Position Tracking Performance for Electro-Hydraulic Actuator System with the Presence of Actuator Internal Leakage

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***Abstract*—Electro-hydraulic actuator (EHA) system is known as one of the highly nonlinear systems due to its parameters uncertainties. Many types of robust controller had been studied and proposed to control the nonlinear EHA system. Different parameters uncertainties test is needed in the procedure to evaluate the controller robustness. In this paper, the effect of the actuator internal leakage to the output actuator displacement is studied. The actuator output displacement is analyzed using Root Mean Square Error (RMSE) by means of giving sinusoidal input reference. The results show that as the actuator internal leakage increases, the RMSE will increase and the actuator will start to vibrate or show damping characteristics.**

***Index Terms*— Electro-Hydraulic Actuator System; Actuator Internal Leakage Coefficient; Performance Analysis**

I. INTRODUCTION

In the past several decades, electro-hydraulic actuator (EHA) system has been very popular in various engineering application, such as robotics [1], surgery [2-3], aeroplane [4-6], and earth moving vehicle [7-9].

Electro-hydraulic actuator (EHA) system has always been selected to be implemented into a system rather than other dynamics, such as electric motor and pneumatic due to its advantages of small size-to-power ratios and ability to produce high force/torque output [10].

In fact, the electrohydraulic system is known to be a highly nonlinear system due to its many parameters uncertainties such as leakage, friction, pressure, and temperature of fluid [11]. It is very difficult to control the dynamic behavior of EHA system. In recent years, many researchers have condcuted a great number of studies to control the dynamics of the electro-hydraulic actuator (EHA) system due to its popularity in the latest technology [1-9],[12,13].

Various control approaches had been studied and proposed in the literature to control the dynamic behavior of EHA system. A sliding mode axis control has been proposed in [1] to reduce the chattering and provide stable force tracking in the electrohydraulic actuator. Experiments had shown strong robustness and good performance in both position and force tracking.

Electro-hydraulic transmission system had been applied by Francis and Kenji in [3] into minimally invasive robotics to perform high precision and improve the haptic feedback of surgery robots. This mechanism is replacing the highly non-linear mechanical friction of thrust wire.

The aforementioned studies proposed the control approaches to control the EHA system. However, studies that focus on the parameter uncertainties are equally important as the studies of the control approaches due to the highly non-linear uncertainties dynamic parameters in EHA system. These studies will be very helpful for the robustness test of the controller proposed. [14-17].

A discrete-time sliding mode control (DSMC) has been proposed in [14] to control the EHA system. The parameters in EHA system such as the different mass of load and spring stiffness had been varied to test the robustness of the proposed control technique. The experiment showed that the proposed control technique is highly robust to the parameters change during the position tracking control.

Other than the mass of load and spring stiffness, there are a lot of parameters that can be considered in research to control the EHA system such as the supply pressure, servo valve gain and the leakage of the valve and cylinder.

This paper will focus on the study of the actuator leakage coefficient and how it changes the dynamic behavior of the electro-hydraulic (EHA) system in open-loop.

The rest of this paper is organized as follows: Section II will describe the model of the system. The simulation studies will be explained in Section III. Section IV will present the results and discussion. Finally, the conclusions are drawn in Section V.

II. EHA SYSTEM MODELLING

As shown in Figure 1, the pipeline will act as a medium of oil transmission between the hydraulic cylinder and the servo valve in an EHA system. The cylinder actuator displacement will be generated by utilizing the servo valve that will regulate the oil flow to the hydraulic cylinder from the cylinder chamber. The counter force against the cylinder actuator will be generated by the damper and spring that are attached to the mass.

