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Identification and Design of Closed loop Hydraulic system with 4/3 Servo valve

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A B S T R A C T

Fluid power actuators play a vital role in the field of mechatronics. The controlling of electrohydraulic actuation system is important in the view of nonlinearity characteristics of hydraulic valves. In order to control the operation of valves, the controller should be designed as well as identification of the system is necessary to know the behavior of the system. This paper provides the derivation of transfer function for a electrohydraulic servo system by using transient response of the cylinder with respect to different set point with different loads .The performance of the system is analyzed using open loop without load, open loop with load, closed loop with load and it is observed that the performance of the system works better using closed loop. Also, in this paper the identification of the electrohydraulic servo system is done using transient response parameters and using Bode plot. It has been found that the poles & zeros of the system determined by the transient response & Bode's Plot are nearly equal. For the transfer function derived from different conditions such as open loop, closed loop, with variable loads, the PID controller is also designed and the performance characteristics hold good with theoretical aspects.

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Introduction:

The range of applications of electrohydraulic servo system includes manufacturing systems, heavy duty material testing devices, hydraulic mini press machine, robotics, steel and aluminium mill equipment. In case of electrohydraulic actuation system, hydraulic power in conjunction with a servo valve is used to provide the desired forces and motion. The desired motion is achieved through a closed loop feedback control systemthat senses the actual deflection and corrects it until the desired position is achieved [1].

This paper reports identification of electrohydraulic servo system to which different sinusoidal inputs with constant amplitude 0.01volt at various frequencies ranges from 1Hz, 2Hz, 5Hz, 10Hz, 20 Hz, 100Hz, 500Hz, 1kHz are applied. The transfer function for the electrohydraulic servo system was derived by using natural frequency $\omega_n$and damping ratio ζ with various set points as well as providing different loads such as 1Kg, 5Kg, and 10Kg. Also, the frequency response in terms of Bode's plot at different load conditions is observed. Then for given transfer function the PID controller has been introduced and performance characteristics in terms of rise time, settling time and peak time are discussed.

Electrohydraulic Servo System:

When closed-loop hydraulic control systems appeared in industry, due to the requirement of very high performance for different applications, where the operators are demanding greater precision, faster operation and simpler adjustment [7].

A servo or a servomechanism is a control system which measures its own output and forces the output to quickly and accurately follow a command signal and can be designed to control almost any physical quantities, e.g. motion, force, pressure, temperature, electrical voltage or current.

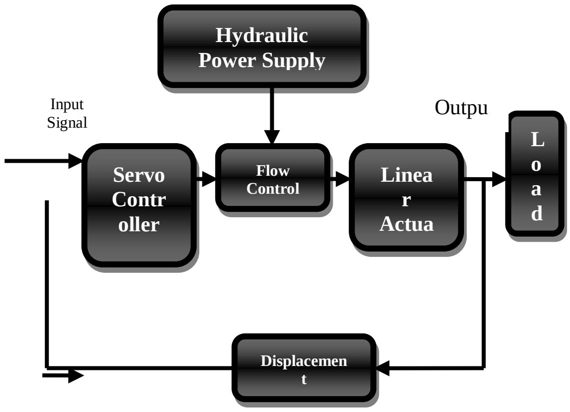

Fig.1: Block diagram for electrohydraulic servo system

Identification and Control of Electrohydraulic Servo System:

Hydraulic servo systems provide larger driving force as well as torque and higher speed of response with faster motion. Though it provides many advantages it exhibits nonlinearity [3]. In order to know the input-output relationship of components, it is required to derive the transfer function. The identification technique may involve time domain analysis in terms of transient response and frequency domain analysis. This paper uses both the time domain approach & frequency domain approach for identification of electrohydraulic servo system. Here, the electrohydraulic servo system consists the flow control valve, linear actuator, servo controller which can be an amplifier or gain and to the linear actuator various loads are given so that cylinder rod position in terms of transient response can be observed. By taking servo valve & linear actuator as a plant as well as a set point of 0.1 volt is given to the servo valve, the block diagram shown in fig.1 can be designed as an open loop block which is in fig.2. In open loop case, the loads are not connected to the linear actuator and the cylinder rod position has been observed. Then different loads like 1kg, 5 kg and 10 kg are given to the cylinder and therequired block diagram representation is shown in fig.3.

