MEASUREMENTS
and CONTROL LAB.

EXPERIMENT N0. 2

MOTOR CONTROL

UNIVERSITY OF JORDAN

FACULTY OF ENGINEERING & TECHNOLOGY

ELECTRICAL ENGINEERING DEPARTMENT

MEASUREMENTS and CONTROL LAB.

Experiment
MOTOR CONTROL

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OBJECTIVES:

The aim of this experiment is to provide students with a sound introduction to the principles of analogue servomechanisms, and by extension to those of closed-loop systems more generally.

EQUIPMENT and APPARATUS:

1. Power supply.
2. Personal computer.
3. Feedback, 33-002 Servo Fundamentals Trainer, which consists of the following:
    - Mechanical Unit 33-100
    - Analogue Unit 33-110
    - Digital unit the 33-120
    - Software pack 33-911

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: +15 V, 0, .15 V at 1.5 A, +5 V, 0, at 0.5 A

The Mechanical Unit

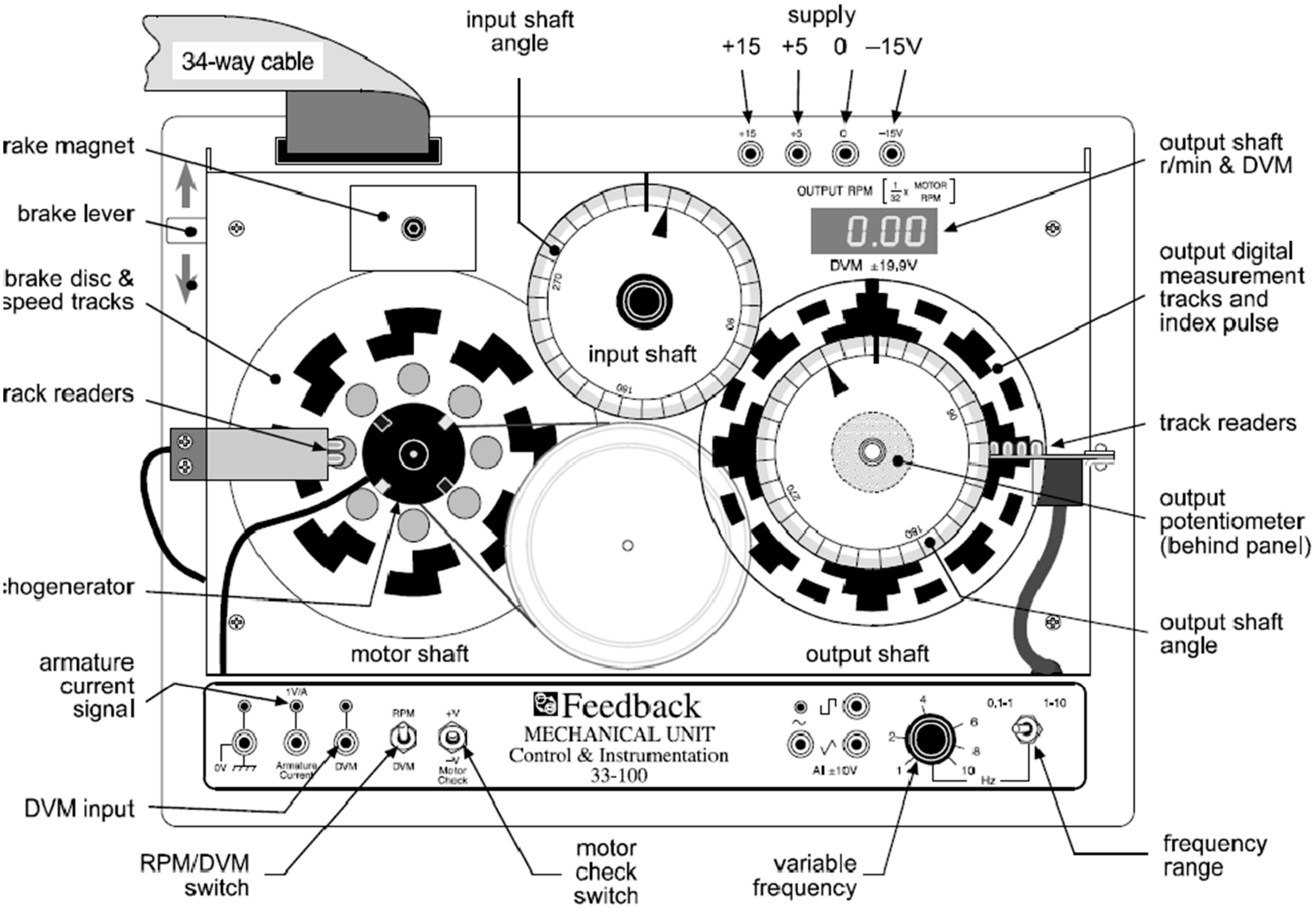

Figure 1. *Feedback Mechanical unit 33-100.*

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, 0-5 V 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.
Armature current signal	This is a voltage waveform indicating the armature current with scale of 1 V/A.
Input shaft	This carries the input potentiometer and scale and gives a signal i in the range ±10 V.
Test signal frequency and range switch	These control the internal oscillator to provide ±10 V square, triangular and sine waveforms with nominal frequency 0.1 to 10 Hz 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 o in the range ±10V.
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.

