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2020-2021

## Experimental title:- Laplace Transform

Summary:-1- Understand the application of Laplace transform.
2. Verify Laplace conversion pairs using the ACS-1000 Analog Control System.

## Procedures:-

A. Verifying Algebraic Functions

$$
a \Leftrightarrow \frac{a}{s}, \quad a t \Leftrightarrow \frac{a}{s^{2}}, \quad \frac{a}{2} t^{2} \Leftrightarrow \frac{a}{s^{3}}
$$

The Laplace transform is essentially an integral transformation.
Perform the following steps using the ACS-13006 Integrator module.

1. Make the necessary connections according to the block and wiring diagrams shown in Figure 1-1.

(a) Block diagram

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(b) Wiring diagram

Figure 1-1
2. On the ACS-13011, set the FUNCTION selector switch to Pulse position, adjust DC offset and AMP control knobs to generate 1 Vpp pulse (low level $=0 \mathrm{~V}$ ) at the FG output terminal. Press the RESET pushbutton switch to stop integrators ACS-13006 (1) and ACS-13006 (2).
3. Set ACS-13006 (1) and ACS-13006 (2) selector switches as follows:

| Selector Switch | ACS-13006(1) | ACS-13006(2) |
| :---: | :---: | :---: |
| T | $\times 1$ | $\times 1$ |
| I.C. | 0 | 0 |
| SYNC. | OP | OP |

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4. Press the ACS-13011 PULSER push-button switch. Using an oscilloscope, measure and record the signals at ACS-13006 (1) $V_{o}$ Output and ACS-13006 (2) $V_{o}$ Output terminals as shown in Figure 1-2 (a). Measure and save as shown. These two outputs are $t$ and $t^{2} / 2$ signals respectively. View the integration time from starting to saturation


Figure 1-2
Since the ACS-13006 (1) and ACS-13006 (2) integrators are used to perform integral operation, the outputs of the two integrators will saturate after a period of time, at this time the outputs are not $t$ and $t^{2} / 2$ waveforms any more. To view the waveforms $t$ and $t^{2} / 2$,change SYNC switch from OP to INI C position and set the initial value to 0 (set the IC control to 0 ). Press the ACS-13011 PULSER push button again. The ACS-13006 integrators will integrate again.
5. At ACS-13006 (1), modify T selector switch to x 10 . First press ACS-13011 RESET push-button switch and then push the PULSER push-button switch. Measure and record the signals at ACS-13006 (1) $V_{o}$ output and ACS-13006 (2) $V_{o}$ output terminals as shown in Figure 1-2 (b).
6. On the ACS-13011, set FUNTION selector switch to Pulse position, adjust AMP and DC OFFSET control knobs to generate a 2 Vpp (low level $=0 \mathrm{~V}$ ) at FG output terminal. Using oscilloscope, Measure the signals at ACS-13006 (1) $V_{o}$ output and ACS-13006 (2) $V_{o}$ output terminals. These two output signals should be 2 t and $t^{2}$ waveforms, respectively.
B. Verifying Exponential Functions

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$$
e^{-a t} \Leftrightarrow \frac{1}{s+a}, 1-e^{-a t} \Leftrightarrow \frac{a}{s(s+a)}
$$

1. Make the necessary connections according to the block and wiring diagrams shown in Figures 1-3.

(a) Block diagram

(b) wiring diagram

Figure 1-3

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2. On ACS-13003, set the $K_{I}$ RANGE selector switch to x10. Adjust $K_{I}$ ontrol knob and set $K_{I}=5$. This makes the transfer function of ACS-13003 control block as $50 / \mathrm{s}$.
3. On ACS-13010, adjust the REPEAT RATE and AMP control knobs to generate $0.5 \mathrm{~Hz}, 1.8 \mathrm{~V}$ square wave at the STEP + output terminal.
4. Measure and record the signals at ACS-13001 $V_{o 1}$ output terminal and ACS-13003 $V_{o}$ output terminal as shown in Figure 1-4. These two outputs are $e^{-a t}$ and 1-e $e^{-a t}$ signals, respectively.


Figure 1-4 $e^{-a t}(\mathrm{CHI})$ and $1-e^{-a t}(\mathrm{CH} 2), a=50$
C. Verifing $t e^{-a t}$ Function

$$
t e^{-a t} \Leftrightarrow \frac{1}{(s+a)^{2}}
$$

1. Make the necessary connections according to the block and wiring diagrams shown in Figure 1-5.

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(a) Block diagram

(b) Wiring diagram

Figure 1-5
2. On ACS-13007, set $K_{I}$ to 5 and on ACS-13007A set $K_{2}$ to 5 .
3. On the ACS-13010, adjust REPEAT RATE and AMP control knobs to generate $0.05 \mathrm{~Hz}, 5 \mathrm{~V}$ square wave at he STEP + output terminal.
4. Set ACS-13006 (1) and ACS-13006 (2) selector switches as follows:

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| Selector Switch | ACS-13006(1) | ACS-13006(2) |
| :---: | :---: | :---: |
| T | $\times 1$ | $\times 1$ |
| I.C. | 0 | 0 |
| SYNC. | OP | OP |

5. From the block diagram of Figures $1-5$, the signal at the ACS-13001 (2) $V_{o 2}$ output terminal is then:

$$
\begin{aligned}
& \frac{1}{(s+a)^{2}}=\frac{1}{(s+5)^{2}} \\
& £^{\left(\frac{1}{(s+5)^{2}}\right)=t e^{-s t}}
\end{aligned}
$$

6. Using oscilloscope, measure and record the signals at ACS-13010 STEP + output and ACS-13001 (2) $V_{o 2}$ output terminals as shown in Figure 1-6


Figure 1-6
Figure 1-7
7. On ACS-13007, set $K_{I}$ to 10 and on ACS-13007A set $K_{2}$ to 10 .
8. From the block diagram of Figure 1-5, the signal at ACS-13001 (2) $V_{o 2}$ output terminal is then :

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$$
\begin{aligned}
& \frac{1}{(s+a)^{2}}=\frac{1}{(s+10)^{2}} \\
& \pm^{-1}\left(\frac{1}{(s+10)^{2}}\right)=t e^{-10 t}
\end{aligned}
$$

9. Using oscilloscope, measure and record the signals at ACS-13010 STEP + output terminal and ACS13001 (2) $V_{o 2}$ output terminal as in Figure 1-7.
10. On ACS-13007, set $K_{I}$ to 1 and on ACS-13007A set $K_{2}$ to 1 .
11. From the block diagram of Figure $1-5$, the signal at ACS-13001 (2) $V_{o 2}$ output terminal is then:

12. Using oscilloscope, measure and record the signals at ACS-13010 STEP + output terminal and ACS13001 (2) $V_{o 2}$ output terminal as in Figure 1-8.

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Figure 1-8
D. Verifying Sine Functions

$$
\sin \omega t \Leftrightarrow \frac{\omega}{s^{2}+\omega^{2}}, \quad \cos \omega t \Leftrightarrow \frac{s}{s^{2}+\omega^{2}}
$$

1. Make the necessary connections according to the block and wiring diagrams shown in Figure 1-9

(a) Block diagram

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(b) Wiring diagram

Figure 1-9
2. On the ACS-13011, set FUNTION selector switch to Pulse position, adjust AMP and DC OFFSET control knobs to generate a $1 \mathrm{Vpp}($ low level $=0 \mathrm{~V})$ at FG output terminal. Press RESET push-button switch to stop integrators ACS-13006 (1) and ACS-13006 (2).
3. Set the ACS-13006 (1) and ACS-13006 (2) selector switches as follows:

| Selector Switch | ACS-13006(1) | ACS-13006(2) |
| :---: | :---: | :---: |
| T | x 1 | x 1 |
| I.C. | 0 | 0 |
| SYNC. | OP | OP |

4. From the block diagram of Figures $1-9$, the signal at the ACS-13001 $V_{o 1}$ output terminal is:

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$$
\frac{s}{s^{2}+T^{2}}=\frac{s}{s^{2}+1}
$$

5. From the block diagram of Figure 1-9, the signal at the ACS-13006 (1) $V_{o}$ output terminal:

$$
\begin{aligned}
& \frac{T}{s^{2}+T^{2}}=\frac{1}{s^{2}+1} \\
& \pm^{4}\left(\frac{1}{s^{2}+1}\right)=\sin t
\end{aligned}
$$

6. Press the ACS-13011 PULSER switch. Using the oscilloscope, measure and record the signals at ACS$13001 V_{o 1}$ output and ACS-13006 (1) Measure the signals at the $V_{o}$ output terminals as shown in Figure 110 .


Figure 1-10
Figure 1-11
At the instant the PULSER switch is pressed, the output signal could be very large even saturated, and then the amplitude will decay gradually, but the oscillatory frequency $\omega$ will remain unchanged. After a period of time, the oscillation will stop. This is because the internal resistance of the integrator capacitor. The greater

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the resistance, the smaller the loss angle. The transfer function of an actual integrator is $\frac{1}{s+K}$, generally K is quite small (due to large resistance) and negligible. The output amplitude of the second-order SIN /COS oscillator will decay or the oscillator will stop due to the loss angle. This will be simulated later.
7. On ACS-13006 (1) and ACS-13006 (2), set the T selector switch to position x10.
8. From the block diagram shown in Figure 1-9, the output signal at ACS-13001 $V_{o 1}$ output terminal is then

9. From the block diagram of Figure $1-9$, the signal at ACS-13006 (1) V ol output terminal is then

$$
\begin{aligned}
& \frac{T}{s^{2}+T^{2}}=\frac{10}{s^{2}+10^{2}} \\
& \pm^{4}\left(\frac{10}{s^{2}+10^{2}}\right)=\sin 10 t
\end{aligned}
$$

10. Press the ACS-13011 PULSER switch. Using oscilloscope, measure and record the signals at ACS$13001 V_{o 1}$ output and 13006 (1) $V_{o}$ output terminal, as shown in Figure 1-11.
E. Verifying $e^{-a t} \sin w t$ Sine Function

11. Make the necessary connections according to the block and wiring diagrams shown in Figure 1-12

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(a) Block diagram


## (b) Wiring diagram

Figure 1-12
2. On ACS-13007, set $K_{1}$ to 1 and on $A C S-13007 A$, set $K_{2}$ to 1 .
3. On ACS-13002, set $K_{p}$ to $81\left(\omega^{2}=81\right)$.
4. On ACS-13005, set K to 1.
5. On the ACS-13010, tern REPEAT RATE and AMP control knobs to generate a $0.1 \mathrm{~Hz}, 5 \mathrm{~V}$ square wave at the STEP + output terminal.
6. Set the ACS-13006 (1) and ACS-13006 (2) selector switches as follows

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| Selactor Switch | ACS-13006(1) | ACS-13006(2) |
| :---: | :---: | :---: |
| T | $\times 1$ | $\times 1$ |
| I.C. | 0 | 0 |
| SYNC. | OP | OP |

7. From the block diagram of Figure 1-12, the signal at the ACS-13001 $V_{o 1}$ output terminal is then:

$$
\pm^{-1}\left(\frac{1}{(5+1)^{2}+9^{2}}\right)=\frac{e^{-t} \sin 9 t}{9}
$$

8. Using the oscilloscope, measure and record the signals at ACS-13010 STEP + output and ACS-13001 $V_{o 1}$ output as shown in Figure 1-13


Figure 1-13
Figure 1-14
9. On ACS-13007, set $K_{I}$ to 0.5 , on ACS-13007A, set $K_{2}$ to 0.5 . On ACS-13002, place $K_{p}$ RANGE selector switch in x10 position and make $K_{p}=10$
10. From the block diagram of Figure 1-12, the signal at ACS-13001 $V_{o 1}$ output terminal is:

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$$
\pm^{-1}\left(\frac{1}{(s+0.5)^{2}+10^{2}}\right)=\frac{e^{-0.5 t} \sin 10 t}{10}
$$


11. Using oscilloscope, measure and record the signals ACS-13010 STEP + output and ACS-13001 $V_{o 1}$ output as shown in Figure 1-14.
12. On ACS-13002, set $K_{p}$ to $49(\omega=7)$. Remain $K_{I}$ and $K_{2}$ unchanged.
13. From the block diagram of Figure 1-12, the signal ACS-13001 $V_{o 1}$ output terminal is:

$$
\pm^{-1}\left(\frac{1}{(s+0.5)^{2}+7^{2}}\right)=\frac{e^{0.5 t} \sin 7 t}{7}
$$

14. Using the oscilloscope, measure and record the signals at ACS-13010 STEP + output and ACS-13001 $V_{o 1}$ output as shown in Figure 1-15


Figure 1-15
Discussion:- Apply Laplace transform for each block diagram associated with the procedures and sketch your answer with the obtained results.

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## Experimental Title:- First-Order System

1- Summary:-1- To study the characteristics of first- order system
2- To measure the steady state gain and time constant of first- order system.
3- To study the transient response of first- order system.

## 2- Introduction and Theory:-

The time response of a system is divided into two parts:
1- Transient response
2- Stable-state response
First- order system can be expressed by first- order differential equation. Most simple first- order system can be defined by the following equation.

$$
\begin{equation*}
\frac{d c(t)}{d t}+a c(t)=b r(t) \tag{1}
\end{equation*}
$$

Where a and b are constant. First- order differential equation is similar to an RL electrical circuit. Transform Equation (1) to Laplace domain, we have:

$$
\begin{aligned}
& s C(s)-c(0)+a C(s)=b R(s) \\
& C(s)=\frac{b}{s+a} R(s)+\frac{c(0)}{s+a}
\end{aligned}
$$

where $[b /(s+a)] R(s)$ is called the zero-state component which is the system response at the initial value 0 $(c(0)=0)$ of, whereas $c(0) /(s+a)$ is the zero-input component which is the system response caused by the initial value $\mathrm{c}(0)$ with no input. Therefore, the transfer function of equation (1) is given by:

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$$
G(s)=\frac{C(s)}{R(s)}=\frac{b}{s+a}
$$

Its block diagram is shown in figure 2-1.


