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2016

Teng, L., Yang, H., & Wang, Y. (2016). Model reference tracking control of linear motor with dead-zone via switched systems subjected to time-varying delay. IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, 589-594.
doi:10.1109/iecon.2016.7793469

<https://hdl.handle.net/10356/144979>

<https://doi.org/10.1109/IECON.2016.7793469>

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Model reference tracking control of linear motor with dead-zone via switched systems subjected to time-varying delay

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Abstract—In this paper, model reference tracking control of linear brushless DC motor with dead-zone is investigated. Compared with traditional control methods which requires the nonlinear model of dead-zone and then compensation is executed, the dead-zone is modeled as time-varying input delay systems. Thus the complex nonlinearities of dead-zone can be ignored. As a result, the whole motor motion can be regarded as switched systems comprised of two subsystems, one is a linear time-varying input delay system when motor enters the dead-zone, and the other one is a linear non-delayed system when motor leaves the dead-zone. The tracking control problems for both subsystems are considered. In particular, a stabilization method based on Lyapunov-Razumikhin function is adopted for system with time-varying delay, which leads to easier implementations of controller synthesis and computation when compared to Lyapunov-Krasovskii function. Simulation and experimental results on a linear motor is provided to illustrate the effectiveness of the proposed method.

I. INTRODUCTION

Precision motion control technique has been widely investigated since it is essential in industrial manufacturing, precision devices and robotics and so on [1]-[2]. However, utilization of servo actuators such as hydraulic servo valves and electrical motors, usually suffer from non-smooth nonlinearities, e.g., saturation, backlash, dead-zone and friction [3]-[5]. Existence of these nonlinearities may cause degradation of control performance or even instability of system if they were not well handled.

Considering systems with dead-zone, it has attracted extensive research interests in the past two decades and many contributions have been achieved. In [6]-[8], adaptive control is theoretically investigated for nonlinear systems with dead-zone by constructing the dead-zone inverse. Adaptive compensation algorithm without considering the dead-zone inverse is shown in [9]-[10]. In [11]-[12], fuzzy logic and neural networks are utilized for dead-zone compensation. In practical applications, dead-zone compensation control of motor-driven systems can be seen in [13]-[15]. Adaptive sliding mode control of electro-hydraulic servo-systems with dead-zone can be found in [16].

However, In the aforementioned works dealing with dead-zone, the dead-zone dynamics is fully enrolled and compensation-based control is investigated. The utilization of

adaptive control usually accompanied by complicated adaptive schemes which make the situation even worse. In addition, although sliding mode control has advantages in robustness of uncertainties and disturbances in nonlinear functions, it may suffer from the chattering phenomena and sensitivity to measurement noise in the systems.

From another point of view, the dead-zone can also be described as dead time. For this reason, the dead-zone can be regarded as systems suffering from input delay. Thus the control theory for time-delay systems can be employed to guarantee the asymptotical stability of motion tracking.

On the other hand, in the case of tracking control of time-delay systems, extensive results have been achieved in the past decade [17]-[19]. Adaptive and adaptive fuzzy control approaches for tracking control of systems with time delay and dead-zone are considered in [20]-[22]. Tracking control of switched time-delay systems is investigated in [23] and [24]. However, it can be seen that the Lyapunov Krasovskii Function (LKF) is mostly used for stability analysis and stabilization in aforementioned approaches handling time delay, which usually leads to a very complicated derivation of stability analysis and controller synthesis.

In this work, we consider position control of a linear brushless DC motor (LBDCM). The whole motor motion can be regarded as switched systems consisting of two subsystems, one is a linear time-varying input-delay system when motor encounters with the dead-zone, and the other one is a linear system without delay when motor leaves the dead-zone. The switching condition is based on the detection of input signal. If the input signal is less than a specific value for motor with a specific load, then it is thought that the dead-zone is detected and the system is switched to system with input delay.

Moreover, model reference tracking control of discrete systems with time-varying delay based on Lyapunov-Razumikhin function (LRF) is investigated, and a simple control strategy to guarantee the tracking stability is provided. Utilization of LRF for stability can alleviate the complexity of controller synthesis compared with LKF. The H_∞ control problem is employed and the control law is computed by solving matrix inequalities.

The rest of this paper is structured as follows. In Section II, problem transition from system with dead-zone to switched systems with input delay is introduced. In Section III, control law of the switched systems is introduced. Simulation on a linear motor servo system which is used to verify the effectiveness of the proposed method is shown in Section IV. In Section V, experimental exhibition is introduced. Finally, some conclusions are given in Section VI.