The Analogue Unit

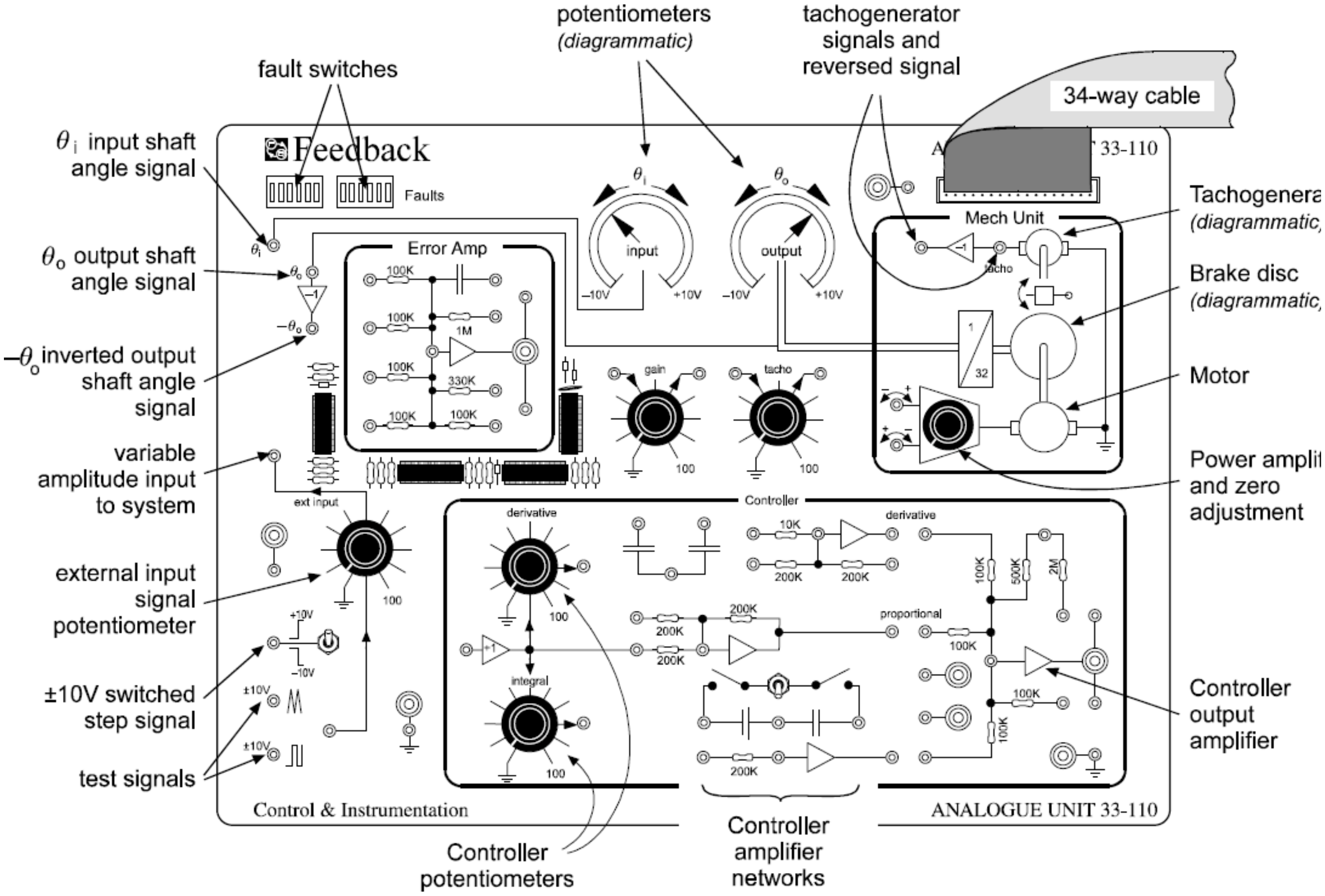

Figure 2. Feedback Analogue Unit 33-110.

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

Upper portion of panel from left to right θi, θo	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.
- θo	This socket provides a reversed output shaft signal required for certain applications.
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 P1 and P2	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.
Test signals	These sockets provide ±10 V low frequency (nominally 0.1 to 10 Hz) 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 P3	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:

The servo is an automatic electromechanical device that uses error-sensing feedback to correct the performance of a mechanism. The term applies only to systems where the feedback or error-correction signals help control mechanical position or other parameters.

A common type of servomotors provides position control. Servos are commonly electrical or partially electronic in nature, using an electric motor as the primary means of creating mechanical force. Other types of servos use hydraulics, pneumatics, or magnetic principles. Usually, servos operate on the principle of negative feedback, where the control input is compared to the actual position of the mechanical system as measured by some sort of transducer at the output. Any difference between the actual and wanted values (an "error signal") is amplified and used to drive the system in the direction necessary to reduce or eliminate the error. An entire science known as control theory has been developed on this type of system.

Automatic Control System

This is a system in which we are controlling the state of a Process, for example 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, see Figure 3. Such a system is therefore called a closed-loop system.

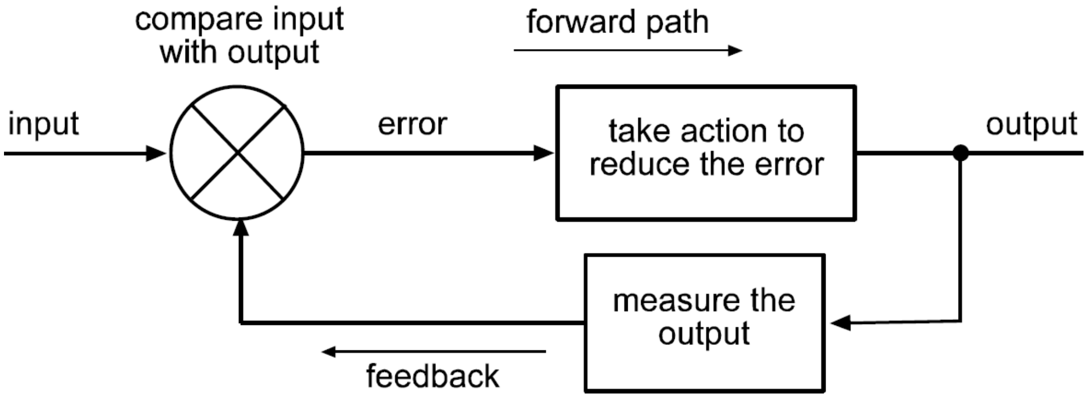

Figure 3. *The Closed Control Loop.*

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**
Set point	**Controlled quantity**	
Desired value		
Demanded value		

Where the system is electrical, the state will normally be represented by signals expressed in volts; in the strip that being rolled in a steel mill it might be, for the width, a signal representing ten inches per volt.

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 Figure 4 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 this experiment.

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.

