VELOCITY FEEDBACK   **ASSIGNMENT 6**

The following Practical is included in this assignment:

6.1   Simple Velocity Feedback

VELOCITY FEEDBACK   **ASSIGNMENT 6**

CONTENT   A servo is studied with reference to the effect of velocity feedback on system stability.

EQUIPMENT
REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A; +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810-01229)*

VELOCITY FEEDBACK   **ASSIGNMENT 6**

OBJECTIVES   When you have completed this assignment you will know that:

ν   Introducing velocity feedback into a closed-loop position control can make it more stable.

ν   The improved stability may enable more gain to be used.

ν   Excessive velocity feedback makes the system slow-acting.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Be familiar with the equipment.

ν   Understand the effect of gain on the transient response of a servo and preferably have completed Assignment 5, The Influence of Gain
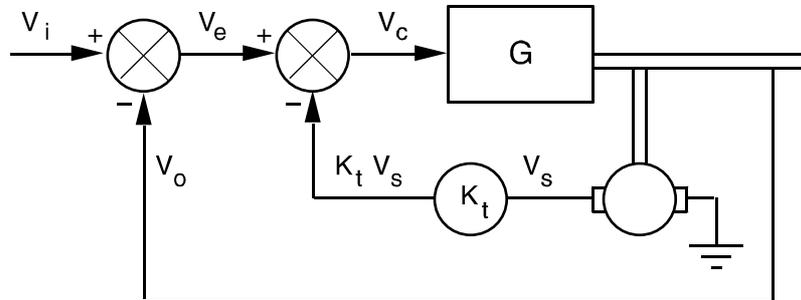
PRELIMINARY PROCEDURE

The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.
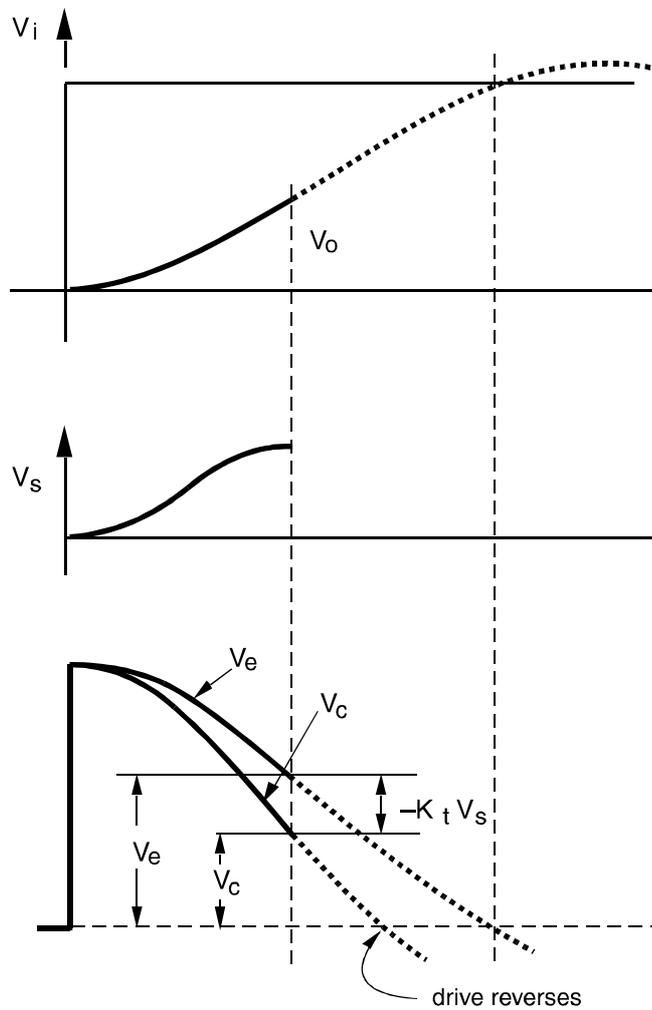
Fig 4.6.1 - Velocity Feedback

Velocity Feedback **Assignment 6**

INTRODUCTION Assignment 5 shows that increasing the gain increases the oscillatory tendency in the response, which is undesirable. There are good practical reasons for using a high gain. An important one is that, due to the brushes and other factors, all practical motors have a constant friction (called **coulomb friction**). Also usually an increased amount of friction force (called **stiction**) has to be overcome to start the motor from rest. Therefore a minimum voltage has to be applied to the motor before rotation starts. This means that there is a minimum input below which the system will not respond; this is termed **dead-band**. If the gain is high the dead-band is reduced, which is advantageous, but the system may display unwanted oscillation in the response.

The form of the system response with high gain can be much improved by applying a feedback signal to the input proportional to the output shaft **velocity**. This arrangement is termed **velocity feedback**, and is illustrated in fig 4.6.1.

In the diagram it is assumed that the input and output signals are available as voltages and a voltage V_s proportional to output shaft speed is available from a tachogenerator. A fraction of this voltage K_tV_s is subtracted from V_e to give V_c, which is the control voltage applied to the power amplifier giving:

$$V_c = V_e - K_tV_s$$

If a step input is applied to the system the error will initially equal the input step and decrease as the motor speeds up. As the motor speed increases the velocity signal V_s increases and subtracts from V_e to give a drive voltage V_c, which is less than the error. This is illustrated in the lowest diagram, and the motor drive goes to zero and reverses before the error goes to zero. This means that the motor begins to slow up before the initial alignment, greatly reducing or even preventing any overshoot.

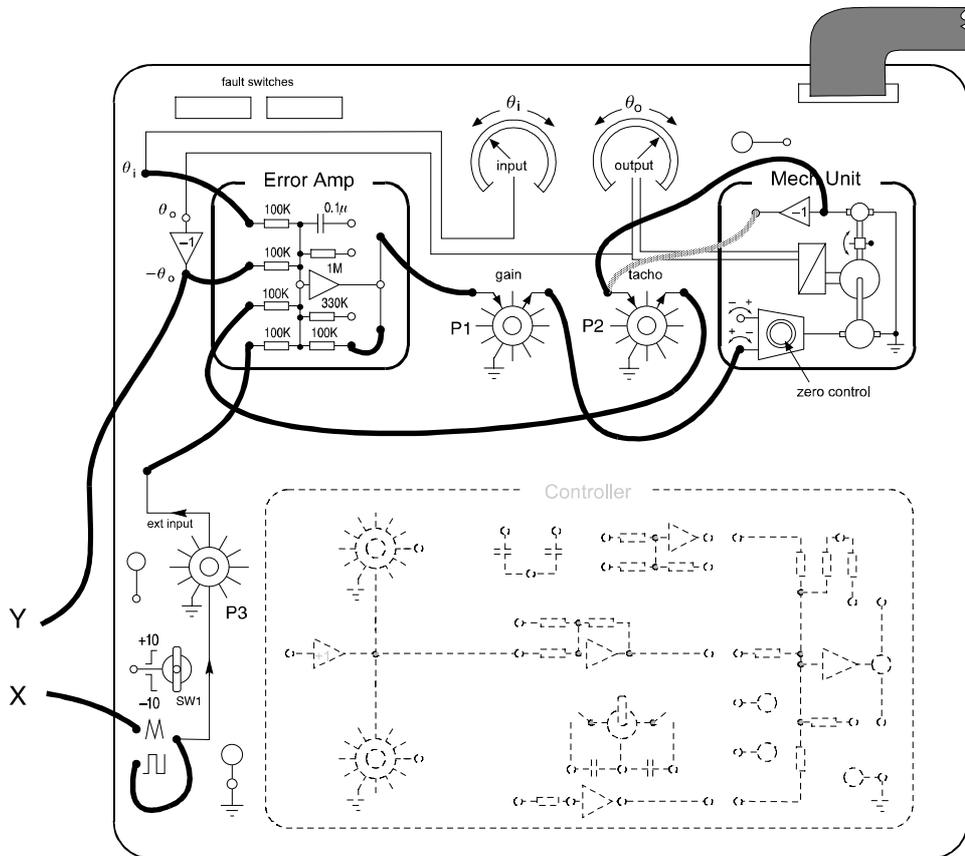**Velocity Feedback**   **Assignment 6**
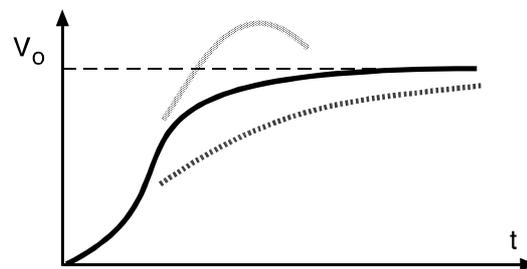

Fig 4.6.2 - Connections for Practical 6.1

Fig 4.6.3 - Dead-beat Response

Velocity Feedback   **Assignment 6**

PRACTICAL 6.1

**Simple Velocity
Feedback**

Arrange the system as in fig 4.6.2, initially omitting the connection from P_2 to the tachogenerator and set P_1 to zero. Connect the oscilloscope for an X-Y display as indicated.

Set the error amplifier feedback resistor to 100K, giving G = 1, and set P_3 to give a V_i of ±5V at 0.1Hz. Turn P_1 to 100 and a slightly oscillatory response should be obtained.

Connect P_2 to one tachogenerator output and increase its setting; if the overshoot decreases the velocity feedback polarity is correct. If the overshoot increases connect to the other socket.

When adjusting the tachogenerator feedback a dead beat response will be obtained when the system aligns in the least possible time, but with no overshoot as in fig 4.6.3. Additional velocity feedback will cause an over-damped response, in which the system slowly moves into alignment.

Increase P_2 until a deadbeat response is obtained, this occurs when the motor just does not reverse. Additional feedback can be obtained by disconnecting θ_i and connecting the tachogenerator to that input as well.

Increase the feedback resistors to 330K, G = 3.3; 1MΩ, G = 10, and in both cases deadbeat response should be obtainable.

These results show that velocity feedback is a very powerful technique to improve transient response when gain is increased.

Note that reversing the polarity of velocity feedback can make a system unstable.

Velocity Feedback   **Assignment 6**

SUMMARY

Velocity feedback is feedback proportional to the velocity of the output shaft. A tachogenerator is often provided for the purpose.

In a position servo it serves the purpose of modifying the (position) error signal so that the modified signal goes to zero before the desired position is reached. This prevents the motor from accelerating right up to the desired position, so that inertia causes it to overshoot.

SYSTEM FOLLOWING ERROR   **ASSIGNMENT 7**

The following Practicals are included in this assignment:

7.1   Following Error

7.2   Velocity Feedback and Following Error

SYSTEM FOLLOWING ERROR   **ASSIGNMENT 7**

CONTENT   A simple system follows a ramp with an error. This following
error is investigated and the effect of velocity feedback on the
error studied.

**EQUIPMENT
REQUIRED**

QTY	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810-01229)*

SYSTEM FOLLOWING ERROR   **ASSIGNMENT 7**

OBJECTIVES   When you have completed this assignment you will know that :

ν   A simple system follows a ramp with an error.

ν   Increasing the gain reduces the error but leads to a deterioration of the transient response.

ν   Velocity feedback can improve the transient response but increases the following error.

KNOWLEDGE LEVEL   Before you start this assignment you should :

ν   Be familiar with the effects of gain and velocity feedback on system performance.

ν   Preferably have completed Assignments 5, The Influence of Gain and 6, Velocity Feedback.

PRELIMINARY PROCEDURE   The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.

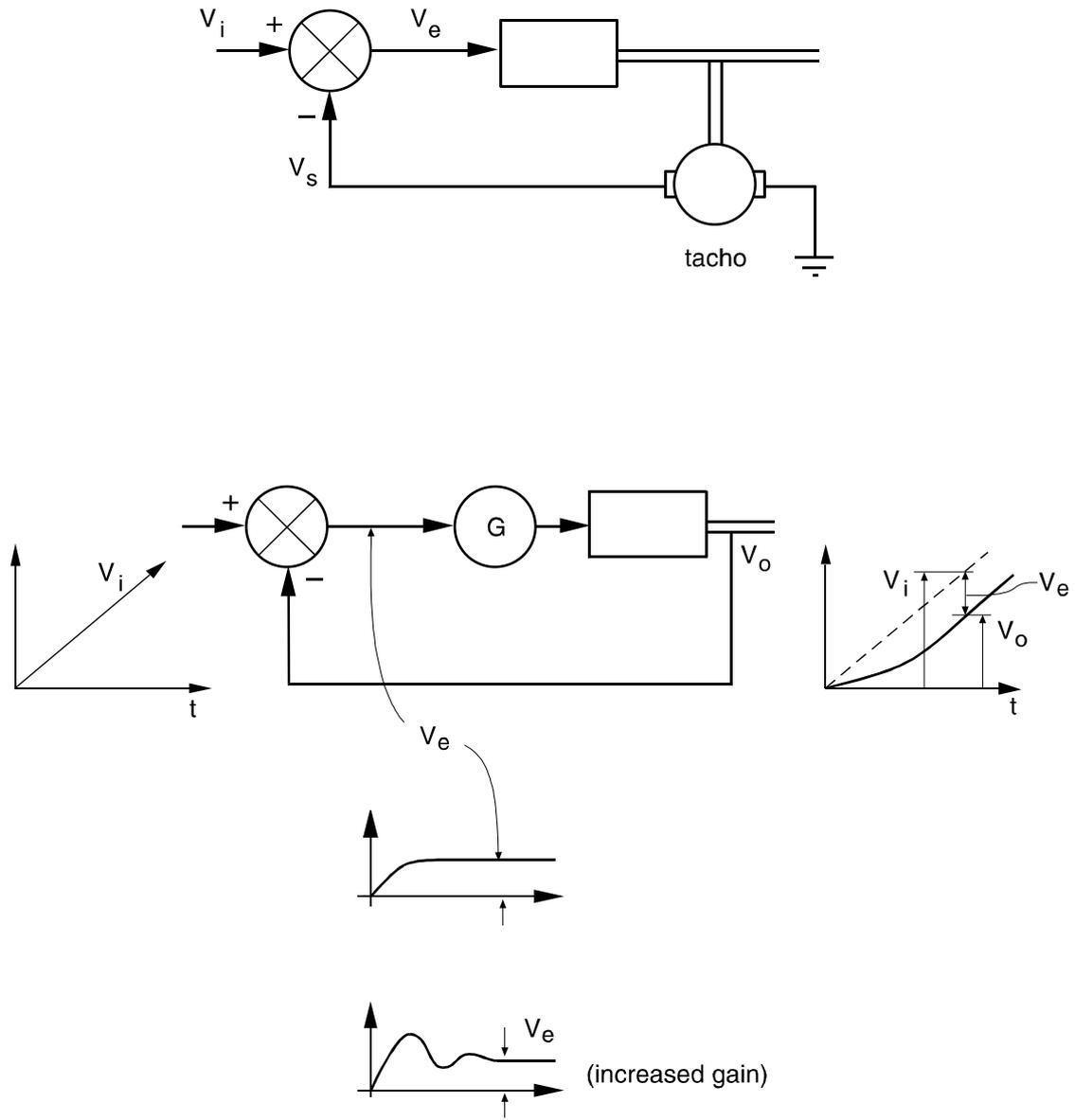**System Following Error**   **Assignment 7**

Fig 4.7.1 - Steady following error

System Following Error   **Assignment 7**

INTRODUCTION

System
Following Error   The step response of a system (considered in Assignment 5) is an important general indication of system performance. Another important characteristic is the system response to a steadily changing input requiring the output to move at a constant speed. This is sometimes termed the **ramp** response and is represented in fig 4.7.1, where all signals are assumed available as voltages.

This general situation could correspond with the requirement for the cutting tool of a lathe to move at a constant speed along a workpiece or a radar dish to sweep at a constant velocity.

If the output is to move at a steady speed then, when the system has settled, there must be an appropriate constant voltage applied to the motor. This voltage can only be obtained from the error. Since the error V_e depends on the difference between input and output

$$V_e = V_i - V_o$$

the system will show a constant following error, that is the output always lags on the input. In terms of the two examples mentioned above, this means that the cutting tool is never exactly where it is commanded to be or the dish does not point exactly where it is intended to point.

If the forward path gain G is increased, then the error for a given speed falls inversely, that is doubling the gain halves the error, however, the system response becomes more oscillatory and the settling time may increase.

System Following Error   **Assignment 7**
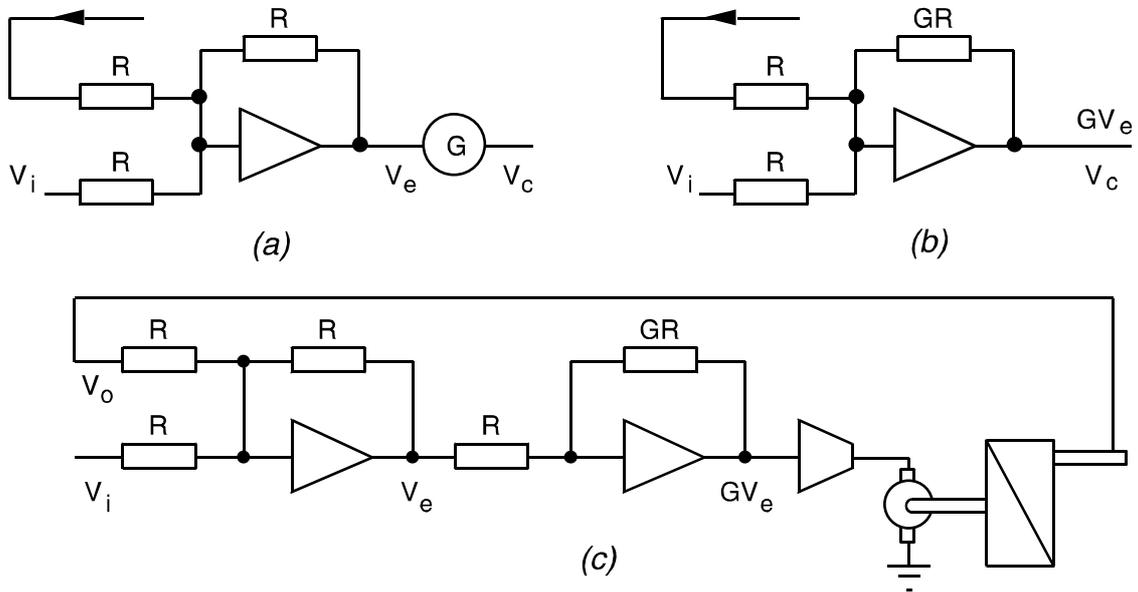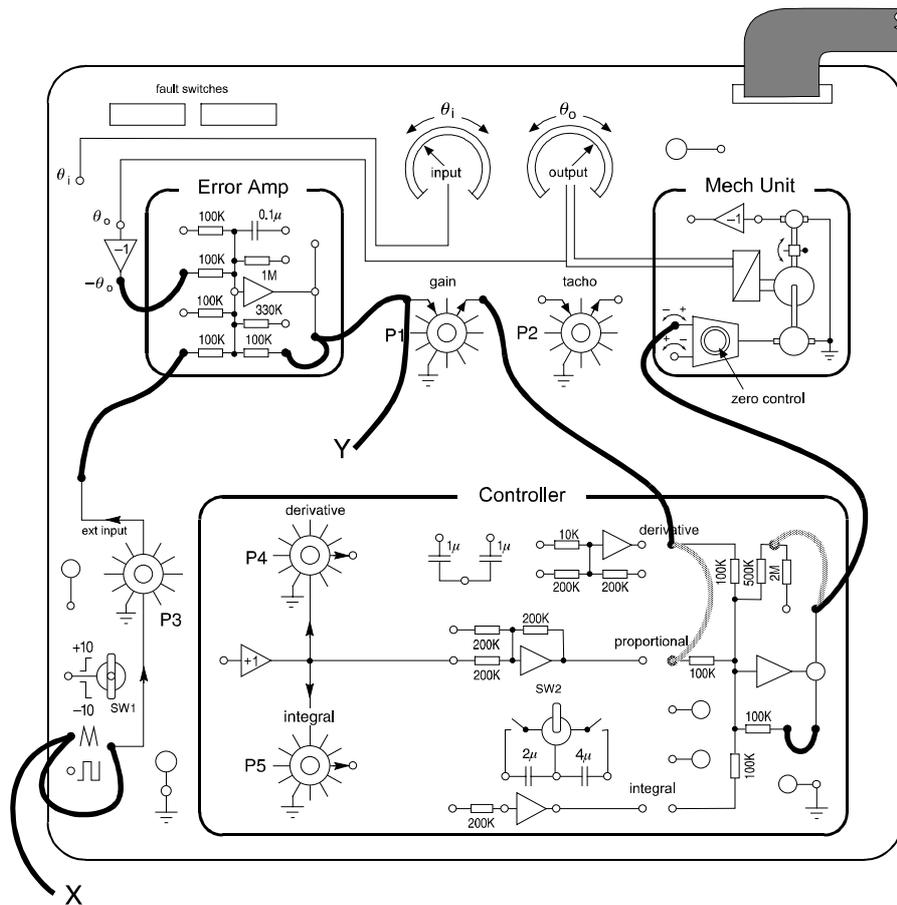

(a)   *(b)*

(c)

Fig 4.7.2 - System for following error investigation

Fig 4.7.3 - System connections for Practical 7.1

System Following Error   **Assignment 7**

PRACTICAL 7.1

Following Error   In order to be able to examine the following error and see how it changes with gain, it is necessary to arrange the system so that the error V_e is directly available as

$$V_e = V_i - V_o$$

from the error operational amplifier as in fig 4.7.2(a). Any additional gain G must be introduced as a separate amplifier, see fig 4.7.2(a), so that for any gain value the direct error is always available. If the system gain G is incorporated in the error operational amplifier as in fig 4.7.2(b) by using an output resistance GR, the amplifier output is GV_e.

For the above reason it is convenient to use the general system of fig 4.7.2(c). It is important to note that if an additional operational amplifier is introduced to provide gain G, this also introduces an additional sign reversal in the loop, giving positive feedback unless some additional sign reversal is introduced (see Practical 4.1 Feedback Polarity).

In the Controller section of the Analogue Unit there is an operational amplifier at the right hand end which enables convenient values of gain to be introduced, and changing the power amplifier input socket provides an additional sign reversal.

The additional amplifier has input resistors of 100KΩ and feedback resistors of 100KΩ, 500KΩ and 2MΩ hence with various different arrangements gains of 1, 2, 5, 20 and 25 can be obtained.

Connect up the system of fig 4.7.3, making an X-Y display of the error.

Apply an input of ±5V at 0.1Hz and estimate the steady following error with controller operational amplifier gain of 1, i.e input and output resistance of 100KΩ and P_1 at 50.

Increase the gain to:
    2   : (2 x 100KΩ input in parallel and 100KΩ output)
    5   : (100KΩ input and 500KΩ output)

Note that the error decreases inversely with increasing gain, but that the transient response deteriorates as expected.
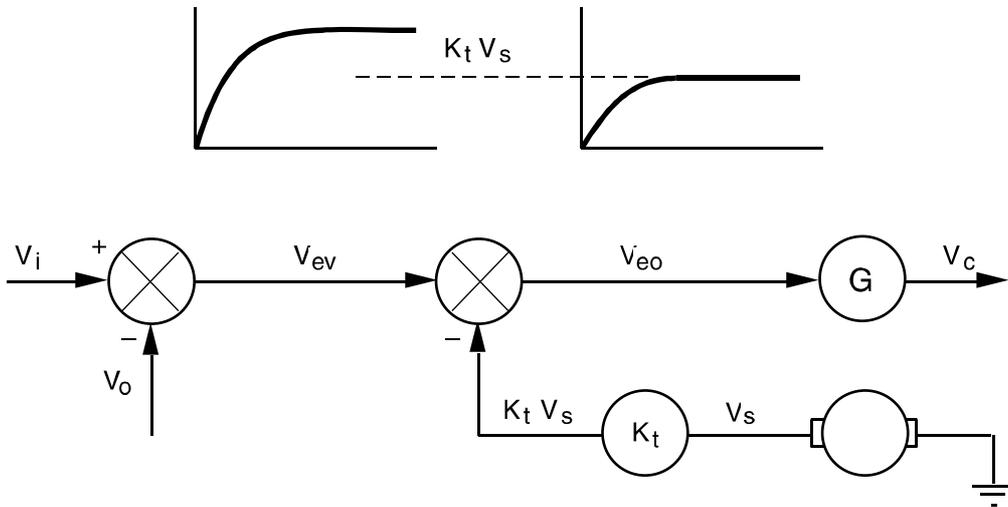
Fig 4.7.4 - Increased following error with velocity feedback
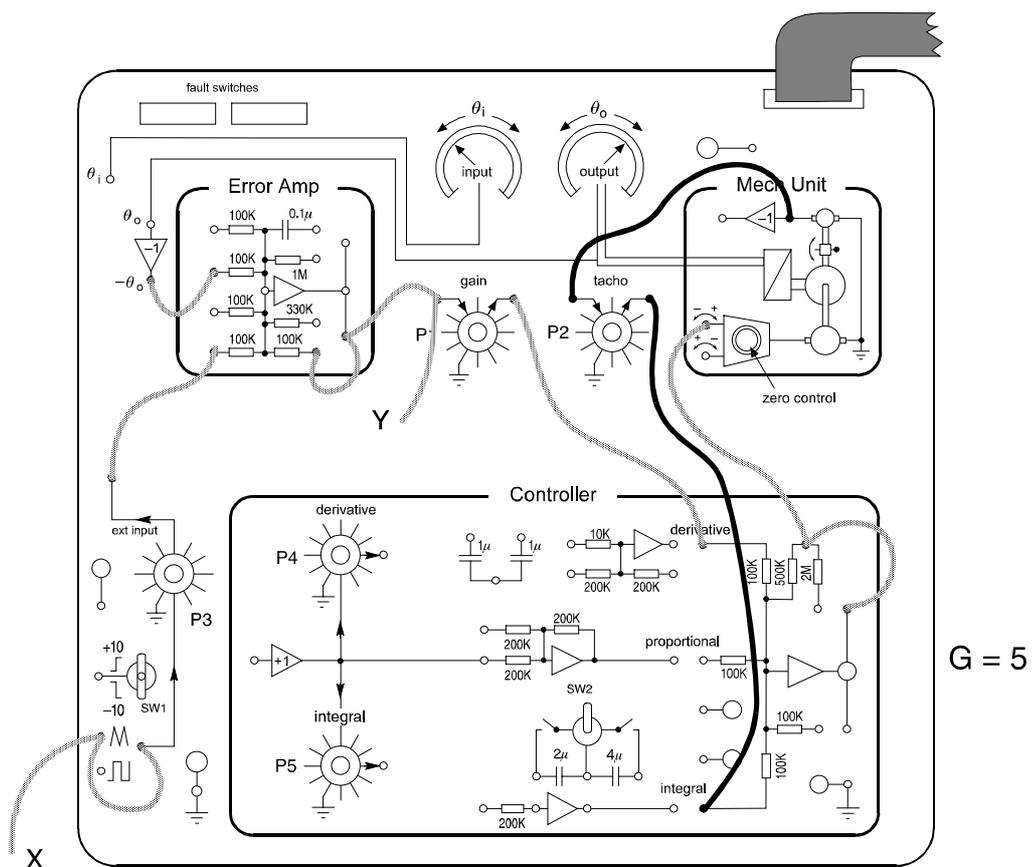
*Fig 4.7.5 - Additional connections (solid) to operational
amplifier of fig 4.7.3 for velocity feedback.*

System Following Error   **Assignment 7**

**Velocity
(tachogenerator)
Feedback and
Following Error**

Since velocity feedback improves the step response transient, it could be supposed that the following error transient response would also be improved. This is correct, but there is the disadvantage that the use of velocity feedback increases the steady following error.

The application of velocity feedback is represented in fig 4.7.4, (see also fig 4.7.1), where V_c is the control voltage applied to the power amplifier. If the system is following at the same steady speed the motor drive V_c must remain constant and hence the signal immediately before the amplifier G must have the same value as the original error (V_{eo}) without velocity feedback. However the actual error between V_i and V_o (V_{ev}) must increase so that when $K_t V_s$ is subtracted, the original error is available as input to G, thus:

error with velocity feedback (V_{ev}) – $K_t V_s$ = original error (V_{eo})

or $V_{ev} = V_{eo} + K_t V_s$

PRACTICAL 7.2

Velocity Feedback

To investigate the effect of velocity feedback on following error:

Connect the system of fig 4.7.3, including the X-Y display and the triangle input signal (shown as shadow connections in fig 4.7.5).

Add the solid connections of fig 4.7.5 which apply velocity feedback, setting P_2 to zero.

Set the controller amplifier gain to 5, and apply a triangle input of ±5V at 0.1Hz.

As P_2 is turned up to 100% the error transient will improve, but the steady following error V_{ev} will increase.

System Following Error   **Assignment 7**

SUMMARY   This assignment has investigated steady following error, which
                               can be an important performance requirement for a control
                               system.

                               It has also been shown that increasing the system gain reduces
                               the steady following error but causes the transient response to
                               deteriorate.

                               It has been shown that velocity feedback will improve the
                               steady following error transient; but will increase the following
                               error.

                               In a later assignment a method of improving the transient
                               response without increasing the following error is investigated.

System Following Error   **Assignment 7**

UNSTABLE SYSTEM **ASSIGNMENT 8**

The following Practicals are included in this assignment:

8.1 Additional Time Constant

8.2 Unstable System

UNSTABLE SYSTEM   **ASSIGNMENT 8**

CONTENT   The effect of an additional time constant is investigated to show that a system which requires high gain can become unstable.

**EQUIPMENT
REQUIRED**

QTY	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1		Oscilloscope, storage or long-persistence, preferably with X-Y facility. *(eg Feedback 1810-01229)*

UNSTABLE SYSTEM

UNSTABLE SYSTEM   **ASSIGNMENT 8**

OBJECTIVES   When you have completed this assignment you will know that :

ν   A time constant can be represented by an operational amplifier circuit.

ν   An additional time constant causes a system transient response to deteriorate.

ν   With high gain the system may become unstable.

KNOWLEDGE LEVEL   Before you start this assignment you should :

ν   Be familiar with the equipment and the general properties of control systems, preferably by completing Assignment 5, The Influence of Gain.

PRELIMINARY PROCEDURE

The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.
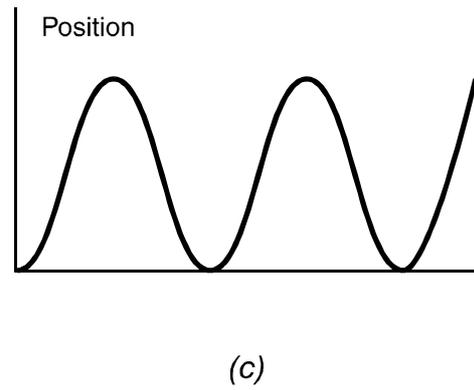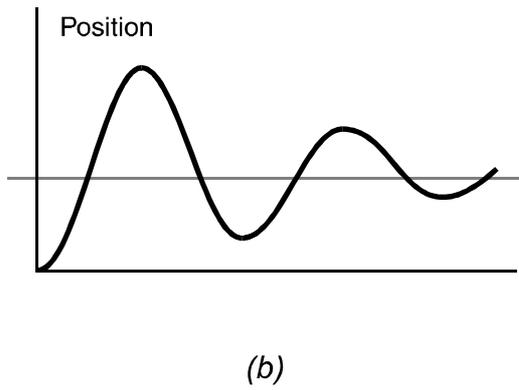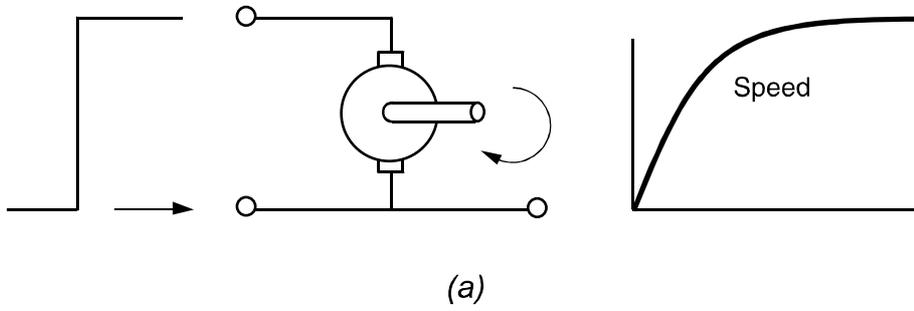
(a)

(b)

(c)

Fig 4.8.1 - System characteristics due to delay.

Unstable System   **Assignment 8**

INTRODUCTION

Unstable System   Motor characteristics are investigated in Assignment 3, Practicals 3.3 and 3.4, and it is shown that there is a delay in the speed response of a motor to a sudden change of supply voltage. If a step voltage is applied the speed response would be generally as in fig 4.8.1a (see also fig 4.3.8).

It is also shown in the closed-loop step response investigation, Assignment 5 and fig 4.5.2, that the delay in the motor response can cause the system to overshoot and then settle with reducing oscillation as in fig 4.8.1b. An additional separate delay in the system can cause more marked overshoot because the motor has been able to move further before the drive is reversed. The additional delay may lead to sustained or increasing amplitude oscillation, as in fig 4.8.1c.

Thus it is very important to avoid significant additional delay in a system even though various procedures used in a system, such as filtering to eliminate noise on signals or signal processing may introduce delays. If such delays become comparable with those inherent in the system then, at least, the transient response will deteriorate.
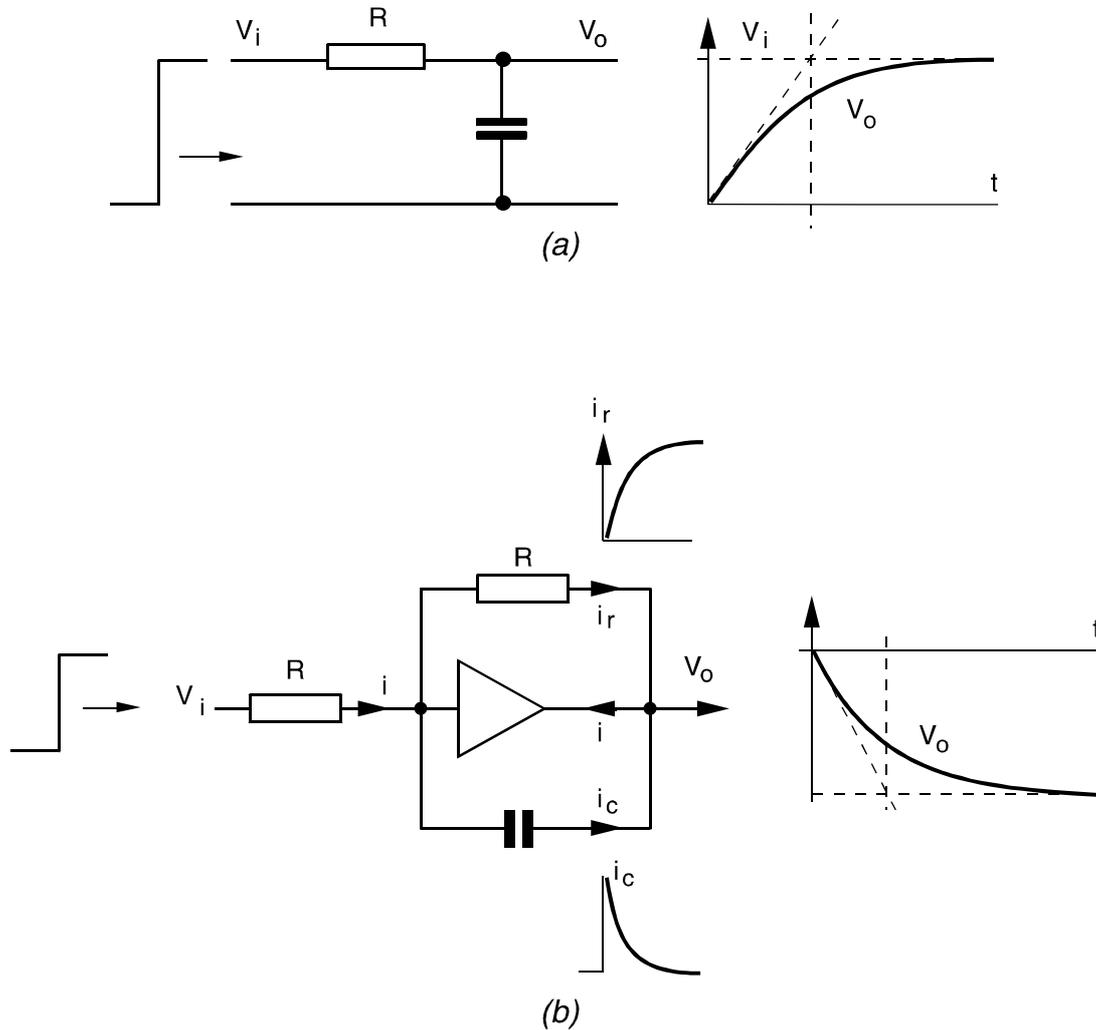
Fig 4.8.2 - Time constant and operational amplifier circuit

Additional
Delay

Most additional delays have the general characteristics of a time-constant, represented by the RC circuit of fig 4.8.2(a), showing the delay in the step response as the capacitor charges through the resistor.

This circuit characteristic may be obtained by the operational amplifier circuit of fig 4.8.2(b) where there is a capacitor in parallel with the output resistor. If a step is applied there is a constant input current since the amplifier input is a virtual earth point.

When the step is applied:

the capacitor current (i_c) = input current (i)

the resistor current (i_r) = 0

Since the input current (i) is constant, thus as the capacitor charges:
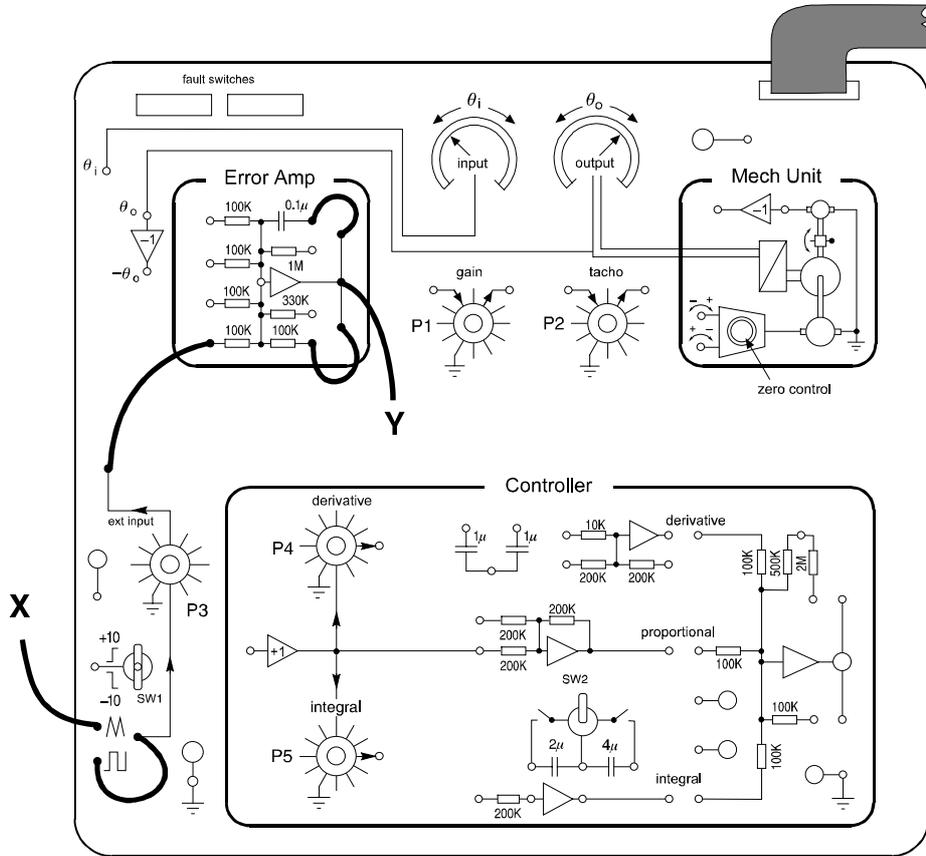
i_c reduces
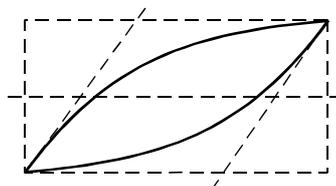
i_r increases

and finally:

$i_c = 0$

$i_r = i$

This gives a voltage output which has a time constant form, with time constant RC, identical with that of the RC circuit of (a), except that the output has reversed polarity.

