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Position Control of Electro-hydraulic Servo-system using Fractional Order PID Controller

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Abstract: ***For modern Mechatronics system, high accuracy position control is inevitable. Electro hydraulic servo systems are widely used in industrial applications because of its several advantages. Position control of servo system is very important for industrial applications. This paper includes modeling, linearization and position control of Electro hydraulic servo system (EHSS) using conventional PID controller as well as fractional order PID controller which is optimized using PSO algorithm were implemented. MATLAB/SIMULINK platform is used.***

Keywords: Electrohydraulics, Fractional order PID, position control

1. Introduction

Electro-hydraulic servo systems has several advantages such as high power weight ratio, self-cooling, good position capability high robustness and large driving forces because of these advantages EHSS has been widely used for industrial applications. From energy consumption point of view EHSS is not much efficient because energy provided by hydraulic supply is constant but actual need is of variable type.

The range of applications for electro-hydraulic servo systems is diverse, and includes manufacturing systems, materials test machines, active suspension systems, mining machinery, fatigue testing, flight simulation, paper machines, ships and electromagnetic marine engineering, injection moulding machines, robotics, and steel and aluminium mill equipment. Hydraulic systems are also common in aircraft, where their high power-to-weight ratio and precise control makes them an ideal choice for actuation of flight surfaces.

The proportional-integral-derivative controllers are most commonly used in industries because of its simplicity in design and good performance including low percentage overshoot and small settling time for slow process. There are several tuning methods are used. The most common method of tuning PID controllers are auto-tuning, Ziegler-Nichols (Z-N) tuning, trial and error method.

Fractional-order calculus deals with derivative and integrals of non integer order. I and D actions of Fractional Order Proportional-Integral-Derivative (FOPID) has wider scope of designs. The performance of FOPID is better than conventional PID controller. Fractional order PID reduces the percentage overshoot, settling time etc.

In this paper, modelling for electrohydraulic servo system is done by state space representation and system is linearized and both PID and FOPID controllers were implemented.

Here, the paper is divided into different sections. In section 2, mathematical modelling of electrohydraulic servo system is explained. In section 3, EHSS is linearized. In section 4 and 5, PID and FOPID controllers and there tuning methods are mentioned. In section 6 simulation results are included.

2. Electrohydraulic Servo System Modeling

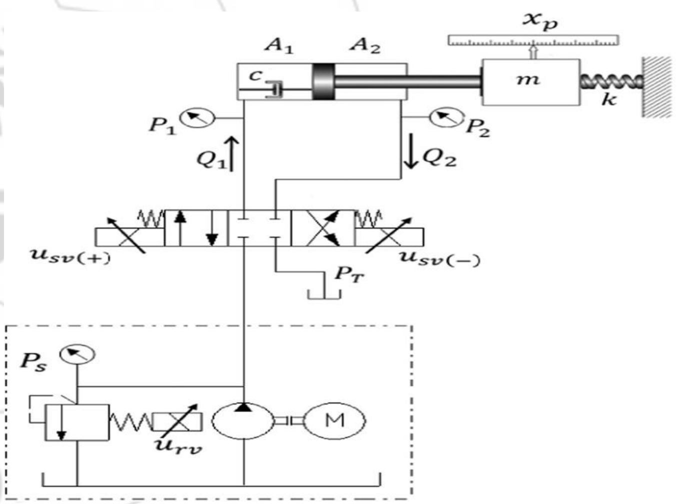

Figure 1: Electro Hydraulic Servo system for position control

Electrohydraulic servo system consists of hydraulic linear actuator, a fixed displacement pump, a proportional relief valve, a proportional directional valve. Fig 1 shows the diagram for position control in electro hydraulic servo system. The dynamics of proportional valve can be described by the following second-order linear differential equation.[1]

$$\ddot{y}_{sv} + 2\varsigma_{sv}\omega_{sv}\dot{y}_{sv} + \omega_{sv}^2 y_{sv} = k_{sv}\omega_{sv}^2 u \qquad (1)$$

Where k_{sv} is the proportional valve gain, ω_{sv} is the natural frequency, ς_{sv} is the damping ratio of the proportional valve, y_{sv} is the spool valve position and u is the input voltage.

