International Journal of Control, Automation, and Systems (2015) 13(2):292-301
DOI 10.1007/s12555-013-0271-x
ISSN:1598-6446 eISSN:2005-4092
http://www.springer.com/12555

Optimal Tracking Control for Discrete-time Systems with Multiple Input Delays under Sinusoidal Disturbances

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Abstract: This study researches the tracking control problem for discrete-time systems with multiple input delays affected by sinusoidal disturbances. This study is organized around the expression of sinusoidal and disturbances and the delay-free transformation. First, based on the periodic characteristic of the sinusoidal disturbance, the sinusoidal disturbances are considered as the output of an exosystem. By proposing a discrete variable transformation, the discrete-time system with multiple input delays and the quadratic performance index are transformed into equivalent delay-free ones. Then, by constructing an augmented system that comprises the states of the exosystems of sinusoidal disturbances, the reference input, and the delay-free transformation systems, the original tracking problem is transformed into the optimal tracking problem for a delay-free system with respect to the simplified performance index. The optimal tracking control (OTC) law is obtained from Riccati and Stein equations. The existent and uniqueness of the optimal control law is proved. A reduced-order observer is constructed to solve the problem of physically realizable for the items of the reference input and sinusoidal disturbances. Finally, the feasibility and effectiveness of the proposed approaches are validated by numerical examples.

Keywords: Discrete-time systems, multiple input delays, observer, optimal tracking control, sinusoidal disturabnces.

1. INTRODUCTION

Typically rejection of sinusoidal or periodic disturbances are common problems in various engineering fields, such as disk drives [1], offshore jacket platforms [2,3], helicopters [4], and ship [5] etc. In generally, the practical systems are especially sensitive to sinusoidal or periodic disturbances. What's worse, the sinusoidal or periodic disturbances as a primary source of performance degradation is frequently encountered in engineering systems. As a result, during the past several decades, a great deal of research result have been reported in the literature that deal with various problem with sinusoidal or periodic disturbances. For example, the disturbance rejection in the case of sinusoidal disturbances with known frequencies has been solved by using internal model control [6], adaptive methods [7], and approximation control techniques [8] etc. What's more, the disturbances rejection with unknown frequencies has been studied for stabile linear system [9], minimum phase linear systems [10], and even nonlinear systems [11,12]. An overview of antidisturbance control for engineering systems with multiple disturbances can be found in [13]. Generally speaking, the problem of rejection of sinusoidal or periodic disturbances could be viewed as matching disturbances in the tracking error dynamics [14].

With the rapid development of computation science, conventional control system architecture has been evolving to discrete-time control, such as chemical processes, communication systems [15,16], and networked control systems [17,18]; in these cases, multiple delays is frequently encountered caused by the communication networks, sensors and/or actuators delays, and computation time of the control algorithm etc. It is well known that if multiple delays are ignored in the control design, it can severely degrade the performance of the closed-loop system, even induce instability [16]. Due to above reasons, the controller design problem for system with multiple delays has been considered in the literatures that deal with various analysis and design problems. For example, multiple input delays has been treated using an internal representation [19]; the observer based output

Manuscript received June 8, 2013; revised April 13, 2014; accepted July 6, 2014. Recommended by Associate Editor Tae-Hyoung Kim under the direction of Editor PooGyeon Park.

This work was supported by the Supported by Program for Scientific Research Innovation Team in Colleges and Universities of Shandong Province, Science Foundation of China under Grant (61201428, 61203105, 61302128), the Natural Science Foundation of Shandong Province under Grant (ZR2011FZ003, ZR2012 FQ016, ZR2011FL022), and the Shandong Distinguished Middle-Aged and Young Scientist Encourage and Reward Foundation Grant BS2014DX015.

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feedback control of time delay systems are available [20-22]; also, the H_∞ control for multiple delay systems is considered to solve the optimal linear quadratic regulation (LQR) problem [23,24].

Compared to the delays in state, the input delays is more frequently encountered in engineering. What's more, it has been a challenging problem to design controller for discrete-time systems with multiple input delays. On the one hand, based on the state augmentation, a non-delay system is introduced. However, if the input delays of the investigated system are large, the state dimension of the transformed system and the computing work would increase exponentially, the "dimension disaster" may arise [25,26]. What's worse, the transformation system may not maintain its stability, controllable and/or observable, and the Riccati equation is very difficult to solve precisely. On the other hand, due to the two-point boundary value (TPBV) problem induced from the time delay systems with quadratic performance index, finding an explicit form of optimal control law remains difficult [27]. Virtually most of the studies on optimal control for discrete-time system with multiple input delays consider only approximate optimal control. For example, [28] proposed a successive approximation approach (SAA) to design a suboptimal control for discrete linear systems with time delay, in which an iterative procedure is introduced to solve the TPBV problem with time-delay items; after that, [29] designed an approximate tracking controller for discrete-time systems with multiple state and input delays based on SAA and an augmented system; [30] deals with the control of SISO linear time-delayed systems, when there are different delays in the output/input transfer function.

Different from the previous works on optimal control for multiply delay systems by using SAA and the augmented method, such as those in [28] and [29], the motivation for this work is to design an optimal tracking control law for discrete-time systems with multiply input delays under sinusoidal disturbances based on a discrete variable transformation. To solve the difficulty of control problem caused by sinusoidal disturbance and multiple input delays, an exosystem is introduced to estimate the sinusoidal disturbance, a non-delayed system is transformed based on the discrete variable transformation, an augmented model is constructed, and the quadratic performance index of the original system is simplified. In terms of design of controller, by solving the optimal control problem for the augmented transformation system and the simplified performance index, an OTC law is obtained from the maximum principle by solving Riccati and Stein equations. In terms of control effect, the objective is to trade off between tracking ability and rejection effect opposed to the multiple input delays and sinusoidal disturbance. In term of the problem of physically realizable, a reduced-order observer is constructed to solve the problem of physically realizable for the items of the reference input and sinusoidal disturbances.