(a)

(b)

Fig 4.8.3 - Circuit for Practical 8.1

Unstable System   **Assignment 8**

PRACTICAL 8.1

**Additional
Time Constant**   In order to investigate the effect of an additional time constant,
                             the error amplifier has a capacitor available to enable the circuit
                             of fig 4.8.2(b) to be made.

                             Connect the error amplifier as in fig 4.8.3(a), and arrange an
                             X-Y display.

                             Apply a square-wave of ±5V at 2Hz and a time constant display
                             as in fig 4.8.3(b) should be obtained.

                             Since:

                                 C = 0.1µF (nominal)
                                 R = 100KΩ
                                 the time constant should be about 0.01 sec.

                             If the 100KΩ is increased the time constant increases, but the
                             steady gain also increases, so that the input must be reduced
                             to prevent overloading, (output ±10V max). Check the effect of
                             R = 330KΩ and R = 1MΩ.
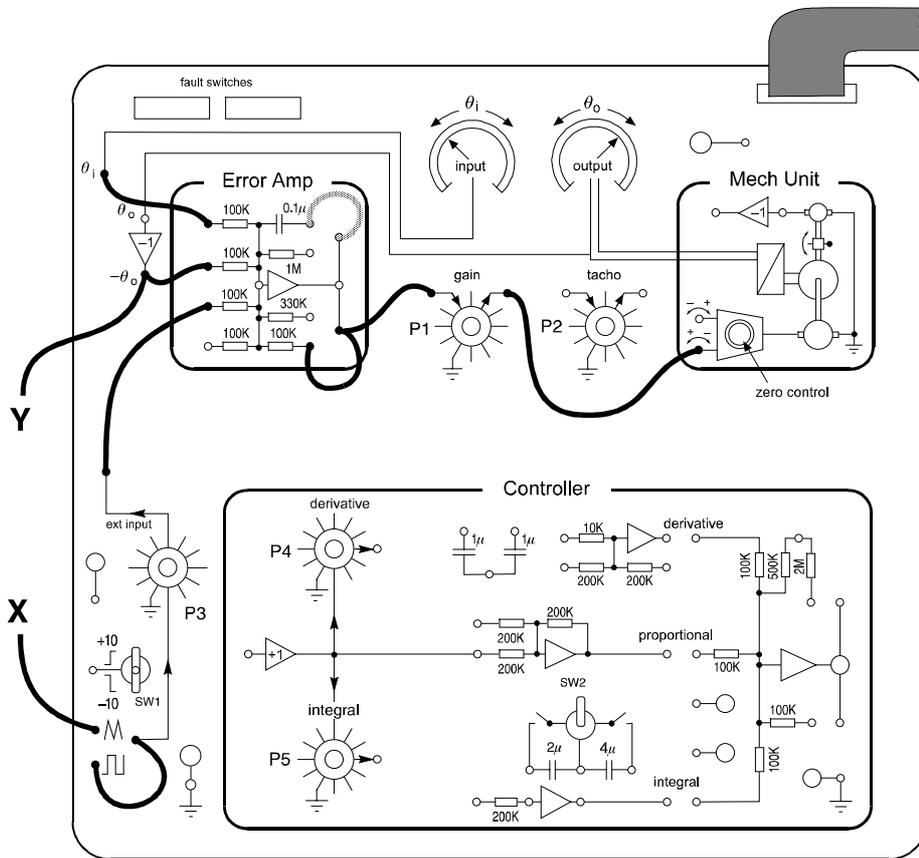
Fig 4.8.4 - Circuit for Practical 8.2 - Unstable system

Unstable System   **Assignment 8**

PRACTICAL 8.2

Unstable System   Connect the system of fig 4.8.4, giving a simple position control with an X-Y display.

Set the error feedback resistor to 100KΩ, without the 0.1µF capacitor. Apply a square wave ±5V at 0.1Hz and set P_1 to 100%.

Note that introducing the capacitor has little effect on the transient, since the time constant (0.01 secs) is small compared with the approximate motor time constant (0.4 - 0.5 sec - see Assignment 3, Practical 3.4).

Set the feedback resistor to 330KΩ and P_1 to 100%. The capacitor will now have a marked effect on the transient. Reduce the input (P_3) to prevent overloading at error amplifier output.

Set the feedback resistor to 1MΩ and connect the capacitor. Set the gain (P_1) and the square wave input to zero. Slowly turn up the gain, at the same time moving the input potentiometer about ±10°. The error amplifier time constant, 0.1 sec, is now appreciable compared to the motor time constant.

The system should eventually maintain self oscillation, with a frequency in the region of 1Hz. Additional gain, if needed, can be obtained from the Controller operational amplifier.

Check that the system can be stabilised by using velocity (tachogenerator) feedback.

Unstable System   **Assignment 8**

SUMMARY   Any additional delay in a system will cause the transient pressure to deteriorate because the motor can overshoot more before the drive signal is reversed.

An additional delay frequently has the characteristics of a time constant and can be represented by an operational amplifier circuit.

The combination of additional delay and high gain can cause a system to become unstable.

SPEED CONTROL SYSTEM   **ASSIGNMENT 9**

The following Practical is included in this assignment:

9.1   Closed-loop Speed Control

SPEED CONTROL SYSTEM   **ASSIGNMENT 9**

CONTENT   A velocity servo (speed control system) is studied with reference to the effect of loading the output shaft with and without the loop closed.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility. *(eg Feedback 1810-01229*

SPEED CONTROL SYSTEM   **ASSIGNMENT 9**

OBJECTIVES   When you have completed this assignment you will know that:

ν   Velocity feedback can be used (without position feedback) to enable a speed to be closely regulated.

ν   The polarity of the feedback is important (as for position feedback).

ν   The effectiveness of the control depends mainly on the gain employed.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Be familiar with the equipment.

ν   Preferably have completed Assignments. 5, The Influence of Gain and 6, Velocity Feedback.

**PRELIMINARY
PROCEDURE**   The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The power supply should be connected by 4mm plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.
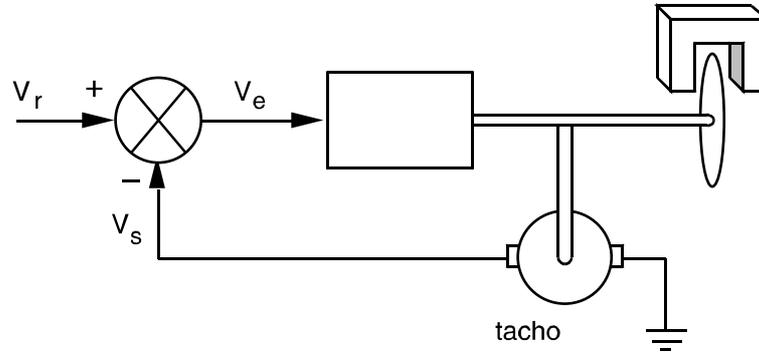
Fig 4.9.1 - Essential features of a 'Closed Loop Speed Control'
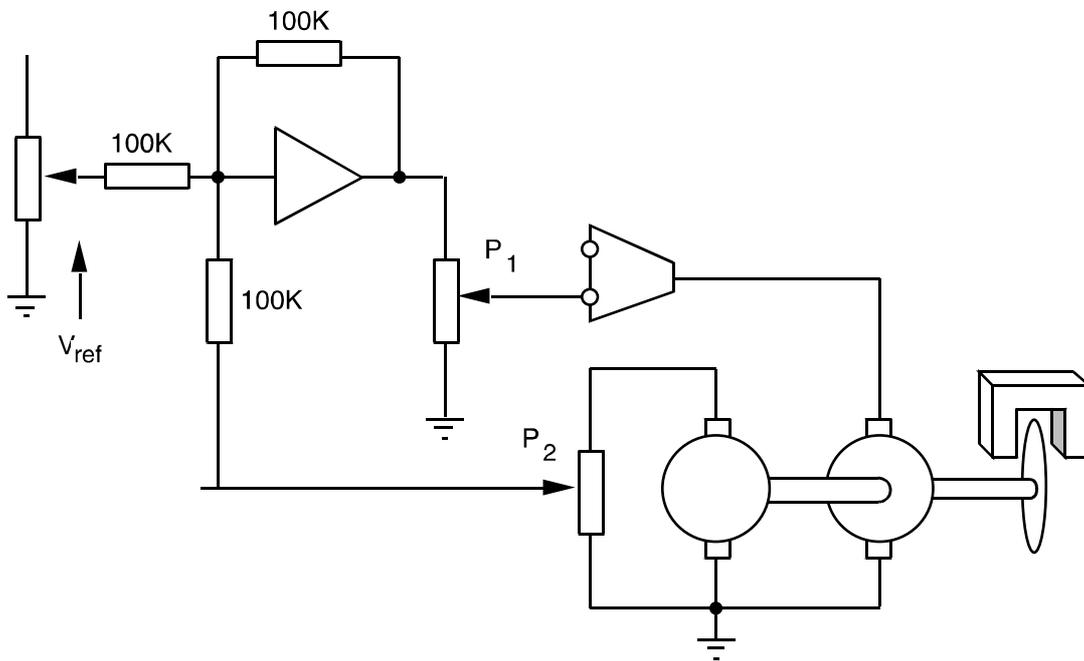

Fig 4.9.2 - Speed Control System

Speed Control System   **Assignment 9**

INTRODUCTION   The previous assignments have been concerned with position control, but an important aspect of closed-loop control is speed control, which has many industrial applications, varying from heavy industrial, such as paper mills or steel rolling mills, to tape or video transport mechanisms.

The essential principle of closed-loop speed control is similar to position control, as illustrated in fig 4.9.1, except that the feedback signal is now an output velocity signal V_s, normally from a tachogenerator, which is compared with a reference voltage V_r to give an error

$$V_e = V_r - V_s$$

In operation the reference is set to a required value, which drives the motor to generate V_s, which reduces the error until the system reaches a steady speed.

If the motor is loaded, eg with the magnetic brake on the 33-100, the speed falls; this tends to increase the error, increasing the motor drive and thus reducing the speed fall for a given load. Note that this implies negative feedback around the loop.

The speed fall with load, sometimes termed '**droop**' is a very important characteristic in speed control systems.

The rotation direction can be reversed by reversing the reference voltage, though many industrial speed control systems are required to operate in one direction only.
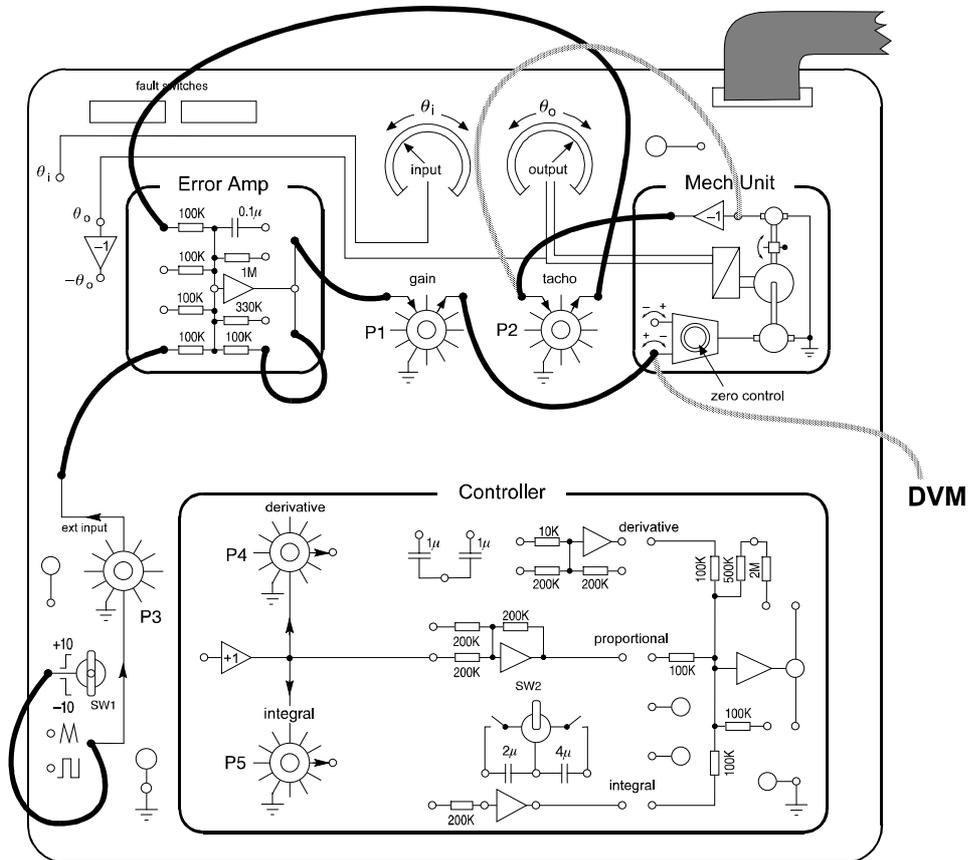
Speed Control System

Fig 4.9.3 - Connections for Practical 9.1

Speed Control System   **Assignment 9**

PRACTICAL 9.1

Closed-loop
Speed Control
A speed control system which can be made with the 33-002 corresponding with fig 4.9.1, is given in fig 4.9.2, with the connection diagram as in fig 4.9.3.

Arrange the system as in fig 4.9.3. Set P_2 (tacho) to zero and set the amplifier feedback resistor to 100KΩ, this gives G = 1. Set P_1 to 100. Set SW1 up to +10 and adjust P_3 to run the motor at 1000 r/min (31.25 r/min at output).

Turn up P_2 slightly, if the speed decreases the loop feedback is negative as required. If the speed increases use the other tachogenerator polarity.

Note that if the system has negative feedback and both the tachogenerator polarity and the power amplifier input are reversed, the system still has negative feedback, but the motor runs in the opposite direction.

Set P_2 to zero and plot the speed against brake setting to full brake load. The general characteristic should be as in fig 4.9.4.
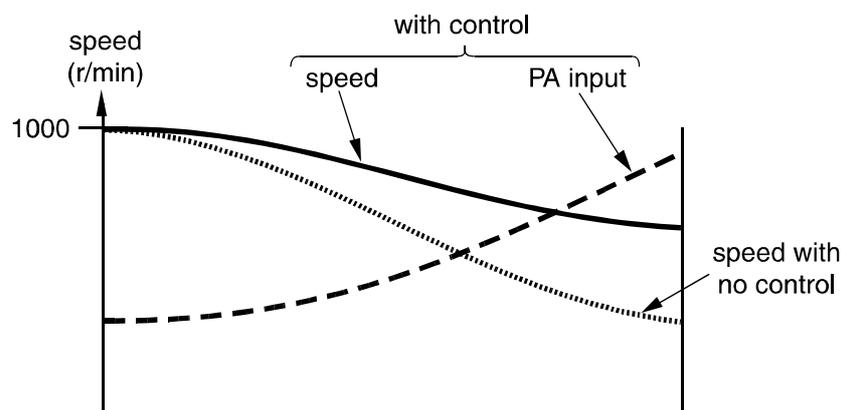

Fig 4.9.4 - Speed Regulation with and without Closed-Loop Control

Note that the armature current, which increases with loading can be measured by correcting the DVM to the Armature Current socket on the Mechanical Unit.

Set P_2 to 100 and readjust P_3 to give 1000 r/min with the brake off. Replot the speed characteristic and error (PA input) up to full brake load. Change the feedback resistor to 330KΩ (G = 3.3), adjust P3 to give 1000 r/min with no load, and replot the load characteristic. The droop should be reduced.

Repeat with G = 10, adjusting P3 as required, and the droop should be less.

The tachogenerator output contains a ripple component which will be amplified in the forward path, and with high gain could saturate the power amplifier.

The ripple can be reduced by connecting a capacitor across the error amplifier output resistor, which introduces a time-constant, (see Assignment 8 and fig 4.82) and reduces the response to fast signals.

With G = 10, set the speed to 1000 r/min on no load and examine the input and output ripple of the error amplifier using the oscilloscope. Note the ripple amplification.

Then connect the 0.1µF capacitor across the output resistor and the ripple will be much reduced. A smaller capacitor could be used.

The introduction of a time-constant as above may be desirable to reduce ripple, but represents an additional delay in the loop, and could cause serious deterioration of the speed step response.

With G = 10, apply a square wave at 0.1Hz and adjust P3 to give a steady speed of ±1000 r/min with no load.

Make an X-Y display with the tachogenerator output to show the step response.

Re-connect the 0.1µF capacitor and note the change in response.

Speed Control System   **Assignment 9**

4 - 9 - 9

SUMMARY   This Practical has shown the general principle of speed control. Increasing the gain would give the system less speed fall at full load. Theoretically an infinite gain would give zero speed fall, but this is impractical. However, good results can be achieved with a different control technique in the error channel.

PRACTICAL
ASPECTS   A problem that may arise in speed control systems, where the full feedback signal is obtained from a tachogenerator, is that the generator output may have an appreciable ripple component due to commutation. This component may be amplified in the system and cause saturation. The ripple can be reduced by filtering in the system, or better by specialised design of the generator.

NOTES

INTRODUCTION TO 3-TERM CONTROL   **ASSIGNMENT 10**

The following Practicals are included in this assignment:

10.1 Derivative Measurement

10.2 Operational Amplifier Integrator

10.3 3-Term Controller Test

INTRODUCTION TO 3-TERM CONTROL   **ASSIGNMENT 10**

CONTENT   To study the effects of combining various levels of proportional, integral and derivative control to produce the 3-term or PID controller.

EQUIPMENT
REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility *(eg Feedback 1810-01229)*

INTRODUCTION TO 3-TERM CONTROL   **ASSIGNMENT 10**

OBJECTIVES   When you have completed this assignment you will know that:

ν   A very versatile control signal can be obtained by combining components depending on the error, the derivative of the error, and on the integral of the error.

ν   With capacitor input, an operational amplifier acts as a differentiator.

ν   The input must be modified, giving partial differentiation, for practical reasons.

ν   With a capacitor in the feedback path, an operational amplifier can act as an integrator.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Understand the basic working of an operational amplifier, including the concept of 'virtual earth'.

ν   Preferably have completed Assignment 2, Operational Amplifier Characteristics.

PRELIMINARY PROCEDURE

The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.

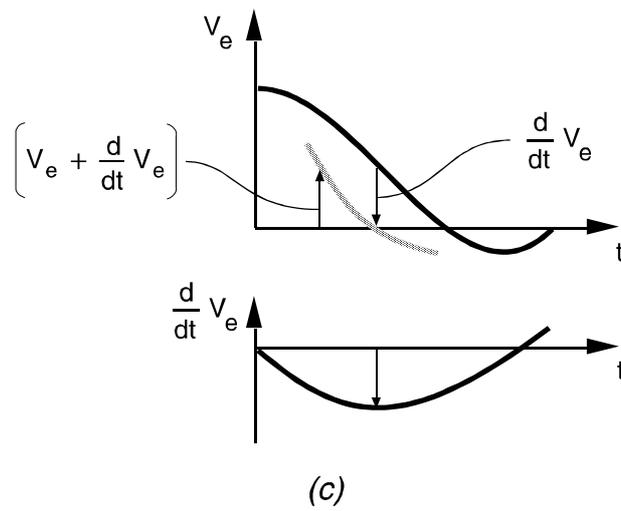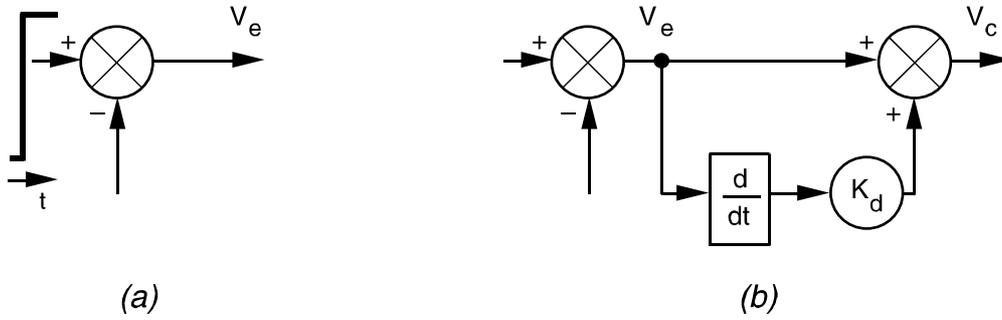**Introduction to 3-Term Control**   **Assignment 10**

(a)   *(b)*

(c)

Fig 4.10.1 - Derivative of Error

Introduction to 3-Term Control   **Assignment 10**

INTRODUCTION   Previous assignments have considered system performance and how this is affected by gain. In principle a higher gain leads to improved performance in respect of reduction of dead-band and following error and also to a reduction of droop with increasing load for a speed control system. The disadvantage of high gain is that the transient response deteriorates, giving overshoots or oscillations. This can be corrected by the use of velocity (tachogenerator) feedback, but that increases the steady following error.

A more general method to improve system performance is to arrange that the drive signal to the motor or other output element is a combination of the direct error, with components of the derivative (rate of change), and integral of the error. Since the final drive signal contains three components or terms, the process is called Three-Term Control.

Derivative
of Error   When a step input signal is applied, the error signal will typically respond as shown in the upper portion of fig 4.10.1(c). The derivative or rate of change of error corresponds graphically with the slope of the error graph. If the derivative is measured the general form will be as the lower diagram. Initially the slope is zero, reaches a maximum negative value (corresponding with rapidly decreasing error) shortly before the system initially reaches alignment and then falls to zero when the system reaches maximum overshoot.

If the derivative signal is added to the error signal, the combination of error and derivative goes to zero before the system aligns (dotted V_e graph). Thus if the power amplifier drive signal V_c is formed from V_e by:

V_c = error + derivative of error

$$= V_e + \frac{dV_e}{dt},$$

then V_c will reverse the motor drive before alignment of the output shaft is reached, much improving the transient response. The arrangement is illustrated in fig 4.10.1(b), where the amount of derivative signal is adjustable by K_d to give:
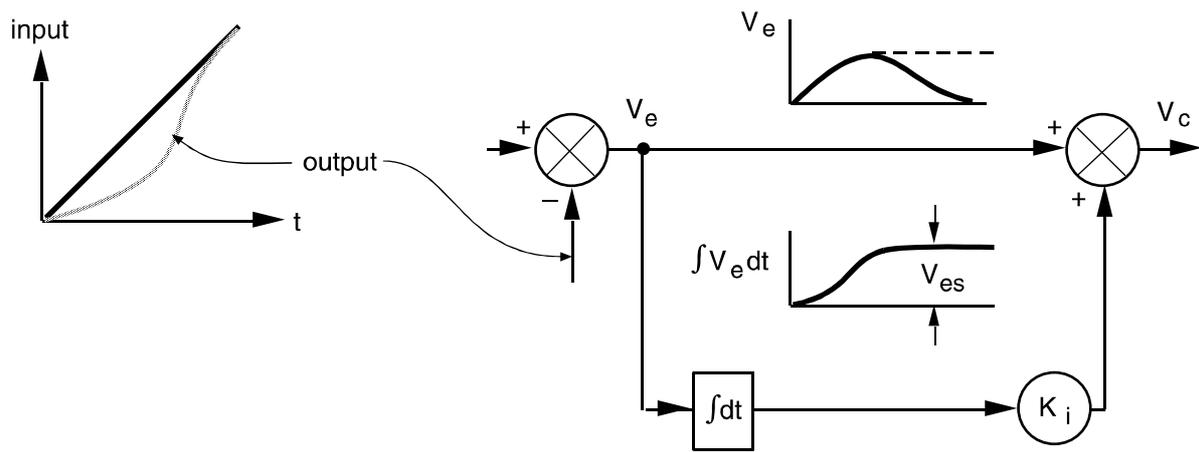
$$V_c = V_e + K_d \frac{dV_e}{dt}.$$

The general effect of error derivative is similar to velocity feedback (see Assignment 6 and fig 4.6.1), but is obtained by operating on the error only.
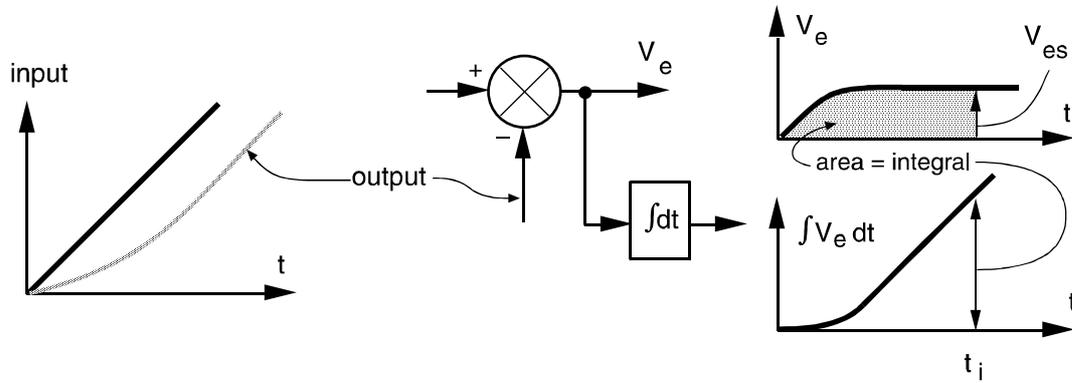
(a) error and integral of error

(b) integration on forward path

Fig 4.10.2 - Integral Control

Introduction to 3-Term Control   **Assignment 10**

Integral of Error

Suppose that a simple position control system is following a ramp input, the steady error (V_{es}) will be exactly that required to drive the motor to make the output speed match the input speed. This is investigated in Assignment 7, and is illustrated in the upper portion of fig 4.10.2(a).

Suppose that the error is integrated by some method. At any time the value of the integral is the area under the error. This is indicated for a particular time t_1 in fig 4.10.2(a). If the error has reached the steady value V_{es}, the integrator output would rise steadily.

If the integrator output is added to the error to form V_c, as in fig 4.10.2(b), the motor control voltage is given by:

$$V_c = V_e + K_i \int V_e \, dt$$

Initially when the ramp is applied the error will occur as in the upper diagram, but the integrator output will gradually build up. This will cause the motor to speed up slightly, reducing the error, but as long as there is **any** error the integrator output will continue to increase. The only situation that will give a constant integrator output is that the error has fallen to **zero**, and this is what happens.

The integrator final output becomes V_{es}, as in fig 4.10.2(b), being the signal required to drive the motor at the speed to match the input.

The use of an integrator in the forward path, which is called **integral control**, gives the characteristic that any steady error is reduced to zero with the integrator output established at exactly the value required to provide the motor drive to maintain the error at zero. Integral control is commonly applied to speed control systems and if the measured speed does not exactly match the required speed due to loading, the integrator will develop an output to reduce the error to zero.

A problem that may arise with integral control is that the integrator takes some time to develop the required output and if the system operating condition suddenly changes, the integrator requires time to readjust. This may lead to a slow and undesirable oscillatory transient response.
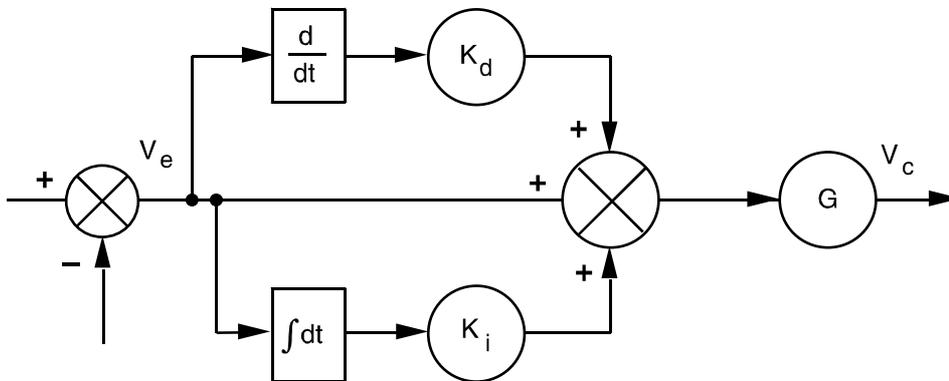
Fig 4.10.3 - Three-Term Control

**Three-Term
Controller**

As mentioned previously, a general controller combines integral and derivative actions, with the direct error as in fig 4.10.3 giving:

V_c = G (error + K_d [derivative of error] + K_i [integral of error])

$$V_c = G\left(V_e + K_d \frac{dV_e}{dt} + K_i \int V_e \, dt\right)$$

where there is an adjustable overall gain G, and the integral and derivative components are individually adjustable. The controller is often referred to as a P.I.D (signifying Proportional + Integral + Derivative) controller.

The processes required in a Three-Term Controller, the generation of derivative and integral signals and their combination in adjustable proportions are very easily realisable in analogue form with operational amplifiers if the signals are available as voltages. However, it is possible to realise Three-Term Controllers in a non-electrical medium such as pneumatics.

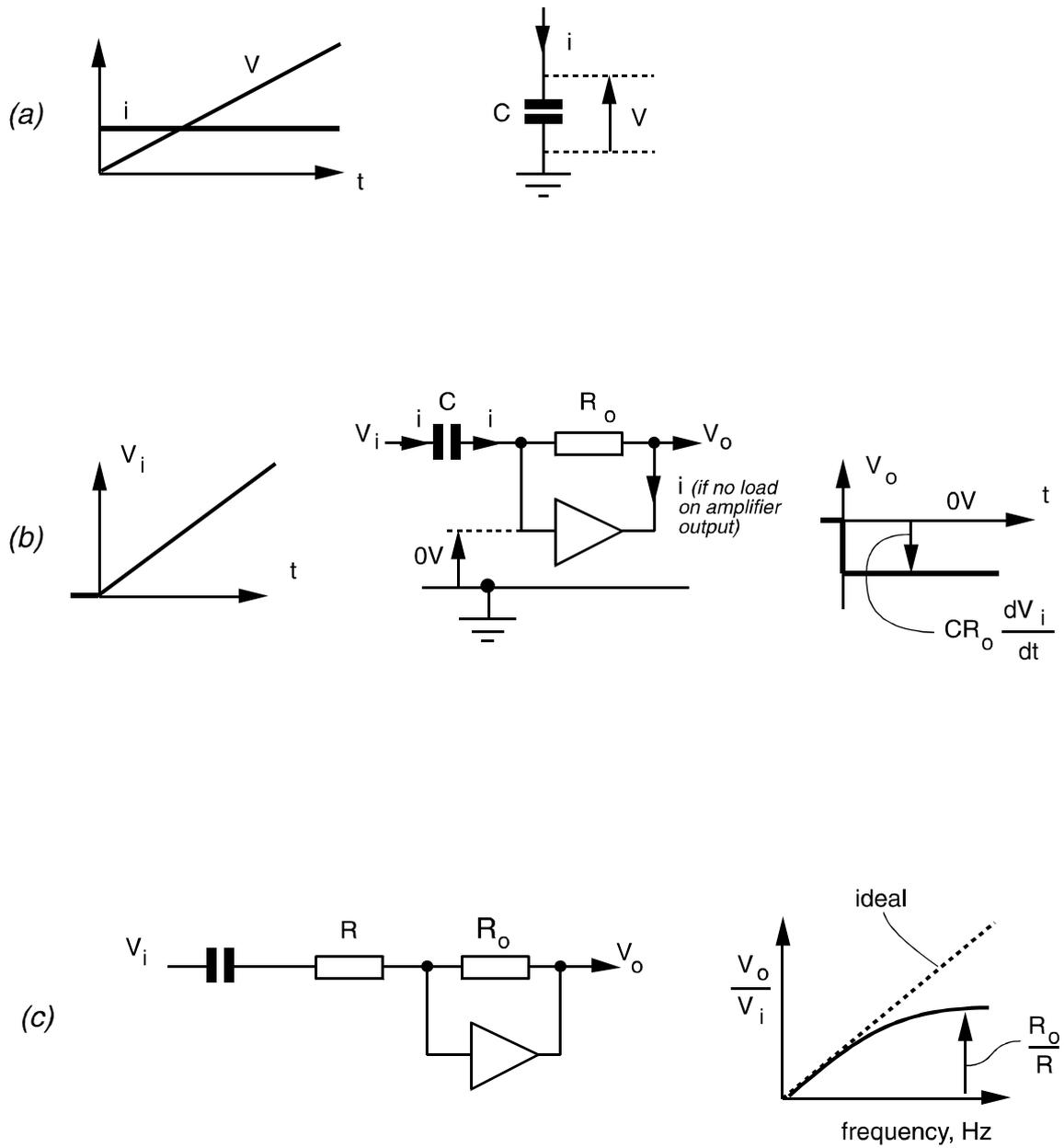**Introduction to 3-Term Control**   **Assignment 10**

NOTES

Introduction to 3-Term Control   Assignment 10

(a)

(b)

(c)

Fig 4.10.4 - Differentiation by Operational Amplifier

Introduction to 3-Term Control   **Assignment 10**

**DIFFERENTIATION
BY OPERATIONAL
AMPLIFIER**

Suppose that a ramp voltage is applied to a capacitor as in fig 4.10.4(a). Since the voltage across the capacitor rises steadily a constant current must flow into the capacitor. The current is proportional to the capacitance C, being given by the relation

$$i = C\frac{dv}{dt}.$$

If the capacitor is used as the input element for an operational amplifier as in (b), the amplifier input will be a virtual earth point (see Assignment 2 and fig 4.2.3) and the amplifier output will be given by

$$V_o = iR_o$$

and since

$$i = C\frac{dv}{dt},$$

finally

$$V_o = -CR_o\frac{dv}{dt},$$

giving the constant output voltage of (b). This indicates the derivative of the input with a scaling factor $-CR_o$.

Although this circuit in principle measures the derivative, there is a limitation in practical application. If the input signal contains noise or disturbance components which are small but rapidly changing, these may cause currents in the capacitor comparable to those of slower changing signals for which the derivative is required. These unwanted components in the input are emphasised and may even saturate the amplifier or some later stage in the amplifying system.

The effect of unwanted rapidly changing high frequency components can be limited by a resistor in series with the capacitor as in fig 4.10.4(c). If the input is changing slowly the input current is largely determined by the capacitor, but if the input is changing fast the current is limited by the resistor giving an overall gain of R_o/R.

In frequency response terms the gain of the ideal differentiator in (c) rises continuously with increasing frequency, noise corresponding with high frequency components. The introduction of an input resistor, called a limited derivative, gives a gain initially rising with frequency, representing correct derivative action, but finally becoming constant preventing emphasis of high frequency components.
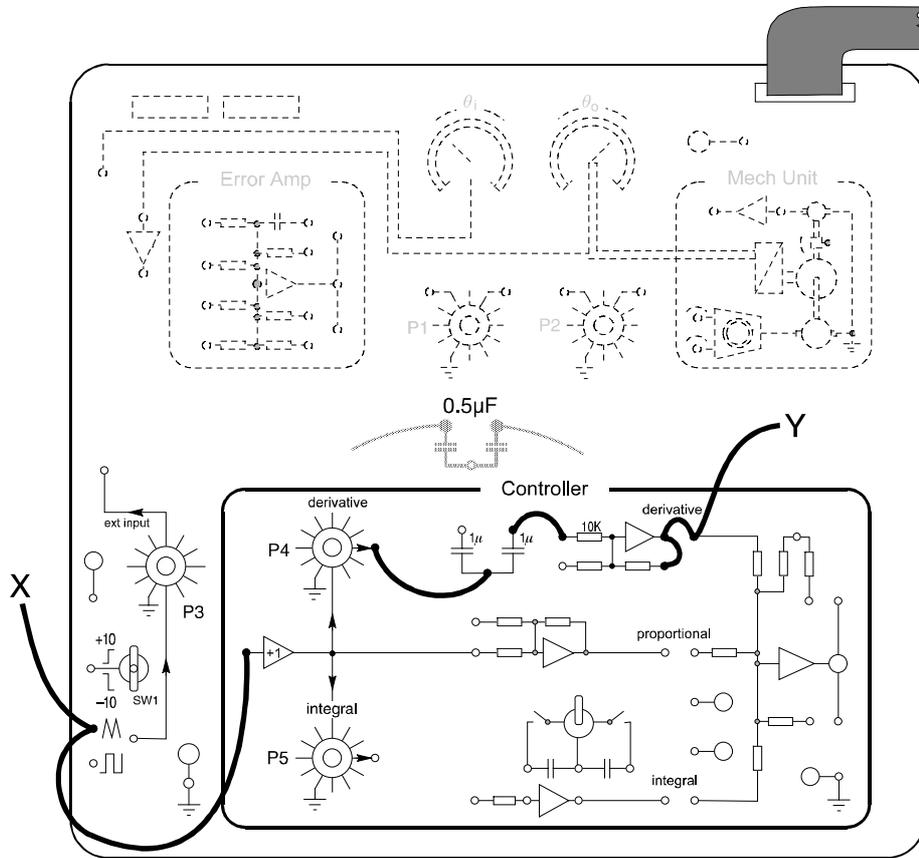
Fig 4.10.5(a) - Connections for Practical 10.1

Fig 4.10.5(b) - X-Y Display

Introduction to 3-Term Control   **Assignment 10**
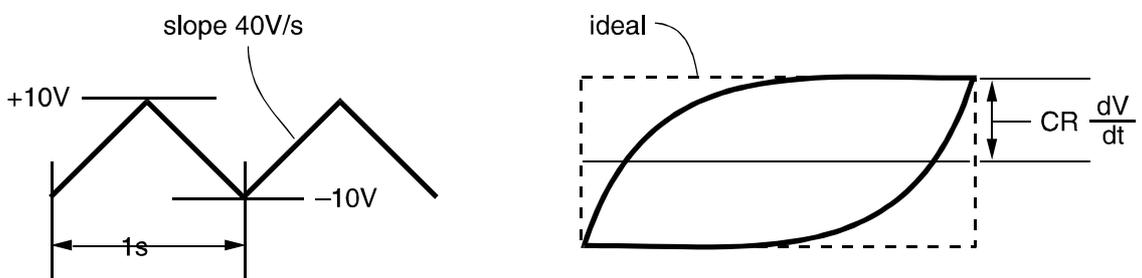

PRACTICAL 10.1

**Derivative
Measurement**

The upper amplifier in the Controller is intended for use as a differentiator. The two 1µF capacitors can be used in series to give 0.5µF, singly to give 1µF or in parallel to give 2µF.

Arrange the circuit of fig 4.10.5(a), where the upper amplifier is connected as a limited differentiator with 1µF capacitor and adjustable input from the triangle test waveform.

Make an X-Y display between the triangle waveform and the amplifier output.

Set the test frequency to about 1Hz, and turn up P_4 to 100. A display should be obtained as in fig 4.10.5(b), the steady value being $CR(^{dV}/_{dt})$. The time-constant start of the waveform is due to the effect of the 10kΩ resistor.

For a frequency of 1Hz, the test waveform changes through 20V in 0.5 second, hence

$$\frac{dv}{dt} = 40 \text{ V/s.}$$

Since the capacitor is 1µF, a voltage rate of change of 1V/s would give i = 1µA, so 40V/s gives i = 40µA, where i is the current in fig 4.10.4(a), (b).

If R_0 = 200kΩ, the steady output voltage would be

$$\pm\, 40\mu A \times 200\,k\Omega \quad (\text{i.e } CR\frac{dv}{dt}) = \pm\, 8V$$

If the frequency is reduced the steady value will fall proportionately.

If the capacitance is reduced to 0.5µF (both capacitors in series), the amplifier output will fall to 50%, but the time to establish the steady value will also fall to 25%.

Set P_4 to zero, and using 1µF, connect directly to the amplifier input socket. As P_4 is turned up a fast initial response will be obtained but a large pulse or oscillation may appear on the output.

