Gain-scheduled H_∞ control for networked superheated steam temperature

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Abstract: This paper investigates the gain-scheduled problem of the networked control for a superheated steam temperature system with consideration of the network QoS. The designed gain-scheduled controller is based on the network QoS, and thus is less conservative than the conventional controller with constant gains. A network data-transmitting mechanism is constructed, in which the variation of the sampling data and the network QoS are comprehensively considered. Based on the proposed comprehensive model for network-based superheated steam temperature control systems, the H_∞ controllers within the framework of cascade control strategy are designed in terms of linear matrix inequities, which guarantee the requirement of H_∞ performance criterion. Finally, a superheated steam system model is used to demonstrate the effectiveness of the proposed design procedures.

Key Words: Gain-scheduled, networked superheated steam temperature, event-trigger

1 Introduction

A superheated steam temperature control system (SSTCS) is one of the most important part among control systems in power plants. The main objective of the SSTCS is to maintain a precision superheated temperature, for example, a limitation of main team temperature (i.e.the outlet temperature of superheated steam) in 600MW super-critical boiler is given by $571 \pm 5°C$. An increase 20% over the designed superheater temperature will cut its fatigue life in half, and the efficiency will reduce 0.5% when dropping the main steam temperature $10°C$ [1]. A cascade control strategy (CCS) is commonly adopted in the SSTCS since the inner loop of the CCS can attenuate the disturbances from the steam side quickly, while the outer loop ensures an accuracy of the control system, thereby improving the system's control performance.

Feedback control systems wherein the control loops are closed through a real-time network are called networked control systems (NCSs) which is used in power plants currently. They differ from traditional control systems in that the connections of their components are via shared communication networks instead of point-to-point wiring. The use of the shared communication networks between control system components is mainly motivated by lower cost, easier maintenance and higher reliability of the closed-loop systems. However, the introduction of the networks complicates the analysis and synthesis problems of control systems. Network-induced time delays, packet losses and network congestions are major issues in front of any NCS designer. Therefore, increasing attention has been paid to the study of NCSs [2, 3, 4, 5], and the references therein.

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In [6], the networked control of discretization-based superheated steam temperature system was studied by using a periodic sampling and releasing method, a state feedback controller with a constant controller gain is given to guarantee the stability of the SSTCS. However, it loses the system's intrinsical characters after discretizating the system, moreover, the network QoS and the necessity of releasing sampling data are not considered.

In fact, the main role of the real-time network, in power plants, lies in transmitting the control signals from varieties of sub-control systems, such as SSTCS, combustion control system, water level auto control system, etc.. Different amount data of each subsystems are required to transmit over the network at any instant, which leads to the status of the network QoS is time-varying, it is unreasonable for controller gains to be a constant. In [7], a state-differential event based sampling scheme with QoS is proposed to reduce the network load, however the controller design approach is not given. Gain scheduled control are studied based on frequency domain methods in [8, 9]. The design of gain-scheduled sampled-data controllers for continuous-time polytopic linear parameter-varying systems is discussed in [10]. However, to the best of the authors knowledge, the controller gain-scheduling based on the network QoS for SSTCS still remains open and challenging, which motivates us to the current study.

Under the conventional periodic data-transmitting mechanism of the NCSs, a large amount of sampling data are released into the network periodically, it may lead to a poor network QoS, and it in turn deteriorates the whole control system. Therefore, it is very important to find a tradeoff between the network QoS and the requirement of control quality of the SSTCS. To reduce a burden of the common shared network, several approaches are taken into account

[11, 12, 13]. However, few studies focus on the network data-releasing mechanism of NCSs by combining the performances of the network and the control in the existing literatures. In fact, if the difference between the value of the released data and the current sampled data is very small, this sampled data do not need to release, since the value of the released packet can be hold till the next data come. Thus the network bandwidth can be saved in that much of the sampled data are not necessary to release into the network for the SSTCS.

