

Two-degree-of-freedom Robust Control for a Non-minimum Phase Electro-hydraulic System

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Abstract: Electro-hydraulic actuator (EHA) system inherently suffers from uncertainties, nonlinearities and time-varying in its model parameters which makes the modeling and controller designs are more complicated. The main objective of this paper is to perform a robust control design using discrete-time sliding mode control (DSMC) with two-degree-of-freedom control strategy. The proposed controller consists of feedback and feedforward combination which capable to reduce phase lag during the trajectory tracking of EHA system. The feedforward controller is developed by implementing the zero phase error tracking control (ZPETC) technique which the main difficulty arises from the nonminimum phase system with no stable inverse. Finally, a chaotic trajectory tracking is performed in the experimental works to show the robustness of DSMC controller and performance comparison is made with Linear-Quadratic-Regulator (LQR) and Proportional-Integral-Derivative (PID) controllers. The findings show that the proposed controller with ZPETC outperforms the LQR and PID controllers in terms of tracking accuracy.

Key Words: Electro-hydraulic Actuator System, Sliding Mode Control, Trajectory Tracking Control and Two-degree-freedom Control Structure

1 INTRODUCTION

Electro-hydraulic actuator (EHA) system emerge in fluid power technology is greatly developed from the beginning of the twentieth century where the works was first introduced by French physicist Braise Pascal in 1640s. The works concerning the principle of differential pressure turn this actuator becomes more crucial nowadays. There are many unique elements and advantages of EHA system over rival actuators such as pneumatic and electrical motor in the market these days. The main advantages of fluid power, which is led to its prominent feature, is the good ratio between forces delivered by the actuator over the weight and its size [1]. The lighter and smaller compact structure in EHA system makes this actuator very suitable to use especially in mobile industrial applications. Moreover, the combination between electrical and hydraulic devices also rendered EHA system be more flexible in implementing to real application with advanced control strategies.

EHA system has become progressively popular in various types of engineering equipment and by utilizing it advantageous, different applications such as aircrafts [2], manufacturing machines [3], fatigue testing [4], hydraulic excavator [5], sheet metal forming process [6] and automotive applications [7] established that the actuator system can be more well-known and crucial nowadays. However, the EHA system is known as a complicated

system which suffers from uncertainties, nonlinearities and disturbances. These inconveniences may lead to degradation of control performance in trajectory tracking of the EHA system.

Nonlinear flow and pressure characteristics, actuator friction, fluid compressibility and leakages are identified as the significant sources of nonlinearity exist in the EHA system [8]. Recent works in [9] established mathematical model of the EHA system by including the effect of compressibility, external leakage in actuator and internal leakage in the servo valve. Most of flow valves also suffer from hard nonlinearities such as dead-zone due to asymmetric overlap in the spool valve design [10, 11]. Besides, the friction phenomena that generally affect the tracking performance are often considered as a nonlinear model in developing the dynamics equation of EHA system [12]. Therefore, a feedback control strategy is always required in designing the high performance trajectory tracking and positioning of EHA system.

Various types of feedback controller ranging from linear to nonlinear type are widely implemented and published among academia and researchers for trajectory tracking control of EHA system. The increasing numbers of works dealing with EHA system over the past decades involved a linear control, intelligent control and nonlinear control approaches such as neural network (NN) [10], self-tuning Fuzzy-PID [13,14], model reference adaptive control (MRAC) [15,16], generalized predictive control (GPC) [17] and sliding mode control (SMC) [18]. There are much works in designing SMC for EHA system previously based

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and position of the hydraulic actuator. The corresponding discrete-time model follows by transforming the continuous-time model in equation (5) with zero-order-hold as in (6).

$$G(z) = \frac{y(k)}{u(k)} = \frac{b_1 z^2 + b_2 z + b_3}{z^3 + a_1 z^2 + a_2 z + a_3} \quad (6)$$