The equation describing the fluid flow distribution into the valve can be written as

$$Q1 = C_d w y_{sv}\sqrt{\frac{2}{\rho}(P_S - P_1)} \quad ; \quad y_v \geq 0 \tag{2a}$$

$$Q1 = C_d w y_{sv}\sqrt{\frac{2}{\rho}(P_1 - P_T)} \quad ; \quad y_{sv} \leq 0 \tag{2b}$$

$$Q_2 = C_d \omega y_{sv}\sqrt{\frac{2}{\rho}(P_2 - P_T)} \quad ; \quad y_{sv} \geq 0 \tag{3a}$$

$$Q_2 = C_d \omega y_{sv}\sqrt{\frac{2}{\rho}(P_s - P_2)} \quad ; \quad y_{sv} \leq 0 \tag{3b}$$

Where

P_1, P_2 - Cylinder chamber pressure.

P_T - Tank pressure

P_S - Supply Pressure

C_d - Coefficient of discharge

ω -valve orifice area gradient

Hydraulic pressure behavior for a compressible fluid volume

$$\dot{P}_1 = \frac{\beta}{V_{01} + A_1 x_p}\left(Q_1 - A_1 \dot{x}_p\right) \tag{4a}$$

$$\dot{P}_2 = \frac{\beta}{V_{02} - A_2 x_p}\left(A_2 \dot{x}_p - Q_2\right) \tag{4b}$$

Here β - fluid bulk modulus (oil), $V_{01} + A_1 x_p$ and $V_{02} - A_2 x_p$ are volumes in the cylinder chambers

Mechanical part of the system can be described by

$$\ddot{x}_p = \frac{1}{m}\left(P_1 A_1 - P_2 A_2 - b\dot{x}_p - c x_p - F_L\right) \tag{5}$$

Where m is the total mass of the piston and load, b is the viscous damping coefficient of the actuator, c is the load stiffness F_L is the external load disturbances.

3. Linearization of EHSS

The nonlinear system can be linearized about an operating point. Equation (2a)-(3b) can be represented as [6]

$$Q_1 = k_q^i x_1 - k_c^i x_3$$

$$Q_2 = k_q^o x_1 + k_c^o x_4 \tag{6}$$

The state variables can be defined as: $x_1 = y_v$, $x_2 = \dot{y}_v$, $x_3 = P_1$, $x_4 = P_2$, $x_5 = x_p$, $x_6 = \dot{x}_p$

Where $k_q^i\left(k_q^o\right)$ and $k_c^i\left(k_c^o\right)$ represents the flow gain of the proportional valve and flow pressure coefficient. $k_q^i\left(k_q^o\right)$ and $k_c^i\left(k_c^o\right)$ can be represented as:

$$k_q^i = C_d \omega \sqrt{\frac{2}{\rho}\Delta P_p},$$

$$k_q^o = C_d \omega \sqrt{\frac{2}{\rho}\Delta P_r},$$

$$k_c^i = \pm\frac{C_d \omega x_1}{\sqrt{2\rho\Delta P_p}},$$

$$k_c^o = \pm\frac{C_d \omega x_1}{\sqrt{2\rho\Delta P_r}} \tag{7}$$

The transfer function for the system becomes

$$\frac{F(s)}{U(s)} = \frac{k_{sp}}{\tau s + 1}\left(\frac{K_s k_e (A_i + A_o)}{(K_p + Cs)(m\, s^2 + bs + k_e) + (A_i^2 s + A_o^2 s)}\right) \tag{8}$$

Where K_S and K_P replaces $K_s^i\left(K_s^o\right)$ and $K_p^i\left(K_p^o\right)$, k_e and d are the parameters which includes the environmental stiffness and damping of the system. C denotes the volume of the fluid trapped at sides of actuator and the bulk modulus of fluids. The changes in the valve characteristics are denoted by the variations in k_{sp} and τ .