The rest of paper is organized as follows. Section 2 formulates the problem to be discussed. In Section 3, an exosystem of the sinusoidal disturbances is introduced, and the transformations of the discrete-time system with multiply input delays and the performance index are given. The main results of this paper are presented in Section 4, in which the OTC law is obtained based on the maximum principle. A reduced-order observer is constructed in Section 5 to solve the physically unrealizable problem for feedforward items. Numerical examples are given in Section 6 to demonstrate the effectiveness and implement of the OTC law. Finally, we conclude our findings in Section 7.

2. PROBLEM FORMULATION

Consider the discrete-time system with multiple input delays under sinusoidal disturbances:

$$\begin{aligned} &x(k+1) = Ax(k-h) + \textstyle\sum_{i=1}^{N} B_i u(k-h_i) + Dv(k), \\ &y(k) = Cx(k), \quad k = 0, 1, 2, \cdots \\ &x(0) = x_0, \\ &u(k) = 0, \quad k < 0, \end{aligned} \tag{1}$$

where $x \in R^n$ denotes the state vector, $u \in R^m$ is the control input, $v \in R^r$ denotes the sinusoidal disturbance signal, $h_i > 0\,(i = 1, 2, \cdots, N)$ are positive time-delays, respectively; $y \in R^q$ is the output vector; N is the account of input delays, $A, B_i (i = 1, 2, \cdots, N)$, C and D are constant matrices of appropriate dimensions.

The sinusoidal disturbance vector $v(k)$ is given by

$$v(k) = \begin{bmatrix} v_1(k) \\ v_2(k) \\ \vdots \\ v_r(k) \end{bmatrix} = \begin{bmatrix} \alpha_1 \sin(\omega_1 k + \varphi_1) \\ \alpha_2 \sin(\omega_2 k + \varphi_2) \\ \vdots \\ \alpha_r \sin(\omega_r k + \varphi_r) \end{bmatrix}, \tag{2}$$

where the amplitude α_i and the phase φ_i are unknown, v_i are measurable; the frequency ω_i is known constant and satisfies

$$-\pi < \omega_1 \le \omega_2 \le \cdots \le \omega_r \le \pi. \tag{3}$$

The reference input (desired output) is given by

$$\begin{aligned} &z(k+1) = Fz(k), \\ &\bar{y} = Hz(k), \end{aligned} \tag{4}$$

where $z \in R^l$, whose initial condition $z(0)$ is unknown; $\bar{y} \in R^q$; F and H are constant matrices of appropriate dimensions. It is assumed that

Assumption 1: System (4) is stable, but unnecessary asymptotically stabile.

Assumption 2: The pair (A, B_1) is completely controllable, and the pair (A, C) is completely observable.

Then, the aim is to find a control law such that the output y tracks the given reference signal $\bar{y}$. The tracking error $e(k)$ is given by

$$e(k) = \bar{y}(k) - y(k). \tag{5}$$

Since System (1) is affected by the external sinusoidal disturbances, it is noteworthy that the control vector $u(k)$

will not tend to zero in the tracking control process. The traditional infinite-time horizon quadratic cost functional associated with (1) is not convergent. In this case, we choose the infinite-time average performance index as follows:

$$J = \lim_{T\to\infty} \frac{1}{T}\sum_{k=0}^{T}\left[e^T(k)Qe(k)+u^T(k)Ru(k)\right]. \tag{6}$$

Then, the optimal tracking control problem for a discrete-time system with multiple input delays under sinusoidal disturbances is formulated to find a control $u^*(k)$ for the discrete-time systems described by (1), (2) and (4) with respected to the performance index (6) that makes the output y tracking the reference input vector $\bar{y}$ while the performance index J obtains the minimum value.

3. MODEL TRANSFORMATION

3.1. Modelling of sinusoidal disturbances

In order to deal with the sinusoidal disturbances, a discrete vector $v_\omega(k)$ is defined as:

$$v_\omega(k) = \left[v_1\left(k-\frac{\pi}{2\omega_1}\right) \ \cdots \ v_r\left(k-\frac{\pi}{2\omega_1}\right)\right]^T. \tag{7}$$

Based on the periodic characteristic of the sinusoidal disturbance (2), the relationship between $v(k)$ and $v_\omega(k)$ can be described as:

$$\begin{cases} v(k+1) = \psi_1 v(k) - \psi_2 v_\omega(k), \\ v_\omega(k+1) = \psi_2 v(k) + \psi_1 v(k), \end{cases} \tag{8}$$

where

$$\begin{cases} \psi_1 = diag\{\cos\omega_1, \ \cdots, \ \cos\omega_r\}, \\ \psi_2 = diag\{\sin\omega_1, \ \cdots, \ \sin\omega_r\}. \end{cases}$$

By introducing the vector $w(k) = [v(k) \ v_\omega(k)]^T$, an exosystem is introduced to describe the sinusoidal disturbance as follows:

$$\begin{cases} w(k)+1 = Gw(k), \\ v(k) = Ew(k), \end{cases} \tag{9}$$

where

$$G = \begin{bmatrix} \varphi_1 & -\varphi_2 \\ \varphi_2 & \varphi_1 \end{bmatrix}, \quad E = \begin{bmatrix} I_r \\ 0 \end{bmatrix}. \tag{10}$$

Then, the sinusoidal disturbance is viewed as the output of the exosystem (9). Note that the eigenvalues $\lambda_i(G)$ of G satisfy

$$|\lambda_i(G)| = 1, \quad i = 1, 2, \cdots, 2r. \tag{11}$$

3.2. Delay-free transformation for model and performance index

As the discrete-time system (1) contains multiple input delays, there is no realizable optimal control law for the traditional quadratics performance index. To deal with the multiple input delays, a discrete vector transformation is proposed as follows:

$$\tilde{x}(k) = x(k) + \sum_{i=0}^{N}\sum_{j=k-h_i}^{k-1} A^{k-h_i-j-1}B_i u(j). \tag{12}$$

Then, System (1) can be transformed into

$$\begin{cases} \tilde{x}(k+1) = A\tilde{x}(k) + \tilde{B}u(k) + Dv(k), \\ y(k) = C\left(\tilde{x}(k) - \sum_{i=0}^{N}\sum_{j=k-h_i}^{k-1} A^{k-h_i-j-1}B_i u(j)\right), \end{cases} \tag{13}$$

where $\tilde{x}(k)$ is the state vector of the non-delayed system (11) and $\tilde{B} = \sum_{i=1}^{N} A^{-h_i}B_i$. It should be noted that the pair $(A, \tilde{B})$ is completely controllable if and only if (A, B_1) is completely controllable [31].