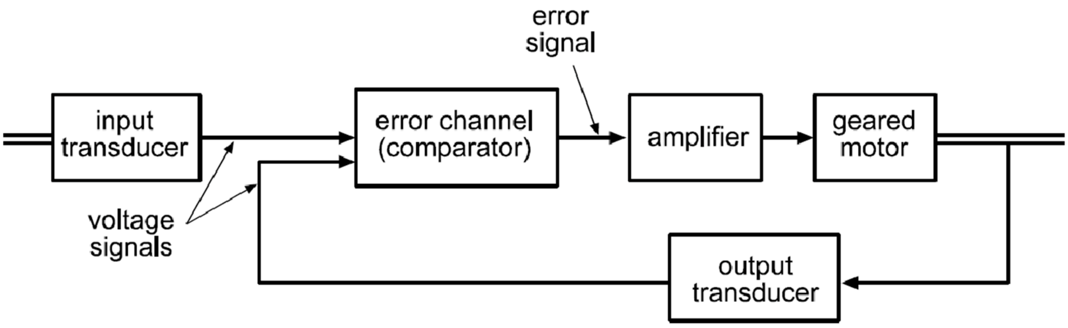

Figure 4. *Block Diagram of an Analogue Closed-Loop System.*

In the system of Figure 4, 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.

Motor, Tachogenerator and Brake Characteristics

The motor is a **permanent magnet type** and can be represented in idealized form as in Figure 6, where Ra is the armature resistance and T1, T2 are the actual motor terminals.

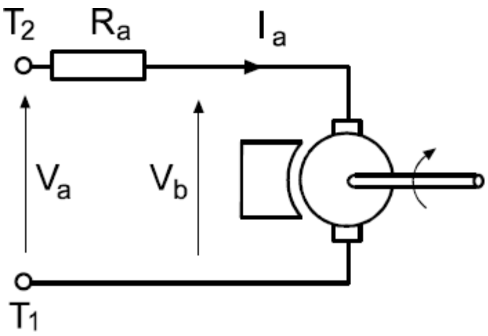

Figure 6. *Representation of a Motor in terms of an Ideal Motor.*

If the motor is stationary and a voltage Va is applied, a current Ia flows which causes the motor to rotate. As the motor rotates a back emf Vb is generated. As the motor speeds up, the back emf increases and Ia falls. In an ideal (loss free) motor, the armature current falls to substantially zero and Vb approximately equals Va. Thus if Va is varied slowly in either polarity, the motor speed is proportional to Va, and a plot of motor speed against Va would have the form of Figure 7.

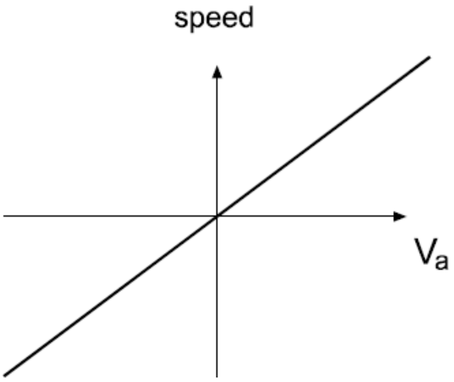

Figure 7. *DC Motor characteristics.*

In the 33-100 the armature voltage Va 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 Va, the motor current may be up to 1 A, while the error channel operates with currents of less than 1 mA 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.

Brake Load

Considering the idealized motor shown in Figure 10(a), when the motor is unloaded the back emf Vb substantially equals the applied voltage Va, 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 Vr (= IaRa) added to Vb matches Va, 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 Figure 10(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.

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.

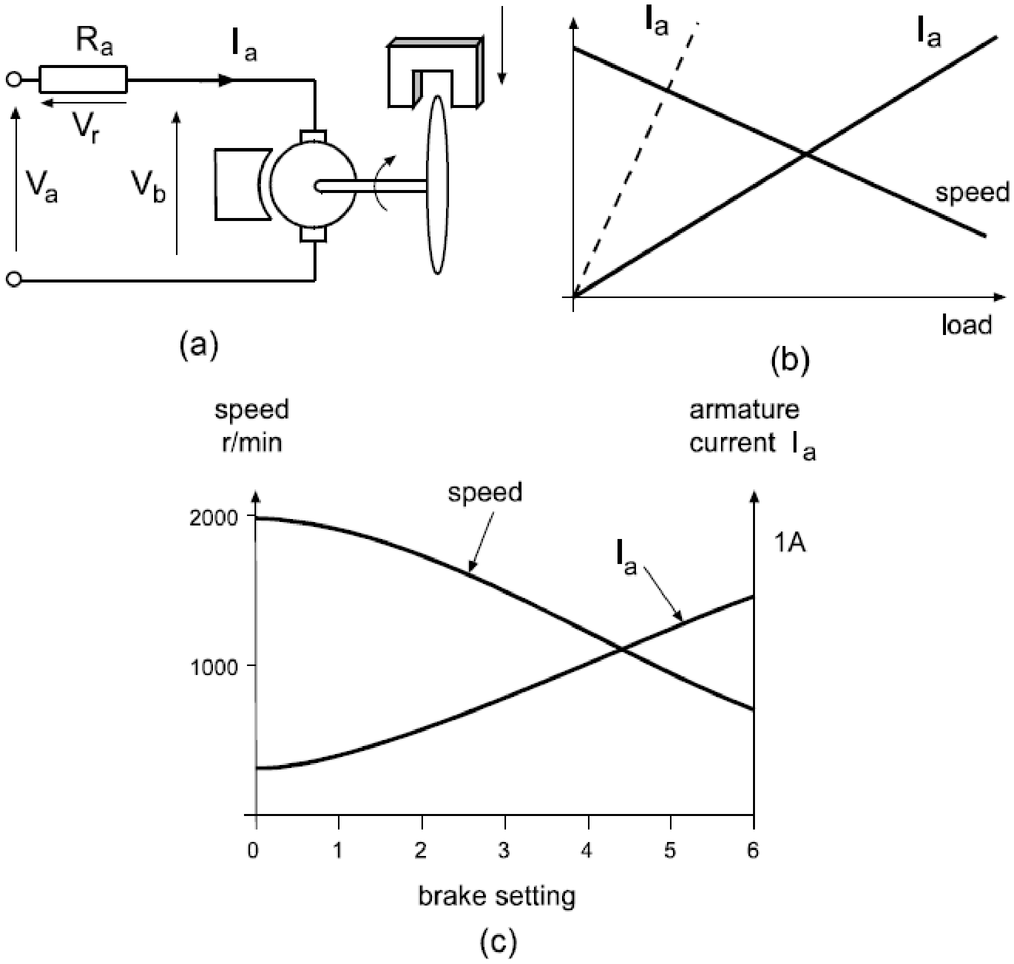

Figure 10. Motor Characteristics Related to Load.