In this paper, we will mainly focus on developing a scheduled controller-gain based on the network QoS for the SSTCS. A network QoS evaluation-index is introduced to design the control strategy and data-transmitting mechanism, such that the network-based superheated steam temperature system can not only adapt the network QoS with a possible control performance but also reduce the burden of the network-bandwidth greatly. Based on those ideas, a comprehensive model which is convenient to analyze is developed. Criteria for stability and H_∞ control are derived in the form of linear matrix inequalities. Applying LMI toolbox of Matlab, one can obtain the parameters of the controller and the network data-transmitting protocol of the network-based SSTCS directly without needing a complicated tuning process. A validation test of network-based SSTCS is given to illustrate the effectiveness of the proposed method.

2 The Modelling of network-based SSTCS

2.1 The CCS for SSTCS

The saturated steam from the drum flows to the low temperature superheater (LTS) inlet header, and then is heated by the flow of hot gases produced from combustion of the fuel (see Fig. 1). After leaving the primary superheater, the steam is carried by conduit to the attemperator header where a spray water is added, the steam temperature is then reduced. The flow of spray water is controlled by a valve to achieve a satisfied steam temperature required by the turbine. Then the steam enters the high temperature superheater (HTS) for additional heating by the flow of hot gases over the tubes. Finally, the outlet header of HTS connects inlet of the turbine.

The part before entering the attemperator is called a leading section, while the section after leaving the attemperator is referred as a inertial section. In general, the inertial section responses more slowly than the leading section under the external disturbances which may be flue quality, steam flow, attemperator water flow, etc.. Therefore, the CCS is commonly adopted to get a good control performance. Fig. 2 gives its block diagram. The inner loop of the CCS can eliminate the influence from the fluctuation of the atsuperheating water flow, and the outer loop is mainly responsible for tracking the set value of main steam temperature. The controller design is quite different from the conventional the CCS due to the use of network circled by the ellipsoid in Fig. 1.

Consider the model of the leading section (P_I) and inertial

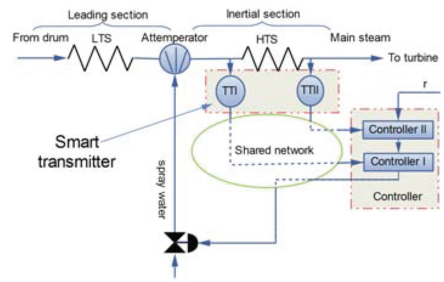

Figure 1: The schematic diagram of network-based SSTCS

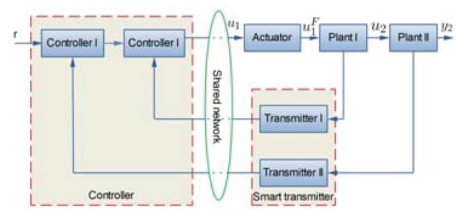

Figure 2: The architecture of NSSTCS

section (P_{II}) as

$$P_I : \begin{cases} \dot{x}_1(t) = A_1x_1(t) + B_{11}u_1(t) + B_{12}\omega_1(t) \\ y_1(t) = C_1x_1(t) + D_1\omega_1(t) \end{cases} \quad (1)$$

$$P_{II} : \begin{cases} \dot{x}_2(t) = A_2x_2(t) + B_{21}u_2(t) + B_{22}\omega_2(t) \\ y_2(k) = C_2x_2(t) + D_2\omega_2(t) \end{cases} \quad (2)$$

where $x_1(t) \in \mathbb{R}^{n_1}$ and $x_2(t) \in \mathbb{R}^{n_2}$ are the state variables, $u_1(t) \in \mathbb{R}^{m_1}$ and $u_2(t) \in \mathbb{R}^{m_2}$ are the control inputs, $y_1(t) \in \mathbb{R}^{q_1}$ and $y_2(t) \in \mathbb{R}^{q_2}$ are the output vectors, which denote outlet temperatures of LTS and HTS, respectively. $A_i, B_{ij}(i, j = 1, 2)$ are known constant matrices with appropriate dimensions, and $\omega_i(k) \in l_2[0, \infty)(i = 1, 2)$ are the disturbances from steam side and gas side.
From the architecture diagram shown in Fig. 1, we have