Figure 2-1 Block diagram of first- order system.
A permanent magnet (PM) dc servo motor is a typical first- order system. If the armature voltage of PM dc servo motor is Va, the relationship between motor speed $\omega$ and armature voltage Va can be expressed by:

$$
\frac{\omega(s)}{V_{a}(s)}=\frac{b}{s+a}
$$

When the input signal of the first- order system is a step, $\mathrm{r}(\mathrm{t})=\mathrm{A} u_{s}(\mathrm{t})$, then

$$
R(s)=\frac{A}{s}
$$

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If the initial value is 0 , the system output will be:

$$
\begin{aligned}
& C(s)=G(s) R(s)=\frac{b A}{s(s+a)}=\frac{b A / a}{s}-\frac{b A / a}{s+a} \\
& c(t)=\left(\frac{b A}{a}-\frac{b A}{a} e^{2 a t}\right) u(t)=\frac{b A}{a}\left(1-e^{-a t}\right) u(t)
\end{aligned}
$$

If the characteristics root of the first-order system $s=-a<0$, this system is a stable system. When time $t$ approaches infinity, the exponential term of $\mathrm{c}(\mathrm{t})$ will become zero.

If the characteristic root $s=-a>0$, this system is an unstable system. When time $t$ approaches zero, the exponential term of $\mathrm{c}(\mathrm{t})$ will become infinity.

In case if initial value is not 0 , the system output is:

$$
\begin{aligned}
& C(s)=G(s) R(s)+\frac{c(0)}{s+a}=\frac{b A}{s(s+a)}+\frac{c(0)}{s+a}=\frac{b A / a}{s}+\frac{c(0)-b A / a}{s+a} \\
& \therefore \quad c(t)=\left(\frac{b A}{a}+\left(c(0)-\frac{b A}{a}\right) c^{-a t}\right) u(t)
\end{aligned}
$$

The following will discuss a very important term - Time Constant $T_{C}$

$$
T_{c}=\frac{1}{a}
$$

Time constant $\mathrm{T}_{\mathrm{C}}$ is the required time that the exponential component of system output $\mathrm{c}(\mathrm{t})$ decreases from $\mathrm{k} e^{-a t}$ to $\mathrm{k} e^{-1}$. If $\mathrm{c}(\infty)-\mathrm{c}(0)=1$ or $\mathrm{c}(\mathrm{t})-\mathrm{c}(0)=1$ and where $\mathrm{c}(0)=0$, time constant $\mathrm{T}_{\mathrm{C}}$ is defined as the time required for the response $\mathrm{c}(\mathrm{t})$ from 0 to $1-1 / \mathrm{e}=0.632$, as shown in figure 2-2.

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Figure 2-2 Time Constant of first- order system.
The system discussed above is the simplest first- order system. Now consider a complicated first- order system,

$$
\begin{equation*}
\frac{d c(t)}{d t}+a c(t)=b_{m} \frac{d^{m} r(t)}{d t^{m}}+\cdots+b_{1} \frac{d r(t)}{d t}+b_{0} r(t) \tag{2}
\end{equation*}
$$

Its transfer function can be expressed by

$$
G(s)=\frac{C(s)}{R(s)}=\frac{b_{m} s^{m}+\cdots b_{1} s+b_{0}}{s+a}
$$

In actual physical systems, infrequently the order of the numerator of transfer function is higher than that of dominator since the amplification increases as the frequency of signal increases. The order of system is determined by the order of the denominator. The following will discuss the steady- state gain and time constant of the system whose order of denominator equals that of numerator.

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Consider the system:

$$
\begin{aligned}
& \frac{d c(t)}{d t}+a c(t)=b_{2} \frac{d r(t)}{d t}+b_{0} r(t) \\
& C(s)=\frac{b_{2} s+b_{0}}{s+a} R(s)+\frac{c(0)+b_{1} r(0)}{s+a}
\end{aligned}
$$

The transfer function is then

$$
G(s)=\frac{C(s)}{R(s)}=\frac{b_{1} s+b_{0}}{s+a}=b_{1}+\frac{b_{0}-a b_{1}}{s+a}
$$

The block diagram is shown in figure 2-3.


Figure 2-3 Block diagram of first-order system.
For a known first-order system with undetermined coefficients, time constant and gain can be found from the input and output waveforms by applying a step signal to the input of the first-order system, and the system coefficients are thus obtained.

Suppose the input and output waveforms of the system as shown in figure 2-4.

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Figure 2-4 Step response of first-order system.
Let $v_{o} / v_{i}=\mathrm{K}$, the steady-state gain K is then

$$
K=\lim _{s \rightarrow 0} \frac{b}{s+a}=\frac{b}{a}
$$

Time constant $T_{C}$ can be measured from figure 2-4 because

$$
\begin{aligned}
& G(s)=\frac{K}{T_{c} s+1}=\frac{b}{s+a} \\
& \therefore T_{c}=\frac{1}{a}, a=\frac{1}{T_{c}}, b=\frac{K}{T_{c}}
\end{aligned}
$$

Where $K$ and $T_{C}$ can be obtained from input and output waveforms shown in figure 2-4. Therefore, the values of a and b are calculated using the determined K and $\mathrm{T}_{\mathrm{C}}$. In other words, system parameters can be determined from input and output waveforms.

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## 3- Procedures and Results:-

The following uses ACS-13008 Second order plant as a first- order system. The block diagram of ACS13008 is shown in figure 2-5.


Figure 2-5 Block diagram of ACS-13008
Complete the connection by refereeing to the block diagram and wiring diagram shown in figure 2-6.

(a) Wiring diagram

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(b) Wiring diagram

Figure 2-6.

## A- Effects of aT on first- order system

1- On ACS-13010, generate a $1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.
2- On ACS-13008, place $T$ selector switch in $x 10$ position, set $a=b=10$. In this case, the transfer function of ACS-13008 is expressed by

$$
\frac{V_{o}^{\prime}(s)}{V_{t}(s)}=\frac{100}{s+100}
$$

The steady-state gain K and Time constant $\mathrm{T}_{\mathrm{C}}$ are expressed as:

$$
G(s)=\frac{K}{T_{c} s+1}=\frac{b T}{s+a T}
$$

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$$
K=\frac{b T}{a T} \text { and } T_{c}=\frac{1}{a T} .
$$

Where
3- Using oscilloscope, measure and record the signals at ACS-13010 step+ output and ACS- $13008 V_{o}^{\prime}$ output terminals. Record the steady-state gain $\mathrm{K}=\frac{b T}{a T}$ and time constant $\mathrm{T}_{\mathrm{C}}$.

4- On ACS- 13008, modify a to 5 . The transfer function of ACS-13008 is then

$$
\frac{V_{o}^{\prime}(s)}{V_{i}(s)}=\frac{100}{s+50}
$$

5- Using oscilloscope measure and record the signals at ACS- 13010 step+ output and ACS- $13008 V_{o}^{\prime}$ output terminals. Compare the results of steps 4 and 5 for the speed of the response. Record the steady-state gain $\mathrm{K}=\frac{b T}{a T}$ and time constant $\mathrm{T}_{\mathrm{C}}$.

6- On ACS-13008, modify a to 1 (in order to increase system gain) and remain b unchanged. Using oscilloscope measure and record the signals at ACS-13010 step+ output and ACS- $13008 V_{o}^{\prime}$ output terminals. Compare the results with steps 4 and 5 for the speed of the response. Record the steady-state gain $\mathrm{K}=\frac{b T}{a T}$ and time constant $\mathrm{T}_{\mathrm{C}}$.

B- Effects of bT on first- order system
1- On ACS-13010, generate a $1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.
2- On ACS-13008, place T selector switch in x 10 position, set $\mathrm{a}=\mathrm{b}=10$. Thus the transfer function of ACS13008 is expressed as:

$$
\frac{V_{0}(s)}{V_{i}(s)}=\frac{100}{s+100} \equiv \frac{b T}{s+a T}
$$

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3- On ACS- 13008, modify b to 5 and remain a unchanged, so the transfer function of ACS-13008 becomes

$$
\frac{V_{o}^{\prime}(s)}{V_{t}(s)}=\frac{50}{s+100}
$$

4- Using oscilloscope measure and record the signals at ACS- 13010 step+ output and ACS-13008 $\mathrm{V}_{\mathrm{o}}^{\prime}$ output terminals. Compare the results with step 4 from part A for the speed of the response. Record the steady-state gain $K=\frac{b T}{a T}$ and time constant $T_{C}$.

5- On ACS- 13008, modify b to 1 and remain a unchanged. Using oscilloscope, measure and record the signals at ACS-13010 step+ output and ACS-13008 Vo output terminals. . Compare the results with (step 4 from part A and step 5from part B) for the speed of the response. Record the steady-state gain $K=\frac{b T}{a T}$ and time constant $\mathrm{T}_{\mathrm{C}}$.

## 4- Discussion:-

1- What is the effect of time constant on the response of first-order system?
2- What is the response of first- order system in time domain? Derive it.
3- What is the effect of increasing and decreasing bT on the response of first-order system.

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Lab. Supervisor: Assist. Prof. Dr. Yousif Ismail Al Mashhadany
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## Experimental Title:- Second- Order System

1- Summary:- 1- To understand the characteristics of the second order system.
.2- To observe the effect of damping rate on the second order system
3. To observe the effect of natural frequency on the second order system.

## 2- Introduction and Theory:-

A second-order system, with a second-order differential equation, in the general form
Can be expressed:

$$
\frac{d^{2} c(t)}{d t^{2}}+a_{1} \frac{d c(t)}{d t}+a_{0} c(t)=b_{n} \frac{d^{n} r(t)}{d t^{n}}+\cdots+b_{1} \frac{d r(t)}{d t}+b_{0} r(t)
$$

If we convert to Laplace

$$
\begin{equation*}
C(s)=\frac{b_{n} s^{n}+\cdots+b_{1} s+b_{0}}{s^{2}+a_{1} s+a_{0}} R(s)+\frac{K(s) R}{s^{2}+a_{1} s+a_{0}} \tag{1}
\end{equation*}
$$

The first term of $\mathrm{C}(\mathrm{s})$ is a zero-state component with a system response at zero initial value $(\mathrm{c}(0)=0)$. The second term is the zero-input component, with no input, the system response caused by the initial value of $\mathrm{c}(0)$. $\mathrm{K}(\mathrm{s})$ is a polynomial associated with the initial value.

When the initial value is zero, the transfer function of equation (1) is:

$$
G(s)=\frac{C(s)}{R(s)}=\frac{b_{n} s^{n}+\cdots+b_{1} s+b_{0}}{s^{2}+a_{1} s+a_{0}}
$$

In this experiment, a simple quadratic system will be considered. The transfer function of the simple quadratic system is as follows

$$
\begin{equation*}
G(s)=\frac{C(s)}{R(s)}=\frac{b_{0}}{s^{2}+a_{1} s+a_{0}} \tag{2}
\end{equation*}
$$

Equation (2) defines the simplest quadratic system. From this equation, it is very difficult to understand the effects of the coefficients $\mathrm{b} 0, \mathrm{a} 0$ and al on the system or system characteristics. For analytical convenience, the quadratic system is usually written in the form below

$$
\frac{C(s)}{R(s)}=\frac{\omega_{n}^{2}}{s^{2}+2 \zeta \omega_{n} s+\omega_{n}^{2}}
$$

If the natural frequency and damping ratio are known, then the characteristics of the second order system are obtained. The block diagram of the second order system is shown in Figure 3-1.

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Figure 3-1 Block diagram of second order system.
The transfer function of this system can be expressed as follows.

$$
\frac{G(s)}{1+G(s) H(s)}=\frac{\frac{\omega_{n}^{2}}{s\left(s+2 \omega_{n} s\right)}}{1+\frac{\omega_{n}^{2}}{s\left(s+2 \omega_{n} s\right)}}
$$

The dynamic behavior of the second order system can be defined using $\omega_{n}$ and $\varsigma$. In the following, the step input response of the second order system will be discussed.