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 aluminum 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 Figure 8, and provides a very convenient load for the motor.

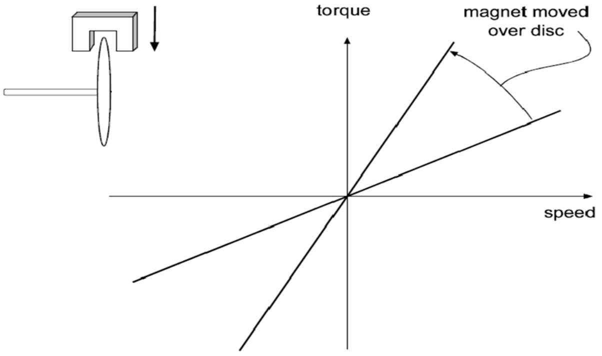

Figure 8. *Characteristic of Magnetic Brake.*

The overall characteristics of a motor may be considered from two aspects, both of which can be related to the idealized representation of Figure 8. These aspects are**: Steady-state**, which are concerned with constant or very slowly changing operating conditions, and **transient**, corresponding with sudden changes, both are important in control system applications.

PROCEDURE:

PART I: Steady-State Characteristics

1. In this part, the motor is operated in a range of steady-state conditions.
2. Arrange the system as shown in Figure 9, where P3 enables a voltage in the range ±10 V to be applied to the power amplifier.

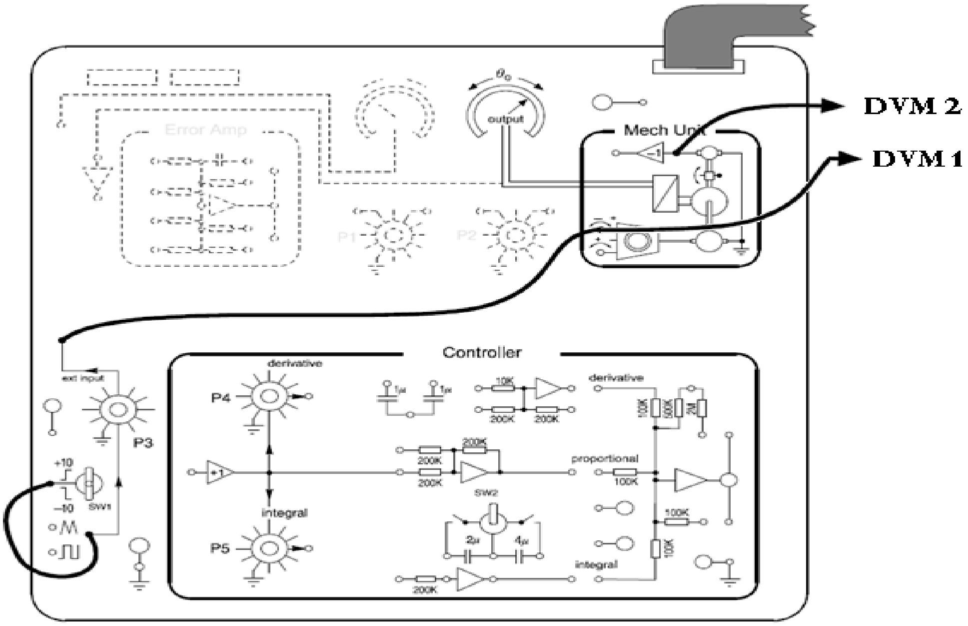

Figure 9. *Connections for PART I.*

3. Use the DVM on the 33-100 for voltage measurements. For each measurement set up the required steady state then switch between DVM 1 and RPM.
4. By setting SW1 and varying P3, fill in the following table, then make a plot of motor speed against amplifier input.

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

Amplifier Input (DVM 1, Volts)	**Tachogenerator Output (DVM 2, Volts)**	**Output Shaft Speed (RPM)**	**Motor Speed (RPM)**
+10			
+7.5			
+5			
+2.5			
0			
-2.5			
-5			
-7.5			
-10			

Plot the tachogenerator characteristics, the generated voltage by the tachogenerator DVM 2 against motor speed.

An important parameter in the use of tachogenerators is the **tachogenerator factor** in (volts per 1000 r/min), which is the change in generated volts for a speed change of 1000 r/min, find it.

PART II: Error Channel and Feedback Polarity

Feedback Polarity

1. Make the connections shown in Figure 12, ignoring for the moment the connection shown as a shadow line, which gives the circuit of Figure 11, setting P1 to zero before connecting to the power amplifier.