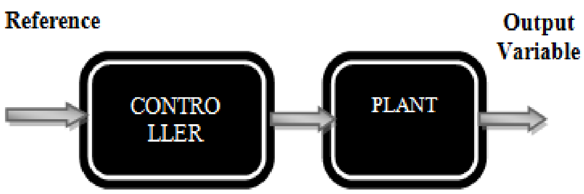

Fig. 2: Open loop Block diagram for electrohydraulic servo valve with linear actuator

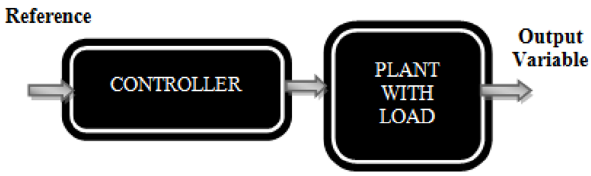

Fig. 3: Open loop Block diagram for electrohydraulic servo valve with actuator connected to load

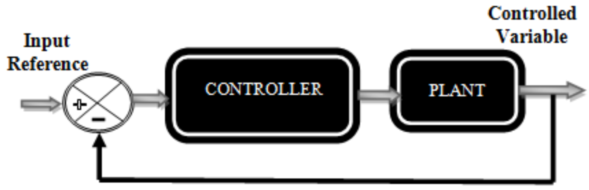

Fig. 4: Closed loop Block diagram for electrohydraulic servo valve with linear actuator

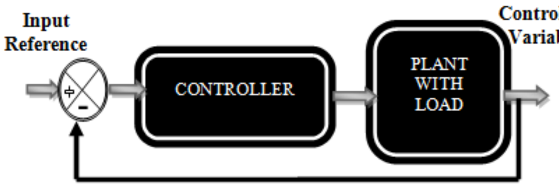

Fig. 5: Closed loop Block diagram for electrohydraulic servo valve with actuator connected to load

By connecting the output to the input with unity feedback, the open loop system shown in fig.2 and fig.3 can be designed into closed loop system shown in fig.4 and fig.5 respectively. From the closed loop response, the transient and steady state response has been analyzed by calculating maximum peak time, damping ratio and natural frequency with varying loads. The transient and steady state error analysis curve is shown in fig.6 which shows the characteristics such as rise time, settling time [4].

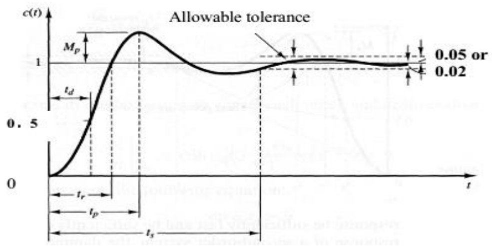

Fig. 6: Transient & steady state response analysis

The time response $c(t_p)$ can be as follows [4].

$$c(t_r) = 1 \Rightarrow 1 - e^{-\zeta\omega_d t_r}(\cos\omega_d t_r + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\omega_d t_r) = 1 \qquad (1)$$

$$\Rightarrow \cos\omega_d t_r + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\omega_d t_r = 0$$

$$\Rightarrow \tan\omega_d t_r = -\frac{\zeta}{\sqrt{1-\zeta^2}} = -\frac{\omega_d}{\sigma} \qquad (2)$$

Now, the rise time can be calculated using equation-3

$$t_r = \frac{1}{\omega_d}\tan^{-1}\left(\frac{\omega_d}{\sigma}\right) \qquad (3)$$

Peak Time t_p to reach the first peak of c(t)

$$\left.\frac{dc(t)}{dt}\right|_{t=t_p} = 0 \Rightarrow (\sin\omega_d t_p)\frac{\omega_n}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t_p} = 0$$

$$\sin\omega_d t_p = 0$$

$$t_p = \frac{\pi}{\omega_d} \qquad (4)$$

$$T_P = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \qquad (5)$$

Maximum overshoot Mp

$$t = t_p = \frac{\pi}{\omega_d}$$

$$m_p = \exp\frac{-\pi\zeta}{\sqrt{1-\zeta^2}} \qquad (6)$$

Settling Time is given by

$$c(t) = 1 - \frac{-\zeta\omega_n t}{\sqrt{1-\zeta^2}}\sin\left(\omega_d t + \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}\right) \qquad (7)$$

The open loop transfer functions have been derived using equation-1 to equation-7 and are given in table.1.