Linearization of EHA system has been studied and employed over the past decades to encounter the nonlinearities subsists in the modeling process. There are numerous researchers who used that linear model in either continuous-time or discrete-time in their proposed control strategy. Most of the modeling approaches for discrete-time model that have been implemented in previous researches are developed from first principle or physical laws. Although the importance of physical modeling is always considered in the controller design, but in real implementation, validation of the physical plant model is necessary in optimizing the use of controller that commonly designs via computer simulation. Furthermore, any changes in the EHA system's parameter may reduce the controller performance and the desired specification possibly not achieved. Therefore, system identification with online estimation technique is always performed as an adaptive mechanism integrating with other control design [25]. The discrete-time transfer function in (6) can be represented in state-space control canonical form.

$$x(k+1) = \Phi x(k) + \Gamma u(k) \quad (7)$$

$$y(k) = \Psi x(k) \quad (8)$$

where

$$\Phi = \begin{bmatrix} -a_1 & -a_2 & -a_3 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \Gamma = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T \text{ and } \Psi = \begin{bmatrix} b_1 & b_2 & b_3 \end{bmatrix}.$$

From the state space model in (7) and (8), the discrete-time transfer function can be derived as

$$\frac{y(k)}{u(k)} = \Psi(zI - \Phi)^{-1} \Gamma = G(z) \quad (9)$$

Since the two-degree-of-freedom controller design is based on cancellation of all of the poles and well-damped zeros of feedback loop systems, the plant dynamics must be known in advance. A discrete-time model is determined experimentally using system identification technique from real plant of EHA system. A third order system is found to be adequate to represent the EHA system and being used in the control analysis [26-27]. The percentage of best fit for a third order model is 95.48% while the final prediction error is 0.0228. The discrete-time transfer function obtained from the identification is represented in (10).

$$G(z) = \frac{y(k)}{u(k)} = \frac{-0.03093 z^2 + 0.3836 z - 0.2738}{z^3 - 1.887 z^2 + 1.056 z - 0.1695} \quad (10)$$

3 DISCRETE SLIDING MODE CONTROL

Basic idea of the perfect tracking control strategy in two-degree-of-freedom structure is to achieve the transfer function from the desired trajectory to the output of the systems to become unity [28]. With that, the feedforward

controller can be designed by the inverse of closed loop system transfer function and the phase error can be eliminated in the tracking control system. A robust control such as SMC is needed in designing the feedback controller to obtain great performance in trajectory tracking control. The controller design is quite unique as compared to any other controller design methods since the performance of the controller depends on the design of the sliding surface and not the state tracking directly. The idea of SMC strategy is to force the trajectory of the states towards the sliding surface and once reached, the states are forced to remain on that surface.

SMC is a type of variable structure control (VSC) developed in the early of 60's in Russia [23]. This robust control technique is originally established in continuous-time. Various researchers have utilized the SMC schemes to control a number of nonlinear and uncertain systems due to its inherent insensitivity property to parameter variations and external disturbances. A research in developing SMC in discrete-time only starts in the late of 80's. It is established that the most crucial step in designing the SMC either in continuous-time or discrete-time is the construction of the sliding surface which is expected to response the desired control specifications and performances. The sliding surface can be expressed in following equation:

$$s(k) = C_{smc} x(k) \quad (11)$$

The reachability condition to ensure the stability in discrete-time is represented by

$$|s(k+1)| < |s(k)| \quad (12)$$

Different from the DSMC design based on equivalent technique, the concept of reaching law can be used to design the DSMC control law and it is proven to be stable by fulfilled the reachability condition [24]. The reaching law in discrete-time is used in the controller design is

$$s(k+1) = (1 - qT_s)s(k) - \eta T_s \text{sign}(s) \quad (13)$$

with $\eta > 0$ and $0 < (1 - qT_s) < 1$

The control law can be designed for the nominal plant model in (7) with uncertainties and disturbances where the uncertain and disturbed plant can be modeled as

$$x(k+1) = (\Phi + \Delta\Phi)x(k) + \Gamma u(k) + Pf(k) \quad (14)$$

Designing the DSMC control law with reaching law gives

$$u(k) = -(C_{smc}\Gamma)^{-1} [C_{smc}\Phi - (1 - qT_s)C_{smc}]x(k) - (C_{smc}\Gamma)^{-1} \eta T_s \text{sign}(s(k)) - (C_{smc}\Gamma)^{-1} [C_{smc}\Delta\Phi x(k) + C_{smc}Pf(k)] \quad (15)$$

