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Two degree-of-freedom control design with improved H_∞ LMI representation

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Abstract

This paper focuses on the two degree-of-freedom (2DOF) control design problem for high-speed and precision tracking system. The requirements for tracking resolution, bandwidth are transformed to the H_∞ norm minimizing problem of tracking error. A 2DOF control design approach based on an improved H_∞ linear matrix inequalities (LMI) representation is proposed. The design approach offers a new LMI to obtain the feedforward controller and feedback controller in 2DOF control scheme. The results of simulation experiment demonstrates the proposed approach could obtain a better tracking performance compared with conventional H_∞ 2DOF design based on bounded real lemma.

Keywords: 2DOF control; improve H_∞ LMI representation; tracking error; bounded real lemma (BRL)

1 Introduction

It is well known that two degree-of-freedom (2DOF) control design which combines the feedforward control and feedback control to achieve the desired tracking performance has been widely applied in trajectory tracking control system [1–7]. 2DOF control could extend the tracking bandwidth and resolution of tracking control system [1, 2]. A 2DOF control scheme with coprime factorization-based feedforward control and PD feedback control achieves fast and precise positioning for vibratory mechanism [3]. The 2DOF control system designed by solving the minimizing problem of the H_∞ norm of weighted function is utilized to enhance the tracking performance of an atomic force microscope [4]. A reference feedforward-type 2DOF (RFF-2DOF) control system is designed for maneuverability matching and gust disturbance rejection in in-flight simulator [5]. The adaptive robust control and zero phase error tracking technique are used in 2DOF control and implemented in servo systems of hard disk drives [6]. The 2DOF control system combined with inversion feedforward controller and high-gain feedback controller could achieve high-precision high-speed positioning in piezoactuators [7].

The H_∞ performance reflects resolution, bandwidth of tracking control system [8–10]. Several robust 2DOF control design approaches take account into H_∞ performance specification in worst system uncertainties and solve the H_∞ optimization problem to improve the tracking performance and robustness. The 2DOF-control design approach discussed in [11] proposes a simultaneous feedforward and feedback controller design in an optimal mixed sensitivity framework to increase the bandwidth for similar robustness and resolution over optima feedback-only designs. The robust inversion-based 2DOF control develops a systematic integration design approach which combines the robust inversion feedforward control and H_∞ mixed sensitivity robust feedback control [12]. A 2DOF control approach combined H_∞-feedback and iterative learning control is formulated in [13].

Linear matrix inequalities (LMI) techniques have come to be essential tools for the analysis and synthesis for control problem [14–16]. Now, many LMI design approach research for control problem of different systems have been reported, such as continuous-time linear time-invariant (LTI) systems [16], discrete-time linear system [17, 18], systems with time delay [19, 20], system with bounded uncertainties [21], and so on. However, there are few LMI design approaches for 2DOF control optimization problems, and the reported LMI design approaches for 2DOF control optimization problems are based on conventional LMI representation of BRL [22, 23], which are somewhat of conservative compared with improved LMI representations [24–26].

The contribution of this paper is presenting a 2DOF design approach based on improved H_∞ LMI for high-speed and precision systems. The 2DOF control system design is formulated by an improved LMI representation, and feedforward controller and feedback controller in 2DOF scheme could be obtained by solving the LMI representation.

This paper is organized as follows. The 2DOF control system and optimization objective are presented in Section 2. In Section 3, an improved H_∞ LMI synthesis for systems are introduced. The LMI representations for design of feedforward controller and feedback controller are investigated in Section 4. The simulation experiment and experiment results are described and discussed in Section 5. Finally, the conclusions are given in Section 6.

2 2DOF control system and optimization objective

Given a system $G(s)$ whose state function is described by

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx. \end{aligned} \tag{1}$$

Consider the 2DOF control system shown in Figure 1. In this figure, $G(s)$ is the transfer function of the given system as described in (1), $G_{\mathrm{FF}}(s)$ and $G_{\mathrm{FB}}(s)$ are the feedforward controller and feedback controller respectively. The signal $r(s)$ represents the reference signal that the 2DOF control system need to track and $u(s)$ represents the input to the plant $G(s)$. The signal $y(s)$ represents the actual output of the entire 2DOF control system.

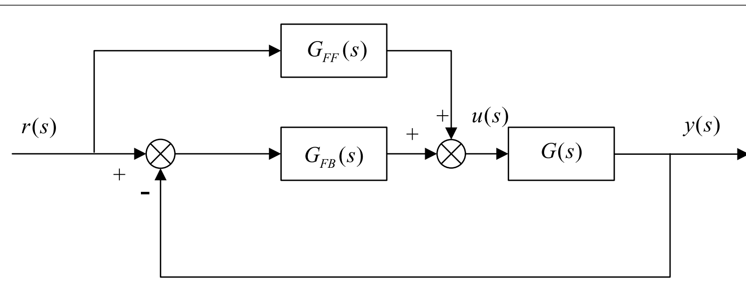

Figure 1 2DOF control system diagram.

The transfer function of the entire 2DOF control system $G_{\mathrm{2DOF}}(s)$ from the reference signal $r(s)$ to actual outputs $y(s)$, is given by

$$G_{\mathrm{2DOF}}(s) = S(s)G(s)\big[G_{\mathrm{FF}}(s) + G_{\mathrm{FB}}(s)\big], \tag{2}$$

where S(s) is the feedback sensitivity function,

$$S(s) = \big(I + G(s)G_{\mathrm{FB}}(s)\big)^{-1}. \tag{3}$$

The tracking error of the entire 2DOF control system $\varepsilon_{\mathrm{2DOF}}(s)$ could be given as

$$\varepsilon_{\mathrm{2DOF}}(s) = I - G_{\mathrm{2DOF}}(s) = S(s)\big(I - G(s)G_{\mathrm{FF}}(s)\big). \tag{4}$$

The control block and tracking error of the 2-DOF control system are now presented. The tracking performance of the entire 2DOF control system can be characterized by tracking error $\varepsilon_{\mathrm{2DOF}}(s)$. Thus, the design goal of 2DOF control design is find a feedforward controller and a feedback controller to make following optimization object satisfied,

$$\min_{G_{\mathrm{FF}},G_{\mathrm{FB}}} \big\| W_p(s)\varepsilon_{\mathrm{2DOF}}(s)\big\|_\infty, \tag{5}$$

where $W_p(s)$ is user-defined weighting function to impose the requirements for the tracking bandwidth and maximum tracking error limitation, and the state-space realization form of W_p is as follow,

$$\begin{aligned} \dot{x}_w &= A_w x_w + B_w u_w, \\ y_w &= C_w x_w + D_w u_w. \end{aligned} \tag{6}$$

3 Improve H_∞ LMI representation

Throughout this paper, the improved H_∞ LMI representations suitable for controller design will be utilized for design of 2DOF control. The LMI representations are presented an follows:

Theorem 1 *Consider the system G in* (1), $\|G(s)\|_\infty < \gamma$ *if there exist symmetric matrix* $P = P^T > 0$, *any appropriately dimensioned matix V and a given scalar λ, such that the following inequality hold*:

$$\begin{bmatrix} -VA^T - AV^T & -B & P + V^T - \lambda VA^T & VC^T \\ * & -\gamma^2 I & -\lambda B^T & D^T \\ * & * & \lambda V + \lambda V^T & 0 \\ * & * & * & -I \end{bmatrix} < 0. \tag{7}$$

Proof Consider the system G, the equivalent LMI representation of BRL [25] could be given as follows:

$$\begin{bmatrix} -A^T V_1^T - V_1 A & -V_1 B & X + V_1 - A^T V_2^T & C^T \\ * & -\gamma^2 I & -B^T V_2^T & D^T \\ * & * & V_2 + V_2^T & 0 \\ * & * & * & -I \end{bmatrix} < 0 \tag{8}$$

if there exit exist symmetric matrix $X = X^T > 0$, and any appropriately dimensioned matrices V_1, V_2, such that the above LMI holds, $\|G(s)\|_\infty < \gamma$.

Assume $V_1 = V$ is negative defined. Thus, V^{-1} is nonsingular. And, set $P = VXV^T$. If we replace V_1 with V^{-1}, V_2 with λV^{-1}. We perform a congruence transformation with $\mathrm{diag}\{VIVI\}$ on the inequality (8), we obtain the inequality (7). □

4 2DOF control design

The H_∞ optimization problem of 2DOF control (5) could be transformed to design the $K(s) = [G_{\mathrm{FF}}(s), G_{\mathrm{FB}}(s)]$ controller composed of feedforward controller G_{FF} and feedback controller G_{FB} which could minimize the H_∞ norm of transfer function from r to z_w in following framework .

In Figure 2, the transfer functions of r to z_w, r to v, u to z_w and u to v in P are given as

$$\begin{bmatrix} z_w \\ r \\ r-y \end{bmatrix} = \underbrace{\begin{bmatrix} W_p & -W_pG \\ I & 0 \\ I & -G \end{bmatrix}}_{P} \begin{bmatrix} r \\ u \end{bmatrix}. \tag{9}$$

And, the state realization of P and K are given as follows:

$$P = \begin{bmatrix} A_p & B_{p1} & B_{p2} \\ C_{p1} & D_{p11} & D_{p12} \\ C_{p2} & D_{p21} & D_{p22} \end{bmatrix}, \tag{10}$$

where $A_p = \left[\begin{smallmatrix} A & 0 \\ -B_wC & A_w \end{smallmatrix}\right]$, $B_{p1} = \left[\begin{smallmatrix} 0 \\ B_w \end{smallmatrix}\right]$, $B_{p2} = \left[\begin{smallmatrix} B \\ -B_wD \end{smallmatrix}\right]$, $C_{p1} = [-D_wD\ C_w]$, $C_{p2} = [-C\ 0]$, $D_{p11} = D_w$, $D_{p12} = 0$, $D_{p21} = I$, $D_{p22} = 0$,

$$K = \begin{bmatrix} A_k & B_k \\ C_k & D_k \end{bmatrix}. \tag{11}$$

Denotes the transfer function from r to z_w as T_{rZ}. In terms of the state space realization of P and K, T_{rZ} is obtained as

$$\begin{aligned} \dot{x}_Z &= A_Zx_Z + B_Zr, \\ Z_w &= C_Zx_Z + D_Zr, \end{aligned} \tag{12}$$

where $A_Z = \left[\begin{smallmatrix} A_p+B_2D_kC_2 & B_2C_k \\ B_kC_2 & A_k \end{smallmatrix}\right]$, $B_Z = \left[\begin{smallmatrix} B_1+B_2D_kD_{21} \\ B_kD_{21} \end{smallmatrix}\right]$, $C_Z = [C_1 + D_{12}D_kC_2\ \ D_{12}C_k]$, $D_Z = D_{11} + D_{12}D_kD_{21}$.

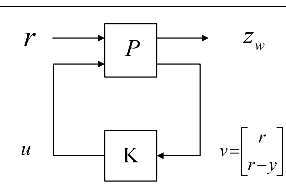

Figure 2 Transformed 2DOF control framework.

Now, the design goal is to compute a controller K, which could render the H_∞ norm of $T_{rZ}(s)$ minimized,

$$\min_{K} \left\| T_{rZ}(s) \right\|_\infty. \tag{13}$$

The solution to the above minimizing problem could be given by the following theorems.

Theorem 2 *There exist a controller K which could render the H_∞ norm of $T_{rZ}(s)$ less than γ,*

$$\left\| T_{rZ}(s) \right\|_\infty < \gamma \tag{14}$$

provided that the scalar λ, symmetric matrices $\hat{P}_{11}$, $\hat{P}_{22}$ and appropriately dimensioned matrices $\hat{P}_{12}$, X, Y, U, $\hat{A}$, $\hat{B}$, $\hat{C}$, $\hat{D}$ satisfy the following LMIs,

$$\begin{bmatrix} \hat{P}_{11} & \hat{P}_{12} \\ * & \hat{P}_{22} \end{bmatrix} < 0, \tag{15}$$

$$\begin{bmatrix} -[A_pX + (A_pX)^T] - [B_{p2}\hat{C} + (B_{p2}\hat{C})^T] & -A_p - B_{p2}\hat{D}C_{p2} - \hat{A}^T & -(B_{p1} + B_{p2}\hat{D}D_{p21}) & \hat{P}_{11} + X^T - \lambda[(A_pX)^T + (B_{p2}\hat{C})^T] & \hat{P}_{12} + U^T - \lambda\hat{A}^T & (C_{p1}X + D_{p12}\hat{C})^T \\ * & -[YA_p + (YA_p)^T] - [\hat{B}C_{p2} + (\hat{B}C_{p2})^T] & -(YB_{p1} + \hat{B}D_{p21}) & \hat{P}_{12}^T + I - \lambda[A_p^T + (B_{p2}\hat{D}C_{p2})^T] & \hat{P}_{22} + Y^T - \lambda[(YA_p)^T + (\hat{B}C_{p2})^T] & (C_{p1} + D_{p12}\hat{D}C_{p2})^T \\ * & * & -\gamma^2 I & -\lambda(B_{p1} + B_{p2}\hat{D}D_{p21})^T & -\lambda(B_{p1} + B_{p2}\hat{D}D_{p21})^T & (D_{p11} + D_{p12}\hat{D}D_{p21})^T \\ * & * & * & \lambda(X + X^T) & \lambda[I + U^T] & 0 \\ * & * & * & * & \lambda(Y + Y^T) & 0 \\ * & * & * & * & * & -I \end{bmatrix} < 0. \tag{16}$$

Proof Consider the Theorem 1, it is obviously that the controller K which could render the inequality (14) hold, if inequality (7) hold with A_Z, B_Z, C_Z, D_Z.

Introduce a partition of V and its inverse $W := V^{-1}$. From $WV = I$, $[W_{11}\ W_{12}]V = [I\ 0]$ and lead to

$$\begin{aligned} F_1 V = F_2, \quad \text{with } F_1 &:= \begin{bmatrix} I & 0 \\ W_{11} & W_{12} \end{bmatrix} = \begin{bmatrix} I & 0 \\ Y & N \end{bmatrix}, \\ F_2 &:= \begin{bmatrix} V_{11} & V_{12} \\ I & 0 \end{bmatrix} = \begin{bmatrix} X^T & M^T \\ I & 0 \end{bmatrix}. \end{aligned} \tag{17}$$

Introduce the linearizing changes of variables as follows:

$$\hat{D} = D_k, \tag{18}$$

$$\hat{C} = D_k C_{p2} X + C_k M, \tag{19}$$

$$\hat{B} = Y B_{p2} D_k + N B_k, \tag{20}$$

$$\hat{A} = Y(A_p + B_{p2} D_k C_{p2})X + N B_k C_{p2} X + Y B_{p2} C_k M + N A_k M. \tag{21}$$

Replace A, B, C, D with A_Z, B_Z, C_Z and D_Z in (7). Performance a congruence transformation with diag$\{F_1 I F_1 I\}$ on both LMI (7), then the LMI terms in (7) become,

$$F_1 A_Z V^T F_1^T = \begin{bmatrix} A_p X + B_{p2}\hat{C} & A_p + B_{p2} D_k C_{p2} \\ \hat{A} & Y A_p + \hat{B} C_{p2} \end{bmatrix}, \tag{22}$$

$$F_1 B_Z = \begin{bmatrix} B_{p1} + B_{p2} D_k D_{p21} \\ Y B_{p1} + \hat{B} D_{p21} \end{bmatrix}, \tag{23}$$

$$C_Z V^T F_1^T = \begin{bmatrix} C_{p1} X + D_{p12}\hat{C} & C_{p1} + D_{p12} D_k C_{p2} \end{bmatrix}, \tag{24}$$

$$F_1 P F_1^T = \hat{P} = \begin{bmatrix} \hat{P}_{11} & \hat{P}_{12} \\ \hat{P}_{12}^T & \hat{P}_{22} \end{bmatrix}, \tag{25}$$

$$F_1 V^T F_1^T = \begin{bmatrix} X & I \\ U & Y \end{bmatrix}, \tag{26}$$

$$U = YX + NM. \tag{27}$$

Now, the LMI (7) with A_Z, B_Z, C_Z and D_Z is recast to LMI (16). The symmetric matrix P in LMI (7) is positive define, thus LMI (15) must hold. This completes the proof. □

Theorem 3 *The controller K is given as following matrices could render the minimizing problem* (13) *satisfied*,

$$D_k = \hat{D}, \tag{28}$$

$$B_k = N^{-1}\big(\hat{B} - Y B_{p2} D_k\big), \tag{29}$$

$$C_k = \big(\hat{C} - D_k C_{p2} X\big) M^{-1}, \tag{30}$$

$$A_k = \big(\hat{A} - Y(A_p + B_{p2} D_k C_{p2}) X - N B_k C_{p2} X - Y B_{p2} C_k M\big), \tag{31}$$

where the scalar λ, symmetric matrices $\hat{P}_{11}$, $\hat{P}_{22}$, and appropriately dimensioned matrices $\hat{P}_{12}$, X, Y, U, $\hat{A}$, $\hat{B}$, $\hat{C}$, $\hat{D}$ could minimize γ in the LMI (16) *subject to LMIs* (15) *and* (16), *and N, M are deduced from $U - YX$.*

Proof It is obviously that the equations (28), (29), (30), (31) are deduced from (18), (19), (20), (21). Equation (27) lead to $NM = U - YX$.

Consider Theorem 2, controller K as matrices (28), (29), (30), (31) could render the minimizing problem (13) satisfied if

$$\min_{\substack{\hat{P}_{11},\hat{P}_{12}\hat{P}_{22},X,\\ Y,U\hat{A},\hat{B},\hat{C},\hat{D}}} (\gamma)$$
$$\text{subject to LMI (15) and (16).} \tag{32}$$

This completes the proof. □

5 Simulation experiment

To demonstrate the proposed design approach, 2DOF controller on a tracking system of an optical disk drive in [27] is designed and a simulation experiment is conducted. And the experiment results show the proposed approach improves the H_∞ performance of 2DOF control system compared with 2DOF design based on BRL.

5.1 Plant model and weighting function

Transfer function of tracking system of optical disk drive is given by

$$\begin{aligned}\dot{x} &= \begin{bmatrix} 0 & 1 \\ -20300 & -4.1 \end{bmatrix} x + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u, \\ y &= [15.8, 0]x.\end{aligned} \tag{33}$$

The weighting function $W_p(s)$ is selected as $\frac{5,000}{s+100}$, and its state space realization is as

$$\begin{aligned}\dot{x}_w &= -100x_w + u_w, \\ y_w &= 5,000x_w.\end{aligned} \tag{34}$$

5.2 Controller design

The theorems presented in Section 4 are applied to design the controller K including feedforward controller G_{FF} and feedback controller G_{FB}.

By Theorem 3, G_{FF} and G_{FB} are obtained as follow which yields the value of γ, namely the minimizing value of $\|W_p(s)\varepsilon_{\mathrm{2DOF}}(s)\|_\infty$ as 0.927.

$$G_{\mathrm{FF}} = \frac{-1.36 \times 10^4 s^3 + 7.13 \times 10^9 s^2 + 1.61 \times 10^{11} s + 1.76 \times 10^{14}}{s^3 + 6,234s^2 + 1.56 \times 10^8 s + 1.38 \times 10^{11}}, \tag{35}$$

$$G_{\mathrm{FB}} = \frac{-938 \times 10^4 s^3 + 4.5 \times 10^{10} s^2 + 3.24 \times 10^{12} s - 1.16 \times 10^{14}}{s^3 + 6,234s^2 + 1.56 \times 10^8 s + 1.38 \times 10^{11}}. \tag{36}$$

However, by the 2DOF control design based on BRL [14], the minimum value of $\|W_p(s)\varepsilon_{\mathrm{2DOF}}(s)\|_\infty$ is 1.52 which is larger than the proposed design approach.

5.3 Simulation results

We conducted the experiments to track a sinusoidal signal at frequencies (10 and 100 Hz) using the proposed 2DOF control approach based on improved LMI representation and the approach based on BRL. The experimental results show that the tracking performance of proposed design approach is better. As shown in Figure 3, at frequency 10 and 100 Hz, the maximum tracking errors using proposed design approach are 0.022 and 0.129, respectively; however, the maximum tracking errors using design approach based on BRL are 0.032 and 0.173, respectively.

6 Conclusion

A 2DOF control design based on improved LMI representation for high-speed and precision tracking systems is proposed in this paper. An improved H_∞ representation is proposed in Theorem 1. The LMIs for 2DOF control design which relies on improved H_∞ LMI representation are presented in Theorems 2 and 3. The proposed approach is employed to design the feedforward controller and feedback controller design in 2DOF control system which could reduce the maximum of tracking error compared with 2DOF control design based on BRL.

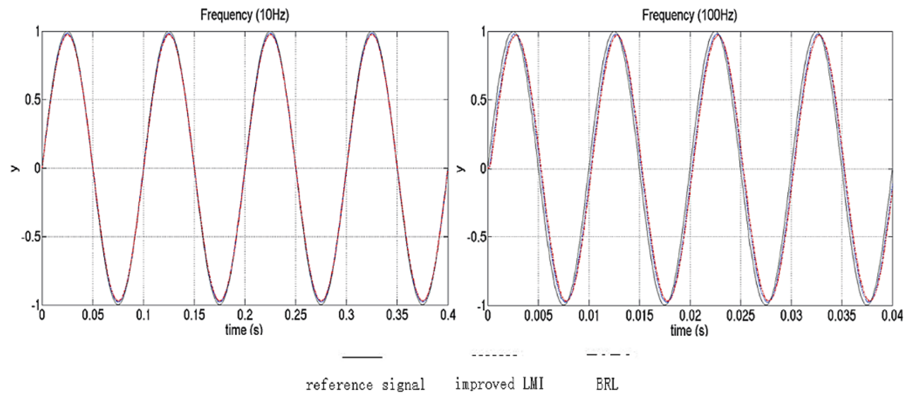

Figure 3 Experimental tracking results.

Competing interests
The authors declare that they have no competing interests.

Author's contributions
The authors jointly worked on deriving the results. All authors read and approved the final manuscript.

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