Table: 1. Open loop transfer function

Load (Kg)	Open-loop Transfer Function
0	$G(S) = \frac{204.121}{S^2 + 24.18S}$
1	$G(S) = \frac{400}{S^3 + 11.02S^2 + 410.02S + 400}$
2	$G(S) = \frac{400}{S^3 + 11.056S^2 + 410.056S + 400}$
5	$G(S) = \frac{400}{S^3 + 11S^2 + 411S + 400}$
10	$G(S) = \frac{400}{S^2 + 10.056S}$

Then the identification technique involves analysis of frequency response of the system at different load conditions as well as to determine order of the system frequency characteristics of the system with feedback at different load condition were performed and the Bode'splot presented. In this paper the Bode diagram is obtained by finding amplitude response-relationship between output and input amplitude with respect to excitation frequency. From the peak value, natural frequency ω_n& damping ratio ζ were determined with different load condition with the assumption that the system is a second order system.The resonant frequency ω_r and the resonant peak M_r for carrying out bode plot can be calculated using equation-8 [5].

$$|G(j\omega)| = \frac{1}{\sqrt{\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}} \qquad (8)$$

Where ω_n is natural frequency

ζ is the damping ratio.

With the derived transfer function for the electrohydraulic servo system, the 3-term controller or integer PID controller implemented and the performance of the system in terms of rise time, peak time and settling time has been discussed. The transfer function for PID controller in S-domain is given in equation-9 and the block diagram for the system is shown in fig.7.

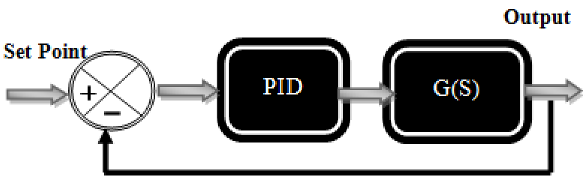

Fig. 7: Block diagram for the PID controller

Simulation and Result:

The electrohydraulic servo system shown in fig.1 has been designed and simulated using MATLAB-Simulink and is shown in fig.8 [7].It is simulated without feedback, with feedback & with load condition (mass is acting as load). It was observed when the input is more than 0.1 u(t) volts; the steady state response doesn't go to 0.1m, it is due to limitation of actuating cylinder and is shown in fig.9. The stroke length is limited to 0.3 meter and the system is quick nonlinear.

The open-loop response of the system with 0, 1, 5,10kg load are presented in fig.10.There was no oscillation in response at no load condition, whereas the oscillation was observed with load condition. Since load (mass) behaves as an inductor, open-loop transfer function with load appears to have second order complex poles. But without load it behaves as only second order type-1 system and for the system with load the natural frequency is presented in table no.2.