$$u_2(t) = y_1(t) \quad (3)$$

Combine Eq. (1)-Eq. (3), it yields

$$\begin{cases} \dot{x}(t) = Ax(t) + B_1u_1(t) + B_2\omega(t) \\ y(t) = Cx(t) + D\omega(t) \end{cases} \quad (4)$$

where $x(t) = [x_1^T(t) \quad x_2^T(t)]^T, y(t) = [y_1^T(t) \; y_2^T(t)]^T, \omega(t) = [\omega_1^T(t) \; \omega_2^T(t)]^T$, and

$$A = \begin{bmatrix} A_1 & 0 \\ B_{21}C_1 & A_2 \end{bmatrix}, B_1 = \begin{bmatrix} B_{11} \\ 0 \end{bmatrix}, B_2 = \begin{bmatrix} B_{12} & 0 \\ B_{21}D_1 & B_{22} \end{bmatrix}$$
$$C = \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}, D = \begin{bmatrix} D_1 & 0 \\ 0 & D_2 \end{bmatrix}$$

From Fig. 2, one can see the control signal of $u_1(t)$ is closed over the shared network. However, in the existed literature on the controller design for the networked control system is based on an assumption that the network situation is invariable. In the next subsection, a gain scheduling with considering the network QoS will be presented.

2.2 The gain scheduling of the network-based SSTCS

Here, an index ε_{t_k} ($\varepsilon_{t_k} \in (0,\ 1]$) is introduced to reflect the statue of the network QoS at data releasing instant t_k, which can be obtained in real-time by detecting the length of the network windows. As is shown in Fig. 3, the network QoS tends to a better network service condition with the increase of the index ε_{t_k}. Specially, the value of ε_{t_k} is measured as $0/1$, it denotes the network QoS is extremely bad/ good enough.

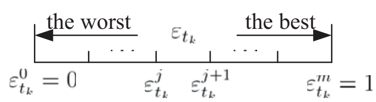

Figure 3: The network QoS index

With consideration of the network QoS, the gain scheduled control law is proposed as follows for $t \in [t_k + \tau_k, t_{k+1} + \tau_{k+1})$:

$$u_1(t) = K(\varepsilon_{t_k})x(t_k) \tag{5}$$

where τ_k ($0 \le \tau_k \le \tau_M$) is the network transmission delay of the k-th released packet, and $K(\varepsilon_{t_k})$ is the controller gain sequence to be designed with the following structure

$$K(\varepsilon_{t_k}) = K_0(\varepsilon_{t_k}) + \varepsilon_{t_k} K_1(\varepsilon_{t_k}) \tag{6}$$

where K_0 and $K_1(\varepsilon_{t_k})$ are controller gains to be designed.

Remark 1 *From Eq. (5), one can see the controller gain is scheduled with the network QoS ε_{t_k} for the different network service condition, which would certainly result in less conservatism than the conventional controller with constant gains only.*

It should be pointed out that the network QoS varies continuously in the period of $[t_k + \tau_k, t_{k+1} + \tau_{k+1}]$, it leads to the index ε_{t_k} varying in a limited range. To reduce the calculation load, we divide the interval of ε_{t_k} into $m+1$ subintervals, i.e. $\cup_{j=0}^{m-1}(\varepsilon_{t_k}^j,\ \varepsilon_{t_k}^{j+1}] = (0,\ 1]$ (see Fig. 3). If ε_{t_k} falls into $(\varepsilon_{t_k}^j,\ \varepsilon_{t_k}^{j+1}]$, that is, $\varepsilon_{t_k} \in (\varepsilon_{t_k}^j,\ \varepsilon_{t_k}^{j+1}]$, then an estimation of the varying index can be made as

$$\bar{\varepsilon}_{t_k} = \frac{1}{2}(\varepsilon_{t_k}^j + \varepsilon_{t_k}^{j+1}) \tag{7}$$

by which the QoS in each releasing period $(t_k\ t_{k+1}]$ is represented.
Then the gain scheduled control law can be substituted by

$$u_1(t) = K(\bar{\varepsilon}_{t_k})x(t_k) \tag{8}$$

where $K_{\varepsilon_{t_k}}$ is the gain at network QoS index $\bar{\varepsilon}_{t_k}$.