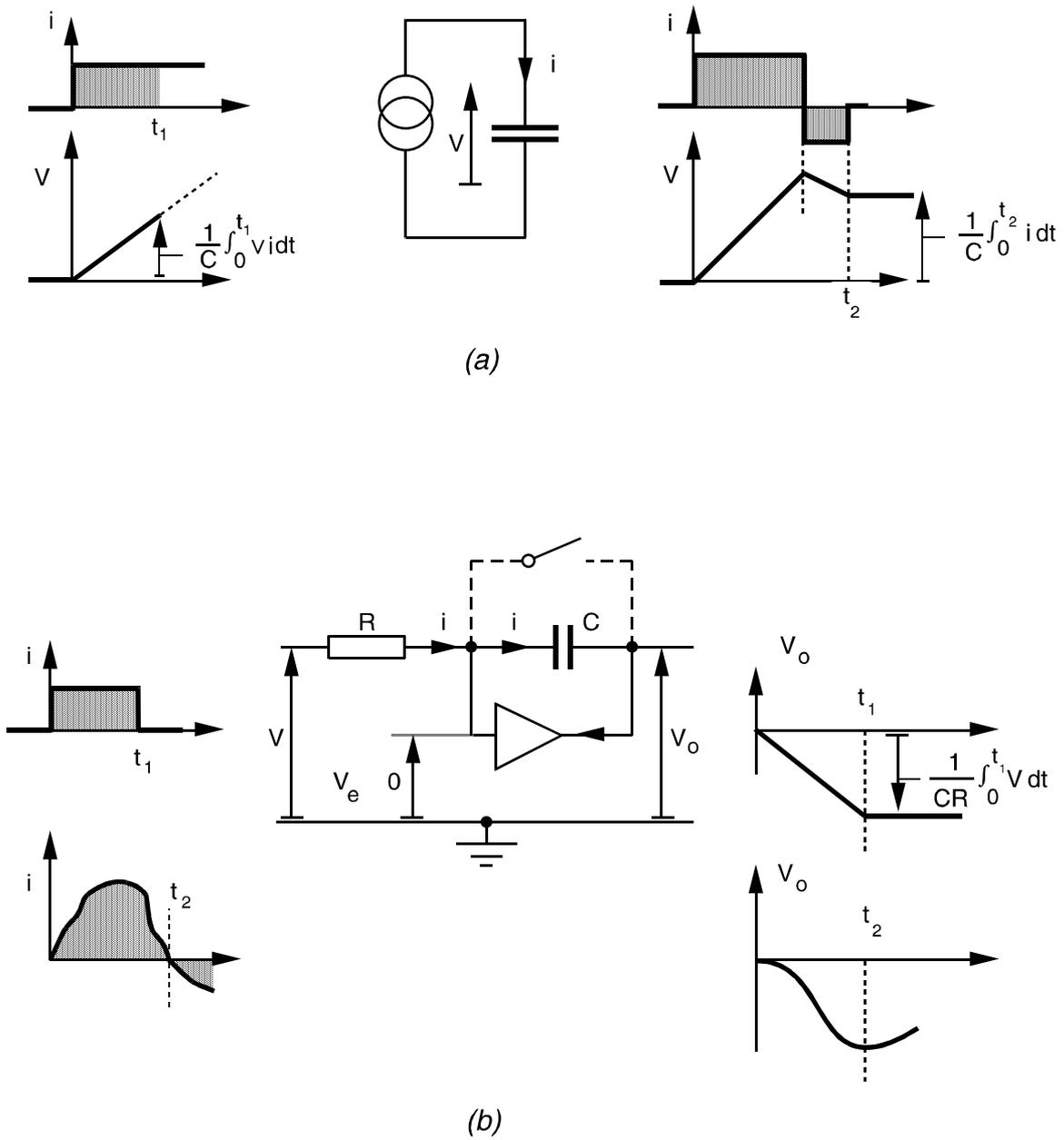**Introduction to 3-Term Control** **Assignment 10**

(a)

(b)

Fig 4.10.6 - Operational Amplifier as Integrator

INTEGRATION BY OPERATIONAL AMPLIFIER

Conversely to fig 4.10.4(a) and page 4.10.11, the voltage across a capacitor is given by the **integral** of the current through the capacitor:

$$v = \frac{1}{C}\int i \ dt.$$

This is illustrated in fig 4.10.6(a). A constant current gives a steady increase of voltage, the voltage representing the area under the current /time plot.

The illustrated current pulse waveform, comprising a positive pulse, a negative pulse and then zero current, gives a final voltage value, which is the overall time integral of the current.

Integration can be obtained by an operational amplifier if the feedback resistor is replaced by a capacitor as in fig 4.10.6(b). If a voltage V is applied an input current i will flow through R and the amplifier output will change to hold the amplifier input point (virtual earth point) substantially at zero. This means that the amplifier output will steadily increase to maintain the current i through the capacitor. The input current is

$$i = \frac{V}{R}.$$

The voltage across the capacitor will be

$$V_c = \frac{1}{C}\int V dt$$

giving the amplifier output as

$$V_o = -\frac{1}{CR}\int V dt$$

which is the negative scaled integral of the input.

If the applied voltage V becomes zero, the current i is also zero and the integrator holds indefinitely whatever output has been obtained, since the amplifier does not ideally draw any current at the virtual earth point. If the input is a general waveform the output is correspondingly scaled integral.

It is often required to set the output of an integrator to zero before the start of integration, and this can be arranged by a switch, mechanical or electronic, connected across the capacitor, as shown dotted, which discharges the capacitor. Integration does not start until the switch is open, irrespective of a possible input signal.

An ideal integrator will hold an accumulated signal indefinitely, however an operational amplifier may draw a very small current at the virtual earth input, which will cause the output to drift very slowly. The drift may or may not be important and depends on the amplifier used.

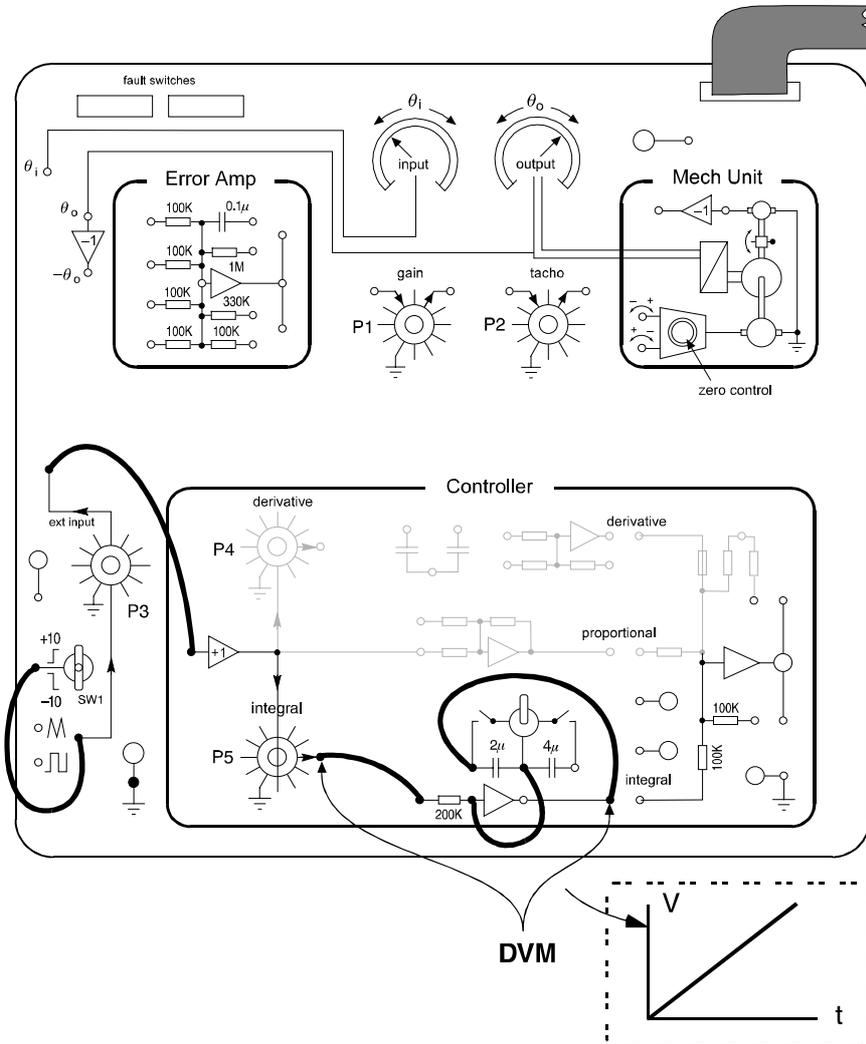# Introduction to 3-Term Control

Assignment 10

Fig 4.10.7 - Connections for Practical 10.2

Introduction to 3-Term Control **Assignment 10**

PRACTICAL 10.2

Operational
Amplifier Integrator

The lower amplifier in the Controller is intended for use as an integrator. The capacitors are 2μF and 4μF and the switch short-circuits both capacitors when set towards the amplifier.

Arrange the integrator amplifier with 2μF as in fig 4.10.7. Set SW1 down to −10 and set P_3 to supply about −3V to the controller input. P_5 can then be used to obtain a smaller voltage for the integrator input resistor.

Short circuit the integrator capacitor by the switch and adjust the integrator input voltage to −1V.

Connect the voltmeter to the amplifier output and open the capacitor switch. The output should move positively and can be reset to zero by closing the switch.

If the input voltage is 1V and the input resistor is 200kΩ, then the input current i is

$$\frac{1V}{200\,k\Omega} = 5\mu A.$$

If the capacitor is 1μF, 5μA gives 5 volts per second

2μF, 5μA gives 2.5 volts per second

hence the output should take about four seconds to move from 0V to +10V.

The +10, 0, −10 switch can be used to make the integrator operate in both directions or **hold** with the switch at 0V.

(If an oscilloscope is available with a long persistence screen and a time base with a 5 to 10 second period, the integrator output can be displayed directly).

Disconnect the input from P_5. Now any current drawn at the virtual earth point will pass through the capacitor and be integrated.

Discharge the capacitor by the switch and then open the switch and estimate the time required for the output to reach 10V — it may be some minutes.

The input current can then be determined, since 1μA gives 0.5 volt/second with 2μF. The value should be much less than 1μA.
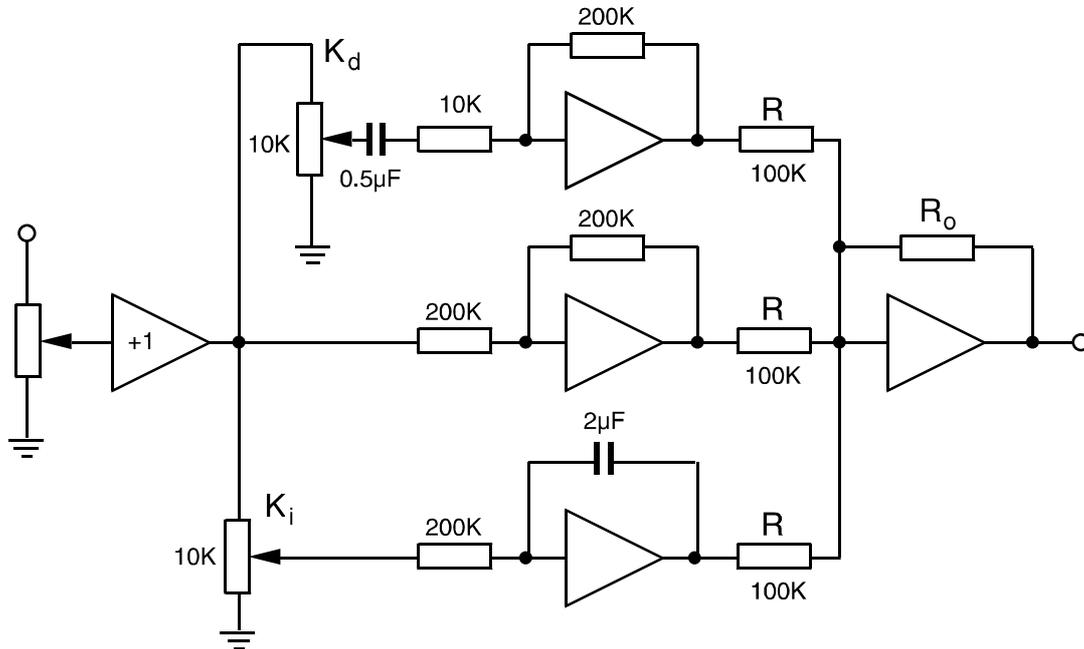
Fig 4.10.8(a) - Operational Amplifier Realisation of 3-Term Controller.
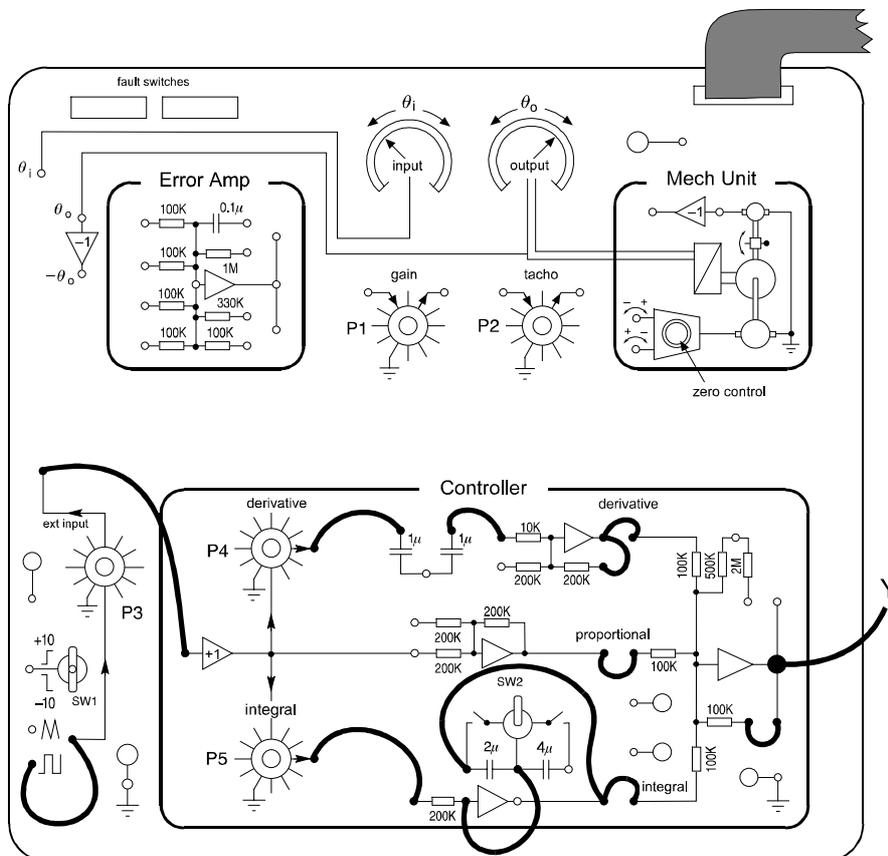

Fig 4.10.8(b) - Controller connections for Practical 10.2

Introduction to 3-Term Control   **Assignment 10**

THREE TERM CONTROLLER REALISATION

The operational amplifier circuits providing integration and differentiation have been investigated and can be combined together with a proportional component to give the '3-Term Controller' of fig 4.10.8(a).

The component values have been chosen so that the circuit can be plugged up on the controller section of the analogue unit as in fig 4.10.8(b). Individual adjustment of K_d(P4) and K_i(P5) is given by the two potentiometers and a fixed overall gain of K is obtained in the output summer by R_o/R.

A very important point in the operational amplifier realisation is that both the integrator and differentiator have a negative sign, hence the proportional component must **also** have a negative sign conveniently provided by an inverting unit in the proportional path. If the individual components are combined in a summer, which introduces an additional sign reversal, there is then no overall sign reversal.

The input is passed through a +1 buffer unit, which provides a high input resistance so that the circuit can be operated from another potentiometer to provide an adjustment on the overall gain K.

PRACTICAL 10.3

3-Term Controller Test

Connect up the circuit of fig 4.10.8(b) with R_O 100KΩ, and apply a square wave ±5V at about 1Hz. Set P_4 and P_5 to zero.

The proportional path has an effective gain of +1 and hence should provide a direct square wave output of ±5V.

Unplug the proportional component from the summer and set P_4 to about 20. The output component will be a pulse as shown in fig 4.10.9. The ideal derivative of a square wave is infinite and of zero duration when the wave changes sign and zero when the wave is constant. A practical differentiator gives a finite pulse as shown.

Set up P_4 to zero and P_5 to 100. Discharge the capacitor by SW2. When SW2 is opened the integrator output will be a triangular waveform of about 6V total swing.

Finally combine all components together to give a waveform generally as in fig 4.10.9.
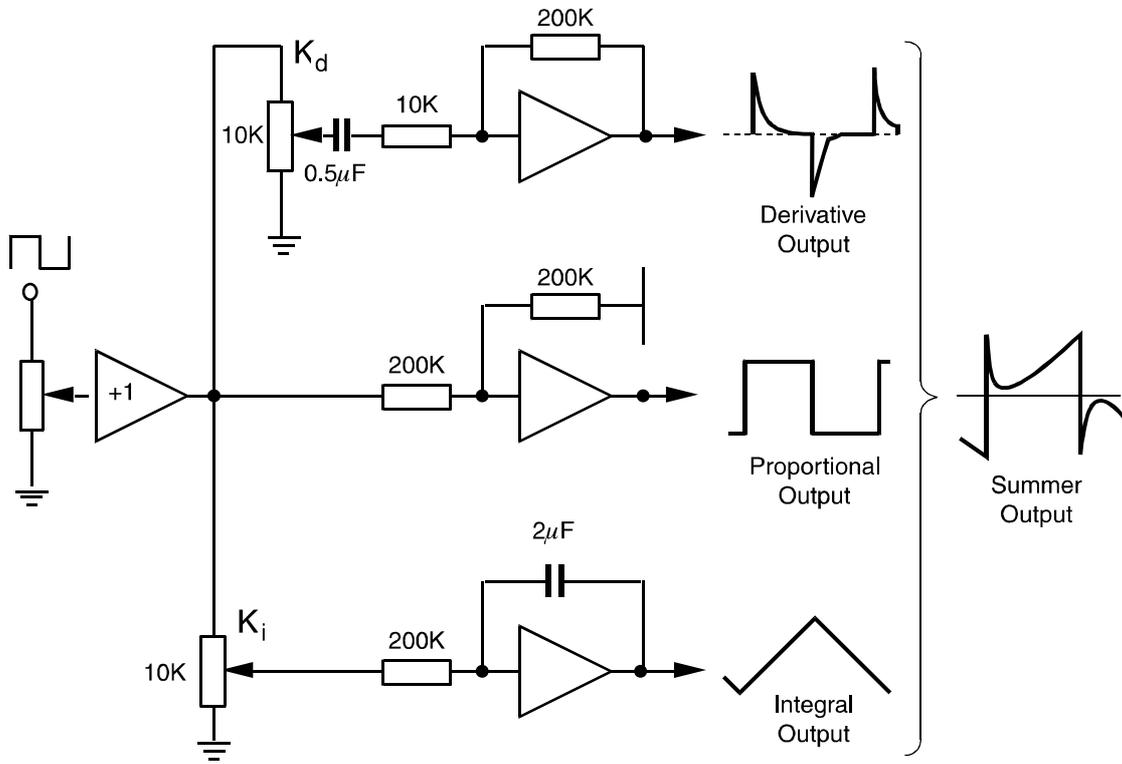
Fig 4.10.9 - P I D Output Waveforms

(sign reversal omitted for components)

Introduction to 3-Term Control   **Assignment 10**

SUMMARY

In a simple system the drive to the output element (commonly a motor) is by the direct error with some forward path gain. This is termed Proportional control, since the drive is proportional to error.

This assignment has investigated the generation of other control signals, or actions, from the error.

The rate of change of error, or derivative, when combined with the direct error gives Proportional + Derivative, or P + D control. The derivative action has characteristics similar to velocity feedback leading to improved transient response.

The Integral of error combined with the direct error gives Proportional + Integral, or P + I control. The integral action has the property of eliminating steady errors, such as that occurring when following a ramp input.

These two control actions combined with the direct error, give 3 Term Control, Proportional + Integral + Derivative or P + I + D control.

This assignment has also shown that derivative and integral control actions can be obtained from the direct error by operational amplifier circuits.

Subsequent assignments (11 and 12) give examples of 3-Term control.

NOTES

APPLICATION OF 3-TERM CONTROL ACTIONS   **ASSIGNMENT 11**

The following Practicals are included in this assignment:

11.1 Proportional plus Derivative (P + D) Control

11.2 X-Y Display of Error Components

11.3 Following error with Derivative Control

11.4 Elimination of Following Error

11.5 Elimination of Disturbance

11.6 Speed Control, Relation between V_{ref} and V_s

11.7 Response to Output Loading

APPLICATION OF 3-TERM CONTROL ACTIONS

ASSIGNMENT 11

CONTENT

To study the effects on transient response when using derivative control.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility *(eg Feedback 1810-01229)*

APPLICATION OF 3-TERM CONTROL ACTIONS

ASSIGNMENT 11

OBJECTIVES

When you have completed this assignment you will know that:

ν Proportional with Derivative control improves transient response

ν Proportional with Integral control eliminates steady errors but may give a slow response

ν The combination of proportional, derivative and integral gives the best response.

KNOWLEDGE LEVEL

Before you start this assignment you should:

ν Be familiar with control system principles, preferably from completing Assignments 5, The Influence of Gain and 7, System Following Error.

ν Be familiar with 3-Term control principles, preferably from completing Assignment 10, Introduction to 3-term Control.

PRELIMINARY PROCEDURE

The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.

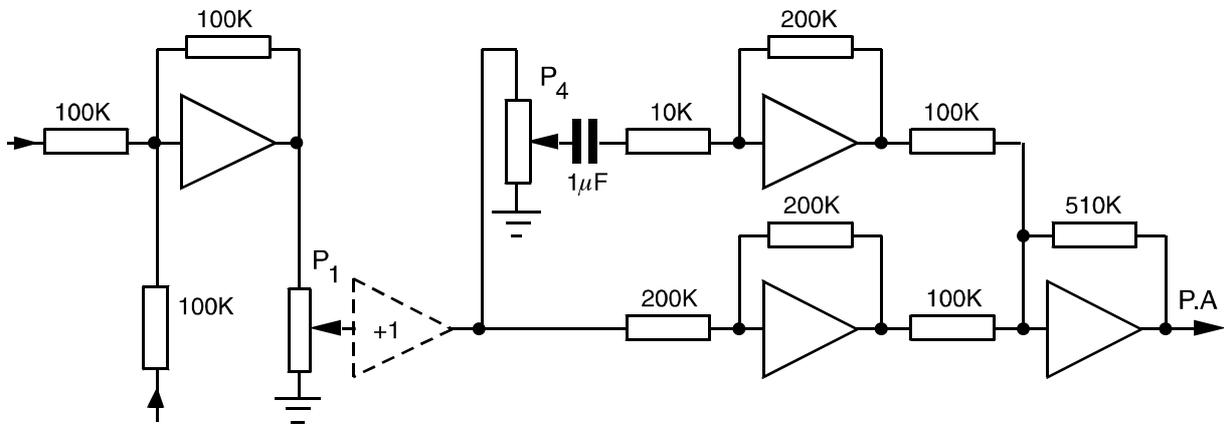## Application of 3-Term Control Actions   Assignment 11
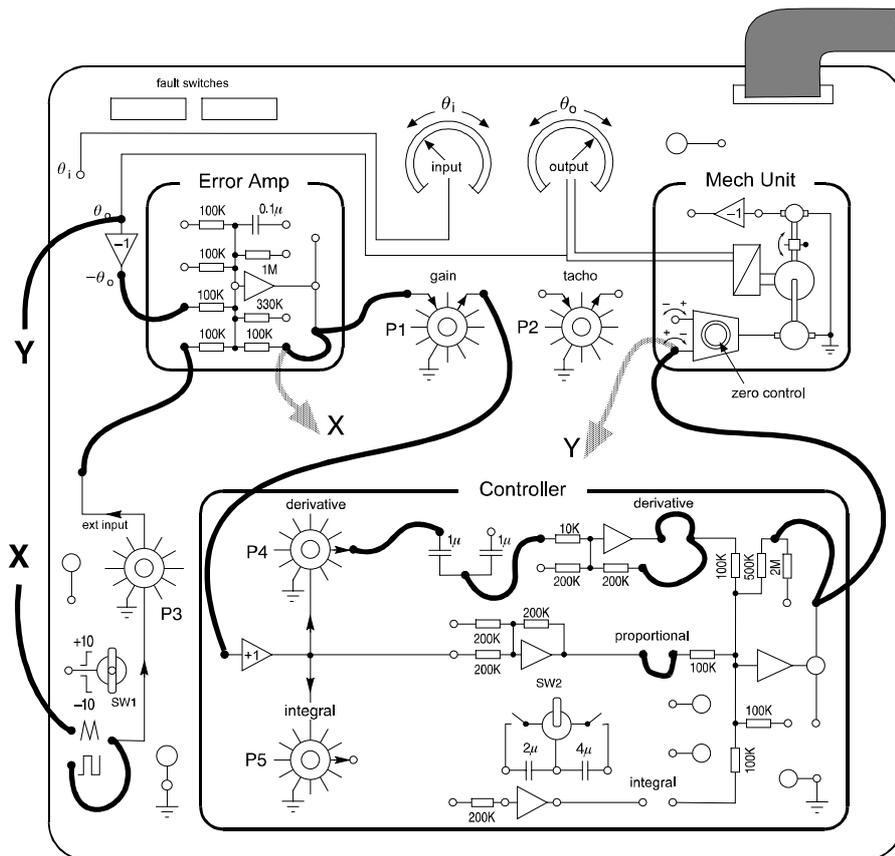

Fig 4.11.1(a) - Circuit for P + D Controller

Fig 4.11.1(b) - P + D Controller connections

Application of 3-Term Control Actions   **Assignment 11**

INTRODUCTION

**Derivative Control
Application**

The general characteristics of derivative control and the operational amplifier realisation of derivative action are given in the initial portion of Assignment 10 and fig 4.10.1 and fig 4.10.4.

The general effect of derivative control is similar to velocity (tachogenerator) feedback in providing improved transient response.

PRACTICAL 11.1

**Proportional plus
Derivative (P + D)
Control**

A circuit to realise proportional + derivative control which can be made on the 33-002 is given in fig 4.11.1(a), with the corresponding connection diagram in (b).

Connect the system of fig 4.11.1(b), note that since the error amplifier gain is unity the true error is available at the amplifier output. There is a gain of 5 in the controller summing amplifier so that P_1 at 100 gives G = 5.

Apply a square wave of about ±3V at 0.2Hz. With P_1 at 100 and P_4 at zero use an X-Y display to examine the output, θ_o, and note that there is a significant transient.

Turn up P_4 which will reduce the transient and a 'dead beat' (just no overshoot) response should be obtainable.

Display the output from the derivative amplifier, note the initial pulse which is derivative response to the initial step edge of the error.

Note that if the error amplifier is overloaded and limits, the derivative does not operate correctly. Investigate the action with an increasing magnitude input and Error Amplifier gain 10, Controller summer gain 1.

PRACTICAL 11.2

X-Y Display of
Error Components   It is possible to make an oscilloscope display that gives a good
demonstration of derivative control operation. In Assignment
10, fig 4.10.1, and the accompanying text, the general principle
of derivative control is explained, showing that the combination
of error and derivative results in the power amplifier drive V_c
reversing before the system has aligned.
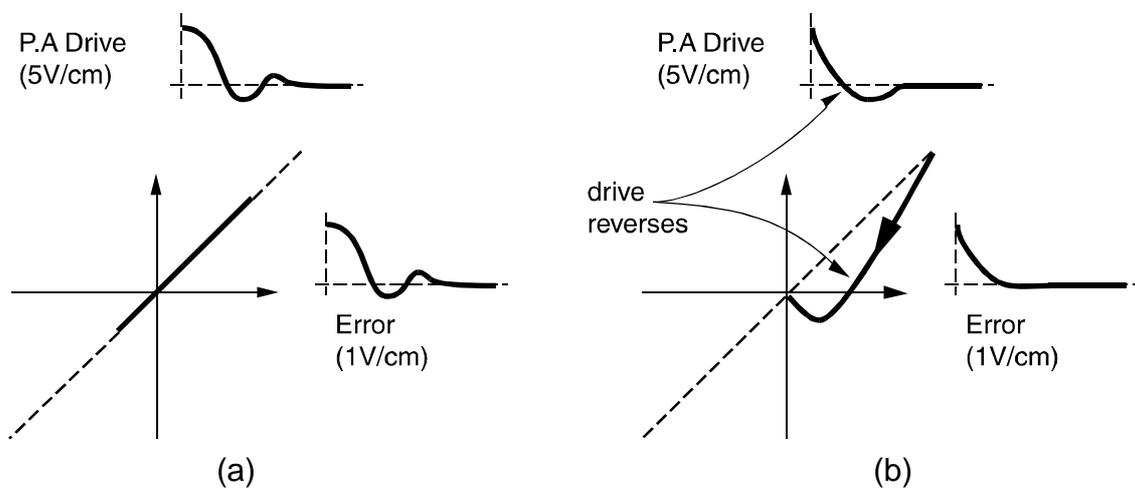
Fig 4.11.2 - X-Y Display showing effect of derivative control.

To illustrate this, consider an X-Y display with the error
horizontal (X) and the power amplifier drive vertical (Y) as in fig
4.11.2(a). If the derivative (P_4) is set to zero in fig 4.11.1(a), the
power amplifier drive is the proportional component
(5 x error). If the X and Y channel gains are in the ratio of 5 : 1,
the step response display will be an oscillatory signal along a
straight line, since both signals have the same form.

If derivative control is introduced the power amplifier drive is
not the same form as the error and the display ceases to be a
straight line. If P_4 is adjusted to give dead-beat response, a
display of the form of (b) will be obtained. This display shows
that the power amplifier drive (vertical) has reversed before the
error has reached zero, so that the motor is slowing up as
alignment is approached.

Make an X-Y display between error (X at 1V/div) and power
amplifier drive (Y at 5V/div), as shown shaded in fig 4.11.1(b).

With P_4 at zero, apply the same square wave input as Practical
11.1, and a display as fig 4.11.2(a), should be obtained.

Application of 3-Term Control Actions   **Assignment 11**

Adjust P_4 as in Test 3 to give a dead-beat response and the display of (b) should be obtained. The power amplifier drive reverses when the derivative component is equal and opposite to the error.

Using an X deflection from the triangle test signal it is useful to examine the error, derivative and power amplifier drive separately.

PRACTICAL 11.3

**Following Error
with Derivative
Control**

Although derivative control has an effect similar to velocity feedback in improving transient response, derivative control does **not** increase the steady following error.

This arises because velocity feedback introduces a constant component proportional to output velocity (see Assignment 7, Introduction to Practical 7.2 and fig 4.7.4), while derivative control does not introduce any constant component.

With the circuit of fig 4.11.1(b), set P_1 at 100 and P_4 at zero, apply a triangular wave input of about ±8V at 0.1Hz. Examine the error, which will show a noticeable transient component, and estimate the magnitude of the steady component when the transient has ceased.

Turn up P_4 and the transient component will be improved but the steady component will be unchanged.

The tests in this assignment have shown the effect of derivative control in improving system transient response and its advantage over velocity feedback in that no additional steady following error component is introduced.

Application of 3-Term Control Actions   **Assignment 11**

SUMMARY   The effect of derivative control is to improve the transient
                         response of a system. The effect arises because derivative
                         control can reverse the drive to the power amplifier before the
                         error is zero. Derivative control has the advantage over velocity
                         feedback that the steady following error is not increased.

                         A useful method to investigate transients is to make an X-Y
                         display between various components. Such displays are
                         termed 'phase-plane' displays, since they show the continuous
                         phase or state of the system. The display or path of the system
                         state is usually termed a trajectory.

Application of 3-Term Control Actions   **Assignment 11**

**INTEGRAL
CONTROL
APPLICATIONS**   The general principles of integral control are given in the integral of error portion of Assignment 10, a common application being the elimination of steady following error illustrated in fig 4.10.2. This application is investigated in Practical 11.4 and another application in Practical 11.5.
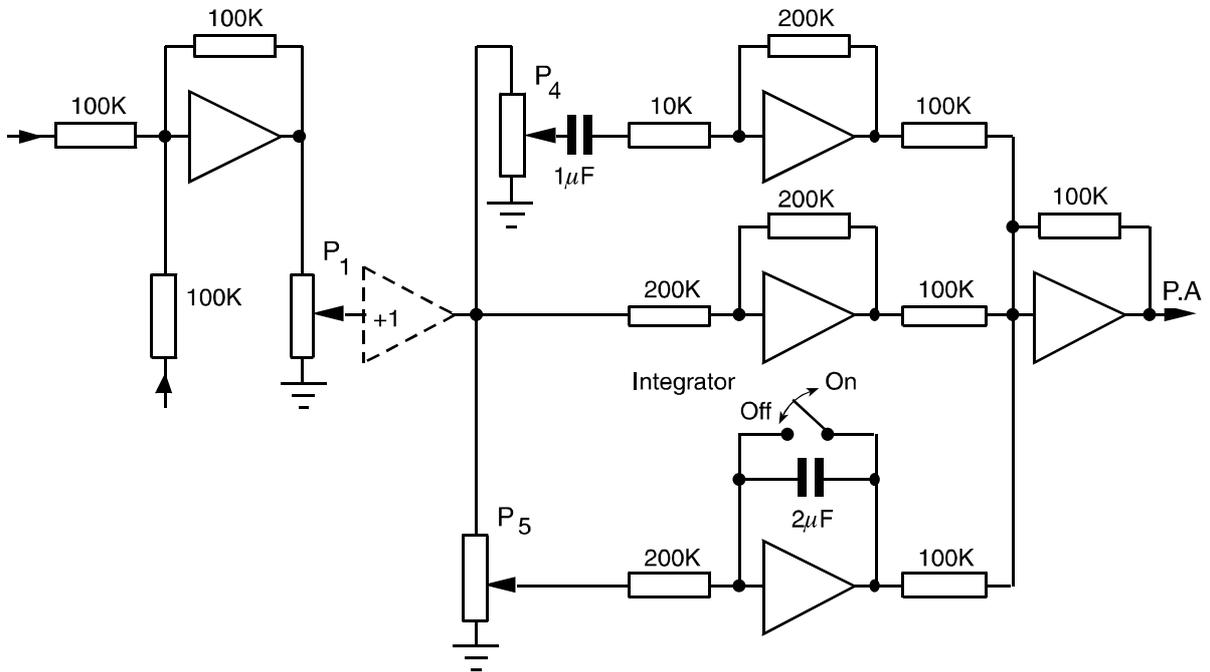
Fig 4.11.3(a) - Circuit diagram
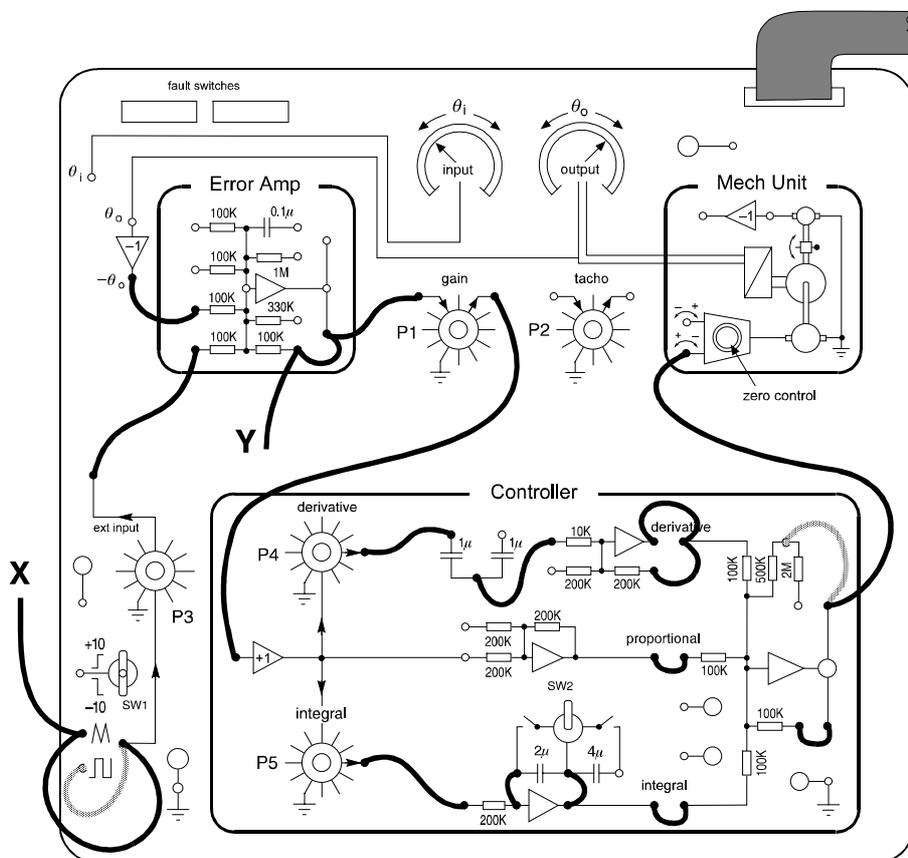

Fig 4.11.3(b)

Application of 3-Term Control Actions   **Assignment 11**

PRACTICAL 11.4

Elimination of Following Error

A circuit to investigate following error is given in fig 4.11.3(a) with connection diagram in (b). The circuit is substantially as in fig 4.11.1, except that an integrator is included.

With the integrator switched OFF (SW2 down), P_4 set to zero, the 3-term summing amplifier feedback resistor set to 100K, and P_1 to 100, the system has a forward gain G = 1. Apply a triangular input of about ±5V at 0.1Hz from P_3.

Make an X-Y display of the error, which should give a constant steady value.

Set the integrator input (P_5) to about 40 and open the integrator short circuit switch.

The error should be "integrated out", though the response may be slow.

Experiment with P_5 adjustment. Note that increasing P_5 eliminates the initial error more quickly but gives a more oscillatory response.

These tests have shown the general property of integral control. An improved transient performance can be obtained by introducing derivative control and increasing the forward path gain.

Change the feedback resistor in the 3 term summing amplifier to 500K, this gives G = 5, but the direct error is still available at the error operational amplifier output.

With triangle input as before, adjust P_4 and P_5 by trial and error to a possible 'best' transient: perhaps just no overshoot. It is useful to increase the input to 0.2Hz.

Display the integrator output to show the output reaching the value required to supply the motor drive.

The adjustment of integral and derivative controls that gives the 'best' transient for following does not give the best step response transient, and some acceptable compromise may be necessary.

Compare the error transients with triangle and step inputs and note that different adjustments of P_4 and P_5 give a slightly better response for each input.