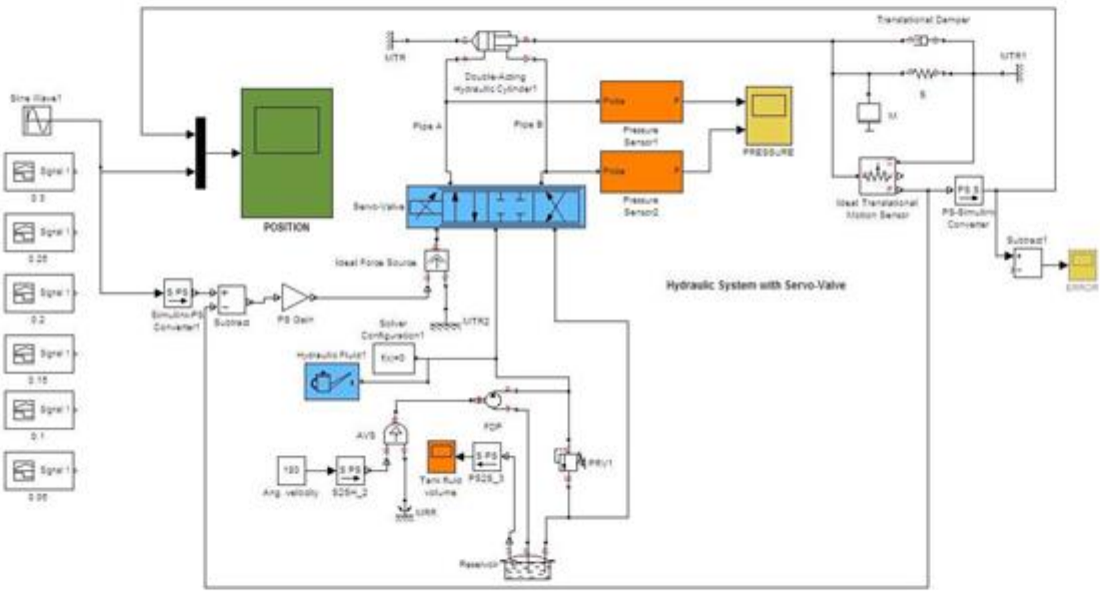

Fig. 8: Electrohydraulic servo system in MATLAB-Simulink environment

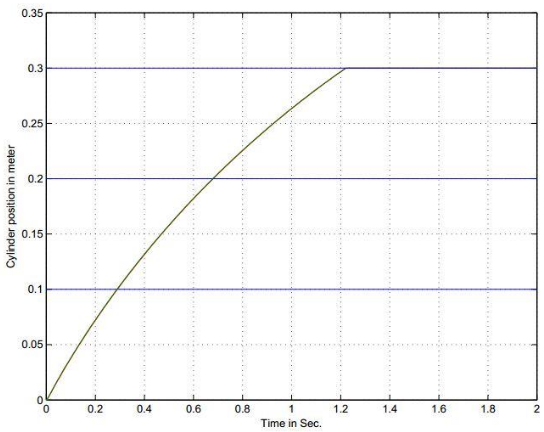

Fig. 9: Cylinder position with no load in open loop

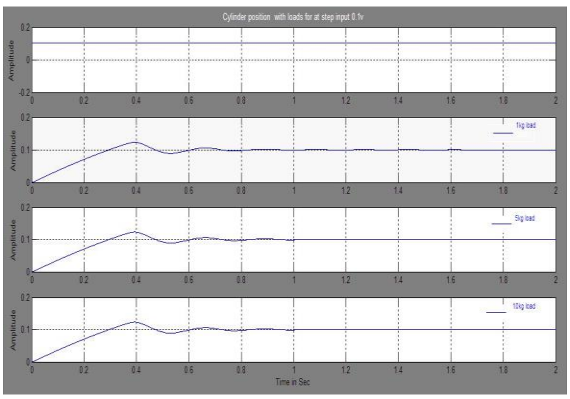

Fig. 10: Cylinder position with different load w.r.t 0.1u(t) in open loop condition

Table-3: Natural frequency & damping factor values

Load (kg)	Maximum point (d_{max})	Peak time (T_p)	Natural frequency ω_n	Damping factor ζ
1	0.1232	0.3949	19.2562	0.2505
2	0.1232	0.3947	18.2581	0.2501
5	0.1232	0.3947	18.2595	0.2504
10	0.1232	0.3952	19.2601	0.2501
100	0.1233	0.3951	18.2600	0.2500
500	0.1238	0.3963	19.2409	0.2471
1000	0.1243	0.3985	17.2300	0.2393

The closed loop response of the electrohydraulic system with no load and with varied load is shown in fig.11 and from the response for different load condition poles & zeros of close-loop transfer function were obtained.