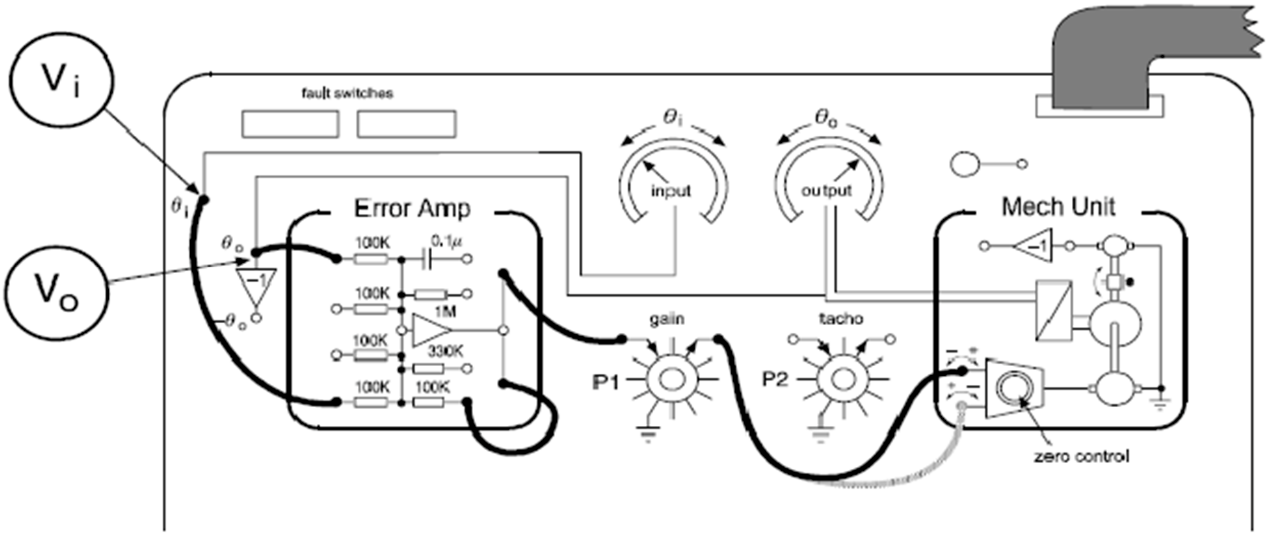

Figure 12. *Connection for PART II.*

2. Switch on the power supply.

3. Set the input potentiometer to 0°. Use the power amplifier zero adjustment to rotate the output shaft to set the 0° line on the scale to be horizontal and to the right. Check that this condition gives a positive Vo value.
4. Measure the maximum voltages from the potentiometer.
5. Slowly increase P1 to 100 and the output shaft should rotate anti-clockwise and finally align vertically with the input.

Note:
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.

6. Set P1 to zero, keeping θi at zero.
7. Plug P1 output to the lower power amplifier input, as shown shaded in Figure 12.
8. Use the power amplifier zero control to rotate the output shaft to set the 0° line on the scale to be horizontal and to the right.
9. Slowly turn P1 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 Vo becomes zero.

10. 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 Vo becomes -10 V, which drives the slider to the right, and then Vo 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 Figure 11, where it is assumed that the input shaft (θi) is set to 0° so that the input signal Vi is zero. The output shaft (θo) zero degree datum line is assumed to be horizontal and to the right, giving a positive Vo. The two potentiometer signals are added in an operational amplifier. With Vi at zero, the amplifier output will be .Vo. 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.

PART V: Speed Control System

1. Arrange the system as in Figure 22. Set P2 (tacho) to zero and set the amplifier feedback resistor to 100 k, this gives G = 1. Set P1 to 100. Set SW1 up to +10 and adjust P3 to run the motor at 1000 r/min (31.25 r/min at output).

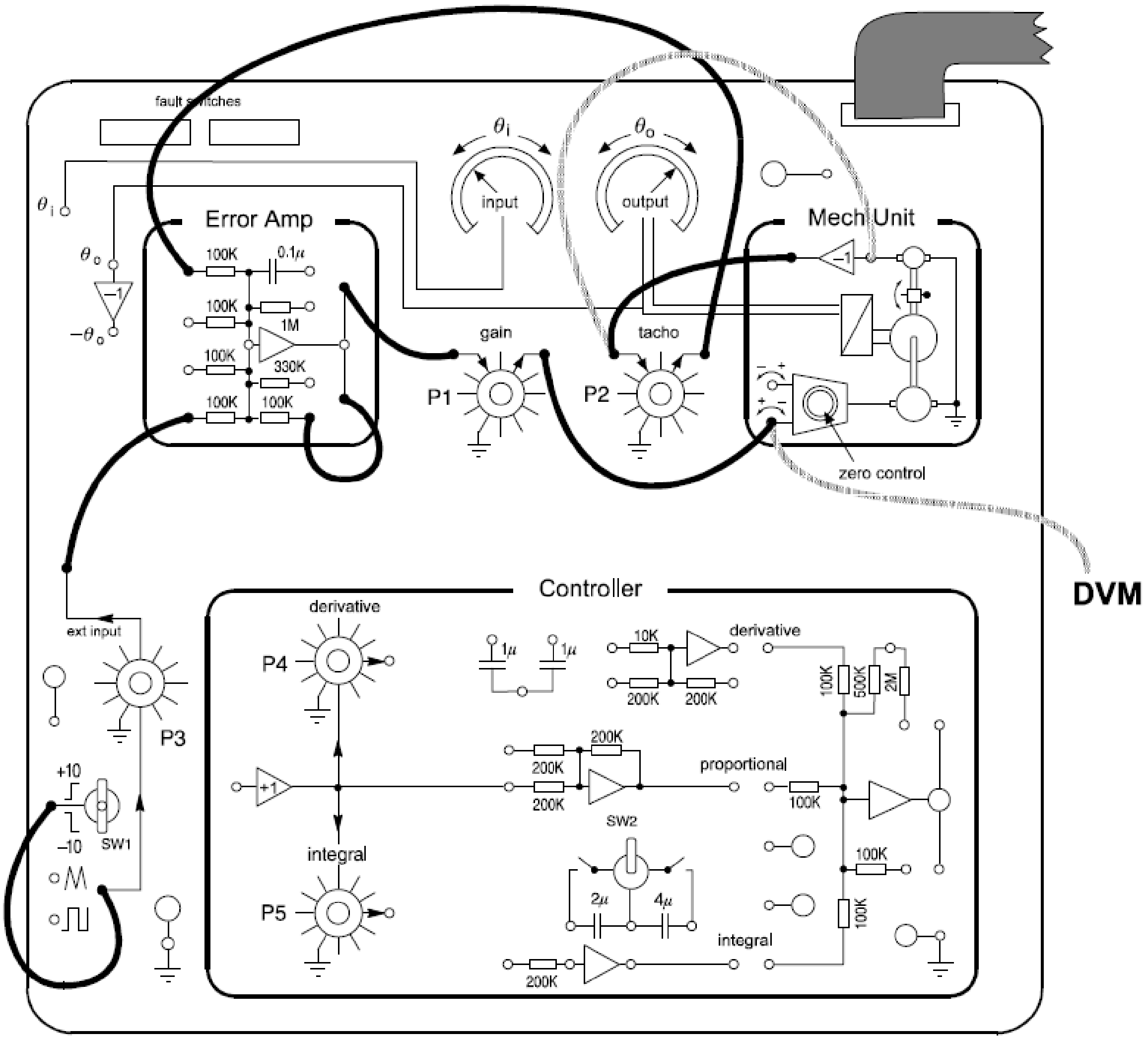

Figure 22. *Connections for PART V.*

2. Turn up P2 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.

3. Set P2 to zero and **fill in the following table then plot the speed against brake setting to full brake load.** The general characteristic should be as in Figure 23.