1- Under Damp State: $0<\varsigma<1$
$\mathrm{C}(\mathrm{s}) / \mathrm{R}(\mathrm{s})$ if rewritten

$$
\frac{C(s)}{R(s)}=\frac{\omega_{n}^{2}}{\left(s+c \omega_{n}+j \omega_{d}\right)\left(s+c \omega_{n}-j \omega_{d}\right)}
$$

$$
\omega_{d}=\omega_{n} \sqrt{1-\zeta^{2}}
$$

Here
,it is called the damped natural frequency. For step input $u_{s}(\mathrm{t})$,

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$$
\begin{aligned}
C(s) & =\frac{1}{s} \frac{\omega_{n}^{2}}{\left(s+\zeta \omega_{n}+j \omega_{d}\right)\left(s+\zeta \omega_{n}-j \omega_{d}\right)} \\
& =\frac{1}{s}-\frac{s+s \omega_{n}}{\left(s+c \omega_{n}\right)^{2}+\omega_{d}^{2}}-\frac{\zeta \omega_{n}}{\left(s+\zeta \omega_{n}\right)^{2}+\omega_{d}^{2}}
\end{aligned}
$$

If inverse Laplace transformation of C (s) is taken

$$
\begin{aligned}
& c(t)=1-e^{-\zeta \omega_{1} t}\left(\cos \omega_{d} t+\frac{\varsigma}{\sqrt{1-\varsigma^{2}}} \sin \omega_{d} t\right) \\
& c(t)=1-\frac{e^{-\varsigma \omega_{n} t}}{\sqrt{1-\varsigma^{2}}} \sin \left(\omega_{d} t+\tan ^{-1} \frac{\sqrt{1-\varsigma^{2}}}{\varsigma}\right)
\end{aligned}
$$

From the above equation, it is seen that the second order system will oscillate at $\omega_{d}$ frequency.
2. Critical Damped Status: $\quad \varsigma=1$
$\mathrm{C}(\mathrm{s}) / \mathrm{R}(\mathrm{s})$ if rewritten

$$
\frac{C(s)}{R(s)}=\frac{\omega_{n}^{2}}{\left(s+\omega_{n}\right)^{2}}
$$

For step input $u_{s}(\mathrm{t})$,

$$
\begin{aligned}
& C(s)=\frac{1}{s} \frac{\omega_{n}^{2}}{\left(s+\omega_{n}\right)^{2}} \\
& C(s)=\frac{1}{s}-\frac{1}{\left(s+\omega_{n}\right)}-\frac{\omega_{n}}{\left(s+\omega_{n}\right)^{2}}
\end{aligned}
$$

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If inverse Laplace transformation of $C(s)$ is taken

$$
c(t)=1-e^{-\omega^{2} t}\left(1+\omega_{n} t\right)
$$

3. Extremely Damped Conditions:
(1) $\varsigma>1$

For step input us ( t ),

$$
C(s)=\frac{1}{s} \frac{\omega_{n}^{2}}{\left(s+\zeta \omega_{n}+\omega_{n} \sqrt{s^{2}-1}\right)\left(s+\zeta \omega_{n}-\omega_{n} \sqrt{s^{2}-1}\right)}
$$

If inverse Laplace transformation of $\mathrm{C}(\mathrm{s})$ is taken


$$
\begin{aligned}
& p_{1}=\left(\varsigma+\sqrt{\varsigma^{2}-1}\right) \omega_{n} \\
& p_{2}=\left(\varsigma-\sqrt{\varsigma^{2}-1}\right) \omega_{n}
\end{aligned}
$$

(2) $\varsigma \gg 1$

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$$
\begin{aligned}
p_{1} & =\left(s+\sqrt{s^{2}-1}\right) \omega_{n} \\
\because p_{2} & =\left(s-\sqrt{s^{2}-1}\right) \omega_{n} \\
\therefore\left|p_{1}\right| & \gg\left|p_{2}\right|
\end{aligned}
$$

$e^{-p 1_{t}}$ is negligible because $e^{-p 2_{t}}$ is too large for $e^{-p 1_{t}}$. In other words, if p 1 and p 2 are distant from each other and - p2 is very close to $\mathrm{j} \omega$ axis (figure $3-2$ ), $e^{-p 1_{t}}$ can be omitted.


Figure 3-2 Polar diagram.
As a result, if the mathematical equation is rewritten

$$
\frac{C(s)}{R(s)}=\frac{s \omega_{n}-\omega_{n} \sqrt{s^{2}-1}}{s+g \omega_{n}-\omega_{n} \sqrt{s^{2}-1}}=\frac{p_{2}}{s+p_{2}}
$$

On the other hand, if the quadratic system p 1 and p 2 are away from each other, this quadratic system may be approximately represented by a first order system.

4-Undamped Condition: $\varsigma=0$
$\mathrm{C}(\mathrm{s}) / \mathrm{R}(\mathrm{s})$ if rewritten

$$
\frac{C(s)}{R(s)}=\frac{\omega_{n}^{2}}{\left(s+j \omega_{n}\right)\left(s-j \omega_{n}\right)}=\frac{\omega_{n}^{2}}{s^{2}+\omega_{n}^{2}}
$$

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For step input us ( t ), the undamped system will continue to oscillate at constant amplitude.

$$
C(s)=\frac{1}{s} \frac{\omega_{n}^{2}}{s^{2}+\omega_{n}^{2}}=\frac{1}{s}-\frac{s}{s^{2}+\omega_{n}^{2}}
$$

If inverse Laplace transformation of $C(s)$ is taken

$$
c(t)=1-\cos \omega_{n} t
$$

Figure 3-3 shows step response curves for different $\varsigma$ values.


Figure 3-3 Step-by-step response of the second order system.
The basic characteristics of a second order system are discussed above. Below are the other characteristics of this system. For step input us ( t ),

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$$
\begin{aligned}
& C(s)=\frac{1}{s} \frac{\omega_{n}^{2}}{s^{2}+2 \zeta \omega_{n} s+\omega_{n}^{2}} \\
& c(t)=1-\frac{e^{-c \omega_{n} t}}{\sqrt{1-s^{2}}} \sin \left(\omega_{d} t+\tan ^{-1} \frac{\sqrt{1-s^{2}}}{\varsigma}\right)
\end{aligned}
$$

Derivative of $\mathrm{c}(\mathrm{t})$

$$
\begin{aligned}
\frac{d c(t)}{d t} & =-\frac{\zeta \omega_{n} e^{-\gamma \omega_{n} t}}{\sqrt{1-\varsigma^{2}}} \sin \left(\omega_{d} t+\tan ^{-1} \frac{\sqrt{1-\zeta^{2}}}{\zeta}\right) \\
& +\frac{e^{-c \omega_{0} t}}{\sqrt{1-\varsigma^{2}}} \omega_{n} \sqrt{1-\varsigma^{2}} \cos \left(\omega_{d} t+\tan ^{-1} \frac{\sqrt{1-\varsigma^{2}}}{\zeta}\right) \\
\therefore \frac{d c(t)}{d t}= & \frac{\omega_{n}}{\sqrt{1-\varsigma^{2}}} e^{-\zeta \omega_{n} t} \sin \omega_{n} \sqrt{1-\zeta^{2} t}
\end{aligned}
$$

If $\mathrm{dc}(\mathrm{t}) / \mathrm{dt}=0$

$$
t=\frac{n \pi}{\omega_{n} \sqrt{1-\varsigma^{2}}} \quad n=0,1,2, \cdots
$$

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$$
t=n \pi / \omega_{n} \sqrt{1-\varsigma^{2}}
$$

when $\mathrm{c}(\mathrm{t})$ is the local minimum or local maximum.

$$
\begin{aligned}
\left.c(t)\right|_{\min \text { or } \max } & =1+\frac{e^{-n \pi \zeta / \sqrt{1-\varsigma^{2}}}}{\sqrt{1-\varsigma^{2}}} \sin \left(n \pi-\tan ^{-1} \frac{\sqrt{1-\varsigma^{-2}}}{\varsigma}\right) \\
& =1+(-1)^{n-1} e^{-n \pi c} / \sqrt{1-\xi^{2}}
\end{aligned} n=0,1,2, \cdots .
$$

Maximum time, $t_{\max }$ occurs instantly

$$
t_{\max }=\frac{\pi}{\omega_{n} \sqrt{1-g^{2}}}
$$

$$
C_{\max }-1=e^{-\pi \zeta / \sqrt{1-\varsigma^{2}}}
$$

As a result, the maximum overshoot
The maximum overshoot is only dependent on the value $\varsigma$ and is independent of $\omega_{n}$. In other words, a certain $\varsigma$ value corresponds to a maximum exceeding.

$$
\left.t\right|_{\max \text { or } \min }=\frac{n \pi}{\omega_{n} \sqrt{1-\varsigma^{2}}} \quad n=0,1,2, \cdots
$$

Now, let's consider how to find the system parameters from the output signal. Consider a known second order system with the following transfer function.

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$$
\frac{C(s)}{R(s)}=\frac{B}{s^{2}+A s+B}
$$

Here, A and B are unknown coefficients. For step entry, if c ( $t$ ) has exceeded the output, the coefficients A and B can be obtained from the output peak $\mathrm{c}(\mathrm{t})$. The following steps are followed:

First compare the two systems.

$$
\frac{C(s)}{R(s)}=\frac{B}{s^{2}+A s+B} \quad \text { and } \quad \frac{C(s)}{R(s)}=\frac{\omega_{n}^{2}}{s^{2}+2 \zeta \omega_{n} s+\omega_{n}^{2}}
$$

If $A$ and $B$ are resolved,

$$
\begin{aligned}
A & =2 \omega_{n} \varsigma \\
B & =\omega_{n}^{2}
\end{aligned}
$$

Figure 3-4 shows the step response of the second order system.

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Figure 3-4 Second order system response.
Cmax, T1 and T2 can be obtained from the $\mathrm{c}(\mathrm{t})$ outlet. The value $\zeta$ can be obtained from the following equations.

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$$
\begin{aligned}
& C_{\max }-1=e^{-\pi / \sqrt{1-\zeta^{2}}} \\
& \frac{-\pi \zeta}{\sqrt{1-\zeta^{2}}}=\ln \left(C_{\max }-1\right) \\
& \pi^{2} \zeta^{2}=\left[\ln \left(C_{\max }-1\right)\right]^{2}-\left[\ln \left(C_{\max }-1\right)\right]^{2} \varsigma^{2} \\
& \quad \zeta^{2}=\left|\frac{\left[\ln \left(C_{\max }-1\right)\right]^{2}}{\pi^{2}+\left[\ln \left(C_{\max }-1\right)\right]^{2}}\right| \\
& \because \zeta \geq 0 \\
& \therefore \zeta=\sqrt{\left|\frac{\left[\ln \left(C_{\max }-1\right)\right]^{2}}{\pi^{2}+\left[\ln \left(C_{\max }-1\right)\right]^{2}}\right|}
\end{aligned}
$$

tmax and $\omega_{n}$, can be found from the following equations

$$
\begin{aligned}
& \because \quad t_{\max }=\frac{\pi}{\omega_{n} \sqrt{1-\xi^{2}}}=T_{1} \\
& \therefore \quad \omega_{n}=\frac{\pi}{t_{\max } \sqrt{1-\varsigma^{2}}}
\end{aligned}
$$

Constants A and B may be obtained using the following equations.

$$
\begin{aligned}
& A=2 \omega_{n} S \\
& B=\omega_{n}^{2}
\end{aligned}
$$

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## 3- Procedures and Results:-

## A- Effects of $\boldsymbol{\varsigma}$ on Second- Order System

1- Complete the connections by referring to the block diagram and wiring diagram shown in figure 3-5

(a) Block diagram

(b) Wiring diagram

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Figure 3-6.
2- On ACS- 13010, generate a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.
3- Since $\mathrm{bT}=\omega_{n}^{2}$ and $\mathrm{aT}=2 \omega_{n} 5$, a fixed value of bT is equivalent to a fixed value of $\omega_{n}$. In case of fixed bT value, a change in aT value is equivalent to a change in $\varsigma$ value. On ACS- 13008, set T selector switch in the x10 position, set b to $10\left(\omega_{n}=10\right)$, thus the transfer function of the system is given by

$$
G(s)=\frac{C(s)}{R(s)}=\frac{100}{s^{2}+a T s+100}
$$

4- Since $\omega_{n}=10, \mathrm{~T}=10$ and $\mathrm{aT}=2 \varsigma \omega_{n}$, thus $\mathrm{a}=2 \varsigma$. Remain b and T unchanged. On ACS-13008, set $\mathrm{a}=4(\varsigma=$ 2). Using oscilloscope, measure and record the signals at ACS-13010 step+ output and ACS- $13008 V_{o}$ output terminals.

5- Repeat step 4 for $\mathrm{a}=2,1,0(\varsigma=1,0.5,0)$ and record the results.
B- Effects of $\omega_{n}$ on Second- Order System
1- On ACS-13010, generate a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.
$2-$ Since $\mathrm{bT}=\omega_{n}^{2}$ and $\mathrm{aT}=2 \omega_{n} \zeta$, a and b will be varied by varying $\omega_{n}$. On ACS-13008, place T selector switch in x 10 position, set b to $10\left(\omega_{n}=10\right)$, set a to $0.4(\varsigma=0.2)$. Using oscilloscope, measure and record the signals at ACS- 13010 step+ output and ACS- $13008 V_{o}$ output terminals.

3- Repeat step2 for $\mathrm{a}=0.32$ and $\mathrm{b}=6.4\left(\varsigma=0.2, \omega_{n}=8\right)$ and record the result.
4- Repeat step2 for $\mathrm{a}=0.2$ and $\mathrm{b}=2.5\left(\varsigma=0.2, \omega_{n}=5\right)$ and record the result.
5- Repeat step2 for $\mathrm{a}=0.16$ and $\mathrm{b}=1.6\left(\varsigma=0.2, \omega_{n}=4\right)$ and record the result.
C- On ACS-13008, set arbitrary values of $\mathrm{a}, \mathrm{b}$ and T , and find the $\varsigma, \omega_{n}$ from the measured output response.

## 4- Discussion:-

1- What is the effect of $\varsigma$ on the response of second -order system?
2- What is the response of second- order system in time domain? Derive it.
3 - What is the effect of increasing and decreasing $\omega_{n}$ on the response of second-order system.

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## Notes

$\omega_{n-}$ is called natural frequency of oscillations.
$\omega_{\mathrm{d}}=\omega_{\mathrm{n}} \sqrt{1-\sigma^{2}}$ is called damping frequency oscillations.
8 -affects damping and called damping ratio.