The developed control law is redesigned due to the unknown terms $\Delta\Phi$ and $f(k)$ which are usually unknown. The assumption where the lower and upper bounds of $C_{smc}\Delta\Phi x(k) + C_{smc}Pf(k)$ is assigned by the following condition

$$-L_d T_s < C_{smc}\Delta\Phi x(k) + C_{smc}Pf(k) < L_d T_s \quad (16)$$

where L_d is the lumped uncertainties and disturbances boundary in the system. The SMC control law is then modified as

$$\begin{aligned}
u(k) = & -(C_{smc}\Gamma)^{-1}[C_{smc}\Phi - (1-qT_s)C_{smc}]x(k) \\
& -(C_{smc}\Gamma)^{-1}\eta T_s \text{sign}(s(k)) \\
& -(C_{smc}\Gamma)^{-1}L_d T_s \text{sign}(s(k)) \quad (17)
\end{aligned}$$

The control law in (16) only guarantees that $s(k)[s(k+1)-s(k)] < 0$ which is not sufficient for a quasi-sliding mode [25]. It is necessary that the control law to guarantees a sliding mode condition where

$$L_d T_s < \frac{\eta T_s}{2(1-qT_s)} \text{ with } \eta > 0, L_d > 0 \quad (18)$$

The resulting SMC control for the bounded uncertainties can be represented as

$$u(k) = -K_{smc}x(k) - K_{sw}\text{sign}(s(k)) \quad (19)$$

where $K_{smc} = (C_{smc}\Gamma)^{-1}[C_{smc}\Phi - (1-qT_s)C_{smc}]$ and $K_{sw} = (C_{smc}\Gamma)^{-1}(\eta + L_d)T_s = (C_{smc}\Gamma)^{-1}\rho_{sw}T_s$.

The selection of the parameter $\rho_{sw} = \eta + L_d$ in the switching control law is usually a trade-off between width of the quasi sliding mode band and robust performance of the system under model uncertainties and disturbances [24]. Therefore, the closed loop system inside the sliding mode band which is without the uncertainties and disturbances can be represented as

$$T(z) = \Psi(zI - \Phi_{cl})^{-1}\Gamma \quad (20)$$

where

$$\Phi_{cl} = \Phi - \Gamma K_{smc} = \Phi - \Gamma(C_{smc}\Gamma)^{-1}[C_{smc}\Phi - (1-qT_s)C_{smc}]$$

Most of tracking control system with DSMC is purposely for minimizing gain error from the output to the desired trajectory. However, the phase error in the trajectory tracking is always neglected in that control scheme. Thus, the trajectory tracking error minimization can be achieved by introducing a feedforward controller to eliminate the zeros and poles in the closed loop system [28]. The main objective in that control scheme is to drive the actuator to follow perfectly the desired trajectory and minimizing the phase lag that regularly caused by feedback loop in closed loop system. For minimum phase model, the perfect tracking control structure can be designed by direct inverse of the closed loop system with DSMC in (20) to achieve a feedforward controller. The feedforward controller is then can be represented by

$$G_{ff}(z) = [T(z)]^{-1} = [\Psi(zI - \Phi_{cl})^{-1}\Gamma]^{-1} \quad (21)$$

It can be observed from the closed-loop transfer function, the numerator which represents the zeroes in the system is dominated by the open-loop system that caused a non-minimum phase problem. The problem of inversion is occurred when the $G_{cl}(z)$ have zeros outside the unit circle where the non-minimum phase of the open-loop EHA system have influenced to the closed loop system dynamics. Direct inverse of the $G_{cl}(z)$ will caused unstable condition in $G_{ff}(z)$. Therefore, method in [28] will be used

in developing the feedforward controller to avoid the instability problem.