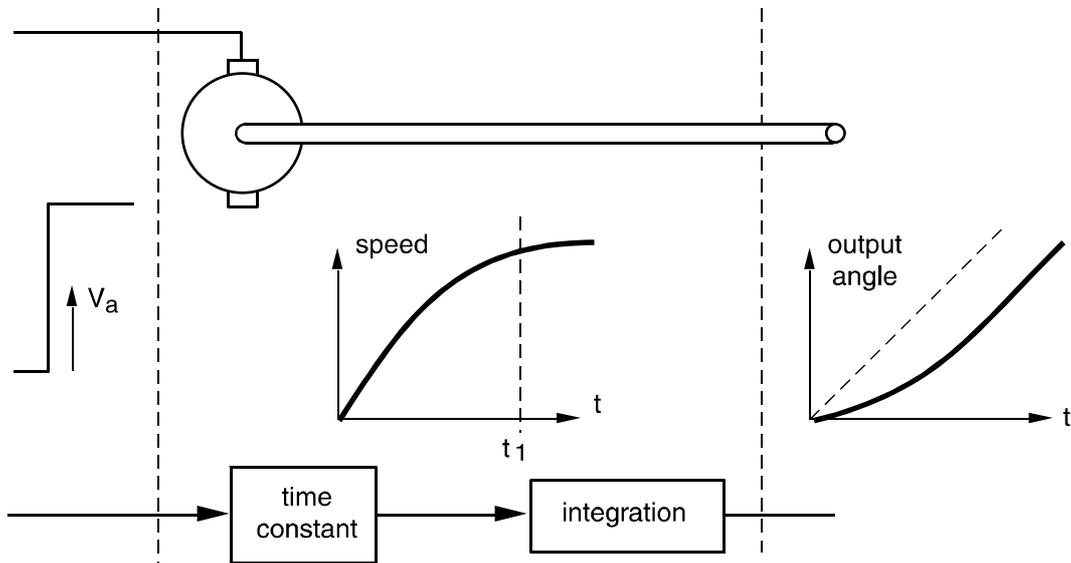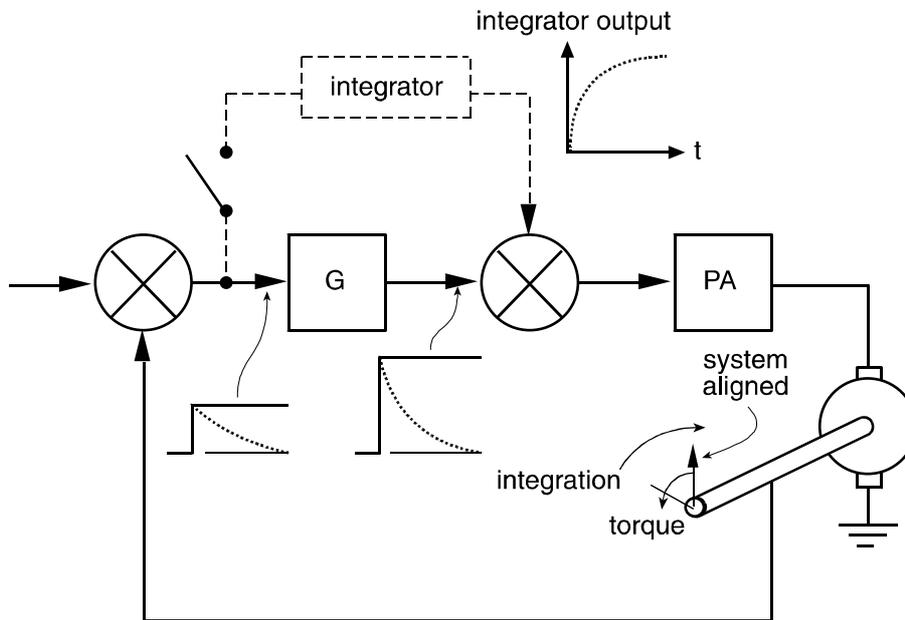## Application of 3-Term Control Actions

Fig 4.11.4 - Motor representation

Fig 4.11.5 - System with disturbance to output

Application of 3-Term Control Actions   **Assignment 11**

PRACTICAL 11.5

**Elimination of
disturbance**

The previous tests have shown that an important application of integral control is to eliminate steady following error. Integral control is not necessary for the steady alignment (i.e step response) of a system with a motor output, but can eliminate the effect of some disturbances.

An ideal motor can be represented, as in fig 4.11.4, by a time constant giving the relation between armature voltage and speed (see Assignment 3 and fig 4.3.7), and an integration giving the relation between speed and output shaft angle, since the output angle will increase however small the velocity. Thus a motor contains an **inherent** integration which for an ideal motor will ensure alignment. However, as mentioned above, the inclusion of a separate integrator may improve the steady alignment against external disturbances.

A simple position control system is illustrated in fig 4.11.5 with an integrator that can be introduced in parallel with the gain to give P + I control. Suppose that the input is at a constant value and the system is aligned (output vertical). If an external torque is applied to the output, which might be wind loading on a rotatable antenna system, the output will be deflected from correct alignment. When this deflection occurs an error signal is produced and the motor will produce a counteracting torque. However, the counteracting torque can only be produced if the system is misaligned. Thus the system will be misaligned to an angle depending on the torque and the system characteristics.

If the integrator is switched on, then when the misalignment error occurs the integrator output will increase and the motor torque will increase, pulling the system back towards alignment. As long as there is **any** error the motor torque will increase until there is zero error. This effect is shown dotted in fig 4.11.5 and finally the integrator provides the input to the motor.

In addition to a direct output disturbance, an integrator can counter any other disturbance that may enter the system after the integrator and cause system misalignment. Such a disturbance might be a power amplifier supply variation, which might cause the motor to rotate slightly.

Application of 3-Term Control Actions **Assignment 11**

**Output
Disturbance**

A controllable output disturbance is not available in the 33-002, but an illustrative test can be carried out as below:

Arrange the system of fig 4.11.3, with 3 term summing amplifier feedback of 510K. Set P_4 and P_5 to the adjustments found to give the 'best' response in Practical 11.4.

Connect the DVM to indicate the armature current (1V/A) from the monitor sockets on the mechanical assembly.

With zero input, P_1 at 100, and integrator OFF, hold the speed disc between finger and thumb and rotate it about 45°. Since the gear reduction is 32 : 1, this corresponds with about 1.5° misalignment.

Note that the armature current increases to a steady value, which will generate a fixed torque, tending to realign the system.

Switch the integrator on and the armature current will start to increase. If the disc is held with only just the force necessary to misalign it, the increasing torque will probably pull the disc back to alignment.

**Disturbance
in System**

A disturbance entering the system after the integrator can be represented by introducing a signal into the 3 term summing amplifier, which is after the integrator with the circuit of fig 4.11.6, using the system of fig 4.11.3 with Controller amplifier gain of 5.

The input potentiometer (θ_i) provides a convenient source of disturbance signal up to ±10V.

Set the input potentiometer to 0° and connect the output to the 100K input as in fig 4.11.6.

Set P_1 to 100, P_4 and P_5 to the adjustments found to give the 'best' response in Practical 11.4.

Switch the integrator OFF and rotate the input potentiometer ±90°. Note that the system follows as though the disturbance was a normal input.

Switch the integrator ON. Rotate the input slowly ±90° and the integrator will counter the disturbance and cancel it when the input is stationary.

Connect P_3 to the square wave test signal at 0.2Hz and apply P_3 output to the 100K input in fig 4.11.6. With the integrator OFF adjust P_3 to give an output movement of ±30°.

Switch the integrator ON and the steady output deflection will be cancelled. Increasing P_5 will give faster cancellation. It is useful to display the integrator output.
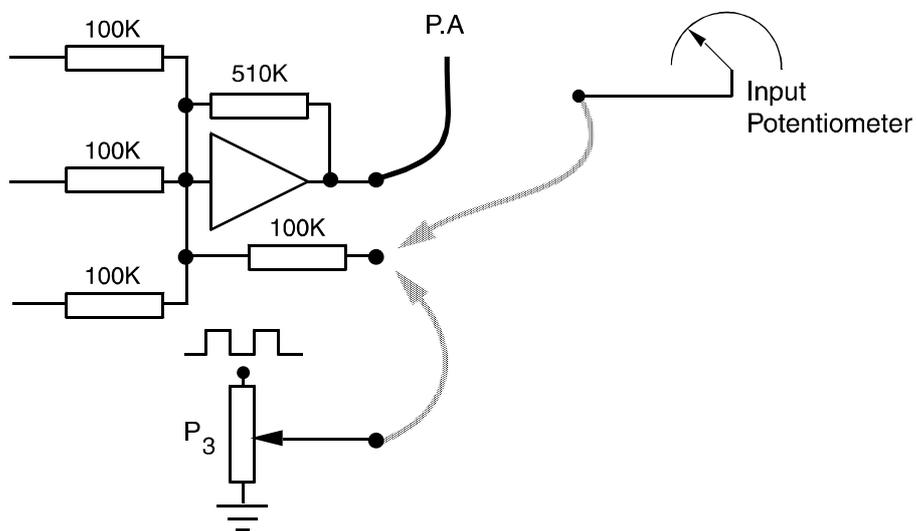

Fig 4.11.6 - Introduction of internal disturbance

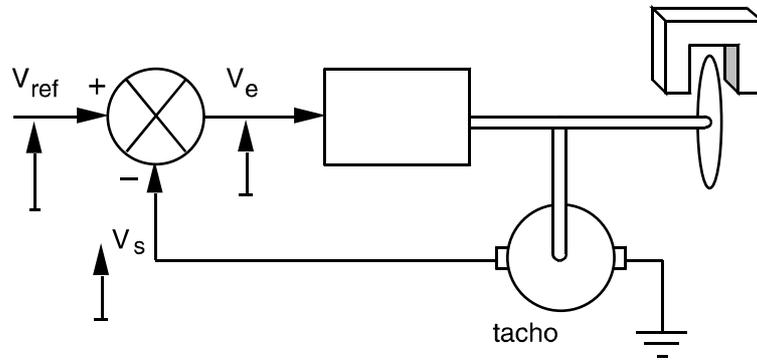## Application of 3-Term Control Actions   Assignment 11

Fig 4.11.7(a) - Essential features of speed control.
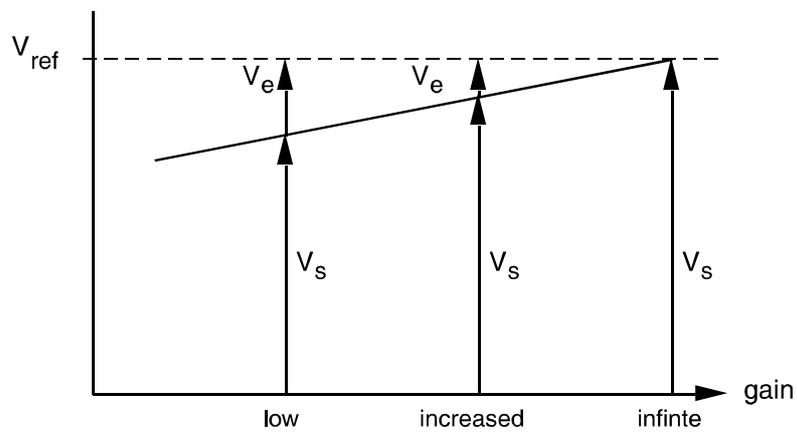
Fig 4.11.7(b) - Closed loop speed control.

Application of 3-Term Control Actions   **Assignment 11**

**SPEED CONTROL
SYSTEM WITH
INTEGRAL CONTROL**   A simple speed control system with the general form of fig 4.11.7(a), is investigated in Assignment 9. The tests demonstrate that increasing the forward path gain reduces the speed fall with load ('droop'). A possible problem associated with increased gain is that the ripple component on the tachogenerator output which could be amplified to cause power amplifier saturation, though this ripple can be filtered out.

The forward path gain of a system also affects the relation between the reference voltage V_{ref} and the speed voltage V_s. This relation

$$V_e = V_{ref} - V_s$$

can be rearranged as

$$V_{ref} = V_e + V_s$$

and represented by the voltage diagram of fig 4.11.7(b). If the forward path gain is low a large V_e may be required so that V_s is much smaller than V_{ref}. As the gain increases V_s approaches V_{ref}, and if the forward path gain is infinite then V_e becomes zero and:

$$V_s = V_{ref}$$

which may be desirable.

If the comparison of V_{ref} and V_s is carried out in an operational amplifier in the circuit of fig 4.11.7(a), then the corresponding equation is strictly

$$V_e = -\left(V_{ref} + V_s\right)$$

and the condition corresponding with infinite gain, ie V_e is zero, becomes

$$V_s = -V_{ref}$$

so that the magnitudes are equal but with opposite signs.

Application of 3-Term Control Actions   Assignment 11
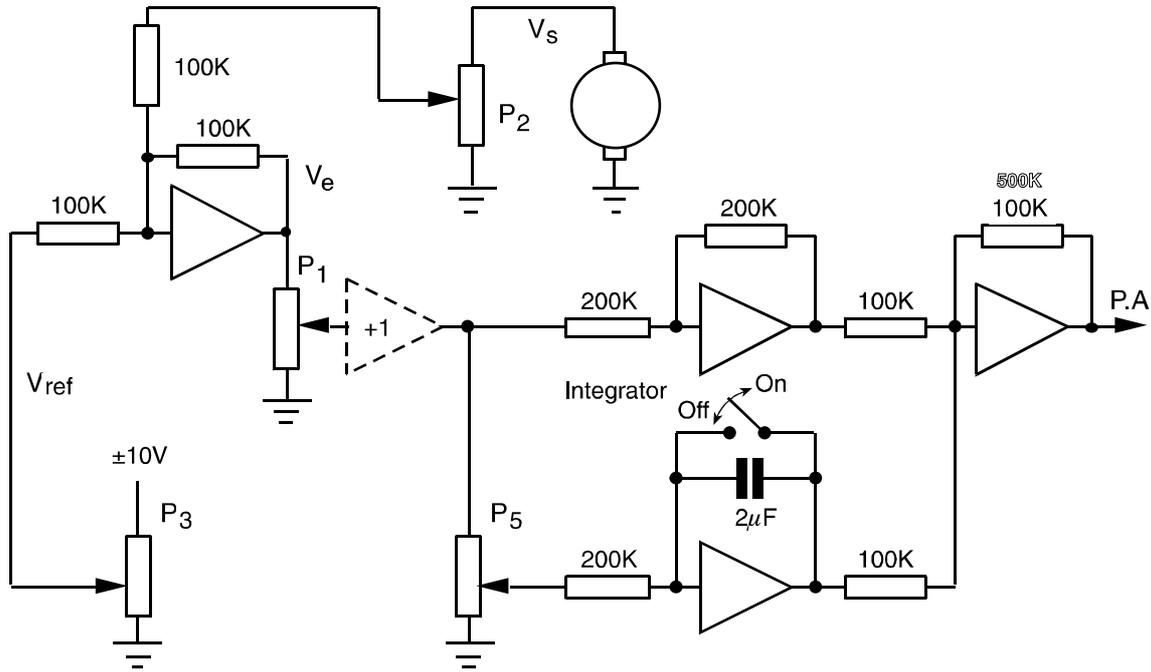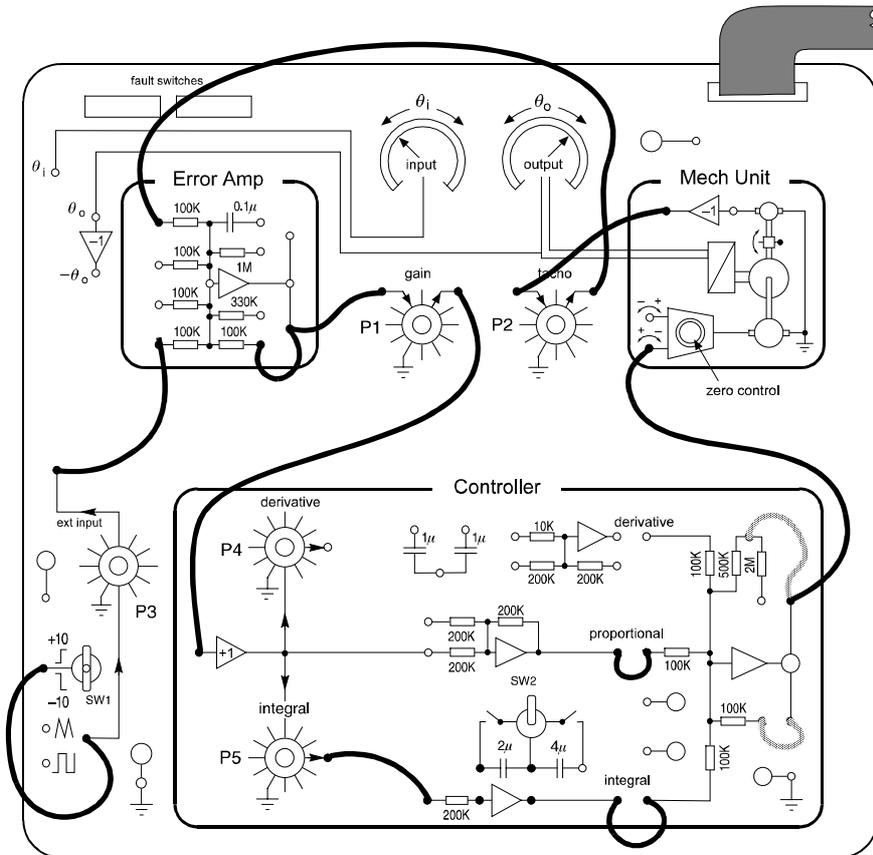

Fig 4.11.8(a) - Speed Control Circuit

Fig 4.11.8(b) - Connection Diagram

Application of 3-Term Control Actions   **Assignment 11**

PRACTICAL 11.6

Relation between
V_{ref} and V_s

A speed control circuit is given in fig 4.11.8(a), with the connection diagram in (b).

Connect the circuit of (b) with Controller Amplifier feedback resistor 100K, which gives G = 1, and switch the integrator OFF. Set P_2 and P_3 at zero and P_1 at 100.

Set SW1 up to +10 and adjust P_3 to give 1000 r/min (31 r/min output), and turn up P_2 slightly.

If the speed falls slightly, the loop feedback is negative as required.

If the speed rises slightly, change the polarity of the tacho-generator supply to P_2.

Set P_2 to 100 and readjust P_3 to give 1000 r/min.

Measure V_{ref}, V_s and V_e and check that the values fit a voltage diagram as fig 4.11.7(b).

Note that the speed voltage (V_s) is much less than V_{ref} because the forward path gain is low (G = 1).

Using the voltmeter set P_3 (V_{ref}) to the value of V_s for 1000 r/min (about 2.5V) and the speed will fall to about 500 r/min.

Change the Controller feedback resistor to 500K (G = 5) and the speed will increase with Vs approaching V_{ref}.

Reduce the Controller feedback to 100K, set P_5 to 100, and switch the integrator ON. The speed will increase so that

$$V_s \cdot V_{ref}$$

and V_e will fall to approximately zero. The integrator is now supplying exactly the drive required so that V_s matches V_{ref}.

Provided that there is an integrator in the forward path, the system will always adjust so that V_e is zero, and hence the speed voltage V_s always equals V_{ref}, which may be desirable for remote control of the speed.

Application of 3-Term Control Actions   **Assignment 11**

PRACTICAL 11.7

**Response to
Output Loading**   The common requirement for a speed control system is to maintain a constant speed against load variations. There are two types of load variation:

> transient: corresponding with rapid load changes
>
> slow: corresponding with slowly varying loads

**Transient Load
Change**   Arrange the system as for Practical 11.6 with brake OFF, integrator ON, P_5 to 100, P_3 set to give 1000 r/min Controller, feedback resistor 100K.

Set the brake quickly to full ON.

The speed will drop and then recover to 1000 r/min as the integrator output increases.

Set the brake quickly OFF.

The speed will rise and then fall slowly as the integrator output decreases.

It is useful to examine both tachogenerator and integrator outputs on an oscilloscope during this action. The system response can be improved by increasing the forward path gain.

Change the Controller feedback resistor to 500K and repeat the test. The response should now be quicker and with reduced speed variation.

Application of 3-Term Control Actions **Assignment 11**

**Slow Load
Change**

Arrange the system as for Practical 11.6, with brake OFF, integrator ON, P5 to 100, P3 set to give 1000 r/min.

Set the Controller feedback to 100K.

Set the brake at 4 or 5 equally spaced positions from off to fully on.

For each position the steady speed should be unchanged, but the integrator output will increase.

Plot the speed and integrator output against brake setting, the general results (1) in fig 4.11.9 should be obtained.

There should be no 'droop' because the power amplifier can supply sufficient power to the motor to maintain speed at full loading.

If the speed falls at full load, reduce the speed to 750 r/min and repeat the test.

If the set speed is significantly increased the system will operate perfectly for initial loading and fall quickly as the power amplifier limits.

Set the brake to OFF.

Adjust P_3 to raise the speed to about 1600 r/min (50 r/min).

Repeat the test, plotting the results and the speed should fall sharply as maximum brake loading is approached, giving results of the form (2) in fig 4.11.9.
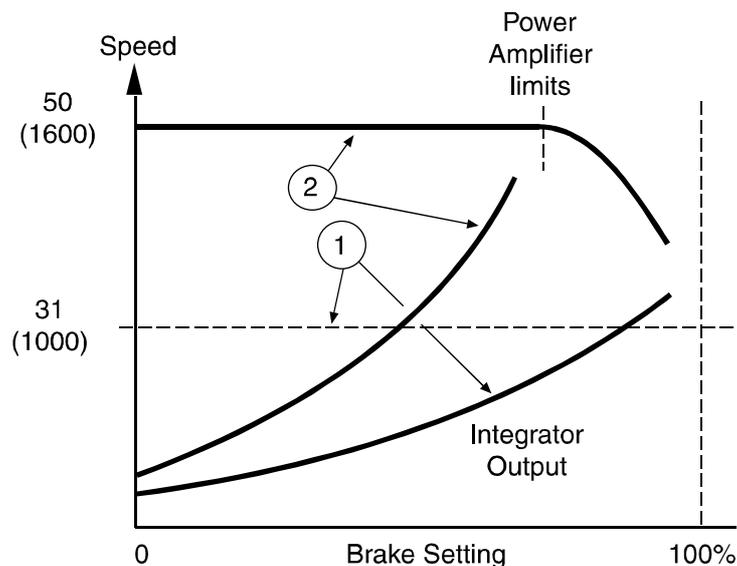
Fig 4.11.9 - Loading characteristics

Application of 3-Term Control Actions   **Assignment 11**

SUMMARY

It has been shown that an important application of integral control is to eliminate steady following error. In this application integral control alone can give a poor transient response, which can be much improved by derivative control.

The integral and derivative control adjustments which give a satisfactory following error transient may not be those that give the best step response, so that some compromise in adjustments may be necessary.

Integral control is not essential for system static alignment, because a system with a motor output will in principle always align to give zero error due to the inherent integration characteristic of a motor.

However, a useful feature of integral control is that it can counter the effect of output member disturbances that may cause misalignment and can also counter some internal system disturbances.

This assignment has shown the effect of integration in causing a system to 'align', i.e for a speed control system to make the output (V_s) equal to the input (V_{ref}). In the case of position control system, there is an inherent integration in the motor (see Practical 11.5, Elimination of Disturbance) which causes alignment. A speed control does not have an inherent integration and hence only 'aligns' when a separate integrator is introduced.

SINGLE AMPLIFIER CONTROL CIRCUITS   **ASSIGNMENT 12**

The following Practicals are included in this assignment:

12.1 Single Amplifier P + D Control

12.2 Single Amplifier P + I Control

12.3 Importance of Resistor in Amplifier Feedback

12.4 Single Amplifier 3-term Control

SINGLE AMPLIFIER CONTROL CIRCUITS   ASSIGNMENT 12

CONTENT   Investigation of single amplifier control circuits enabling restricted control actions to be obtained.

EQUIPMENT
REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility *(eg Feedback 1810-01229)*

SINGLE AMPLIFIER CONTROL CIRCUITS   **ASSIGNMENT 12**

OBJECTIVES   When you have completed this assignment you will know that:

ν   A single amplifier can provide P + D or P + I or P + D +I control.

ν   Single amplifier circuits are not as versatile as a full 3-term controller.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Be familiar with 3-term control principles.

ν   Preferably have completed Assignment 10, Introduction to 3-Term Control.

**PRELIMINARY
PROCEDURE**   The Analogue Unit and Mechanical Unit should be connected together by the 34-way ribbon cable.

The Power Supply should be connected by 4mm-plug leads to the +15V, +5V, 0V and −15V sockets at the back of the Mechanical Unit.

Single Amplifier Control Circuits   **Assignment 12**

INTRODUCTION

**Single Amplifier
Control Circuits**

The previous assignments have investigated the general principles of a 3-Term Controller and considered a number of applications. The 3-Term Controller is a standard and versatile controller much used in position, process, temperature and similar control systems. However, the actions of a 3-Term Controller, proportional, derivative and integral can be combined, though with less versatility, in a single operational amplifier circuit which has use in situations where no adjustment of control is necessary and this results in a much simpler circuit.

This assignment considers three single amplifier configurations which are useful.

Single Amplifier Control Circuits   **Assignment 12**
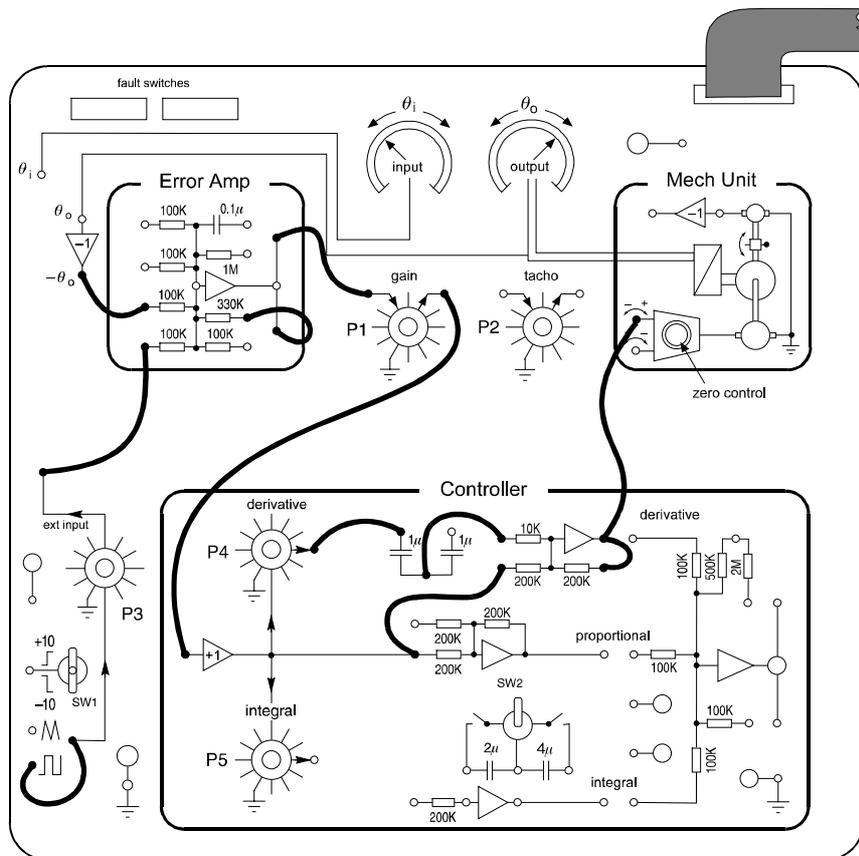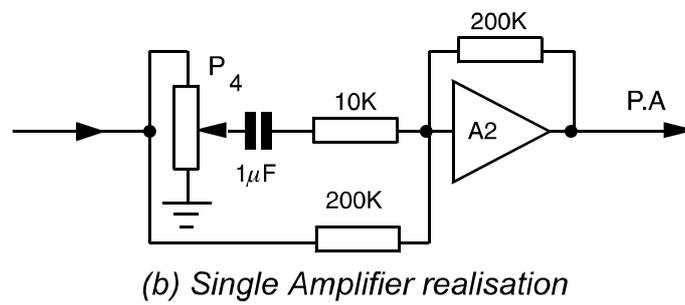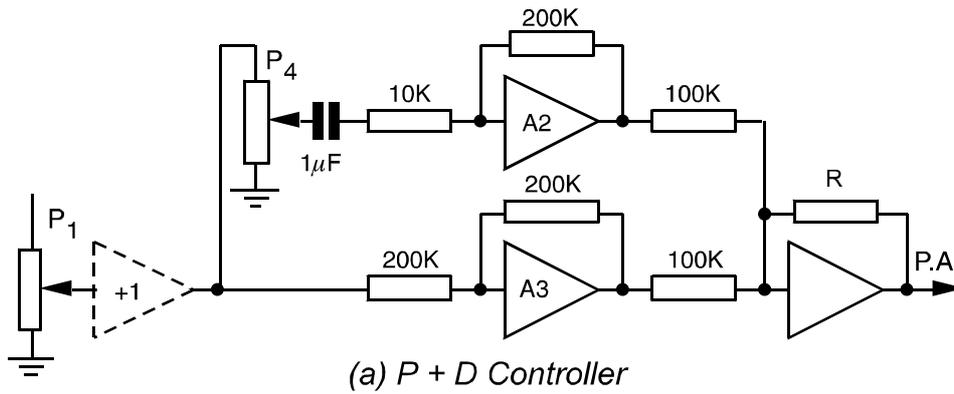
NOTES

Single Amplifier Control Circuits Assignment 12

(a) P + D Controller

(b) Single Amplifier realisation

(c) Connections for Single Amplifier P + D control

Fig 4.12.1

Single Amplifier Control Circuits   **Assignment 12**

PRACTICAL 12.1

**Single Amplifier
P + D Control**

The circuit of a P + D controller is given in fig 4.12.1(a). Since the input to A_2 is a virtual earth point (see Assignment 2), a unity gain proportional component can be added to A_2 output by an input resistor as in (b). The output from A_2 could then drive the power amplifier directly.

It is important to note that the controller of (a) has two amplifiers in each path to the P.A input, while the simpler circuit has only one and hence causes a sign reversal, which must be compensated by reversing the power amplifier drive (see Practical 4.2).

Connect the system of fig 4.12.1, as shown in (c), giving G = 3.3, which uses the circuit of (b).

Set P_1, P_3 and P_4 to zero.

Use the power amplifier zero to set the output index away from 0°. Slowly turn up P_1 and the output index should rotate to 0° indicating negative feedback.

If the rotation is away from zero use the other power amplifier input.

Set P_1 to 100 and with a frequency of 0.1Hz, adjust P_3 to give about ±45° motion at the output.

Turn up P_4 and it should be possible to obtain dead-beat operation.

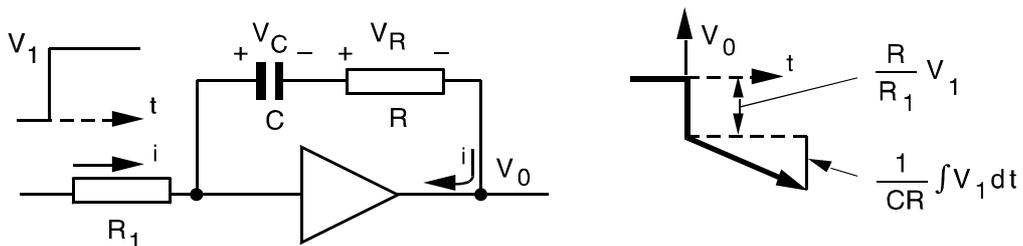This practical has shown that it is possible to combine proportional and derivative control in a single amplifier.
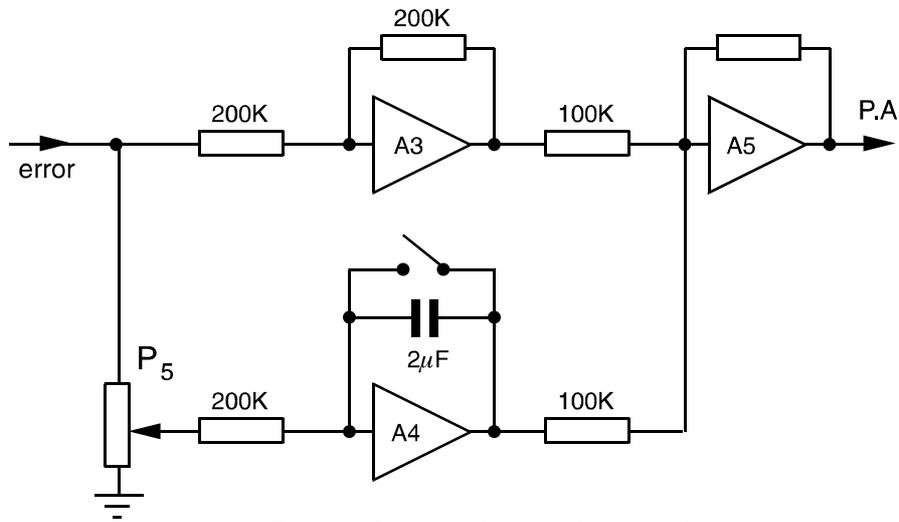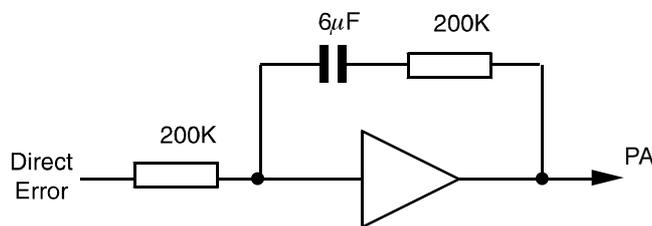
(a) Proportional + integral control

(b) Single amplifier realisation

(c) Component values

Fig 4.12.2 - Single Amplifier P + I Control

Single Amplifier Control Circuits 　　　　　　　　　　　**Assignment 12**

PRACTICAL 12.2

Single Amplifier
P + I control

The proportional + integral control of fig 4.12.2a can also be combined in a single amplifier with the general arrangement of (b).

If a step input is considered for (b) the input current will be:

$$i = \frac{V_1}{R_1}$$

This current passes through the series capacitor and resistor to give:

$$V_C = \frac{1}{C} \int i \, dt = \frac{1}{CR} \int V_1 \, dt$$

$$V_R = iR = \frac{R}{R_i} V_1$$

The output voltage V_o will be the sum of these two voltages giving:

$$V_0 = (-)\left(\frac{R}{R_1} V_1 + \frac{1}{CR} \int V_1 \, dt \right)$$

representing proportional + integral components of V_I.

If R_1 is chosen as a convenient value, the relative size of the proportional and integral components can be adjusted by choice of R, C, but without the convenience of continuous adjustment available with the circuit of (a). Also (b) has an inherent sign reversal.

Component
Values

In Assignment 11, Practical 11 4, Elimination of Following Error, the controller used is as in fig 4.12.2(a), which gives unity proportional gain and P_5 was set to about 30.

If the circuit of (b) is used, with the error applied directly to the input resistor, it could be convenient to use R_1, R = 200K as in (c). However, the current in the input resistor in (b), and hence through the capacitor, will be about three times greater than in (a). Thus to obtain the same integral rate with (b), the capacitor should be about 3 x 2μF (6μF). The above general principle establishes a set of values for (c).

Single Amplifier Control Circuits
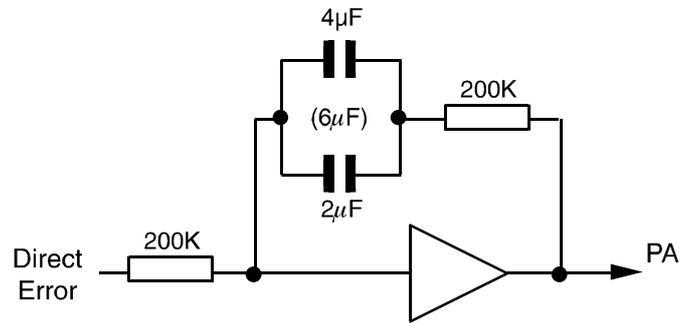
Assignment 12

(a) P + I Controller
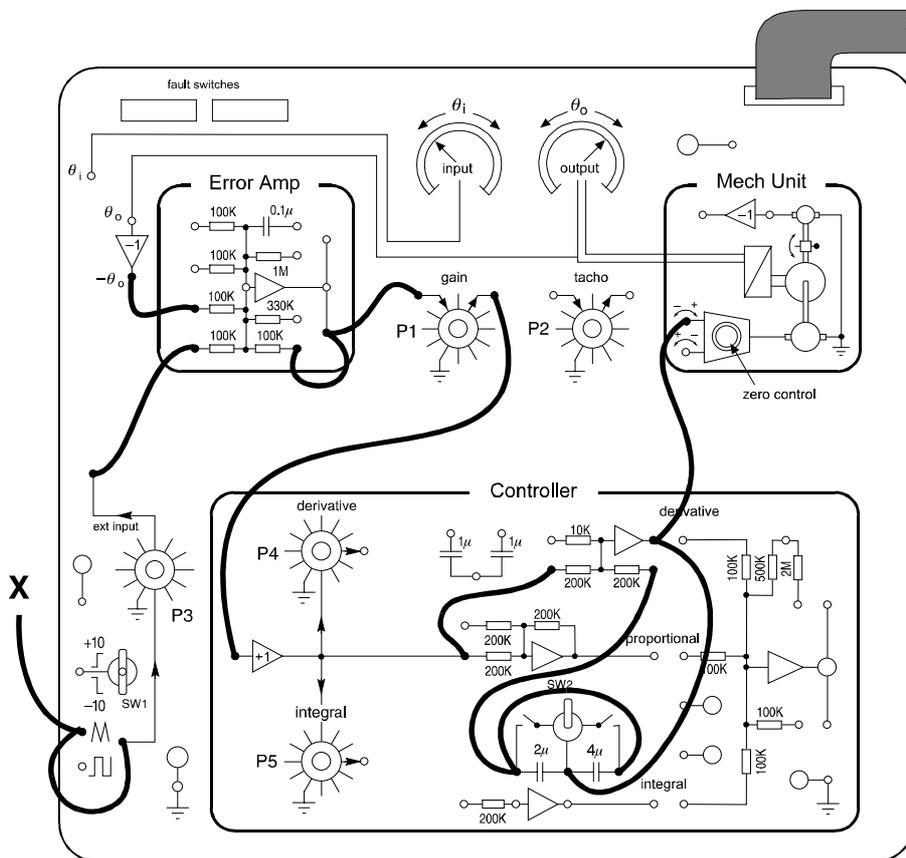
(b)

Fig 4.12.3 - System with single amplifier P + I

Connect the system of fig 4.12.3(b). Note that the controller of (a) is arranged round the upper amplifier, with 2µF and 4µF capacitors in parallel.

Short-circuit the capacitor by SW2 and set P_1 to 100, giving a proportional gain of unity.

Adjust P_3 to give output motion of about ±90° at 0.1Hz.

Display the following error.

If SW2 is opened the integrating action occurs and the following error will be eliminated, with a transient, as in Assignment 11, Practical 11.4.

PRACTICAL 12.3

**Importance of
Resistor in
Amplifier Feedback**

It is important to note that the 200K in series with the 6µF, which corresponds with the proportional control component, is **essential** for system stability. A system containing a motor which represents a time-constant and an integration and another separate pure integration is fundamentally unstable and will always go into increasing amplitude oscillation when disturbed.

To investigate this:

Disconnect the power amplifier input and connect the 6µF capacitor directly across the amplifier to give a pure integrator.

Short circuit the capacitor with SW2 and reconnect the power amplifier.

Set P_3 to zero and P_1 to about 50 and use the power amplifier zero to set the output index at about 10°.

Open SW2 and the system should slowly oscillate with increasing amplitude.

Repeat the test with different settings for P_1 which will just cause a change of oscillation frequency.