Sourz- is called damping factor or actual damping or damping coecficient.

## Experimental Title:- Transient Response Specifications

## 1- Summary:-

1- To study the important specifications of transient response .
2- To measure the important specifications of transient response.

## 2- Introduction and Theory:-

Transient and steady-state responses of first- order and second- order systems have been discussed in the previous experiments. The important specifications of transient response required for evaluating a system's performance will be discussed in this experiment.

There are energy storage elements existing in actual physical systems so that the output cannot follow the input signal immediately or simply transient state. In designing a control system designers always wish to make the system response as quick as possible and with quite small error or without error. In order to evaluate a system's performance, some system specifications must be defined and used as the standards to evaluate system's performance.

In general, system specifications are defined by using the transient response to step input. Since the transient response to step input is affected by the initial conditions, a standard initial value must be defined. The standard initial value is that the system output and its derivative term are 0 . Under the situations of standard initial value and step input, the system specifications can be defined from the output response. Generally the most often used specifications include:

1- Delay time $t_{d} \quad$ 2- Rise time $t_{r} \quad$ 3- Peak time $t_{p} \quad$ 4- Maximum overshoot $M_{p} \% \quad$ 5- Settling time $t_{s}$

If the output of the system is $\mathrm{c}(\mathrm{t})$, the specifications above are defined as follows:
1- $t_{d}$ - Delay time
The delay time, $t_{d}$, is defined as the time required for the system $\mathrm{c}(\mathrm{t})$ from the initial value $\mathrm{c}(0)$ to $\mathrm{c}(\infty) / 2$, as shown in figure 4-1.

## 2- $t_{r}$-Rise time.

The rise time, $t_{r}$, is defined as the time required for the system $\mathrm{c}(\mathrm{t})$ from $10 \%$ to $90 \%$ of final value $\mathrm{c}(\infty)$, as shown in figure 4-2.

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Figure 4-1 Delay time $t_{d}$
Figure 4-2 Rise time $t_{r}$
3- $t_{p}$ - Peak time
The peak time, $t_{p}$, is defined as the time required for the system $\mathrm{c}(\mathrm{t})$ from initial value $\mathrm{c}(0)$ to peak value $C_{\max }$, as shown in figure 4-3.

4- $M_{p} \%$ - Percent maximum overshoot
$M_{p} \%$ is computed by subtracting the final value $\mathrm{c}(\infty)$ from the peak value $\mathrm{c}\left(t_{p}\right)$ of $\mathrm{c}(\mathrm{t})$ and dividing by the final value $\mathrm{c}(\infty)$, and then multiplying the result by 100 .
$M_{p} \%=\frac{\mathrm{c}\left(t_{p}\right)-\mathrm{c}(\infty)}{\mathrm{c}(\infty)} \times 100 \%$
The maximum overshoot is illustrated in figure 4-4.


Figure 4-3 Peak time $t_{p}$
Figure 4-4 Max. Overshoot $M_{p}$

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## 5- $t_{s}$ - Settling time

The settling time, $t_{s}$, is defined as the time required for the system $\mathrm{c}(\mathrm{t})$ from zero initial value $\mathrm{c}(0)$ to satisfy the following conditions. $\frac{\left|\mathrm{c}\left(t_{p}\right)-\mathrm{c}(\infty)\right|}{|\mathrm{c}(\infty)|}<2 \%$ or $5 \%, \quad \mathrm{t}>t_{s}$, The settling time is illustrated in figure 45.

(a) Settling time $t_{s}(2 \%)$
(b) Settling time $t_{s}(5 \%)$

Figure 4-5 Settling time $t_{s}$
The specifications of first- order and second- order systems are discussed as follows:
1- First- Order System

(1)Delay time $t_{d}$

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$$
\begin{gathered}
\frac{b}{a}\left(1-e^{-a / d}\right)=\frac{b}{2 a}\left(1-e^{-\infty}\right) \\
1-e^{+1 t_{d}}=0.5 \\
t_{d}=\frac{\ln (0.5)}{-a}
\end{gathered}
$$

(2) Rise time $t_{r}$


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As discussed above, we can find that the specifications of first -order system $t_{d}, t_{r}, t_{s}$ are related to only the pole $\mathrm{p}=-\mathrm{a}$ or time constant $T_{c}=1 / \mathrm{a}$. If the pole locations on the left- half s-plane and the locations is far from the origion(that is, small time constant $T_{c}$ ), the values of $t_{d}, t_{r}, t_{s}$ will be small and the speed of system response will be quick.

## 2- Second- Order System

Consider the following transfer function of a second- order system.


For a step input, system response (output response) is

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(1) Delay time $t_{d}$


If $\varsigma$ and $\omega_{n}$ are known, $t_{d}$ can be solved from the above equation.
(2) Rise time $t_{r}$


If $\varsigma$ and $\omega_{n}$ are known, $t_{1}$ and $t_{2}$ can be solved and then
$t_{r}=t_{1}-t_{2}$
(3)Peak time $t_{p}$. From previous experiments, we have

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(4) Percent maximum overshoot $M_{p} \%$. From previous experiments, we have
$M_{p}=e^{\sqrt{1-\varsigma^{2}}} \times 100 \%$
(5) Settling time $t_{s}$

$$
\text { (a) }\left|\begin{array}{c}
c\left(t_{,}\right)-c(\infty) \\
c(\infty)
\end{array}\right|<5 \%, t_{0} \approx 3 T=\frac{3}{5 \omega_{m}}
$$

(b)

$$
\left|\frac{c\left(x_{x}\right)-c(\infty)}{c(\infty)}\right|<2 \%, x,-4 \lambda=\frac{4}{s \omega_{\mu}}
$$

## 3- Procedures and Results:-

## A- First- Order System

The following uses ACS- 13008 Second Order Plant as a first- order system. The block diagram is shown in shown in figure 4-6.


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Figure 4-6 Block diagram of first- order system.

1- Complete the connections by referring to the block diagram and wiring diagram shown in figure 4-7


Figure 4-7.
2- On ACS- 13010, generate a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.

3- On ACS-13008, place $T$ selector switch in $x 10$ position, set $\mathrm{a}=\mathrm{b}=10$. In this case, the transfer function of ACS-13008 is expressed by
$\mathrm{G}(\mathrm{s})=\frac{C(s)}{R(s)}=\frac{100}{s+100}=\frac{b T}{s+a T}$
4- Using oscilloscope, measure and record the signals at ACS-13010 step+ output and ACS- $13008 V_{o}^{\prime}$ output terminals. Determine $t_{d}, t_{r}, t_{s}$ from the recorded output signals.
$t_{d}=\frac{\ln (0.5)}{-a}=\frac{-0.693}{-a T}=\frac{0.693}{100}=0.00693, t_{r}=\frac{2.2}{a T}=0.022, t_{s} \approx \frac{3}{a T}=0.03 \quad(5 \%)$
5- On ACS-13008, modify a to 5. Thus the transfer function of ACS-13008 becomes $\mathrm{G}(\mathrm{s})=\frac{100}{s+50}$
6- Using oscilloscope, measure and record the signals at ACS-13010 step+ output and ACS- $13008 V_{o}^{\prime}$ output terminals. Determine $t_{d}, t_{r}, t_{s}$ from the recorded output signals.

7- On ACS- 13008, modify b to 5 . The transfer function of ACS- 13008 is thus $\mathrm{G}(\mathrm{s})=\frac{50}{s+50}$
8- Using oscilloscope, measure and record the signals at ACS-13010 step+ output and ACS- $13008 V_{o}^{\prime}$ output terminals. Determine $t_{d}, t_{r}, t_{s}$ from the recorded output signals.

## B- Second Order- System

The following uses ACS- 13008 Second Order Plant as a second- order system. The block diagram is shown in figure 4-8.


Figure 4-8 Block diagram of second- order system.
1- Complete the connections by referring to the block diagram and wiring diagram shown in figure 4-9.

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(a) Block diagram


Figure 4-9.

## B1- Effects of $\boldsymbol{\varsigma}$ on Transient Response

1- On ACS-13010, generate a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.
2- Since $\mathrm{bT}=\omega_{n}^{2}$ and $\mathrm{aT}=2 \omega_{n} \zeta$, a fixed value of bT is equivalent to a fixed value of $\omega_{n}$. In case of fixed bT value, a change in aT value is equivalent to a change in $\varsigma$ value. On ACS- 13008, set T selector switch in the x10 position, set b to $10\left(\omega_{n}=10\right)$, thus the transfer function of the system is given by

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$\mathrm{G}(\mathrm{s})=\frac{C(s)}{R(s)}=\frac{100}{s^{2}+a T s+100}$
3- Since $\omega_{n}=10, \mathrm{~T}=10$ and $\mathrm{aT}=2 \varsigma \omega_{n}$, then $\mathrm{a}=2 \varsigma$. Remain b and T unchanged. On ACS-13008, set $\mathrm{a}=4(\varsigma=$ 2). Using oscilloscope, measure and record the signals at ACS- 13010 step+ output and ACS- $13008 V_{o}$ output terminals. Determine $t_{d}, t_{r}, t_{s}, t_{p}, M_{p}$ from the recorded output signals.

4- Repeat step 3 for $\mathrm{a}=2,1,0.4(\varsigma=1,0.5,0.2)$ and record the results. Determine $t_{d}, t_{r}, t_{s}, t_{p}, M_{p}$ from the recorded output signals.

5- For $\omega_{n}=10, \varsigma=0.5$ examples:
$\frac{e^{-0.5 \times 10 t_{d}}}{\sqrt{1-0.5^{2}}} \sin \left[10 \sqrt{1-0.5^{2}} t_{d}-\tan ^{-1} \frac{\sqrt{1-0.5^{2}}}{-0.5}\right]=$ Constant
When constant $=0.5$, compute $t_{d}=0.13$.
When constant $=0.1$, compute $t_{1}=0.05$. When constant $=0.9$, compute $t_{2}=0.21$ and $t_{r}=t_{2}-t_{1}=0.16$.
$t_{s} \approx \frac{3}{0.5 \times 10}=0.6, t_{p}=\frac{\pi}{10 \sqrt{1-0.5^{2}}}=0.36 . M_{p}=\frac{-0.5 \pi}{\sqrt{1-0.5^{2}}} \times 100 \%=16 \%$.

## B-2- Effects of $\omega_{\boldsymbol{n}}$ on Transient Response

1- On ACS-13010, generate a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the step+ output terminal.
$2-$ Since $\mathrm{bT}=\omega_{n}^{2}$ and $\mathrm{aT}=2 \omega_{n} 5$, a and b will be varied by varying $\omega_{n}$. On ACS- 13008 , place T selector switch in x 10 position, set b to $10\left(\omega_{n}=10\right)$, set a to $0.4(\varsigma=0.2)$. Using oscilloscope, measure and record the signals at ACS- 13010 step+ output and ACS- $13008 V_{o}$ output terminals. Determine $t_{d}, t_{r}, t_{s}, t_{p}, M_{p}$ from the recorded output signals.

3- Repeat step 2 for $\mathrm{a}=0.32$ and $\mathrm{b}=6.4\left(\varsigma=0.2, \omega_{n}=8\right)$ and record the result. Determine $t_{d}, t_{r}, t_{s}, t_{p}, M_{p}$ from the recorded output signals.

4- Repeat step2 for $\mathrm{a}=0.2$ and $\mathrm{b}=2.5\left(\varsigma=0.2, \omega_{n}=5\right)$ and record the result. Determine $t_{d}, t_{r}, t_{s}, t_{p}, M_{p}$ from the recorded output signals.

5- Repeat step2 for $\mathrm{a}=0.16$ and $\mathrm{b}=1.6\left(\varsigma=0.2, \omega_{n}=4\right)$ and record the result. Determine $t_{d}, t_{r}, t_{s}, t_{p}, M_{p}$ from the recorded output signals.

## 4- Discussion:-

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Compare between theoretical results and the practical obtained results for transient specifications values' including first- order and second- order systems.

## Experimental Title:- Steady- State Error

1- Summary:- 1- Examine the steady-state error of the output tray.
2- Measure the steady-state error from the response to different test inputs for different system types.

## 2- Introduction and Theory:-

For a control system, the difference between the steady-state output and the desired target is called the steadystate error, and the steady-state error is one of the criteria used to evaluate the performance of the control system. Most textbooks use mathematical methods to analyze and analyze a steady-state error in different system types.

1. We know from the control books that the system time response can be divided into two parts:
(1) Transient response
(2) Steady-state response

If c ( t$)$ represents the time response of a system, system response can be mathematically expressed as
$\mathrm{c}(\mathrm{t})=c_{t}(\mathrm{t})+\operatorname{css}_{t}(\mathrm{t})$. Here $c_{t}(\mathrm{t})$ represents the transient peak, $\operatorname{css}_{t}(\mathrm{t})$ represents the steady-state response.

## 2. Definitions of transient response and steady-state response:

(1) Transient response: The transient response is part of the system response. After a certain time, the temporary response disappears or decreases to 0 . Thus $c_{t}(\mathrm{t})$ can be expressed as: $\lim _{t \rightarrow \infty} c_{t}(\mathrm{t})=0$
(2) Steady-state response: After the transient response disappears, the rest is called the steady-state response $\operatorname{css}_{t}(\mathrm{t})$.
(3) Steady-state error: It is impossible for the output loop to be exactly the same as the input signal of the physical system. In the output response of a physical system, the transient response $c_{t}(\mathrm{t})$ is present. The

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transient response is part of the system dynamic behavior and the system characteristics play an important role in understanding. This experiment will focus on the issue of steady-state error.