4. PID Controller in EHSS

The most popular type of controller which were widely used in almost all process control industries are Proportional-Integral-derivative controllers. Some complex industrial control system may contain PID as there major control building block. PID are feedback type controllers. The PID controllers can be easily implemented.

There are different methods for tuning PID controllers. They are Ziegler Nichols, Cohen and coon, auto tuning etc. Here in this paper Ziegler Nichols and auto tuning are used.

A. Ziegler-Nichols tuning

Ziegler-Nichols is a rigorous method for tuning PID controllers. Z-N rule produce good values for PID gain parameters.

Step 1: Check whether the proportional control gain is positive or negative.
Step 2: Turn P-only mode of the controller.
Step 3: Increase the value of proportional gain until a sustained periodic oscillation is obtained.

Step 4: Mark the proportional gain as K_u, the ultimate gain and also measure the period of oscillation as the ultimate period , P_u.

Step 5: Using the above values, K_c, τ_D, τ_I can be obtained.

Table 1: Ziegler- Nichols Tuning Rules

	K_c	τ_I	τ_D
P control	$K_u/2$		
PI control	$K_u/2.2$	$P_u/1.2$	
PID control	$K_u/1.7$	$P_u/2$	$P_u/8$

5. FOPID Controller in EHSS

Fractional order PID controller is also a generalized form of integer order PID controller. Here the output of FOPID is a linear combination of the input and the fractional integer or derivative of the output. Fractional order control has the potential to accomplish what other controllers cannot. The other advantages of fractional order controllers are they have better disturbance rejection ratios and less sensitive to parameter variations.

The definition used for differintegral are:[3]
- Riemann - Liouville definition
- Grundwald – Letnikov definition

Riemann – Liouville definition:

$$ {}^{RL}_{a}D^{\alpha}_{t} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \quad (9)$$

Condition for (9) is n-1 < α < n and Γ (.) is the gamma function.

Grundwald – Letnikov definition:

$$ {}^{GL}D^{\alpha}_{a} F(t) = \underset{h\to 0}{Lt} \frac{1}{h^{\alpha}} \sum_{j=0}^{(t-a)/h} (-1)^j \begin{bmatrix} \alpha \\ j \end{bmatrix} f(t-jh) \quad (10)$$

Where a and t are the limits of operator.

$$ \begin{bmatrix} \alpha \\ j \end{bmatrix} = \frac{\Gamma(\alpha+1)}{\Gamma(j+1)\Gamma(\alpha-j+1)} \quad (11)$$

The time equation of FOPID controller is given by:

$$ u(t) = K_p e(t) + K_{D0} D_t^{\alpha} e(t) + K_{I0} D_t^{-\beta} e(t) \quad (12)$$

A. Particle Swarm Optimization

Particle Swarm Optimization (PSO) population-based stochastic optimization technique. It is a biologically inspired computational search and optimization method developed in 1995 by Eberhart and Kennedy based on the social behaviours of birds flocking. PSO is widely used for solving optimisation problems. PSO consists of a swarm of particles moving in a D dimensional search space. Each particle has position represented by position vector $X_i = (x_{i1}, x_{i2}, ..., x_{iD})$ and velocity is represented by $V_i = (v_{i1}, v_{i2}, ..., v_{iD})$. The best position for particle can be represented as vector $P_i = (p_{i1}, p_{i2}, ..., p_{iD})$, i denotes the index of the particle. The best position among all the neighbours of the particle is stored as $P_g = (p_{g1}, p_{g2}, ..., p_{gD})$. The modification of the particle's position can be mathematically modelled as following:

$$ v_{id}^{(t+1)} = \omega v_{id}^{(t)} + c_1 rand_1 (p_{id} - x_{id}^{(t)}) + c_2 rand_2 (p_{gd} - x_{id}^{t}) \quad (13)$$

