Jadavpur University

Department of Instrumentation & Electronics Engineering

Control Systems Laboratory

Laboratory Instruction Sheets

2017

Jadavpur University
Department of Instrumentation and Electronics Engineering
Control Systems Laboratory

Experiment no. 1

STUDY OF A DC POSITION CONTROL SYSTEM

Objective: *To study the steady-state and transient performance of a dc position control system for different loop gains and to study the effect of velocity feedback on such a system.*

Apparatus: Note the apparatus used in standard tabular form.

Procedure:

1. Study the block diagram and circuit diagram of the system and the functions of the different components. In particular, study how the gain of the input amplifier is varied in steps and how the gain of the velocity feedback signal can be varied and its polarity can be reversed.

2. Keep selector plug SP1 in position A, switch S1 closed, switches S2 and S4 open and link LK1 open. Turn on the mains switch and measure the output voltage at the output of the reference pot V_r (point TP1) for shaft position θ_r in the range of 0 to 360° in steps of 30°. Calculate the value of K_p from the V_r vs. θ_r graph.

3. Derive from the block diagram that the transfer function of the motor between the armature voltage and the output speed can be given by

$$G_m(s) = \frac{\Omega_m(s)}{V_o(s)} = \frac{A_m}{1 + s\,T_m}$$

   To measure the value of the gain constant A_m first note that the reduction gear train has a speed ratio of 16:1. Keep S2 and S4 open and S1 closed and apply a small voltage of, say, 0.5V, from the reference pot so that the time taken for 60 or 100 revolutions of the load shaft can be measured. Also measure the corresponding voltage across the armature terminals of the servomotor. A_m is then given by the ratio of the steady-state motor speed to the terminal voltage.
   Take the appropriate voltage reading so that the gain constant K_{TG} of the tachogenerator can be determined.

4. Note that the amplifier gain A can be set at values of 4.55 (=1000k/220k), 10 (=2200k/220k) and 21.4 (=4700k/220k) in the positions A, B and C, respectively, of the selector plug SP1. Closed-loop step response for a gain setting A = 4.55 can be observed by the following steps:
   - Keep mains switch closed and link LK1 open.
   - Keep both S1 and S2 closed.

- Keep both the reference and feedback pots in the same initial angular positions, say, 10°.
- Advance the angular position of the ref pot to 60° more (clockwise) than the initial angle.
- Now close the link LK1. This is equivalent to a step displacement of 60° in the reference input. By noting the steady-state angular position of the feedback potentiometer on the dial the steady-state error can be determined.

5. For three more 60° step inputs of 70° to 130°, 130° to 190° and 190° to 250°, experimentally determine the values of the steady-state error and calculate the average value of modulus of steady-state error, avg($|E_{ss}|$).

   Repeat step 5 for the two higher values of A and again determine avg($|E_{ss}|$) in each case.

6. For 90° step input (from 10° to 100°) calculate the peak overshoot in % for the highest value of A by noting the initial value, peak value and final value of θ_c by using an analog multimeter.

7. Repeat step 6 for the next lower value of A.

8. From step 7 calculate the value of the damping ratio ζ for the closed-loop system for the highest value of A. Hence calculate the value of the motor time constant $T_{m.}$

9. Keep A at its highest setting, S3 in normal position and S4 closed. Keep the velocity feedback setting pot at the extreme clockwise position and measure the value of the peak overshoot for a step input of 90°. Analytically explain why the overshoot should reduce now.

10. Keep S3 in reverse position and all other settings in the same position as in step 9 observe the nature of step response corresponding to a step input of 90°. Explain analytically the nature of the step response.

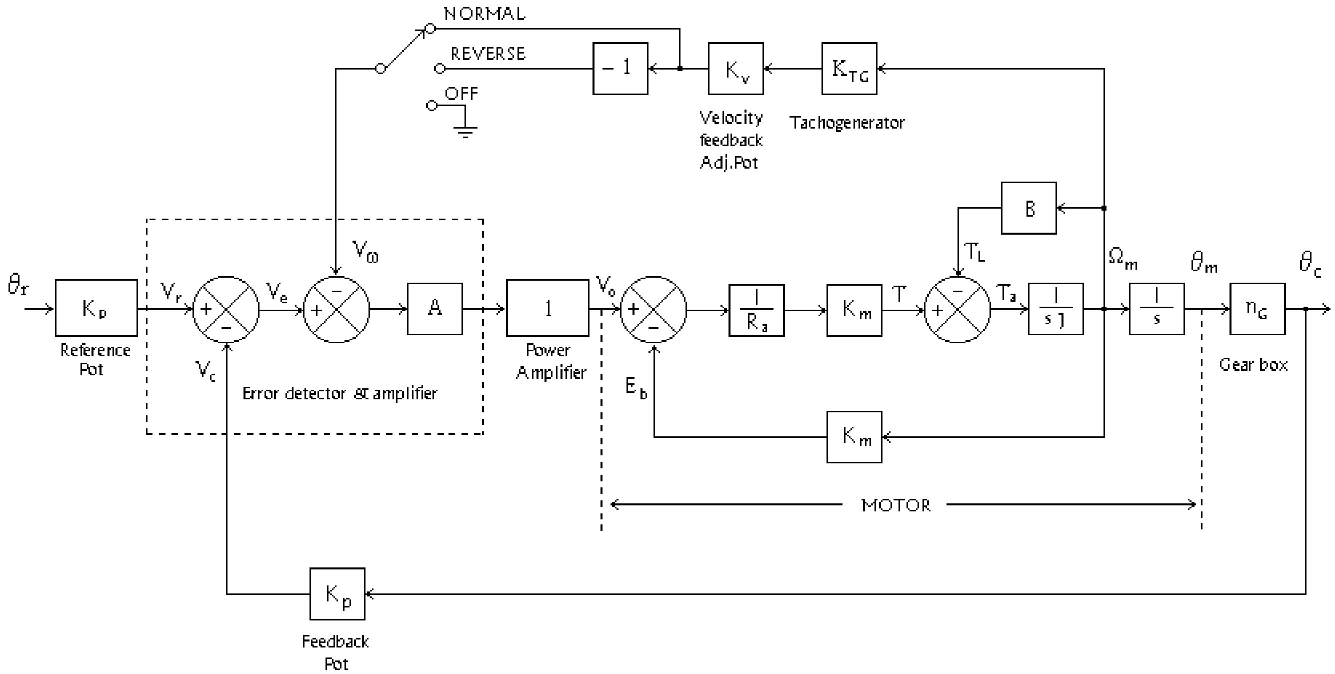
Report:

