DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF ENGINEERING SCIENCE AND TECHNOLOGY, SHIBPUR

Advanced Control Systems Laboratory (EE-751)

7th Semester Electrical

Experiment No. 751/1

1. Title: SERVO FUNDAMENTALS TRAINER

2. Objective: Provides introduction to the principles of analogue servomechanisms through closed-loop angular position control of a d.c. servo motor through a P and PD control.

3. Apparatus: Fill up **Table 3**.

4. Familiarisation with Apparatus:

It consists of a Mechanical Unit (MU) and an Analogue Unit (AU).

Mechanical Unit (MU) houses a *d.c. servo motor*. Shaft of the motor carries a *magnetic brake disc, a tacho generator* (speed transducer) and *an output potentiometer* (analogue angle transducer). Motor drives shaft through a 32:1 belt reduction. On lower left corner of MU are ***meters*** for measuring voltage, armature current and speed. A digital voltmeter (*DVM*) measures voltage/r.p.m. and displays it. On MU are *frequency adjustment* knobs of the square and triangular waves in the Analogue Unit (AU).

AU (Fig. 3) connects to the MU (Fig. 2) through a 32-way ribbon cable.

In AU the ***power supplies*** used as **reference inputs** – i) A steady ± 10 V d.c., ii) a ± 10 V triangular wave and a ± 10 V square wave. SW is a three position switch (up, center and bottom) to connect ± 10 V. The amplitude of these signals are varied through potentiometer $\mathbf{P_3}$.

On AU, OPAMP, $\mathbf{A_1}$, acts as an ***error detector***. Potentiometers $\mathbf{P_1}$ and $\mathbf{P_2}$ control gains of the system. ***Power amplifier***, supplies the motor input voltage. Outputs of **speed transducer** (tacho generator) and **angle transducer** (output potentiometer) are brought (from MU to AU at points 'tacho' and 'θ_o' resp and are ***measured outputs*** (used for speed or position feedback).

In lower part of AU lies ***controller***, with proportional (P), Integral (I) and derivative (D) control - implemented through OPAMPS, resistors and capacitors.

Fig 2 and 3 resp show schematic diagrams of the MU and AU. The Analogue Unit (**AU**) and the Mechanical Unit (**MU**) can be combined to configure the basic system in Fig 1.

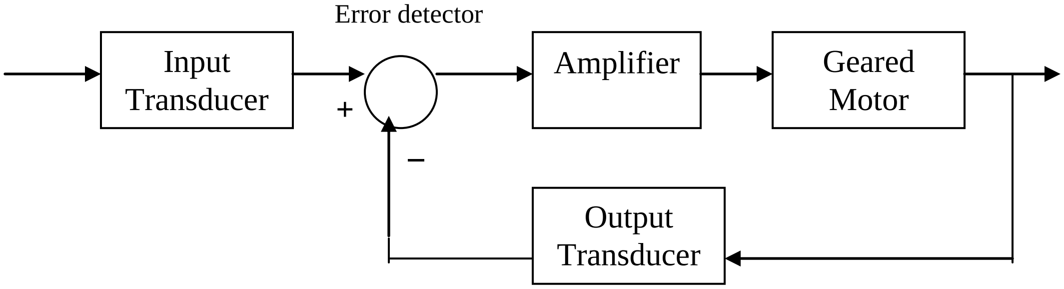


Fig. 1 Analogue Control System

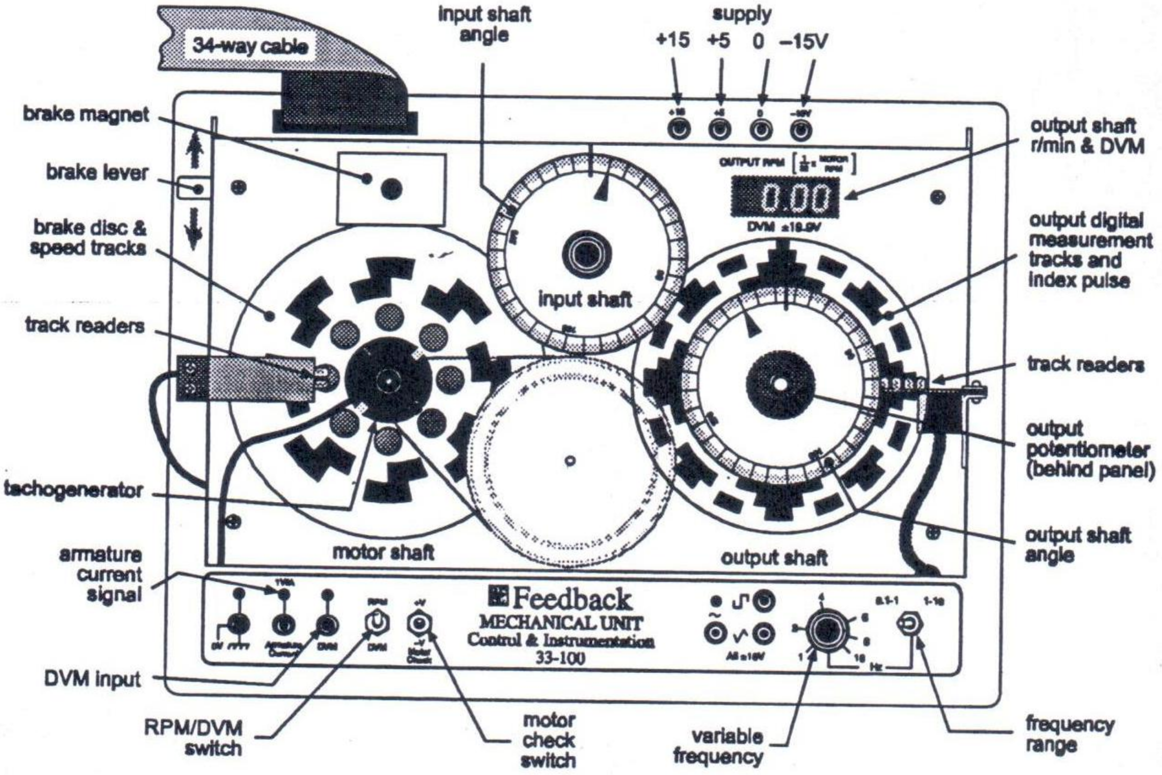


Fig 2. - The Mechanical Unit.