$$ x_{id}^{(t+1)} = x_{id}^{(t)} + v_{id}^{(t+1)} \quad (14)$$

B. Design of FOPID using PSO

The control parameters such as $K_p, K_I, K_D, \mu, \lambda$ can be designed using PSO algorithm. Here the particle considered is k=[$k_p, k_I, k_D, \mu, \lambda$] and these are the five controlled parameters used in FOPID. The dimension of population can be determined by the number of particle in the population. For the stability of closed loop, the cost function is penalized with a penality factor [avr]

$$ P(k) = P_1 \text{ if k is unstable, o else} \quad (15)$$

The total evaluation of a particle k can be obtained as

$$ F(k) = J(k) + P(k) \quad (16)$$

The flow chart of PSO based FOPID is shown in FIG 2.

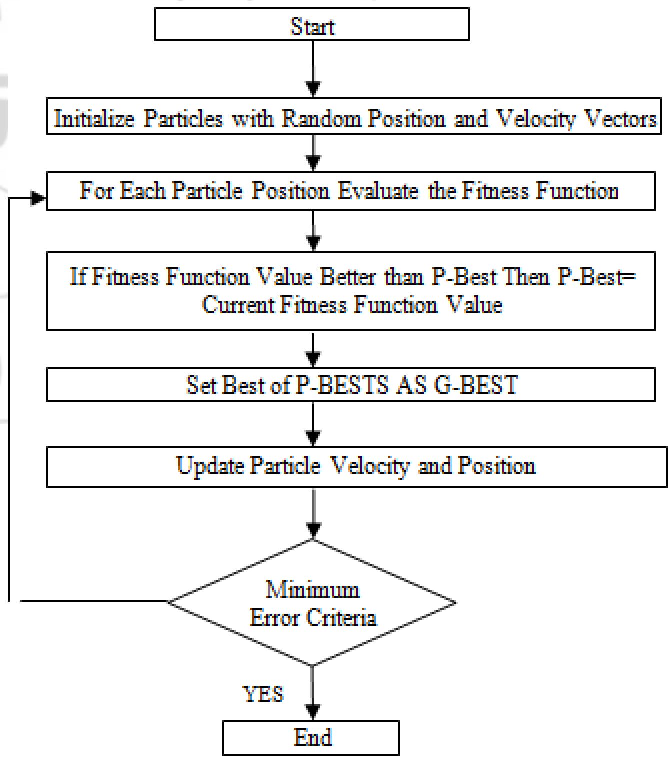

Figure 2: Flow Chart Of PSO Based FOPID Controller

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6. Simulation Results

Here the performance of the controller derived is illustrated using simulation results. The simulation is carried out in MATLAB/Simulink environment using the linearized equation derived from the section 3. Here the step input signal and square wave references are used. The root locus and bode plot of the system in the equation(8) is obtained in the fig.3-4. From the response it is observed that the system is stable. The reference input given is of constant amplitude usually it is kept as unity.