1. Record all the experimental data in tabular form.

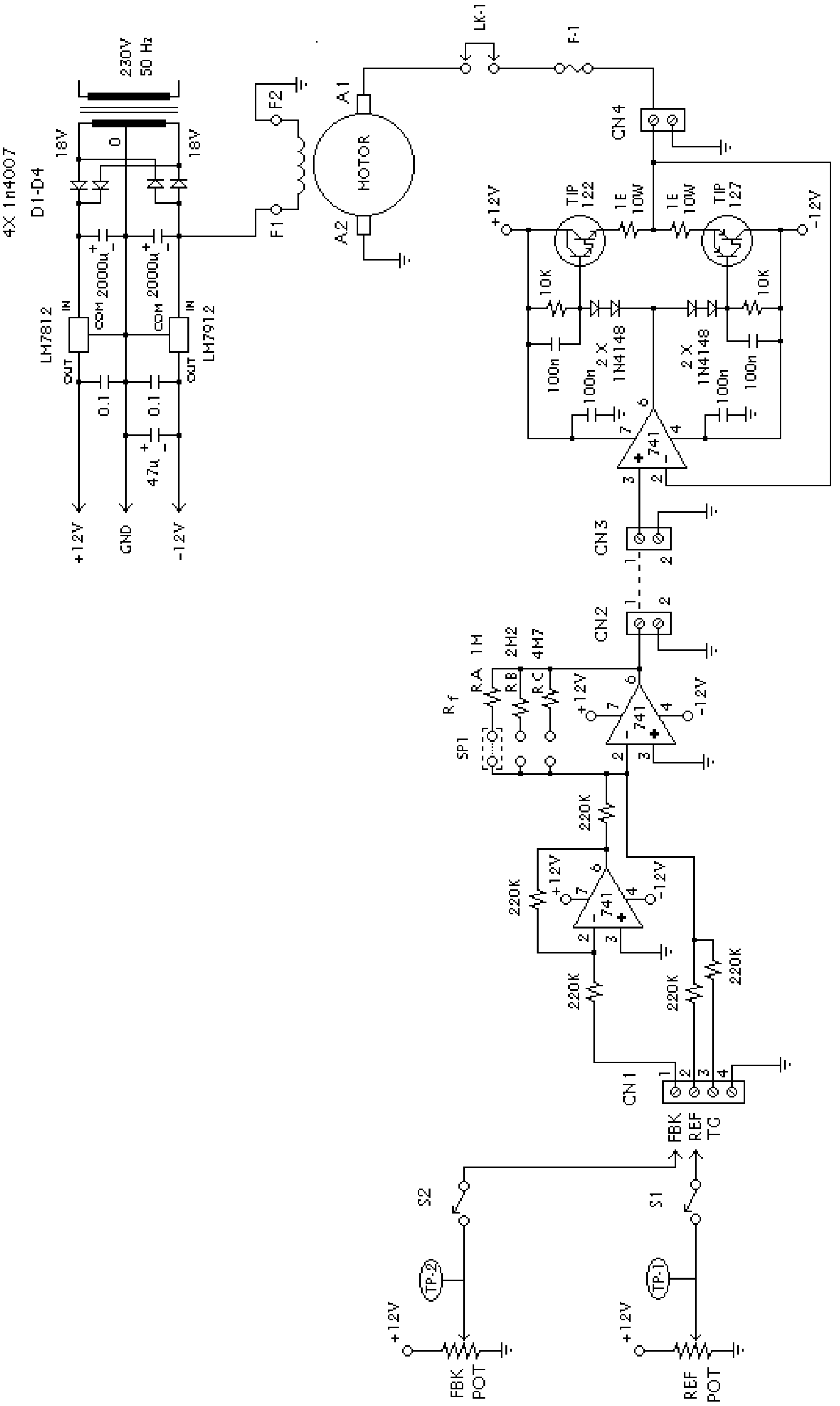
2. Calculate the closed-loop transfer functions of the system for the highest value of A and (a) no velocity feedback (K_v=0) and (b) normal velocity feedback with K_v=1.