Brake Setting	Armature current Ia (Amps)	Output Shaft Speed (RPM)	Motor Speed (RPM)
0			
1			
2			
3			
4			
5			
6			

4. Set P2 to 100 and readjust P3 to give 1000 r/min with the brake off.
5. **Fill in the following table, then plot the speed characteristic and error (Power Amplifier input).**

Brake Setting	Ia (Amps)	Output Shaft Speed (RPM)	Motor Speed (RPM)	PA Input (Volts)
0				
1				
2				
3				
4				
5				
6				

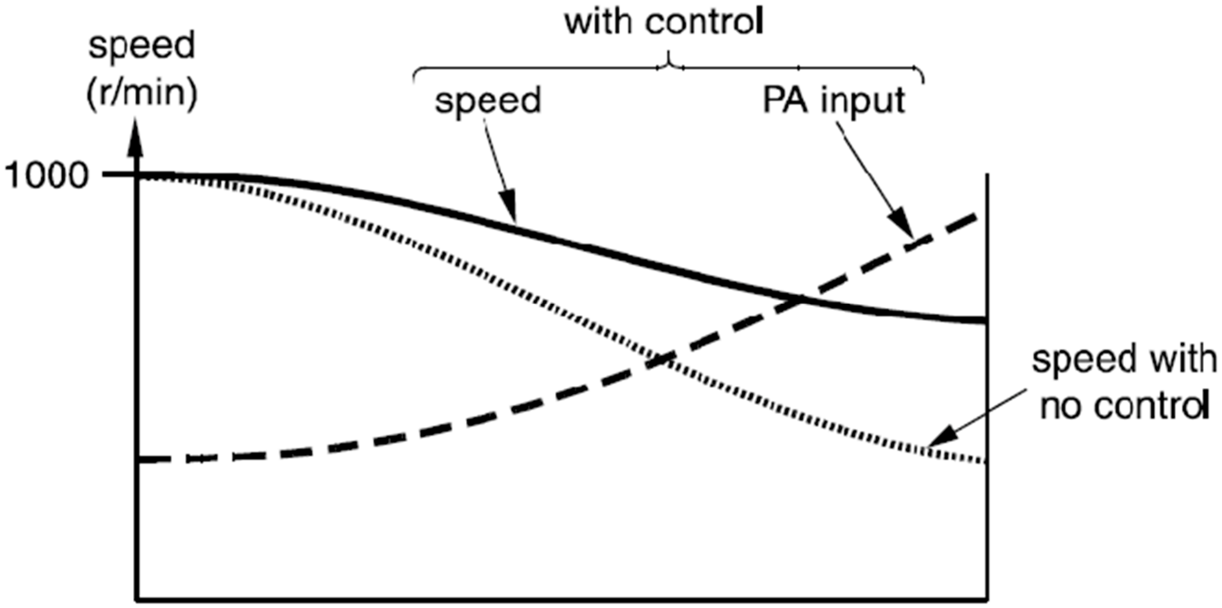

Figure 23. *Speed Regulation with and without Closed-Loop Control.*

1. **ALL** the requested diagrams in the experiment.

PART III: The Influence of Gain

A general system has the form shown in Figure 13, where an input x and an output y are compared to give an error e with the relation:

$e = x - y$

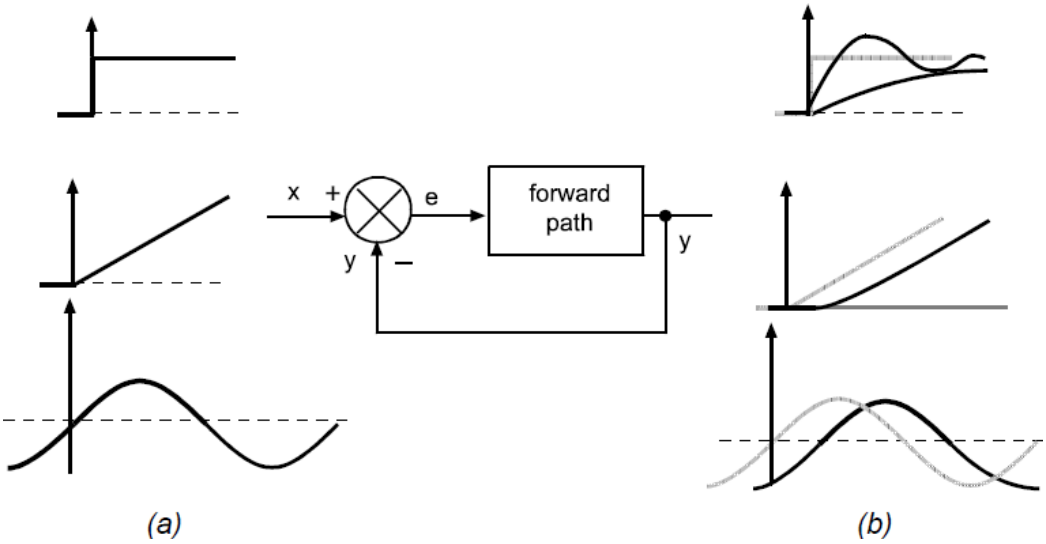

Figure 13. *A general system with (a) Test Signals and (b) Typical Responses.*

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.

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 Figure 14(a), where the input (Vi), output (Vo) and error (Ve) are all voltages and the forward path gain (G) is shown separately, the voltage applied to the power amplifier being GVe.