It should be noted that this system has characteristics which differ from the unstable system of Assignment 8, which requires a definite gain value before going unstable. Many systems will in fact go unstable if enough gain (usually far above normal) is introduced. The present system is unstable for **any** value of gain.
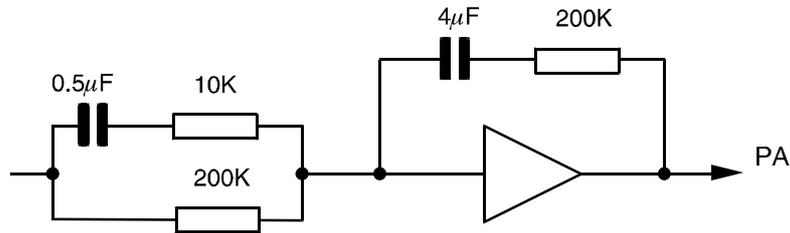
Fig 4.12.4 - Single amplifier P + I + D
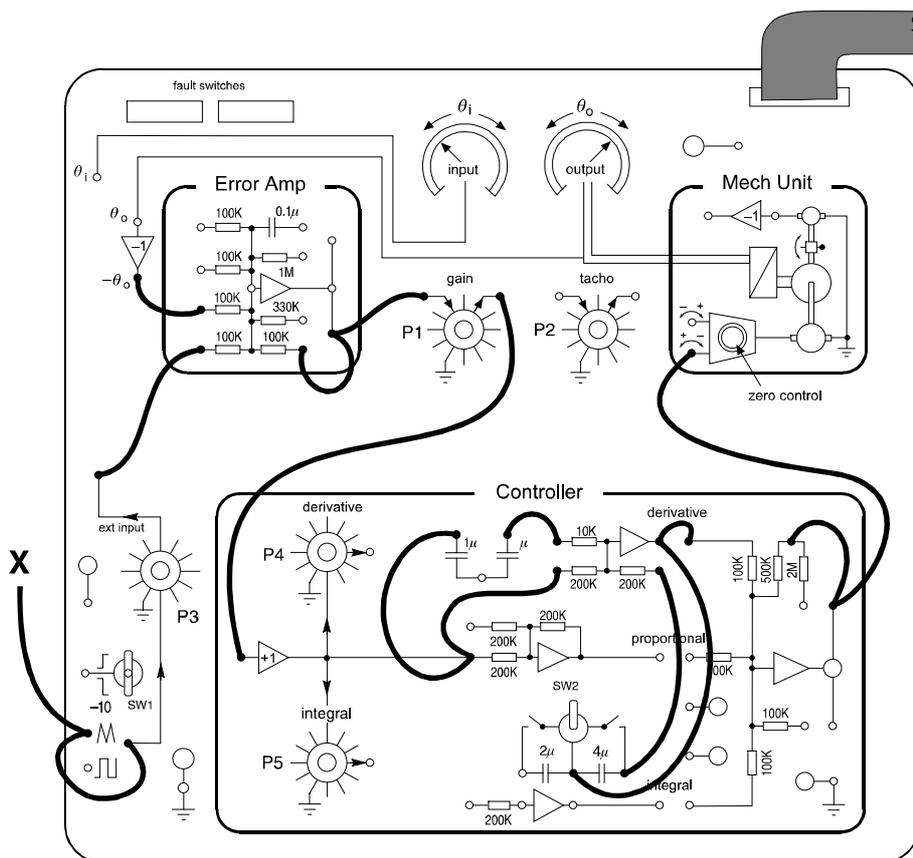
Fig 4.12.5 - System with single amplifier P + I + D

Single Amplifier Control Circuits   **Assignment 12**

PRACTICAL 12.4

**Single Amplifier
3-term Control**   Since derivative control improves the transient response of a system and can be introduced by an RC circuit across an operational amplifier input resistor, see fig 4.12.1(b), this can be applied across the input resistor of the P + I circuit of fig 4.12.2(c). This is shown in fig 4.12.4 and represents single amplifier P + I + D control.

In Practical 11.4 (Elimination of Following Error with G = 5) the settings for derivative (P_4) with 1µF and integral (P_5) with 2µF to obtain the 'best' response, are of the order of 50.

In the circuit of fig 4.12.4, the full input voltage is applied directly to the derivative capacitor and input resistor, thus trial values of derivative and integrating capacitors might be 0.5µF and 4µF, (see note about component values in Practical 12.2).

Arrange the system of fig 4.12.5, which contains the circuit of fig 4.12.4.

Set P_3 to give an output of ±90° and examine the error. The response should be comparable with that in Practical 11.4, but the capacitors would need adjustment.

The gain of 5 provided by the controller amplifier could be incorporated in the compensating circuit by reducing the integrating capacitor by 5 and increasing the output resistor by 5.

It is useful to experiment with different capacitor combinations and observe the effect on ramp and step transients.

Single Amplifier Control Circuits **Assignment 12**

SUMMARY
This assignment has investigated single amplifier circuits to give the characteristics of 3-term control. However, the circuits examined are not as versatile as a proper 3-term controller, since they do not have facilities for continuous adjustments.

The circuits are not substitutes for a full 3-term controller, but have application in particular situations where the component values are chosen to meet system requirements.

**TRANSIENT VELOCITY FEEDBACK
AND DERIVATIVE FEEDFORWARD**   **ASSIGNMENT 13**

The following Practicals are included in this assignment:

13.1 Transient Velocity Feedback

13.2 Derivative Feedforward

**TRANSIENT VELOCITY FEEDBACK
AND DERIVATIVE FEEDFORWARD**   **ASSIGNMENT 13**

CONTENT   This assignment introduces two additional methods which can
                            have application to following error reduction.

**EQUIPMENT
REQUIRED**

QTY	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility *(eg Feedback 1810-01229)*

**TRANSIENT VELOCITY FEEDBACK
AND DERIVATIVE FEEDFORWARD**   **ASSIGNMENT 13**

OBJECTIVES   When you have completed this assignment you will know that :

ν   Transient Velocity Feedback and Derivative Feedforward
are techniques which can have applications to following
error reduction.

KNOWLEDGE LEVEL   Before you start this assignment you should :

ν   Be familiar with control system principles and following error
characteristics preferably by completing Assignments
5, The Influence of Gain; 6, Velocity Feedback and
7, System Following Error

**PRELIMINARY
PROCEDURE**   The Analogue Unit and Mechanical Unit should be connected
together by the 34-way ribbon cable.

The power supply should be connected by 4mm-plug leads to
the +15V, +5V, 0V and −15V sockets at the back of the
Mechanical Unit.

**Transient Velocity Feedback
and Derivative Feedforward**
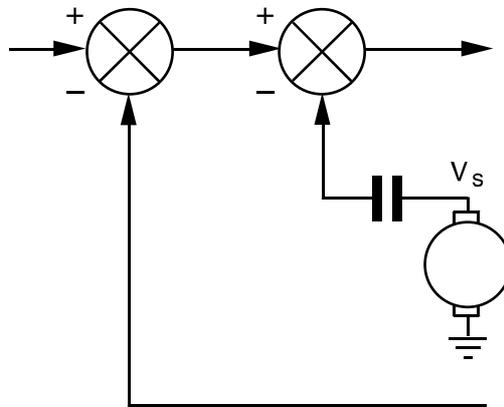
(a) General Principle
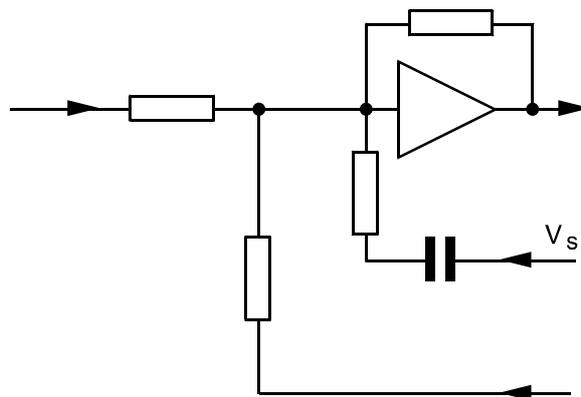
(b) Circuit arrangement

Fig 4.13.1 - Transient Velocity Feedback

**Transient Velocity Feedback
and Derivative Feedforward**   **Assignment 13**

PRACTICAL 13.1

**Transient velocity
feedback**

Velocity (tachogenerator) feedback has a powerful effect in improving transient response, but also has the effect of increasing following error. The error increase is due to the steady component of the feedback, while it is the **changing** component during transients, which really gives the transient response improvement, see Assignment 6 and fig 4.6.1. For systems with a high gain in order to give a small error the increase due to velocity feedback may be undesirable.

If a capacitor is placed in the velocity feedback line as in fig 4.13.1a, which may in practice be an operational amplifier, as in (b), the steady component is blocked, preventing increased error, but the varying component is transmitted. Hence the description transient velocity feedback.

The improvement in response may not be as marked as direct velocity feedback, which can give dead-beat response from a system with an initially very poor response. It can however give a significant improvement without increasing the following error in systems with a high forward gain to obtain a small error.

Transient Velocity Feedback and Derivative Feedforward
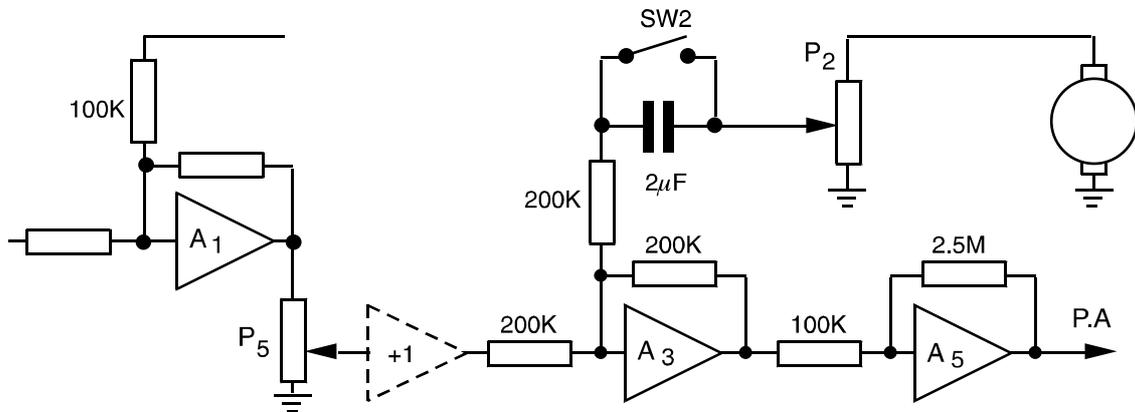
a) Circuit Diagram
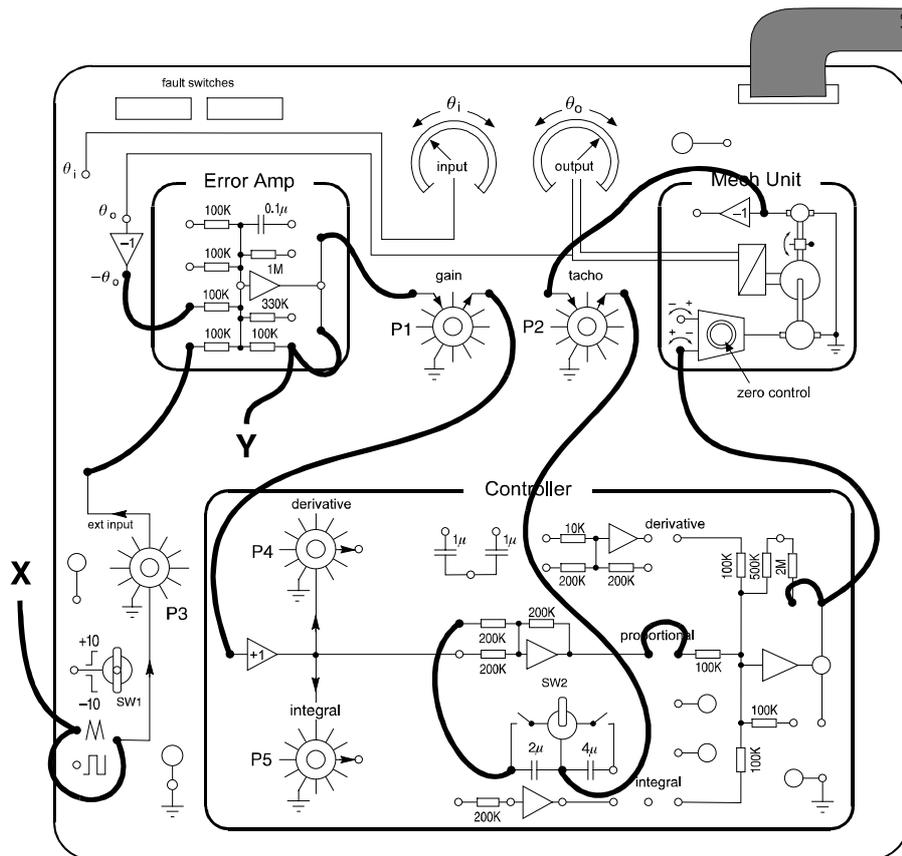
(b) Connection Diagram

Fig 4.13.2 - System with Transient Velocity Feedback

A system with transient velocity feedback is given in fig 4.13.2(a), where the tachogenerator signal is supplied to the proportional amplifier through an integration capacitor, which can be short-circuited by SW2. There is a gain of about 25 in A_5 to give small error, but the direct error is available at the error amplifier output. The connection diagram is given in (b).

Connect the circuit of fig 4.13.2(b) and set P_1, P_2 to zero and close SW2.

Set P_1 to 100 and the system may be unstable or if perturbed by the motor check switch on the Mechanical Assembly may go unstable.

A small amount of tachogenerator feedback (P_2) will stabilise the system.

Adjust P_3 to give about ±90° at the output at 0.2Hz, and examine the error.

Note that the steady error magnitude is almost proportional to the velocity feedback since G = 25, and hence (see fig 4.7.4) V_{ev} is nearly equal to $K_t V_s$.

Open SW2 blocking the steady tachogenerator signal and after the initial transient the error will be much reduced.

It is useful to try different values of capacitor in the tachogenerator line. Values 0.5μF, 1μF can be obtained using the derivative capacitors.

These tests demonstrate the operation of transient velocity feedback.

Derivative Feedforward   **Assignment 13**
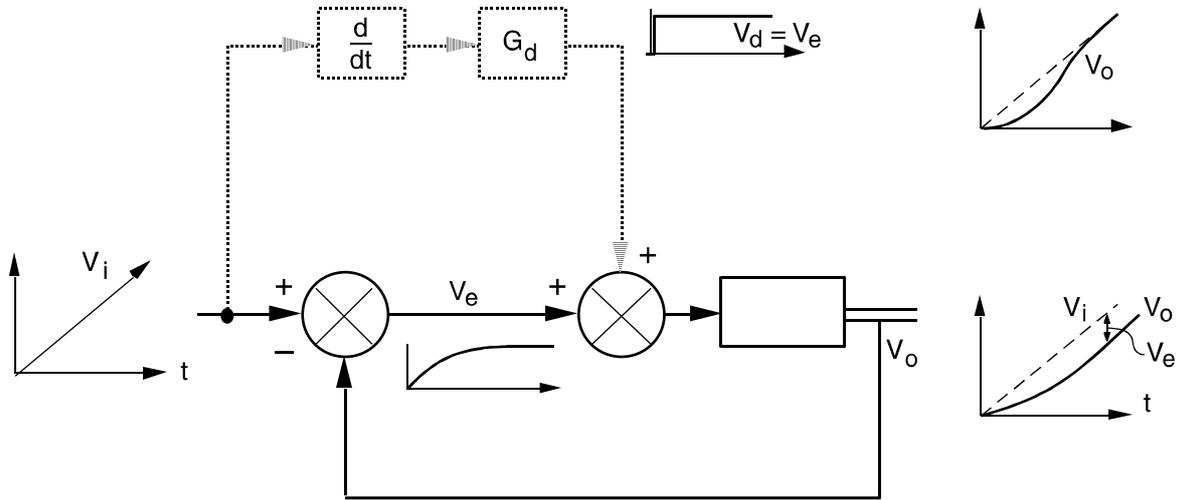
Fig 4.13.3 - Input derivative feedforward

Derivative Feedforward   **Assignment 13**

PRACTICAL 13.2

Feedforward   If a system is following a ramp input a constant drive signal must be supplied to the motor, which is normally provided by the following error, as in fig 4.13.3, where the shaded portion is ignored. The following error can be zero if integral control is used.

If the input is differentiated directly as represented by the dotted portion of fig 4.13.3, this would provide a constant signal V_d as shown, which could be added into the forward path through an adjustable gain G_d. If it is arranged that

$$\frac{d(input)}{dt} . G_d = V_e$$

then the differential signal will provide the necessary drive and

following error $= (V_i - V_o) = 0$

If the input slope varies, requiring a different drive value to the motor, this will automatically occur, since the differentiator output will change.
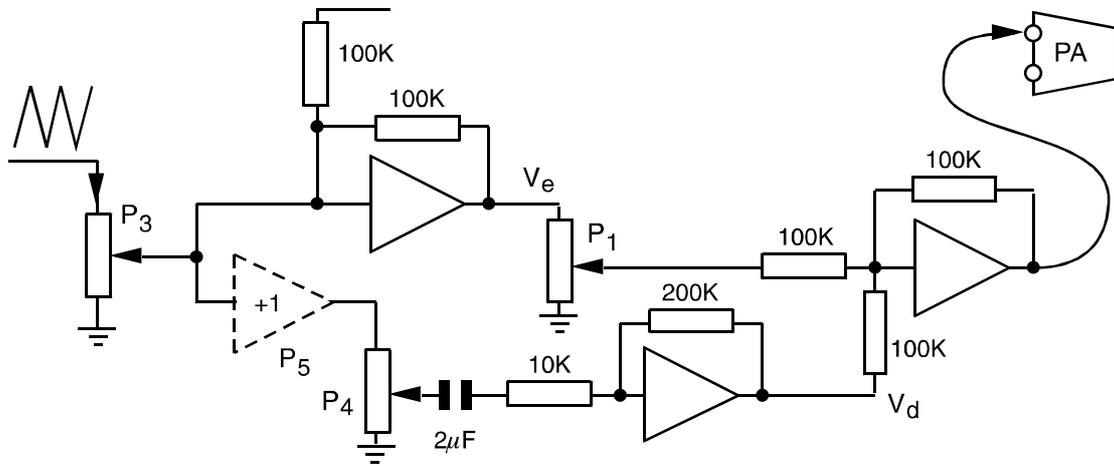
(a) Derivative feedforward circuit
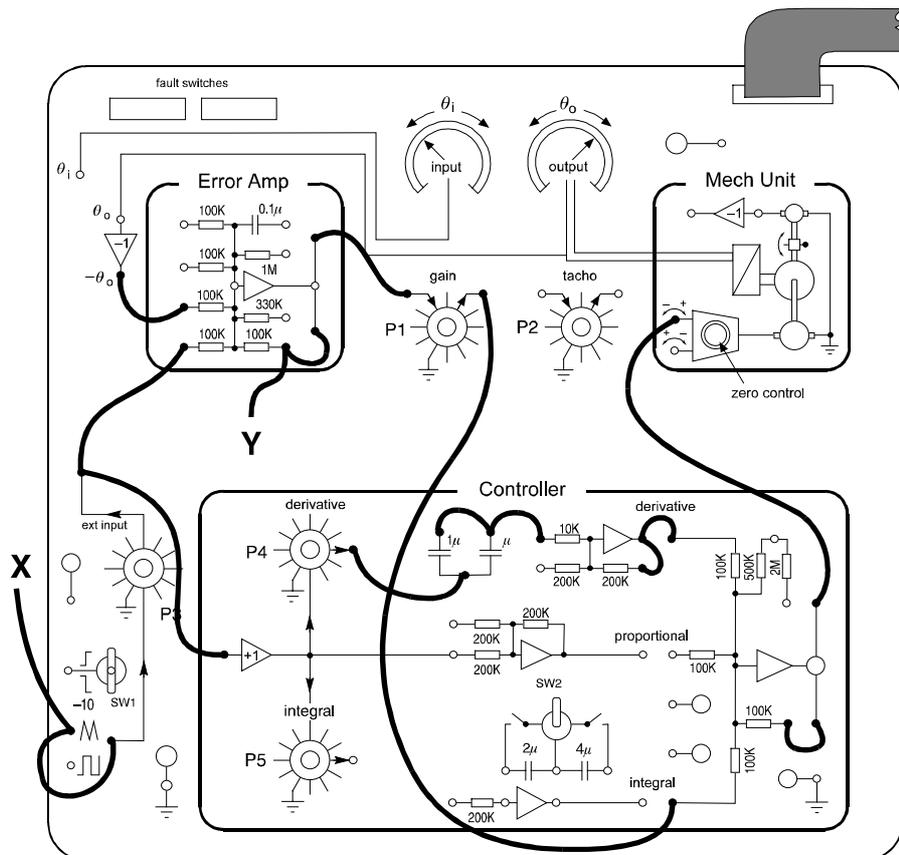
(b) Connection Diagram

Fig 4.13.4 - System with feedforward

Derivative Feedforward   **Assignment 13**

A circuit to investigate feedforward is given in fig 4.13.4(a) with connection diagram in (b). The differentiation can be carried out in the derivative circuit, and the normal error (V_e) and differentiated signal (V_d) added in the Controller output amplifier and applied to the power amplifier. Note that since there is one additional amplifier in the forward path, the power amplifier input polarity must be changed to give overall **negative** feedback.

Make an X-Y display of error amplifier output (V_e), set P_4 to zero and P1 to 100.

Adjust P_3 to give about ±90° at the output at 0.1Hz.

Turn P_4 up and it should be possible to eliminate the following error after an initial transient.

If a larger derivative signal is required, the 100K input to the Controller output amplifier can be reduced to 50K by using another 100K input in parallel.

Note that it is possible to 'overcompensate' by excessive derivative signal, the system then leading the input in steady state.

Note that adjusting P_3 or increasing the triangle frequency does not affect the steady state error elimination.

Although feedforward provides a technique to eliminate following error, it requires an exact adjustment (P_4), while integral control, though introducing a significant transient, does not require an exact adjustment.

In addition, any noise on the input is emphasised by feedforward, whilst integral control does not emphasise noise.

SUMMARY   This assignment has investigated two aspects of control system design which have application in particular situations.

NOTES

INTRODUCTION   **ASSIGNMENTS 14 & 15**

All experimental work up to the end of Assignment 13 that requires an external test signal has used either a step or a ramp input. These signals are very convenient since they indicate the performance of the system in the time domain in a manner which is easily appreciated and where the effects of various compensations, such as velocity feedback, three-term control, are easily demonstrated.

These test signals are not convenient when numerical design work is required, for example: what change in gain will affect the damping by a certain amount, or how much tachogenerator feedback is required to reduce excessive overshoot to an acceptable value.

In order to deal with this type of problem, more mathematical design methods are required, the most basic of which is the concept of frequency response. This involves the determination, either practically or theoretically, of the response of a system to a steady sinusoidal input. This method enables systems with parameters already known from theory, or from separate measurements, to be designed for a specified performance. Alternatively for an unknown system an overall characteristic can be measured and design then to proceed based on the measured characteristic. The full background of the frequency response method is extensive and is treated in detail in all introductory books on control.

Assignment 14 provides a very basic introduction to frequency response principles and the practicals investigate these principles with analogue experiments using the controller facilities on the control board of the 33-002 system.

Assignment 15 investigates the application of frequency response principles to the complete 33-002 system.

INTRODUCTION   **ASSIGNMENTS 14 & 15**

NOTES

TRANSFER FUNCTIONS AND
CLOSED-LOOP FREQUENCY RESPONSE PRINCIPLES   **ASSIGNMENT 14**

The following Practicals are included in this assignment:

14.1   Frequency Response of Time Constant

14.2   Frequency Response of Integration

14.3   Closed-loop System Experiments

14.4   Oscillation

TRANSFER FUNCTIONS AND
CLOSED-LOOP FREQUENCY RESPONSE PRINCIPLES   **ASSIGNMENT 14**

CONTENT   ν   To investigate the frequency response characteristic of a
                         time constant and an integration.

                     ν   To investigate and predict the characteristics of a simple
                         analogue closed-loop system containing the above
                         elements.

EQUIPMENT
REQUIRED

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility *(eg Feedback 1810-01229)*

TRANSFER FUNCTIONS AND
CLOSED-LOOP FREQUENCY RESPONSE PRINCIPLES   **ASSIGNMENT 14**

OBJECTIVES   When you have completed this assignment you will:

ν   Have investigated the frequency response characteristics of
    two very common control system elements, a time constant
    and an integration

ν   Know that the effect of closing a feedback loop round a
    system can have a marked effect on the overall transfer.
    Know the cause of this effect and understand how it may be
    predicted.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Be familiar with control system principles, particularly ideal
    motor characteristics, Assignment 3.

ν   Be familiar with the influence of gain, Assignment 5.

**Transfer Functions and
Closed-loop Frequency Response Principles** **Assignment 14**

Transfer function

In frequency response testing a sinusoidal input is applied to some object which may be a circuit or part of a control system and the relation considered between input and output signals. This is illustrated in Fig 4 14.1(a) where at some frequency ω_1, V_1, is the input and V_2 is the output or response.

(a) Input and Output

(b) Plots of magnitude and phase   (c) Frequency response locus
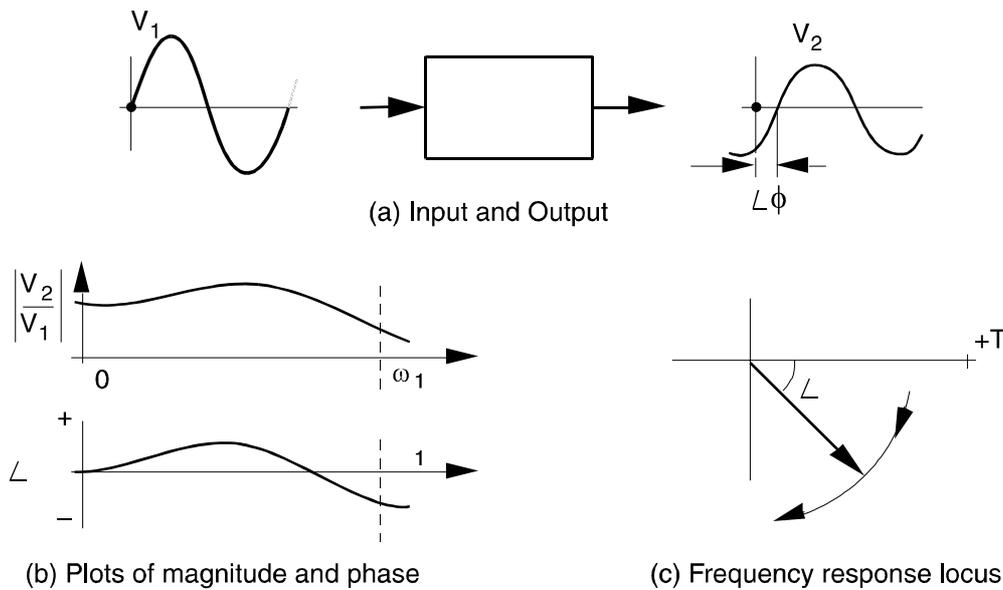
Fig 4 14.1 - Transfer function relations

In general the output will differ in magnitude from the input and there will also be a phase difference $\angle\phi$ in the illustration. The ratio of the magnitudes $|V_1|$ and $|V_2|$ and phase angle can be plotted separately against frequency as in (b). The results in (a) might correspond with the points shown. Alternatively the magnitude ratio and phase angle can be plotted as a polar plot as in (c) to give a *frequency response locus.* Where arrows give the direction of increasing frequency along the locus. The *transfer function* is the combination of magnitude and phase information:

$$|\text{ Transfer }| = \left|\frac{V_2}{V_1}\right| \; ; \; \angle \text{ (Transfer)} = \angle\phi$$

The frequency response locus plot or **polar plot** of a system is very important in control system design.

**Time Constant
and Integration**

Two very important system concepts are a time constant and an integration. Both these have already been mentioned in the context of a motor transient response in Practical 3.3, (Fig 4.3.7) and Practical 11.5 (Fig 4.11.4) and also in connection with an operational amplifier in Fig 4.8.2 and Fig 4.10.6. The characteristics have been considered in the time domain but are very important in frequency domain analysis.

**Transfer Functions and
Closed-loop Frequency Response Principles** **Assignment 14**

**Frequency Response
of a time constant**

If the frequency response of a time constant (ideally a simple RC circuit as in Fig 4.14.2.(a) is measured the magnitude and phase characteristics will be as in (b).

(a) time constant

(c) polar plot

(b) magnitude and phase
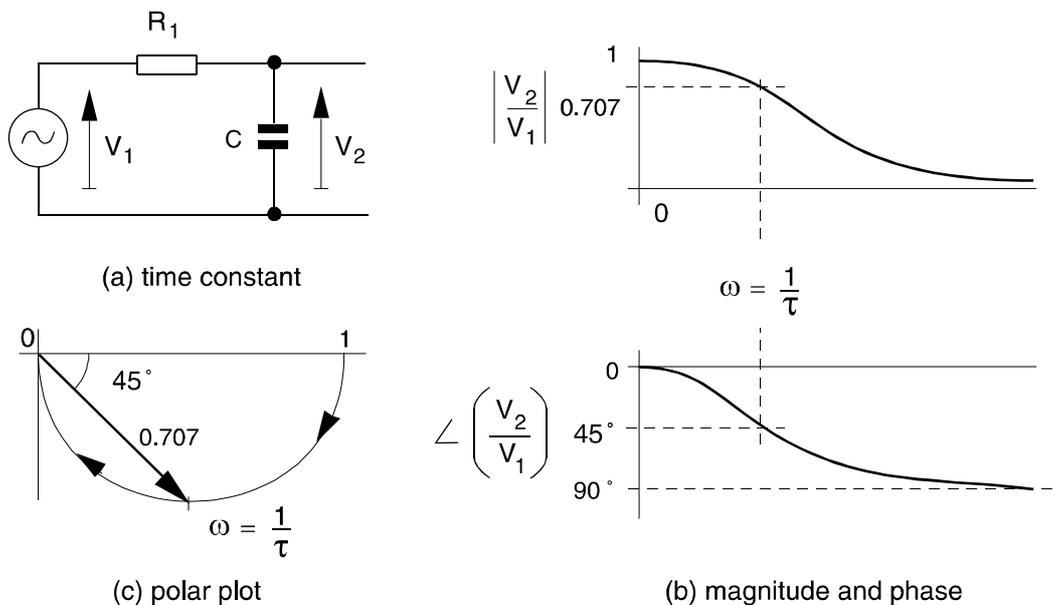
Fig 4 14.2 - Time constant characteristics

The transfer magnitude is unity at d.c. but as the frequency increases the reactance of the capacitor falls and the output gradually decreases. It can be shown that when:

$$\omega = \frac{1}{CR} = \frac{1}{\tau}; \quad \left|\frac{V_2}{V_1}\right| = \frac{1}{\sqrt{2}} = 0.707$$

$$\angle\left(\frac{V_2}{V_1}\right) = \angle\phi = -45°$$

where ω is frequency in radians/second

(frequency in Hz = $\frac{\omega}{2\pi}$)

This particular point is indicated on a polar plot in (c), and it can be shown that the complete frequency response is a semi-circle between +1 and the origin. The condition where $\omega = \frac{1}{\tau}$ is referred to as the '45°- point'.

The operational amplifier representation of a time constant has been covered already in Fig 4.8.2 but this representation is

Transfer Functions and
Closed-loop Frequency Response Principles

reversed in polarity (see p 4.8.6 last line) due to the operational amplifier. If an additional "−1" amplifier is arranged before (or after) then the overall response is identical with a time constant.

(a) Time constant

(b) Phase shift display
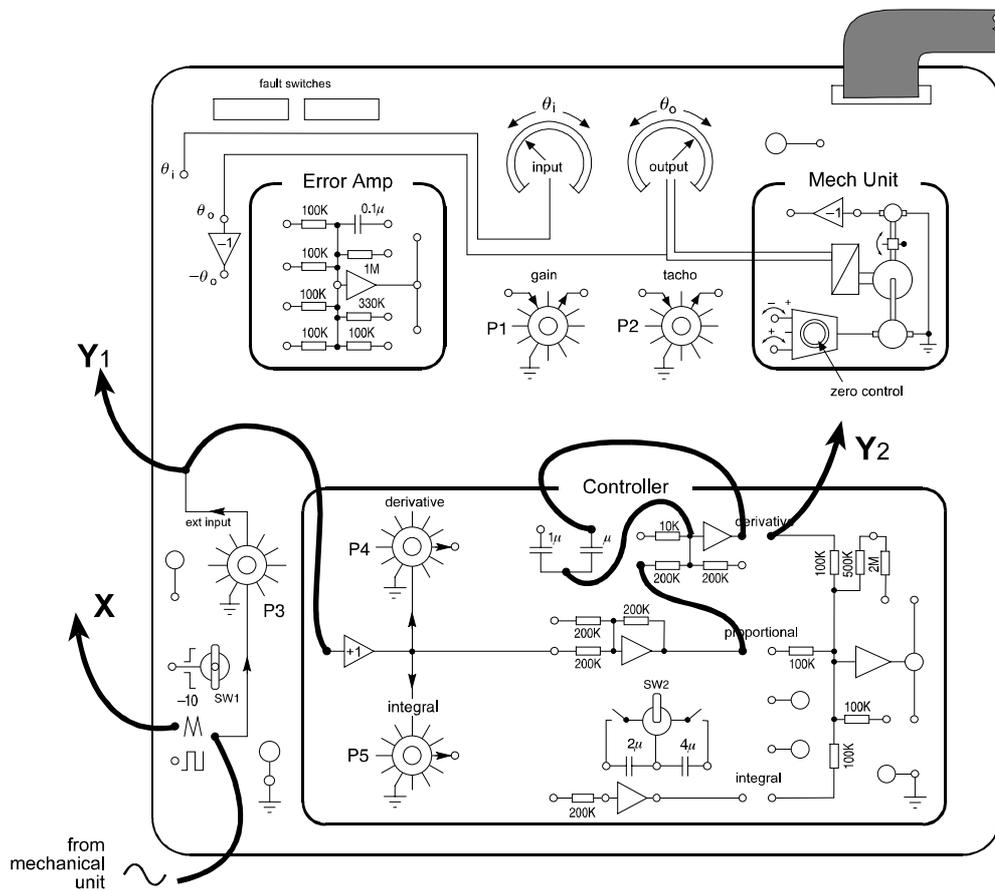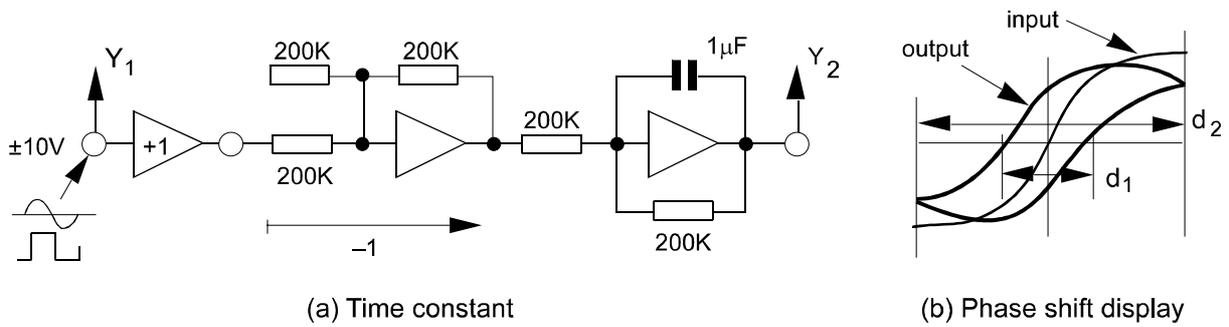
(c) Connection diagram

Fig 4 14.3 - Time constant

**Transfer Functions and
Closed-loop Frequency Response Principles**   **Assignment 14**

PRACTICAL 14.1

**Frequency response
of time constant**   A suitable circuit can be plugged up using the amplifiers in the
controller portion of the analogue board (33-110) as in
Fig 4.14.3(a), with the patching diagram of Fig 4.14.3(c).

Using a double beam long persistence oscilloscope display
input on Y_1 and output on Y_2 and apply sinewave input in the
range 0.1-10.0Hz and synchronise the trace to the squarewave.
At low frequencies the output will be substantially equal to the
input and in phase, but as the frequency is increased the output
will decrease in magnitude and lag behind the input generally
as in Fig 4.14.2(b).

Since: $\tau = CR = 200K \times 1\mu F = 0.2\,sec$

the "45° point" will occur for:

$$\omega = \frac{1}{\tau} \text{ or } \omega = 5rad/sec = \frac{5}{2\pi} \cong 0.8Hz$$

Check that the relative phase and magnitude are approximately
correct with 0.8Hz applied.

If the squarewave input is applied at a lower frequency a
response of the form of Fig 4.8.2 will be obtained.

A more convenient display for phase angle examination is to
use the triangular wave to provide an X-deflection and display
the output on the Y channel. The input sinewave will be in
phase with the triangle and give a single line sinewave passing
through the origin as in Fig 4.14.3(b). The output being out of
phase will give the looped display. The phase shift is given by
the ratio:

$$\angle\phi = \frac{d_1}{d_2} \times 90°$$

and at $\omega = \frac{1}{\tau}$ the output zero crossing points lie halfway
between the origin and end at the trace.

NOTES

**Transfer Functions and
Closed-loop Frequency Response Principles**   **Assignment 14**

**Frequency response
of integration**

The general characteristics of integration and integration by an operational amplifier are covered in Assignment 10 and Fig 4.10.6. In electrical terms the value of the integral of a signal or waveform is represented by the voltage developed across a capacitor when a current corresponding with the signal or waveform is passed through a capacitor as in Fig 4.14.4(a).
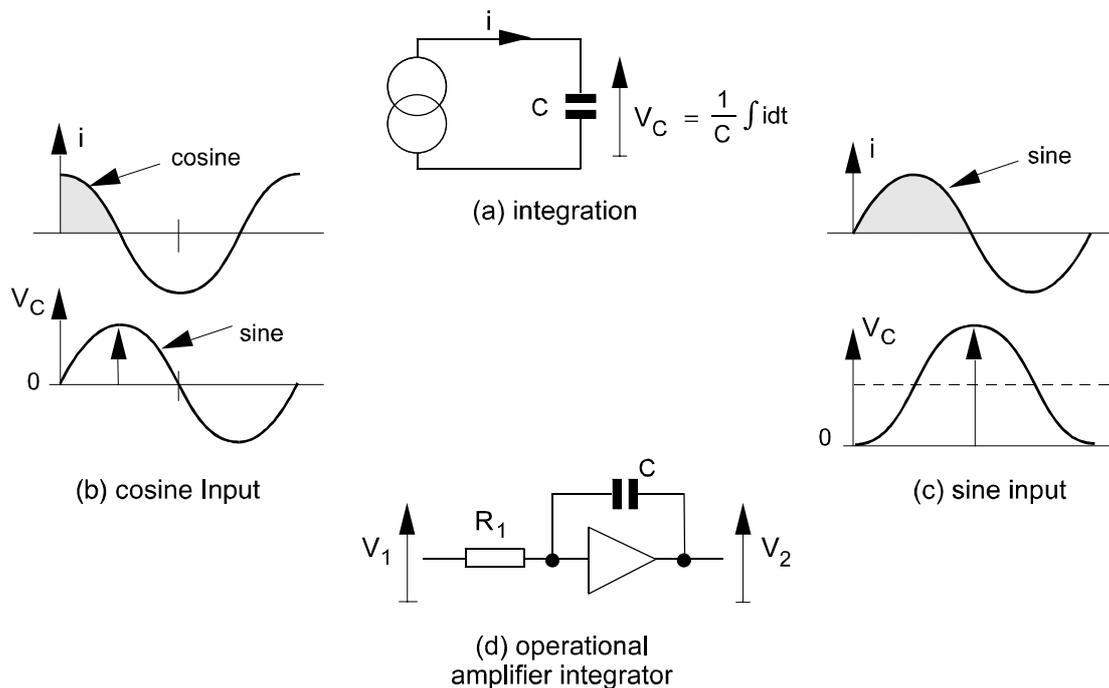
Fig 4.14.4 - Integration characteristics

If a cosine current is passed through the capacitor as in (a), the first quarter cycle will give a positive voltage due to accumulation of charge, and the second quarter cycle will discharge the capacitor to give zero volts. The waveform developed will be a positive half sinewave. The process repeats for the next half cycle in the negative sense giving a negative half cycle.

If a sinewave current is applied as in (c) the voltage rises during the first half cycle and then decreases to zero during the second half cycle. Thus the output is a d.c. level together with a negative cosine waveform. In both cases the peak output, ignoring the d.c. component in (c), lags the input by 90°

In addition in both cases, if the frequency of the input is increased, the magnitude of the maximum value of V_c falls because the current charges or discharges the capacitor for a shorter time. Conversely, if the frequency is reduced the charge or discharge lasts longer and the output increases.

The magnitude/frequency relation between current and voltage is expressed for a.c. signals using the *reactance* of the capacitor:

$$V_2 = i \times \frac{1}{\omega C}$$

If an operational amplifier integrator is considered as in (d), the current through the capacitor is given by:

$$i = \frac{V_1}{R}$$

and if this is an a.c. signal then:

$$V_0 = (-) \frac{i}{\omega C}$$

hence the transfer magnitude of an operational amplifier integrator, is:

$$\left| \frac{V_2}{V_1} \right| = \frac{1}{\omega CR} = \frac{1}{2\pi fCR} \qquad \begin{array}{l} \omega = \text{radians / sec} \\ f = \text{frequency Hz} \end{array}$$

Transfer Functions and
Closed-loop Frequency Response Principles   **Assignment 14**

giving a magnitude/frequency relation as in Fig 4.14.5(a).