3. Calculate and plot the transient output position responses for a 90° step displacement input for both case (a) and (b) above. Determine the values of peak overshoot, peak time and settling time for 5% band from the plot in each case.

Rev 4/Aug 2, 2007



Block diagram of DC position control system



Circuit diagram of the DC position control system

Roll no:

Signature of class teacher:
Date:

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Experiment no. 2

Identification of A Linear System from Step Response Test

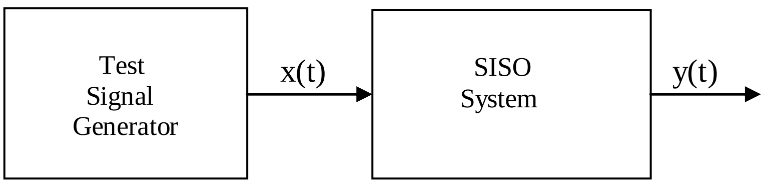
Objective: *To identify the second-order model of a simple linear system from its step response.*

Apparatus: Note the apparatus used in the standard tabular form below:

Item No.	Item	Specifications	Model No.	Serial No.	Make

Familiarization with the setup:

The system is a linear, single-input-single-output (SISO) one that produces a damped oscillatory response corresponding to a voltage step input. Instead of using a voltage step function as input, a unipolar rectangular pulse signal is used so that observation of the time domain response in an oscilloscope becomes easy. The output high and low duration of the input pulses are so chosen that each is greater than the *settling time* of the system. The system



Block diagram of the test setup

may be of an order higher than 2nd, but a 2nd-order *model* of the system can be identified from the step response by observing some important characteristics of the response.

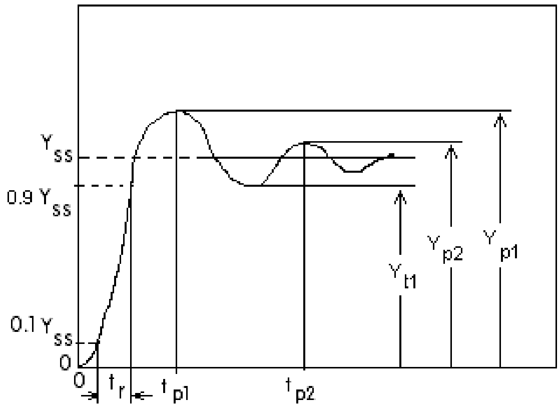
Procedure:

1. Connect the first and second channels of an oscilloscope to the input and output, respectively, of the system and turn on the signal source.
2. Sketch the waveform of the input signal x(t) and measure its amplitude A_x, output high duration T_H, and output low duration T_L. Record data in tabular form and calculate the signal frequency.
3. Observe and sketch the output response y(t) corresponding to any *leading edge* of the input x(t), which will be similar to that shown in the next figure.

4. From the output response measure the following and record the data in a tabular form:

a) The steady-state value of response, Y_{ss},
b) Rise time, t_r,
c) Amplitude Y_{p1} of the first peak and the corresponding time t_{p1},
d) Amplitude corresponding to the first undershoot, Y_{t1},
e) Amplitude Y_{p2} of the second peak and the corresponding time t_{p2},

5. Calculate the DC gain of the system, K as Y_{ss}/A_x.
6. Calculate the peak percentage overshoot M_{p1} and determine the damping factor ζ of the system from M_{p1}.



Step Response of a Linear Oscillatory System

7. Calculate the damped angular frequency of oscillation, ω_d, and hence the natural frequency of oscillation, ω_n.
8. Express the transfer function of the system in the standardized (or, *prototype*) 2nd-order form given by

$$T(s)= K\omega_n^2/(s^2+2\zeta\omega_n s+\omega_n^2)$$

Report:

1. Compute the values of y(t) for the identified system corresponding to a step input $A_xU(t)$ upto $t = 4/\zeta\omega_n$ and plot it on a graph paper. Measure values of Y_{p1}, Y_{t1}, Y_{p2}, t_r, t_{p1} and t_{p2} from the plotted graph. Compare these values with the experimentally obtained ones. Also determine the settling time T_s for 5% tolerance band.
2. Calculate the attenuation ratio defined as $\psi = (Y_{p2} - Y_{ss})/(Y_{p1}-Y_{ss})$ from experimental data. Derive an expression for ψ in terms of M_{p1}.
3. Assume that the identified system comprises of a unity-feedback system of the type $G(s)= K_A K_P/(s(s+a))$. Assume $K_A = 1$ and calculate the values of K_P and a. What is the *order* and *type* of the system G(s)? K_A can be considered as the gain of an amplifier placed in the forward path.
4. For what value of K_A will the system have a damping ratio of 0.707? What is the corresponding peak overshoot?