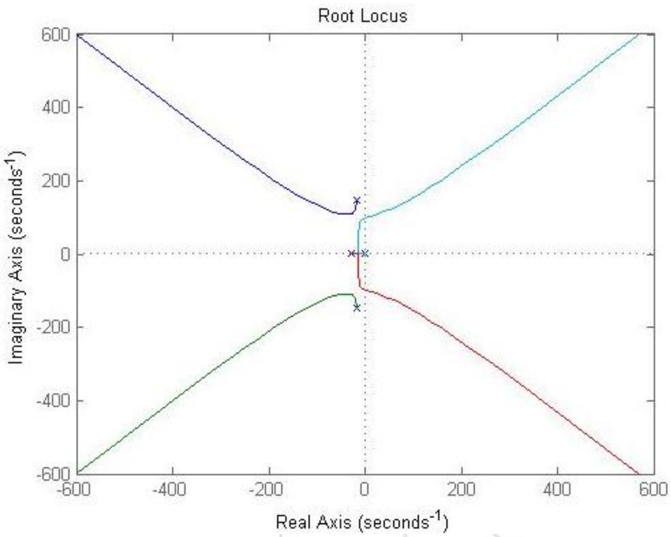

Figure 3: Root Locus of Linearised System

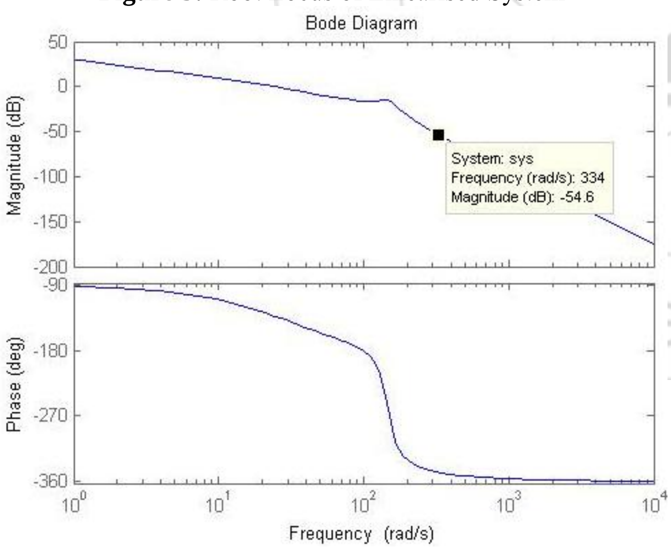

Figure 4: bODE Plot of Linearised System

Table 2: Operating values and parameter ranges for linear transfer function

Parameters	*Nominal Value*
C	$1.5\times10^{-11} m^3/Pa$
b	700N/m/s
m	20Kg
A1	$0.00203\, m^2$
A2	$1.00152\, m^2$
k_e	$75\, KN/m$
K_s	$0.375\, m^3/Pa.s$
K_p	$2.5\times10^{-12}\, m^2/s$
k_{sp}	$.0012\, m/V$
τ	35 ms

The values for the linear transfer functions are obtained from Table 2. The step response of the system for different PID and FOPID are shown in Fig.5-8. The response of FOPID controller for square wave response is shown in Fig. 9.

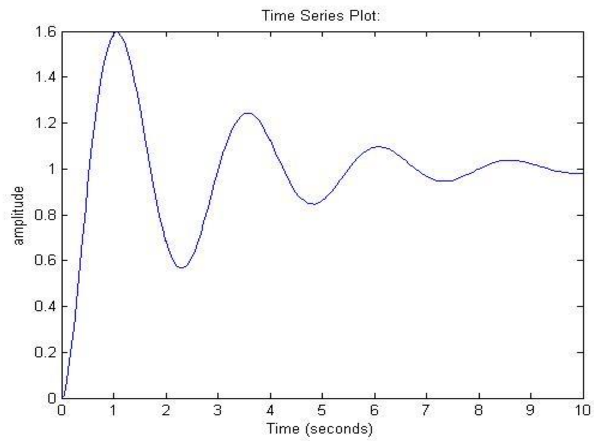

Figure 5: Step response of electro hydraulic servo system for PID tuned using Ziegler Nichols method

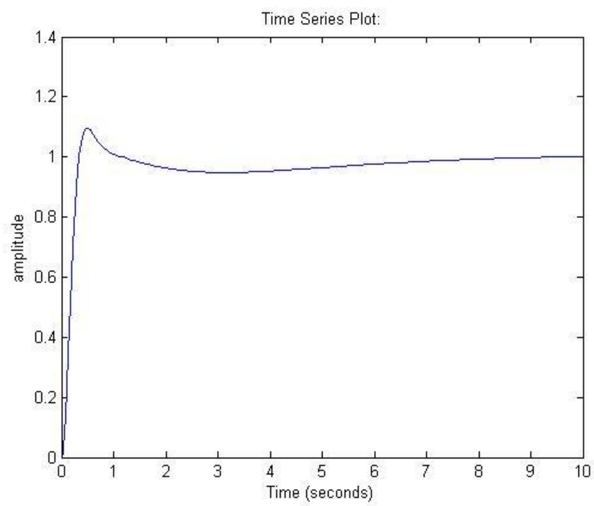

Figure 6: Step response of electro hydraulic servo system for PID tuned using Auto tuning method