2.3 Network data-transmitting scheme

Fig. 4 shows the theoretic block diagram of the sampling & releasing mechanism. Decision-making body embedded in the smart releasor determines whether or not the sampled data should be released into the network in this study, which is a trade-off between the network QoS and the QoC of SSTCS. On the one hand, to get a better QoC of the SSTCS, more sampled data are demanded to transmit over the network under a good network QoS, however, this does not indicate all the sampled data are necessary to release into the network for theirs value closing to the ones at the former sampling instant. On the other hand, it will worsen the network QoS if releasing much more sampling data under a limited network bandwidth.

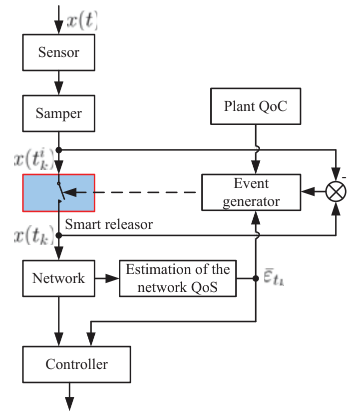

Figure 4: Block diagram of the smart releasor

The trade-off between the netwrok QoS and QoC of the SSTCS is proposed as follows to determine whether or not the sampled data should be transmitted.

$$\|M_{\bar{\varepsilon}_{t_k}}^{\frac{1}{2}}[x(t_k) - x(t_k^i)]\| \le f(\bar{\varepsilon}_{t_k})\|M_{\bar{\varepsilon}_{t_k}}^{\frac{1}{2}}x(t_k^i)\| \tag{9}$$

where t_k^i is a sampling instant ($i = 0, 1, \cdots, l$), $t_k, t_{k+1}, \cdots$ denote the releasing instants, $M_{\bar{\varepsilon}_{t_k}}$ is a positive matrix to be determined, $f(\bar{\varepsilon}_{t_k})$ is a dynamic threshold determined by the network QoS, which is defined by

$$f(\bar{\varepsilon}_{t_k}) = 1 - \bar{\varepsilon}_{t_k} \tag{10}$$

Fig. 5 shows the sequence of the sampling and releasing data, from which one can see that the data at instant $t_k^1, \cdots, t_k^{l-1}$ are discarded before entering the network by reason that those data do not satisfy the releasing conditions expressed in Eq. (9). Thus the network bandwidth can be saved much more.

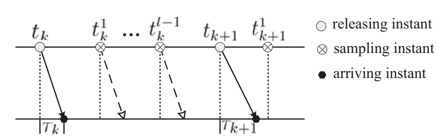

Figure 5: The sequence of sampling and releasing data

Remark 2 *If the network QoS is good enough, the dynamic threshold $f(\bar{\varepsilon}_{t_k})$ in Eq. (10) tends to 0. The releasing-constrain condition in Eq. (9) does not hold any more, that is, all the sampled data are released into the network under the this condition. It turns to the case of traditional periodic sampling and releasing mechanism.*

From the above analysis, the next releasing instant can be expressed as

$$t_{k+1} = t_k^l, \qquad l = \max_{i \geq 0}\; i+1 \;\text{ subject to (9)} \tag{11}$$

Remark 3 *Different from the periodic sampling and releasing mechanism, packets releasing depend on not only the time period but also the event generator triggered by the condition (9), therefore, we call this data transmitting scheme as event-triggered mechanism.*

3 Gain scheduled design for SSTCS under the event-triggered mechanism

In this section, we aim to design the gain-scheduled controller $K_{\varepsilon_{t_k}}$ of the event-trigger based networked SSTCS and the adjustable parameter M in the transmitting condition (9), such that the closed-loop SSTCS is asymptotically stable in an H_∞ sense.