II. PRELIMINARIES

In this section, the motor model, dead-zone model and the switched systems are introduced.

A. Plant Model

The frequency response of a linear motor driven by a motor drive working in torque control mode is defined by

$$\frac{Y(s)}{U(s)} = \frac{b}{s(s+a)} \quad (1)$$

where $Y(s)$ is the rotor position. $U(s)$ is the I_q command current expressed in terms of voltage. From (1), the following continuous state space model is obtained:

$$\dot{x}(t) = A_c x(t) + B_c u(t) + E_c w(t) \quad (2)$$

where $w(t)$ represents the disturbances and parameter uncertainties, and

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, A_c = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix}, B_c = \begin{bmatrix} 0 \\ b \end{bmatrix}, E_c = \begin{bmatrix} 0 \\ c \end{bmatrix}.$$

where x_1 and x_2 represent the position and the speed, respectively. Discretize the above model with sampling time T_s using the following method

$$A = e^{A_c T_s}, B = \int_0^{T_s} e^{A_c \tau} d\tau B_c, E = \int_0^{T_s} e^{A_c \tau} d\tau E_c.$$

Then the discrete system can be got:

$$x(k+1) = Ax(k) + Bu(k) + Ew(k) \quad (3)$$

B. Dead-zone Model and Switched Systems

A typical dead-zone model is shown in Fig. 1, where v and u represent the rotor speed and the applied voltage, respectively.

The mathematical model of the dead-zone is described as follows:

$$v(t) = \begin{cases} m_r(u(t) - b_r) & u(t) \geq b_r, \\ 0 & b_l < u(t) < b_r, \\ m_l(u(t) + b_l) & u(t) \leq b_l. \end{cases} \quad (4)$$

where b_l , b_r , m_l , and m_r are constants and represent left break-point, right break-point, left slope, and right slope of the dead-zone. It is shown that when the control input is less than some specific values, the actuator will enter the dead-zone. To avoid the dead-zone, one direct method is to let the control input always larger than the upper bound of dead-zone. In this work, the dead-zone is handled via a time-delay approach that the detailed nonlinearities of dead-zone can be ignored. Thus,

Fig. 1. Dead-zone model.

we only need to know an upper bound of the dead-zone. To further simplify the controller design, suppose

$$u_{dz} \geq \max\{|b_r|, |b_l|\} \quad (5)$$

where u_{dz} stands for an upper bound of the dead-zone for the input signal.

The motor dynamics with dead-zone are modeled as switched time-delay systems with input delay:

$$x(k+1) = Ax(k) + Bu(k) + Ew(k) \quad |u(k)| \geq u_{dz} \quad (6a)$$

$$x(k+1) = Ax(k) + Bu_d(k) + Ew(k) \quad |u(k)| < u_{dz} \quad (6b)$$

where $u_d(k)$ is the delayed input. From (6a) and (6b), it can be seen that the two systems are utilized in different conditions. If the dead-zone does not occur, then the linear system without delay will be investigated and the corresponding feedback controller will be applied. However, if dead-zone exists, i.e., $|u(k)| < u_{dz}$, then the system with input delay will be utilized that a new feedback control law is applied. Under such circumstances, the previous state rather than the current state will be used for feedback to obtain a control law which is larger than the upper bound of the dead-zone.

C. Reference Model

The linear desired reference model is given as follows:

$$x_r(k+1) = A_r x_r(k) + B_r r(k) \quad (7)$$

where $x_r(k)$ and $r(k)$ represent the reference state and input reference signal, respectively. A_r denotes a specific asymptotically stable matrix.

Furthermore, the H_∞ control problem can be described as:

$$\sum_{k=0}^{\infty} \{(x(k) - x_r(k))^T Q (x(k) - x_r(k))\} \leq \rho^2 \sum_{k=0}^{\infty} \tilde{w}(k)^T \tilde{w}(k) \quad (8)$$

where $x(k) - x_r(k)$ represents the tracking error. Q is a positive definite weighting matrix. ρ describes the disturbance

Fig. 2. Controlled system with dead-zone.

attenuation level, and $\tilde{w}(k) = [w^T(k), r^T(k)]^T$ represents the disturbance and reference input.

III. MAIN RESULTS

In this section, the control framework and stabilization conditions for the switched systems are introduced.

The control framework can be seen in Fig. 2. It uses two buffers to preserve the current and past feedback states and reference states, respectively, where N is the buffer size. If the dead-zone is not detected, then system (6a) is considered that the current feedback state and reference state are employed for controller computation. Otherwise, if the dead-zone exists, (6b) is considered that previously delayed states are adopted.