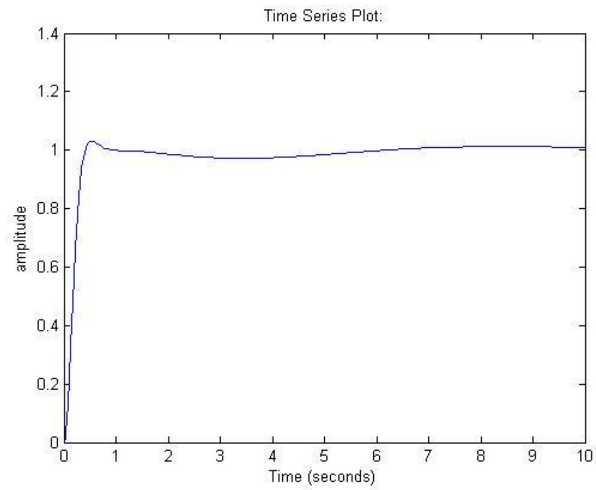

Figure 7: Step response of electro hydraulic servo system for PID tuned using PSO method

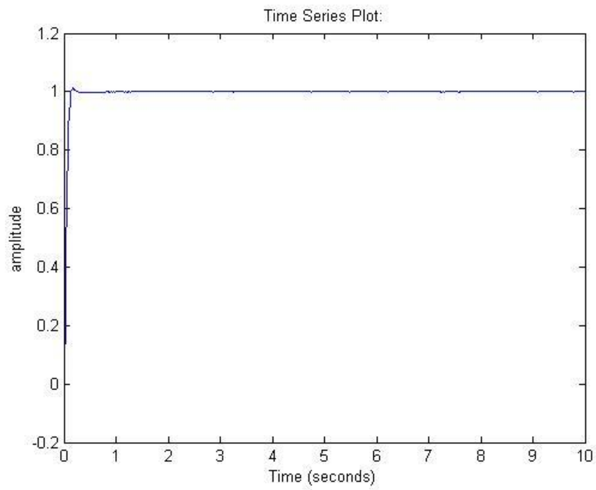

Figure 8: Step response of electro hydraulic servo system for FOPID controller

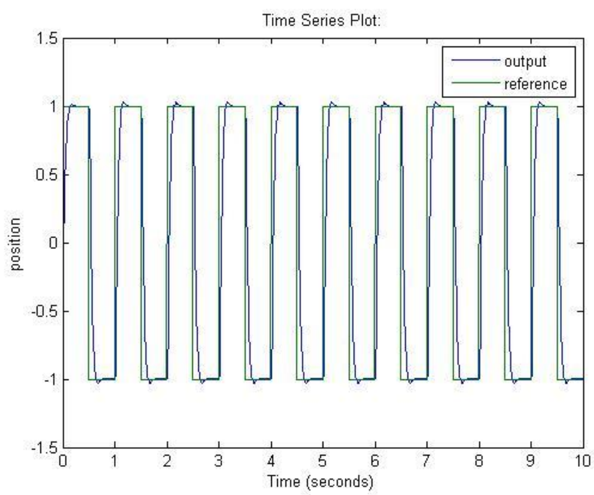

Figure 9: Response of electro hydraulic servo system for FOPID controller for square wave Response

7. Conclusion

In this paper the electrohyraulic servo system is modeled and then linearised. The step response for the controllers is obtained. Here the controllers used are of PID and FOPID. The PID controllers are tuned using auto tuning, Ziegler Nichols Tuning, and PSO optimized PID controller were used. From these three types of PID controller the step response of PSO optimized PID controller is much better i.e., the settling time is much reduced when compare to others. Also the fractional order controller is implemented. FOPID controllers have much faster settling time when compared to PID controller. The position tracking of FOPID controllers are obtained. The EHSS exactly tracks the reference signal when FOPID controllers are used.

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