3.1 Model of event-trigger based networked SSTCS

By using the controller (8) scheduled with the network QoS, the closed loop SSTCS can be obtained as

$$\begin{cases} \dot{x}(t) = Ax(t) + B_1K(\bar{\varepsilon}_{t_k})x(t_k) + B_2\omega(t) \\ y(t) = Cx(t) + D\omega(t) \end{cases} \tag{12}$$

For convenience, we define $e(t) = x(t_k) - x(t_k^i)$ and $\tau(t) = t - t_k^i$ at every subintervals $[t_k^i + \tau_k^i,\ t_k^{i+1} + \tau_k^{i+1})$ $(i = 0, 1, \cdots, l-1)$, the closed loop SSTCS for $t \in [t_k + \tau_k, t_{k+1} + \tau_{k+1})$ can be further rewritten as

$$\begin{cases} \dot{x}(t) = Ax(t) + B_1K(\bar{\varepsilon}_{t_k})e(t) \\ \qquad + K(\bar{\varepsilon}_{t_k})x(t-\tau(t)) + B_2\omega(t) \\ y(t) = Cx(t) + D\omega(t) \end{cases} \tag{13}$$

From the above analysis, one can easily know that

$$0 \leq \tau(t) \leq \tau_M + h = \bar{\tau} \tag{14}$$

where h is a sampling period.

So far, we can rewrite the closed-loop network-based SSTCS for $[t_k + \tau_k, t_{k+1} + \tau_{k+1})$ as

$$\begin{cases} \dot{x}(t) = \bar{A}\zeta(t) & \text{(15a)} \\ y(t) = \bar{C}\zeta(t) & \text{(15b)} \end{cases}$$

where $\zeta(t) = [x^T(t)\; x^T(t-\tau(t))\; x^T(t-\bar{\tau})\; e^T(t)\; \omega^T(t)]^T$, $\bar{A} = \begin{bmatrix} A & B_1K(\bar{\varepsilon}_{t_k}) & 0 & B_1K(\bar{\varepsilon}_{t_k}) & B_2 \end{bmatrix}$, and $\bar{C} = \begin{bmatrix} C & 0 & 0 & 0 & D \end{bmatrix}$.

First, assuming $K(\bar{\varepsilon}_{t_k})$ is known, and $M_{\bar{\varepsilon}_{t_k}}$ is known as well, we study the conditions under which the system (15) achieves asymptotical stability with H_∞ performance γ. This proposition plays an instrument role in the controllers design procedure.

Theorem 1 *For a given constant γ, matrices $K(\bar{\varepsilon}_{t_k})$ and $M_{\bar{\varepsilon}_{t_k}}$, the network-based closed-loop SSTCS (12) under the network data-transmitting constraint (9) is asymptotically stable with γ-disturbance attenuation, if there exist matrices $P > 0, Q > 0$ and $R > 0$ with appropriate dimensions such that*

$$\Gamma_{t_k} = \begin{bmatrix} \Gamma_{11} + \bar{A}^TP + P\bar{A} & * & * \\ \bar{\tau}P\bar{A} & -PR^{-1}P & * \\ \bar{C} & 0 & -I \end{bmatrix} < 0 \tag{16}$$

where

$$\Gamma_{11} = \begin{bmatrix} Q-R & * & * & * & * \\ R & \Theta & * & * & * \\ 0 & R & -R & * & * \\ 0 & 0 & 0 & -M_{\bar{\varepsilon}_{t_k}} & * \\ 0 & 0 & 0 & 0 & -\gamma^2 I \end{bmatrix}$$

$$\Theta = -Q - 2R + (1-\bar{\varepsilon}_{t_k})^{-1}M_{\bar{\varepsilon}_{t_k}}$$

Proof: Construct a Lyapunov-Krasovskii functional candidate as

$$V(x_t) = x^T(t)Px(t) + \int_{t-\bar{\tau}}^{t} x^T(s)Qx(s)ds + \bar{\tau}\int_{-\bar{\tau}}^{0}\int_{t-s}^{t} \dot{x}^T(v)R\dot{x}(v)dvds \tag{17}$$

The derivative of $V(x_t)$ along with the solution of system (15) is expressed as

$$\begin{aligned}\dot{V}(x_t) = \;& 2x^T(t)P\bar{A}\zeta(t) + x^T(t)Qx(t) \\ & + x^T(t-\bar{\tau})Qx(t-\bar{\tau}) + \bar{\tau}^2\dot{x}^T(t)R\dot{x}(t) \\ & - \bar{\tau}\textstyle\int_{t-\bar{\tau}}^{t}\dot{x}^T(s)R\dot{x}(s)ds \end{aligned} \tag{18}$$