(a) transfer magnitude   (b) polar plot
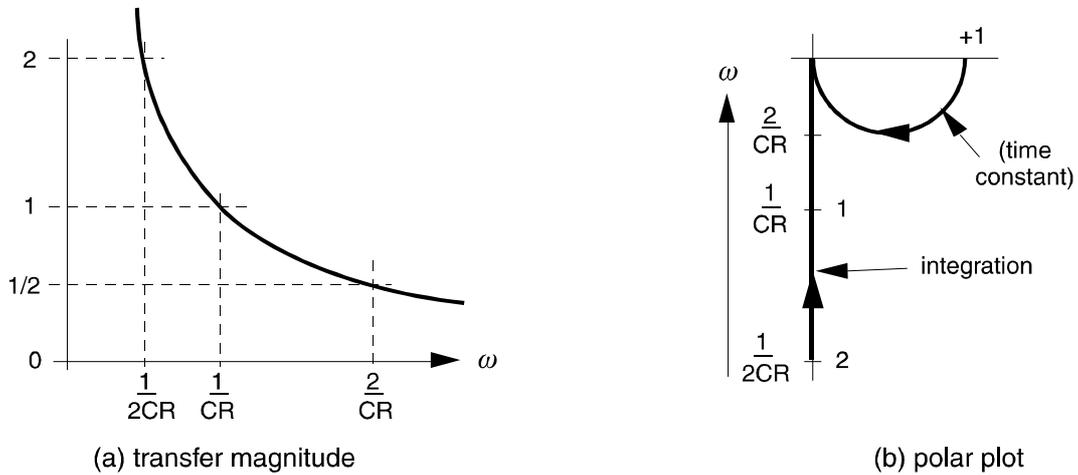
Fig 4.14.5 - Integration characteristics

$$\text{For} \quad \omega = \frac{1}{CR}; \qquad \left|\frac{V_2}{V_1}\right| = 1$$

at very low frequencies:

$$\left|\frac{V_2}{V_1}\right| \rightarrow \infty$$

and at very high frequencies:

$$\left|\frac{V_2}{V_1}\right| \rightarrow 0$$

The polar plot (which is a straight line) is shown in (b) illustrating the constant 90° lag. The semi-circular plot for a time constant is also indicated for comparison.

Transfer Functions and
Closed-loop Frequency Response Principles
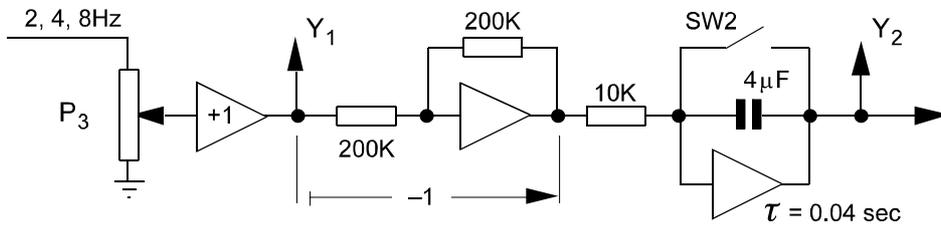
Assignment 14

(a) Circuit for integration
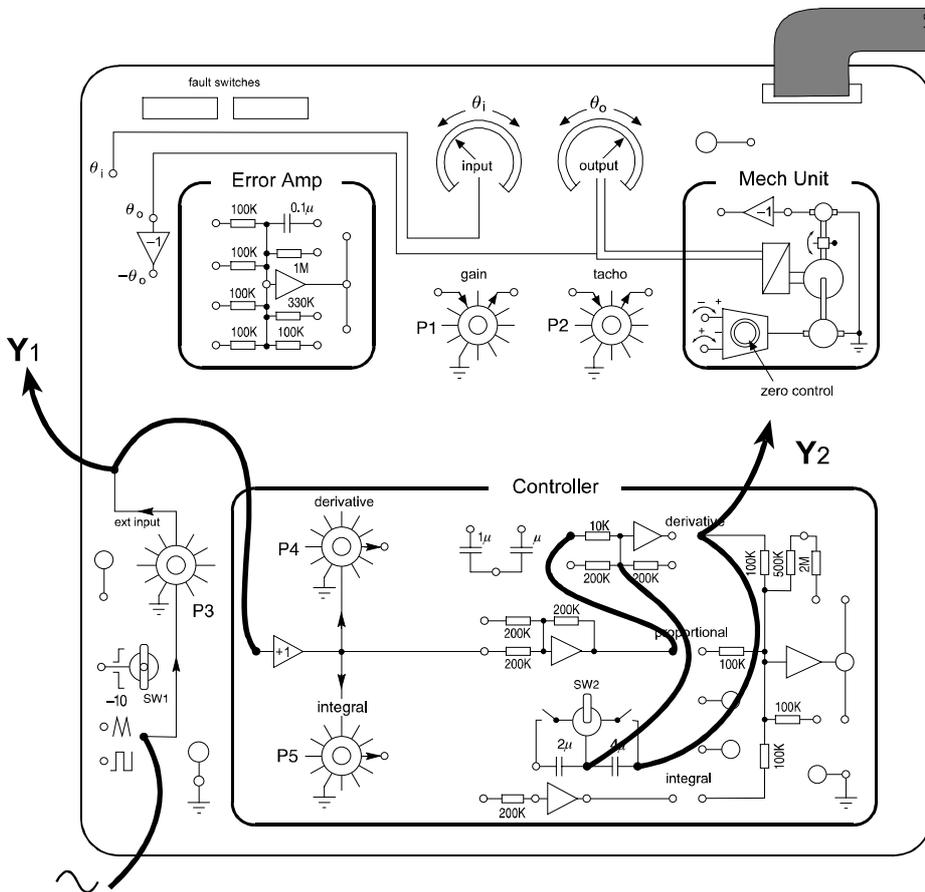
(b) Circuit diagram

Fig 4.14.6

**Transfer Functions and
Closed-loop Frequency Response Principles**   **Assignment 14**

PRACTICAL 14.2

**Frequency response
of integration**   A convenient arrangement to investigate the frequency response of integration is shown in Fig 4.14.6(a), with the connection diagram as in (b).
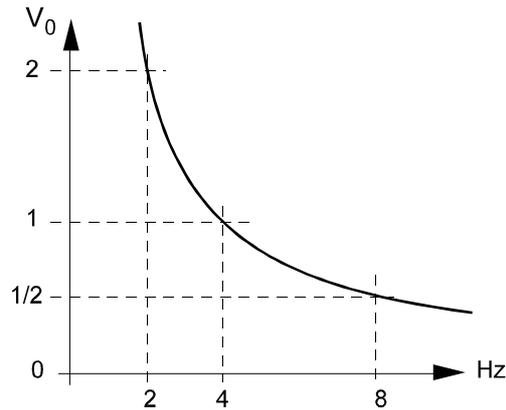
(c) Frequency response

Fig 4.14.6

Since for a integrator the transfer magnitude is unity for:

$$\omega \ = \ \frac{1}{CR} \ = \ \frac{1}{\tau}$$

and since $\tau = 0.04$ sec, unity transfer occurs for:

$$\omega \ = \ \frac{1}{0.04} \ = \ 25 \ \text{rads} \, / \, \text{sec} \ \cong \ 4\text{Hz}$$

giving the response of (c).

Connect a two channel CR0 to display the input and output and close SW2 to short circuit the integrator. Set the waveform generator to 4Hz and synchronise the CR0 trace to display 3 or 4 complete cycle on Y_1, and adjust the amplitude to ± 2V.

Open SW2 and the output should be sinusoidal lagging by 90° and approximately ± 2V but with a d.c. component depending on the exact point in the input cycle that the switch is opened.

Repeat the test but with input 2Hz and 8Hz and a.c. output components ± 4V and ± 1V respectively confirming the general form of (c).

NOTES

**Transfer Functions and
Closed-loop Frequency Response Principles**

Assignment 14

**Frequency response
of time constant
and integration**

As explained in connection with Practicals 3.3 and 3.4 and also Fig 4.11.5 and Practical 11.5, an ideal motor can be represented by a time constant (relating armature voltage and speed) followed by an integration (relating speed and output shaft position). From the frequency response point of view an ideal motor can be represented by two blocks with response loci as in Fig 4.14.7(a).

(a) Ideal motor

(b) Combined locus
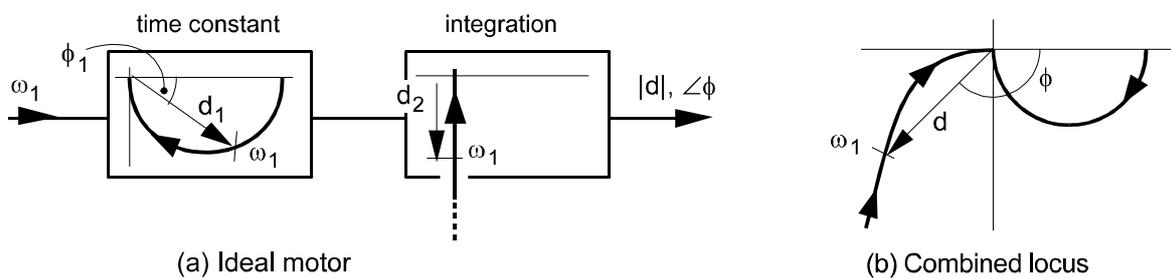
Fig 4.14.7 - Frequency Response of Ideal Motor

For any frequency the overall magnitude and phase angle is found by multiplying the individual magnitudes and adding the phase angles, hence if an input is applied at ω_1 the overall transfer is given by:

$$d = d_1 \, d_2 \qquad\qquad \phi = \phi_1 + 90°$$

The combined locus is shown in (b) and for low frequencies has a large magnitude with 90° lag and for high frequencies has a decreasing magnitude with a lag approaching 180°.

For $\omega = \dfrac{1}{\tau_1}$ (where τ_1 is the motor speed time constant) the overall lag is 45° + 90° = 135°.

**Transfer Functions and
Closed-loop Frequency Response Principles**   **Assignment 14**

**Closed-loop
Frequency Response**   The combined locus of Fig 4.14.7(b) shows that the overall magnitude response "d" falls continuously with increasing frequency. However, when a feedback loop is closed round a system as in Fig 4.14.8(a), which could represent a position control system, the closed-loop frequency response may be **very different** from the open-loop response depending on the gain.

If the input signal is sinusoidal then the signals throughout the system will be sinusoidal and the ideas developed previously can be applied. In particular the relation between error (E) and output (θ_o) will vary with frequency as in Fig 4.14.8b which corresponds with the combined locus of Fig 4.14.7b. The error signal is given by the relation:

$$E = \theta_i - \theta_o$$

can be re-arranged as

$$\theta_i = E + \theta_o$$

which implies that if θ_o is added to E, as in (c), to give the point p the line from the origin to p represents the input θ_i. This diagram indicates the **relative magnitude** of the signals so that the **form** is independent of the actual signal magnitudes. The diagram also gives the phase-angles between the signals which **again** is independent of the actual magnitudes.

The operating condition at p might correspond with a frequency ω_1 and indicate that the input and output are about equal giving.

$$\left|\text{system transfer}\right| = \left|\frac{\theta_o}{\theta_i}\right| = \text{approx } 1$$

If the frequency is reduced to ω_o with operating point q, then it can be seen that again.

$$\left|\text{system transfer}\right| = \left|\frac{\theta_o}{\theta_i}\right| = \text{approx } 1$$

and as the frequency is reduced θ_o and θ_1 become more nearly equal so that the transfer approached unity which is correct since at d.c. (i.e. $\omega \rightarrow 0$) the system will align perfectly. If a higher frequency ω_2 is considered with operating point r, θ_o is

much smaller than θ_i and the transfer decreases. These results show that the closed-loop transfer magnitude will have the general form of the initial gain response in Fig 4.14.9(a).
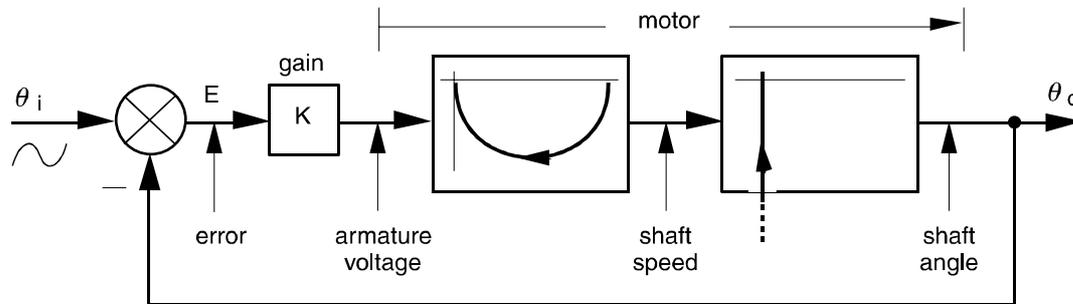
(a) Frequency domain representation of position control system

(b) Motor characteristics

(c) Closed-loop signals

(d) Closed-loop signals at ω_2 with increased gain
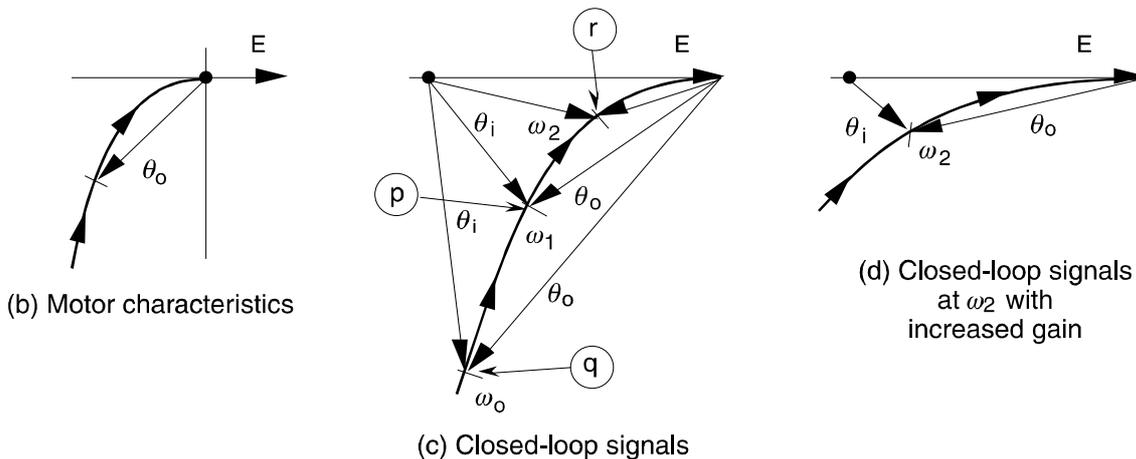
Fig 4.14.8 - Position control system and closed-loop signals

If the gain K is increased, say to about 3, then all values of θ_o will increase by a factor of 3 in Fig 4.14.8(b),(c) and in particular for frequency ω_2 the form of (c) will change to (d) and:

$$|\text{Transfer}|_{\omega = \omega_2} = \left|\frac{\theta_o}{\theta_1}\right| = \text{approx } 4$$

again at very low frequencies the transfer approaches unity and at high frequencies decreases giving the general form of the "increased gain" response of Fig 4.14.9(a). In general terms the peak occurs because due to the phase shift in the forward path approaching 180°, together with the increased gain, the feedback signal (θ_o) nearly provides the error signal. This implies that the system is approaching *self-oscillation.*

(a) Frequency response   (b) Step response
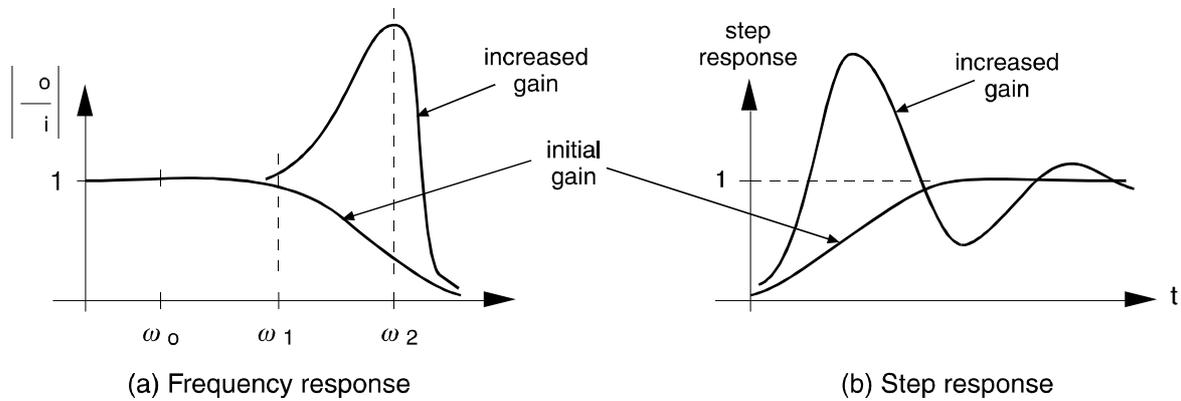
Fig 4.14.9 - Closed-loop responses

The form of the step response (b) is closely related to the corresponding frequency response. If the frequency response has no peak, as for the 'initial gain' condition, the step response has no overshoot. If the frequency response has a marked peak, as for 'increased gain', the step response has a very evident oscillatory component with frequency approximately that of the peak.

A step response overshoot of about 25%, sometimes regarded as a practical maximum, corresponds with a frequency response peak of about 1.3.

Transfer Functions and
Closed-loop Frequency Response Principles   **Assignment 14**

Nyquist Stability
Criterion   The diagram of Fig 4.14.8(b) forms the basis of a method of
system design. In application the error (E) is assumed unity
and the origin of the frequency response locus taken as the
origin, giving the diagram of Fig 4.14.10(a).

| (a) General diagram | (b) Locus with max phase lag of 270° | (c)   Oscillatory system (1) stable after compensation (2) |
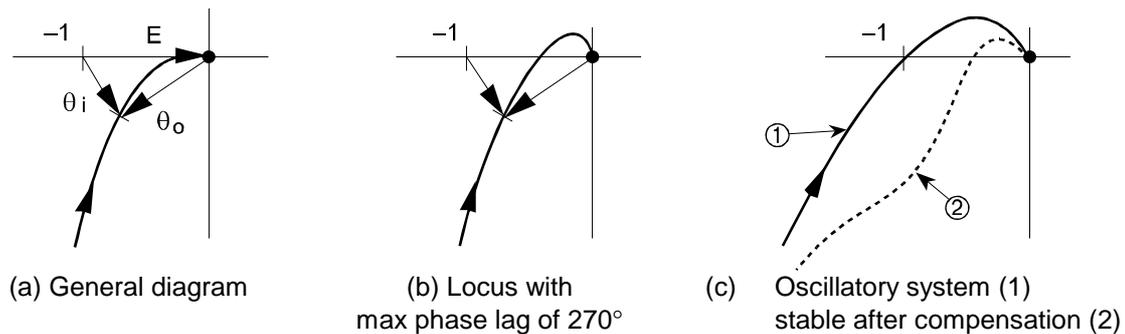
Fig 4.14.10 - Nyquist Diagrams for system design

The closeness of the frequency response locus to the "–1"
point indicates the magnitude of frequency of the frequency
response peak and hence the form of the step response. If the
system has an additional time constant in the forward path the
maximum phase lag will be 270° with the form of (b). If the
locus passes through the "–1" point, as in (c), which would
occur for (b) if the gain is increased, the system **oscillates**. The
diagrams form the basis of the *Nyquist Stability Criterion* which
provides a very instructive method for introductory system
analysis and design.

From considerations of practical systems the responses of
Fig 4.14.9 indicate a major general problem. As the system
gain is increased the transient response deteriorates but at the
same time a high gain may be required to counter the effect of
dead-band in the motor or to reduce steady following error. The
general solution is to introduce networks in the forward path
giving additional transfer functions, termed **compensation**,
which provide a high gain at low frequencies but reduce the
gain at frequencies where the existing forward path introduces
increasing phase shift. These networks (a 3-term controller for
example) modify or **re-shape** the overall frequency locus to
give adequate clearance of the "–1" point, perhaps as shown
dotted in Fig 14.10(c). Detailed investigation of such methods is
beyond the scope of an introductory manual but would be
covered in any general book on control systems.
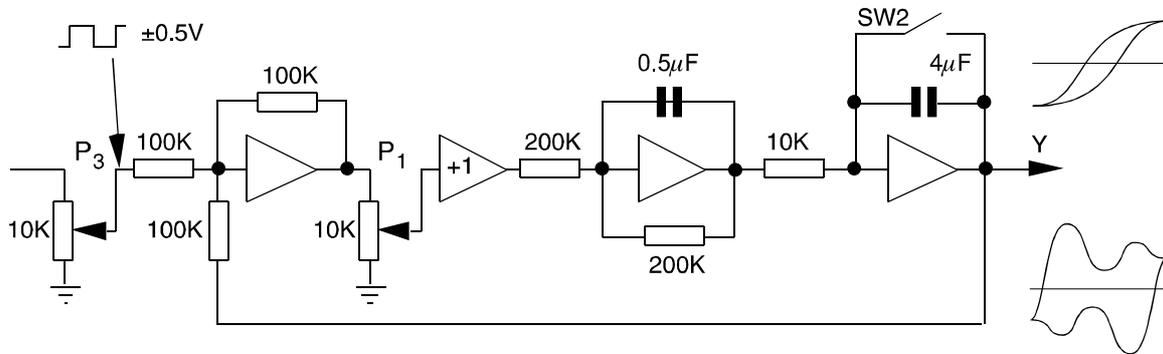
(a) Circuit diagram
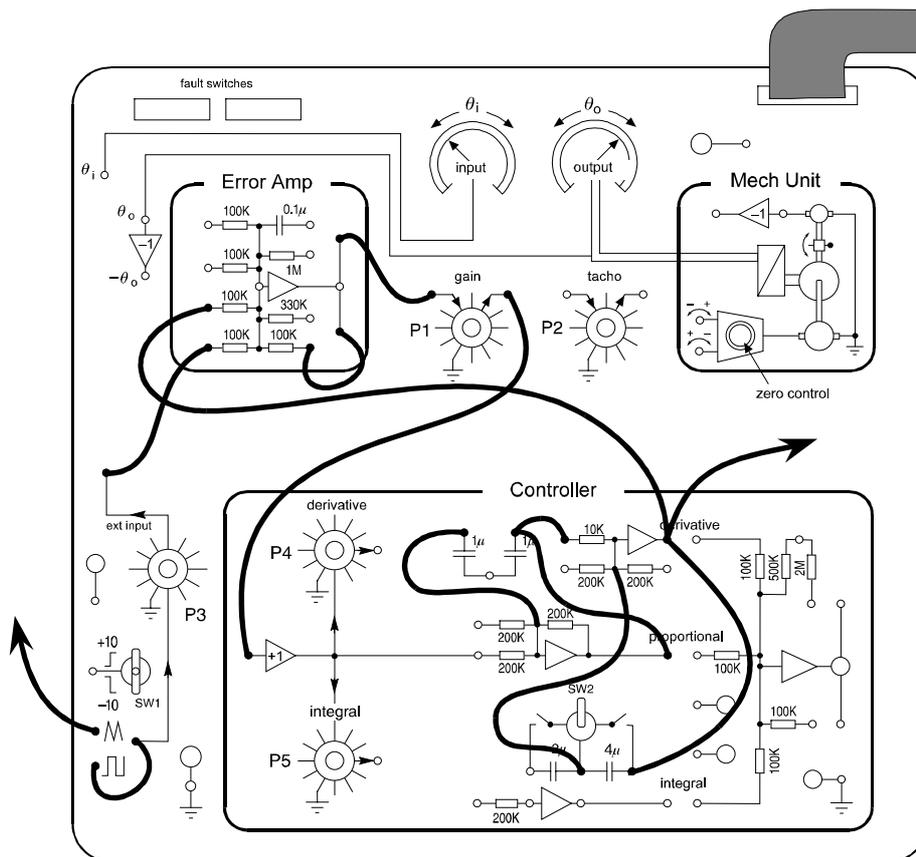
(b) Connection diagram

Fig 4.14.11 - Closed-loop system

Transfer Functions and
Closed-loop Frequency Response Principles   **Assignment 14**

PRACTICAL 14.3

Closed-loop
System experiments   A convenient system to investigate the closed-loop characteristics just covered is given in Fig 4.14.11(a), with connection diagram in (b). Note that the system contains 3 operational amplifiers in the loop giving overall **negative** feedback and will thus be stable at d.c.

Transient Response   Apply a squarewave at 0.5Hz to P_3 and adjust to give $\pm0.5V$ to the input 100KΩ.

Setting the error amplifier feedback resistor to 100KΩ, 330KΩ and 1MΩ and adjusting P_1 note the range of step responses that can be obtained at Y with SW2 both closed and open. These vary from no overshoot (gain <1) to marked oscillation or "ringing" for gain of 10. The response with a gain of 1 has a similar form to the 33-002 servo system with a gain of 1.

Frequency Response   It is instructive to check the form of Fig 4.14.8(c) as applied to the present system. The time-constant is 0.1 seconds, hence:

$$\omega = \frac{1}{\tau} = 10 \text{ rads}/\text{sec} = 1.6\text{Hz}$$

gives (T = Transfer):

$$\angle T = -45° : \qquad | T | = 0.707$$

The integrator has:

$$|T| = \frac{1}{\omega CR} : \qquad \angle T = -90°$$

and with:

$$R = 10\text{K}\Omega, \ C = 4\mu f : \quad |T| = \frac{25}{\omega}$$

thus for:

$$\omega = 10 \qquad\qquad |T| = 2.5$$

and the complete forward path with 100 KΩ feedback resistor and P1 at 100% from the error amplifier output to Y

$$| T | = 0.707 \times 2.5 = 1.75 : \angle -45° - 90° = \angle -135°$$

**Transfer Functions and
Closed-loop Frequency Response Principles**   **Assignment 14**

Hence if the error signal is taken as one unit, Fig 4.14.8(d) becomes Fig 4.14.12(a). It is convenient to take the origin (0) at the right hand end of the error and hence the left hand end is −1, referred to as the **'−1 point'**.

(a) Closed-loop diagram for $\omega = 10$

(b) Closed-loop diagram for forward path gain = 10 $\omega = 50$ (8Hz) closed loop gain 5
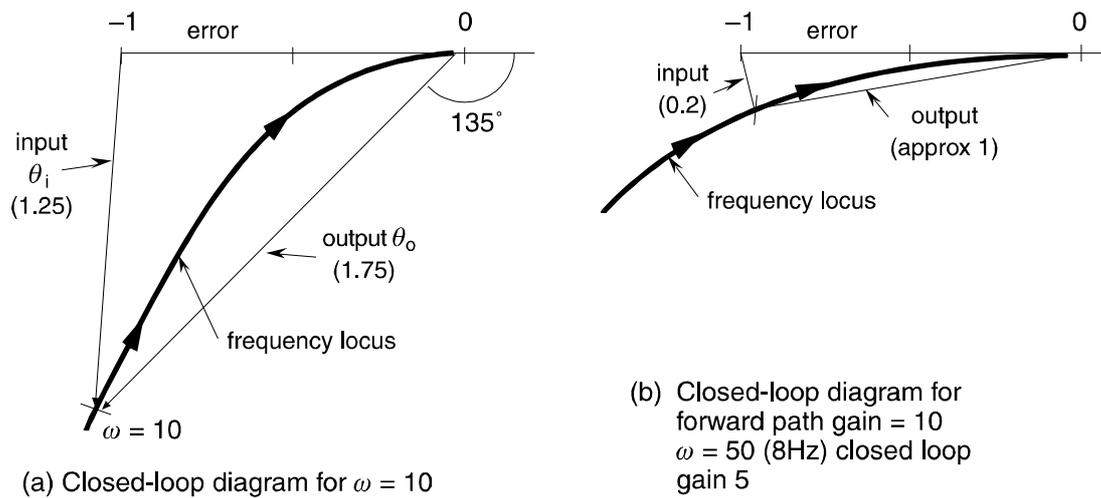
Fig 4.14.12 - Closed-loop signal diagrams

and θ_i can be measured (or calculated) as 1.25, thus:

$$| \text{ closed loop overall transfer } | = \frac{1.75}{1.25} = 1.4$$

To confirm this experimentally connect the sinewave signal to P_3 and set the frequency to 1.6Hz. Since the result is sensitive to the actual frequency, adjust the frequency accurately, either by counting cycles (the X deflection in the same frequency), 20 cycles take 12.5 secs, or by using a counter/timer.

With the forward gain set to 1, adjust P_3 to give (say) ±5V at the error amplifier input and then measure the output at Y. The ratio should be about 1.75.

Transfer Functions and
Closed-loop Frequency Response Principles | **Assignment 14**

Response peaks
with change of gain   The relation between gain and frequency response peak can be checked setting the gain and input magnitude as below and then adjusting the frequency for maximum response at Y. The input is reduced with increasing frequency because the voltage at the error amplifier output increases with increased gain. The approximate results should be:

> gain 1   input ±5V | overall transfer | =1.7 at 3Hz
>
> gain 3   input ±1V   = 3 at 5Hz
>
> gain 10   input ±0.2V   = 5 at 8Hz

The form of the closed-loop diagram for a gain of 10 and 8 Hz is given at 4.14.12(b), assuming that the gain of 10 occurs separately **after** the error amplifier.

These general results show the relation between transient response and peak in the frequency response and indicate that for a small overshoot the frequency peak should not exceed 1.5 or less.

(a) Condition for oscillation at ω_o (b) $\angle 90°$ condition

(c) Modification to fig 4.14.11(a) for oscillation

Fig 4.14.13 - Oscillatory system

PRACTICAL 14.4

Oscillation

If the frequency response locus of Fig 4.14.12 passes **through** the "−1" point as in Fig 4.14.13(a), for a frequency ω_o this implies that **no external input** is required and the system will maintain **self-oscillation** at ω_o.

The essential requirement for the locus to pass through the "−1"point is:

(i) $\angle$ forward path = 180°

(ii) |forward path transfer| = 1

    i.e. forward path transfer = −1

The present system cannot maintain oscillation because a time-constant and integration cannot give $\angle$ 180°. However, if an additional time-constant is introduced then $\angle$ 180° can be obtained at some frequency. A modification to the system of Fig 4.14.11a to introduce an additional time-constant is given in Fig 4.14.13c where the error amplifier feedback is changed to 1MΩ with 0.1μF in parallel. This gives a time constant of 0.1 sec together with a d.c. gain of 10x.

Since there are now 2 time constants of 0.1 sec

for ω = 10, $\angle$ 45 + 45 = 90°

$\angle$ integrator = 90° constant

    $\angle$ forward path = 180°

and with a loop gain of 1 the system could oscillate.

Using an X-Y display of the output of the second time constant apply ±1V at 1.6Hz (ω = 10), from P_3 and close SW2 which stops any feedback.

The output of the error amplifier for 1.6Hz will be:

    ±10 x 0.707 = ±7.07 volts

and the output of the second time constant will be:

    ±707 x 7.07 = ±5V

with 90° phase shift to give the display of (b). Check that varying the frequency slightly causes the display to rotate slightly indicating increase or decrease in phase-shift.

For $\omega = 10$ the gain of the integrator will be:

$$\frac{25}{\omega} = 2.5$$

hence the loop gain (with P_1 at 100%) will be:

$$5 \times 2.5 = 12.5$$

Since a loop gain of 1 is required oscillation would occur with P_1 at about 8% which is a difficult adjustment. If the 10K integrator input resistor is replaced by the 2 x 200K resistors also available at the input to the derivative amplifier, in parallel as shown dotted giving 100K, the integrator gain becomes:

$$\frac{2.5}{\omega} = 0.25$$

and the max loop gain is now.

$$5 \times 0.25 = 1.25$$

and the system should oscillate with about 80% of P_1.

To check this set P_3 to zero and display the error amplifier output. Set P_1 to 100% and open SW2. Oscillation should slowly build up and will eventually saturate the amplifier causing "flats" on the waveform. Reduce P_1 slowly and it should be possible to maintain oscillation with almost no flat showing.

If there is insufficient gain for oscillation the maximum loop gain can be doubled to 2.5 by connecting the second 200K at the input to the proportional amplifier.

**Transfer Functions and
Closed-loop Frequency Response Principles** **Assignment 14**

CONCLUSION The practicals in this assignment show how the characteristics of a closed-loop system can be inferred from the relation between the open loop frequency response locus and the "–1" point. If the locus passes close to this point the system will have an unsatisfactory transient response.

The ideas above form the basis of the *Nyquist Stability Criterion,* originally developed in connection with the stability of feedback telephone repeater amplifiers, but applicable to any open-loop/closed-loop situation. Other methods are available but the Nyquist method has a simple background. In addition it can be applied to situations where the detail is known (as in the system of this assignment) and the locus can be calculated, or to systems when the detail is not known but the locus can be measured experimentally.

NOTES

APPLICATION OF FREQUENCY RESPONSE
METHODS TO THE 33-002 CONTROL SYSTEM   ASSIGNMENT 15

Assignment 14 has covered the principles of frequency response analysis applied to individual elements such as a time constant and an integration and also to closed-loop systems.

Assignment 15 covers their application to the 33-002 analogue control system together with the standard control actions of proportional, integral and derivative.

The following Practicals are included in this assignment:

15.1   Time Constant

15.2   Motor Transfer

15.3   Proportional & Derivative Control

15.4   Integral Control

15.5   Velocity (tachogenerator) Control

**APPLICATION OF FREQUENCY RESPONSE
METHODS TO THE 33-002 CONTROL SYSTEM**   **ASSIGNMENT 15**

CONTENT   ν   To apply frequency response methods to the measurement
                            of motor characteristics.

                       ν   To investigate the effect of proportional, derivative, integral
                            control and velocity feedback by frequency response
                            methods.

**EQUIPMENT
REQUIRED**

Qty	Designation	Description
1	33-110	Analogue Unit
1	33-100	Mechanical Unit
1	–	Power Supply ±15V dc, 1.5A +5V dc, 0.5A *(eg Feedback PS446 or 01-100)*
1	–	Oscilloscope, storage or long persistence, preferably with X-Y facility *(eg Feedback 1810-01229)*

**APPLICATION OF FREQUENCY RESPONSE
METHODS TO THE 33-002 CONTROL SYSTEM**   **ASSIGNMENT 15**

OBJECTIVES   When you have completed this assignment you will:

ν   Have investigated the background to the Nyquist Stability
Criterion and its application to simple control systems.

ν   Know how the shape of the forward path locus affects the
closed loop performance and how the shape is modified by
various control actions.

KNOWLEDGE LEVEL   Before you start this assignment you should:

ν   Be familiar with control system principles

ν   Have completed Assignment 14.

Application of Frequency Response
Methods to the 33-002 Control System
Assignment 15
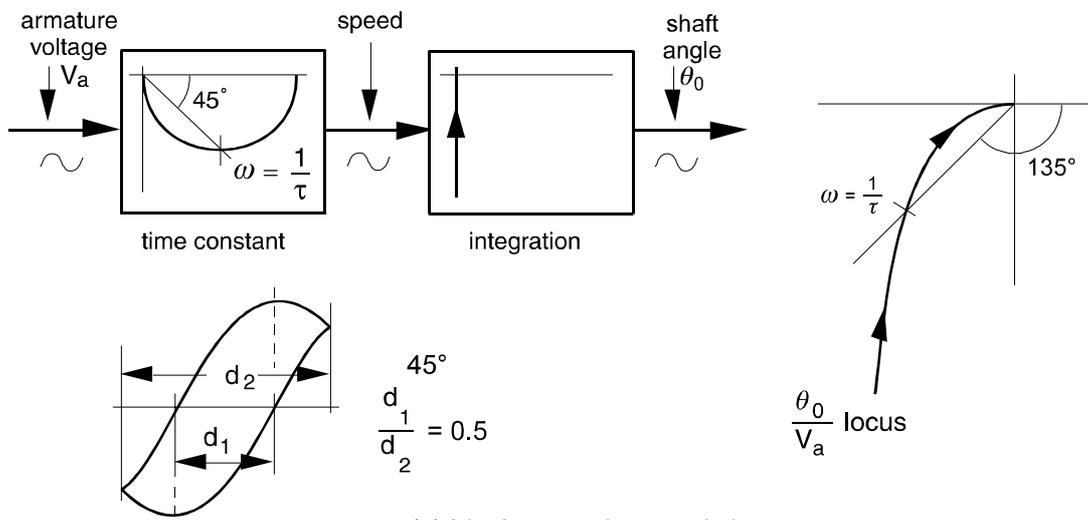
(a) Ideal motor characteristics
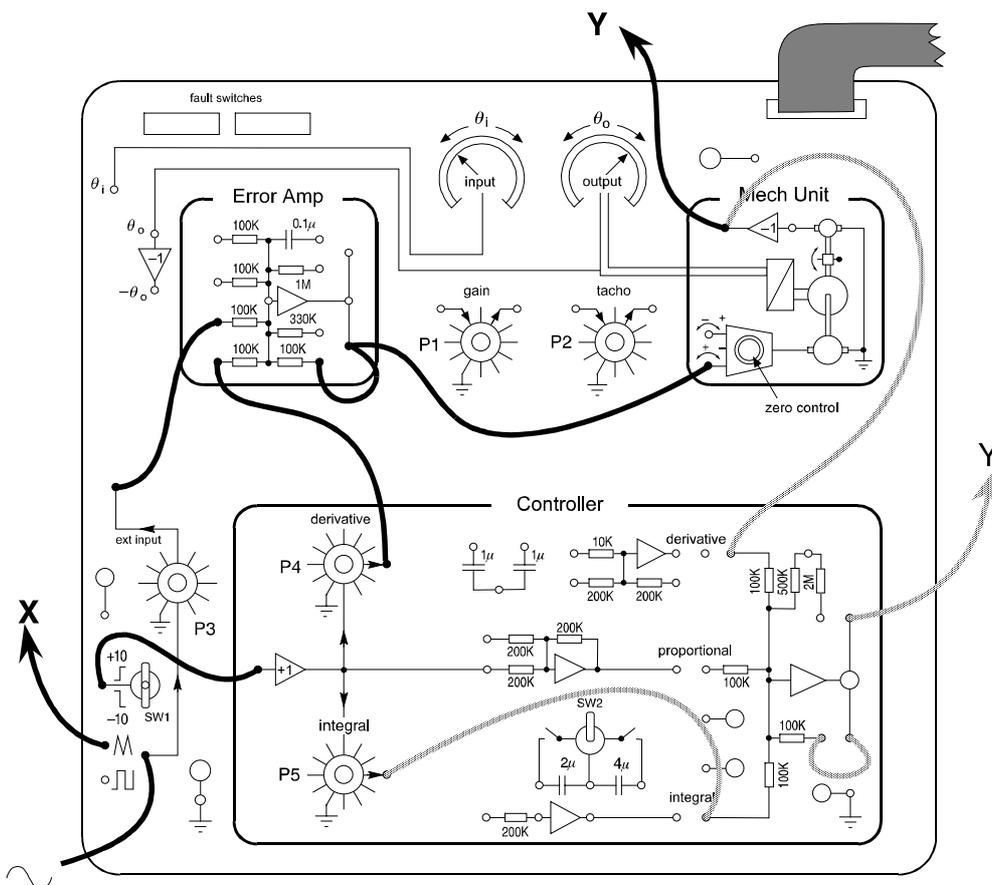
(b) System for time constant measurement

Fig 4.15.1 - Time constant measurement

Application of Frequency Response
Methods to the 33-002 Control System

Assignment 15

Motor characteristics
An ideal motor can be represented as in Fig 4.15.1(a), by a time constant and an integration with frequency response loci as shown. The derivation of these characteristics is developed in Practicals 3.3 and 3.4 and also Practical 11.5 Fig 4.11.5 and Fig 4.14.7.