When the transient response disappears, the system enters a steady-state operating state. A comparison between the steady-state response and the input signal indicates the accuracy of the system. If the input signal and the steady-state response are different, the difference between the two is called the steady-state error of the system.
(4) Commonly used test signals to analyze time response:
(1) Step Signal: The mathematical expression of the step signal is as follows:

$$
r(t)=\left\{\begin{array}{lll}
a & \text { if } & t \geq 0 \\
0 & \text { if } & t<0
\end{array}\right.
$$

$$
r(t)=a u(t)
$$

$$
R(s)=\frac{a}{s}
$$

If we convert it to the Laplace domain:
The step signal waveform is shown in Figure 5-1.


Figure 5-1 Step signal.
(2) Ramp signal: The mathematical expression of the ramp signal is as follows:

$$
r(t)=\left\{\begin{array}{lll}
a t & \text { if } t \geq 0 \\
0 & \text { if } t<0
\end{array} \quad r(t)=a t u(t)\right.
$$

or

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$$
R(s)=\frac{a}{s^{2}}
$$

If we convert it to the Laplace domain:
Ramp signal waveform is shown in Figure 5-2.


Figure 5-2 Ramp signal Figure
(3) Parabolic signal: The mathematical expression of the parabolic signal is as follows:
$r(t)=\left\{\begin{array}{cc}\frac{a}{2} t^{2} & \text { if } t \geq 0 \\ 0 & \text { if } t<0\end{array}\right.$

$$
r(t)=\frac{\pi}{2} t^{2} u(t)
$$

or

$$
R(s)=\frac{a}{s^{3}}
$$

If we convert it to the Laplace domain:
The parabolic signal waveform is shown in Figure 5-3. The three signals mentioned above can be easily analyzed using Laplace transform. The Laplace transform is a useful tool in assessing system performance.
5. Most of the actual physical systems have a steady-state error due to the inherent friction and other factors inherent in real physical systems. When designing a control system, errors must be reduced or minimized within acceptable limits.
6. Causes of steady-state error:
(1) Steady-state error due to non-linear factors: The steady-state error of most physical systems results from non-linear characteristics of the system, such as friction, saturation, dead zone, and recoil. A detailed analysis of the non-linear system error is highly complex and is beyond the scope of this experiment.

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(2) Steady-state error in linear systems: In a linear system, there is a close relationship between steady-state error, system type and input signal. Different system types and different input signals will produce different steady state errors. First, consider the system type definition. Consider the block diagram of the control system shown in Figure 5-4.


Figure 5-4 Block diagram of the control system

G (s) H (s) can be expressed as:

$$
G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{s^{j}\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)}
$$

The system type is determined by j without considering $\mathrm{m}, \mathrm{n}$ and K . The relationship between system type and j is listed in the following table

| $\mathbf{j}$ | System Type |
| :---: | :---: |
| 0 | 0 (type 0 system) |
| 1 | 1 (type 1 system) |
| $\vdots$ | $\vdots$ |

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For example,

$$
G(s) H(s)=\frac{E(s+s)}{s(1+s)(2+s)} j=1
$$

type 1 system, Once we understand the system type definition, we will now address the $\mathrm{E}(\mathrm{s})$ or $\mathrm{e}(\mathrm{t})$ error. From the block diagram in Figure 5-4,

$$
e(t)=r(t)-b(t)
$$

If we convert to Laplace

$$
\begin{aligned}
E(s) & =R(s)-B(s) \\
& =R(s)-C(s) H(s) \\
& =R(s)-E(s) G(s) H(s) \\
& \therefore E(s)=\frac{R(s)}{1+G(s) H(s)}
\end{aligned}
$$

Steady-state error ess is defined as follows:

$$
\begin{aligned}
e_{s s} & =\lim _{t \rightarrow \infty} e(t) \\
& =\lim _{s \rightarrow 0} s E(s) \\
& =\lim _{s \rightarrow 0} \frac{s R(s)}{1+G(s) H(s)}
\end{aligned}
$$

The effects of the input signal and the system type on the steady-state will be discussed as follows:

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(i) Steady-state error due to step input. The step input signal is expressed as follows

$$
R(s)=\frac{a}{s} \quad \text { or } \quad r(t)=a u(t)
$$

The step error constant KP is defined as follows:

$$
\begin{aligned}
& K_{p}=\lim _{s \rightarrow 0} G(s) H(s) \\
& e_{a}=\lim _{s \rightarrow 0} \frac{s R(s)}{1+G(s) H(s)}=\lim _{s \rightarrow 0} \frac{a}{1+G(s) H(s)}=\frac{a}{1+\lim _{s \rightarrow 0} G(s) H(s)}=\frac{a}{1+K_{p}}
\end{aligned}
$$

(a) Type 0 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)} \\
& K_{p}=\lim _{s \rightarrow 0} G(s) H(s)=K \\
& e_{n s}=\frac{a}{1+K_{p}}=\frac{a}{1+K}
\end{aligned}
$$

This shows that the type 0 system has a steady-state error resulting from the structure of the step input.
(b) Type 1 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{2} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{s\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)} \\
& K_{N}=\lim _{s \rightarrow 0} G(s) H(s)=\infty \\
& e_{s}=\frac{a}{1+K_{p}}=\frac{a}{1+\infty}=0
\end{aligned}
$$

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This indicates that the step input loop of the type 1 system does not have a steady-state error.
(c) Type 2 system

$$
G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{s^{2}\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)}
$$

$$
K_{p}=\lim _{s \rightarrow 0} G(s) H(s)=\infty
$$

$$
e_{s s}=\frac{a}{1+K_{p}}=\frac{a}{1+\infty}=0
$$

This shows that the step input of the type 2 system does not have a steady-state error.
(ii) Steady-state error due to ramp entry: The ramp input signal is expressed as follows.

$$
R(s)=\frac{a}{s^{2}} \quad \text { or } \quad r(t)=a t u(t)
$$

Ramp fault constant KV is defined as follows:

$$
\begin{aligned}
& K_{v}=\lim _{s \rightarrow 0} s G(s) H(s) \\
& e_{s}=\lim _{s \rightarrow 0} \frac{s R(s)}{1+G(s) H(s)}=\lim _{s \rightarrow 0} \frac{a}{s+s G(s) H(s)}=\frac{a}{K_{s}}
\end{aligned}
$$

(a) Type 0 system

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$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)} \\
& K_{s}=\lim _{\min _{0}} s G(s) H(s)=0 \\
& a_{s}=\frac{a}{K_{r}}=\infty
\end{aligned}
$$

This means that the output of the type 0 system cannot follow the ramp input.Therefore, the steady-state error will increase over time.
(b) Type 1 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{t} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{s\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)} \\
& K_{v}=\lim _{s \rightarrow 0} s G(s) H(s)=K \\
& c_{u}=\frac{a}{K_{v}}=\frac{a}{K}
\end{aligned}
$$

This shows that the type-1 ramp input of the type 1 system has a steady-state error due to its structure.
(c) Type 2 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{1} s\right)(1}{s^{2}\left(1+b_{1} s\right)(1} \\
& K_{p}=\lim _{s \rightarrow 0} s G(s) H(s)=\infty \\
& e_{e}=\frac{a}{K_{n}}=\frac{a}{\infty}=0
\end{aligned}
$$

This indicates that the ramp input response of the type 2 system does not have a steady-state error.
(iii) Steady-state error due to parabolic input. The parabolic input signal is expressed as follows.

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$$
R(s)=\frac{a}{s^{3}} \quad \text { or } \quad r(t)=\frac{a}{2} t^{2} u(t)
$$

Parabolic error constant Ka is defined as

$$
\begin{aligned}
& K_{\sim}=\lim _{x \rightarrow 0} s^{2} G(s) H(s) \\
& \ell_{s}-\lim _{x \rightarrow 0} \frac{s R(s)}{1+G(s) H(s)}-\lim _{x \rightarrow 0} \frac{a}{s^{2}+s^{2} G(s) H(s)}-\frac{a}{K_{A}}
\end{aligned}
$$

(a) Type 0 system
$G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)}$
$K_{a}=\lim _{s \rightarrow 0} s^{2} G(s) H(s)=0$
$c_{s a}=\frac{a}{K_{a}}=\infty$

This indicates that the output of the type 0 system cannot follow the parabolic input and that the steady-state error will increase over time.
(b)Type 1 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdot \cdot\left(1+a_{n} s\right)}{s\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdot\left(1+b_{m} s\right)} \\
& K_{\phi}=\lim _{s \rightarrow 0} s^{2} G(s) H(s)=0 \\
& c_{s s}=\frac{a}{K_{a}}=\infty
\end{aligned}
$$

This indicates that the output of the type 1 system cannot follow the parabolic input and that the steady-state error will increase over time.

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(c) Type 2 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{s^{2}\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)} \\
& K_{a}=\lim _{\rightarrow 0} s^{2} G(s) H(s)=K \\
& e_{m}=\frac{a}{K_{n}}=\frac{a}{K}
\end{aligned}
$$

This shows that the parabolic input response of the type 2 system has a natural steady-state error.
(d) Type 3 system

$$
\begin{aligned}
& G(s) H(s)=\frac{K\left(1+a_{1} s\right)\left(1+a_{2} s\right) \cdots\left(1+a_{n} s\right)}{s^{3}\left(1+b_{1} s\right)\left(1+b_{2} s\right) \cdots\left(1+b_{m} s\right)} \\
& K_{a}=\lim _{s \rightarrow 0} s^{2} G(s) H(s)=\infty \\
& e_{s s}=\frac{a}{K_{a}}=\frac{a}{\infty}=0
\end{aligned}
$$

This shows that the parabolic input response of the type 3 system does not have a steady-state error.
The explanations above can be summarized as follows:


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| 3 | $\infty$ | $\infty$ | $\infty$ | 0 | 0 | 0 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |

## 3- Procedures and Results:-

(A) The block diagram of the type 0 system is shown in Figure 5-5.


Figure 5-5 Block diagram of Type 0 system

## A-1. Step input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-6.

(a) Block diagram

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(b) Wiring Diagram

Figure 5-6
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS-13010 STEP + output terminal.
3. At ACS-13008, set the selector switch T to x 10 , set $\mathrm{a}=\mathrm{b}=10$. Thus the transfer function of the ACS-13008 is expressed as follows:

$$
G(s)=\frac{V_{0}(s)}{V_{s}(s)}=\frac{b T}{s+a T}=\frac{100}{s+100}
$$

This system is a type 0 system with step input and the steady-state error is expressed by the following equation:

$$
e_{s t}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100}{s+100}} \frac{1}{s}=0.5
$$

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4. Using the oscilloscope, measure and record the signals on the ACS-13010 STEP + output and ACS-13001 Vol output terminals. Observe the steady-state error ess to see if it is stable.
5. In ACS-13008, set $a=20$ and $b=10$. Repeat step 4 and obtain the result. Observe the steady-state error ess to see if it matches the theoretical value.

## A-2. Ramp input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-7.

(a) Block diagram

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## (b) Wiring diagram.

Figure 5-7.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS- 13010 output terminal.
3. In ACS-13008, set the T selector switch to $\mathrm{x} 10, \mathrm{a}=\mathrm{b}=10$. Thus, the transfer function of ACS-13008 is expressed as follows:

$$
G(s)=\frac{V_{0}(s)}{V_{1}(s)}=\frac{b T}{s+a T}=\frac{100}{s+100}
$$

This system is type 0 system with ramp input and steady-state error is expressed by the following equation:

$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100}{s+100}} \frac{1}{s^{2}}=\infty
$$

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4. Using the oscilloscope, measure and record the signals on the ACS-13010 RAMP output and ACS-13001 Vol output terminals.
5. On ACS-13008, make $\mathrm{a}=20$ and $\mathrm{b}=10$. Repeat step 4 and get the result. Observe the steady-state error ess to see if it matches the theoretical value.

## A-3. Parabolic input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-8.

(a) Block diagram


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(b) Wiring diagram

Figure 5-8.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS-13010 output terminal.
3. At ACS-13008, set the selector switch T to x 10 , set $\mathrm{a}=\mathrm{b}=10$. Thus, the transfer function of the ACS13008 is expressed as follows:

$$
G(s)=\frac{V_{0}(s)}{V_{1}(s)}=\frac{b T}{s+a T}=\frac{100}{s+100}
$$

This system is type 0 system with parabolic input and steady-state error is expressed by the following equation:

$$
e_{x z}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100}{s+100}} \frac{1}{s^{3}}=\infty
$$

4. Using the oscilloscope, measure and record the signals at the ACS-13010 PARABOLIC and ACS-13001 Vo1 output terminals. Observe the steady-state error ess to see if it increases over time.
5. In ACS-13008, set $\mathrm{a}=20$ and $\mathrm{b}=10$. Repeat step 4 and obtain the result. Observe the steady-state error ess to see if it matches the theoretical value.

B- Type 1 system
The block diagram of the type 1 system is shown in Figure 5-9.


Figure 5-9 Block diagram of Type 1 system.

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## B-1. Step input

1. Make the necessary connections by using the block and connection diagrams shown in Figure 5-10.

## ACS-13001

ACS-13010

(a) Block diagram

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(b) Wiring diagram.