<u>5 . Experiments:</u> Complete the following two steps before starting the experiments.
1. Connect the MU and AU together by the 34-way cable.
2. The power supply unit is connected to the back of the MU. (**Strictly follow the colour code – Red: +15 V, Pink: +5 V, Black 0 V, Grey: -15 V).** Do not switch on.

<u>Expt 1.1</u>: Identification of various components of the Servo Fundamentals Trainer

Show the position of the following components <u>on the instruction sheet as well as the apparatus</u>:
<u>Mechanical Unit</u> - i) d.c. servo motor, ii) tacho generator, iii) analogue angle transducer, iv) DVM, v) frequency adjustment knob.

<u>Analogue Unit</u> - vi) power amplifier, vii) power supplies - viii) steady ± 10 V d.c., ix) ± 10 V triangular wave and x) ± 10 V square wave, xi) **P_3,** xii) OPAMP - the error detector, xiii) **P_1,** xiv) **P_2 ,** xv) ‘tacho’ and xvi) ‘θ_o’ - measured outputs, xvii) controller - P I D.

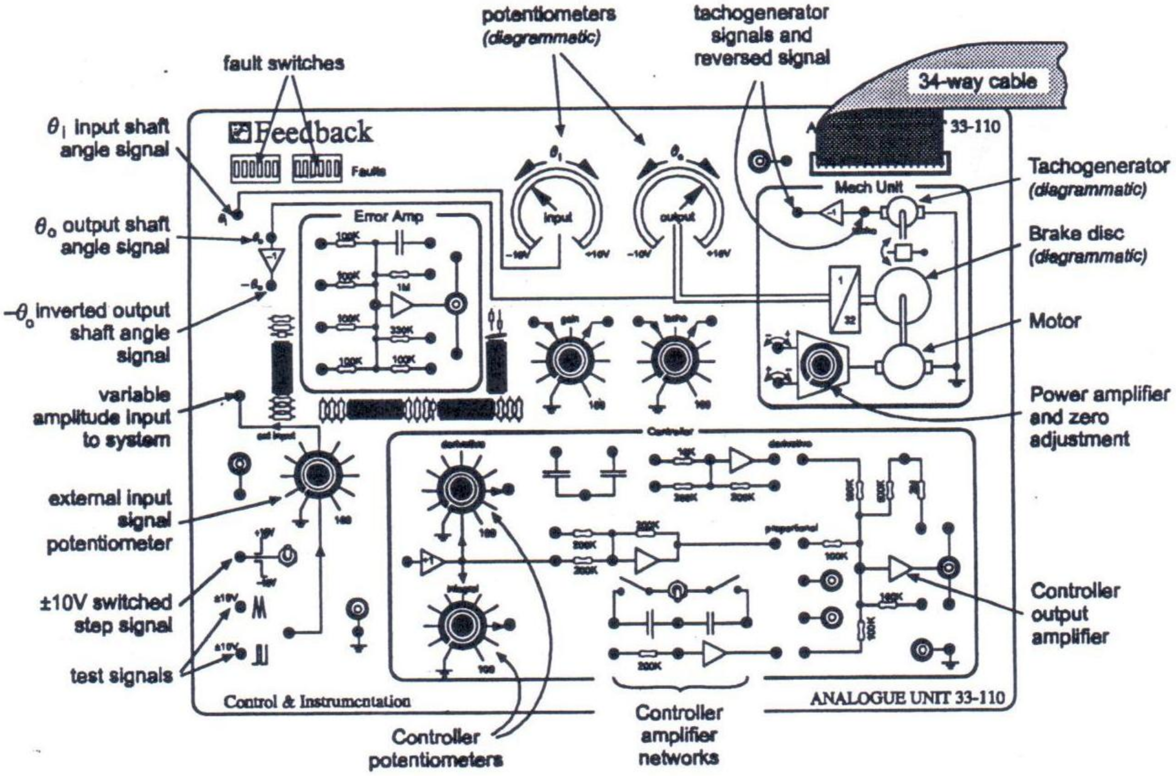


Fig 3, - The Analogue Unit

<u>Expt 1.2:</u>: Effect of variation of forward path gain on step response of a closed loop position control system. (Fig 5 & 6)

The block diagram of the <u>automatic closed loop position control system</u> using the servomotor is shown in Fig 4 below:

<u>Objective:</u> to examine how the step response is affected by a change in forward path gain **G** (a positive constant). Here gain **G** determines how much voltage is applied to the motor for a given error.

Fig 4 is implemented in a circuit in **Fig 5.** The measured output is the angular position of the motor, θ_o. Gain **G**, is increased by increasing the feedback resistor in the error amplifier as in **Fig 6(a)** (Resistor $\mathbf{R_F}$). The forward path gain can be further varied by adjusting P_1.