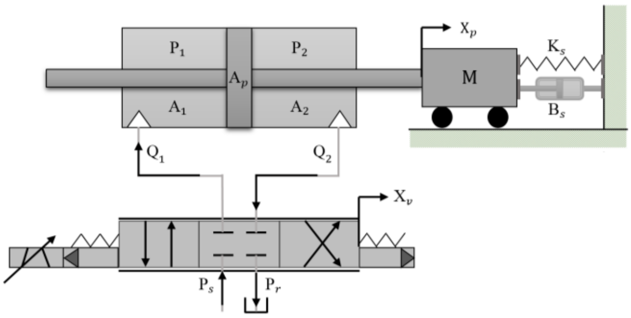

Figure 1: Schematic diagram of EHA system

The coil connected to the servo valve will supply the electric current to produce the mechanical motion of the spool valve. The servo spool valve will be driven by the torque motor that receives the power source to the desired position. The electrical signal of the motor is given as in Equation (1), [18].

$$V = \frac{dI}{dt} L_c + R_c I \tag{1}$$

where R_c and L_c are the coil resistance and inductance respectively.

The dynamics of the servo valve are represented by an equation that is related from the motor to electric current drive, as expressed in Equation (2).

$$\frac{d^2 x_v}{dt^2} + 2\xi\omega_n \frac{dx_v}{dt} + \omega_n{}^2 = I\omega_n{}^2 \tag{2}$$

where ω is the natural frequency of servo valve, while ξ is the damping ratio.

The spool valve is unexposed from dead-zone problems and leakage flows for each port in servo valve mechanical design. The chamber flow Q, controlled by servo valve can be modeled from the orifice equations that relate the pressure difference P_v and spool valve displacement x_v. The ideal orifice equation is written in Equation (3).

$$Q = K x_v \sqrt{\Delta P_v} \tag{3}$$

Pressure for each chamber can be obtained by defining the relation between volume, flow rate, and bulk modulus as expressed in Equations (4) and (5).

$$P_1 = \frac{\beta}{V_{line} + A_p(x_s + x_p)} \int (Q_1 - q_{12} - q_1 - \frac{dV_1}{dt})dt \tag{4}$$

$$P_2 = \frac{\beta}{V_{line} + A_p(x_s - x_p)} \int (\frac{dV_2}{dt} - Q_2 - q_{21} - q_2)dt \tag{5}$$

The interior leaking flow rate in the hydraulic cylinder is defined by the relation in Equation (6) and (7):

$$q_{12} = K_{Lin} \bullet (P_1 - P_2) \tag{6}$$

$$q_{21} = K_{Lin} \bullet (P_2 - P_1) \tag{7}$$

And the exterior leaking flow rate in the hydraulic cylinder is defined by the equations in Equation (8) and (9):

$$q_1 = K_{Lex} \bullet P_1 \tag{8}$$

$$q_2 = K_{Lex} \bullet P_2 \tag{9}$$

Through the overall dynamics equation of moving mass, spring, and damper, the total force produced by hydraulic actuator can be obtained in Equation (10).

$$F_p = A_p(P_1 - P_2) = M_p \frac{d^2 x_p}{dt^2} + B_s \frac{dx_p}{dt} + K_s x_p + F_f \tag{10}$$

The parameters used in this research have been tabulated in Table 1 [18,19].

Table 1 EHA System Parameters

Symbol	Description	Value
R_c	Servo-valve coil resistance	100 Ω
L_c	Servo-valve coil inductance	0.59 H
I_{sat}	Torque motor saturation current	0.02 A
ξ	Servo-valve damping ratio	0.48
ω	Servo-valve natural frequency	543 rad/s
K	Servo-valve gain	$2.38\times10^{-5} m^{5/2}/kg^{1/2}$
β	Hydraulic fluid bulk modulus	$1.4x10^9 N/m^2$
P_s	Pump pressure	$2.1x10^7 P_a$
P_r	Return pressure	0 Pa
K_s	Spring stiffness	10 Nm
X_s	Total actuator displacement	0.1 m
A_p	Piston area	$645\times10^{-6} m^2$
M_p	Total mass	9 kg
B_s	Damping coefficient	2000 Ns/m
K_{Lin}	Actuator internal leakage coefficient	1×10^{-12}
K_{Lex}	Actuator external leakage coefficient	0

III. Simulation Studies

As discussed earlier in the introduction, this paper focuses on the study of the actuator internal leakage. Basically, the actuator internal leakage will be divided into four levels with different leakage coefficient as tabulated in Table 2.