4 FEEDFORWARD CONTROLLER DESIGN

Since the direct inverse of the closed loop transfer function is unfeasible, the approximation of the feedforward controller can be implemented to represent the inverse of closed loop system and cancelled the poles and zeros. The direct inversion of closed loop system can be represented as:

$$\begin{aligned}
G_{ff}(z) &= [G_{cl}(z)]^{-1} = \frac{D_{cl}(z)}{N_{cl}(z)} \\
&= \frac{z^3 - 1.7022z^2 + 0.9009z - 0.1404}{-0.03093z^2 + 0.3836z - 0.2738} \quad (22)
\end{aligned}$$

The block diagram as shown in Figure 2 described the approximation of feed-forward control design for nonminimum phase systems using ZPETC strategy. The proposed method can be divided into three blocks which are gain compensation filter, phase compensation filter and stable inverse. From equation (22), one of the poles in the feed-forward controller is outside in the unit circle. In the feed-forward design, equation in (22) can be represented in delay form.

$$G_{ff}(z^{-1}) = \frac{1 - 1.7022z^{-1} + 0.9009z^{-2} - 0.1404z^{-3}}{-0.03093z^{-1} + 0.3836z^{-2} - 0.2738z^{-3}} \quad (23)$$

The numerator of the closed-loop systems can be factorized in the feed-forward controller,

$$\begin{aligned}
G_{ff}(z^{-1}) &= \frac{D_{cl}(z^{-1})}{N_{cl}^{+}(z^{-1})N_{cl}^{-}(z^{-1})} \\
&= \frac{1 - 1.7022z^{-1} + 0.9009z^{-2} - 0.1404z^{-3}}{-0.0309z^{-1}(1 - 0.76z^{-1})(1 - 11.654z^{-1})} \quad (24)
\end{aligned}$$

where

$$N_{cl}^{+}(z^{-1}) = -0.0309z^{-1}(1 - 0.76z^{-1})$$

$$N_{cl}^{-}(z^{-1}) = 1 - 11.654z^{-1}$$

Based on the proposed method, stable inverse can be stated as following equation;

$$\begin{aligned}
G_{ff1}(z^{-1}) &= \frac{D_{cl}(z^{-1})}{N_{cl}^{+}(z^{-1})} \\
&= \frac{1 - 0.6798z^{-1} - 0.2405z^{-2} + 0.1350z^{-3}}{-0.0309z^{-1}(1 - 0.76z^{-1})} \quad (25)
\end{aligned}$$

In advance form, the phase compensation filter can be described as;

$$G_{ff2}(z) = z^d N_{cl}^{-}(z) = z(1 - 11.654z) \quad (26)$$

where $d=1$ and the gain compensation filter is

$$G_{ff3} = \frac{1}{[N_{cl}^{-}(1)]^2} = \frac{1}{[1 - 11.654(1)]^2} = 0.00881 \quad (27)$$

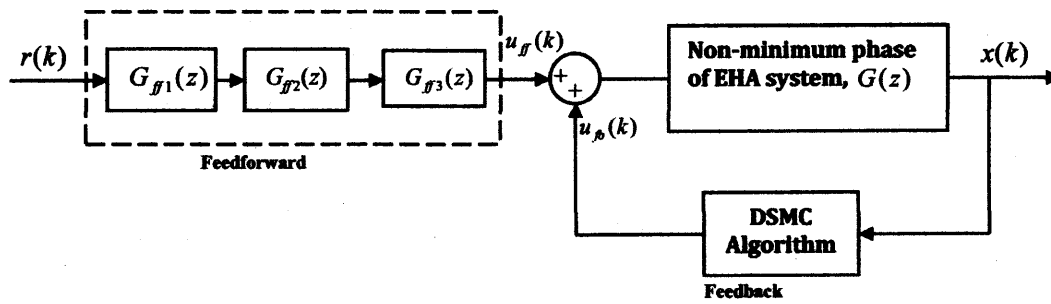


Fig 2. Two-degree-of-freedom control structure with Discrete Sliding Mode Control