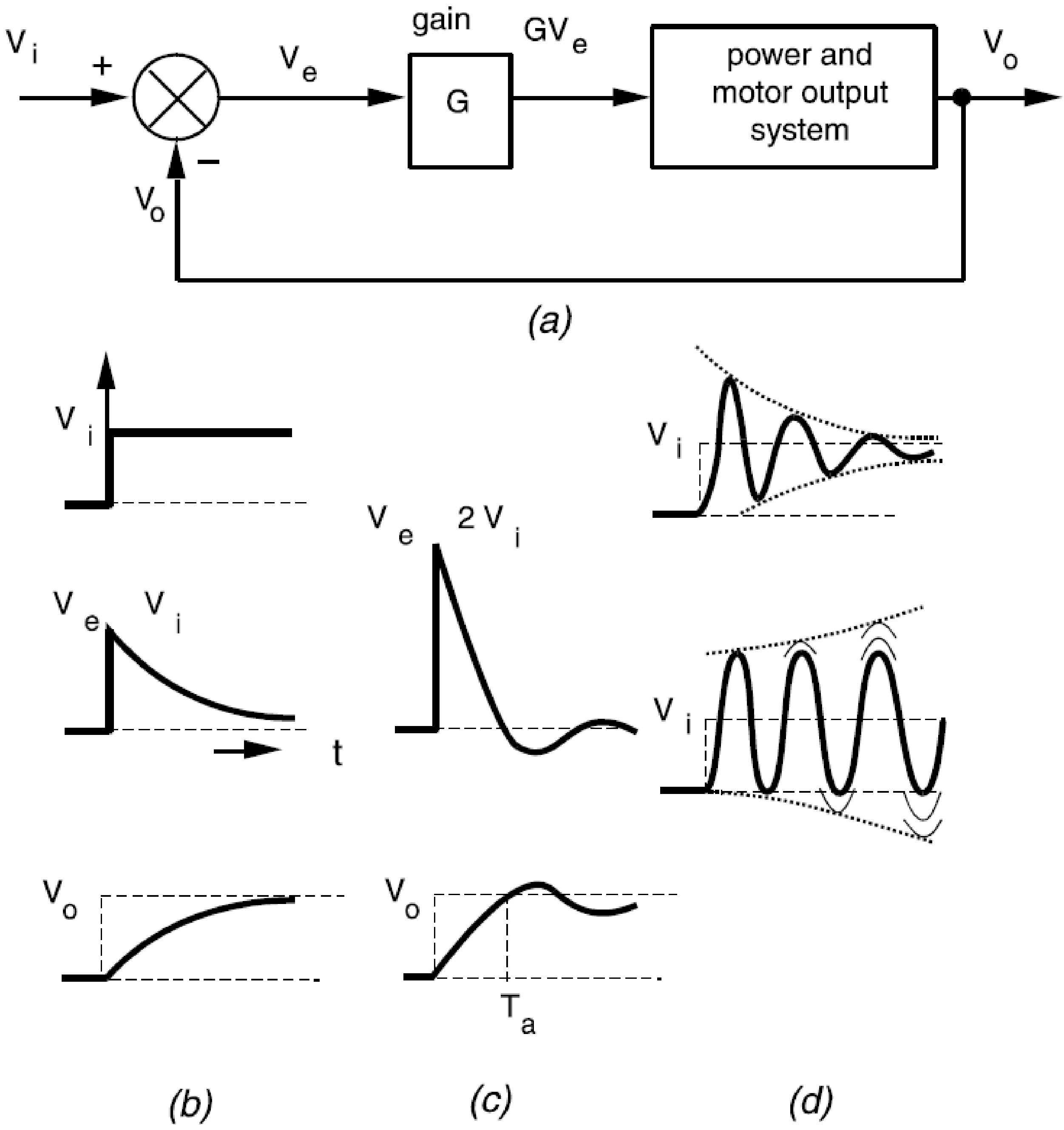

Figure 14. *Effect of Varying Gain on Step Response.*

If a step Vi is applied, the initial value of the error is equal to Vi as in Figure 14(b), since Vo is zero. If the gain is 1, the power amplifier input is initially Vi 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 2Vi, 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 PART I. 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 Vi increases the power amplifier drive (2Vi) 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 Vi.