A. System with Input Delay

Considering (6b), if the feedback control law for system with input delay is given as:

$$u_d(k) = K(x_d(k) - x_{rd}(k)) \quad (9)$$

where $x_d(k)$ and $x_{rd}(k)$ are delayed state and delayed reference state, respectively, then the augmented system can be described as follows:

$$\bar{x}(k+1) = \bar{A}\bar{x}(k) + \bar{A}_d\bar{x}_d(k) + \bar{E}\bar{w}(k) \quad (10)$$

where

$$\bar{x}(k) = \begin{bmatrix} x(k) \\ x_r(k) \end{bmatrix}, \bar{x}_d(k) = \begin{bmatrix} x_d(k) \\ x_{rd}(k) \end{bmatrix},$$

$$\bar{A} = \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix}, \bar{A}_d = \begin{bmatrix} BK & -BK \\ 0 & 0 \end{bmatrix},$$

$$\bar{E} = \begin{bmatrix} E & 0 \\ 0 & B_r \end{bmatrix}, \bar{w}(k) = \begin{bmatrix} w(k) \\ r(k) \end{bmatrix}.$$

The H_∞ control problem for the aforementioned augmented systems can be described as follows:

$$\sum_{k=0}^{k_f} \{(x(k) - x_r(k))^T Q (x(k) - x_r(k))\} =$$

$$\sum_{k=0}^{k_f} \{\bar{x}(k)^T \bar{Q} \bar{x}(k)\} \leq \rho^2 \sum_{k=0}^{k_f} \bar{w}(k)^T \bar{w}(k) \quad (11)$$

where

$$\bar{Q} = \begin{bmatrix} Q & -Q \\ -Q & Q \end{bmatrix} \quad (12)$$

In this work, to reduce the complexity of controller synthesis, the LRF rather the LKF is adopted for stabilization

of input-delay system (10). As disturbance is involved, the H_∞ control problem is considered to attenuate the impact of the disturbance. However, as LRF is employed, the typical H_∞ performance can not be guaranteed. Instead, the following H_∞ -like stabilization condition of (10) is investigated:

$$V(\bar{x}^+) - \tau \bar{V}(\bar{x}) + \bar{x}^T \bar{Q} \bar{x} - \rho^2 \bar{w}^T \bar{w} < 0 \quad (13)$$

where $V(\bar{x}^+) = \bar{x}^{+T} \bar{P} \bar{x}^+$, $\bar{V}(\bar{x}) = \max\{V(\bar{x}), V(\bar{x}_d)\}$ with $V(\bar{x}) = \bar{x}^T \bar{P} \bar{x}$ and $V(\bar{x}_d) = \bar{x}_d^T \bar{P} \bar{x}_d$, and $\tau \in \mathbb{R}_{(0,1)}$.

Theorem 1: If there exist positive definite matrix $\bar{P}$, positive scalar $\tau \in \mathbb{R}_{(0,1)}$, such that the following matrix inequality is feasible

$$\begin{bmatrix} \bar{A}^T \bar{P} \bar{A} - \tau \gamma \bar{P} + \bar{Q} & * & * \\ \bar{A}_d^T \bar{P} \bar{A} & \bar{A}_d^T \bar{P} \bar{A}_d - \tau \gamma_d \bar{P} & * \\ \bar{E}^T \bar{P} \bar{A} & \bar{E}^T \bar{P} \bar{A}_d & \bar{E}^T \bar{P} \bar{E} - \rho^2 I \end{bmatrix} < 0 \quad (14)$$

where γ and γ_d are pre-set valued positive scalars satisfying $\gamma + \gamma_d = 1$, then the augmented system is asymptotically stable under the control law $\pi = K(x_d(k) - x_{rd}(k))$, and the H_∞ -like control performance is guaranteed.