Figure 5-10.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS- 13010 output terminal.
3. On the ACS-13008, set the selector switch T to $\mathrm{x} 10, \mathrm{a}=\mathrm{b}=10$. Thus the ACS-13008's transfer function:

$$
G(s)=\frac{V_{0}(s)}{V_{i}(s)}=\frac{b T}{s+a T} \frac{1}{s}=\frac{100}{s^{2}+100 s}
$$

This system is a type 1 system with step input. Steady-state error is expressed by the following equation:

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$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100}{s^{2}+100 s}} \frac{1}{s}=0
$$

4. Using the oscilloscope, measure and record the signals on the ACS-13010 STEP + output and ACS-13001 Vol output terminals. Observe the steady-state error ess to see if it is equal to zero.
5. In ACS-13008, set $\mathrm{a}=20$ and $\mathrm{b}=10$. Repeat step 4 and get the result. Observe the steady-state error ess to see if it matches the theoretical value.

## B-2. Ramp input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-11.

(a) Block diagram

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(b) Wiring diagram

Figure 5-11.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS- 13010 output terminal.
3. In ACS-13008, set the $T$ selector switch to $\mathrm{x} 10, \mathrm{a}=\mathrm{b}=10$. Thus, the transfer function of the ACS-13008 is expressed as follows:

$$
G(s)=\frac{V_{0}(s)}{V_{i}(s)}=\frac{b T}{s+a T} \frac{1}{s}=\frac{100}{s^{2}+100 s}
$$

This system is type 1 system with ramp input. The steady-state error is expressed by the following equation:

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$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100}{s^{2}+100 s} s^{2}}=1
$$

4. Using the oscilloscope, measure and record the signals on the ACS-13010 RAMP output and ACS-13001 Vol output terminals. Observe the steady-state error ess to see if it is stable.
5. In ACS-13008, set $a=20$ and $b=10$. Repeat step 4 and obtain the result. Observe the steady-state error ess to see if it matches the theoretical value.

## B-3. Parabolic input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-12.

(a) Block diagram

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(b) Wiring diagram

Figure 5-12.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS- 13010 output terminal.
3. In ACS-13008, set the T selector switch to $\mathrm{x} 10, \mathrm{a}=\mathrm{b}=10$. Thus, the transfer function of the ACS-13008 is expressed as follows:

$$
G(s)=\frac{V_{0}(s)}{V_{1}(s)}=\frac{b T}{s+a T} \frac{1}{s}=\frac{100}{s^{2}+100 s}
$$

This system is a type 1 system with parabolic input. The steady-state error is expressed by the following equation:

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$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100}{s^{2}+100 s} s^{3}}=\infty
$$

4. Using the oscilloscope, measure and record the signals on the ACS-13010 PARABOLIC output and ACS13001 Vol output terminals. Observe the steady-state error ess to see if it increases over time.
5. In ACS-13008, set $a=20$ and $b=10$. Repeat step 4 and obtain the result. Observe the steady-state error ess to see if it matches the theoretical value.

## C. Type 2 System

The block diagram of the type 2 system is shown in Figure 5-13.


## C-1. Step input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-14.

(a) Block diagram

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(b) Wiring diagram

Figure 5-14.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS-13010 STEP + output terminal.
3. In the ACS 13009, set the T selector switch to x 10 , set z to 0.1 and set p to 1 .
4. Set the selector switches on ACS-13006 (1) and ACS-13006 (2) to the positions shown in the following table.

| Selector Switch | ACS-13006(1) | ACS-13006(2) |
| :---: | :---: | :---: |
| T | $\times \mathbf{1}$ | $\times \mathbf{1 0}$ |
| I.C. | $\mathbf{0}$ | $\mathbf{0}$ |
| SYNC | OP | OP |

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The transfer function of this system is as follows:

$$
G(s)=\frac{V_{o}(s)}{V_{i}(s)}=\frac{1}{s} \frac{s+1}{\frac{s}{10}+1} \frac{10}{s}=\frac{100 s+100}{s^{3}+10 s^{2}}
$$

This system is type 2 system with step input. The steady-state error is expressed by the following equation:

$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{s \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100 s+100}{s^{3}+10 s^{2}}} \frac{1}{s}=0
$$

5. Using the oscilloscope, measure and record the signals on the ACS-13010 STEP + output and ACS-13001 Vol output terminals. Observe the steady-state error ess to see if it is equal to zero.

## C-2. Ramp input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-15.

(a) Block diagram

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(b) Wiring diagram

Figure 5-15.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS-13010 STEP + output terminal.
3. In the ACS 13009, set the T selector switch to x 10 , set z to 0.1 and p to 1 .
4. Set the selector switches on ACS-13006 (1) and ACS-13006 (2) to the positions shown in the following table:

| Selector Switch | ACS-13006(1) | ACS-13006(2) |
| :---: | :---: | :---: |
| T | $\times \mathbf{1}$ | $\times \mathbf{1 0}$ |
| I.C. | $\mathbf{0}$ | $\mathbf{0}$ |
| SYNC | OP | OP |

The transfer function of this system is as follows:

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$$
G(s)=\frac{V_{0}(s)}{V_{1}(s)}=\frac{1}{\frac{s}{s} \frac{s}{s}+1} \frac{10}{s}=\frac{100 s+100}{s^{3}+10 s^{2}}
$$

This system is type 2 system with ramp input. Steady-state error is expressed by the following equation:

$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{z \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100 s+100}{s^{3}+10 s^{2}} s^{2}}=0
$$

5. Using the oscilloscope, measure and record signals on the ACS-13010 RAMP output and ACS-13001 Vo1 output terminals. Observe the steady-state error ess to see if it is equal to zero.

## C-3. Parabolic input

1. Make the necessary connections using the block and connection diagrams shown in Figure 5-16.


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(b) Wiring diagram

Figure 5-16.
2. Produce a $0.1 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square waveform at the ACS-13010 STEP + output terminal.
3. In the ACS 13009 , set the T selector switch to x 10 , set z to 0.1 and set p to 1 .
4. Set the selector switches on ACS-13006 (1) and ACS-13006 (2) to the positions shown in the following table:


The transfer function of this system is as follows

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$$
G(s)=\frac{V_{0}(s)}{V_{i}(s)}=\frac{1}{s} \frac{s+1}{\frac{s}{10}+1} \frac{10}{s}=\frac{100 s+100}{s^{3}+10 s^{2}}
$$

This system is type 2 system with parabolic input. Steady-state error is expressed by the following equation:

$$
e_{s s}=\lim _{s \rightarrow 0} s E(s)=\lim _{x \rightarrow 0} s \frac{1}{1+G(s)} R(s)=\lim _{s \rightarrow 0} s \frac{1}{1+\frac{100 s+100}{s^{3}+10 s^{2}}} \frac{1}{s^{3}}=0.09
$$

5. Using the oscilloscope, measure and record the signals on the ACS-13010 PARABOLIC output and ACS13001 Vo1 output terminals. Observe the steady-state error ess to see if it is stable.

## 4- Discussion:-

Compare between theoretical steady - state error's results and the practical steady-state error's obtained results for type ( 0,1 and 2 ) systems whenever applying step, ramp and parabolic signals for each

## Experimental Title:- System Simulation

1- Summary:- 1- To learn how to describe a physical system using differential equation.
2- To find the solutions of the differential equation in order to understand the characteristics of physical systems.

3- To observe the output response of control system using ACS- 1000 Analog Control System.

## 2- Introduction and Theory:-

Figure 6-1 shows a typical spring- mass- damper system.


Figure 6-1 Typical spring-mass- damper system.
The spring force is $-\mathrm{ky}(\mathrm{t})$ and damping force is $-\mathrm{c} \dot{y}$. In view of force, the system of figure 6-1 can be expressed as shown in figure 6-2.


Figure 6-2 Typical spring- mass- damper system in view of force

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According to Newton's second law, yields

$$
\sum_{i} F_{t}(t)=m \dot{j}(t)
$$

$f_{i}(t)$ Includes spring force $k y(t)$, damping force $c \dot{y}(t)$ and external force $F(t)$. Thus

$$
\begin{equation*}
F(t)-k y(t)-c \dot{c}(t)=m \dot{y}(t) \tag{1}
\end{equation*}
$$

Eq.(1) can be rewritten as

$$
\begin{equation*}
m \ddot{y}(t)+c \dot{y}(t)+k y(t)=F(t) \tag{2}
\end{equation*}
$$

When $\mathrm{F}(\mathrm{t}) \neq 0$, Eq.(2) is called the nonhomogeneous differential equation. To find the solution of this differential equation, follow these steps:

## 1- Find Homogeneous Solution

The differential equation of Eq.(2) is called the homogeneous differential equation when $\mathrm{F}(\mathrm{t})=0$; that is,

$$
m \ddot{y}(t)+c \dot{y}(t)+k y(t)=0
$$

The characteristic equation is

$$
m \lambda^{2}+c \lambda+k=0
$$

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The roots of characteristic equation are:

$$
\lambda_{1,2}=\frac{-c \pm \sqrt{c^{2}-4 m k}}{2 m}
$$

Thus homogeneous solution may be one of the following three cases:
(1) $c^{2}-4 m k>0$ or $c^{2}>4 m k$

The roots $\lambda_{1}, \lambda_{2} \in \mathrm{R}$ and $\lambda_{1} \neq \lambda_{2}$, the homogeneous solution is:

$$
y_{h}(t)=a_{1} e^{\lambda_{1} t}+a_{2} e^{k_{2} t}
$$

(2) $c^{2}-4 m k=0$ or $c^{2}=4 m k$

The roots $\lambda_{1}, \lambda_{2} \in \mathrm{R}$ and $\lambda_{1}=\lambda_{2}=\lambda$, the homogeneous solution is:

$$
y_{h}(t)=\left(a_{1}+a_{2} t\right) e^{k t}
$$

## (3) $c^{2}-4 m k<0$ or $c^{2}<4 m k$

The roots $\lambda_{1}, \lambda_{2} \in \mathrm{C}$ and $\lambda_{1} \neq \lambda_{2}$, if $\lambda_{1,2},=\mathrm{p} \pm \mathrm{iq}$, the homogeneous solution is then:

$$
y_{k}(t)=e^{p t}\left(a_{1} \cos q t+a_{2} \sin q t\right)
$$

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$a_{1}, a_{2}$ in the homogeneous solutions above are the constant coefficients depending on the initial values $y(0)$, $\dot{y}(0)$.

## 2. Find particular Solution $y_{p}(\mathrm{t})$

The relationship between the specific solution $y_{p}(t)$ and $\mathrm{F}(\mathrm{t})$ is shown in the table below.


As can be seen from the table, the particular solution $y_{p}(\mathrm{t})$ consists of $\mathrm{F}(\mathrm{t})$ and the differentiation term of $\mathrm{F}(\mathrm{t})$.

## 3. Complete Solution

Adding the homogeneous solution $y_{h}(\mathrm{t})$ to particular solution $y_{p}(\mathrm{t})$, yields: $\mathrm{y}(\mathrm{t})=y_{h}(\mathrm{t})+y_{p}(\mathrm{t})$
Mathematical method was used to find the solutions of a non-homogeneous differential equation. In the following section, control blocks of the ACS-1000 Analog Control System will be used to solve the second order differential equation. In essential, the analog control system is an analog computer; therefore we transfer differential equation to the state diagram. The state diagram of Eq.(2) is shown in figure 6-3.


Figure 6-3 State diagram of typical spring- mass- damper system.
This state diagram can be expressed in block diagram form as shown in Figure 6-4.

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Figure 6-4 Block diagram of typical spring-mass-damping system

## 3- Procedures and Results:-

To use the ACS-1000 control blocks, the block diagram in figures 6-4 is redrawn as shown in Figure 6-5.


Figure 6-5 Block diagram.
Make the necessary connections according to the block and wiring diagrams shown in Figure 6-6.

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(a) Block diagram.


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(b) Wiring diagram.

Figure 6-6.

## A. Find Homogeneous Solution: $F(t)=0$

1. On the ACS-13010, set the AMP control knob to produce a square wave of 0 V at the $\mathrm{STEP}+$ output terminal. That is, $\mathrm{F}(\mathrm{t})=0$.
2. Set the ACS-13006 (1) and ACS-13006 (2) selector switches as follows:

3. On ACS-13005, set K to $1(\mathrm{~m}=1)$. Proceed to the following cases:

## A-1. $c^{2}-4 m k>0$ or $c^{2}>4 m k, F(t)=0$

(1) In this case, the ACS-13006 (1) is used as the master block of the two integrators. To set these two integrators to the initial mode, set the SYNC switch to INI.C and set the initial values of the two integrators to $0 \mathrm{~V}(\mathrm{y}(0)=0, \dot{y}(0)=0)$.
(2) In ACS-13007, set K to $3(\mathrm{c}=3)$. In ACS-13007A, set the K to $1(\mathrm{k}=1)$. Thus, the system satisfy $c^{2}>$ 4 mk . Record the c and k values $(\mathrm{m}=1)$.
(3) Find the values of $a_{1}, a_{2}, \lambda_{1} \lambda_{2}$ by substituting the recorded values $\mathrm{c}, \mathrm{m}, \mathrm{k}, \mathrm{y}(0)$ and y '( 0 ) into the characteristic equation and differential equation. Plot $y_{h}(\mathrm{t})$ waveform according to the equation:

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$$
y_{h}(t)=a_{1} e^{\lambda_{t} t}+a_{2} e^{\lambda_{2} t}
$$

(4) In ACS-13006 (1), set the SYNC switch to OP. Using the oscilloscope, measure and record the signals on the ACS-13010 STEP + output and ACS-13006 (2) Vo output terminals. Compare the result with the plotted $\mathrm{y}(\mathrm{t})$ in Step (3). Do they agree with each other?
(5) Changing initial value
(a) Set the SYNC switch to INI.C at ACS-13006 (1). Set the initial value of ACS-13006 (2) to $+5 \mathrm{~V}(\mathrm{y}(0)=$ 5) and the initial value of ACS-13006 (1) to $0 \mathrm{~V}(\dot{y}(0)=0)$. Repeat steps (2) to (4) and record the result.
(b) Set y $(0)=-5, \dot{y}(0)=0$. Repeat steps 2 to 4 and record the results.