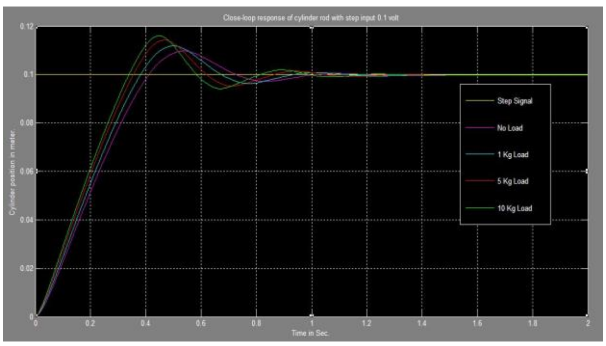

Fig. 11: Closed loop response of electrohydraulic servo system

Then in order to obtain the frequency response of the system, a sinusoidal signal having varied frequency has been given to the electrohydraulic system at no load as well as different loads and correspondingly output peak amplitude has been calculated. The output response i.e. cylinder rod position at 20Hz frequency with feedback & no load is shown in fig.12.

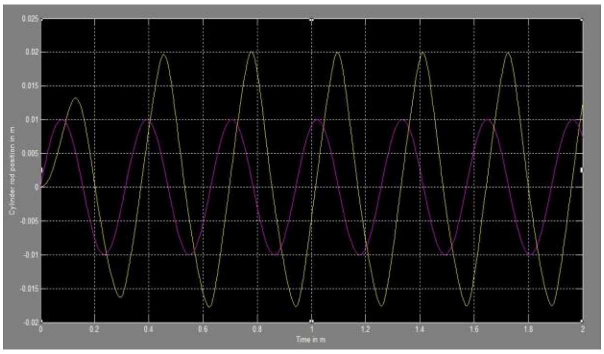

Fig. 12: Cylinder rod position at Frequency 20Hz with feedback & without load

Table: 3. Gain at different frequency with no load

Frequency in Hz	Amplitude of output	Gain in dB
1	0.01	0
2	0.01	0
5	0.0101	0.086427476
10	0.0119	1.510939228
20	0.0199	5.977061528
50	3.9385×10^{-3}	-8.093383004
100	9.5122×10^{-4}	-20.43638966
200	2.6625×10^{-4}	-31.49420767
500	5.0402×10^{-5}	-45.91698966
1000	1.2783×10^{-5}	-57.86734422
2000	4.3856×10^{-6}	-67.15941964

In order to obtain Bode plot, the output value and the gain in dB w.r.t no load, 1k.g, 2kg, 5 Kg and 10 Kg are give in table no.3 table no.4, table no.5, table no.6 and table no.7 respectively.

Table: 4. Gain at different frequency with 1 kg load

Frequency in Hz	**output amplitude**	**Gain in dB**
1	0.01	0
2	0.01	0
5	0.0102	0.086427476
10	0.0127	1.510939228
20	0.0199	5.977061528
50	3.9453×10^{-3}	-8.093383004
100	9.2892×10^{-4}	-20.43638966
200	2.7365×10^{-4}	-31.49420767
500	6.0259×10^{-5}	-45.91698966
1000	1.1845×10^{-5}	-57.86734422
2000	4.2147×10^{-6}	-67.15941964

Table: 5. Gain at different frequency with 2 kg load

Frequency in Hz	Output amplitude	Gain in dB
1	0.01	0
2	0.01	0
5	0.0102	0.172003435
10	0.0119	1.510939228
20	0.0199	5.977061528
50	3.9342×10^{-3}	-8.102871319
100	9.3107×10^{-4}	-20.62035333
200	2.8004×10^{-4}	-31.05559862
500	5.1473×10^{-5}	-45.76841038
1000	1.6615×10^{-5}	-55.58999309
2000	2.7278×10^{-6}	-71.2837495

Table: 6. Gain at different frequency with 5 kg load

Frequency in Hz	Output amplitude	Gain in dB
1	0.01	0
2	0.01	0
5	0.0102	0.172003435
10	0.0119	1.510939228
20	0.02	6.020599913
50	3.9643×10^{-3}	-8.036669751
100	9.2731×10^{-4}	-20.65550114
200	2.7776×10^{-4}	-31.12660593
500	6.5798×10^{-5}	-43.63574614
1000	1.4393×10^{-5}	-56.83697349
2000	5.4988×10^{-6}	-65.19464152