Table 2 Actuator Leakage Coefficient

Leakage level	Description	Leakage coefficient
1	Normal leak (standard real case)	1e-12
2	Small leak	1e-11
3	Medium leak	1e-10
4	Large leak	1e-09

A standard real case of the leakage coefficient is adopted from [19], which is considered as leakage level 1 and the rest is a predicted value by 10 times reduction from the normal leakage.

A sinusoidal input in terms of voltage is fit into the electro-hydraulic system and the output performance analysis is done on its actuator's position tracking performance in meter. Figure 2 illustrates the Electro-Hydraulic Actuator (EHA) system, which is utilized by using the established system in [18].

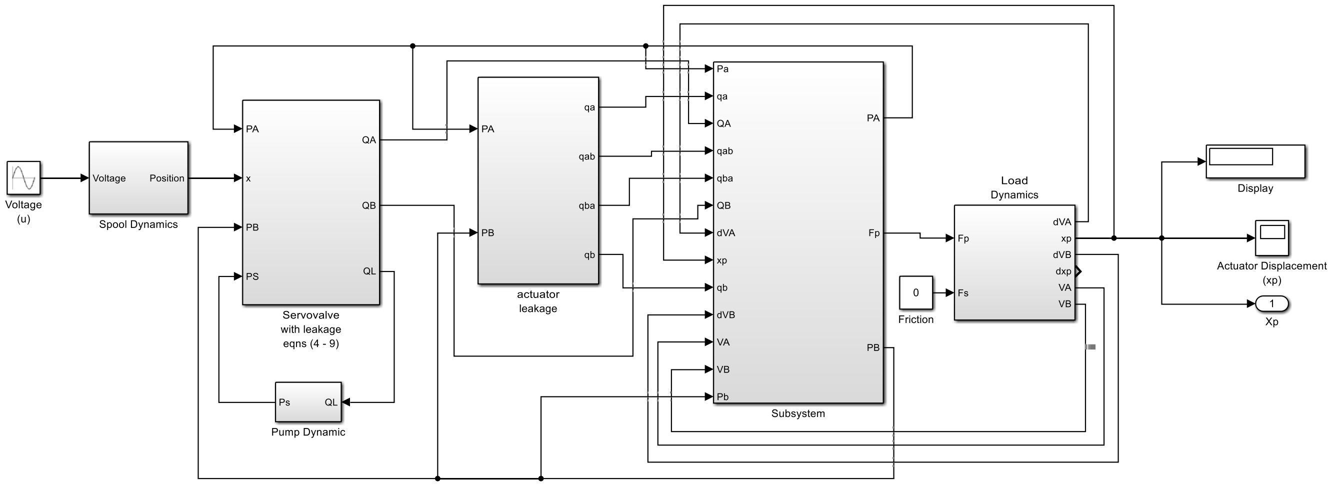

Figure 2: The Electro-Hydraulic Actuator (EHA) System

The internal leakage coefficient in the actuator is varied from level 1 to level 4 for each simulation experiment and the results will be discussed in the next section.

IV. Results And Discussion

The simulation work has been done by using MATLAB/SIMULINK 2016 software. Using the value of actuator internal leakage coefficient in Table 2, the simulation experiment is run to study the effect of the leakage to the displacement of the actuator. Figure 3 shows the graph of the displacement of the actuator in meter when it is fit in the sinusoidal input signal.