Since the System (1) is transformed into (13) by using (12), quadratic performance index (6) should be reconstructed to an equivalent form corresponding to the transformation system (13). By using (4) and (5), the quadratic performance index (6) is transformed into an equivalent form as follows:

$$\begin{aligned} J = \sum_{k=0}^{\infty}\Big[& \tilde{x}^T(k)C^TQC\tilde{x}(k) + 2z^T(k)H^TQCU_1 \\ & - 2z^T(k)H^TQH\tilde{x}(k) - 2\tilde{x}^T(k)C^TQCU_1 \\ & + U_1^TC^TQCU_1 + u^T(k)Ru(k)\Big], \end{aligned} \tag{14}$$

where $U_1 = \sum_{i=0}^{N}\sum_{j=k-h_i}^{k-1} A^{k-h_i-j-1}B_i u(j)$. According to System (1), (4), (13), and (14), one gets

$$\begin{cases} \sum_{k=0}^{\infty}\left[z^T(k)H^TQCU_1\right] = \sum_{k=0}^{\infty}\left[z^T(k)C_2u(k)\right] \\ \sum_{k=0}^{\infty}\left[\tilde{x}^T(k)C^TQCU_1\right] \\ \quad = \sum_{k=0}^{\infty}\left[\tilde{x}^T(k)C_1u(k) + w^T(k)C_3u(k) + \Delta_1\right] \\ \sum_{k=0}^{\infty}\left[U_1^TC^TQCU_1\right] = \sum_{k=0}^{\infty}\left[u^T(k)R_1u(k) + 2\Delta_1\right], \end{cases} \tag{15}$$

where

$$C_1 = \sum_{i=1}^{N}\sum_{j=1}^{h_i}\left(CA^j\right)^T QACA^{j-1-h_i}B_i,$$

$$C_2 = \sum_{i=1}^{N}\sum_{j=1}^{h_i}\left(HF^j\right)^T QACA^{j-1-h_i}B_i,$$

$$C_3 = \sum_{t=1}^{N}\sum_{i=1}^{h_t}\sum_{j=0}^{h_t-j}\left(CA^jDEG^{i-1}\right)^T QCA^{j+i-h_t-1}B_t,$$

$$\Delta_1 = \left(\left(CA^{-j}B_iu(k+i-1)\right)^T QCA^{i-j-1}B_i\right)u(k),$$

$$R_1 = \sum_{i=1}^{N}\sum_{j=1}^{h_i}\left(CA^{-j}B_i\right)^T QCA^{-j}B_i.$$

Based on (14) and (15), performance index (6) can be simplified into the following form:

$$
\begin{aligned}
J = \lim_{T\to\infty} \frac{1}{T}\sum_{k=0}^{T}\Big[& u^T(k)\tilde{R}u(k) + z^T(k)C_2u(k) \\
& - z^T(k)H^TQ\tilde{x}C(k) + \tilde{x}^T(k)C^TQC\tilde{x}(k) \\
& - 2\tilde{x}^T(k)C_1u(k) - 2w^T(k)C_3u(k)\Big].
\end{aligned} \tag{16}
$$

3.3. Equivalent optimal regulation problem

Defining the vector $\varphi(k) = [\tilde{x}(k)\ \ z(k)\ \ w(k)]^T$. Combining (12) with System (4) and (9), one has the following state space expression in an augmented form:

$$
\begin{aligned}
\varphi(k+1) &= A_1\varphi(k) + B_1u(k), \\
y(k) &= \bar{C}\varphi(k),
\end{aligned} \tag{17}
$$

where

$$
A_1 = \begin{bmatrix} A & 0 & DE \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix},\quad B_1 = \begin{bmatrix} \tilde{B} \\ 0 \\ 0 \end{bmatrix},\quad \bar{C} = \begin{bmatrix} C \\ 0 \\ 0 \end{bmatrix}^T.
$$

Based on (17), the performance index (16) can be rewritten as:

$$
\begin{aligned}
J = \lim_{T\to\infty} \frac{1}{T}\sum_{k=0}^{T}\Big[& \varphi^T(k)\tilde{Q}\varphi(k) \\
& + 2\varphi^T(k)Mu(k) + u^T(k)\tilde{R}u(k)\Big],
\end{aligned} \tag{18}
$$

where

$$
\tilde{Q} = \begin{bmatrix} C^TQC & -H^TQC & 0 \\ H^TQC & H^TQH & 0 \\ 0 & 0 & 0 \end{bmatrix},
$$

$$
M = \begin{bmatrix} -C_1 \\ C_2 \\ -C_1 \end{bmatrix}.
$$

Note that the performance index equation (18) includes a cross term involving $\varphi(k)$ and $u(k)$. To obtain the optimal control vector $u(k)$, let us define

$$
\begin{cases}
\hat{Q} = \tilde{Q} - M\tilde{R}^{-1}M^T, \\
\bar{u}(k) = \tilde{R}^{-1}M^T\varphi(k) + u(k),
\end{cases} \tag{19}
$$

Then, equation (18) becomes

$$
J = \lim_{T\to\infty} \frac{1}{T}\sum_{k=0}^{T}\Big[\varphi^T(k)\hat{Q}\varphi(k) + u^T(k)\tilde{R}u(k)\Big]. \tag{20}
$$

By substituting (19) into (17), one gets

$$
\varphi(k+1) = \left(A_1 - B_1\tilde{R}^{-1}M^T\right)\varphi(k) + B_1\bar{u}(k). \tag{21}
$$

Then, the original optimal tracking control of the system given by (1), (2), and (4) with respected to the performance index (6) is equivalent to the quadratic optimal control of System (21) with the performance index given by (20).