Table: 7. Gain at different frequency with 10 kg load

Frequency in Hz	Output amplitude	Gain in dB
1	0.01	0
2	0.01	0
5	0.0102	0.172003435
10	0.0119	1.510939228
20	0.0199	5.977061528
50	3.9516×10^{-3}	-8.064540465
100	9.3033×10^{-4}	-20.62725949
200	2.6865×10^{-4}	-31.48605573
500	6.3171×10^{-5}	-43.98978246
1000	2.0116×10^{-5}	-53.92916746
2000	9.6097×10^{-6}	-60.34824419

To determine order of the system frequency characteristics of the system with feedback at different load condition were performed and the Bode's plot presented in fig.13 & fig.14.

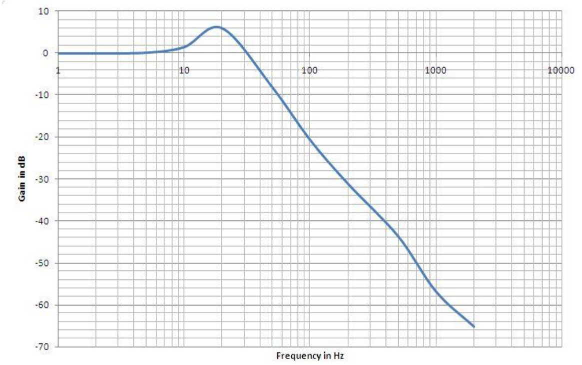

Fig. 13: Bode plot with no load condition

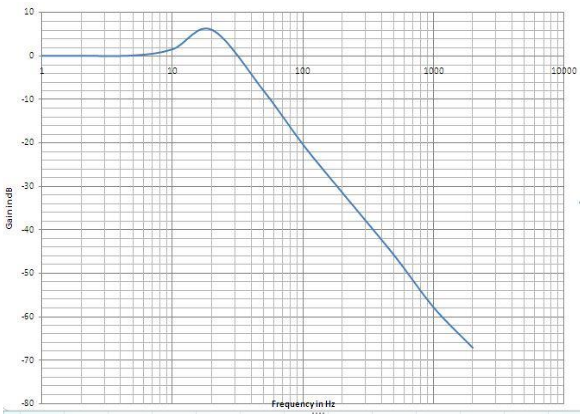

Fig. 14. Bode plot for 5kg & 10 kg load

From the above Bode's Plot all the corner frequency are determined. The ζ of complex corner frequency was determined by taking overshoot at the corner frequency.

Table-8: Poles and Corner frequency from Bodeplot

Load(Kg)	Poles	Corner frequency(Hz)
0	-45.9169	500
1	-44.3995	500
2	-45.7684	500
5	-43.6357	500
10	-43.9897	500

It has been found that the poles & zeros of the system determined by the transient response &Bode's Plot are nearly equal (because of observational error). Therefore most expected Transfer Function is

$$G(S) = \frac{400}{S^2 + 10.056S} \qquad (9)$$

Then with derived transfer functions, the PID controllers for the system are designed and transient parameters are observed in the table no.9.

Table: 9. Transient parameters

Load (in Kg)	Rise time (sec)	Settling time (sec)	Peak time (Sec)
No load	0.0308	0.101	1.09
1	0.684	2.22	1.09
5	0.685	2.22	1.08
10	0.074	0.242	1.06

Conclusion and Future Work:

This paper takes a case study of electrohydraulic servo valve which is connected to a cylinder and defined the performance of the servo system with varied loads not only in open loop case but also in closed loop case .Also, from the observation it has been found that the system performance is better in closed loop condition and PID controller designed. The identification of the system is done with both time domain and frequency domain approach.In future we can improve the performance of electrohydraulic system with nonlinearity conditions as well as design of fractional order controller to the system .Also, the system can be identified using fractional order synthesis.

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