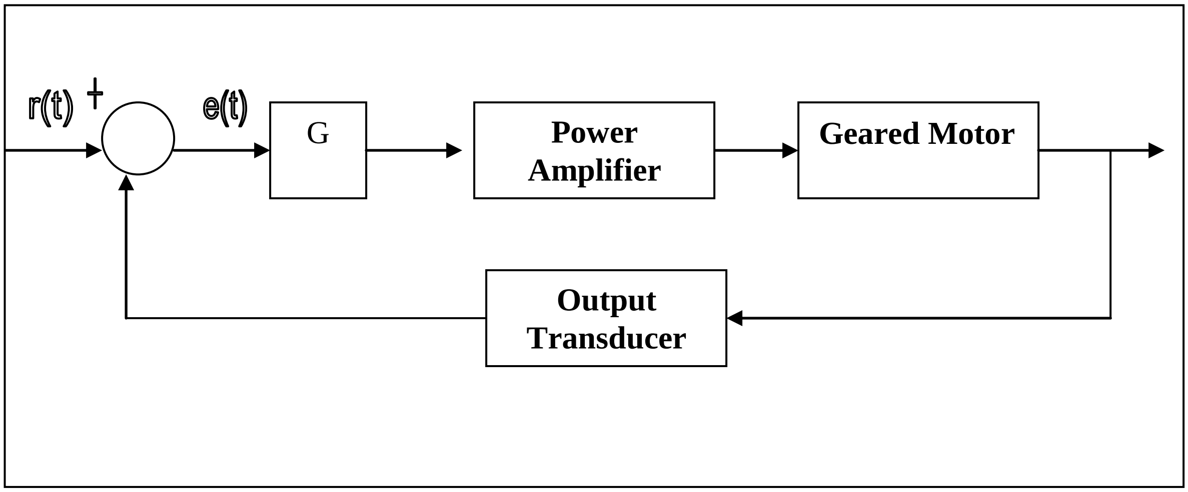


Fig 4 Block diagram of the closed loop system.

Procedure:

1. Connect the setup as in **Fig. 5**. Do not switch ON. It is a negative feedback arrangement using Error Amplifier $\mathbf{A_1}$ (in differential mode) and potentiometer $\mathbf{P_1}$. The variable *reference input* comes from $\mathbf{P_3}$ and is connected to the input **A** of error amp $\mathbf{A_1}$. The *measured output* is the motor position and comes from the θ_o output (after an inversion) to input **B** of $\mathbf{A_1}$. The output of $\mathbf{A_1}$, the error, (= reference-measured value) is fed to $\mathbf{P_1}$ and finally to the power amplifier which supplies the motor. The circuitry of the OPAMP $\mathbf{A_1}$ as an error detector is shown in **Fig 6a**. The gain of the OPAMP may be changed by adjusting the feedback resistor $\mathbf{R_F}$**.**
2. Put $\mathbf{P_3}$ and $\mathbf{P_1}$ to zero position (rotate fully CCW).
3. Set the input square wave signal frequency to about 0.1 Hz.
4. Switch ON supply. Set $\mathbf{P_1}$ to zero. Adjust $\mathbf{P_3}$ = 3. Now turn $\mathbf{P_1}$ = 50 or until motor rotates freely.
5. Connect oscilloscope. Adjust its settings. Note value of $\mathbf{R_F}$, the rise time and overshoot in **Table 1**. Roughly sketch the CRO response on paper.
6. Switch off supply.
7. Change $\mathbf{R_F}$ to 330 kΩ. Switch ON. Repeat step 5. Switch off supply.
8. Change $\mathbf{R_F}$ to 1 MΩ. Switch ON. Repeat step 5.

Expt 1.3 Automatic Position control of a d.c. servo motor by a P-D controller. **(Fig 7a & 7b)**

1. A control signal is obtained by combining the error, the derivative of the error and the integral of the error – through a PID controller. The PID controller is implemented in the 'Controller' section of the AU through OPAMP with 1 μF capacitor input, an OPAMP (acts as a 'differentiator'). With a 2 μF capacitor in the feedback path, an OPAMP acts as an integrator.

2. The error is produced by the OPAMP $\mathbf{A_1}$. The *measured output* is the motor position, θ_0, coming from an **output potentiometer** (after an inversion) to the input **B** of $\mathbf{A_1}$. The output of $\mathbf{A_1}$ is fed to the Controller in AU. The forward path gain may be adjusted by changing $\mathbf{P_1}$ and the controller may be configured for **proportional (P), derivative (D)** or/ and **integral (I)** action.