PRACTICAL 15.1

Time Constant
The time constant can be measured by using the principles of Practical 14.1 and Fig 4.14.3(c) by applying a sinusoidal input to the power amplifier and displaying the tachogenerator signal which is proportional to speed. The frequency is then adjusted to determine the "45° frequency" similarly to Fig 4.14.3(b). However, for small motors, such as used in the 33-002 Mechanical Unit, the effects of brush friction and stiction which distort the display at the zero crossing, i.e. where the motor stops and reverses, may prevent a good estimate being obtained. These effects can be largely eliminated if a speed "offset" is used causing the motor always to rotate in one direction. A display can be made using the solid line system of Fig 4.15.1b where +10V is applied via the +1 amplifier and P_4 enables an offset to be applied.

Initially set P_4 to zero, the frequency to 0.1Hz and adjust P_3 to give about ±5V at the tachogenerator output. As the frequency is increased the display will show the effect of phase shift but the zero crossing distortion is evident though an estimate of the time constant can be made.

To introduce offset set P_3 to zero and adjust P_4 so that the tachogenerator output is about 3V steady. Then adjust P_3 so that the sinewave component is about ±2.5V and the motor does not stop. The Y-shift of the CRO can be used to move the display towards the centre of the screen. If the shift available is inadequate a useful technique is to pass the tachogenerator output to Y by the additional dotted links through the controller summing amplifier enabling a shift to be introduced via P_5 to cancel the steady component

The 45° shift should occur at about 0.4Hz (=2.5 rads/sec) corresponding with a time constant of about 0.4 sec.

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**

$$\frac{\theta_0}{E} = \text{forward path transfer}$$
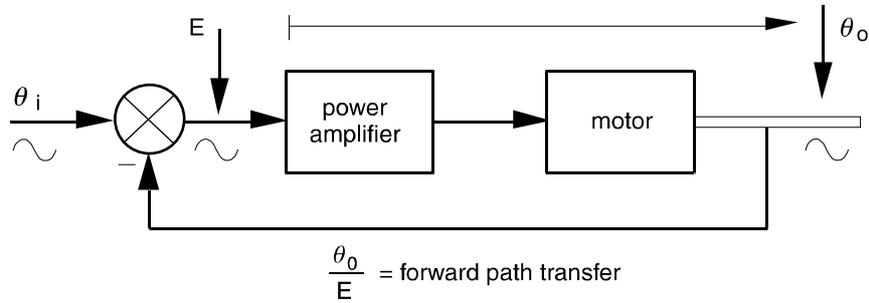
(a) Forward path transfer measurement

sinewave from mechanical assembly
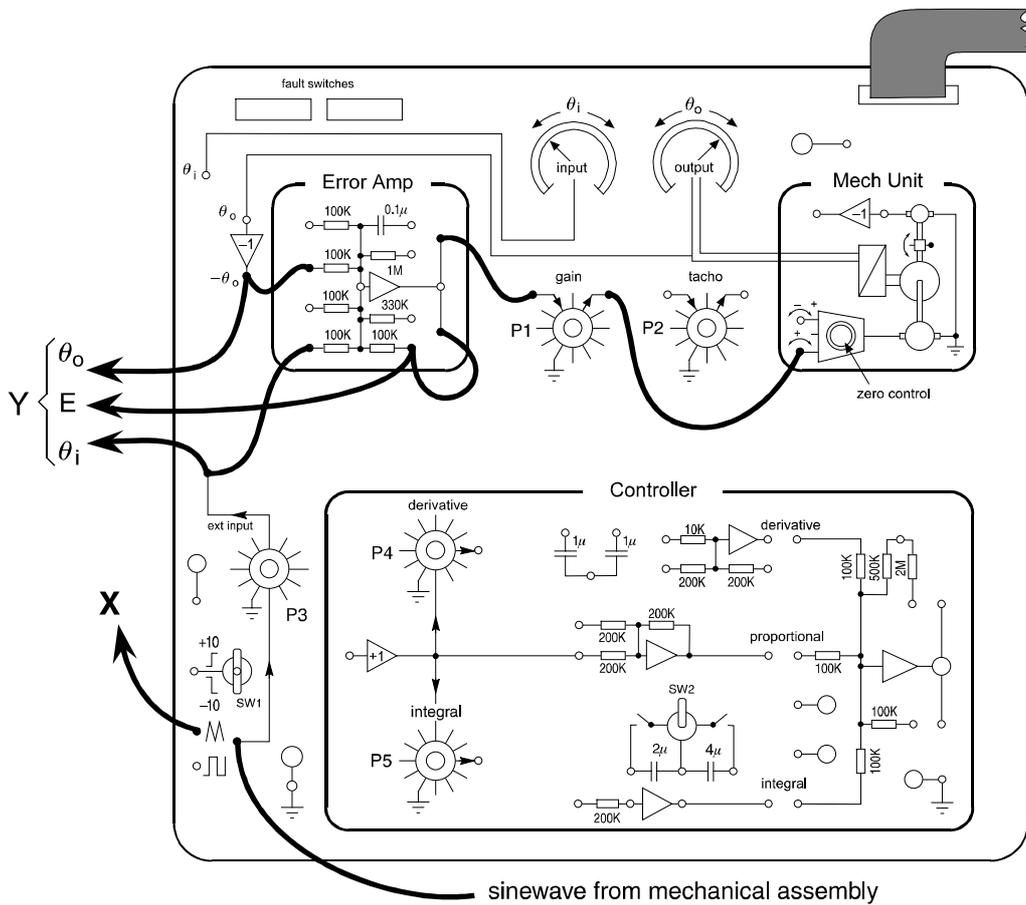
(b) System arrangement

Fig 4.15.2 - Transfer Function Measurement

**Application of Frequency Response
Methods to the 33-002 Control System**   **Assignment 15**

Motor transfer

Since the motor contains an integration it is not possible to measure the overall transfer directly because the motor shaft rotates through many revolutions and will also creep in one direction or the other because the number of rotations usually differs in each direction.

It is however possible to measure the forward path transfer by operating the system under closed-loop and measuring input, error and output as in Fig 4.15.2(a). The forward path transfer is the same as the motor transfer in frequency characteristics except for an overall gain in the power amplifier.

PRACTICAL 15.2

To measure the forward path transfer locus, arrange the simple control system of Fig 4.15.2(b) with an X-Y display. For each frequency the Y input will be taken successively from error, output and input. It is convenient to make a table of results as below, from which the results and locus will be plotted. The actual values obtained depend somewhat on the particular system used and those quoted are merely an example set. For each frequency make a quick check of the three signal amplitudes then adjust P_3 so that the largest signal is (say) $\pm 8V$. The relative amplitude of the signals depends on the frequency. The figures without brackets are experimental results which are then normalised (NOR) by dividing by the error amplitude. A convenient range of frequencies is $0.3 \rightarrow 0.6$Hz and the gain P_1, should be 100%

Hz	E		θ_0		θ_i		$G = \dfrac{\theta_0}{\theta_i}$
	EXP	**NOR**	**EXP**	**NOR**	**EXP**	**NOR**	
0.3	4	(1)	8	(2)	6.2	(1.55)	1.3
0.4	6.4	(1)	8	(1.25)	5.5	(0.86)	1.45
0.5	8	(1)	7	(0.87)	4.5	(0.56)	1.55
0.6	8	(1)	4.5	(0.56)	4.4	(0.55)	1

Table of Signal Measurements

Application of Frequency Response
Methods to the 33-002 Control System   Assignment 15
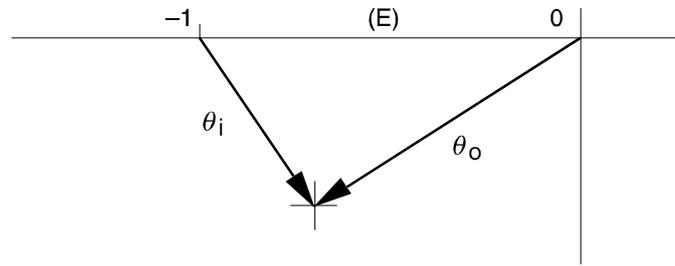
(a) Construction using normalised values
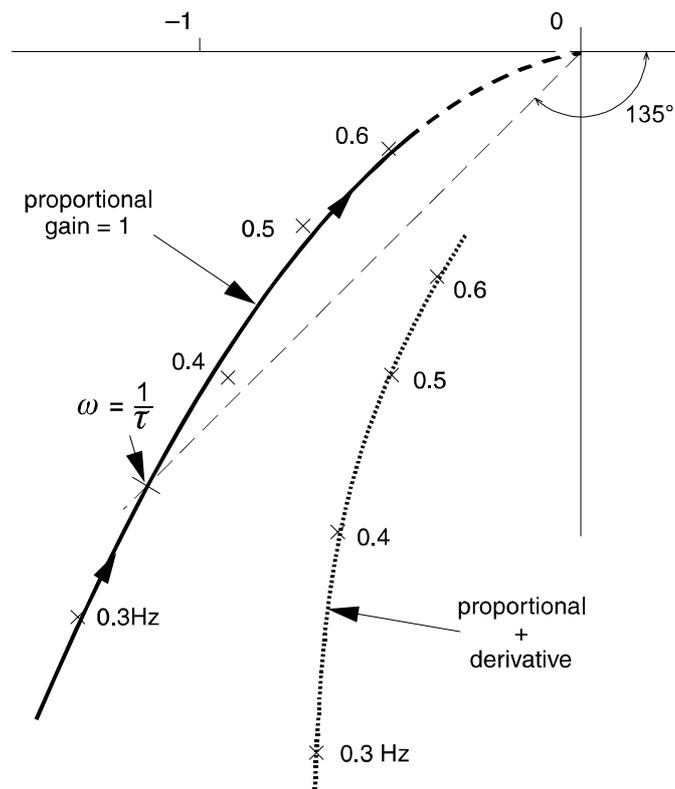
(b) Locus plots
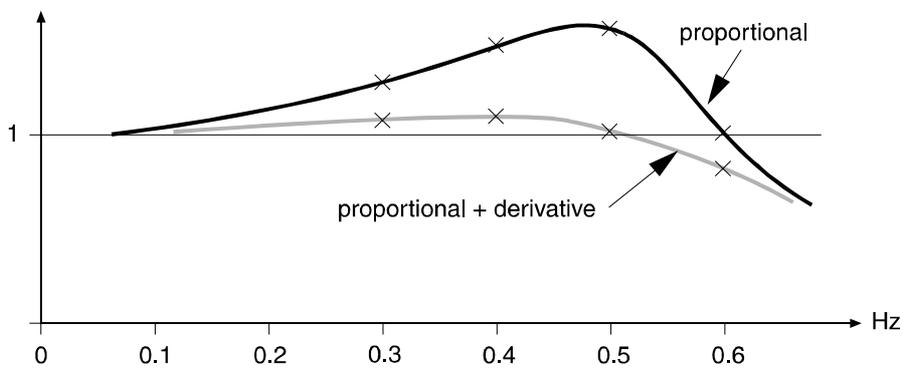
(c) Closed-loop frequency responses

Fig 4.15.3 - Forward path locus plots and closed-loop responses

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**

The locus plot can be obtained by using the construction of Fig 4.15.3(a) which was developed under the section *closed-loop frequency response* in Assignment 14 and also Fig 4.14.8(c). It is convenient to take the unit error as (say) 5cm and individual points can be located by striking arcs of normalised θ_o, θ_I from 0,-1. The result should be generally as the locus in Fig 4.15.3(b) which corresponds with the previous table of values. The closed-loop response peak in (c) will be about 1.5 at about 0.5Hz which will give a step overshoot of about 50% and is a little high for an "acceptable" response. The motor time constant can also be estimated from the frequency corresponding with a forward path phase angle of (–) 135° as shown.

For comparison the forward path transfer and closed loop response with the addition of derivative feedback are also shown in Fig 4.15.3(b), (c).

These results are obtained in Practical 15.3.

If the forward path gain is increased to (say) 3x, then the locus expands radially by 3x and a higher frequency value will lie close to the "-1" point giving a more marked peak. If a higher gain is used it should be noted that the signal at the error amplifier output should be **divided** by the gain to give the correct experimental error value i.e. corresponding with the values **not** bracketed in the table. Also the system takes an appreciable time to settle to a steady state after any change when using higher gain so measurements may not be as convenient as with unity gain.

Application of Frequency Response
Methods to the 33-002 Control System

Assignment 15
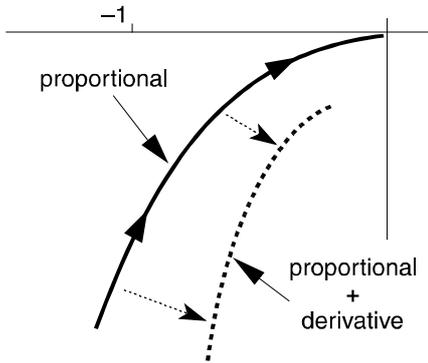
(a) Introduction of derivative control
moves locus away from −1 point
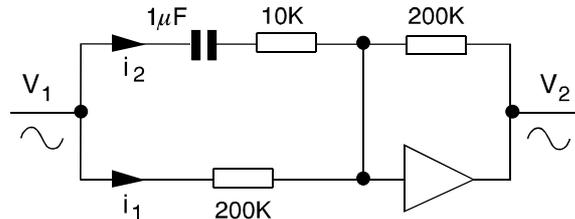
(b) Proportional + derivative control
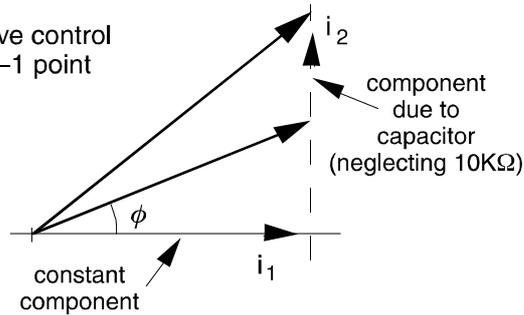
(c) Phase lead obtained from circuit of (b)
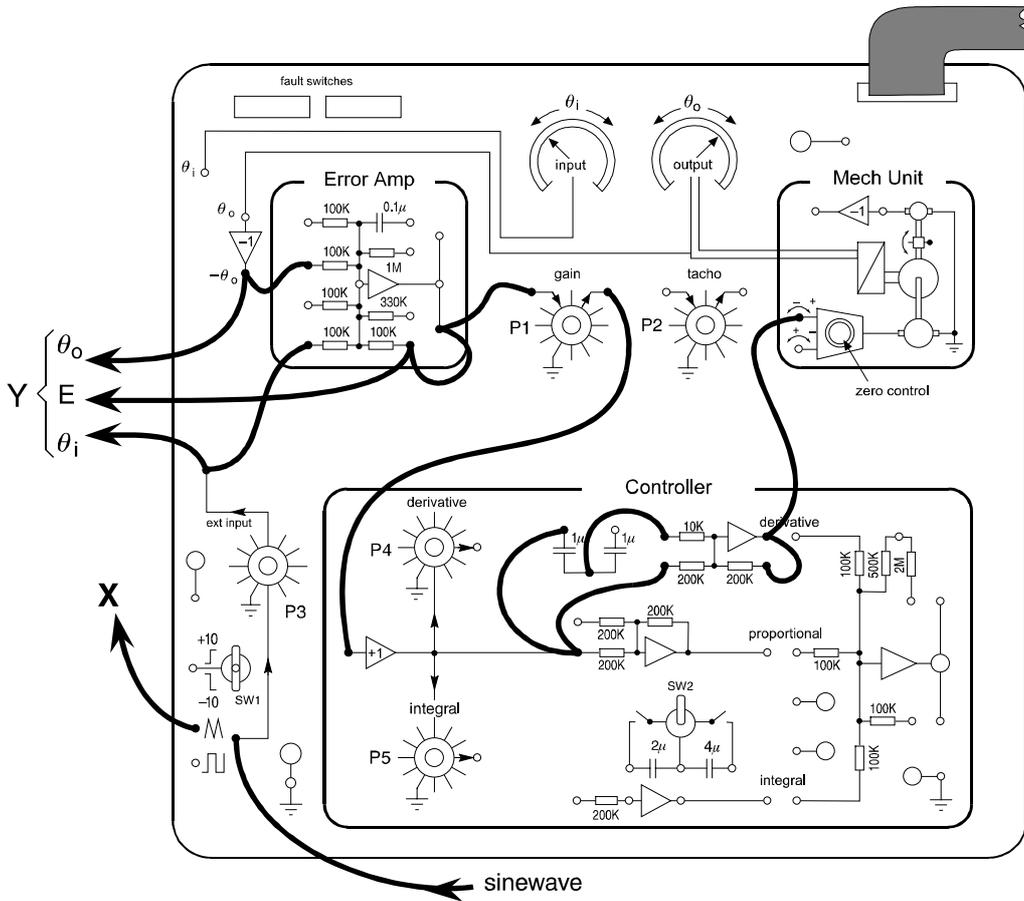
(d) System arrangement

Fig 4.15.4 - Application of derivative control

**Application of Frequency Response
Methods to the 33-002 Control System** **Assignment 15**

**Proportional plus
Derivative Control**

The system of Fig 4.15.2 used simple proportional control which sets a limit (about 1 for the 33-002) to the gain that can be used without the locus passing too close to the "–1" point and the transient response becoming unacceptable. Derivative control (see Assignment 10, Fig 4.10.4 and Assignment 11, Fig 4.11.1.(a) provides much improved transient response. In frequency response terms the improved transient response occurs because derivative control provides a **phase advance** which can be arranged to swing the locus away from the "–1" point as shown in Fig 4.15.4(a).

The circuit of Fig 4.15.4(b) shows values available in the controller which will provide phase advance. In the circuit of (b) the output voltage contains a component due to i_1, and another due to i_2. For a given V_1, i_1, is independent of frequency and could be represented by the horizontal component in (c). Since i_2 is the current through a capacitor this increases with frequency and also **leads** i_1 by 90°, neglecting the small effect of the 10KΩ. Thus the overall transfer for the circuit has a leading angle, ϕ, which **increases** with frequency.

PRACTICAL 15.3

The circuit of Fig 4.15.4(d) gives a system with proportional + derivative control using the circuit of (b). Note that since there is an additional amplifier in the forward path the + input socket to the power amplifier is used to maintain overall negative feedback.

For the values of (b) an estimate of the phase lead at about 0.5Hz ($\cong$ 3.1 rad/sec) can be made as follows:

reactance of capacitor $= \dfrac{1}{\omega c} = \dfrac{10^6}{\omega}$ for 1μF, giving 310KΩ

thus $i_2 = \dfrac{200}{310}\, i_1, = 0.66\, i_1$

hence vertical component in (c) = 0.66 x horizontal component giving $\angle \phi$ about 30°

Using the same measurement technique as in Practical 15.2, construct the corresponding table for 0.3→0.6Hz and plot the locus on the same diagram as for your Fig 4.15.3(b). The results should be generally as the Proportional + Derivative locus shown which was measured with the circuit of Fig 4.15.4(b).

The control has a dramatic effect on the transient response even when the gain is increased to 3.

**Application of Frequency Response
Methods to the 33-002 Control System**   **Assignment 15**

Integral Control

Integral control eliminates steady errors in various situations (see Assignment 11) but has particular application when following a ramp input (Practical 11.4). The general characteristic in all these situations is that the integrator accumulates a signal, by integrating the error, and the accumulated signal eventually cancels the steady error.

The frequency response characteristic of integration has already been used in connection with motors (see also Fig 4.14.5) and a system containing a motor and an additional integration as in Fig 4.15.5, will have an additional constant $\angle 90°$ lag so that for very low frequencies the forward path locus will start with $\angle -180°$ and finally reaches the origin with $\angle -270°$ passing **outside** the "–1" point as shown and on closed-loop the system will be completely unstable with oscillation building up for **any** value of gain.
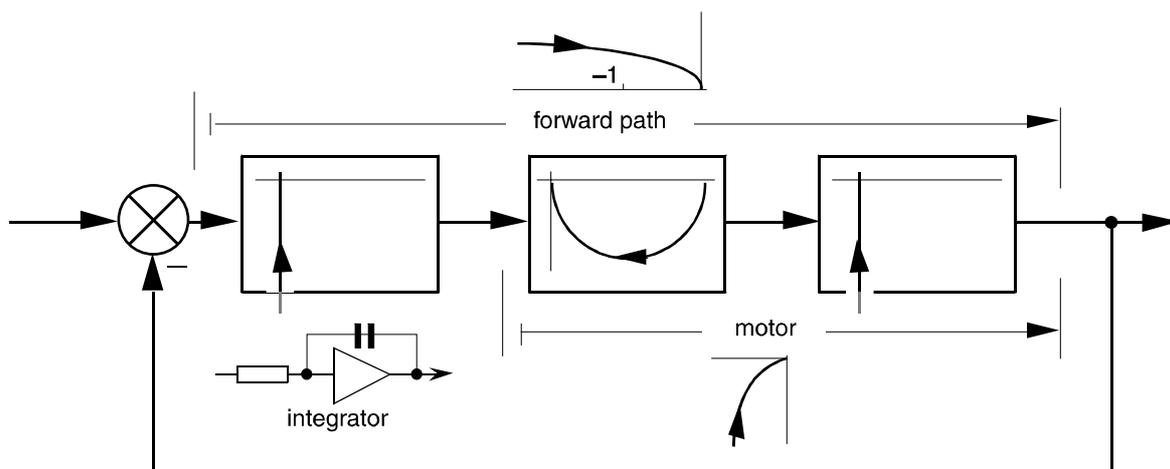
Fig 4.15.5 - System with Motor and additional integration

If integral control is to be used the form of the locus at frequencies corresponding with the region of the "–1" point must be re-shaped to pass adequately **inside** the "–1" point. This process can be achieved by using a full PID controller but it is convenient to develop the ideas in steps to appreciate the background principles.

If a resistor is placed in series with the capacitor as in Fig 4.15.6(a) (see also Fig 4.12.2 in Assignment 12) the integration action is essentially unchanged at d.c. or very low frequencies,

Application of Frequency Response
Methods to the 33-002 Control System
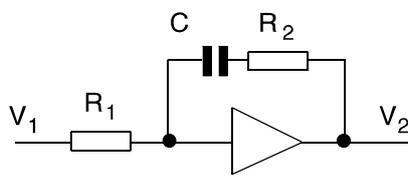
(a) Integrator with resistor (R $_2$)
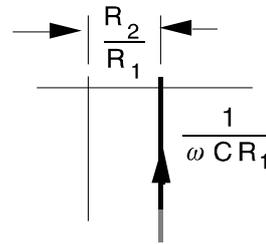
(b) Frequency response locus
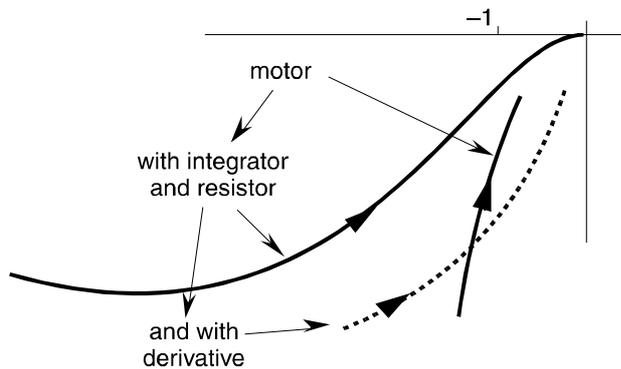
(c) Frequency response loci

Fig 4.15.6 - Integral Control

but at higher frequencies the reactance of the capacitor is very much smaller than R_2 and the amplifier transfer becomes constant at

$$\frac{V_2}{V_1} = (-)\frac{R_2}{R_1}$$

reducing the $\angle -90°$ to zero giving a frequency response locus as in Fig 4.15.6(b).

[using the 'j' notation the amplifier transfer is:

$$\frac{V_2}{V_1} = (-)\frac{R_2 + \dfrac{1}{j\omega C}}{R_1} = (-)\left(\frac{R_2}{R_1} + \frac{1}{j\omega CR_1}\right)$$

indicating the transfer locus shown, neglecting the negative sign].

The locus of (b) in series with that of the motor gives the form shown in (c) which passes below the "–1" point but still introduces some lag so that the combined locus is closer to the "–1" point than the motor alone leading to poorer transient response. Finally derivative control can be added to swing the locus away from the "–1" point.

Application of Frequency Response
Methods to the 33-002 Control System

Assignment 15

(a) P + I + D System

(b) Response loci
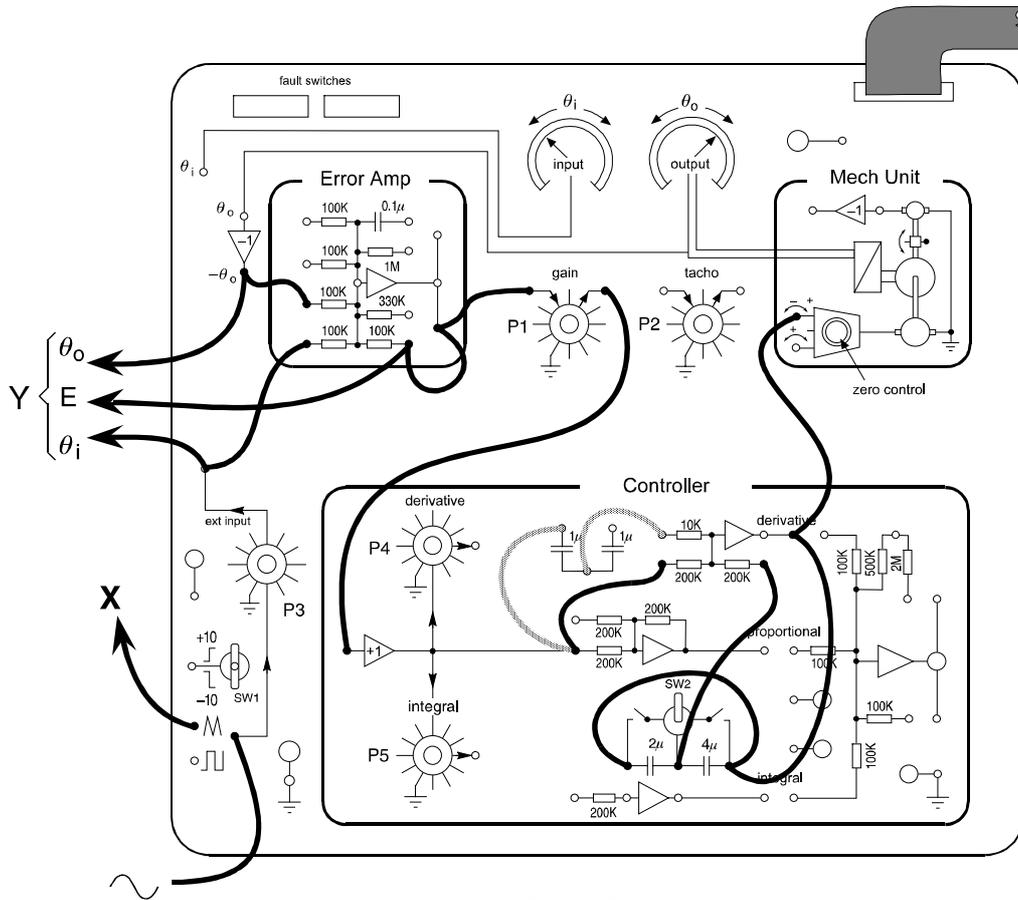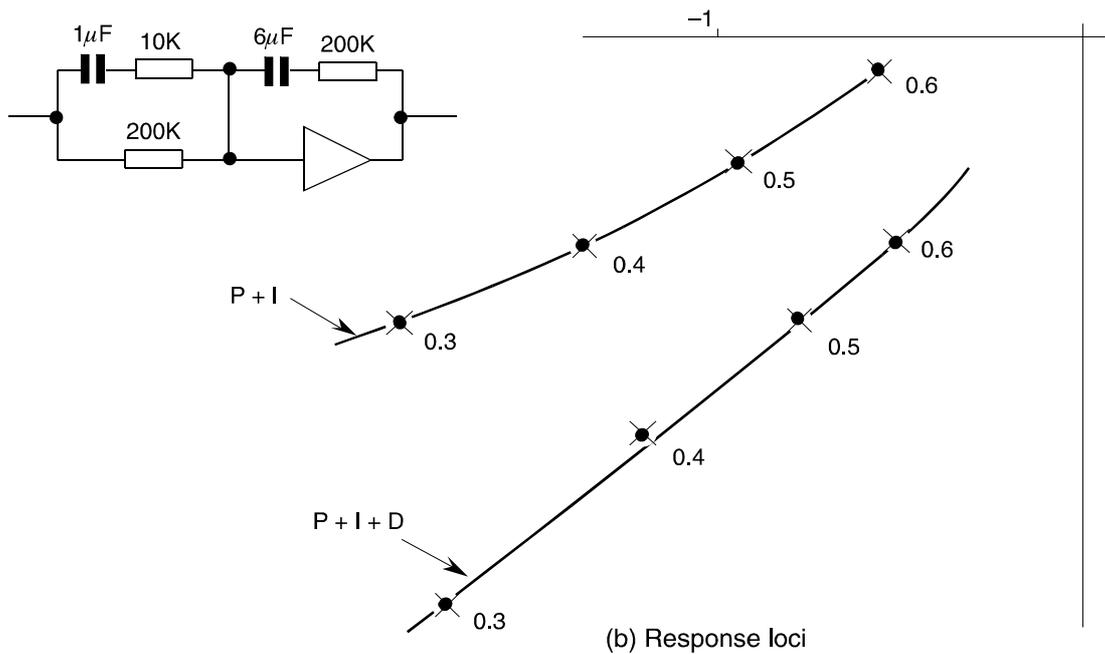
Fig 4.15.7 - Integral Control with Derivative added

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**

PRACTICAL 15.4

To investigate integral control it is convenient to arrange the simple system with single amplifier control combining integral and derivative as in Fig 4.15.7(a) (see also single amplifier PID control Fig 4.12.4). Make sure the integrator control switch is OPEN.

Initially remove the links to the 1μf capacitor and as for the previous practicals make a table of values for E, θ_o and θ_i for (say) 0.3, 0.4, 0.5, 0.6Hz with maximum value $\pm$ 8V. Plot the normalised results and the locus should have the general form of Fig 4.15.7b, passing the closer to the "−1" point and with a response peak of perhaps 3x. Note the step response, (input say $\pm$ 3V at 0.1Hz)

Make the links to the 1μf capacitor and again plot the locus which should have the form shown showing the derivative effect and again examine the step response.

For the present (more complicated) system it is not easy to correlate the precise transient detail with the frequency response shape and some adjustment of gain and component values could be required. However, see the comment at the end of Practical 11.4 (p4.11.10).

Application of Frequency Response
Methods to the 33-002 Control System
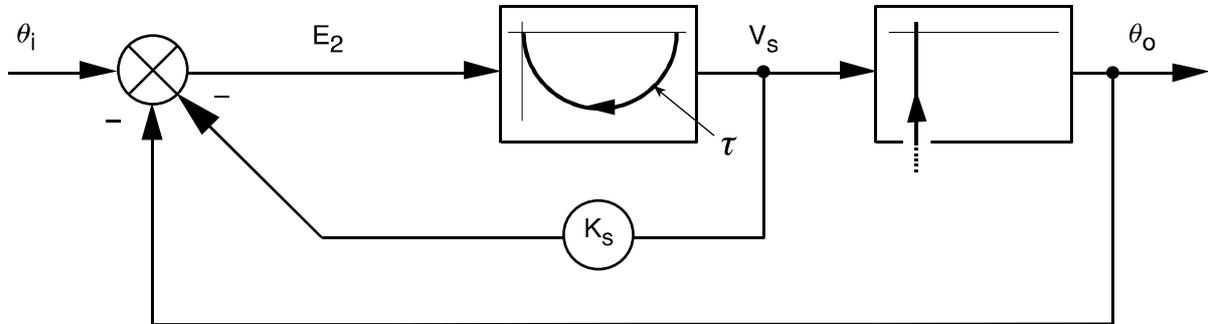
(a) System with ideal motor and velocity feedback
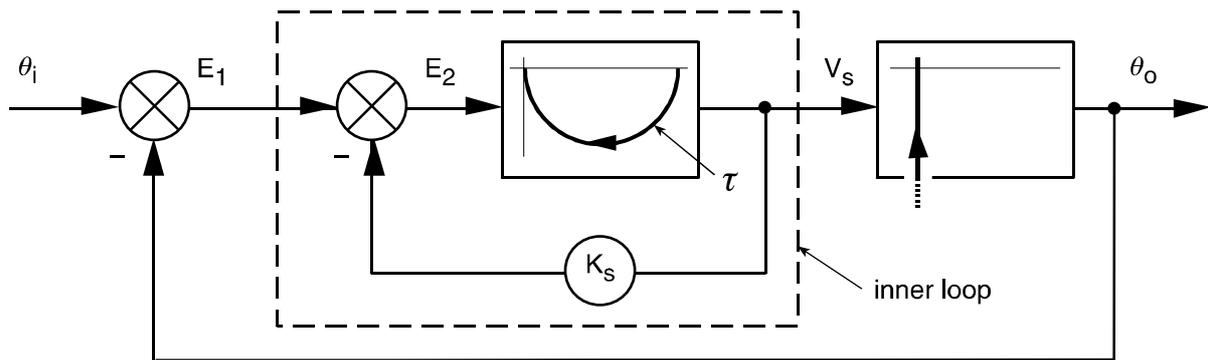
(b) System redrawn showing inner loop
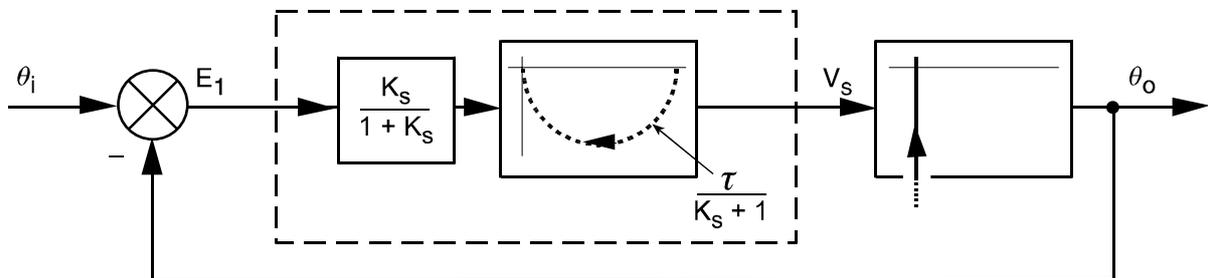
(c) System equivalent to (b) showing reduced time constant

Fig 4.15.8 - Representations of system with Velocity Feedback

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**

Velocity
(Tachogenerator)
Feedback   The introduction of velocity feedback provides a very powerful
method of improving the transient response (see Assignment
6), and it is instructive to analyse the effect in frequency
response terms. Velocity feedback is normally combined with
the output feedback as shown in Fig 4.15.8(a), for a system
with an ideal motor in the forward path. For investigation it is
convenient to consider two separate feedback paths as shown
in (b). In both diagrams (a) and (b)

$$E_2 = \theta_I - \theta_o - k_S V_S$$

so that the overall result is the same. With the representation of
(b) there is an **inner** closed-loop system between E_1 and V_S,
and it can be shown that the result of this inner loop is to
reduce the **effective** time constant of the motor as in (c).

[using the 'j' notation and the standard closed-loop relation
applied to (b)

$$\frac{V_S}{E_1} = \frac{\dfrac{1}{1+j\omega\tau}}{1+\dfrac{K_S}{1+j\omega\tau}} = \left(\frac{K_S}{K_S+1}\right)\frac{1}{\left(1+j\omega\dfrac{\tau}{K_S+1}\right)}$$

indicating that the **effective** time constant between E_1 and V_s is

reduced to $\dfrac{\tau}{K_S+1}$]

The effect of the reduced time constant is that for any
frequency the phase lag in the forward path is reduced and the
response locus swings to the **right**, away from the -1 point, as
in Fig 4.15.9. This greatly improves the transient response of
the system.

**Application of Frequency Response
Methods to the 33-002 Control System**
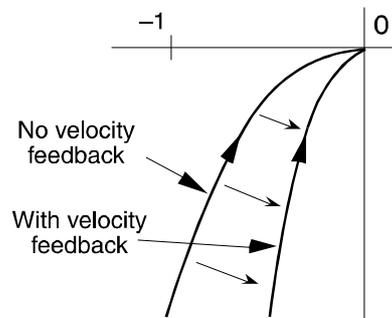
Fig 4.15.9 - Effect of reduced time constant due to velocity feedback

NOTES

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**
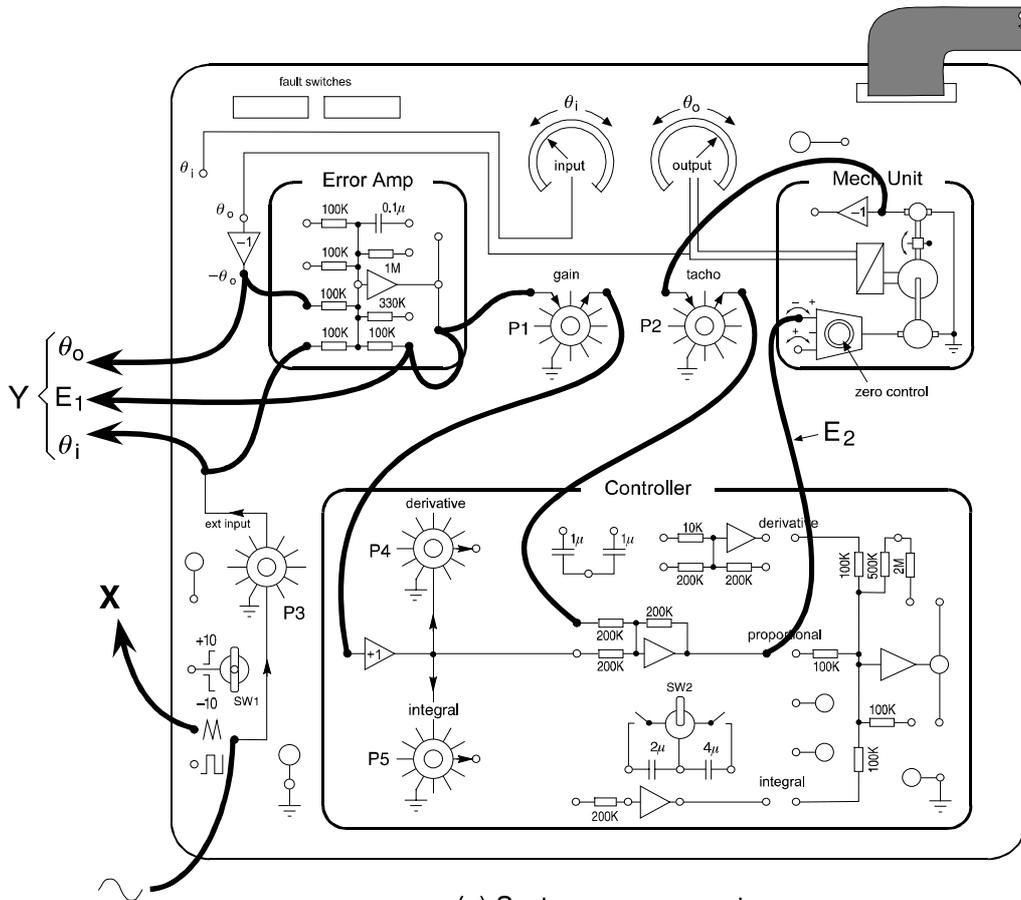
(a) System arrangement
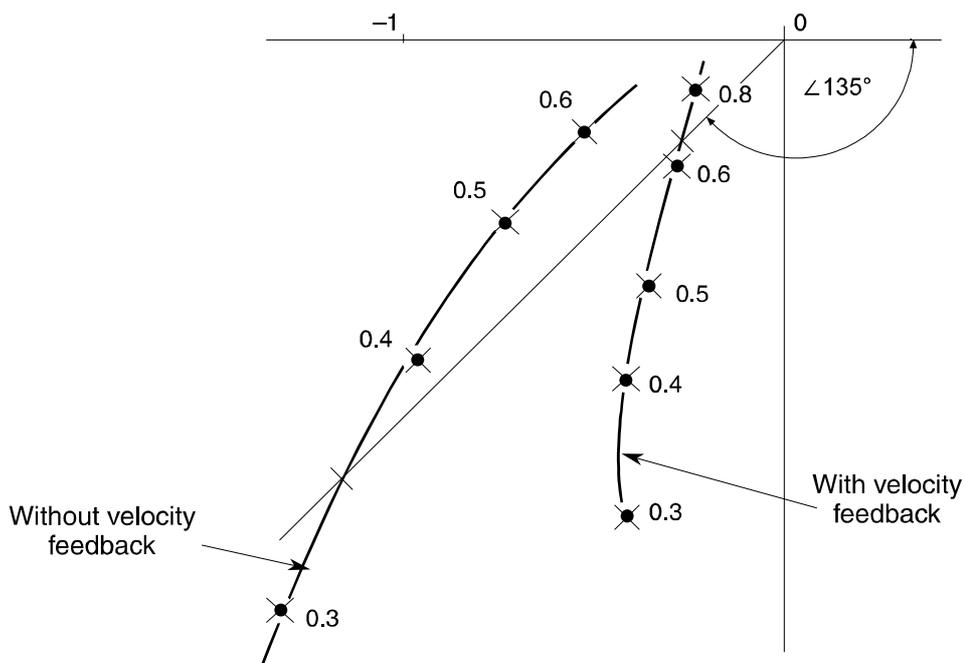
(b) Effect of velocity feedback on forward path locus

Fig 4.15.10 - Velocity Feedback

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**

PRACTICAL 15.5   To investigate velocity feedback a system must be arranged with the form of Fig. 4.15.8(b), where **both**

$$E_1 = (\theta_i - \theta_0) \quad \text{and} \quad E_2 = (E_2 - K_sV_s)$$

are available. If the velocity feedback is connected to an additional 100kΩ input to the *error amplifier* the system will have the form of (a) and the amplifier output will be E_2 and not E_1.