## A-2. $c^{2}-4 m k=0$ or $c^{2}=4 m k, F(t)=0$

(1) In this case, the ACS-13006 (1) is used as the master block of the two integrators. To set these two integrators to the initial mode, set the SYNC switch to INI.C and set the initial values of the two integrators to $0 \mathrm{~V}(\mathrm{y}(0)=0, \dot{y}(0)=0)$.
(2) In ACS-13007, set K to $2(\mathrm{c}=2)$. In ACS-13007A, set K to $1(\mathrm{k}=1)$. These make the system satisfy $c^{2}$ $=4 \mathrm{mk}$. Record the values of c and $\mathrm{k}(\mathrm{m}=1)$.
(3)Find the values of $a_{1}, a_{2}, \lambda$ by substituting the recorded values $\mathrm{c}, \mathrm{m}, \mathrm{k}, \mathrm{y}(0)$ and y ' $(0)$ into the characteristic equation and differential equation. Plot $y_{h}(\mathrm{t})$ waveform according to the equation:

$$
y_{h}(t)=\left(a_{1}+a_{2} t\right) e^{d t}
$$

(4) In ACS-13006 (1), set the SYNC switch to OP. Using the oscilloscope, measure and record the signals on the ACS-13010 STEP + output and ACS-13006 (2) Vo output terminals. Compare the result with the plotted $y(t)$ in step (3). Do they agree with each other?
(5) Changing initial value

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(a) Set the SYNC switch to INI.C at ACS-13006 (1). Set the initial value of ACS-13006 (2) to $+5 \mathrm{~V}(\mathrm{y}(0)=$ 5) and the initial value of ACS-13006 (1) to $0 \mathrm{~V}(\dot{y}(0)=0)$. Repeat steps 2 to 4 and record the result.
(b) Set $\mathrm{y}(0)=-5, \dot{y}(0)=0$. Repeat steps 2 to 4 and record the result.

## A-3. $c^{2}-4 m k<0$ or $c^{2}<4 m k, F(t)=0$

(1) In this case, the ACS-13006 (1) is used as the master block of the two integrators. To set these two integrators to the initial mode, set the SYNC switch to INI.C and set the initial values of the two integrators to $0 \mathrm{~V}(\mathrm{y}(0)=0,) \cdot \dot{y}(0)=0)$.
(2) In ACS-13007, set K to $1(\mathrm{c}=1)$. In ACS-13007A, set K to $1(\mathrm{k}=1)$. Thus, the system satisfy $c^{2}<4 \mathrm{mk}$. Record the c and k values $(\mathrm{m}=1)$.
(3)Find the values of $a_{1}, a_{2}, \lambda_{1,2}=p \pm i q$ by substituting the recorded values $\mathrm{c}, \mathrm{m}, \mathrm{k}, \mathrm{y}(0)$ and $\mathrm{y}{ }^{\prime}(0)$ into the characteristic equation and differential equation. Plot $y_{h}(\mathrm{t})$ waveform according to the equation:

$$
y_{h}(t)=e^{p t}\left(a_{1} \cos q t+a_{2} \sin q t\right)
$$

(4) In ACS-13006 (1), set the SYNC switch to OP. Using the oscilloscope, measure and record the signals on the ACS-13010 STEP + output and ACS-13006 (2) Vo output terminals. Compare the result with the plotted $\mathrm{y}(\mathrm{t})$ in Step (3). Do they agree with each other?
(5) Changing initial value
(a) Set the SYNC switch to INI.C at ACS-13006 (1). Set the initial value of ACS-13006 (2) to $+5 \mathrm{~V}(\mathrm{y}(0)=$ 5) and the initial value of ACS-13006 (1) to $0 \mathrm{~V}(\dot{y}(0)=0)$. Repeat steps 2 to 4 and record the result.
(b) Set y $(0)=-5, \dot{y}(0)=0$. Repeat steps 2 to 4 and record the result.
B. Find Complete Solution: $F(t) \neq(0$ (External force added)

1. Replace the ACS-13010 module in Figure 6-6 with the ACS-13011 and connect the ACS-13011 FG OUTPUT terminal to the ACS-13005 V1 input terminal. While holding down the PULSER switch, generate a pulse of 1 V at the FG OUTPUT terminal by setting the AMP control knob, that is $(\mathrm{F}(\mathrm{t})=1)$. This manually

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generates a step function. To synchronize the step input signal and the integrator; connect the SYNC terminal of the ACS-13006 to the SYNC terminal of the ACS-13011.
2. Set ACS-13006 (1) and ACS-13006 (2) controls as follows:

3. On ACS-13005, set K to $1(\mathrm{~m}=1)$. According to the block diagram in Figure 6-7, proceed to the following cases:


Figure 6-7.

## B-1. $\mathrm{c}^{2}-4 \mathrm{mk}>0$ or $\mathrm{c}^{2}>4 \mathrm{mk}, \mathrm{F}(\mathrm{t})=\mathrm{u}_{\mathrm{s}}(\mathrm{t})$

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(1) In this case, the ACS-13006 (1) is used as the master block of the two integrators. To set these two integrators to the initial mode, set the SYNC switch to INI.C and set the initial values of the two integrators to $0 \mathrm{~V}(\mathrm{y}(0)=0, \dot{y}(0)=0)$.
(2) In ACS-13007, set K to $3(\mathrm{c}=3)$. In ACS-13007A, set the K to $1(\mathrm{k}=1)$. Thus, the system satisfy $c^{2}>$ 4 mk . Record the c and k values $(\mathrm{m}=1)$.
(3) Find the values of $a_{1}, a_{2}, \lambda_{1} \lambda_{2}$ by substituting the recorded values $\mathrm{c}, \mathrm{m}, \mathrm{k}, \mathrm{y}(0)$ and y '( 0 ) into the characteristic equation and differential equation. Plot $y_{h}(\mathrm{t})$ waveform according to the equation:

$$
y(t)=a_{1} e^{\lambda_{1} t}+a_{2} e^{\lambda_{2} t}+k_{1}
$$

(4) In ACS-13006 (1), set the SYNC switch to OP. press the RESET button of ACS-13011 to synchronize the integrator with function generator. Press PULSER pushbutton switch. Using the oscilloscope, measure and record the signals at ACS-13011 FG OUTPUT and ACS-13006 (2) Vo output terminals. Compare the result with the plotted $\mathrm{y}(\mathrm{t})$ in Step (3). Do they agree with each other?
(5) Changing initial value
(a) Set the SYNC switch to INI.C at ACS-13006 (1). Set the initial value of ACS-13006 (2) to $+5 \mathrm{~V}(\mathrm{y}(0)=$ 5) and the initial value of ACS-13006 (1) to $0 \mathrm{~V}(\dot{y}(0)=0)$. Repeat steps (2) to (4) and record the result.
(b) Set y $(0)=-5, \dot{y}(0)=0$. Repeat steps 2 to 4 and record the result.

## $B-2 . c^{2}-4 m k=0$ or $c^{2}=4 m k, F(t)=u_{s}(t)$

(1) In this case, the ACS-13006 (1) is used as the master block of the two integrators. To set these two integrators to the initial mode, set the SYNC switch to INI.C and set the initial values of the two integrators to $0 \mathrm{~V}(\mathrm{y}(0)=0, \dot{y}(0)=0)$.
(2) In ACS-13007, set K to $2(\mathrm{c}=2)$. In ACS-13007A, set K to $1(\mathrm{k}=1)$. These make the system satisfy $c^{2}$ $=4 \mathrm{mk}$. Record the values of c and $\mathrm{k}(\mathrm{m}=1)$.
(3)Find the values of $a_{1}, a_{2}, \lambda$ by substituting the recorded values $\mathrm{c}, \mathrm{m}, \mathrm{k}, \mathrm{y}(0)$ and y '(0) into the characteristic equation and differential equation. Plot $y_{h}(\mathrm{t})$ waveform according to the equation:

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$$
y(t)=\left(a_{1}+a_{2} t\right) e^{\lambda t}+k_{1}
$$

(4) In ACS-13006 (1), set the SYNC switch to OP. Press the RESET button of ACS-13011 to synchronize the integrator with function generator. Press PULSER pushbutton switch. Using the oscilloscope, measure and record the signals at ACS- 13011 FG OUTPUT and ACS-13006 (2) Vo output terminals. Compare the result with the plotted $\mathrm{y}(\mathrm{t})$ in Step (3). Do they agree with each other?
(5) Changing initial value
(a) Set the SYNC switch to INI.C at ACS-13006 (1). Set the initial value of ACS-13006 (2) to $+5 \mathrm{~V}(\mathrm{y}(0)=$ 5) and the initial value of ACS-13006 (1) to $0 \mathrm{~V}(\dot{y}(0)=0)$. Repeat steps 2 to 4 and record the result.
(b) Set y $(0)=-5, \dot{y}(0)=0$. Repeat steps 2 to 4 and record the result.

## B-3. $c^{2}-4 m k<0$ or $c^{2}<4 m k, F(t)=u_{s}(t)$

(1) In this case, the ACS-13006 (1) is used as the master block of the two integrators. To set these two integrators to the initial mode, set the SYNC switch to INI.C and set the initial values of the two integrators to $0 \mathrm{~V}(\mathrm{y}(0)=0,) \cdot \dot{y}(0)=0)$.
(2) In ACS-13007, set K to $1(\mathrm{c}=1)$. In ACS-13007A, set K to $1(\mathrm{k}=1)$. Thus, the system satisfy $c^{2}<4 \mathrm{mk}$. Record the c and k values $(\mathrm{m}=1)$.
(3)Find the values of $a_{1}, a_{2}, \lambda_{1,2}=p \pm i q$ by substituting the recorded values $\mathrm{c}, \mathrm{m}, \mathrm{k}, \mathrm{y}(0)$ and $\mathrm{y}^{\prime}(0)$ into the characteristic equation and differential equation. Plot $y_{h}(\mathrm{t})$ waveform according to the equation:

$$
y(t)=e^{p t}\left(a_{1} \cos q t+a_{2} \sin q t\right)+k_{1}
$$

(4) In ACS-13006 (1), set the SYNC switch to OP. press the RESET button of ACS-13011 to synchronize the integrator with function generator. Press PULSER pushbutton switch. Using the oscilloscope, measure and

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record the signals at ACS-13011 FG OUTPUT and ACS-13006 (2) Vo output terminals. Compare the result with the plotted $\mathrm{y}(\mathrm{t})$ in Step (3). Do they agree with each other?
(5) Changing initial value
(a) Set the SYNC switch to INI.C at ACS-13006 (1). Set the initial value of ACS-13006 (2) to $+5 \mathrm{~V}(\mathrm{y}(0)=$ 5) and the initial value of ACS-13006 (1) to $0 \mathrm{~V}(\dot{y}(0)=0)$. Repeat steps 2 to 4 and record the result.
(b) Set $\mathrm{y}(0)=-5, \dot{y}(0)=0$. Repeat steps 2 to 4 and record the result.

## 4- Discussion:-

Show in steps how to express the differential equation of typical spring- mass - damper system to block diagram form? What are the effect of $\mathrm{m}, \mathrm{k}, \mathrm{c}, \mathrm{F}(\mathrm{t}), \mathrm{y}(0)$ and $\dot{y}(0)$ at your results?

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## Experimental Title: - Dominant Pole of Second- Order System

1- Summary: -

1. To understand the dominant pole of a second-onder system.
2. To verify that a second-order system can be approximated by a first-order system.

2- Introduction and Theory: -

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If tivid roots of a second-order system are real and distinct and the two roots are far apart from gach other, the second-order system can be approximated by a first-order system whose root is close to the origin.

The transfer function of a second-order system can be factored as

$$
\frac{C(s)}{R(s)}=\frac{a b}{(s+a)(s+b)}=\frac{X}{s+a}+\frac{Y}{s+b}
$$

Solving for $X$ and $Y$, we have

$$
X=\frac{a b}{b-a} \text { and } Y=\frac{a b}{b-a}
$$

Applying partiat fraction techrigle to the transfer function above, it is expanded as

$$
\frac{c(s)}{R(x)^{2}-\frac{a b-a x}{b-a}-\frac{a b}{b-a s+b}}
$$

For a stop input, then

$$
C(s)=\frac{1}{s}\left[\frac{a b}{b-a s+a}-\frac{1}{b-a b s+b}\right]
$$

In order to return to time domain, take inverse Laplace transform of $\mathrm{C}(\mathrm{s})$

$$
c(f)=1-\frac{b}{b-a} e^{-x}+\frac{a}{b-a} e^{-b}
$$

Consider the following transfer function of afirst-order system

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$$
\frac{C_{1}(s)}{R(s)}=\frac{a}{s+\bar{a}}
$$

For a step input, then

$$
C_{1}(s)=\frac{1}{s} \frac{a}{s+a}
$$



In order to retuin to time domain, apply inverse Laplace transform to $\mathrm{C}_{7}(\mathrm{~s})$

$$
(9)-19 e^{-6}
$$

Now porgider the difference between first- and second-order systems.

$$
\begin{aligned}
c(t) & =c_{1}(t)-c(t)=1-e^{-a t}-\left[1-\frac{b}{b-a} e^{-a t}+\frac{a}{b-a} e^{-b t}\right] \\
& =\frac{1}{b / a-1}\left(e^{-\alpha t}-e^{-\omega t}\right)
\end{aligned}
$$

The magnitude of $e(t)$ indicates the closeness between tho two systênis. If e(t) is very small, these two systems are very close to each other, or the-response of second-order system is very close to that of first-order system. In such a case, the seconc-order systom can be replaced by a first-order isystem. Figure 9-1 shows the $|e(t)|$ curves. In this figure, $X$ axis is scaled by the ratig of t/a, curves 1 to 5 indicate $b=1,1 a, b=2 a, b=5 a, b=10 a$ and $\mathrm{b}=20 \mathrm{a}$, respectively, From theses curves, the greator the b value or the smaller the $|e(t)|$ value, the respothse of a second-order system is much close to that of a first-order system. When b approaches infinity, the e(t) approaches zero.