Rev 1/July 30, 2003

Roll no:

Signature of class teacher:
Date:

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Experiment no. 3

STUDY OF A STEPPER MOTOR TRANSLATOR

Objective:

To study the sequencer and driver circuits of a stepper motor translator and is operation in manual and free-running, full-stepping modes for both directions of rotation.

Apparatus: Note the apparatus used in standard tabular form.

Procedure:

1. Take a cursory view of the system block diagram. The functions of the building blocks will be apparent after going through the steps below.

2. Study the switch-debouncer circuit. Consider that the push button is pressed from the normal or released (B) to pressed (A) position, when there are several bounces at A before the contact is finally made. Sketch the waveforms at input A and output X and hence justify the name of the circuit.

3. Study the circuit diagram of the clock source used in AUTO mode, which uses an LM555 in astable multivibrator mode. Find the minimum and the maximium values of the output frequency f_0 for C = 220 nF, R_A = 2.2k, R_{BK} = 10k and R_{BV} = 100k potentiometer.

4. Study the circuit diagram of the divider using a JK flip-flop. Sketch the input clock and output waveforms for f_0 = 100 Hz.

5. The 4-phase waveform generator uses a type 7474 dual D flip-flop. Starting form an initial state of Q1 = Q2 = 0 write the truth table for the circuit showing the clock pulse no., inputs D1 and D2, and outputs Q1 and Q2. Taking the input clock as reference, sketch the Q1, $\overline{Q1}$, Q2 and $\overline{Q2}$ wave- forms. Observe that Q2 lags Q1 by 90 deg, $\overline{Q1}$ lags Q2 by 90 deg and $\overline{Q2}$ lags $\overline{Q1}$ by 90 deg. Defining QA = Q1, QB = Q2, QC = $\overline{Q1}$ and QD = $\overline{Q2}$, we may say that the pulse sequence is A-B-C-D. This will later be seen to correspond to clockwise (FORWARD) direction of rotation of the motor. The Q1 and Q2 outputs can be 'frozen' at 0, even in the presence of clock pulse, by setting the common $\overline{CLR}$ input to 0. This logic is used for electronic RUN/STOP control.

6. When the two EXOR gates are connected as shown an output equals the corresponding data input or its complement, depending on whether the control input labeled CON is 0 or 1, respectively. Each EXOR gate thus acts as a controllable buffer/inverter gate. For CON = 1, therefore, QB = $\overline{Q2}$ and QD = Q2, while QA and QC have their earlier definitions. Sketch the four waveforms of QA, QB, QC and QD in this case. Observe that the pulse sequence now is A-D-C-B, which is opposite to

the previous sequence. The corresponding direction of rotation of the motor will be counter-clockwise (REVERSE).

7. Study the drive circuit for each motor winding. The output transistor acts as a ‘lowside’ or negative-side motor switch for each motor phase and is turned on when the corresponding drive signal is low. Note the function of the freewheeling diode placed across each motor phase. Also observe that the two of the phase winding are excited at a time (e.g., AB-BC-CD-DA-…), giving rise to full-stepping mode of operation.

8. Keep the POWER switch in OFF position, the motor RUN/STOP switch in STOP position and the AUTO/MANUAL mode switch in MANUAL position. Manually bring the pointer on the motor shaft to zero position on the dial and set the direction switch to FORWARD position. Now turn on the POWER switch and set the RUN/STOP switch to RUN position. Press the STEP push button 50 times and observe the direction of rotation and the total angular displacement. Calculate the step angle, i.e. the displacement per pulse, from this observation. Put the direction switch to REVERSE position now and reapply 50 pulses. The pointer should again come back to zero position. Put the RUN/STOP switch to STOP position once again.

9. Use following switch settings:

Auto/Manual:	AUTO
Run/Stop:	STOP
Forward/Reverse:	FORWARD
Power:	ON

   Use an oscilloscope to set the out put frequency f_0 of the astable multivibrator to 40 Hz. Measure the duty cycle of this waveform. Also measure the frequency f_1 and the duty cycle of the frequency divider output.

10. Set the RUN/STOP switch to RUN position and measure the time required for 10 complete revolutions of the shaft. Calculate the stepping rate in steps/s from this observation. Verify that the stepping rate equals f_1.