4. DESIGN OF OTC LAW BASED ON THE REDUCED-ORDER OBSERVER

4.1. The OTC law

In this subsection, the designed OTC law will be given more detail below.

Theorem 1: Consider the optimal tracking control problem for discrete-time system given by (1), (4) under the sinusoidal disturbance (2) with respect to quadratic performance index (6), the OTC law uniquely exists and can be formulated as

$$
\begin{aligned}
u(k) = -S^{-1}\Big\{ & \left(\tilde{B}^TP_{11}DE + \tilde{B}^TP_{13}G - C_3^T\right)w(k) \\
& + \left(\tilde{B}^TP_{12}F + C_2^T\right)z(k) + \left(\tilde{B}^TP_{11}A - C_1^T\right)\tilde{x}(k)\Big\},
\end{aligned} \tag{22}
$$

where $S = \tilde{R} + \tilde{B}^TP_{11}\tilde{B}$, P_{11} is the unique positive definite solution of the Riccati equation

$$
P_{11} = C^TQC - C_1\tilde{R}^{-1}C_1^T + S_1^TP_{11}\nabla S_1, \tag{23}
$$

where $S_1 = A + \tilde{B}\tilde{R}^{-1}C_1^T$, $\nabla = I - \tilde{B}S^{-1}\tilde{B}^TP_{11}$, and P_{12} and P_{13} are unique solution of the following Stein equations

$$
\begin{cases}
P_{12} = S_1^T\nabla P_{12}F - S_1^TP_{11}\nabla\tilde{B}\tilde{R}^{-1}C_2^T \\
\qquad + C_1\tilde{R}^{-1}C_2^T - C^TQH, \\
P_{13} = S_1^T\nabla P_{13}G - C_1\tilde{R}^{-1}C_3^T \\
\qquad + S_1^TP_{11}\nabla(DE + \tilde{B}\tilde{R}^{-1}C_3^T).
\end{cases} \tag{24}
$$

The minimum value of performance index is given by

$$
\begin{aligned}
J_{\min} = {} & x^T(0)P_{12}z(0) + x^T(0)P_{13}w(0) + z^T(0)P_{23}w(0) \\
& + \frac{1}{2}\Big[x^T(0)P_{11}x(0) + z^T(0)P_{22}z(0) + w^T(0)P_{33}w(0)\Big],
\end{aligned} \tag{25}
$$

where P_{22}, P_{23}, and P_{33} are the unique solution of the following Lyapunov equations

$$
\begin{aligned}
P_{22} = {} & F^TP_{22}F - C_2\tilde{R}^{-1}C_2^T - \left(\tilde{B}\tilde{R}^{-1}C_2^T\right)^TP_{12}F \\
& + \left[\left(\tilde{B}\tilde{R}^{-1}C_2^T\right)^TP_{11} - F^TP_{12}^T\right]\nabla\tilde{B}\tilde{R}^{-1}C_2^T + H^TQH \\
& + F^TP_{12}^T\tilde{B}S^{-1}\tilde{B}^T\left[P_{11}\left(\tilde{B}\tilde{R}^{-1}C_2^T\right) - P_{12}F\right],
\end{aligned} \tag{26}
$$

$$
\begin{aligned}
P_{23} = {} & F^TP_{23}G + C_2\tilde{R}^{-1}C_3^T - \left(\tilde{B}\tilde{R}^{-1}C_2^T\right)^TP_{13}G \\
& + \left[F^TP_{12}^T - \left(\tilde{B}\tilde{R}^{-1}C_2^T\right)^TP_{11}\right]\nabla\left(DE + \tilde{B}\tilde{R}^{-1}C_3^T\right) \\
& + \left[F^TP_{12}^T - \left(\tilde{B}\tilde{R}^{-1}C_2^T\right)^TP_{11}\right]\tilde{B}S^{-1}\tilde{B}^TP_{13}G,
\end{aligned} \tag{27}
$$

$$
\begin{aligned}
P_{33} = {} & G^TP_{33}G + \left(DE + \tilde{B}\tilde{R}^{-1}C_3^T\right)^TP_{13}G - C_3\tilde{R}^{-1}C_3^T \\
& + \left[\left(DE + \tilde{B}\tilde{R}^{-1}C_3^T\right)^T\nabla - G^TP_{13}^T\tilde{B}S^{-1}\tilde{B}^T\right] \\
& \times\left[P_{11}\left(DE + \tilde{B}\tilde{R}^{-1}C_3^T\right) + P_{13}G\right].
\end{aligned} \tag{28}
$$

Proof: Applying the maximum principle to System (17) with the quadratic index (18), the optimal control law is obtained

$$\bar{u}(k) = -S^{-1}B_1^T P\left(A_1 - B_1\tilde{R}^{-1}M^T\right)\varphi(k), \tag{29}$$

where P is the solution of the following Riccati equation

$$\begin{aligned} P &= \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{12}^T & P_{22} & P_{23} \\ P_{13}^T & P_{23}^T & P_{33} \end{bmatrix} \\ &= \hat{Q} - \left(A_1 - B_1\tilde{R}^{-1}M^T\right)^T PS_2\left(A_1 - B_1\tilde{R}^{-1}M^T\right), \end{aligned} \tag{30}$$

where $S_2 = I - B_1[\tilde{R} + B_1PB_1^T]^T B_1^T$.

Based on the optimal theory, the minimization perfromance index can be obtained

$$J_{\min} = \frac{1}{2}\varphi^T(0)P\varphi(0). \tag{31}$$

By substituting the related matrix into (29), (30), and (31), the optimal tracking control law (22), Riccati matrix (23), Stein matrix (24), Lyapunov matrix (26), (27), (28), and the minimum value of the performance index (25) are obtained.

In the followings, we will prove that the OTC (22) is existent and unique. Obviously, the existence and uniqueness of (22) is equivalent to that of P_{11}, P_{12}, and P_{13}. Directly following from Assumption 2, the matrix P_{11} is existent and unique. Based on (25) and (31), one gets

$$\begin{aligned} \tilde{x}(k+1) &= \left(I - S_3P_{11}\right)S_1\tilde{x}(k) + \Big\{DE + \tilde{B}\tilde{R}^{-1}C_3^T \\ &\quad -S_3\left[P_{13}G + P_{11}\left(DE + \tilde{B}^T\tilde{R}^{-1}C_3^T\right)\right]\Big\}w(k) \\ &\quad -\left[\tilde{B}\tilde{R}^{-1}C_2^T + S_3\left(P_{12}F - P_{11}\tilde{B}\tilde{R}^{-1}C_2^T\right)\right]z(k), \end{aligned} \tag{32}$$

where $S_3 = \tilde{B}(\tilde{R} + \tilde{B}^T\tilde{R}^{-1}\tilde{B})^{-1}\tilde{B}^T$. According to optimal regulator theory, one gets

$$\begin{aligned} &\left|\lambda_i\left\{\left(I - S_3P_{11}\right)\left(A + \tilde{B}^T\tilde{R}^{-1}C_1^T\right)\right\}\right|\left|\lambda_j(G)\right| < 1, \\ &i = 1, 2, \cdots, n; \quad j = 1, 2, \cdots, 2r. \end{aligned} \tag{33}$$

According to Assumption. 2, we obtain

$$\begin{aligned} &\left|\lambda_i\left\{\left(I - S_3P_{11}\right)\left(A + \tilde{B}^T\tilde{R}^{-1}C_1^T\right)\right\}\right|\left|\lambda_j(F)\right| < 1, \\ &i = 1, 2, \cdots, n; \quad j = 1, 2, \cdots, l. \end{aligned} \tag{34}$$

Then, P_{11} is the unique positive definite solution of the Riccati Matrix equation (23); P_{12} and P_{13} are the unique solution of the Stein matrix equations (24), respectively. When P_{11}, P_{12}, and P_{13} are derived, $u^*(k)$ can be determined from (22), respectively. Therefore, the OTC law is existent and unique. From (12) and (22), one gets

$$\begin{aligned} x(k) &\le \|\tilde{x}(k)\| + \sum_{i=0}^{N} h_i \max_{1\le s\le h_i}\Big\{\left\|\tilde{B}S^{-1}\left(\tilde{B}^TP_{11}A - C_1^T\right)\right\| \\ &\quad \times\left\|A^{s-1-h_i}\right\|\|\tilde{x}(k-s)\|\Big\} \\ &\quad + \sum_{i=0}^{N} h_i \max_{1\le s\le h_i}\Big\{\left\|A^{s-1-h_i}\right\|\|z(k-s)\| \\ &\quad \times\left\|\tilde{B}S^{-1}\left(\tilde{B}^TP_{12}F + C_2^T\right)\right\|\Big\} + \sum_{i=0}^{N} h_i \max_{1\le s\le h_i}\Big\{\left\|A^{s-1-h_i}\right\| \\ &\quad \times\|w(k-s)\|\left\|\tilde{B}S^{-1}\left(\tilde{B}^TP_{11}DE + \tilde{B}^TP_{13}G - C_3^T\right)\right\|\Big\}. \end{aligned} \tag{35}$$

Because $\|\tilde{x}(k)\|$, $\|z(k)\|$, and $\|w(k)\|$ are bounded, $\|x(k)\|$ is bounded. Then, the OTC law (22) is a stabilizing control law for time-delay System (1).

According to the Assumption (2), P_{22}, P_{23}, and P_{33} are the unique solutions of Lyapunov Matrix Equations (26)-(28), respectively. Therefore, the minimum value of the performance index is existent. This is the end of proof.

Remark 1: The OTC law in (26) contains the state variable $z(k)$ and $w(k)$ for exosystem (4) and (10), which is physically unrealizable. In the practical engineering, we can introduce the following reference input observer to make it physically realizable.

4.2. Design of the reduced-order observer

In this subsection, a reduce-order observer is proposed to estimate the states of the reference input and the sinusoidal disturbances in order to solve physically unrealizable problem of the OTC law.

Construct a $(n+l+2r)\times(n+l+2r)$ dimension non-singular matrix as $T = (\bar{C}, T_1) \in R^{(n+l+2r)\times(n+l+2r)}$. Note that

$$T_1 = \begin{bmatrix} H_1 & H_1 \end{bmatrix}, \quad H_1 = \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix}, \quad H_2 = \begin{bmatrix} H_{12} \\ H_{22} \end{bmatrix}, \tag{36}$$

where H_{11}, H_{12}, H_{21}, and P_{22} are the $n\times q$, $n\times(n+l+2r-q)$, $(l+2r)\times q$, and $q\times(n+l+2r-q)$ dimension constant matrices, respectively. Let

$$\begin{cases} \bar{\varphi}(k) = T\varphi(k) = \begin{bmatrix} \bar{\varphi}_1(k) \\ \bar{\varphi}_2(k) \end{bmatrix}, \quad S = TB_1 = \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \\ M = TA_1T^{-1} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}. \end{cases} \tag{37}$$

Then, the augmented System (17) is reformed as

$$\begin{cases} \bar{\varphi}_1(k+1) = M_{11}\bar{\varphi}_1(k) + M_{12}\bar{\varphi}_2 + S_1u(k), \\ \bar{\varphi}_2(k+1) = M_{21}\bar{\varphi}_1(k) + M_{22}\bar{\varphi}_2 + S_2u(k), \\ y(k) = \bar{\varphi}_1(k). \end{cases} \tag{38}$$

Construct the state observer as follows

$$\begin{cases} \eta(k+1) = (M_{22} - LM_{12})\eta(k) + (S_2 - LS_1)u(k) \\ \qquad\qquad + (M_{22}L - LM_{12}L + M_{21} - LM_{11})y(k), \\ \hat{\varphi}_2(k) = \eta(k) + Ly(k), \end{cases} \tag{39}$$

where $\hat{\varphi}_2(k)$ is the estimate of $\bar{\varphi}_2(k)$, L is the observer gain. Because the pair $(\bar{C} \ \ A_1)$ is completely observerable, it is easy to prove the pair $(M_{22}\ \ M_{12})$ is completely observerable. By choosing the observer gain $\bar{L}$ and using the pole placement, the eigenvalues of the $(M_{22}-LM_{12})$ can be placed to the anticipant place. According to (39) and (40), we obtain

$$\begin{aligned}\varphi(k) &= T^{-1}\bar{\varphi}(k)\\ &= H_1 y(k)+H_2\bar{\varphi}_2(k).\end{aligned} \tag{40}$$

According to (38), (39), and (40), the state $\tilde{x}$ and the state $[z(k)\ \ w(k)]^T$ can be estimated at the same time. Construct the reduced-order state observer as follows:

$$\begin{cases}\hat{\tilde{x}}(k) = H_{12}\eta(k)+\left(H_{11}+H_{12}L\right)y(k)\\ \begin{bmatrix}\hat{z}(k)\\ \hat{w}(k)\end{bmatrix} = H_{22}\eta(k)+\left(H_{21}+H_{22}L\right)y(k).\end{cases} \tag{41}$$

In order to obtain the physically realizable OTC law, submitting the estimate state $\hat{\tilde{x}}$ and $[\hat{z}(k)\ \ \hat{w}(k)]^T$ to the state $\tilde{x}$ and $[z(k)\ \ w(k)]^T$, one gets

$$\begin{aligned}u(k) = -S^{-1}\{&[S_4H_{12}+\psi H_{22}]\eta(k)\\ &+[\psi(H_{21}+H_{22}L)+S_4(H_{11}+H_{12}L)]y(k)\},\end{aligned} \tag{42}$$

where

$$\begin{cases}S_4 = \tilde{B}^T P_{11}A - C_1^T\\ \psi = \left[\tilde{B}^T P_{12}F + C_2^T \quad \tilde{B}^T P_{11}DE + \tilde{B}^T P_{13}G - C_3^T\right].\end{cases}$$

Remark 1: Because the control law (42) is the dynamic control law with a reduced-order observer, it is not the optimal control law. In order to obtain the control effect of the control law approximating to the optimal control law (22), using the pole placement to the true part is the smallest negative, the outputs $\hat{\tilde{x}}$ and $[\hat{z}(k)\ \ \hat{w}(k)]^T$ tend to the state $\hat{\tilde{x}}$ and $[z(k)\ \ w(k)]^T$.

5. SIMULATION

Numerous simulations are undertaken in order to demonstrate the feasibility and effectiveness of the proposed OTC in this section. In order to make a further research on testing the algorithm's validity, the discrete-time systems with different values and terms for multiple input delays are considered.

5.1. The industrial electric heater with single input delay

In this simulation, the optimal tracking problem for an industrial electric heater with single input delay under sinusoidal disturbances is considered. Based on [19], the heater is divided into five heating zones, each of which is a control input. Five thermocouples are located in the heater to measure its temperature profile. The control problem is to maintain the temperature profile of the process to meet the specific requirements for heat treatment. The system is described by (1) with the specific matrices:

$$\begin{aligned}A &= \begin{bmatrix}0.974 & 0.151 & 0.197 & -0.059 & 0.071\\ 0.015 & 0.889 & 0.270 & 0.119 & -0.220\\ 0.064 & 0.121 & 1.001 & -0.035 & -0.028\\ -0.051 & 0.093 & 0.288 & 0.826 & 0.026\\ 0.017 & 0.019 & 0.293 & 0.035 & 0.871\end{bmatrix},\\ B &= \begin{bmatrix}0.537 & -0.112 & 0.100 & 0.047 & 0.259\\ -0.517 & 0.735 & 0.575 & 0.407 & -0.125\\ 0.295 & 0.315 & 1.164 & -0.299 & 0.239\\ -0.202 & 0.197 & 0.417 & 0.665 & 0.114\\ -0.118 & 0.163 & 0.204 & 0.233 & 0.365\end{bmatrix},\\ C &= diag[1\ \ 1\ \ 1\ \ 1\ \ 1],\\ D &= diag[0.1\ \ 0.2\ \ 0.15\ \ 0.3\ \ 0.2],\\ x(0) &= [-4\ \ 4\ \ 0.5\ \ 6\ \ 3]^T\end{aligned} \tag{43}$$

and the external sinusoidal disturbances is $v(k)$ given by

$$v(k) = \begin{bmatrix}0.5\sin\left[(\pi/18)k+\pi\right]\\ 0.2\sin\left[(\pi/10)k\right]\\ 0.3\sin\left[(\pi/2)k\right]\\ 0.1\sin\left[(\pi/12)k\right]\\ 0.5\sin\left[(\pi/10)k+\pi\right]\end{bmatrix}. \tag{44}$$

The reference input and quadratic performances index are chosen as

$$\begin{cases}F = \begin{bmatrix}0.87 & 0.01 & -0.01 & 0.01 & -0.01\\ 0.01 & 0.85 & -0.01 & -0.01 & -0.05\\ 0.01 & -0.01 & 0.88 & -0.01 & 0.01\\ 0.01 & -0.01 & -0.01 & 0.997 & 0.05\\ -0.1 & 0.02 & 0.01 & -0.05 & 0.95\end{bmatrix},\\ H = diag[1\ \ 1\ \ 1\ \ 1\ \ 1],\\ Q = diag[1.5\ \ 1\ \ 0.2\ \ 0.3\ \ 0.8],\\ R = diag[0.5\ \ 0.2\ \ 1\ \ 1\ \ 1].\end{cases} \tag{45}$$

Then, the simulation results are shown in Figs. 1-5 with single input delay $h_1 = 2$ by using proposed control law. In order to demonstrate the effectiveness of the presented OTC law, the comparison results between the temperature changes y in the five heating zones and the reference input $\bar{y}$ are shown in Figs. 1-3, respectively, where the solid lines give the reference input $\bar{y}$. Also, The curves of OTC laws and tracking errors in the different heating zones are presented in Fig. 4-5, respectively.

It can be seen from Figs. 1-3 that the tracking errors between system output y and reference input $\bar{y}$ are larger in the earlier stage. This is caused by the input delays and initial value of the control system. In addition, caused by the different weight in Q, the tracking results of y_1, y_2, and y_5 are better than y_3 and y_4. Anyhow, as time goes by, the system output y catches up with the reference input $\bar{y}$, and the tracking error $e(k)$ converges

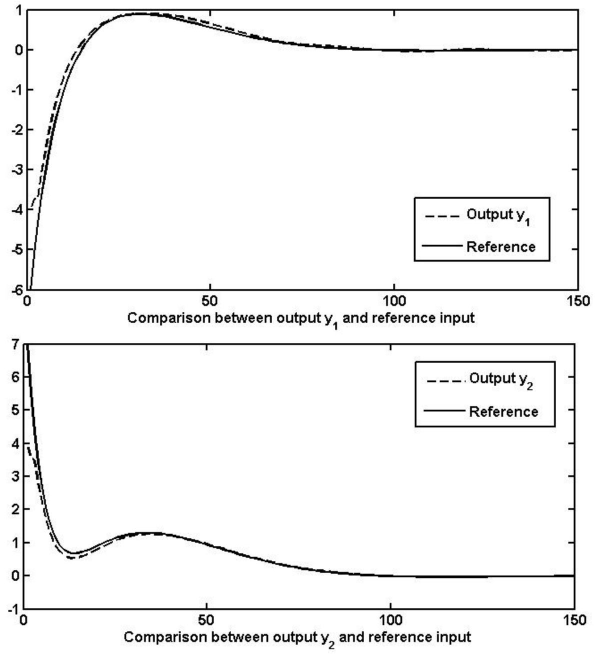

Fig. 1. Curves of the comparison results between outputs and reference input.

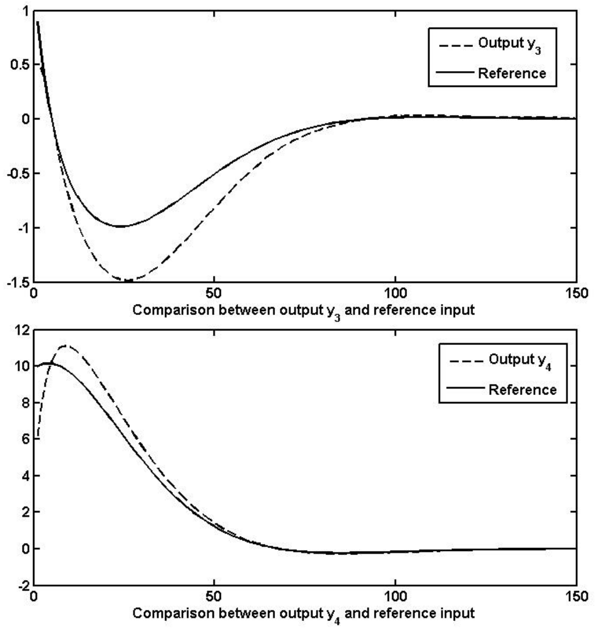

Fig. 2. Curves of the comparison results between outputs and reference input.

to a small value, even at zero. What's more, the disturbance rejection with respect to the sinusoidal disturbances is achieved for all choices of such parameters expect frequencies. Then, the tracking ability and disturbance rejection of the designed tracking control law are certified.

5.2. Mathematical example with two input delays

In order to verify the elasticity of the proposed control law, the discrete-time system with input delays h_1 and h_2 is considered, where

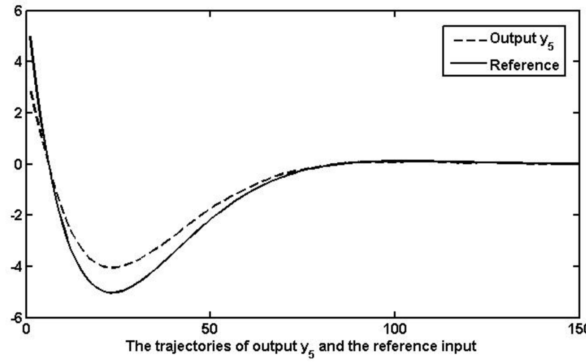

Fig. 3. Curves of the comparison results between outputs and reference input.

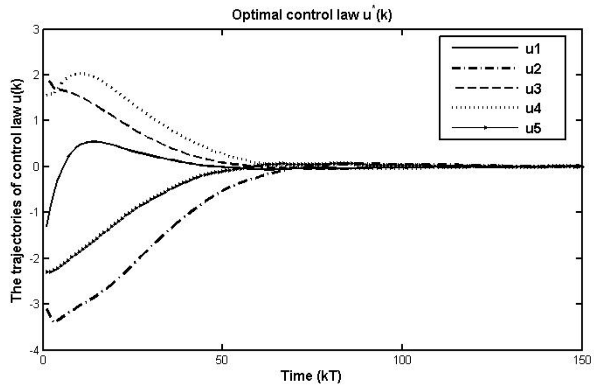

Fig. 4. Curves of OTC law.

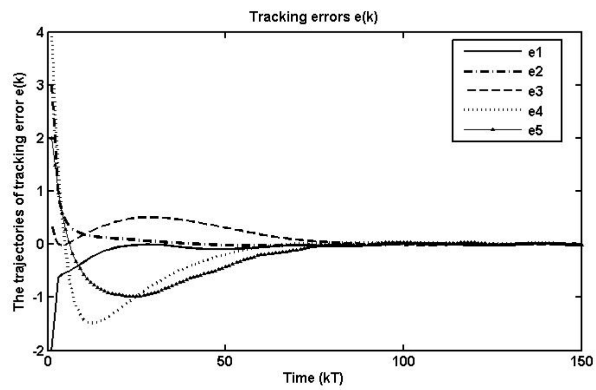

Fig. 5. Curves of tracking error with signal input delay.

$$\begin{cases} A = \begin{bmatrix} 0.9 & 0.1 \\ -0.2 & 1 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0.1 \\ 0.15 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 0.1 \end{bmatrix}, \\ D = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}, \quad C = \begin{bmatrix} 0.1 & 0 \end{bmatrix}, \quad x(0) = \begin{bmatrix} 2 \\ 0 \end{bmatrix}, \\ v(k) = [0.5\sin[(\pi/10)k + \pi] \quad \sin((\pi/18)k)]. \end{cases} \tag{46}$$

The desired output described as (4) and the quadratic performance index described by (6) are chosen as

$$\begin{cases} F = \begin{bmatrix} 0.8 & 0.3 \\ -0.4 & 0.95 \end{bmatrix}, \quad H = \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T, \quad x(0) = \begin{bmatrix} 3 \\ 0 \end{bmatrix}^T, \\ Q = 1, \quad R = 1. \end{cases} \tag{47}$$

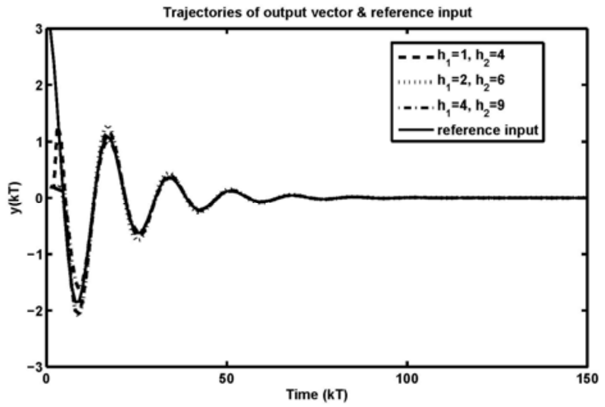

Fig. 6. Curves of comparison results of reference input and system output.

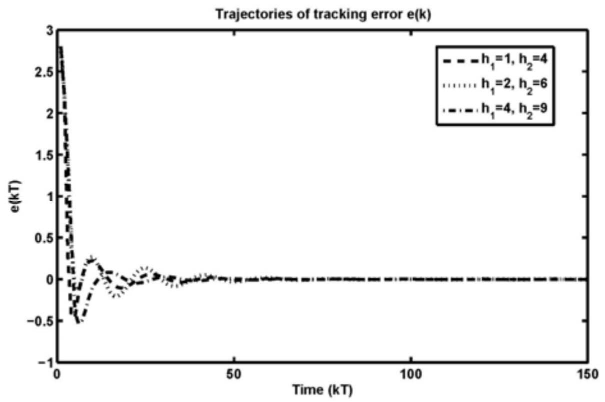

Fig. 7. Curves of tracking error with different input delays.

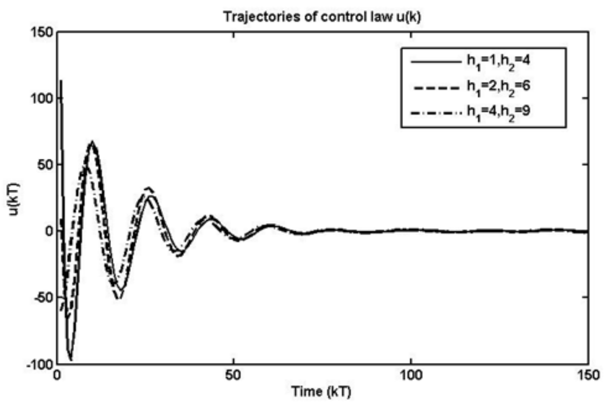

Fig. 8. Curves of OTC laws with different input delays.

To illustrate the performance of tracking reference input and disturbance rejection, the input delays are set as $h_1 = 1$, $h_2 = 4$, $h_1 = 2$, $h_2 = 6$, and $h_1 = 4$, $h_2 = 9$. Then, the comparison results among the open-loop system and the closed-loop system are presented. The simulation curves of the comparison results of reference input $\bar{y}$ and system output y, tracking error $e(k)$, and the presented OTC law, are presented in Figs. 6-8, respectively. The performance index values at different situation are listed in Table 1.

Table 1. Performance indexes with different input delays.

h_1, h_2	1, 4	2, 6	4, 9	Open-Loop
$J_{\min}$	2.355	3.543	7.072	20.186

As similar with the simulations in Case 1, the tracking error is the largest in the early state. Meanwhile, with the increase of values of input delays h_1 and h_2, the performance indexes are increasing in Table 1. However, this does not mean that the presented tracking control law is not able to keep the output performance in spite of the delay. This situation is mainly caused by the input delays and initial conditions. Actually, the performance indexes have been made good improvement compared by the open-loop situation. From Fig. 6-8, it should be noted that, in spite of the more items of input delays in Case 2, the tracking ability and disturbance rejection are still provided effectively by using the proposed control law.

It can be seen from Case 1 and Case 2, the proposed OTC law is valid for the optimal tracking control problem for the discrete-time system with multiple input delays under sinusoidal disturbances. It should be noted that, with the increased items and values of input time delays, the proposed control law still provides effective abilities of tracking the reference input and disturbance rejection. Therefore, the proposed control law in this papers is effective and easy to implement, track the reference input, and reject the external sinusoidal disturbances.

6. CONCLUSIONS

This paper has been concerned with the development of optimal vibration control for tracking control law has been designed for discrete-time system with multiple input delays under sinusoidal disturbances. It deployed an effective control strategy to suppress vibration caused by the sinusoidal disturbances and enhance the tracking abilities for the reference signal.

This work has presented an interesting approach that transforms a discrete-time system with multiple input delays into a non-delayed system in form, and the quadratic performance index has been transformed into a relevant format without the explicit appearance of time delay. Another significant improvement is on the OTC law. OTC law can eliminate the negative effects of the sinusoidal disturbances and multiple input delays, and maintain the tracking ability in an optimal fashion.

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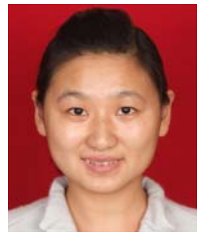

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