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3- Procedures and Results:-

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1. Complete the connections by referring the the block Uipgram and wiring diagram shown in Figure 9-2.

(a) Block diagram

(b) Wring diagram
2. On ACS-13010, generate a $0.05 \mathrm{~Hz}, 1 \mathrm{Vpp}$ square wave at the STEP + putput terminal.
3. Set ACS-13006 selector switches as folionst

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| Selector Switch | ACS-13006 |
| :---: | :---: |
| $T$ | $\times 1$ |
| LC. | 0 |
| SYNC. | $O P$ |

4. On ACS-13008, place T selector switch in $\times 1$ position, set $a=b=1$. In this case, the transfer function of this system is

$$
G(x)=\frac{C(s)}{g(s)}=\frac{1}{(s+1)(s+1)}
$$

Using oscilloscope, measure and record the signals at ACS-13006 Vo output (C1 (s)) and ACS-13008 Vo' output (C(s)) terminals.
5. On ACS-13008, place $T$ selector switch in $\times 10$ position, set $a=b=1$ In this case, the tranafer function of this system is expressed by

$$
G(s)=\frac{C(s)}{R(s)}=\frac{10}{(s+1)(s+10)}
$$

Using oscilloscope, measure and record the signals at ACS- 13006 Vo output (C1 (s)) and ACS-13008 Vo' output (C(s)) terminals.
6. On ACS-13008, place $T$ selector switch in $\times 10$ position, set $a=b=10$. Thus the transfor function of this system is

$$
G(s)=\frac{C(s)}{R(s)}=\frac{100}{(s+1)(s+100)}
$$

Using oscilloscope, measure and record the signals at ACS- 13006 Vo output (C1 (s)) and ACS-13008 Vo' output (C(s)) terminals.

## 4- Discussion:

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According to your results, discuss whether or not second-order system can by approximated by first- order system.

## Experimental Title: - Proportional Controller

## 1- Summary: -

## 1. To study the effects of $P$ controller on varieus systems.

## 2- Introduction and Theory: -

PID (Proportional-Integral-Derivative) controller is one of the most widely used controllers in Industry. In this experiment, we wil use step response to study the effects of $P$ controlier on the systems.

## 1. First-Order Plants

First-order plants can be divided into two types:
(1) Type 0 System

$$
G(s)=\frac{p_{1}}{s+p_{1}}
$$

When a $P$ controler is added to the system, the block diagram is shown in Figure 11-1.


Figure 11-1 Block diagram of first-order type 0 system with $P$ controllior

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The open-loop transfer function is then

$$
G(s)=\frac{K_{p} p_{1}}{s+p_{1}}
$$

and the closed-looptransterfunction is

$$
M(s)=\frac{K_{r} p_{1}}{s+\left(1+K_{F}\right) p_{1}}
$$

For a step input $u_{s}(t)$, we first conslder the steady-state error $e_{s s}$ of tho type 0 system with P controllor. By definition af steady-state error, we have

$$
e_{N}=\frac{1}{1+K_{p}}
$$

It is 0 ovious that an increase in $K_{p}$ value reduces the steady-state emror. Next let us conshder the fransient response. From the closed-foop transfer function, the pole p Cof the aystóm is

$$
\alpha R p=-\left(1+K_{f}\right) p_{1}
$$

From the equation above, increasing $K_{p}$ makes the pole far from the origin (see the root locus shown in Figure 11-2), so the response becomes fast


Figure 11-2 Root locus plot

As mentionod aboye, the greater the $K_{p}$, the faster the systom response, and the smaller the steady-state error. However, this system ahways exists steady-state error unless $K_{p}=\infty$

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## (2) Type 1 System

$$
G(s)=\frac{1}{s}
$$

Figure 11-3 shows the block diagram of type 1 systern with $P$ controller.


Figure 11-3 Block diagram of first-prder type 1 system with P controller

The open-lobp transfer function is then
and the-closed-loop transfer function is

$$
M(s)=\frac{K_{P}}{s+K_{F}}
$$

For a system without $P$ controller, $\theta_{i s}=0$ according to the formula of steady-state error. With $P$ controller, the type of plant is not changed and no steady-state error is generated.

From the closed-loop transfer function, the pole of system is

$$
p=-K_{F}
$$

An increase in K makes the pole far from the origin (see Figure 11-4) so that the response becomes tast?

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Figure 11-4 Root locus plot

As discussed above, the step response of this system has no steady-state error so that the steady-state error is not affected by Kp. For transient response, the greator the $K_{p}$, the faster the system responsor

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Therefore P controiler affects a first-order plant on:
(a) Transient response

The greater the $K_{p}$, the faster the system responsiof
(b) The steady-state error of step response.

If the original system has steady-statesefpol, the greater the $K_{p}$, the smaller the steady-state error is. However, it always has steady-state error unless $K_{p}=\infty$. If the original system has no steady-state error, the amount of $K_{p}$ does not affect the/steady-state error.

## Seconid-OrderPlants

Second-order plants can be divided into the following three types:
(1) Type 0 System

Figure 11-5 shows the block diagram of a type 0 system with $P$ controller.


Figure 11-5 Block-diagram of second-order type 0 system with $P$ controller

The open-foop ransfecfunction is

and the closed-loop transfer function is expressed by

$$
M(s)=\frac{K_{p} b_{0}}{s^{2}+a_{1} s+\left(a_{0}+K_{p} b_{0}\right)}
$$

Furthermore typo 0 plant can be divided into three types:
(a) Two roots are real and distinct-

The root locus plot is shown in Figure 11-6.

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Figure 11-6 Root locus (two roots are real and distinct)
(b) Trpproots are real and equal

Root locus is shown in Figure 11-7.


Figure 11-7 Root locus (two roots are real and equal)
(c) Two roots arereal and equal

Robt locus is shown in Figure 11-8.


Figure 11-8 Root locus (two roots are roal and equal)

Now let us discuss the steady-state ecror $\mathrm{e}_{n a}$ from the open-loop transfer function.
By definition of steady-strotaiseror, then

$$
c_{s i}=\frac{1}{1+\left(K_{p} b_{0} / a_{0} b R_{2} \square\right.}
$$

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 Mss. Yasameen Kamil 2020-2021As can be seen, the greater the $K_{p}$, the smaller the-steady-state error. Let us consider the transient response from the closediloop transter funstion by letting $a_{1}=2 \zeta \omega_{n}$, and $a_{0}+K_{p} b_{0}=\omega_{n}^{2}$. Since $a_{5}, a_{s}, b_{0}$ aro the coefficients of plant, they are constant. $K_{p}$ is the adjustable gain $g$. $P_{c}$ coritroller, thus the greater the $K_{p}$, the greater the natural frequency $\omega_{n i}$ in addition, $2, \omega_{n}$ is constant, therofore the greater the $6 W_{j}$, the smaller the $\zeta$ From the properties of a second-order system, the greater the $\omega_{k}$ the faster the system response; whereas the magnitude of $\zeta$ not onty affects the response speed, but also causes an overshoot on system response, The smaller the $\zeta$, the faster the system responso, and the greater the -overshoot. As discussed above, the greater the $K_{p}$, the faster the system response, the greater the overshoot, and the smaller the steady-state error.
(2) Type 1 System

$$
G(s)=\frac{p_{1}}{s\left(s+p_{1}\right)}
$$

The block diagram of type 1 plant with $P$ controller is shown in Figure 11-9.


Figure 1199 Block diagram of second-order type 1 system plus $P$ controller

Figure 11-10 shows its root locus plot.


Figure 11 -10 Root locus plot

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The open-loop transfer function is

$$
G(s)=\frac{K_{p} p_{1}}{s\left(s+p_{1}\right)}
$$

and the closed-loop transfer function is

$$
M(s)=\frac{K_{r} p_{1}}{s^{2}+p_{1} s+K_{p} p_{1}}
$$

For a atate error The type of system is not changed when $P$ controller is added to the system, so this system still has no steady-state error.

Now we discuss the transient response from the closed-loop transfer function by letting $p_{1}=2 \zeta \omega_{n}$ and $K_{p} p_{1}=\omega_{m}^{2}$. Since $p_{7}$ is the coefficient of the plant, so it is constant. $\mathrm{K} p$ is an adjustable gain of P controller, the greater the K a the greater the natural frequency $\omega_{n i}$ in addition, $2 \zeta \omega_{n}$ is constant, therefore the Greater the $\omega_{10}$ the smaller the $\zeta$, In other words, the greater the $K_{p}$, the greater the $\omega_{n}$ and the smaller the $\zeta_{r}$. According to the properties of a second-order system, the greater the $\omega_{n}$, the faster the system response; whereas the magnitude of $\zeta$ not only affects the response speed, but also causes an overshoot on system response. The smaller the $\zeta$, the faster the systern, response, and the greater the overshoct. As discussed above, the greatek the, $K$, the faster the system response, and the greater the overshqpt inis kind of system has no steady-state error.

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(3) Type 2 Systern

$$
G(s)=\frac{1}{s^{2}}
$$

The block diagram of tho typo 2 system with $P$ controller is shown in Figure 11-11.


Figure 11-11 Block diagracr of second-order type 2 system with P controller

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Root locus plot is shown in Figure 11-12.


Figure 11-12 Root locus plot

The open-loop transfer function is given by

$$
G(s)=\frac{K_{p}}{s^{2}}
$$

and the closed-loop transfer function is given by

$$
M(s)=\frac{K_{r}}{s^{2}+K_{p}}
$$

For the step input $U_{5}(t)$, the system will oscillate and the frequency of oscillation is determined by $K_{\text {- }}$. Therelationship between the frequency of oscillation $\omega$ and $K_{p}$ can be described by the equation $\omega^{2}=K_{p}$. The greater the $K_{p}$, the higher the frequendy

Therefore p controller affects a second-order plant on:
(a) Transient response

The greater the $K_{p}$, the faster the systom response. When the $K_{f}$, increases to a certain value, an overshoot is generated.
(b) Steady-state error of step response

If the original system has steady-state error, increasing Kp reducasthe steadystate error, but the system always exists steady-state error unless $\mathrm{K}_{\mathrm{p}} \mathrm{mos}$, If the original system has no steady-state error, then the steady-state error is not affected by $K_{P}$.

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## 3- Procedures and Results:-

The following uses ACS-13008 Second Order Pyant to simulato a dc servo motor:
A. P Controller Used in Closed-Loop DC Seryo Motor Speed Control

1. Complete the connections by referring to the block diagram and wiring diagram shown in Figure 11-13.

(a) Block diagram

(b) Wiring diagram

Figure 11-13
2. On ACS-13010, generate a 0.05 Hz 1 Vpp square wave at the STEP+ output terminal.

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3. On ACS -13008 , place $T$ selector switch in $\times 10$ position, set $a=b=5$. In this case, the transfer function of ACS-13008 is

$$
G_{P}(s)=\frac{50}{s+50}
$$

The closed-loop transfer function is then

$$
M(s)=\frac{50 K_{r}}{s+\left(50+50 K_{p}\right)}
$$

4- On ACS-13002, set $\mathrm{Kp}=1$. Using oscilloscope, measure and record the signals at ACS- 13010 step+ output and ACS- $13008 \mathrm{Vo}^{\prime}$ output terminals.

5- Repeat step 4 for $K p=5,10$ and record the results.
6- Compare the recorded steady- state errors and transient responses for different Kp values.

## B. P Controller Used in Closed-Loop DC Servo Motor Position Control

Complete,the connections by referring to the block diagram and wiring diagram afigwn in Figure 11-15.

(a) Block diagram

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(b) Wiring dfagram

Figute 11-15

3. On ACS-1300B, place $T$ switch in $\times 1$ position, set $a=b=5$. Thus the transfer function of ACS-13008 is

$$
G_{f}(x)=\frac{5}{s(s+5)}
$$

Tho elowec-loop transfor function is then

$$
K P(x)=\frac{5 K_{P}}{s^{2}+5 x+5 K_{P}}
$$

4- On ACS- 13002, set $\mathrm{Kp}=1$. Using oscilloscope, measure and record the signals at ACS- 13010 step+ output and ACS- 13008 Vo output terminals.

5- Repeat step 4 for $\mathrm{Kp}=2,5$ and 10 and record the results.
6- Compare the recorded steady- state errors and transient responses for different $K p$ values.

## 4- Discussion:-

Compare between theoretical effect of Kp at first order and second order systems regarding steady- state errors and transient responses with the practical obtained results whenever applying step input signal.

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