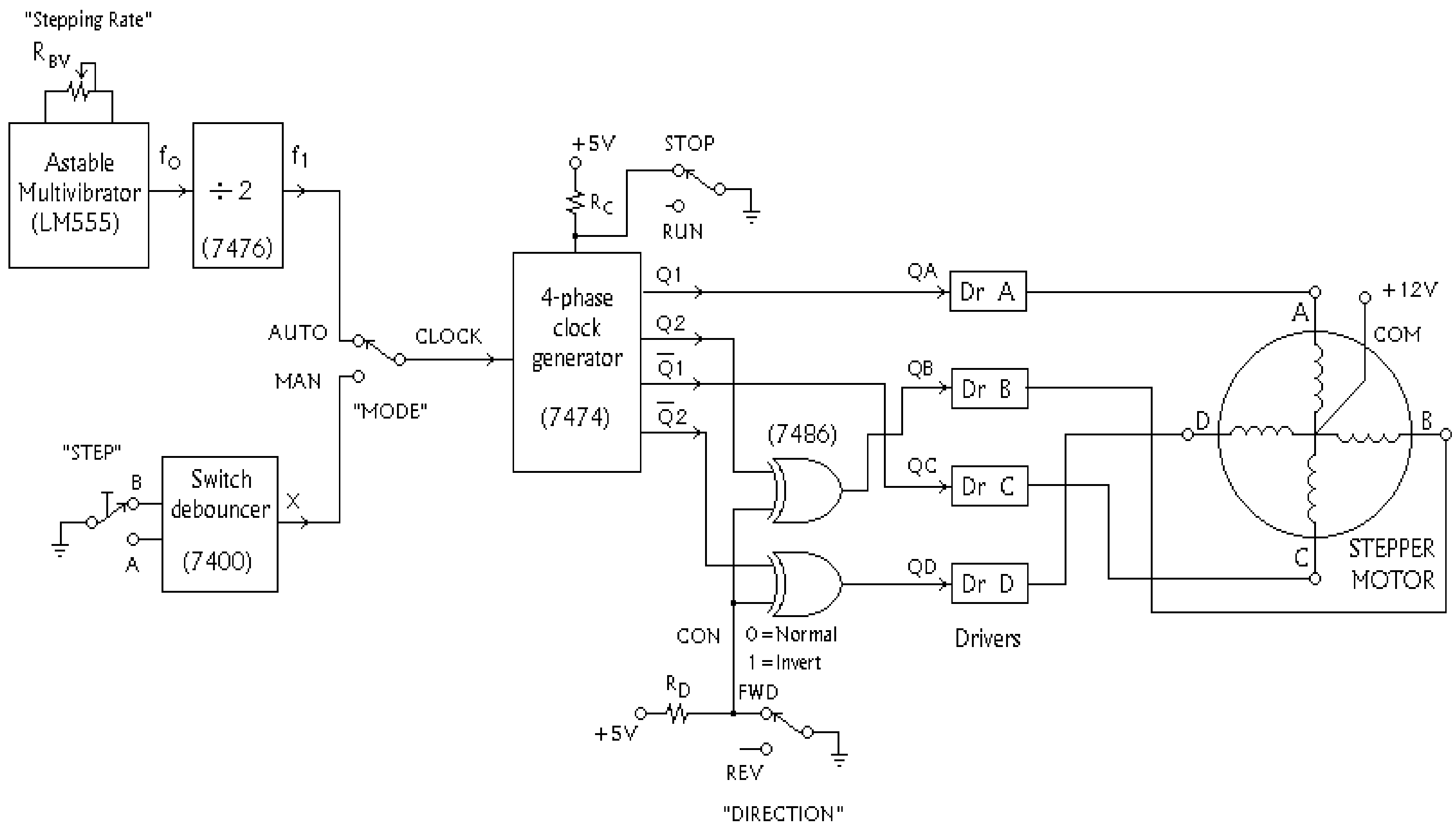
11. Keeping all settings unchanged setting f0 to 250 Hz use QA in channel 1 of the 'scope and use it for triggering. Display QB, QC and QD in channel 2, one at a time, to view the waveforms discussed earlier.

12. Check that by varying the position of the rate potentiometer the stepping rate can indeed be varied.

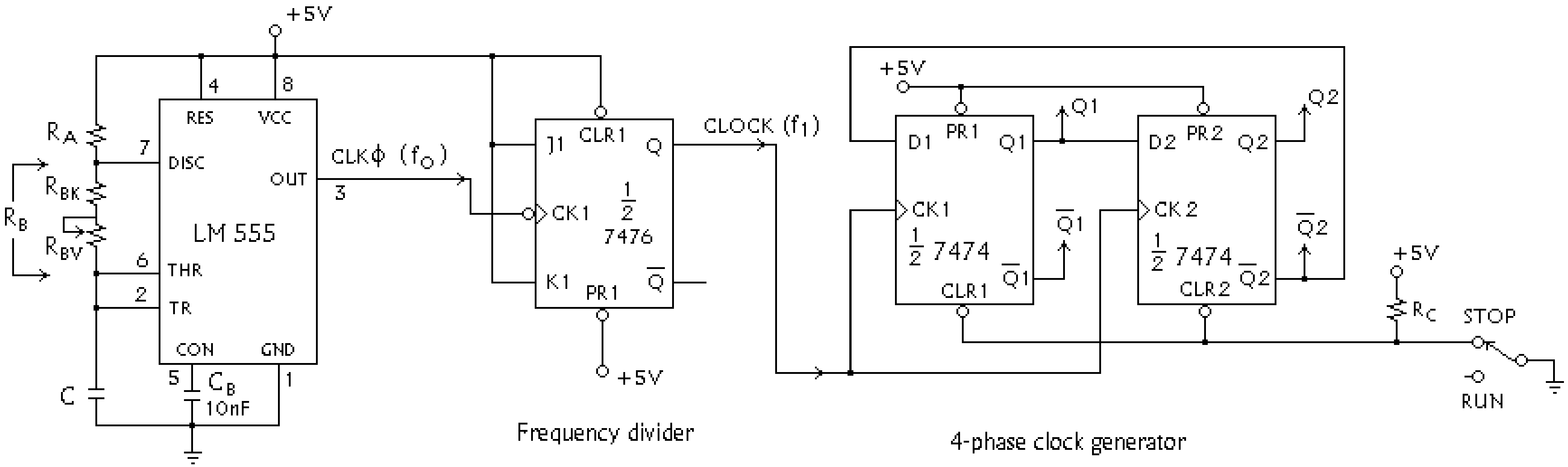
Report:

1. Sketch all the relevant waveforms.
2. Tabulate the recorded experimental data whenever possible.
3. Theoretically calculate the lowest and highest stepping rates from the calculated values of minimum and maximum f_0.

Signature of Lab. Teacher:



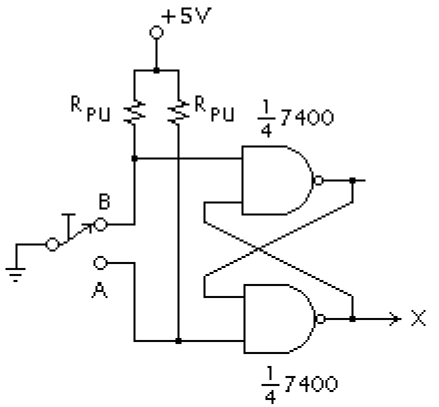
Block Diagram of Stepper Motor Translator



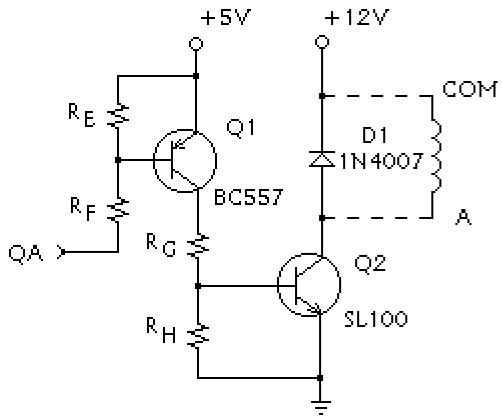
Frequency divider

4-phase clock generator

Astable multivibrator



Switch debouncer using 7400



A typical driver stage (Phase A)

Stepper Motor Translator: Circuit Details

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Experiment no. 4

Study of Step Response of A Linear 2nd order System using *MATLAB*

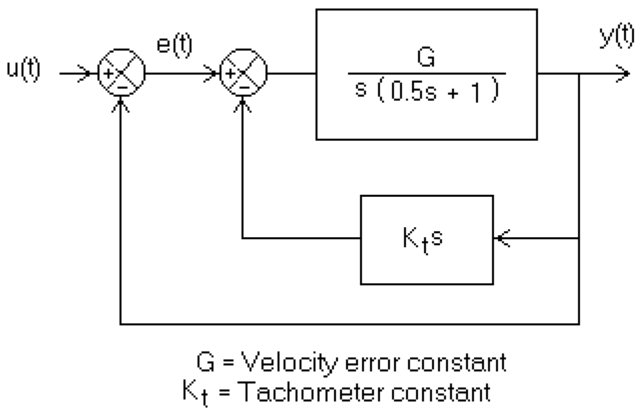
Objective:

To study the performance measures of a linear 2nd order system with variable parameters corresponding to a step input.

Software used: Note the manufacturer's name, version number and release date of the MATLAB software in use.

Familiarization with the system:

The system is a linear, single-input-single-output (SISO) one with u, y and e as input, output and error, respectively. Apart from the unity-gain output (e.g. position) feedback, it also employs output rate (e.g. velocity) feedback with a variable gain K_t.



Transfer function block diagram of the system

Procedure:

1. Calculate the overall transfer function T(s) = Y(s)/U(s) of the system and write it in a standardized form with the coefficient of s^2 equal to unity. In this form it is easy to identify the natural frequency of oscillation ω_n and the damping ratio ζ of the system. Express both of these parameters in terms of G and K_t. Also express K_t in terms of ζ.
2. Click on the MATLAB icon on the desktop to invoke the MATLAB program. On the MATLAB command window use the online help to learn the usage of the following MATLAB commands:

input	plot	close
tf	pause	clc
feedback	grid	hold
clear	axis	
step	ginput	

3. In command window go to file | new | m-file to open the MATLAB editor/debugger. Now enter the following text:

```
clear; close; clc;
G = input('Enter the value of G: ');
Kt = input('Enter the value of Kt: ');
num1 = G; den1 = [0.5 1 0];
sys1 = tf(num1,den1) % check with the manually computed TF
num2 = [Kt 0]; den2 = [0 1];
sys2 = tf(num2,den2) % check with the manually computed TF
sys3 = feedback(sys1,sys2) % check with the manually computed TF
sys = feedback(sys3,1) % check with the manually computed TF
pause;
t = 0:0.1:5; % initial_time:time_interval:final_time : alter as required
y = step(sys,t);
t1 = [0 5]; yss_upper = [1.05 1.05]; yss_lower = [0.95 0.95];
plot(t,y);
hold;
plot(t1,yss_upper,'r',t1,yss_lower,'r'); % 5% tolerance band
grid;
axis ([0 5 0 1.6]); % set plot axes parameters
ginput(4)
```

Use the file menu of the editor to save the code with a filename expt4.m. Now the program can be executed by going to tools | run in the editor window.