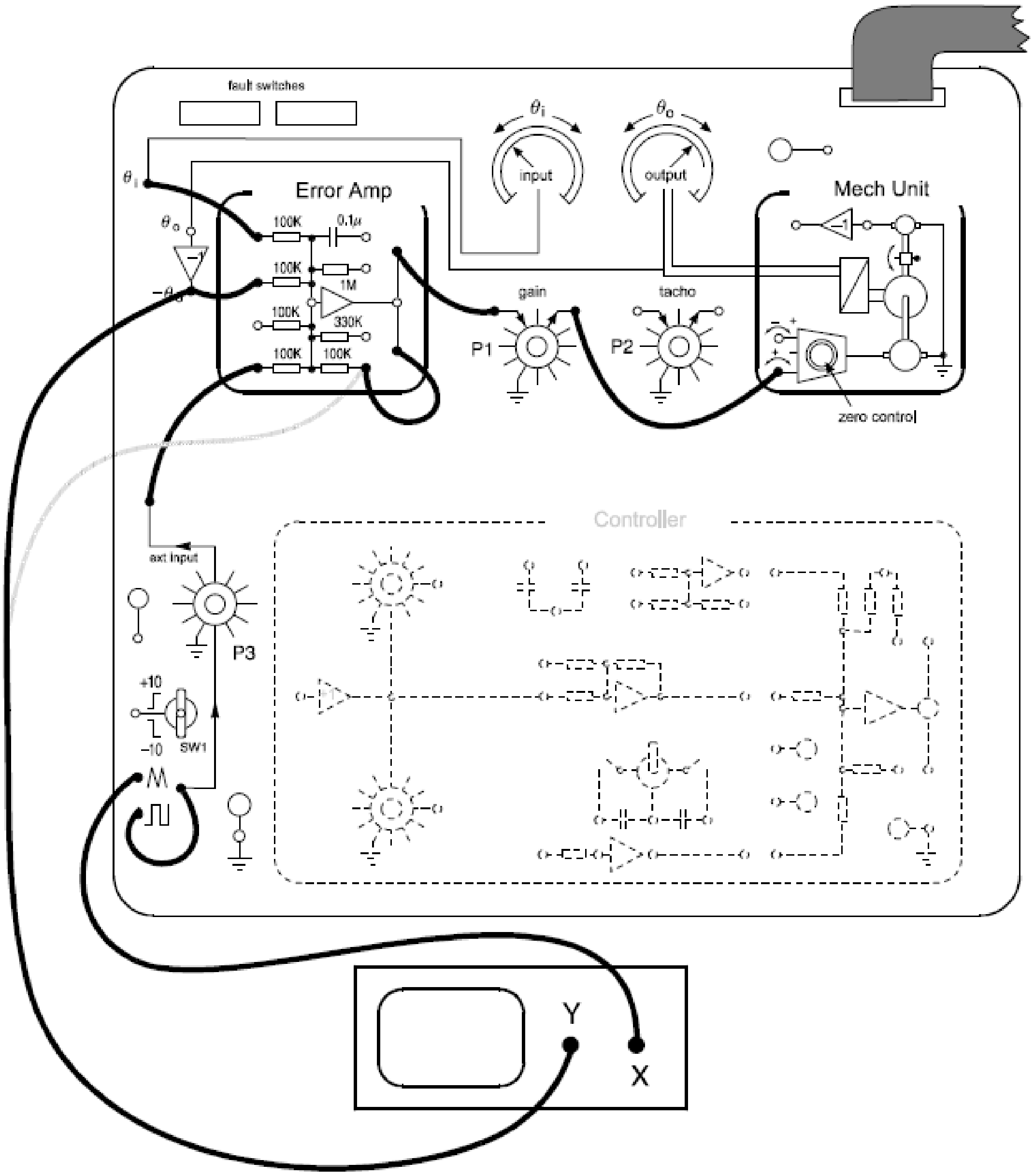

Figure 15. Connection for PART III.

1. Arrange the system with the solid connections of Figure 15, with the error amplifier feedback resistor 100 k, giving G = 1.
2. Set the test signal frequency to about 0.1 Hz and adjust P3 to provide a square wave input of ±5 V (approx 50%).
3. Set P1 to zero.

4. Turn up P1 until the motor just rotates and the system will give a response similar to Figure 14.
5. By increasing P1, **fill in the following table.**

Note
System behavior could be:
Critical damping, when $\zeta = 1$
Over-damping, when $\zeta > 1$
Under-damping, when $0 \le \zeta < 1$

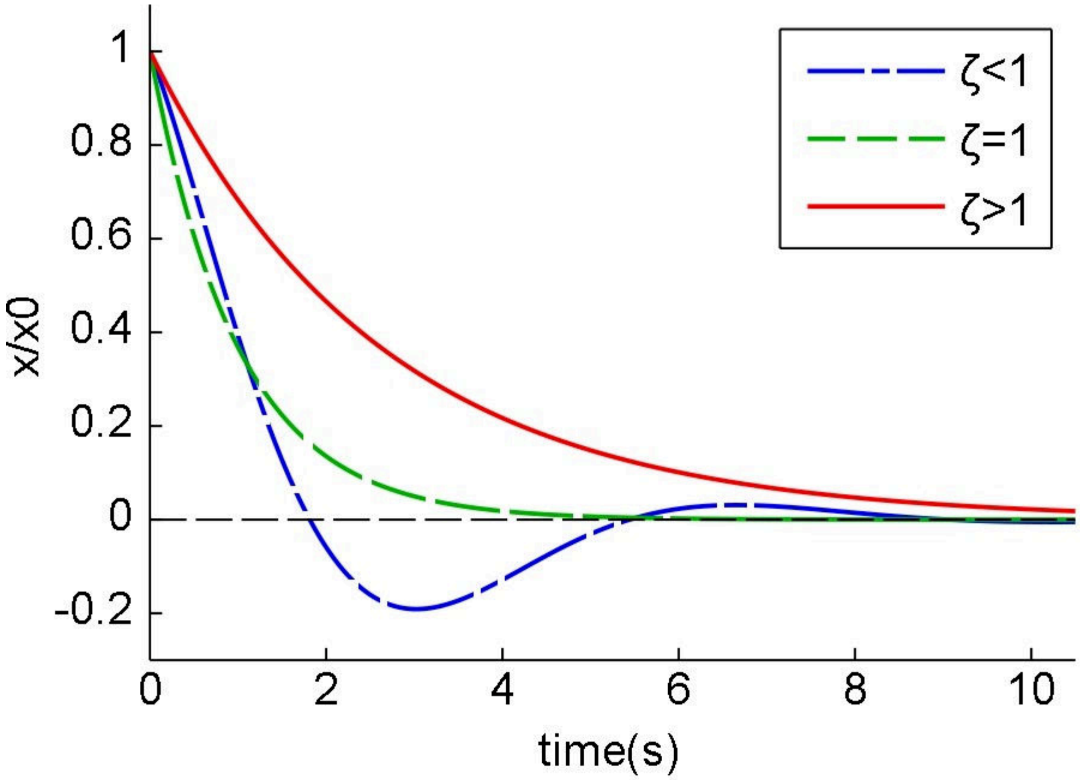

Figure 16. *System possible behaviors.*

P1 percentage value (%)	Ta (Settling Time) (s)	Peak Vo Value (Volts)	Overshoot Value (Volts)	Overshoot Percentage (%)	System behavior
0					
10					
20					
30					
50					
70					
80					
100					

- **What is the P1 percentage value that makes the system just overshoots?**
- **How long the system takes to reach steady state (Ta)? It is useful to examine the output of the error amplifier which passes through zero at Ta.**
- **What is the relationship between the Time to reach steady state (Ta) and the overshoot value?**

When the gain is increased further, it is useful to examine the error amplifier output, which is GVe, 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 ±5 V input gives an initial error (Ve) of 10 V.

1. Set the amplifier feedback resistor to 330 k giving G = 3.3.
2. With P1 at 100 adjust P3 until the peak amplifier error (GVe) is about 10 V.
3. Repeat the previous steps with G = 3.3.

P1 percentage value (%)	Ta (Settling Time) (s)	Peak Vo Value (Volts)	Overshoot Value (Volts)	Overshoot Percentage (%)	System behavior
0					
10					
20					
30					
50					
70					
80					
100					

- **What is the P1 percentage value that makes the system just overshoots?**
- **How long the system takes to reach steady state (Ta)? It is useful to examine the output of the error amplifier which passes through zero at Ta.**