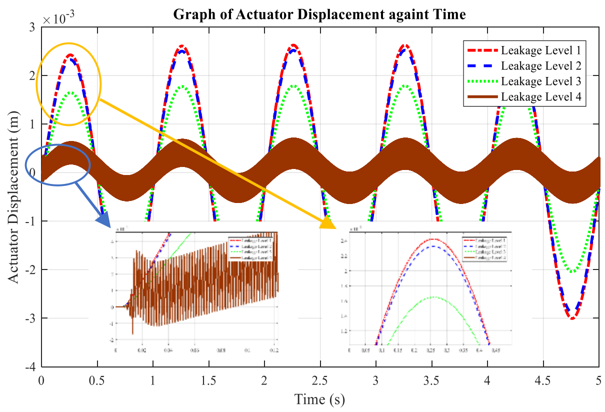

Figure 3: Graph of Actuator Displacement against Time

From Figure 3, we can see that when the small leak happened to the EHA system, which is leakage level 2, the actuator displacement is almost the same as when the normal leakage happened to the EHA system, which is leakage level 1. The tracking performance had shown a great degradation when leakage level 3 and leakage level 4 happened to the EHA system. The actuator showed damping when it comes to leakage level 4. This is due to the inconsistent pressure that happened in chamber 1 and chamber 2 of the actuator. Figure 4 shows the graph of the actuator displacement error in meter for each leakage level when the sinusoidal input reference signal is fed into the EHA system.

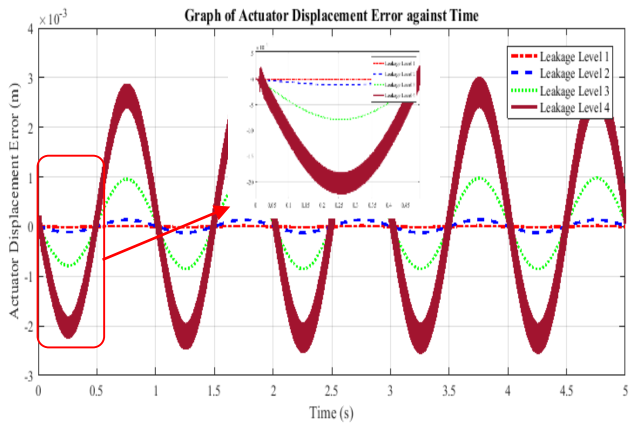

Figure 4: Graph of Actuator Displacement Error against Time

The root mean square error for the tracking performance is calculated and tabulated in Table 3. We can see that when the large leak happened, the actuator has a high RMSE and the actuator was no longer functioning well.

Table 3 Root Mean Square Error (RMSE)

Leakage Level	Root Mean Squared Error (RMSE)
1	0.0095×10^{-3}
2	0.0908×10^{-3}
3	0.6436×10^{-3}
4	1.7680×10^{-3}

Figure 5 shows the graph of the RMSE when it is tabulated against the actuator internal leakage coefficient. The graph shows that the RMSE gradually increased as the leakage level increases from level 1 to level 4.

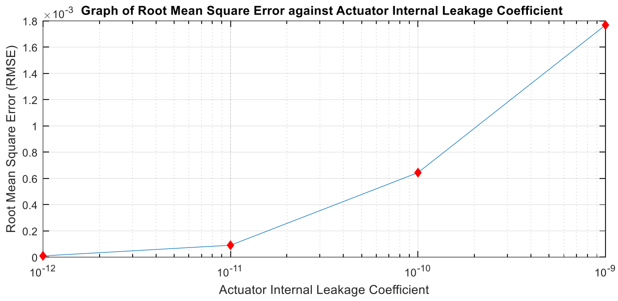

Figure 5: Graph of RMSE against Actuator Internal Leakage Coefficient

V. CONCLUSION

This paper studied the effect of actuator leakage to the displacement of the actuator, which is the hydraulic cylinder. From the simulation done by using MATLAB/SIMULINK, the actuator leakage coefficient had affected the position tracking performance of the hydraulic cylinder. As the leakage level increases, significant performance degradation has been shown through RMSE analysis. Therefore, it can be concluded that a research on the controller is necessary to overcome the parameter change in EHA system. A robust type of controller can be further studied to improve the position tracking performance of EHA system when the presence of the actuator internal leakage.

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