3. A circuit to realize P+D control is in **Fig. 7(a)** and the corresponding connections are given in **Fig. 7(b)**.

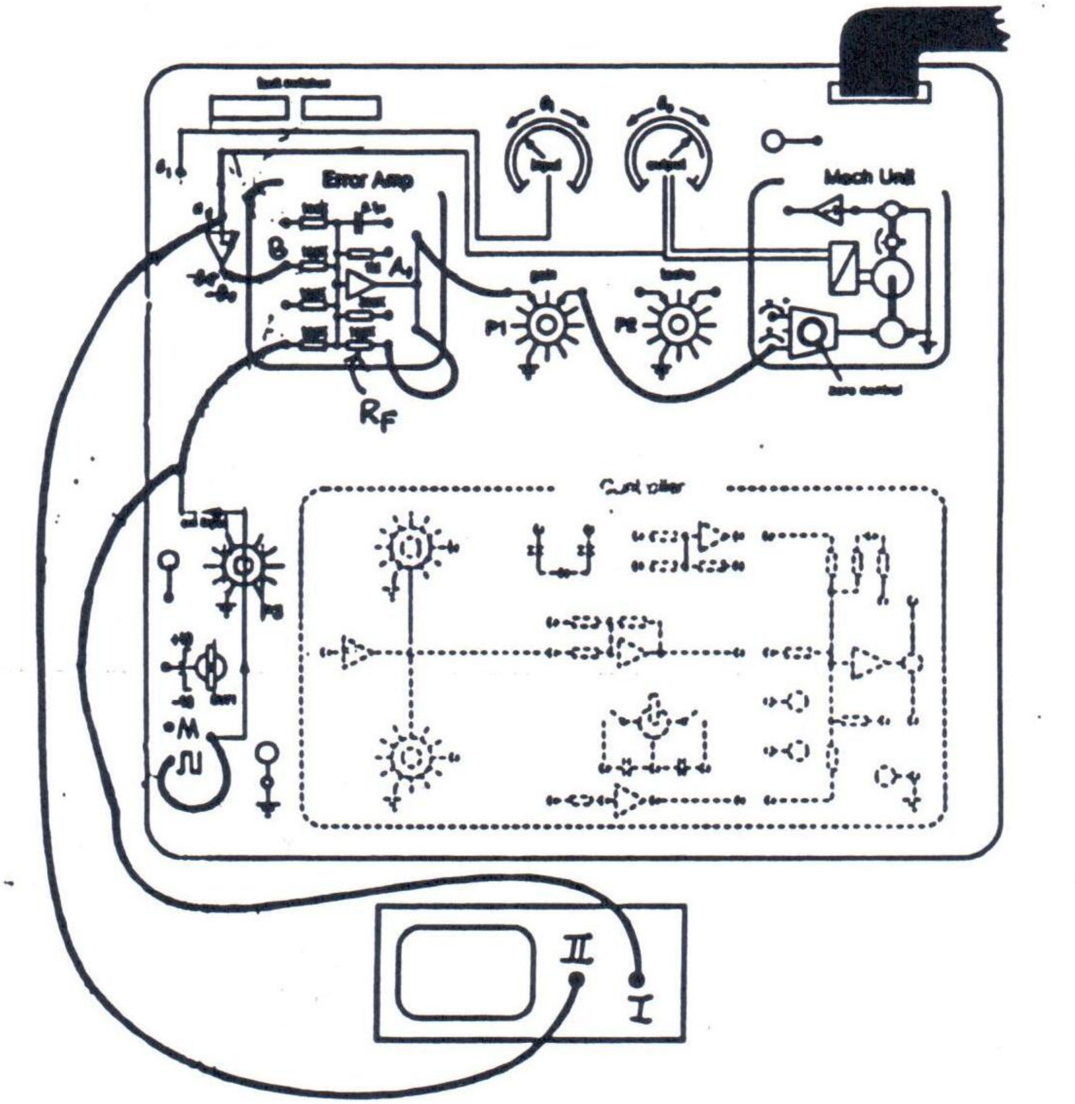
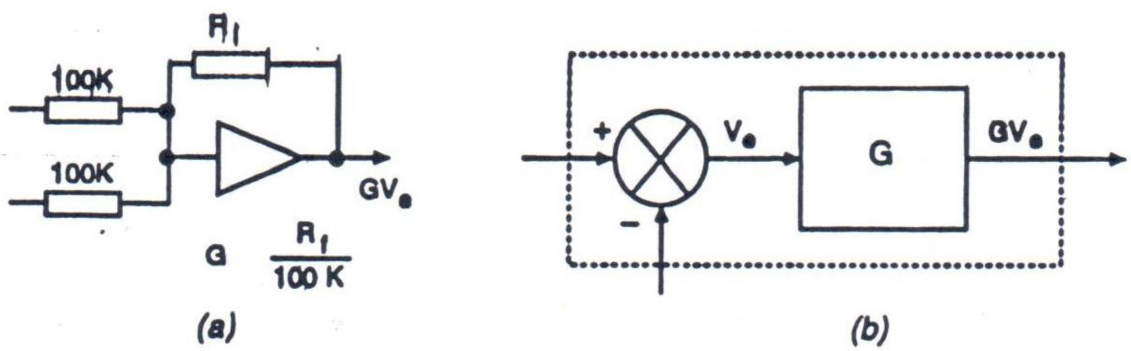


Fig 5.. - Connections for Practical 1.2.

Procedure:

1. Connect as in **Fig. 7**. Do not switch ON.
2. Connect the setup as in **Fig. 7(b)**. Do not switch on.
3. Keep $P_1 = 0$ and $P_4 = 0$. Adjust the frequency of the square wave test signal to 0.2 Hz on the MU. Switch on the power. Make $P_3 = 3$.
4. Make $P_1 = 100$ and $P_4 = 0$ to get a forward path gain = 5 (check and explain). Adjust the CRO to display the input and output waveforms. Take readings to fill up **Table 2**.
5. Roughly sketch the response.
6. Turn up P_4 (derivative action increased) to 50 and note change in output response θ_0. Fill up **Table 2**.
7. Roughly sketch the response on the same axes as in step 5 (to note the change in response).



(a) (b)

Fig 6 - The Error Channel

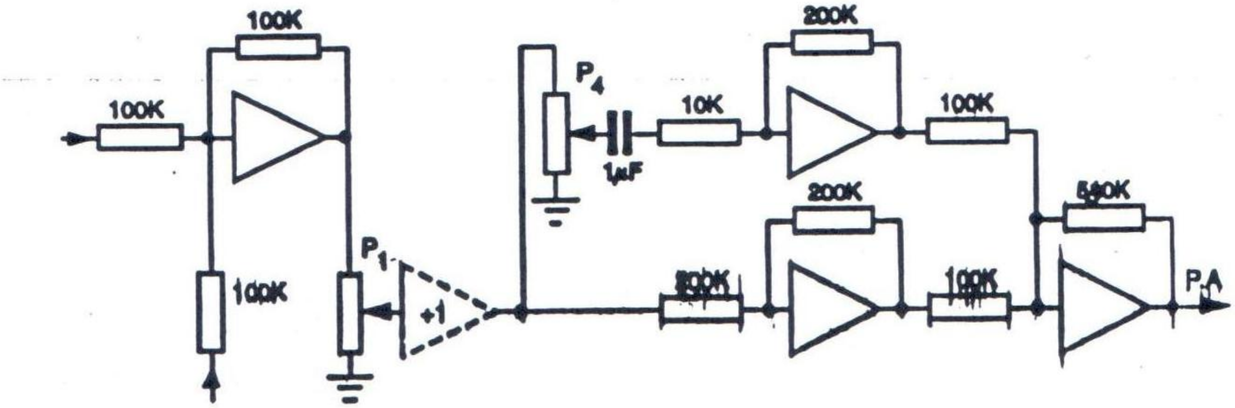


Fig. 7 (a) - Circuit for P + D Controller

6. **Report**:

Expt no. 1.1:

1. Mark all the components on a (Xerox copy of) the schematic diagrams of the AU and MU.

Expt no. 1.2:

i. State the effects of a change in the forward path gain G on the transient and steady state response.
iii. Comment on the stability of the open loop and closed loop systems.
iv. What device is used as the output transducer?