4. Run the program for G = 4 and K_t = 0 (i.e., no output rate feedback). Calculate the overall transfer function and verify the same from the program output. Use the 'pause' command and modify the parameters of the 'axis' statement, whenever necessary. Measure the values of rise time, 1^{st} and 2^{nd} peak overshoots, 1^{st} and 2^{nd} peak times, and settling time (for 5% band). Compute the damping ratio ζ, attenuation ratio, damped frequency ω_d and natural frequency ω_n from the data obtained from the plots.

5. With K_t = 0, repeat step 4 for G = 6 and 8. Comment on the effect of increase in G on peak overshoot, rise time and settling time.

6. Set G = 8 now. Calculate the values of K_t for ζ = 0.3, 0.6 and 0.9. For each of these values of K_t, measure rise time and peak overshoot. Observe that when ζ increases one of the performance measures, namely, first peak overshoot, improves, while the other (rise time) deteriorates. This necessitates a compromise or *tradeoff* in selection of K_t. For each K_t, make a copy of the response vector y in a table having time t in the first column and y in the second. Keep space for third and fourth columns with headings of error, e = (1-y) and e^2, respectively. Record values of t and y till |e| does not exceed 0.05 anymore. (This can also be coded in MATLAB)

7. To avoid the problem associated with the contradictory requirements of multiple performance figures, a single time-domain performance index (PI) is sometimes preferred. One such common PI is the integral square error or ISE defined as

$$\text{ISE} = \int_0^{\infty} e^2 \, dt.$$

Control system designers select system parameters so that the ISE is *minimized*. (What is the ISE for an ideal position control system?) We propose to compute the ISE by numerical integration for each of the values of ζ considered earlier.

8. Calculate the value of K_t for $\zeta = 0$ (undamped oscillation). Is this K_t negative? Run the program with this K_t and G = 8 and observe the step response. A similar result was observed /(will be observed) in another experiment for incorrect polarity of speed feedback.

Report:

1. Tabulate the measured and computed results obtained in steps 4 and 5 above. Plot the variations of rise time and peak overshoot as functions of ζ.

2. From the data obtained in step 7 of procedure compute the ISE for each value of ζ considered. Rectangular integration should suffice and the process of summation should be stopped when e^2 falls below 0.0025. (i.e., $|e| < 0.05$) This will save computational effort considerably. Plot the ISE vs. ζ graph. Conclude from this graph which is the 'best' choice for ζ and hence, K_t.

3. Why are G and K_t called the *velocity error constant* and *tachometer constant*, respectively?

4. Suggest and define another popular time-domain performance index.

5. Rewrite the last few lines of the m-file so that the squared error is directly plotted as a function of time.

Rev 6/July 23, 2018

Roll number:

Signature of class teacher:
Date:

Department of Instrumentation and Electronics Engineering
Control Systems Laboratory

Experiment no. 5

Study of the Effect of a Forward-path Lead Compensator on the Performance of a Linear Feedback Control System

Objective:

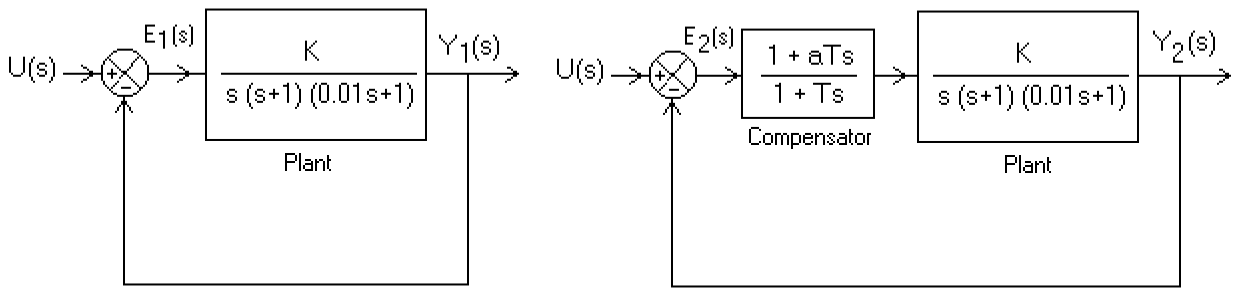
1. *To measure the gain and phase margins of an uncompensated linear 3rd order, type-1 system from its Bode plot.*
2. *To study the bode plot of a suggested forward-path lead compensator.*
3. *To recalculate the gain and phase margins of the compensated system.*
4. *To compare the step responses of the unity-feedback uncompensated and compensated systems.*

Software used:

Note the manufacturer's name, version number and release date of the MATLAB software in use.