A convenient system arrangement is as in Fig. 4.15.10(a), where the error amplifier output is E_1, in Fig. 4.15.8(b), and the central amplifier, in the controller is used to add the velocity signal from the tachogenerator to E_1, to form E_2, which drives the motor. Note that since there is an additional amplifier in the forward path the power amplifier drive must be applied to the + input socket to maintain overall negative feedback.

Initially set P_2 to zero and P_1, to 100% and make a table of values of E_1, θ_l and θ_0, as in Practical 15.2, over the range 0.3 to 0.6 Hz, and make a normalised forward path locus plot. If this has already been done for the particular equipment in use the same results can be used.

Then set P_2 to 100% and make another normalised forward path locus plot E_1, θ_i, θ_0, which should have the general form shown in Fig. 4.15.10(b). The effect of velocity feedback on the locus is very marked and measurements can be taken to a higher frequency. If the $\angle-135°$ line is drawn the new effective time constant can be estimated from the frequency at which the line crosses the new locus and should be of the order of 50% of the original value. Also the closed-loop frequency response does not show any peak.

Finally a step input can be applied to show the improvement in the transient response.

Application of Frequency Response
Methods to the 33-002 Control System   **Assignment 15**

CONCLUSION   Assignment 15 has outlined the general principles of frequency response analysis for simple closed-loop systems and their application to the 33-002 system. These applications show how the performance of a system at the design stage can be inferred from a knowledge of the transfer function of individual components or from measurement of the overall characteristic when the individual component characteristics are not known.

There are many other methods of system design some based on different representations of the frequency response method (Bode Diagrams) or others based on more advanced interpretations of frequency response principles (Root locus method and State Space Analysis). The simple frequency response method however provides a very instructive introduction.

SWITCHED FAULTS   **APPENDIX A**

INTRODUCTION   This fault information is intended for instructors, who may then decide how the faults and information are to be used. If considered appropriate, the complete appendix can be removed from the manuals available to students.

This appendix gives general information about the switched faults. Section 1 covers the analogue system (analogue unit + mechanical unit) and Section 2 the digital system (digital unit + mechanical unit). For each system the faults are distributed throughout the system, though controlled by switches at the top left of the Analogue or Digital Unit. The faults are intended to represent the type of circuit or component failure that could occur in a system.

The faults are introduced by applying +5V to control lines through the switches. The relation between switch number and controlled fault is determined by a removable header in a socket underneath the panel adjacent to the switches. The fault position can therefore be changed by re-arranging the header links. The following fault information is based the header being 'straight linked' which is the factory default setting.

For each fault there is a brief description of the effect on the system, together with a test or CRO display to identify the fault.

The Default Setting for the switches is all OFF.

Switched Faults   **Appendix A**

CHANGING THE
SETTINGS   A jumper block beneath the panel enables the instructor to
transfer the faults to different switches. The block supplied with
the kit, is straight wired across the block, fig A1. To make the
change, it is recommended that new jumper blocks be
obtained, although it is possible to unsolder the existing block.
See fig A2.

Switches on top
surface of panel

Jumper blocks
beneath the panel

Fig A1

Switches on top
surface of panel

Jumper blocks
beneath the panel
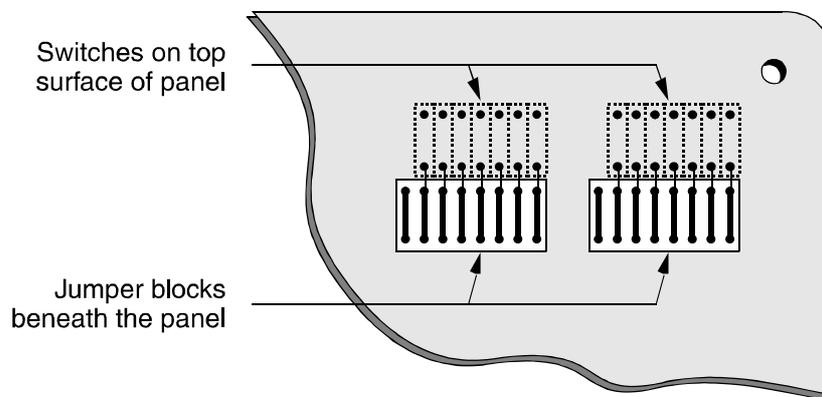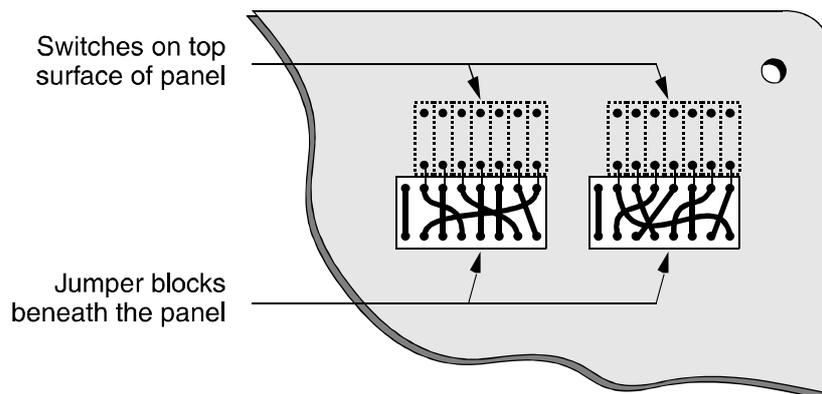
Fig A2 Typical jumper transposition

Switched Faults   **Appendix A**

**Access to the
Jumper Blocks**

In order to get at the jumper blocks, the board must be removed from the protective tray to which it is normally attached. The attachment is by plastic rivets, shown in section in fig A3, which may be released after pushing out the central rod by means of a piece of stiff wire or other suitable implement.
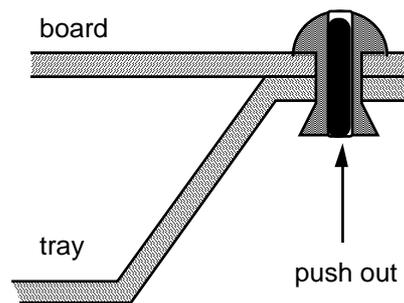
Fig A.3 - Removal of rivet fasteners from board
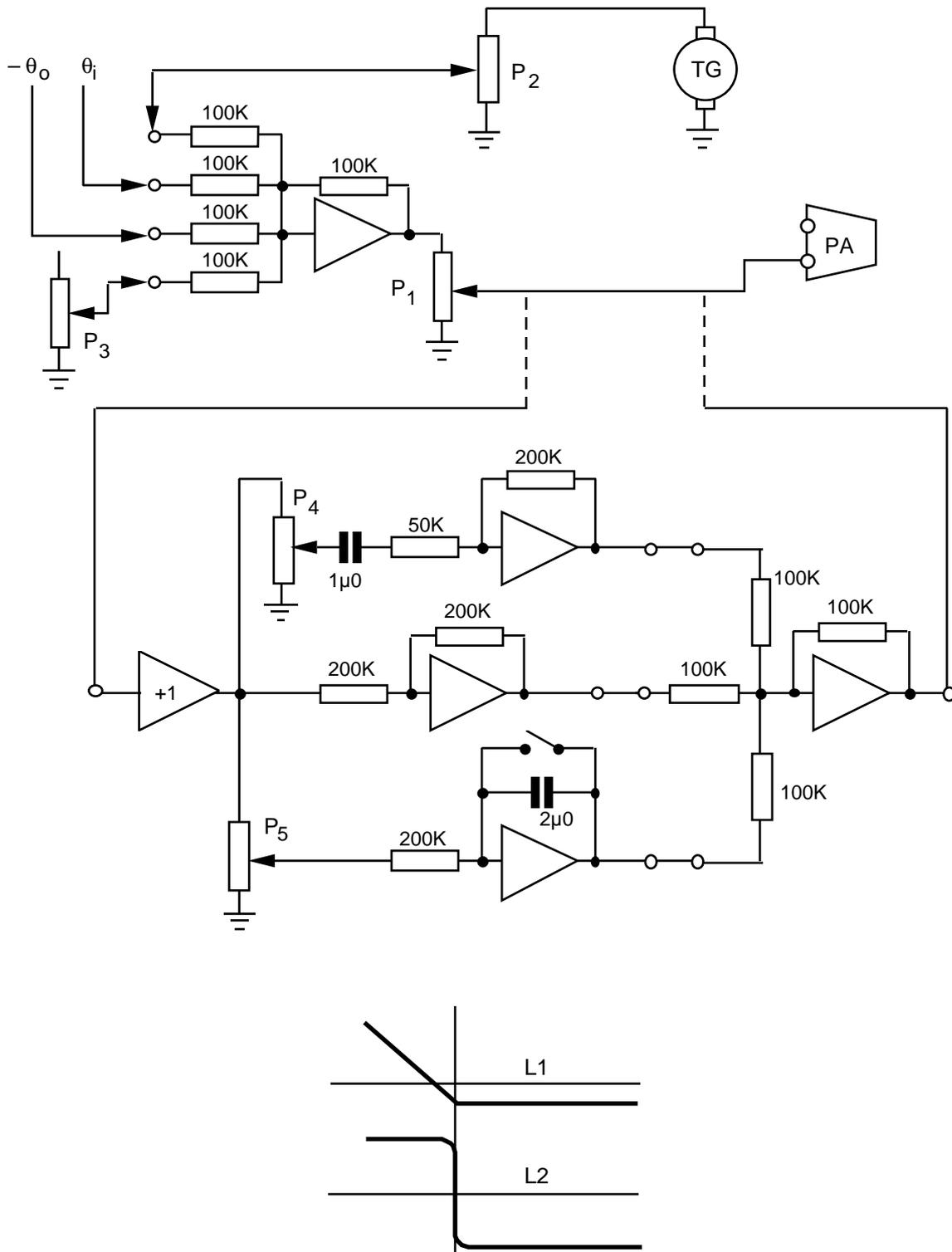
Fig A4 - Circuit for analogue system fault investigation

Switched Faults **Appendix A**

SECTION 1

**Analogue System
Faults**   The circuit of a system which is convenient for fault investigation is given in fig A4.

FAULT LIST   The number designates the relevant switch in the default state, i.e with no crossed jumpers on the header.

Left switchbank   1   Error amplifier output much reduced for one polarity.

2   Open-circuit all feedback resistors on error amplifier, max output ±5V.

3   Loss of input potentiometer signal (θ_i).

4   Fault in Mechanical Unit on +10V supply to input/output potentiometers.

5   Fault in −1 unit in output potentiometer (θ_O).

6   Non-symmetrical gain fault in power amplifier.

Right switchbank   1   Open-circuit derivative input resistor in PID summer.

2   Short circuit proportional amplifier feedback.

3   PID integrator operates in one polarity only.

4   Tachogenerator failure.

5   Not used

6   Not used

FAULT IDENTIFICATION

Left Switchbank

Switch 1	Error amplifier output much reduced for one polarity.
	The effect on the system is to give normal performance in one direction but very slow in the other. Check, with G = 3, by rotating θ_i or applying a square wave input.
To identify the fault	Disconnect θ_i, $-\theta_O$ and set P_1 to zero. Apply triangle input of ±10V from P_3. An X-Y display of amplifier output should be as L1 in fig A4.
Switch 2	Open-circuit all feedback resistors on error amplifier, max output ±5V.
	The effect on the system is to cause sustained small amplitude oscillation with low value of gain.
	Check by setting G = 1, and oscillation will commence as P_1 is increased from zero.
	Note that the system follows substantially as normal, but oscillates when stationary.
To identify the fault	Disconnect θ_i, $-\theta_O$, and set P_1 to zero. Apply triangle input of ±10V from P_3. An X-Y display of amplifier output should be as L2 in fig A4.
Switch 3	Loss of input potentiometer signal (θ_i).
	The effect is that the system does not respond to θ_i rotation.
To identify the fault	Check with voltmeter or oscilloscope that ±10V supply is on the potentiometer in the Mechanical Unit and that a variable voltage is supplied from the slider. Hence fault must be open-circuit in connection to θ_i socket.
Switch 4	Fault in Mechanical Unit on +10V supply to input/output potentiometers.
	Positive supply to both potentiometers reduced to about +2.5V.
	Has several effects in the input system:
	If θ_i disconnected and no external input, the output moves to about +90°.
	System responds to external input but about +90° misaligned.

	If θ_i is connected system follows θ_i, or external input substantially normal, except that the response to an external signal increases slightly when the fault is applied.

To identify the fault   Measure voltage range at θ_i socket as input potentiometer is rotated.

Switch 5   Fault in -1 unit in output potentiometer (θ_O).

Gain in -1 unit increases to about -3 for positive inputs.

The effect is that $-\theta_O$ follows θ_i for anticlockwise rotation from $0°$, but θ_O is reduced to about one third of θ_i for clockwise rotation.

For external input, θ_O response is also non-symmetrical.

Check by applying a square-wave to give $\pm90°$ rotation without fault and then apply fault.

To identify the fault   Set output to about $+ 45°$ using θ_i and no fault. Then set P_1 to zero, measure volts at $-\theta_O$ with and without fault. Alternatively, set P_1 to zero and set motor to run by the analogue zero adjustment. With an oscilloscope examine θ_O, then $-\theta_O$ with and without fault.

Note   If the system is changed to use θ_O (not $-\theta_O$) and the power amplifier input socket changed (to give overall negative feedback) the system responds normally but with reversed rotation.

If a triangle waveform is applied to give about $\pm60°$ rotation, an X-Y display of $-\theta_O$ shows the effect of the fault.

Switch 6   Non-symmetrical gain in power amplifier.

Power amplifier gain falls to about one third of normal for one input polarity.

The most significant effect is to increase the following error in one direction, square wave transient is slightly affected.

Check by applying triangle input to give about $\pm150°$ output and make an X-Y display of the error amplifier output with G = 1. The following error in one direction will increase when the fault is applied.

To identify the fault   Disconnect θ_O and apply a square wave to drive the motor. Without fault the speed is the same in both directions. With fault speed falls in one direction.

Switched Faults   **Appendix A**

Right Switchbank   Faults 1, 2, 3 occur in the PID circuit, which should be connected as in fig A4.

Switch 1   Open-circuit derivative input resistor in PID summer.

                            Effect is failure of derivative control signal.

                            To check, apply a square-wave with G = 3, and P + D control with derivative (P_4) set to zero. Adjust P_3 to give about ±60° at output.

                            Without fault derivative (P_4) reduces transient, with fault transient unchanged.

To identify fault   Examine derivative amplifier output on oscilloscope with square wave applied, which shows that derivative circuit is operating correctly.

                            Hence fault probably open circuit in 100K input resistor to summer.

                            Confirm by applying derivative signal to 100K normally used for integrator signal.

Switch 2   Short circuit proportional amplifier feedback.

                            Failure of proportional control component.

                            To check apply square-wave with G = 3 to give about ±60°. Set derivative (P_4) to 100 and system responds normally. Apply fault and system continues to respond, due to the derivative component, but with reduced amplitude.

                            If P_3 quickly set to zero θ_O may not return to 0° due to lack of proportional component.

To identify fault   Oscilloscope shows no output from proportional amplifier, although signal at input 200K resistor. Using other 200K input resistor makes no difference. Indicates probable failure of amplifier or short circuit output resistor.

Switch 3   PID integrator operates in one polarity only.

                            Elimination of following error by integral control operates in one direction only.

                            To check apply triangle at 0.1Hz, with G = 1, to give ±120° at output. Make an X-Y display of the error amplifier output. Use integral control (2µF capacitor, P_5 about 40) to eliminate the error after initial transient. With fault, error only eliminated in one direction.

Switched Faults   **Appendix A**

To identify fault   Make X-Y display of integrator output which shows motor full
                         motor drive only supplied in one direction.

Switch 4   Tachogenerator failure.

                         With G = 3, apply square-wave input and use tachogenerator
                         output to give overdamped response. Fault causes loss of
                         tachogenerator signal.

To identify fault   Check with oscilloscope that there is no output at
                         tachogenerator socket, but the signal is present at
                         tachogenerator connection tag on the Mechanical Unit. Hence
                         failure is an open-circuit within the system.

                         Applying full magnetic brake, which increases the drive
                         required to the PA, emphasises the effect

Switched Faults   **Appendix A**

SECTION 2

**Digital System
Faults**   The relevant Practicals containing the circuits for each fault are
                            shown in brackets below.

FAULT LIST   The number designates the relevant switch in the default state,
                            i.e with no crossed jumpers on the header.

Left switchbank   1   Loss of one bit in PWM reference count. (Assig.1 Prac.2)

                            2   Loss of one bit in PWM signal count. (Assig.1 Prac.2)

                            3   Loss of index pulse. (Assig.4 Prac.2)

                            4   Fault in Mechanical Unit on +10V supply to input/output
                                potentiometers. (Assig.3 Prac.2)

                            6   Non-symmetrical gain fault in power amplifier. (Assig.5
                                Prac.1)

Right switchbank   1   Loss of MSB in D/A converter. (Assig.2 Prac.2)

                            2   Loss of conversion stop signal in A/D converter. (Assig.1
                                Prac.1)

                            3   Loss of one bit in A/D output to A bus. (Assig.1 Prac.1)

                            4   Tachogenerator failure. (Assig.2 Prac.2)

                            5   Loss of inner track (direction) signal on speed/incremental
                                disc. (Assig.4 Prac.3)

                            6   Loss of one track signal from Gray code. (Assig.4 Prac.1)

Switched Faults **Appendix A**

**FAULT
IDENTIFICATION**

Left Switchbank

Switch 1	Loss of one bit in PWM reference count.
	The effect on the system is to lose the 330Hz audible PWM signal and the loss of motor control for one half of the PWM input cycle.
To identify the fault	Display PWM output on oscilloscope. The waveform will be seen to be at one of its limits (either full max or full min), during the loss of control.
Switch 2	Loss of one bit in PWM signal count.
	Not immediately evident unless PWM output is being displayed on an oscilloscope.
To identify the fault	Display PWM output waveform on oscilloscope. Modulation of pulse width will be seen to be erratic and jerky.
Switch 3	Loss of index pulse.
	The student should be directed to study Assignment 4, Practical 2. Student should notice that no synchronisation of traces occur. ie. there is no index pulse.
To identify the fault	Connect 'Index Pulse' led into circuit and monitor.
Switch 4	Fault in mechanical unit on +10V supply to input/output potentiometers.
	The effect on the system is to lose motor control over a large proportion of the positive half cycle. Input potentiometer shows limited output
To identify the fault	Monitor θ_i or θ_O on oscilloscope. Trace should show loss of full voltage range ($-10V$ to $+10V$).
Switch 6	Non-symmetrical gain fault in power amplifier.
	Power amplifier gain falls to about one third of normal for one input polarity.
	The most significant effect is to increase the following error in one direction, square wave transient is slightly affected.
To identify the fault	Apply a square wave to drive the motor. Without fault the speed is the same in both directions. With fault speed falls in one direction.

Switched Faults **Appendix A**

Right Switchbank

Switch 1	Loss of MSB in D/A converter.

Evident in all experiments in which the D/A converter is used. The effect is that the motor will drive very erratically in one direction only.

To identify fault Monitor D/A output with oscilloscope.

Switch 2 Loss of conversion stop signal in A/D converter.

A/D converter will count to minimum (−127) and stop due to lack of stop signal.

To identify fault Stop signal pulses can be monitored on the digital board at the 'eoc' (end of conversion) socket (C3).

Switch 3 Loss of one bit in A/D output to A bus.

The student should be directed to study Assignment 1, Practical 1. Student should notice that the motor runs very erratically and that the trace displayed on the oscilloscope is distorted. ie. there will be steps in the signal.

To identify fault Trigger the oscilloscope from normal internal trigger and monitor A/D output.For a smooth sawtooth input, a smooth sawtooth output should be seen at the A/D output.

Switch 4 Tachogenerator failure.

When running under speed control with tachometer feedback, motor run away occurs if feedback is lost.

To identify fault Check with oscilloscope that there is no output at tacho-generator socket, but the signal is present at tachogenerator connection tag on the Mechanical Unit. Hence failure is an open-circuit within the system.

Switch 5 Loss of inner track (direction) signal on speed/incremental disc.

The student should be directed to study Assignment 4, Practical 3. The software shows a graphical comparison of the encoder output alongside the tacho output. If the fault exists, the encoder output will be seen to be permanently at a minimum level.

To identify fault The output of the encoder can be monitored at point A6 on the digital unit. A healthy signal will be displayed as a square wave.

Switch 6 Loss of one track signal from Gray code.

The effect on the system is for the drive to become very erratic.

To identify fault The Gray code outputs can be monitored on the digital unit. Check with oscilloscope to find missing signal.

MECHANICAL UNIT DETAILS APPENDIX B

Mechanical Unit   Fig B1 shows the general arrangement of the panels. The unit is common to both Analogue and Digital systems. Since all signals, including supplies, for both units are available from the 34-way socket, the unit can be operated from any source of suitable signals connected to the 34-way socket.

Power Supplies   External supplies of +15V and −15V at 1.5A and of +5V at 0.5A are required. The input sockets (4mm) are protected against accidental misconnection of supplies, though misconnection may blow a fuse.
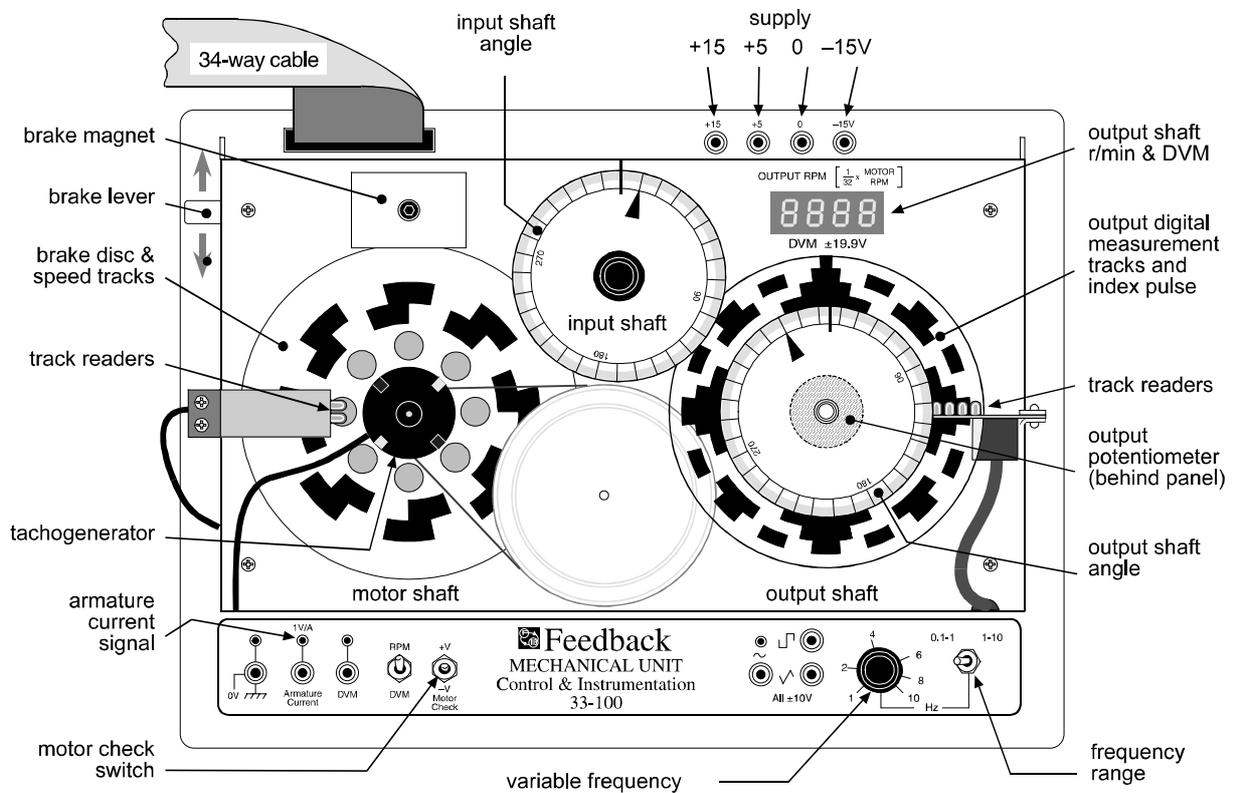
Fig B1 - Mechanical Unit

Mechanical Unit Details   Appendix B

Motor shaft	This carries the brake disc, together with a 2-phase speed track and tachogenerator.
Brake disc and magnet	The brake is applied by the lever projecting at the left. The lever scale is provided to enable settings to be repeated.
Speed tracks and readers	These provide two-phase, 0-5V square waves at 8 cycles per revolution. These signals are available on the 34-way socket but are not used in the Analogue system.
Motor check switch	This enables the motor to be rotated as an initial check. See initial check procedure in Chapter 2.
Armature current signal	This is a voltage waveform indicating the armature current with scale of 1V/A.
Input shaft	This carries the input potentiometer and scale and gives a signal θ_i in the range ±10V.
Test signal frequency and range switch	These control the internal oscillator to provide ±10V square and triangular waveforms with nominal frequency 0.1 to 10Hz in two ranges. The waveforms are connected to the 34-way socket.
Output shaft	This carries the output potentiometer and digital angular measurement tracks. The potentiometer provides θ_o in the range ±10V.
Digital measurement and readers	The digital tracks give 6 bit Gray code (64 locations) information and are read by infra-red readers. The 6-bit information is supplied as 0 or 5V to six pins on the 34-way socket.
Index pulse	At one pulse per revolution this provides an output shaft reference point for incremental control connected to a pin on the 34-way socket.
Output speed display	This provides a direct reading of output shaft speed in r/min in the range 00.0 to 99.9, derived from the speed tracks on the brake disc. Since the reduction ratio is 32:1, a motor speed of 1000 r/min gives 31.1 r/min at the output shaft.

Mechanical Unit Details   **Appendix B**

SQUARE WAVE —— O 34   33 O —— TRIANGLE WAVE

TACHOGENERATOR '+' —— O 32   31 O —— TACHOGENERATOR '−'

PA ZERO —— O 30   29 O —— TIME CONSTANT SWITCHING FOR ANALOGUE SYSTEM. (see Appendix C)

PA + INPUT —— O 28   27 O —— PA − INPUT

ERROR $(\theta_i - \theta_o)$ —— O 26   25 O —— SEE NOTE AFTER PIN 5

INPUT SHAFT θ_i —— O 24   23 O —— θ_o OUTPUT SHAFT

+5V —— O 22   21 O —— 0V

+10V —— O 20   19 O —— −10V

+15V —— O 18   17 O —— −15V

GRAY CODE FAULT —— O 16   15 O —— SPEED/INCREMENTAL FAULT

TACHOGENERATOR FAULT —— O 14   13 O —— PA GAIN FAULT

θ_o FAULT —— O 12   11 O —— +10V FAULT

PWM DRIVE —— O 10   9 O —— INDEX PULSE

0° SPEED/INCREMENTAL —— O 8   7 O —— 90° SPEED/INCREMENTAL

GRAY : MSB —— O 6   5 O

O 4   3 O

O 2   1 O —— GRAY : LSB

Fig B2 - Mechanical Unit 34-way Connector (top view)

Mechanical Unit Details   Appendix B

34-way Connector
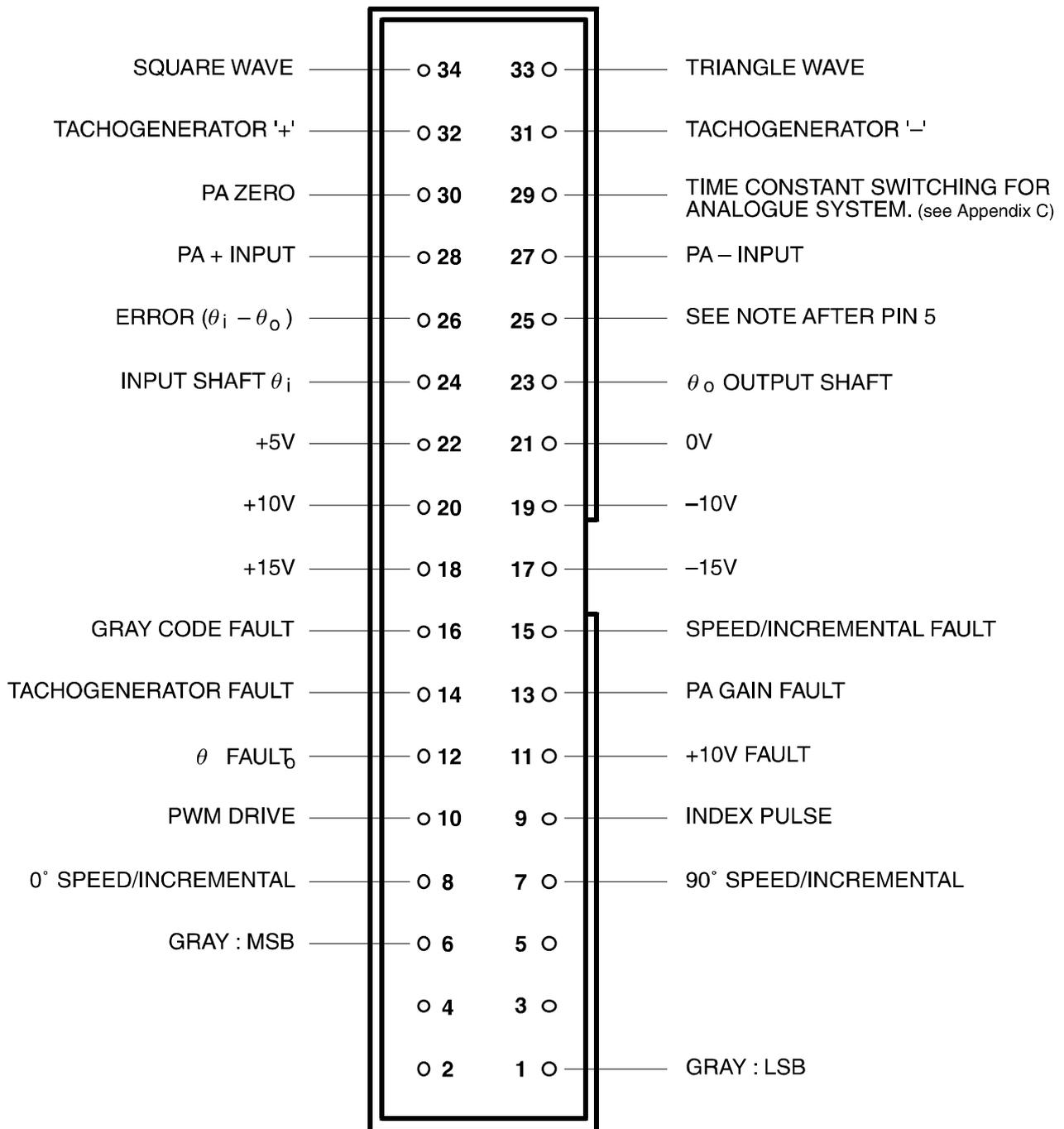**Pin Details**   All digital outputs, pins 1-9 are 0/+5V from trigger circuits.

Pin 1   ⎫   LSB : outer track

Pin 2   ⎪

Pin 3   ⎪
               ⎬   Gray Code tracks : black 0V, white 5V
Pin 4   ⎪

Pin 5   ⎪

Pin 6   ⎭   MSB : inner track

                              Gray Code 31/32 transition aligns with 0° (0V) on output potentiometer and
                              with index pulse (pin 9)

Pin 7   ⎫   90°   speed/increment signals

Pin 8   ⎭   0°   90° lags 0° for clockwise rotation

                              8 pulses/revolution with 32 : 1 reduction gives 256 pulses per output shaft
                              rotation

Pin 9   Index pulse (5V) : aligns with 31/32 Gray Code transition and 0° (0V) on
                              output potentiometer

Pin 10   PWM drive input : if not used leave unconnected

                              Input 0/+5V variable mark-space ratio square wave about 300Hz. Motor
                              stationary for 1 : 1 ratio.

                              +5 gives anticlockwise rotation   ⎫
                                                                      ⎬ about 2000 r/min
                              0 gives clockwise rotation   ⎭

                              Input must source 0.25mA at +5V
                                         sink   0.25mA at +0V

Pins 11 to 16   Control optional faults in Mechanical Unit.

                              If unconnected unit operation is normal.

                              +5V (10K internal input resistor) operates fault.

                              For fault details see Appendix A, Sec. I or Sec II.

                              Left Switchbank LS : Right Switchbank RS.

Pin 11   Fault in +10V supply to potentiometer   (Sec. I LS4)

Pin 12   Fault in –1 unit for θ_O (Sec. I, or II, LS5 :
                                                                             see note after pin 34)

Pin 13   PA gain fault   (Sec. I or II, LS6)

Pin 14   Tachogenerator fault   (Sec. I or II, RS4)

Mechanical Unit Details   Appendix B

Pin 15	Speed/Incremental track fault	(Sec. II, RS5)
Pin 16	Gray Code fault	(Sec. II, RS6)

Pin 17	−15V	
Pin 18	+15V	After fuses

Pin 19	−10V	Internal references : 5mA max loading
Pin 20	+10V	+10V not affected by potentiometer supply fault (pin 11)

Pin 21	0V

Pin 22	+5VAfter fuse

Pin 23	θ_O : output potentiometer slider	nominal −10V to +10V over about −165° to +165° clockwise rotation gives +ve change
Pin 23	θ_i : input potentiometer slider	

Pin 25	See note after pin 34.

Pin 26	Error $(\theta_i − \theta_O)$ or $(−\theta_O)$: see note after pin 34.

Pin 27	PA −ve input : +ve signal anticlockwise	±8V about ±2,500 r/min input resistance 500K motor time constant about 0.5 sec.
Pin 28	PA +ve input : +ve signal clockwise	

Pin 29	Time constant switching for analogue system

Pin 30	PA zero : up to ±15V gives about ±600 r/min : input resistance 39K

Pin 31	Tachogenerator −ve for clockwise rotation	nominal 2.5V/1000 r/min outputs from operational amp
Pin 32	Tachogenerator +ve for clockwise rotation	

Pin 33	Triangle	Test signals ±10V nominal; 0.1 → 10.0Hz
Pin 34	Square	Max loading 10KΩ

Note concerning Pins 12, 25 and 29

The error $(\theta_i − \theta_O)$ on pin 26 is formed in a differentially connected operational amplifier.

Applying +5V to pin 25 disables the θ_i signal to the amplifier, but not to pin 24, hence pin 26 gives $(−\theta_O)$. This facility is used with the Analogue Control Unit.

Applying +5V to pin 12 gives a fault condition causing the gain from θ_O to increase 3x for +ve θ_O signals.

+5V is applied to pin 29 (through the 34-way cable) to increase the analogue system time constant.

FEEDBACK PRODUCT RE-NUMBERING   **APPENDIX C**

CHANGED
SFT154 NUMBERS   In order to associate items in the existing range of Feedback equipment into related groups and to allow for continuing expansion, a new numbering system is being introduced.

Under the new system items will have an initial number indicating the major category in which the item falls together with a specific identification number.

All control equipment, hydraulic, pneumatic and electrical will be in the '30' series with categories 30-39, with introductory electrical control being in category '33'. In particular the existing SFT154 Servo Fundamentals Trainer units are re-numbered as below:

Old Number	Item	New Number
SFT154C	Mechanical Unit	33-100
SFT154A	Analogue Unit	33-110
SFT154B	Digital Unit	33-120
SFT154	Digital Software	33-910

and all units in current and future production will carry the new numbers.

The overall performance of the Servo Fundamentals Trainer is unchanged but some additional facilities and minor changes have been introduced into the 33/100 Mechanical Unit.

The units are normally supplied as one of three kits as follows:

   33-001   Complete Analogue and Digital System

   33-002   Analogue System (33-100 + 33-110)

   33-003   Digital System (33-100 + 33-120 + 33-910)

33-100 (SFT154C)
Mechanical Unit   The waveform generator now provides a sinewave output over the range 0.1-10Hz, with amplitude ±10V. The sinewave is available at sockets on the panel but is not connected through to the analogue and digital boards as are the triangle and squarewaves.

The output shaft speed display now provides a DVM ±19.99V. The display input is selected on the panel by a DVM/RPM switch with socket input for the DVM.

The absolute encoder (gray code) on the output shaft and the incremental/speed encoder on the motor shaft are of changed design but have the same performance as previously.

The armature current signal has been removed from pin 29 on the 34-way connector but is still available on the panel.

System Time Constant   The time constant is arranged to be slightly reduced for the digital system. This enables the effect of control delay due to increasing sampling interval in the computer to be demonstrated easily within the normal operating time scale. The analogue system time constant remains as in the SFT154.

The time constant adjustment occurs automatically by a link in the 33/110 Analogue Unit when this unit is connected to a Mechanical Unit.

33-110 (SFT154A)
Analogue Unit   The time constant change referred to above is switched by a link under the 34-way analogue unit socket between pin 22 (+5V) and pin 29.

All 33/110 units contain this link and any SFT154A units modified to contain this link by Feedback have a yellow marker to the right of the 34-way socket.

If an unmodified SFT154A is to be used with a 33/100 Mechanical Unit the link should be introduced as below.
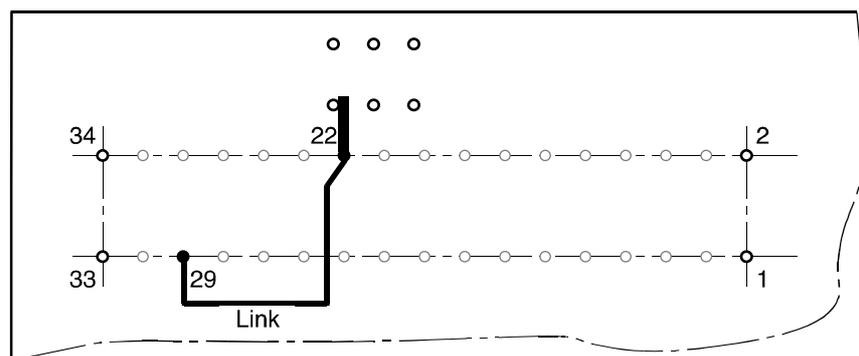
View on underside of board

Fig C1

A modified SFT154A should not be connected to a SFT154C

33-120 (SFT154B)
Digital Unit   There is no change to this unit.