Based on Jensen inequality [14], we have

$$\begin{aligned} & -\bar{\tau}\int_{t-\bar{\tau}}^{t}\dot{x}^T(s)R\dot{x}(s)ds \leq \\ & \begin{bmatrix} x(t) \\ x(t-\tau(t)) \\ x(t-\bar{\tau}) \end{bmatrix}^T \begin{bmatrix} -R & * & * \\ R & -2R & * \\ 0 & R & -R \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau(t)) \\ x(t-\bar{\tau}) \end{bmatrix} \end{aligned} \tag{19}$$

Recall the definition of $\tau(t)$ and $e(t)$, the data-releasing constraint (9) can be rewritten as

$$f(\bar{\varepsilon}_{t_k})x^T(t-\tau(t))M_{\bar{\varepsilon}_{t_k}}x(t-\tau(t)) - e^T(t)M_{\bar{\varepsilon}_{t_k}}e(t) \geq 0 \tag{20}$$

Combining with Lemma (19), we have

$$\begin{aligned} \dot{V}(x_t) \leq\; & 2x^T(t)P\bar{A}\zeta(t) + x^T(t)Qx(t) \\ & + x^T(t-\bar{\tau})Qx(t-\bar{\tau}) \\ & + \begin{bmatrix} x(t) \\ x(t-\tau(t)) \\ x(t-\bar{\tau}) \end{bmatrix}^T \begin{bmatrix} -R & * & * \\ R & -2R & * \\ 0 & R & -R \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau(t)) \\ x(t-\bar{\tau}) \end{bmatrix} \\ & - e^T(t)M_{\bar{\varepsilon}_{t_k}}e(t) + f(\bar{\varepsilon}_{t_k})x^T(t-\tau(t))M_{\bar{\varepsilon}_{t_k}}x(t-\tau(t)) \\ & + y^T(t)y(t) - \gamma^2\omega^T(t)\omega(t) - y^T(t)y(t) + \gamma^2\omega^T(t)\omega(t) \end{aligned}$$

By using Schur complement, it is not difficult to derive

$$\dot{V}(x_t) + y^T(t)y(t) - \gamma^2\omega^T(t)\omega(t) < 0 \tag{21}$$

from Eq. (16) and Eq. (21) for any $\omega(t) \in l_2[0\ \infty)$.

Since $\cup_{k=0}^{\infty}[t_kh + t_k,\ t_{k+1}h + \tau_{k+1}) = [0, \infty)$, we can conclude that

$$V(\infty) - V(0) \leq \int_0^{\infty} \gamma^2\omega^T(s)\omega(s) - y^T(s)y(s)ds \tag{22}$$

by using a similar analysis method in [15].

Under the zero initial condition, we have $V(0) = 0$, it yields

$$\int_0^\infty y^T(s)y(s)ds \le \int_0^\infty \gamma^2 \omega^T(s)\omega(s)ds \quad (23)$$

for $V(\infty) > 0$. This completes the proof.

Next we aim to design the controller gain $K_{\bar{\varepsilon}_{t_k}}$ in (8) and determine the parameter M in the transmitting condition (9) based on Theorem 1. Define $X = P^{-1}, \bar{Q} = XQX, \bar{R} = XRX, \bar{M}_{\bar{\varepsilon}_{t_k}} = XM_{\bar{\varepsilon}_{t_k}}X$, and $J = diag\{X, X, X, X, I, I\}$. Pre- and post-multiplying Eq. (16) with J and their transposes, we can obtain the following result by noting that $-PR^{-1}P \le -2\epsilon P + \epsilon^2 R$, where scalar $\epsilon > 0$.