Expt. No. 1.3:

i. State the effect of the derivative action on transient response and tracking error in a single sentence.

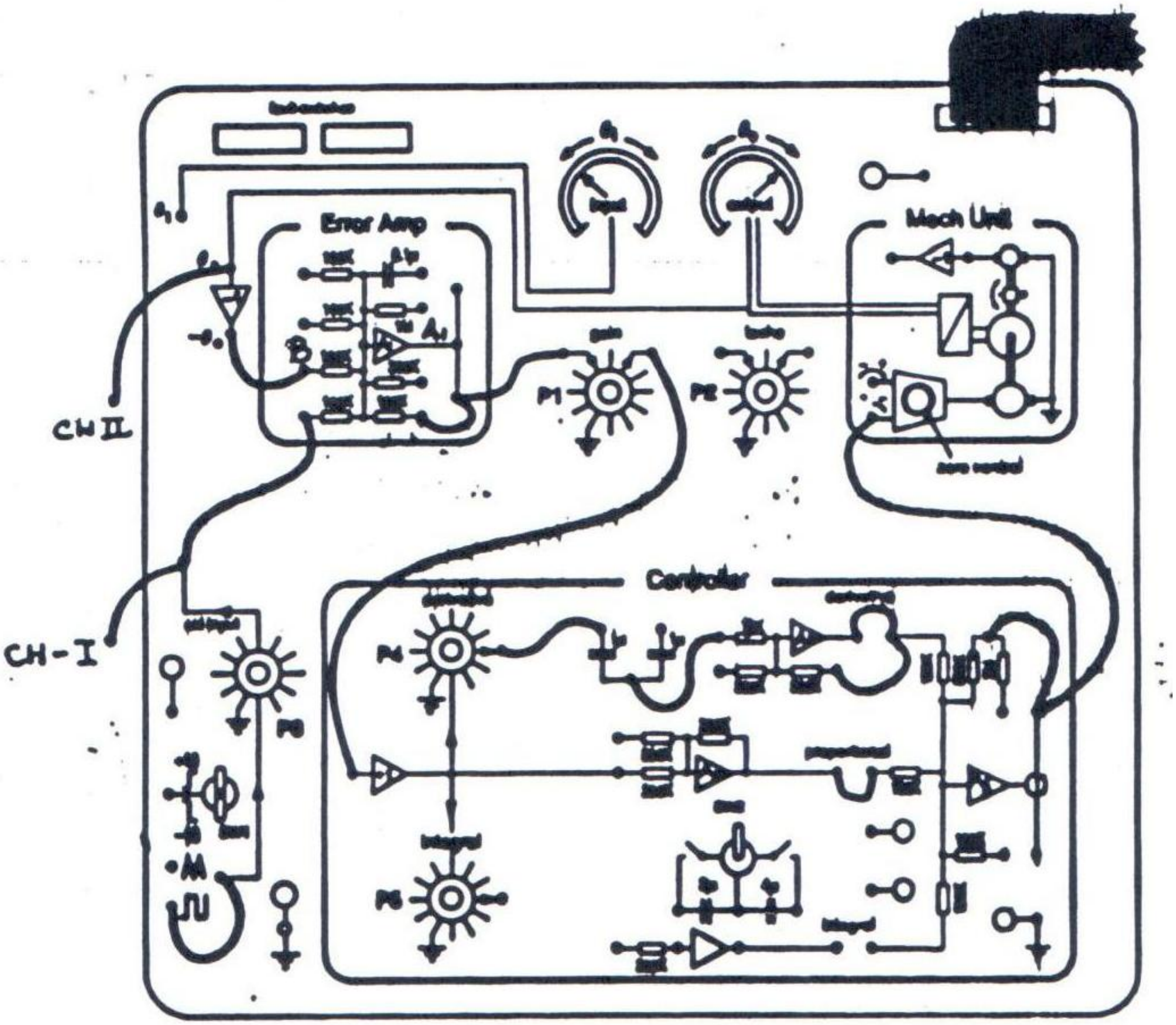


Fig 7 (b) - P + D Controller connections

Practice Questions (for labtest)

1. In expt 1.2, for the diagram in Fig 4, find open loop and closed loop transfer functions (in terms of circuit parameters) assuming suitable symbols for the motor parameters. (No need to search for numerical values.)
2. Draw the block diagram of the circuit in Fig. 7(b).
3. Calculate the gain of the OPAMPS in the P and the D sections of the Controller in Fig. 7.

References:

1. Automatic Control Systems – B. C. Kuo.
2. Control Systems Engineering, Norman S. Nise, John Wiley & Sons.
3. Manual of Servo Fundamentals Trainer, Feedback Ltd.

Table 1

Sl No.	**R_F**	Rise time	Peak overshoot	Gain of the Error Amplifier	Nature of damping	Rough Location of CL poles
1.	100 K					
2.	330 K					
3.	1 M					

Table 2

Sl No.	P_1	P_4	Rise time	Peak overshoot	Change in response
1.	100	0			
2.	100	50			

Table 3

Sl. No.	**Item**	**Make & model no.**
1.	Analogue Unit	
2.	Mechanical Unit	
3.	Power Supply Unit	
4.	Storage Oscilloscope	

Control System Laboratory

Experiment no.751/2

1. Title: STUDY OF A SYNCHRO BASED D.C. POSITION CONTROL SYSTEM

2. Object: To be familiar with a position control system comprising of error sensing synchro devices, thyristorised amplifier, balanced bridge demodulator and DC separately excited (actuator) motor.