Familiarization with the system:

The original or uncompensated open-loop system is of 3rd-order, type-1 variety and, therefore, when operated with unity negative feedback will have a zero steady-state error for a step input, irrespective of the value of the gain K. However, since the velocity error coefficient K_c of the system equals K (prove this), the steady-state error corresponding to a unit ramp input is 1/K. To attain a given value of this error, say



The original system   The compensated system

0.01, a K of 100 is required. Using the Routh-Hurwitz criterion, the value of the critical gain K_c, for which the system is critically stable, can be determined. It will be seen that since K_c is very close to 100, the closed-loop system will exhibit very poor relative stability. It is manifested in the form of very low *gain margin* (GM) and *phase margin* (PM) in the frequency domain and also in the form of a highly oscillatory step response in the time domain.

One popular way of alleviating the stability problem, without compromising the given velocity error specification, is to add a lead compensator block with a transfer function $G_c(s)= (1+aTs)/(1+Ts)$, a>1, before the plant. Verify that this modification does not change the value of K_v, and thus the value of the steady state velocity error. There are suitable design methods to determine values of 'a' and 'T', the two parameters of the compensator, in order that given GM and PM specifications are met. Without going into the design techniques, we will use a = 10 and T = 0.015 (second) for this experiment.

Procedure:

1. Click on the MATLAB icon on the desktop to invoke the MATLAB program. In command window, go to file | new | m-file to open the MATLAB editor/debugger. Copy the first twelve lines of the sample program given at the end of this section. Use the file menu of the editor to save the code with a filename expt6.m. Now the program can be executed by going to tools | run in the editor window. From the MATLAB command window measure the values of gain crossover frequency, phase margin, phase crossover frequency and gain margin of the uncompensated system.
   Reduce the plant gain K to 50 (= 100/2) now. Observe that the phase-vs-frequency plot has remained unchanged, but the gain-vs-frequency plot has shifted downwards by 6 dB (= 20 log 2). Again read the values of gain crossover frequency, phase margin, phase crossover frequency and gain margin. Record the data in the present and the previous paragraph in a single table.

2. Restore the value of K to 100 now. Copy five more lines of the sample program (up to line 16). Run the program and make a free-hand sketch of the Bode plot of the lead compensator. Using the data cursor record the values of very low frequency gain, very high frequency gain, maximum phase lead φ_m and the corresponding angular frequency $\omega_{m.}$

3. Extend the program up to line 25 and run it. Observe the Bode plot of the compensated system and read the values of gain crossover frequency, phase margin, phase crossover frequency and gain margin.

4. Copy the remaining lines of the sample program. Observe the unit step responses of the original and the compensated systems. Approximately measure the maximum peak overshoots of the two systems.

5. Record the closed-loop transfer functions of the original and compensated systems. Observe that the order of the system has increased after compensation and yet the system has better relative stability.

SAMPLE PROGRAM:

```
clear; close; clc;          % Expt 6 – Control Lab                    % (Line 1)
nump = [100];                              % Specifies the plant TF numerator
denp = [0.01 1.01 1 0];                    % Specifies the plant TF denominator
sysp = tf(nump,denp);
w = logspace (-1, 4, 100);
bode(sysp, w); grid on;
[Gm,Pm,Wcp,Wcg] = MARGIN(sysp); Gm_db = 20*log10(Gm);
Gm_db
Wcg
Pm
```

```
Wcp                 % (Line 11)
pause;
numc = [0.15 1];
denc = [0.015 1];
bode(numc, denc, w);
grid on; % (Line 16)
pause;
[num, den] = series (numc, denc, nump, denp);   % The open-loop cascaded system
sys_OL = tf(num,den);
bode(sys_OL, w); grid on;
[Gm,Pm,Wcp,Wcg] = MARGIN(sys_OL); Gm_db = 20*log10(Gm);
Gm_db
Wcg
Pm
Wcp                 % (Line 25)
pause;
[n1, d1] = feedback (nump, denp, 1, 1, -1); % The original closed-loop system
t= 0:0.02:5;
y1 = step (n1, d1, t);
[n2, d2] = feedback (num, den, 1, 1, -1); % the compensated closed-loop system
y2 = step (n2, d2, t);
subplot(2,1,1);plot (t, y1); grid on; title('The original closed-loop system');
subplot(2,1,2);plot (t, y2); grid on; title('The compensated closed-loop system');
```

Report:

1. Reproduce all the data in tabular form and the free-hand sketch of the Bode plot of the compensator obtained in step 2 of procedure. Compare the theoretical values of φ_m and ω_m with the experimentally obtained ones.

2. Show that for a<1, a compensator with a transfer function $G_c(s)= (1+aTs)/(1+Ts)$ always produces a phase lag, independent of the frequency. What should be a suitable name for such a compensator?

3. Consider an operational amplifier-based, unity-gain, inverting amplifier with both input and feedback resistors of value R. Connect capacitors C1 and C2 across the input and feedback resistors, respectively. Derive the transfer function $E_o(s)/E_i(s)$ and show that, barring the negative sign, it *realizes* $G_c(s)$. Express ‘a’ and ‘T’ in terms of the component values.

Rev 1/July 23, 2018

Roll no:

Signature of class teacher:
Date: