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Discrete Time Mixed LQR/$H_\infty$ Control Problems

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1. Introduction

This chapter will consider two discrete time mixed LQR/$H_\infty$ control problems. One is the discrete time state feedback mixed LQR/$H_\infty$ control problem, another is the non-fragile discrete time state feedback mixed LQR/$H_\infty$ control problem. Motivation for mixed LQR/$H_\infty$ control problem is to combine the LQR and suboptimal $H_\infty$ controller design theories, and achieve simultaneously the performance of the two problems. As is well known, the performance measure in optimal LQR control theory is the quadratic performance index, defined in the time-domain as

$$J := \sum_{k=0}^{\infty} (x^T(k)Qx(k) + u^T(k)Ru(k))$$

while the performance measure in $H_\infty$ control theory is $H_\infty$ norm, defined in the frequency-domain for a stable transfer matrix $T_{zw}(z)$ as

$$\|T_{zw}(z)\|_{\infty} := \sup_{w \in \mathbb{C}} \sigma_{\text{max}}[T_{zw}(e^{jw})]$$

where, $Q \succeq 0, R > 0$, $\sigma_{\text{max}}(\bullet)$ denotes the largest singular value.

The linear discrete time system corresponding to the discrete time state feedback mixed LQR/$H_\infty$ control problem is

$$x(k + 1) = Ax(k) + B_1 w(k) + B_2 u(k)$$

$$z(k) = C_1 x(k) + D_{12} u(k)$$

with state feedback of the form

$$u(k) = Kx(k)$$

where, $x(k) \in \mathbb{R}^n$ is the state, $u(k) \in \mathbb{R}^m$ is the control input, $w(k) \in \mathbb{R}^q$ is the disturbance input that belongs to $L_2[0, \infty)$, $z(k) \in \mathbb{R}^p$ is the controlled output. $A$, $B_1$, $B_2$, $C_1$ and $D_{12}$ are known matrices of appropriate dimensions. Let $x(0) = x_0$.

The closed loop transfer matrix from the disturbance input $w$ to the controlled output $z$ is
\[ T_{zw}(z) = \begin{bmatrix} A_k & B_k \\ C_k & 0 \end{bmatrix} := C_k(zI - A_k)^{-1}B_k \]

where, \( A_k := A + B_2K \), \( B_k := B_1 \), \( C_k := C_1 + D_{12}K \).

Recall that the discrete time state feedback optimal LQR control problem is to find an admissible controller that minimizes the quadratic performance index (1) subject to the systems (2) (3) with \( w = 0 \), while the discrete time state feedback \( H_\infty \) control problem is to find an admissible controller such that \( \|T_{zw}(z)\|_\infty < \gamma \) subject to the systems (2)(3) for a given number \( \gamma > 0 \). While we combine the two problems for the systems (2)(3) with \( w \in L_2[0, \infty) \), the quadratic performance index (1) is a function of the control input \( u(k) \) and disturbance input \( w(k) \) in the case of \( x(0) \) being given and \( \gamma \) being fixed. Thus, it is not possible to pose a mixed LQR/ \( H_\infty \) control problem that is to find an admissible controller that achieves the minimization of quadratic performance index (1) subject to \( \|T_{zw}(z)\|_\infty < \gamma \) for the systems (2)(3) with \( w \in L_2[0, \infty) \) because the quadratic performance index (1) is an uncertain function depending on the uncertain disturbance input \( w(k) \). In order to eliminate this difficulty, the design criteria of state feedback mixed LQR/ \( H_\infty \) control problem should be replaced by the design criteria

\[ \sup_{w \in L_2} \inf_k \{ f \} \] subject to \( \|T_{zw}(z)\|_\infty < \gamma \)

because for all \( w \in L_2[0, \infty) \), the following inequality always exists

\[ \inf_k \{ f \} \leq \sup_{w \in L_2} \inf_k \{ f \} \]

The stochastic problem corresponding to this problem is the combined LQG/ \( H_\infty \) control problem that was first presented by Bernstein & Haddad (1989). This problem is to find an admissible fixed order dynamic compensator that minimizes the expected cost function of the form

\[ J = \lim_{t \to \infty} E(x^TQx + u^TRu) \] subject to \( \|T_{zw}\|_\infty < \gamma \).

Here, the disturbance input \( w \) of this problem is restricted to be white noise. Since the problem of Bernstein & Haddad (1989) involves merely a special case of fixing weighting matrices \( Q \) and \( R \), it is considered as a mixed \( H_2 / H_{\infty} \) problem in special case. Doyle et al. (1989b) considered a related output feedback mixed \( H_2 / H_{\infty} \) problem (also see Doyle et al., 1994). The two approaches have been shown in Yeh et al. (1992) to be duals of one another in some sense. Also, various approaches for solving the mixed \( H_2 / H_{\infty} \) problem are presented (Rotea & Khargonekar, 1991; Khargonekar & Rotea, 1991; Zhou et al., 1994; Limebeer et al. 1994; Sznajer, 1994; Rotein & Sznajer, 1998; Sznajer et al., 2000). However, no approach has involved the mixed LQR/ \( H_{\infty} \) control problem until the discrete time state feedback controller for solving this problem was presented by Xu (1996). Since then, several approaches to the mixed LQR/ \( H_{\infty} \) control problems have been presented in Xu (2007, 2008).

The first goal of this chapter is to, based on the results of Xu (1996, 2007), present the simple approach to discrete time state feedback mixed LQR/ \( H_{\infty} \) control problem by combining the Lyapunov method for proving the discrete time optimal LQR control problem with an
extension of the discrete time bounded real lemma, the argument of completion of squares of Furuta & Phoojaruenchanachi (1990) and standard inverse matrix manipulation of Souza & Xie (1992).

On the other hand, unlike the discrete time state feedback mixed LQR / $H_\infty$ control problem, state feedback corresponding to the non-fragile discrete time state feedback mixed LQR / $H_\infty$ control problem is a function of controller uncertainty $\Delta F(k)$, and is given by

$$u(k) = \hat{F}_x x(k), \quad \hat{F}_x = F_x + \Delta F(k)$$

where, $\Delta F(k)$ is the controller uncertainty.

The closed-loop transfer matrix from disturbance input $w$ to the controlled output $z$ and quadratic performance index for the closed-loop system (2) (4) is respectively

$$\hat{T}_{zw}(z) = \begin{bmatrix} A_{\hat{F}_x} & B_{\hat{F}_x} \\ C_{\hat{F}_x} & 0 \end{bmatrix} = C_{\hat{F}_x} (zI - A_{\hat{F}_x})^{-1} B_{\hat{F}_x}$$

and

$$\hat{j} := \sum_{k=0}^{\infty} \left\{ Q^{1/2} x(k) \right\}^T + \left\{ R^{1/2} u(k) \right\}^T + \gamma^2 \| u \|_F^2$$

where, $A_{\hat{F}_x} := A + B_{\hat{F}_x}, B_{\hat{F}_x} := B_1, C_{\hat{F}_x} := C_1 + D_{12} \hat{F}_x$, $\gamma > 0$ is a given number.

Note that the feedback matrix $\hat{F}_x$ of the considered closed-loop system is a function of the controller uncertainty $\Delta F(k)$, this results in that the quadratic performance index (1) is not only a function of the controller $F_x$ and disturbance input $w(k)$ but also a function of the controller uncertainty $\Delta F(k)$ in the case of $x(0)$ being given and $\gamma$ being fixed. We can easily know that the existence of disturbance input $w(k)$ and controller uncertainty $\Delta F(k)$ makes it impossible to find $\sup_{w \in C_{zw}} \inf_{\Delta F} \{ j \}$, while the existence of controller uncertainty $\Delta F(k)$ also makes it difficult to find $\sup_{w \in C_{zw}} \{ j \}$. In order to eliminate these difficulties, the design criteria of non-fragile discrete time state feedback mixed LQR/ $H_\infty$ control problem should be replaced by the design criteria

$$\sup_{w \in C_{zw}} \{ j \} \text{ subject to } \|T_{zw}(z)\|_\infty < \gamma.$$
problem is said to be a non-fragile control problem. Recently, the non-fragile controller approach has been used to a very large class of control problems (Famularo et al. 2000, Haddad et al. 2000, Yang et al. 2000, Yang et al. 2001 and Xu 2007).

The second aim of this chapter is to, based on the results of Xu (2007), present a non-fragile controller approach to the discrete-time state feedback mixed LQR/\(H_\infty\) control problem with controller uncertainty.

This chapter is organized as follows. In Section 2, we review several preliminary results, and present two extensions of the well known discrete time bounded real lemma. In Section 3, we define the discrete time state feedback mixed LQR/\(H_\infty\) control problem. Based on this definition, we present the both Riccati equation approach and state space approach to the discrete time state feedback mixed LQR/\(H_\infty\) control problem. In Section 4, we introduce the definition of non-fragile discrete time state feedback mixed LQR/\(H_\infty\) control problem, give the design method of a non-fragile discrete time state feedback mixed LQR/\(H_\infty\) controller, and derive the necessary and sufficient conditions for the existence of this controller. In Section 5, we give two examples to illustrate the design procedures and their effectiveness, respectively. Section 6 gives some conclusions.

2. Preliminaries

This section reviews several preliminary results. First, we consider the discrete time Riccati equation and discrete time Riccati inequality, respectively

\[ X = A^T X (I + RX)^{-1} A + Q \]  

and

\[ A^T X (I + RX)^{-1} A + Q - X < 0 \]  

with \( Q = Q^T \geq 0 \) and \( R = R^T > 0 \).

We are particularly interested in solutions \( X \) of (5) and (6) such that \((I + RX)^{-1} A\) is stable. A symmetric matrix \( X \) is said to be the stabilizing solution of the discrete time Riccati equation (5) if it satisfies (5) and is such that \((I + RX)^{-1} A\) is stable. Moreover, for a sufficiently small constant \( \delta > 0 \), the discrete time Riccati inequality (6) can be rewritten as

\[ X = A^T X (I + RX)^{-1} A + Q + \delta I \]  

Based on the above relation, we can say that if a symmetric matrix \( X \) is a stabilizing solution to the discrete time Riccati equation (7), then it also is a stabilizing solution to the discrete time Riccati inequality (6). According to the concept of stabilizing solution of discrete time Riccati equation, we can define the stabilizing solution \( X \) to the discrete time Riccati inequality (6) as follow: if there exists a symmetric solution \( X \) to the discrete time Riccati inequality (6) such that \((I + RX)^{-1} A\) is stable, then it is said to be a stabilizing solution to the discrete time Riccati inequality (6).
If $A$ is invertible, the stabilizing solution to the discrete time Riccati equation (5) can be obtained through the following simplectic matrix

$$
S := \begin{bmatrix}
A + RA^{-T}Q & -RA^{-T} \\
-A^{-T}Q & A^{-T}
\end{bmatrix}
$$

(8)

Assume that $S$ has no eigenvalues on the unit circle, then it must have $n$ eigenvalues in $|\lambda| < 1$ and $n$ in $|\lambda| > 1$ \((i = 1, 2, \ldots, n, n + 1, \ldots, 2n)\). If $n$ eigenvectors corresponding to $n$ eigenvalues in $|\lambda| < 1$ of the simplectic matrix (8) is computed as

$$
\begin{bmatrix}
u_1 \\
u_2 \\
\end{bmatrix}
$$

then a stabilizing solution to the discrete time Riccati equation (5) is given by

$$
X = \begin{bmatrix}
v_1 & \cdots & v_n
\end{bmatrix}
\begin{bmatrix}
u_1 & \cdots & u_n
\end{bmatrix}^{-1}
$$

Secondly, we will introduce the well known discrete time bounded real lemma (see Zhou et al., 1996; Iglesias & Glover, 1991; Souza & Xie, 1992).

**Lemma 2.1 (Discrete Time Bounded Real Lemma)**

Suppose that $\gamma > 0$, $M(z) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \in RH_\alpha$, then the following two statements are equivalent:

i. $\|M(z)\|_\infty < \gamma$.

ii. There exists a stabilizing solution $X \geq 0$ ( $X > 0$ if $(C, A)$ is observable) to the discrete time Riccati equation

$$
A^TXA - X + \gamma^{-2}(A^TXB + C^TD)U_1^{-1}(B^TXA + D^TC) + C^TC = 0
$$

such that $U_1 = I - \gamma^{-2}(D^TD + B^TXB) > 0$.

In order to solve the two discrete time state feedback mixed LQR/ $H_\infty$ control problems considered by this chapter, we introduce the following reference system

$$
x(k + 1) = Ax(k) + B_1w(k) + B_2u(k) \quad \hat{z}(k) = \begin{bmatrix} C_1 \\ \Omega_{1/2} I \\ 0 \end{bmatrix} x(k) + \begin{bmatrix} D_{12} \\ \Omega_{1/2} z_0(k) \\ 0 \end{bmatrix} u(k)
$$

(9)

where, $\Omega = \begin{bmatrix} Q & 0 \\ 0 & R \end{bmatrix}$ and $\hat{z}(k) = \begin{bmatrix} z(k) \\ z_0(k) \end{bmatrix}$.

The following lemma is an extension of the discrete time bounded real lemma.

**Lemma 2.2** Given the system (2) under the influence of the state feedback (3), and suppose that $\gamma > 0$, $T_{zw}(z) \in RH_\alpha$; then there exists an admissible controller $K$ such that $\|T_{zw}(z)\|_\infty < \gamma$ if there exists a stabilizing solution $X_{\alpha} \geq 0$ to the discrete time Riccati equation

$$
A_K^TX_{\alpha}A_K - X_{\alpha} + \gamma^{-2}A_K^TX_{\alpha}B_KU_1^{-1}B_K^TX_{\alpha}A_K + C_K^TC_K + Q + K^TRK = 0
$$

(10)
such that \( U_1 = I - \gamma^2 B_k^T X_e B_k > 0 \).

**Proof:** Consider the reference system (9) under the influence of the state feedback (3), and define \( T_0 \) as

\[
T_0(z) := \begin{bmatrix} A_K & B_k \\ \Omega(z) & 0 \end{bmatrix}
\]

then the closed-loop transfer matrix from disturbance input \( \tilde{w} \) to the controlled output \( \tilde{z} \) is

\[
T_{zw}(z) = \begin{bmatrix} T_{zw}(z) \\
T_0(z) \end{bmatrix}
\]

Note that \( \gamma^2 I - T_{zw} T_{zw}^* > 0 \) is equivalent to

\[
\gamma^2 I - T_{zw} T_{zw}^* > T_0^* T_0 > 0 \quad \text{for all} \quad w \in L_2([0, \infty)),
\]

and \( T_{zw}(z) \in RH_{\infty} \) is equivalent to \( T_{zw}(z) \in RH_{\infty} \), so \( \|T_{zw}(z)\|_{\infty} < \gamma \) implies \( \|T_{zw}(z)\|_{\infty} < \gamma \). Hence, it follows from Lemma 2.1. Q.E.D.

To prove the result of non-fragile discrete time state feedback mixed LQR/\( H_{\infty} \) control problem, we define the inequality

\[
A_{F_e}^T X_e A_{F_e} - X_e + \gamma^2 A_{F_e}^T X_e B_{F_e} U_1^{-1} B_{F_e}^T X_e A_{F_e} + C_{F_e}^T C_{F_e} + Q + F_e^T R F_e < 0
\]

(11)

where, \( U_1 = I - \gamma^2 B_{F_e}^T X_e B_{F_e} > 0 \).

In terms of the inequality (11), we have the following lemma:

**Lemma 2.3** Consider the system (2) under the influence of state feedback (4) with controller uncertainty, and suppose that \( \gamma > 0 \) is a given number, then there exists an admissible non-fragile controller \( F_e \) such that \( \|F_e\|_{\infty} < \gamma \) if for any admissible uncertainty \( \Delta F(k) \), there exists a stabilizing solution \( X_e \geq 0 \) to the inequality (11) such that \( U_1 = I - \gamma^2 B_{F_e}^T X_e B_{F_e} > 0 \).

**Proof:** Suppose that for any admissible uncertainty \( \Delta F(k) \), there exists a stabilizing solution \( X_e \geq 0 \) to the inequality (11) such that \( U_1 = I - \gamma^2 B_{F_e}^T X_e B_{F_e} > 0 \). This implies that \( X_e \geq 0 \) is such that \( A_{F_e} + \gamma^2 B_{F_e}^T U_1^{-1} B_{F_e} X_e A_{F_e} \) is stable.

Let \( A_{F_e} = A + B_{F_e} F_e \) and \( C_{F_e} = C_1 + D_{12} F_e \); then we can rewrite (11) as

\[
A_{F_e}^T X_e A_{F_e} - X_e + \gamma^2 A_{F_e}^T X_e B_{F_e} U_1^{-1} B_{F_e}^T X_e A_{F_e} + C_{F_e}^T C_{F_e} + Q + F_e^T R F_e < 0
\]

where, \( U_2 = B_{F_e}^T U_2 B_{F_e} + I + R \), \( U_3 = \gamma^2 X_e B_{F_e} U_1^{-1} B_{F_e} X_e + \gamma^2 \),

\[
\Delta N_F = (A_{F_e}^T U_2 B_3 + F_e^T U_2 + \Delta F(k) U_2) U_2^T (B_{F_e}^T U_3 A + U_2 F_e + U_2 \Delta F(k))
\]

Since \( \Delta F(k) \) is an admissible norm-bounded time-varying uncertainty, there exists a time-varying uncertain number \( \delta(k) > 0 \) satisfying

\[
A_{F_e}^T X_e A_{F_e} - X_e + \gamma^2 A_{F_e}^T X_e B_{F_e} U_1^{-1} B_{F_e}^T X_e A_{F_e} + C_{F_e}^T C_{F_e} + Q + F_e^T R F_e
+ \Delta N_F + \delta(k) I = 0
\]

(12)
Note that $A_{F_k} + \gamma^{-2}B_{F_k}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k}$ is stable for any admissible uncertainty $\Delta F(k)$. This implies that $A_{F_k} + \gamma^{-2}B_{F_k}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k}$ is stable. Hence, $(U_1^{-1}B_{F_k}^T X_\alpha A_{F_k}, A_{F_k})$ is detectable. Then it follows from standard results on Lyapunov equations (see Lemma 2.7 a), Iglesias & Glover 1991) and the equation (12) that $A_{F_k}$ is stable. Thus, $A_{F_k} = A_{F_k} + B_2\Delta F(k)$ is stable for any admissible uncertainty $\Delta F(k)$.

Define $V(x(k)) := x^T(k)X_\alpha x(k)$, where $x$ is the solution to the plant equations for a given input $w$, then it can be easily established that

$$
0 = \sum_{k=0}^{\infty} [-\Delta V(x(k)) + x^T(k+1)X_\alpha x(k+1) - x^T(k)X_\alpha x(k)]
$$

$$
= \sum_{k=0}^{\infty} [-\Delta V(x(k)) - \|w\|^2 + \gamma^2\|w\|^2 - \gamma^2 \|U_1^{1/2}(w - \gamma^{-2}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} x)\|^2]
$$

$$
+ x^T(A_{F_k}^T X_\alpha A_{F_k} - X_\alpha + \gamma^{-2}A_{F_k}^T X_{B_k} B_{F_k} U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} + C_{F_k}^T C_{F_k}) x]
$$

Add the above zero equality to $J$ to get

$$
J = \sum_{k=0}^{\infty} [-\Delta V(x(k)) - \|w\|^2 + \gamma^2\|w\|^2 - \gamma^2 \|U_1^{1/2}(w - \gamma^{-2}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} x)\|^2]
$$

$$
+ x^T(A_{F_k}^T X_\alpha A_{F_k} - X_\alpha + \gamma^{-2}A_{F_k}^T X_{B_k} B_{F_k} U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} + C_{F_k}^T C_{F_k}) x]
$$

Substituting (11) for the above formula, we get that for any $u(k)$ and $w(k)$ and $x(0) = 0$,

$$
J < -\|\xi_0\|^2 + \gamma^2\|w\|^2 - \gamma^2 \|U_1^{1/2}(w - \gamma^{-2}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} x)\|^2
$$

Note that $\|\xi_0\|^2 = \sum_{k=0}^{\infty} \hat{x}^T(k)Q\hat{x}(k)$, and define that $r := w - \gamma^{-2}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} x$, we get

$$
\|\xi_0\|^2 - \gamma^2\|w\|^2 < -\gamma^2 \|U_1^{1/2}r\|^2
$$

Suppose that $\Gamma$ is the operator with realization

$$
x(k+1) = (A + B_2\hat{F}_\infty)x(k) + B_{F_k} w(k)
$$

$$
r(k) = -\gamma^{-2}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} x(k) + w(k)
$$

which maps $w$ to $r$.

Since $\Gamma^{-1}$ exists (and is given by $x(k+1) = (A + B_2\hat{F}_\infty + \gamma^{-2}B_{F_k} U_1^{-1}B_{F_k}^T X_\alpha A_{F_k})x(k) + B_{F_k} r(k)$), $w(k) = \gamma^{-2}U_1^{-1}B_{F_k}^T X_\alpha A_{F_k} x(k) + r(k)$), we can write

$$
\|\xi_0\|^2 - \gamma^2\|w\|^2 < -\gamma^2 \|U_1^{1/2}r\|^2 = -\gamma^2 \|w\|^2 \leq \kappa \|w\|^2
$$
for some positive $\kappa$. This implies that there exists an admissible non-fragile controller such that $\|T_{zw}\|_\infty < \gamma$. Note that $\gamma^2 I - T_{zw}^T T_{zw} > 0$ is equivalent to
\[
y^2 I - T_{zw}^T T_{zw} > T_0^T T_0 > 0 \text{ for all } w \in L_2(0, \infty)
\]
so $\|T_{zw}\|_\infty < \gamma$ implies $\|T_{zw}\|_\infty < \gamma$, and we conclude that there exists an admissible non-fragile controller such that $\|T_{zw}\|_\infty < \gamma$. Q. E. D.

3. State Feedback

In this section, we will consider the discrete time state feedback mixed LQR/ $H_\infty$ control problem. This problem is defined as follows: Given the linear discrete-time systems (2)(3) with $w \in L_2(0, \infty)$ and $x(0) = x_0$ and the quadratic performance index (1), for a given number $\gamma > 0$, determine an admissible controller $K$ that achieves
\[
\sup_{w \in L_2} \inf_K \{ J \} \text{ subject to } \|T_{zw}(z)\|_\infty < \gamma.
\]

If this controller $K$ exists, it is said to be a discrete time state feedback mixed LQR/ $H_\infty$ controller.

Here, we will discuss the simplified versions of the problem defined in the above. In order to do this, the following assumptions are imposed on the system

Assumption 1 $(C_1, A)$ is detectable.

Assumption 2 $(A, B_2)$ is stabilizable.

Assumption 3 $D_{12}^T [C_1 \quad D_{12}] = [0 \quad I]$.

The solution to the problem defined in the above involves the discrete time Riccati equation
\[
A^T X_\gamma A - X_\gamma - A^T X_\gamma \hat{B}(\hat{B}^T X_\gamma \hat{B} + \hat{R})^{-1} \hat{B}^T X_\gamma A + C_1^T C_1 + Q = 0
\]
where, $\hat{B} = [\gamma^{-1} B_1 \quad B_2]$, $\hat{R} = \begin{bmatrix} -I & 0 \\ 0 & R + I \end{bmatrix}$. If $A$ is invertible, the stabilizing solution to the discrete time Riccati equation (13) can be obtained through the following simplectic matrix
\[
S_{\gamma} := \begin{bmatrix} A + \hat{B} \hat{R}^{-1} \hat{B}^T A^{-T} (C_1^T C_1 + Q) & -\hat{B} \hat{R}^{-1} \hat{B}^T A^{-T} \\ -A^{-T} (C_1^T C_1 + Q) & A^{-T} \end{bmatrix}
\]
In the following theorem, we provide the solution to discrete time state feedback mixed LQR/ $H_\infty$ control problem.

Theorem 3.1 There exists a state feedback mixed LQR/ $H_\infty$ controller if the discrete time Riccati equation (13) has a stabilizing solution $X_\gamma \geq 0$ and $U_1 = I - \gamma^{-2} B_1^T X_\gamma B_1 > 0$.

Moreover, this state feedback mixed LQR/ $H_\infty$ controller is given by
\[
K = -U_2^{-1} B_2^T U_3 A
\]
where, $U_2 = R + I + B_2^T U_3 B_2$, and $U_3 = X_\gamma + \gamma^{-2} X_\gamma B_1 U_1^{-1} B_1^T X_\gamma$.

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In this case, the state feedback mixed LQR/H\(_\infty\) controller will achieve
\[
\sup_{\omega \in \omega_0} \inf_k \left\{ J \right\} = x_0^T (X_x + \gamma^2 X_w - X_u) x_0 \quad \text{subject to} \quad \left\| T_{zw} \right\|_\infty < \gamma.
\]
where, \( \hat{A}_k = A_k + \gamma^2 B_k U^T x_k A_k \), \( X_w = \sum_{k=0}^{\infty} \left\{ (A_k + \gamma^2 B_k U^T x_k A_k) X_k (A_k + \gamma^2 B_k U^T x_k A_k)^T \right\} \), and
\( X_x = \sum_{k=0}^{\infty} \left\{ (\hat{A}_k + \gamma^2 C_k C_k' \hat{A}_k) X_k (\hat{A}_k + \gamma^2 C_k C_k' \hat{A}_k)^T \right\} \).

Before proving Theorem 3.1, we will give the following lemma.

**Lemma 3.1** Suppose that the discrete time Riccati equation (13) has a stabilizing solution \( X_x \geq 0 \) and \( U_1 = I - \gamma^2 B_k^T X_k B_k > 0 \), and let \( A_k = A + B_k K \) and \( K = -U_2^T B_k^T U_2 A \); then \( A_k \) is stable.

**Proof:** Suppose that the discrete time Riccati equation (13) has a stabilizing solution \( X_x \geq 0 \) and \( U_1 = I - \gamma^2 B_k^T X_k B_k > 0 \). Observe that
\[
\begin{bmatrix}
\gamma^2 B_k^T X_k B_k \\
X_k \end{bmatrix} \gamma^2 B_k^T X_k B_k A_k + \begin{bmatrix}
-I & 0 \\
0 & R + I
\end{bmatrix} = \begin{bmatrix}
-U_1 & \gamma^2 B_k^T X_k B_k \\
\gamma^2 B_k^T X_k B_k A_k + U_2^T B_k^T U_2 A_k + R + I
\end{bmatrix}
\]

Also, note that \( U_1 = I - \gamma^2 B_k^T X_k B_k > 0 \), \( U_3 = X_x + \gamma^2 X_k B_k U^T x_k X_k \), and \( U_5 = R + I + B_k^T U_2 B_k \); then it can be easily shown by using the similar standard matrix manipulations as in the proof of Theorem 3.1 in Souza & Xie (1992) that
\[
(B_k^T X_k B_k + \gamma) = \begin{bmatrix}
-U_1 & U_1^T B_k^T U_2^T U_1^T U_2 \\\nU_2^T B_k^T U_1 & U_2^T U_2
\end{bmatrix}^{-1}
\]

where, \( \hat{B}_k = \gamma^2 B_k^T X_k B_k \).

Thus, we have
\[
A^T X_k B_k (B_k^T X_k B_k + \gamma) A = -\gamma^2 A^T X_k B_k U^T x_k X_k A + A^T U_2 B_k^T U_2 B_k U_2 A
\]

Rearranging the discrete time Riccati equation (13), we get
\[
X_x = A^T X_x A + \gamma^2 A^T X_k B_k U^T x_k X_k A - A^T U_3 B_k^T U_2 B_k U_2 A + C_k^T C_k + Q
\]

Thus,
\[
\begin{align*}
X_x &= \sum_{k=0}^{\infty} \left\{ (\hat{A}_k + \gamma^2 C_k C_k' \hat{A}_k) X_k (\hat{A}_k + \gamma^2 C_k C_k' \hat{A}_k)^T \right\} \\
&= \sum_{k=0}^{\infty} \left\{ (A_k + \gamma^2 B_k K U^T x_k A_k) X_k (A_k + \gamma^2 B_k K U^T x_k A_k)^T \right\} \\
&= \sum_{k=0}^{\infty} \left\{ (\hat{A}_k + \gamma^2 C_k C_k' \hat{A}_k) X_k (\hat{A}_k + \gamma^2 C_k C_k' \hat{A}_k)^T \right\}
\end{align*}
\]
that is,

$$A_K^T X_K A_K - X_o + \gamma^{-2} A_K^T X_K B_K U_1^T B_K^T X_K A_K + C_K^T C_K + Q + K^T R K = 0 \quad (14)$$

Since the discrete time Riccati equation (13) has a stabilizing solution $X_o \geq 0$, the discrete time Riccati equation (14) also has a stabilizing solution $X_o \geq 0$. This implies that $A_K = A_K + \gamma^{-2} B_K U_1^T B_K^T X_K A_K$ is stable. Hence $(U_1^T B_K X_K A_K, A_K)$ is detectable. Based on this, it follows from standard results on Lyapunov equations (see Lemma 2.7 a), Iglesias & Glover 1991) that $A_K$ is stable.

Proof of Theorem 3.1: Suppose that the discrete time Riccati equation (13) has a stabilizing solution $X_o \geq 0$ and $U_1 = I - \gamma^{-2} B_K^T X_K A_K > 0$. Then, it follows from Lemma 3.1 that $A_K$ is stable. This implies that $T_{zw}(z) \in RH_{\infty}$. By using the same standard matrix manipulations as in the proof of Lemma 3.1, we can rewrite the discrete time Riccati equation (13) as follows:

$$A^T X_o A - X_o + \gamma^{-2} A^T X_o B_K U_1^T B_K^T X_o A_K - A^T U_3 B_2 U_2^T B_2^T U_3 A + C_1^T C_1 + Q = 0$$

or equivalently,

$$A_K^T X_K A_K - X_o + \gamma^{-2} A_K^T X_K B_K U_1^T B_K^T X_o A_K + C_K^T C_K + Q + K^T R K = 0$$

Thus, it follows from Lemma 2.2 that $\|T_{zw}(z)\|_\infty < \gamma$.

Define $V(x(k)) = x^T(k) X_o x(k)$, where $X_o$ is the solution to the discrete time Riccati equation (13), then taking the difference $\Delta V(x(k))$ and completing the squares we get

$$\Delta V(x(k)) = x^T(k+1) X_o x(k+1) - x^T(k) X_o x(k)$$

$$= x^T(k) (A_K^T X_K A_K - X_o) x(k) + x^T(k) A_K^T X_K B_K w(k)$$

$$+ w^T(k) (A_K^T X_K A_K - X_o) x(k) + w^T(k) B_K^T X_K B_K w(k)$$

$$= -||x||^2 + \gamma^{-2} ||w||^2 - \gamma^{-2} \left( \frac{1}{2} ||w - \gamma^{-2} U_1^T B_K^T X_K A_K x||^2 \right)$$

$$+ x^T (A_K^T X_K A_K - X_o + \gamma^{-2} A_K^T X_K B_K U_1^T B_K^T X_K A_K + C_K^T C_K) x$$

Based on the above, the cost function $J$ can be rewritten as:

$$J = \sum_{k=0}^{\infty} \hat{x}^T(k) \Omega(k) \hat{x}(k) = \sum_{k=0}^{\infty} \left( -\Delta V(x(k)) - ||x||^2 + \gamma^{-2} ||w||^2 - \gamma^{-2} \left( \frac{1}{2} ||w - \gamma^{-2} U_1^T B_K^T X_K A_K x||^2 \right) \right)$$

$$+ x^T (A_K^T X_K A_K - X_o + \gamma^{-2} A_K^T X_K B_K U_1^T B_K^T X_K A_K + C_K^T C_K + Q + K^T R K) x \quad (15)$$

On the other hand, it follows from the similar arguments as in the proof of Theorem 3.1 in Furuta & Phoojaruenchanachai (1990) that

$$A_K^T X_K A_K - X_o + \gamma^{-2} A_K^T X_K B_K U_1^T B_K^T X_K A_K + C_K^T C_K + Q + K^T R K$$

$$= A^T X_o A - X_o + \gamma^{-2} A^T X_o B_K U_1^T B_K^T X_o A - A^T U_3 B_2 U_2^T B_2^T U_3 A + C_1^T C_1 + Q$$

$$+ (K + U_2^T B_2^T U_3 A)^T U_2 (K + U_2^T B_2^T U_3 A)$$

At the same time note that
\[-\gamma^2 A^T X_A B_1 U_1^1 B_1^T X_A A + A^T U_1 B_1 U_2^1 B_2^T U_2 A\]
\[= A^T X_A \hat{B} (\hat{B}^T X_A \hat{B} + \hat{R})^{-1} \hat{B}^T X_A A\]

We have
\[A_k^T X_A A_k - X_A + \gamma^2 A_k^T X_A B_1 U_1^1 B_1^T X_A A_k + C_k^T C_k + Q + K^T R K\]
\[= A^T X_A A - X_A - A^T X_A \hat{B} (\hat{B}^T X_A \hat{B} + \hat{R})^{-1} \hat{B}^T X_A A + C_1^T C_1 + Q\]
\[+ (K + U_1^T B_1^T U_3 A)^T U_2 (K + U_2^T B_2^T U_3 A)\]

Also, noting that the discrete time Riccati equation (13) and substituting the above equality for (15), we get
\[J = \sum_{k=0}^{\infty} (X_k - X_{k+1}) - \frac{\gamma^2}{2} \left( w^T w + \gamma^2 \left| U_1^T (w - \gamma^{-1} U_1^T B_1 X_k A_k) x_k \right| \right)^2 \]

Based on the above, it is clear that if \( K = -U_1^T B_1^T U_3 A \), then we get
\[\inf_{k} J = x_0^T X_A x_0 - \frac{\gamma^2}{2} \left| w^T w + \gamma^2 \left| U_1^T (w - \gamma^{-1} U_1^T B_1 X_k A_k) x_k \right| \right|_2^2 \]

By letting \( w(k) = \gamma^{-1} U_1^T B_1 X_k A_k \) for all \( k \geq 0 \), we get that \( x(k) = \tilde{A}_k x_0 \) with \( \tilde{A}_k \) which belongs to \( L_2(0, \infty) \). Since \( \tilde{A}_k = A - \hat{B} (\hat{B}^T X_A \hat{B} + \hat{R})^{-1} \hat{B}^T X_A A \) is stable. Also, we have
\[w(k)^T w = \gamma^{-2} x_0^T X_A x_0, \|w(k)\|_2 = x_0^T X_A x_0\]

Then it follows from (17) that
\[\sup_{w \in L_2} \inf_{k} J = x_0^T (X_A + \gamma^{-2} X_w - X_w) x_0\]

Thus we conclude that there exists an admissible state feedback controller such that
\[\sup_{w \in L_2} \inf_{k} J = x_0^T (X_A + \gamma^{-2} X_w - X_w) x_0 \text{ subject to } \|T_{w\omega}\|_\infty < \gamma \quad \text{Q.E.D.}\]

4. Non-fragile controller

In this section, we will consider the non-fragile discrete-time state feedback mixed LQR/H∞ control problem with controller uncertainty. This problem is defined as follows:
Consider the system (2) (4) satisfying Assumption 1-3 with \( w \in L_2(0, \infty) \) and \( x(0) = x_0 \), for a given number \( \gamma > 0 \) and any admissible controller uncertainty, determine an admissible non-fragile controller \( F_\gamma \) such that
where, the controller uncertainty $\Delta F(k)$ considered here is assumed to be of the following structure:

$$\Delta F(k) = H_k F(k) E_k$$

where, $H_k$ and $E_k$ are known matrices of appropriate dimensions. $F(k)$ is an uncertain matrix satisfying

$$F^T(k) F(k) \leq I$$

with the elements of $F(k)$ being Lebesgue measurable.

If this controller exists, it is said to be a non-fragile discrete time state feedback mixed LQR/$H_\infty$ controller.

In order to solve the problem defined in the above, we first connect the its design criteria with the inequality (11).

**Lemma 4.1** Suppose that $\gamma > 0$, then there exists an admissible non-fragile controller $F_\infty$ that achieves

$$\sup_{\omega \in \Omega} \{ J \}$$

subject to $\| F_{\omega \in \Omega}(\omega) \|_\infty < \gamma$ if for any admissible uncertainty $\Delta F(k)$, there exists a stabilizing solution $X_{\infty} \geq 0$ to the inequality (11) such that $U_1 = I - \gamma^{-2} B_{\infty}^T X_{\infty} B_{\infty} > 0$.

**Proof:** Suppose that for any admissible uncertainty $\Delta F(k)$, there exists a stabilizing solution $X_{\infty} \geq 0$ to the inequality (11) such that $U_1 = I - \gamma^{-2} B_{\infty}^T X_{\infty} B_{\infty} > 0$. This implies that the solution $X_{\infty} \geq 0$ is such that $A_{\infty} + \gamma^{-2} B_{\infty} U_1^{-1} B_{\infty}^T X_{\infty} A_{\infty}$ is stable. Then it follows from Lemma 2.3 that $\| F_{\omega} \|_\infty < \gamma$. Using the same argument as in the proof of Lemma 2.3, we get that $A_{\infty}$ is stable and $J$ can be rewritten as follows:

$$J = \sum_{k=0}^{\infty} (-\Delta V(x(k))) = \| \dot{x} \|^2 + \gamma^2 \| e \|^2 - \gamma^2 \left\| U_1^{1/2} (w - \gamma^{-2} U_1^{-1} B_{\infty}^T X_{\infty} A_{\infty}) x \right\|^2$$

Substituting (11) for (18) to get

$$J < x_0^T X_{\infty} x_0 - \| \dot{x} \|^2 + \gamma^2 \| e \|^2 - \gamma^2 \left\| U_1^{1/2} (w - \gamma^{-2} U_1^{-1} B_{\infty}^T X_{\infty} A_{\infty}) x \right\|^2$$

or

$$\dot{J} < x_0^T X_{\infty} x_0 - \| \dot{x} \|^2 - \gamma^2 \left\| U_1^{1/2} (w - \gamma^{-2} U_1^{-1} B_{\infty}^T X_{\infty} A_{\infty}) x \right\|^2$$

By letting $w = \gamma^{-2} U_1^{-1} B_{\infty}^T X_{\infty} A_{\infty} x$ for all $k \geq 0$, we get that $x(k) = \tilde{A}_{\infty}^k x_0$ with $\tilde{A}_{\infty} = A_{\infty} + B_{\infty} U_1^{-1} B_{\infty}^T X_{\infty} A_{\infty}$ which belongs to $L_2(0, +\infty)$ since $\tilde{A}_{\infty}$ is stable. It follows
from (19b) that $\sup \{ \int \}_{w \in \mathcal{L}_2} = x_0^T X_0 x_0$. Thus, we conclude that there exists an admissible non-fragile controller such that $\sup \{ \int \}_{w \in \mathcal{L}_2} = x_0^T X_0 x_0$ subject to $\| \Gamma \| < \gamma$. Q. E. D.

**Remark 4.1** In the proof of Lemma 4.1, we let $w = \gamma^{-2} B_1^T X_x A_{\hat{F}_x} x$ for all $k \geq 0$ to get that $x(k) = \hat{A}_{\hat{F}_x}^k x_0$ with $\hat{A}_{\hat{F}_x} = A_{\hat{F}_x} + \gamma^{-2} B_{\hat{F}_x} U_1^{-1} B_{\hat{F}_x}^T X_x A_{\hat{F}_x}$ which belongs to $L_2[0, +\infty)$ since $\hat{A}_{\hat{F}_x}$ is stable. Also, we have

$$\| x^T \|_2^2 = \gamma^{-4} x_0^T X_w x_0, \quad \| w \|_2^2 = x_0^T X_w x_0.$$ 

Then it follows from (19a) that

$$I < x_0^T (X_x + \gamma^{-2} X_w - X_x) x_0$$  \hspace{1cm} (20)

where, $X_w = \sum_{k=0}^{\infty} \{ (\hat{A}_{\hat{F}_x}^k)^T A_{\hat{F}_x}^T X_x B_{\hat{F}_x} U_1^{-1} B_{\hat{F}_x}^T X_x A_{\hat{F}_x} \hat{A}_{\hat{F}_x}^k \}, \quad \text{and} \quad X_x = \sum_{k=0}^{\infty} \{(A_{\hat{F}_x}^k)^T C_{\hat{F}_x}^T C_{\hat{F}_x} \hat{A}_{\hat{F}_x}^k \}.$$

Note that $\hat{A}_{\hat{F}_x}$ depends on the controller uncertainty $\Delta F(k)$, thus it is difficult to find an upper bound of either of $X_x$ and $X_w$. This implies that the existence of controller uncertainty $\Delta F(k)$ makes it difficult to find $\sup \{ \int \}_{w \in \mathcal{L}_2} \{ J \}$ by using (20). Thus, it is clear that the existence of the controller uncertainty makes the performance of the designed system become bad.

In order to give necessary and sufficient conditions for the existence of an admissible non-fragile controller for solving the non-fragile discrete-time state feedback mixed LQR/ $H_\infty$ control problem, we define the following parameter-dependent discrete time Riccati equation:

$$A^T X_x A - X_x - A^T X_x \hat{B}(\hat{B}^T X_x \hat{B} + \hat{R})^{-1} \hat{B}^T X_x A + \rho^2 E_k^T E_k + C_1^T C_1 + Q_\delta = 0$$  \hspace{1cm} (21)

where, $\hat{B} = \begin{bmatrix} -I & B_2 \end{bmatrix}$, $\hat{R} = \begin{bmatrix} -I & 0 \\ 0 & I + R \end{bmatrix}$, $Q_\delta = Q + \delta I$ with $\delta > 0$ being a sufficiently small constant, $\rho$ is a given number satisfying $\rho^2 I - H_{11}^T U_2 H_{11} > 0$, $U_1 = I - \gamma^{-2} B_1^T X_x B_1 > 0$, $U_3 = B_2^T U_2 B_2 + I + R$ and $U_3 = X_x + \gamma^{-2} X_x B_1 U_1^{-1} B_2^T X_x$. If $A$ is invertible, the parameter-dependent discrete time Riccati equation (21) can be solved by using the following symplectic matrix

$$\hat{S}_x := \begin{bmatrix} A + \hat{B} \hat{R}^{-1} \hat{B}^T A^{-T} (\rho^2 E_k^T E_k + C_1^T C_1 + Q_\delta) - \hat{B} \hat{R}^{-1} \hat{B}^T A^{-T} \\ -A^{-T} (\rho^2 E_k^T E_k + C_1^T C_1 + Q_\delta) A^{-T} \end{bmatrix}$$

The following theorem gives the solution to non-fragile discrete time state feedback mixed LQR/ $H_\infty$ control problem.

**Theorem 4.1** There exists a non-fragile discrete time state feedback mixed LQR/ $H_\infty$ controller iff there is a given number $\rho$ and a sufficiently small constant $\delta > 0$, then there exists a stabilizing solution $X_x \geq 0$ to the parameter-dependent discrete time Riccati equation (21) such that $U_1 = I - \gamma^{-2} B_1^T X_x B_1 > 0$ and $\rho^2 I - H_{11}^T U_2 H_{11} > 0$.
Moreover, this non-fragile discrete time state feedback mixed LQR/$H_\infty$ controller is

$$F_\infty = -U_3^{-1}B_2^T U_3 A$$

and achieves $\sup\{J\}_{\omega \in L_2} = x_0^T X_\infty x_0$ subject to $\|F_\infty\|_\infty < \gamma$.

Proof: Sufficiency: Suppose that for a given number $\rho$ and a sufficiently small constant $\delta > 0$, there exists a stabilizing solution $X_\infty \geq 0$ to the parameter-dependent Riccati equation (21) such that $U_1 = 1 - \gamma^{-2} B_2^T X_\infty B_1 > 0$ and $\rho^2 I - H_0^T U_2 H_k > 0$. This implies that the solution $X_\infty \geq 0$ is such that $A - \bar{B}(\bar{B}^T X_\infty \bar{B} + \bar{R})^{-1} \bar{B}^T X_\infty A$ is stable. Define respectively the state matrix and controlled output matrix of closed-loop system

$$A_{F_\infty} = A + B_2(-U_3^{-1}B_2^T U_3 A + H_k F(k)E_k)$$
$$C_{F_\infty} = C_1 + D_{12}(-U_3^{-1}B_2^T U_3 A + H_k F(k)E_k)$$

and let $A_{F_\infty} = A - B_2 U_2^{-1} B_2^T U_3 A$ and $\bar{F} = -U_3^{-1}B_2^T U_3 A + H_k F(k)E_k$, then it follows from the square completion that

$$A_{F_\infty}^T X_\infty A_{F_\infty} = X_{\infty} + \gamma^{-2} A_{F_\infty}^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A_{F_\infty} + C_{F_\infty}^T C_{F_\infty} + Q + F_{F_\infty}^T \bar{F}$$  \hspace{1cm} (22)

$$= A^T X_\infty A - X_{\infty} + \gamma^{-2} A^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A + C_1^T C_1 + Q + F_{F_\infty}^T U_2 F + \bar{F}^T U_2 \bar{F}$$

where, $\Delta \bar{N} = E_{F_\infty}^T (k)H_0^T U_2 H_k F(k)E_k$. Noting that $\rho^2 I - H_0^T U_2 H_k > 0$, we have

$$\Delta \bar{N} = -E_{F_\infty}^T (k)(\rho^2 I - H_0^T U_2 H_k)F(k)E_k + \rho^2 E_{F_\infty}^T (k)F(k)E_k \leq \rho^2 E_{F_\infty}^T (k)E_k$$  \hspace{1cm} (23)

Considering (22) and (23) to get

$$A_{F_\infty}^T X_\infty A_{F_\infty} - X_{\infty} + \gamma^{-2} A_{F_\infty}^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A_{F_\infty} + C_{F_\infty}^T C_{F_\infty} + Q + F_{F_\infty}^T \bar{F}$$

$$\leq A^T X_\infty A - X_{\infty} + \gamma^{-2} A^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A + C_1^T C_1 + Q + \rho^2 E_{F_\infty}^T E_k - A^T U_2 B_2 U_2^{-1} B_2^T U_3 A$$

Also, it can be easily shown by using the similar standard matrix manipulations as in the proof of Theorem 3.1 in Souza & Xie (1992) that

$$A^T X_\infty B(\bar{B}^T X_\infty \bar{B} + \bar{R})^{-1} \bar{B}^T X_\infty A = -\gamma^{-2} A^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A + A^T U_2 B_2 U_2^{-1} B_2^T U_3 A$$

This implies that (21) can be rewritten as

$$A^T X_\infty A - X_{\infty} + \gamma^{-2} A^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A + C_1^T C_1 + Q - A^T U_2 B_2 U_2^{-1} B_2^T U_3 A + \rho^2 E_{F_\infty}^T E_k = 0$$  \hspace{1cm} (25)

Thus, it follows from (24) and (25) that there exists a non-negative-definite solution to the inequality

$$A_{F_\infty}^T X_\infty A_{F_\infty} - X_{\infty} + \gamma^{-2} A_{F_\infty}^T X_\infty B_2 U_2^{-1} B_2^T X_\infty A_{F_\infty} + C_{F_\infty}^T C_{F_\infty} + Q + F_{F_\infty}^T \bar{F} < 0$$
Note that \( A - \hat{b}(\hat{b}^T X_a \hat{b} + \hat{R})^{-1} \hat{b}^T X_a = A_{F_e} + \gamma^{-2} B_1 U_1^T B_1^T X_a A_{F_e} \) is stable and \( \Delta F(k) \) is an admissible uncertainty, we get that \( A_{\hat{F}_e} + \gamma^{-2} B_1 U_1^T B_1^T X_a A_{\hat{F}_e} \) is stable. By Lemma 4.1, there exists a non-fragile discrete time state feedback mixed LQR/\( H_\infty \) controller. 

Necessity: Suppose that there exists a non-fragile discrete time state feedback mixed LQR/\( H_\infty \) controller. By Lemma 4.1, there exists a stabilizing solution \( X_\infty \geq 0 \) to the inequality (11) such that \( (A_{\hat{F}_e} + \gamma^{-2} B_1 U_1^T B_1^T X_a A_{\hat{F}_e} - \gamma^{-2} A_{\hat{F}_e} + \gamma^{-2} B_1 U_1^T B_1^T X_a A_{\hat{F}_e})^T X_\infty + C_{\infty}^T C_{\infty} + Q + F_{\infty}^T R_{\infty} + \Delta \hat{N} < 0 \) and \( \Delta \hat{N} = (A^{T} U_1 B_2 + F_{\infty}^T U_2) \Delta F(k) + \Delta F^{T}(k)(B_1^T U_1 A + U_2 F_{\infty}) + \Delta F^{T}(k) U_2 \Delta F(k) \) (26)

Note that \( \rho^2 I - H_{\infty}^T U_2 H_{\infty} > 0 \) and

\[
\Delta \hat{N} = \rho^2 E_{\infty}^T F^{T}(k) F(k) E_{\infty} + (A^T U_1 B_2 + F_{\infty}^T U_2) H_{\infty} (\rho^2 I - H_{\infty}^T U_2 H_{\infty})^{-1} H_{\infty}^T
\]
\[
\times ((B_1^T U_1 A + U_2 F_{\infty}) - (A^T U_1 B_2 + F_{\infty}^T U_2) H_{\infty} (\rho^2 I - H_{\infty}^T U_2 H_{\infty})^{-1} E_{\infty}^T F^{T}(k))
\]
\[
\times (\rho^2 I - H_{\infty}^T U_2 H_{\infty})(\rho^2 I - H_{\infty}^T U_2 H_{\infty})^{-1} H_{\infty}^T (B_1^T U_1 A + U_2 F_{\infty}) - F(k) E_{\infty}) < 0
\]
\[
\leq \rho^2 E_{\infty}^T E_{\infty} + (A^T U_1 B_2 + F_{\infty}^T U_2) H_{\infty} (\rho^2 I - H_{\infty}^T U_2 H_{\infty})^{-1} H_{\infty}^T (B_1^T U_1 A + U_2 F_{\infty}) < 0
\]

(27)

It follows from (26) and (27) that

\[
A_{\hat{F}_e}^T X_a A_{\hat{F}_e} - X_\infty + \gamma^{-2} A_{\hat{F}_e}^T X_a B_1 U_1^T B_1^T X_a A_{\hat{F}_e} + C_{\infty}^T C_{\infty} + Q + F_{\infty}^T R_{\infty} + \rho^2 E_{\infty}^T E_{\infty} + (A^T U_1 B_2 + F_{\infty}^T U_2) H_{\infty} (\rho^2 I - H_{\infty}^T U_2 H_{\infty})^{-1} H_{\infty}^T (B_1^T U_1 A + U_2 F_{\infty}) < 0
\]

(28)

Using the argument of completion of squares as in the proof of Theorem 3.1 in Furuta & Phooharanenchanchai (1990), we get from (28) that \( F_{\infty} = U_2^T B_1^T U_2 A \), where \( X_\infty \) is a symmetric non-negative-definite solution to the inequality

\[
A^T X_a A - X_\infty + \gamma^{-2} A^T X_a B_1 U_1^T B_1^T X_a A + C_{\infty}^T C_{\infty} + Q - A^T U_1 B_2 U_2^T B_1^T U_2 A + \rho^2 E_{\infty}^T E_{\infty} < 0
\]

or equivalently, \( X_\infty \) is a symmetric non-negative-definite solution to the parameter-dependent discrete time Riccati equation

\[
A^T X_a A - X_\infty + \gamma^{-2} A^T X_a B_1 U_1^T B_1^T X_a A + C_{\infty}^T C_{\infty} + Q = - A^T U_1 B_2 U_2^T B_1^T U_2 A + \rho^2 E_{\infty}^T E_{\infty} = 0
\]

(29)

Also, we can rewrite that Riccati equation (29) can be rewritten as

\[
A^T X_a A - X_\infty - A^T X_a \hat{b}(\hat{b}^T X_a \hat{b} + \hat{R})^{-1} \hat{b}^T X_a A + \rho^2 E_{\infty}^T E_{\infty} + C_{\infty}^T C_{\infty} + Q = 0
\]

(30)
by using the similar standard matrix manipulations as in the proof of Theorem 3.1 in Souza & Xie (1992). Note that \( A - \hat{B}(\tilde{B}^T \hat{X}_e \hat{B} + \hat{R})^{-1} \hat{B}^T \hat{X}_e A = A_{F_e} + \gamma^2 B_1 U_1^{-1} B_1^T X_e A_{F_e} \) and \( DF(k) \) is an admissible uncertainty, the assumption that \( A_{F_e} + \gamma^2 B_1 U_1^{-1} B_1^T X_e A_{F_e} \) is stable implies that \( A - \hat{B}(\tilde{B}^T \hat{X}_e \hat{B} + \hat{R})^{-1} \hat{B}^T \hat{X}_e A \) is stable. Thus, we conclude that for a given number \( \rho \) and a sufficiently small number \( \delta > 0 \), the parameter-dependent discrete time Riccati equation (30) has a stabilizing solution \( X_e \) and \( U_1 = I - \gamma^2 B_1^T X_e B_1 > 0 \) and \( \rho^2 I - H_k^T U_2 H_k > 0 \). Q. E. D.

5. Numerical examples

In this section, we present two examples to illustrate the design method given by Section 3 and 4, respectively.

Example 1 Consider the following discrete-time system in Peres and Geromel (1993)

\[
x(k + 1) = Ax(k) + B_1 u(k) + B_2 u(k)
\]

\[
z(k) = C_1 x(k) + D_{12} u(k)
\]

where,

\[
A = \begin{bmatrix} 0.2113 & 0.0087 & 0.4524 \\ 0.0824 & 0.8096 & 0.8075 \\ 0.7599 & 0.4874 & 0.4832 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0.6135 \\ 0.2749 \\ 0.8807 \end{bmatrix}
\]

\[
C_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad D_{12} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix}, \quad B_1 = I.
\]

In this example, we will design the above system under the influence of state feedback of the form (3) by using the discrete-time state feedback mixed LQR/\( H_\infty \) control method displayed in Theorem 3.1. All results will be computed by using MATLAB. The above system is stabilizable and observable, and satisfies Assumption 3, and the eigenvalues of matrix \( A \) are \( p_1 = 1.6133, p_2 = 0.3827, p_3 = -0.4919 \) thus it is open-loop unstable.

Let \( \gamma = 2.89, R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \), we solve the discrete-time Riccati equation (13) to get

\[
X_e = \begin{bmatrix} 2.9683 & 1.1296 & 0.1359 \\ 1.1296 & 6.0983 & 2.4073 \\ 0.1359 & 2.4073 & 4.4882 \end{bmatrix} > 0,
\]

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Thus the discrete-time state feedback mixed LQR/ $H_\infty$ controller is

$$K = \begin{bmatrix} -0.3640 & -0.5138 & -0.3715 \\ -0.2363 & -0.7176 & -0.7217 \end{bmatrix}.$$  

Example 2 Consider the following discrete-time system in Peres and Geromel (1993)

$$x(k + 1) = Ax(k) + B_1w(k) + B_2u(k)$$

$$z(k) = C_1x(k) + D_{12}u(k)$$

under the influences of state feedback with controller uncertainty of the form (4), where, $A$, $B_1$, $B_2$, $C_1$ and $D_{12}$ are the same as ones in Example 1; the controller uncertainty $\Delta F(k)$ satisfies

$$\Delta F(k) = E_K F(k) E_K^T F(k) F(k) \leq I$$

where, $E_K = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}$, $H_K = \begin{bmatrix} 0.0100 & 0 & 0 \\ 0 & 0.0100 & 0 \end{bmatrix}$.

In this example, we illustrate the proposed method by Theorem 4.1 by using MATLAB. As stated in example 1, the system is stabilizable and observable, and satisfies Assumption 3, and is open-loop unstable.

Let $\gamma = 8.27$, $R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $\rho = 3.7800$, and $\delta = 0.0010$, then we solve the parameter-dependent discrete-time Riccati equation (21) to get

$$X = \begin{bmatrix} 18.5238 & 3.8295 & 0.1664 \\ 3.8295 & 51.3212 & 23.3226 \\ 0.1664 & 23.3226 & 22.7354 \end{bmatrix} > 0,$$

$$U_1 = I - \gamma^2 B_1^T X B_1 = \begin{bmatrix} 0.7292 & -0.0560 & -0.0024 \\ -0.0560 & 0.2496 & -0.3410 \\ -0.0024 & -0.3410 & 0.6676 \end{bmatrix} > 0, \quad U_2 = \begin{bmatrix} 609.6441 & 723.0571 \\ 723.0571 & 863.5683 \end{bmatrix},$$

$$\rho^2 I - H_K^T U_2 H_K = \begin{bmatrix} 14.2274 & -0.0723 & 0 \\ -0.0723 & 14.2020 & 0 \\ 0 & 0 & 14.2884 \end{bmatrix} > 0.$$
Based on this, the non-fragile discrete-time state feedback mixed LQR/ $H_\infty$ controller is

$$F_\infty = \begin{bmatrix} -0.4453 & -0.1789 & -0.0682 \\ -0.1613 & -1.1458 & -1.0756 \end{bmatrix}$$

6. Conclusion

In this chapter, we first study the discrete time state feedback mixed LQR/ $H_\infty$ control problem. In order to solve this problem, we present an extension of the discrete time bounded real lemma. In terms of the stabilizing solution to a discrete time Riccati equation, we derive the simple approach to discrete time state feedback mixed LQR/ $H_\infty$ control problem by combining the Lyapunov method for proving the discrete time optimal LQR control problem with the above extension of the discrete time bounded real lemma, the argument of completion of squares of Furuta & Phoojaruenchanachi (1990) and standard inverse matrix manipulation of Souza & Xie (1992). A related problem is the standard $H_\infty$ control problem (Doyle et al., 1989a; Iglesias & Glover, 1991; Furuta & Phoojaruenchanachai, 1990; Souza & Xie, 1992; Zhou et al. 1996), another related problem is the $H_\infty$ optimal control problem arisen from Basar & Bernhard (1991). The relations among the two related problem and mixed LQR/ $H_\infty$ control problem can be clearly explained by based on the discrete time reference system (9)(3). The standard $H_\infty$ control problem is to find an admissible controller $K$ such that the $H_\infty$-norm of closed-loop transfer matrix from disturbance input $w$ to the controlled output $z$ is less than a given number $\gamma > 0$ while the $H_\infty$ optimal control problem arisen from Basar & Bernhard (1991) is to find an admissible controller such that the $H_\infty$-norm of closed-loop transfer matrix from disturbance input $w$ to the controlled output $z$ is less than a given number $\gamma > 0$ for the discrete reference system (9)(3). Since the latter is equivalent to the problem that is to find an admissible controller $K$ such that $\sup_{w \in L_2} \inf_{K} \{J\}$, we may recognize that the mixed LQR/ $H_\infty$ control problem is a combination of the standard $H_\infty$ control problem and $H_\infty$ optimal control problem arisen from Basar & Bernhard (1991). The second problem considered by this chapter is the non-fragile discrete-time state feedback mixed LQR/ $H_\infty$ control problem with controller uncertainty. This problem is to extend the results of discrete-time state feedback mixed LQR/ $H_\infty$ control problem to the system (2)(4) with controller uncertainty. In terms of the stabilizing solution to a parameter-dependent discrete time Riccati equation, we give a design method of non-fragile discrete-time state feedback mixed LQR/ $H_\infty$ controller, and derive necessary and sufficient conditions for the existence of this non-fragile controller.

7. References


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Discrete-Time Systems comprehend an important and broad research field. The consolidation of digital-based computational means in the present, pushes a technological tool into the field with a tremendous impact in areas like Control, Signal Processing, Communications, System Modelling and related Applications. This book attempts to give a scope in the wide area of Discrete-Time Systems. Their contents are grouped conveniently in sections according to significant areas, namely Filtering, Fixed and Adaptive Control Systems, Stability Problems and Miscellaneous Applications. We think that the contribution of the book enlarges the field of the Discrete-Time Systems with signification in the present state-of-the-art. Despite the vertiginous advance in the field, we also believe that the topics described here allow us also to look through some main tendencies in the next years in the research area.

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