Apparatus Used:

1. Synchro Generator:115/90 Volts, 60 Hz
2. Synchro Control Transformer:90/57.5 Volts, 60 Hz
3. Balanced Bridge Demodulator
4. DC Servo Motor and Reduction Gear Arrangement 110, 10A.

3. Theory: A *d. c. motor* is used to position any *load* mounted on its shaft. The *reference angular position* of the load is given on the *synchro generator (TX) rotor*. The *synchro control transformer* (CT) is mounted on the shaft of the motor and load. When the load is not "positioned'' (i.e there is a mismatch between the angular positions of the TX & CT), an error voltage appears at the rotor terminals of the CT. This error voltage triggers the *thyristors* in a way so that the *d.c. motor* is supplied with a voltage and the motor rotates in a direction to nullify the error voltage. In this way the load is positioned according to the reference position.

Depending upon the reference position (angular) of synchro TX, the position control system must be able to drive the controlled d. c. motor shaft to the required angle.

Hence the error in angular position is sensed by synchro TX-CT system comprising of synchro generator and synchro transformer. Since the driving motor is a d.c. separately excited motor, speed control in both directions is achieved by controlling armature voltage. A *thyristorised converter* is used as the power amplifier capable of supplying armature current in both directions (*Dual converter*). # Note 1.

4. Procedure:

1. Note that an external armature resistance is connected to the d.c. motor.

Expt 4.1 Identify i) power amplifier block, ii)synchro error generator block, iii) demodulator block and iv) path of flow of armature current and v)thyristor triggering current in the circuit diagram.

3. Now make the error voltage zero by shorting the error voltage input terminal on the controller board and make sure that the synchro control transformer output is not shorted.

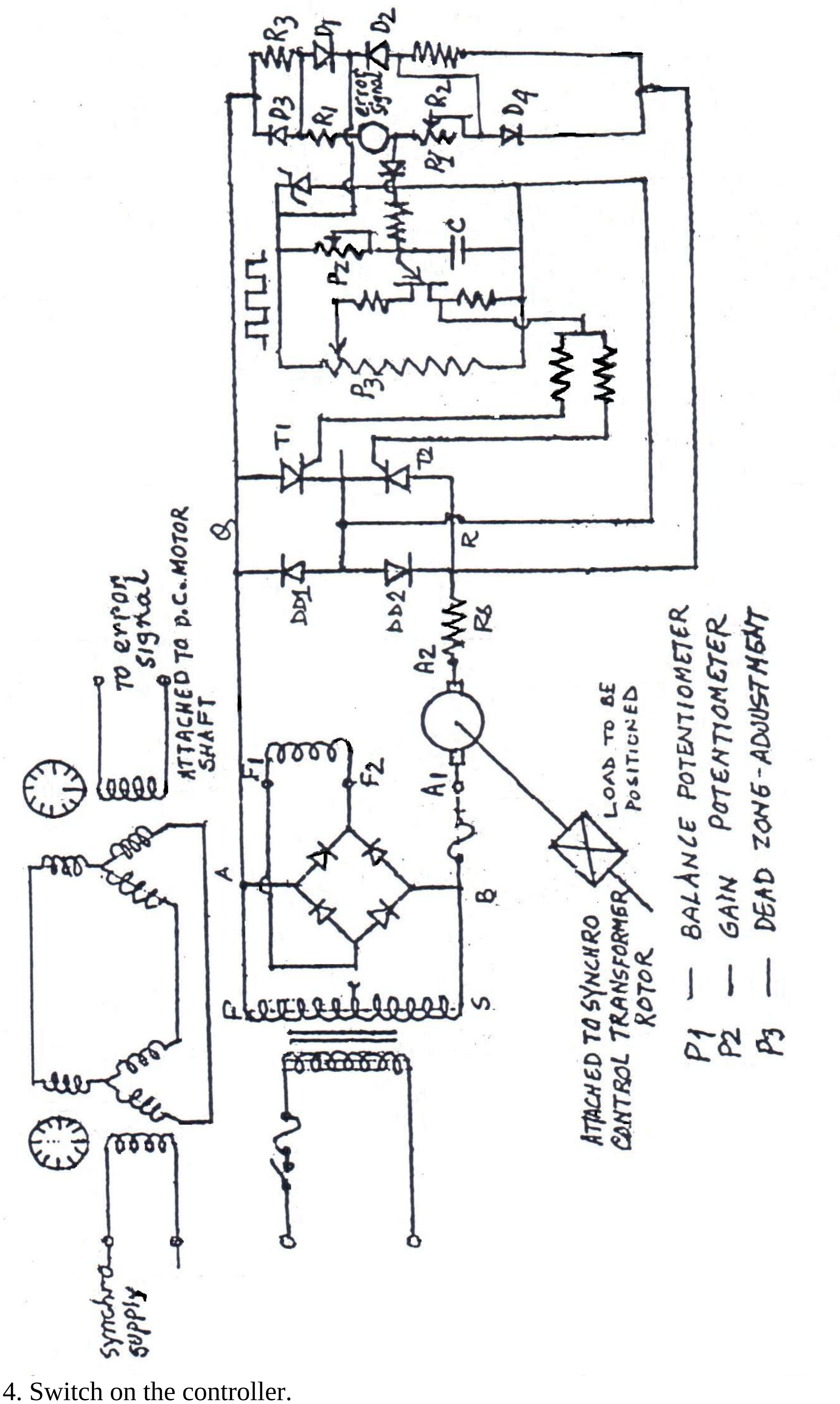


FIG 1 POSITION CONTROL SYSTEM

4. Switch on the controller.

5. Now the controller is ready for further experiments.

6. Connect the error voltage from synchro CT to the error voltage terminal on the controller board. Observe (by changing the TX input in steps) that the output shaft (CT shaft) follows the input shaft (TX shaft) rotation in both the direction.

7. Apply a step change in the reference position and observe the response in the system.

Expt 4.2 Determination of Synchro Characteristics:

The motor is not allowed to rotate by short circuiting the armature. By varying the Synchro TX reference angular position, tabulate the synchro control transformer output voltage in **Table 1**. The armature resistance is present in the circuit to avoid short circuiting of the power amplifier.

Expt 4.3 Determination of the Controller Characteristics:

This procedure is followed like the previous one. With the same set of reference angle position tabulate the DC voltage across the series (armature) resistance in **Table 1.**

Expt 4.4 Observation of the different waveforms:

With the motor not allowed to rotate, observe and trace the waveforms across i) across the capacitance and ii) error signal by varying Input reference position in synchro generator for $+30^0$, -30^0 and 0^0 values of firing angle of the thyristor.

5. Report:

1) Plot the Input/Output Characteristics of the synchro error generator.
2) Plot the Input/Output characteristics of the controller on the same graph paper.
3) Paste the traced waveforms with proper labeling and respective values.
4) Draw the illustrative waveforms showing the working principle of the controller.

Appendix:

Note 1: Since error signal is an alternating signal, the sense of rotation is derived from the phase angle of the error signal w.r.t the reference signal. Therefore a phase sensitive *demodulator* is incorporated (balanced bridge demodulator) before the power amplifying stage.

Procedure to balance the Controller:

1. Observe that the controlled disc may be rotating.
2. Keeping P_3, P_2 at maximum, adjust P_1 such that the disc stops rotating. This is the method of *balancing* the demodulator i.e with error voltage zero the disc must not rotate.
3. Slightly vary P_1 and observe the sensitivity of the controller by observing the immediate direction of rotation of the controlled disc. The disc will rotate in either direction whenever the P_1 is increased or decreased from the balanced condition. The sensitivity may be increased by adjusting **gain potentiometer (P_2)** and **dead zone potentiometer (P_3)**.

Table 1 (Expts 4.2 and 4.3)

Sl No.	Reference Angular Position of TX ( )	Error Voltage across CT ( )	Voltage Across Series Resistance ( )

Control System Laboratory

Experiment no. 751/3

1. Title: DESIGN OF A LEAD COMPENSATOR FOR A STANDARD SECOND ORDER SYSTEM

2. Objective: To be familiar with lead compensator design

3. Theory:

Set Under Test:

A second order plant is simulated (in hardware) using passive R-L-C components and OPAMPS as shown below in **Fig. 1**. Its control system equivalent is also shown in **Fig. 2**.

Lead compensator**:**

A schematic diagram of an electrical lead network is shown in **Fig. 3**. The name “lead network” comes from the fact that for a sinusoidal input $\mathbf{e_i}$**,** the output $\mathbf{e_o}$**,** the network is also sinusoidal with phase lead. The phase lead angle is a function of the frequency

Lead compensation essentially yields an appreciable improvement in transient response.

4. Experiments:

Expt 4.1 Design a lead compensator such that ω_n is doubled but ξ remains unchanged. This implies that rise time in the step response of compensated system will be halved while the peak overshoot remains the same as that of the uncompensated one.

Procedure:

4.2.1. Insert values of ω_n and ξ as given below:

$$\omega_n = \mathbf{5230} \text{ rad/sec} \tag{4.1}$$

$$\xi = \mathbf{0.24} \tag{4.2}$$

in the open loop transfer function **G(s)** (in **Fig. 2**):

$$G(s) = \frac{\omega_n^{\,2}}{s(s+2\xi\omega_n)} \tag{4.3}$$

and find the closed loop characteristic polynomial by applying unity feedback around (4.3) (without the compensator). Hence first obtain the existing closed loop poles, $\mathbf{s_{e1}}$ and $\mathbf{s_{e2}}$ of the uncompensated plant (using ω_n and ξ found in eqns (4.1) and (4.2) resp).

4.2.2. Next find the desired closed loop poles, $\mathbf{s_{d1}}$ and $\mathbf{s_{d2}}$ after making ω_n double and keeping ξ unchanged in (4.3) (i.e., in $\mathbf{s_{e1}}$ and $\mathbf{s_{e2}}$). Fill in **Table 1.**

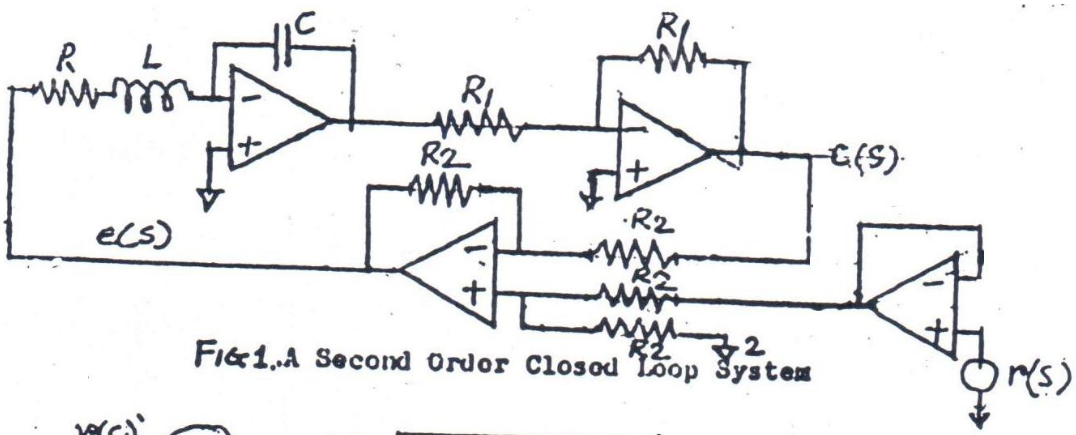


FIG 1. A Second Order Closed Loop System

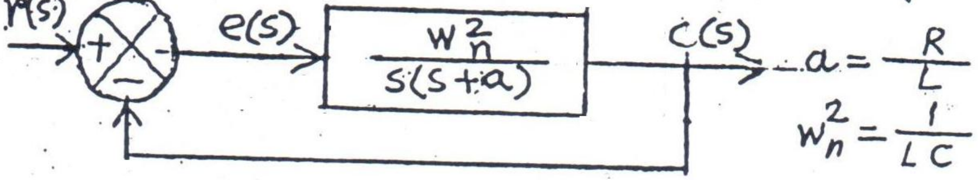
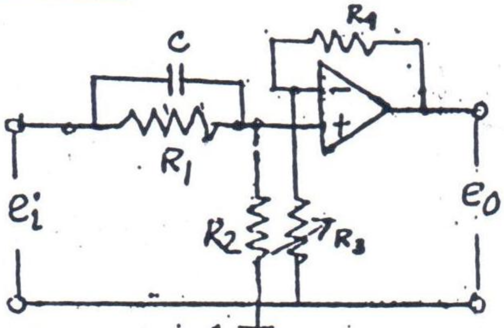


FIG 2. Equivalent Control System Representation

FIG 3. Lead Network



$$\frac{E_o(s)}{E_i(s)} = \left(\frac{s+\frac{1}{T}}{s+\frac{1}{\alpha T}}\right)K_c$$

$$R_1 C = T, \quad \frac{R_2}{R_1+R_2} = \alpha < 1$$

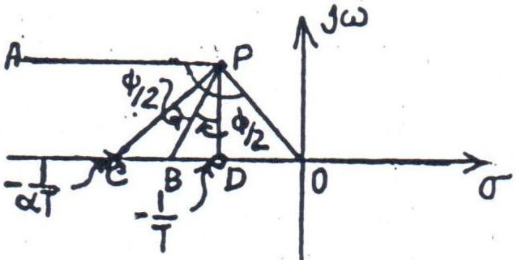


FIG 4. Determination of the pole and zero of a Lead Network

4.2.3. Compensator design using Root Locus:

The compensator T.F. is given by:

$$G_C(s) = \frac{K_C\left(s+\frac{1}{T}\right)}{\left(s+\frac{1}{\alpha T}\right)}$$

i) Find the angle contribution **θ,** of the poles of G(s) (in (4.3)) at the point $\mathbf{s_{d1}}$**.**Note that since **θ** is not an odd multiple of 180 deg., $\mathbf{s_{d1}}$ does not lie on the root locus.

ii) Now determine the angle **φ,** to be contributed by the lead compensator, to fulfill the angle criterion at $\mathbf{s_{d1}}$. Hence to make $\mathbf{s_{d1}}$ lie on the root locus**,** i.e., to make it a closed loop pole,

$$\boldsymbol{\varphi + \theta = -180^0} \qquad (4.4)$$

Find **φ** from the above. Fill **Table 1.**

iii) Now make the following construction (Fig. 4) on a graph paper to locate the pole and zero of the lead compensator:

Locate $\mathbf{s_{d1}}$ (found in step 4.2.2) on the s-plane at point **P** on an ordinary graph paper (choosing the same enlarged scale in x and y axes so that the entire graph paper covers the second quadrant). Draw line **AP** parallel to the x-axis. Line **PB** bisects the angle **OPA**. Draw two lines **PC** and **PD** making angle **φ/2** with the bisector **PB**. C and **D** respectively give the locations of the pole and zero of the lead compensator. Fill up **Table 2**.

Value of C $\left(-\frac{1}{T}\right)$ = location of compensator zero

Value of D $\left(-\frac{1}{\alpha T}\right)$ = location of compensator pole

iv) To find K_C: the forward path transfer function of the compensated system is given by,

$$\mathbf{G_{OL}(s) = K_C G_c(s)\, G(s)}$$

$\mathbf{K_C}$ is the gain of the amplifier (in the lead compensator) included to fulfill magnitude criterion at $\mathbf{s_{d1}}$**.** To make $\mathbf{s_{d1}}$ a closed loop pole, $\mathbf{K_C}$ is to found from: -

$$\left|K_C G_C(s_{d1}) G(s_{d1})\right| = 1 \qquad (4.5)$$

and fill in **Table 2.**

4.2.4 Fabrication of the Compensator: The compensator circuit given in **Fig. 3** may now be fabricated using the values obtained in steps (iii) and (iv). Choosing **C = 1 µF** and $\mathbf{R_3}$ **= 1 KΩ**, choose $\mathbf{R_1}$, $\mathbf{R_2}$ and $\mathbf{R_4}$ from nearest available standard ones. Fill up **Table 3.** Now fabricate the lead compensator along with the OPAMP on a bread-board. Required power supplies for the IC are available on the experimental setup.

4.2.5 Validation of design: Attach the compensator to the experimental setup. Observe on a CRO and roughly sketch the step responses of the system with and without compensation (on same axes). Take readings to complete **Table 4.**

Table 1

Existing closed loop poles s_{e1}	Desired Closed Loop Poles s_{d1}	Angle Contribution of the Open Loop pole and Zero at s_d Θ	Angle to be Compensated $\emptyset$

Table 2

Compensator Zero $\left(-\frac{1}{T}\right)$	Compensator Pole $\left(-\frac{1}{\alpha T}\right)$	Compensator Gain K_C	Compensator Transfer Function $G_c(s)$

Table 3

Components	Calculated Value	Actual Value Used
R_1		
R_2		
R_3		
R_4		
C		

Table 3

	Peak Overshoot (%)	**Rise Time (secs)**
Before compensation		
After compensation		

6.Report:

1. Produce the complete design steps showing all calculations made.
2. Attach rough sketches of the step responses of the compensated and uncompensated systems.
3. Comment on how far the design objectives could be fulfilled by you and the possible reasons behind them. Could you use proportional gain only to fulfill the design objectives?

7. References:

1. Modern Control Engineering – K. Ogata (2nd Edition)
2. Feedback Control System Analysis and Synthesis – J. J. D'Azzo and C. H. Houpis.