5 RESULTS AND DISCUSSION

In the experimental study, a chaotic trajectory tracking performance of the proposed controller scheme is evaluated. The chaotic reference trajectory is developed as used by [29] in their simulation study. The algorithm to generate the desired trajectory is presented as

$$\begin{aligned}\dot{r}(t) &= a[y(t) - r(t)] \\ \dot{y}(t) &= (c - a)r(t) - r(t)z(t) + cy(t) \\ \dot{z}(t) &= r(t)y(t) - bz(t)\end{aligned}\quad (28)$$

where a , b and c are constant parameters in the reference trajectory design.



Fig 3. Experimental Workbench of EHA system

Figure 3 depicts the complete test bed of the EHA system. The experimental design for EHA system is composed of a single-rod and double acting hydraulic cylinder, which is driven by a direct servo valve Bosch Rexroth 4WREE6, 40lpm flow rate at 80 bar. The dimensions of hydraulic cylinder are 63/30/300 (mm). Piston position is measured by using 300mm draw wire sensor. The sampling time is set at 5 milliseconds which caused a nonminimum phase model where direct inverse of the closed loop system with DSMC can be achieved to perform a two-degree-of-freedom controller design.

A chaotic trajectory as illustrated in Figure 4 is implemented as a desired position for the EHA system. This trajectory consists of different desired point over 50% of the maximum stroke of hydraulic actuator. This trajectory tracking control is conducted for 100 seconds of

experiment. The LQR and PID controller are also implemented in this experimental study. The LQR controller is constructed in two-degree-of-freedom control structure similar with the proposed controller while the PID control is designed with conventional feedback structure. For practical comparison, the DSMC parameters are determined based on the closed loop poles as given by the LQR controller. The PID controller is tuned by using the Ziegler-Nichols technique. All the parameters of developed controllers are tabulated in Table 1.

Table 1. Controller Parameters

Controller	Parameter	Value
DSMC	q	147.0254
	ρ_{sm}	200
	c_1	1.0000
	c_2	-1.0082
	c_3	0.3284
LQR	k_1	0.6140
	k_2	-0.4611
	k_3	0.0826
PID	K_p	1.8
	K_i	0.03
	K_d	0.16

From the experimental results, it shows that the tracking performance for both DSMC and LQR in Figure 4 is improved with the two-degree-of-freedom controller design where the piston position can track the chaotic trajectory quite well as compared with conventional PID controller. It can be seen that the PID controller suffers due to phase lag during the tracking process. The tracking error as illustrated in Figure 5 shows that DSMC and LQR result small error while the PID controller has shown significant tracking error. It is shows that DSMC with two-degree-of-freedom control strategy is very sensitive towards any changes in the system parameters. DMSC also is found to be capable to handle dead-band nonlinearity which occurs due to Coulomb friction and overlap of valve ports in the EHA system. The root-mean-square-error (RMSE) of the tracking error for 100 seconds of tracking control as tabulated in Table 1 described that DSMC perform better

tracking performance as compared with LQR and PID controller.

Root-mean-square-error (RMSE) for 100 seconds of experiment is determined and tabulated in Table II. Based on the error analyses, control efforts and observation on the tracking performance, the DSMC provides more suitable and better performance in trajectory tracking control and ensured that the control system in under stable condition. However, the RMSE for DSMC did not show any

significant improvement as compared with LQR strategy. It is found there are small variation in the system's parameters due the 100 seconds of experiments. Thus, a robustness test is needed to evaluate the proposed DSMC designed by reducing 50% of the supply pressure in the EHA system. Figure 6 shows the tracking error for a chaotic reference trajectory during the robustness test. The RMSE for all controllers in both experiments are tabulated in Table 2.