Proof: Multiplying $\begin{bmatrix} \bar{x}^T & \bar{x}_d^T & \bar{w}^T \end{bmatrix}$ and its transpose from both sides of (14), respectively, yields that

$$(\bar{A}\bar{x}(k) + \bar{A}_d\bar{x}_d(k) + \bar{E}\bar{w}(k))^T \bar{P} (\bar{A}\bar{x}(k) + \bar{A}_d\bar{x}_d(k) + \bar{E}\bar{w}(k)) - \tau \gamma \bar{x}^T(k) \bar{P} \bar{x}(k) - \tau \gamma_d \bar{x}_d^T(k) \bar{P} \bar{x}_d(k) + \bar{x}^T(k) \bar{Q} \bar{x}(k) - \rho^2 \bar{w}^T(k) \bar{w}(k) < 0 \quad (15)$$

Since $\tau \gamma \bar{x}^T(k) \bar{P} \bar{x}(k) + \tau \gamma_d \bar{x}_d^T(k) \bar{P} \bar{x}_d(k) \leq \tau \bar{V}(\bar{x})$ due to $\gamma + \gamma_d = 1$, then

$$V(\bar{x}^+) - \bar{V}(\bar{x}) + \bar{x}^T(k) \bar{Q} \bar{x}(k) - \rho^2 \bar{w}^T(k) \bar{w}(k) < 0 \quad (16)$$

Proof is thus completed.

For convenience, $\bar{P}$ can be described as

$$\bar{P} = \begin{bmatrix} P_c & \\ & P_r \end{bmatrix} \quad (17)$$

Then (14) can be rewritten as

$$\begin{bmatrix} \Theta_{11} & * & * & * & * & * \\ -Q & \Theta_{22} & * & * & * & * \\ \Theta_{31} & 0 & \Theta_{33} & * & * & * \\ \Theta_{41} & 0 & \Theta_{43} & \Theta_{44} & * & * \\ E^T P_c A & 0 & \Theta_{53} & \Theta_{54} & \Theta_{55} & * \\ 0 & B_r^T P_r A_r & 0 & 0 & 0 & \Theta_{66} \end{bmatrix} < 0 \quad (18)$$

where $\Theta_{11} = A^T P_c A - \tau \gamma P_c + Q$, $\Theta_{22} = A_r^T P_r A_r - \tau \gamma P_r + Q$, $\Theta_{31} = -\Theta_{41} = (BK)^T P_c A$, $\Theta_{33} = (BK)^T P_c BK - \tau \gamma_d P_c$, $\Theta_{43} = -(BK)^T P_c BK$, $\Theta_{44} = (BK)^T P_c BK - \tau \gamma_d P_r$, $\Theta_{53} = -\Theta_{54} = E^T P_c BK$, $\Theta_{55} = E^T P_c E - \rho^2 I$, $\Theta_{66} = B_r^T P_r B_r - \rho^2 I$.

B. System Without Delay

The control law for the non-delayed counterpart (6a) is given as follows:

$$u(k) = K(x(k) - x_r(k)) \quad (19)$$

Then the augmented system can be described as:

$$\tilde{x}(k+1) = \tilde{A}\tilde{x}(k) + \tilde{E}\tilde{w}(k) \quad (20)$$

where

$$\tilde{x}(k) = \begin{bmatrix} x(k) \\ x_r(k) \end{bmatrix}, \tilde{w}(k) = \begin{bmatrix} w(k) \\ r(k) \end{bmatrix},$$

$$\tilde{A} = \begin{bmatrix} A + BK & -BK \\ 0 & A_r \end{bmatrix}, \tilde{E} = \begin{bmatrix} E & 0 \\ 0 & B_r \end{bmatrix}.$$

The H_∞ stabilization condition of (20) is given as follows:

$$\tilde{x}^+ T \tilde{P} \tilde{x}^+ - \tilde{x}^T \tilde{P} \tilde{x} + \tilde{x}^T \tilde{Q} \tilde{x} - \rho^2 \tilde{w}^T \tilde{w} < 0 \quad (21)$$

Theorem 2: If there exist a positive definite matrix $\tilde{P}$, such that the following matrix inequality is feasible

$$\begin{bmatrix} \tilde{A}^T \tilde{P} \tilde{A} - \tilde{P} + \tilde{Q} & * \\ \tilde{E}^T \tilde{P} \tilde{A} & \tilde{E}^T \tilde{P} \tilde{E} - \rho^2 I \end{bmatrix} < 0 \quad (22)$$

then the augmented system is asymptotically stable under the control law $\pi = K(x(k) - x_r(k))$, and the H_∞ control performance is guaranteed.

Proof for this system is very common. Thus is omitted here. Similarly, (22) can be rewritten as

$$\begin{bmatrix} \Lambda_{11} & * & * & * \\ -(BK)^T P_c (A + BK) - Q & \Lambda_{22} & * & * \\ E^T P_c (A + BK) & -E^T P_c BK & \Lambda_{33} & * \\ 0 & B_r^T P_r A_r & 0 & \Lambda_{44} \end{bmatrix} < 0 \quad (23)$$

where $\Lambda_{11} = (A + BK)^T P_c (A + BK) - P_c + Q$, $\Lambda_{22} = (BK)^T P_c BK + A_r^T P_r A_r - P_r + Q$, $\Lambda_{33} = E^T P_c E - \rho^2 I$, $\Lambda_{44} = B_r^T P_r B_r - \rho^2 I$.