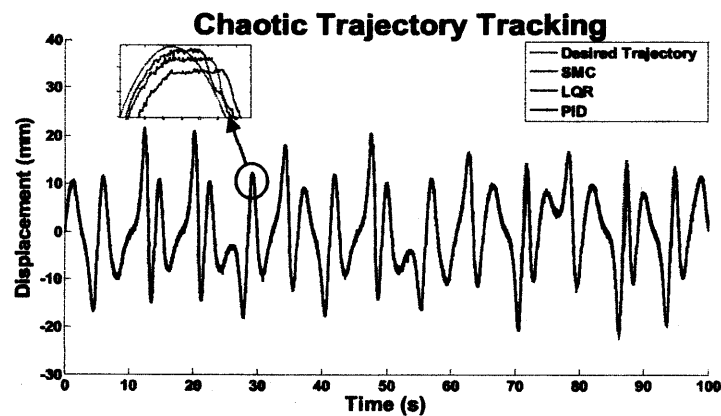


Fig 4. Chaotic Trajectory Tracking for DSMC, LQR and PID controllers.

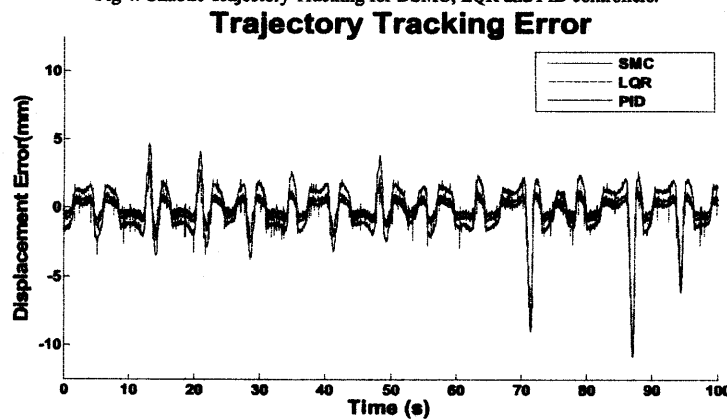


Fig 5. Trajectory tracking error for DSMC, LQR and PID controller under constant supply pressure

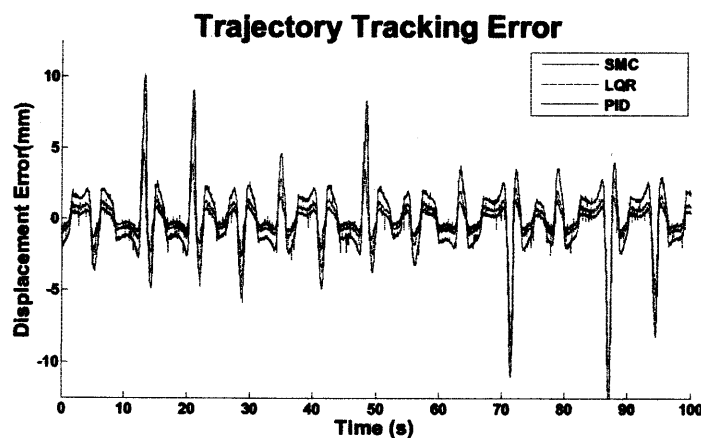


Fig 6. Trajectory tracking error for DSMC, LQR and PID controller under 50% of supply pressure

Table2. RMSE

Controller	DSMC	LQR	PID
RMSE (constant supply pressure)	1.0192	1.2543	1.8071
RMSE (50% of supply pressure)	1.2311	1.6574	2.1259

6 CONCLUSION

In this study, the tracking control performance of DSMC in the two-degree-of-freedom control structure with ZPETC is evaluated through experimental study for a chaotic type of trajectory. Theoretical analysis is developed in DSMC to ensure that the system is under stable condition and its parameters are determined based on the desired closed loop response. The experimental results show that the DSMC provides better performance in tracking accuracy and is compared to the LQR and PID controller. As conclusion, the robustness of DSMC is guaranteed for a system which is subjected with uncertainties and disturbances.

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