C. Control Algorithm

Denote the feedback gains for systems (10) and (20) as K_{delay} and $K_{nondelay}$, respectively. The controller computation is shown as follows:

Step 1: Let $u(k) = K_{nondelay}(x(k) - x_r(k))$, if $|u(k)| > u_{dz}$, go to Step 4, otherwise, go to Step 2;

Step 2: Let $i = 1$ and go to Step 3;

Step 3: $u(k) = K_{delay}(x(k-i) - x_r(k-i))$, if $|u(k)| > u_{dz}$, go to Step 4, otherwise, $i = i + 1$, and repeat Step 3;

Step 4: Apply $u(k)$ to the actuator, then let $k = k + 1$ and return to Step 1.

IV. SIMULATION RESULTS

The LBDCM servo system is shown in Fig. 3. The system consists of an isolated power supply, a dSpace DS1103 controller, an LBDCM and a current amplifier which works in torque control mode. The model of the current amplifier and the LBDCM is first identified by using Matlab system identification toolbox.

Fig. 3. LBDCM drive system.

The identified system plant model is

$$\frac{Y(s)}{U(s)} = \frac{2.5996}{s(s+2.932)} \quad (24)$$

The sampling time is selected as : $T_s = 0.001s$. The reference system is constructed as follows:

$$x_r(k+1) = A_r x_r(k) + B_r r(k) \quad (25)$$

where $A_r = A - BL_f$, $B_r = pB$, with $L_f = [0.77887 \ 0.01204]$, and $p = 0.77887$.

Then the controller gain K_{delay} for delayed system can be calculated by solving (18), where $\gamma = 0.8$, $\gamma_d = 0.2$, $Q_{delay} = \text{diag}\{0.00001, 0.000001\}$, $\rho_{delay} = 1$, thus $K_{delay} = [-43.8595 \ -44.3529]$. The controller gain $K_{non-delay}$ for system without delay can be got by solving (23). Moreover, to solve (23), the two-step procedure in [25] is utilized to get an optimal solution, where $Q_{nondelay} = \text{diag}\{1, 1\}$, $\rho_{nondelay} = 5$, thus $K_{nondelay} = [-125.2217 \ -61.4933]$. The dead-zone for input signal is set as $|u| \leq 0.1$.

The simulation result is shown in Fig. 4. The effect of controller switching could be seen in Fig. 4(c). When the control voltage is lower than the dead-zone, the delayed state is searched. The search depth is shown in Fig. 4(d). For this simulation, the controller usually need to search back around 40 samples before it can find a control signal that is large enough to bring the system out of dead-zone.

This simulation validates that the switching mechanism is functioning. However, due to that the model does not include

Fig. 4. Simulation results for tracking of a sinusoidal signal.

any nonlinear friction and the system is linear, the desired trajectory and the simulated result coincide. This is not true and experiment verification is necessary.

V. EXPERIMENT RESULTS

To conduct the experiment, the simulation model is first ported into Simulink and then built into the DS1103 platform for execution. A sinusoidal reference trajectory is first tested and the results are shown in Fig. 5. The reference and actual position trajectory are plotted in Fig. 5(a). The tracking error of using non-delayed control method and with delay control method are compared in Fig. 5(b), where we can see that the method with delay control results in smaller tracking error. Fig. 5(d) shows that the speed error is decreased due to the proposed method for dead-zone. Fig. 5(e) is the control input voltage and shows similar switching pattern within dead zone. The dead-zone is present when the speed is close to zero.

A near square wave trajectory is also tested and similar results are shown in Fig. 6. The proposed delay control method improves the tracking performance at deadzone. However, this

Fig. 5. Experimental results for tracking of a sinusoidal signal.

method is not suitable for position regulation (as in the case of the pulse top/bottom). Through this test, we found that the proposed method is effective for dynamic motion tracking.

Both experiments reveal that there are still quite large tracking error. This is due to the reference model used doesn't include the non-linear behavior. How to reduce this tracking error is another topic and will be present in future works.

VI. CONCLUSIONS

Position tracking control of a linear brushless DC motor with dead-zone is investigated in this work. The system with

Fig. 6. Experimental results for tracking of a square signal.

dead-zone is described as switched system with input delay. Simulation result shows that the proposed method is effective.

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