Theorem 2 *For given constants γ, ϵ, the network-based closed-loop SSTCS (12) under the network data-transmitting constraint (9) is asymptotically stable with γ-disturbance attenuation, if there exist matrices $X > 0, \bar{Q} > 0$ and $\bar{R} > 0$ and matrix $\bar{M}_{\bar{\varepsilon}_{t_k}}, Y$ with appropriate dimensions, such that*

$$\bar{\Gamma}_{t_k} = \begin{bmatrix} \bar{\Gamma}_{11} + \tilde{A} + \tilde{A}^T & * & \\ \bar{\tau}\tilde{A} & -2\epsilon X + \epsilon^2 \bar{R} & * \\ \tilde{C} & 0 & -I \end{bmatrix} < 0 \quad (24)$$

where

$$\begin{aligned} \bar{\Gamma}_{11} &= \begin{bmatrix} \bar{Q} - \bar{R} & * & * & * & * \\ \bar{R} & \bar{\Theta} & * & * & * \\ 0 & \bar{R} & -\bar{R} & * & * \\ 0 & 0 & 0 & -\bar{M}_{\bar{\varepsilon}_{t_k}} & * \\ 0 & 0 & 0 & 0 & -\gamma^2 I \end{bmatrix} \\ \bar{\Theta} &= -\bar{Q} - 2\bar{R} + (1 - \bar{\varepsilon}_{t_k})^{-1}\bar{M}_{\bar{\varepsilon}_{t_k}} \\ \tilde{A} &= \begin{bmatrix} AX & B_1(Y_1 + Y_2) & 0 & B_1(Y_1 + Y_2) & B_2 X \end{bmatrix} \\ \tilde{C} &= \begin{bmatrix} CX & 0 & 0 & 0 & D \end{bmatrix} \end{aligned}$$

Moreover, the controller gain of the network-based SSTCS in (12) and its corresponding data-transmitting parameter in (9) at instant t_k are given as:

$$K_0(\bar{\varepsilon}_{t_k}) = Y_1 X^{-1}; \quad (25)$$

$$K_1(\bar{\varepsilon}_{t_k}) = \bar{\varepsilon}_{t_k}^{-1} Y_2 X^{-1}; \quad (26)$$

$$M_{\bar{\varepsilon}_{t_k}} = X^{-1}\bar{M}_{\bar{\varepsilon}_{t_k}} X^{-1} \quad (27)$$

Next we will give an algorithm of calculating the controller gain of the closed-loop SSTCS in (12) at every releasing instant.

Algorithm:

Step 1: Initialize the parameters γ and m;

Step 2: Detect the character of the network QoS at releasing instant t_k and normalize it as a network QoS index ε_{t_k}, find the interval ε_{t_k} belongs to, and then evaluate the index $\bar{\varepsilon}_{t_k}$ according to (7);

Step 3: Calculate the controller gain $K_{\varepsilon_{t_k}}$ and its corresponding data-transmitting parameter $M_{\bar{\varepsilon}_{t_k}}$ at instant t_k according to Theorem 2 by utilizing the LMI Toolbox;

Step 3: $i = i + 1$, and determine whether the sampled-datum is needed to release at every sampling instant t_k^i according to (11). If the condition (9) is satisfied, repeat this step, otherwise, go to the next step;

Step 4: $k = k + 1, i = 0$;

Step 5: Go to Step 1;

4 Tests and results analysis

In this section, we provide a model of superheated steam system to illustrate the effectiveness of the proposed design method. The parameters of the leading section and inertial section in (1) and (2) are given by [6]:

$$\begin{aligned} A_1 &= \begin{bmatrix} -2.1 & -1.2 & -0.1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, B_{11} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, B_{12} = \begin{bmatrix} 0.02 \\ 0.05 \\ 0.06 \end{bmatrix} \\ A_2 &= \begin{bmatrix} -0.3667 & -0.0111 \\ 1 & 0 \end{bmatrix}, B_{21} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, B_{22} = \begin{bmatrix} 0.01 \\ 0.03 \end{bmatrix} \\ C_1 &= \begin{bmatrix} 0 & 0 & 0.1 \end{bmatrix}, C_2 = \begin{bmatrix} 0 & 0 & 0.0111 \end{bmatrix} \\ D_1 &= 0.2, D_2 = 0.1 \end{aligned}$$

where the disturbance $\omega_1(t) = 0.01e^{-0.3t}sin0.1t$, and $\omega_2(t) = 0.1e^{-0.1t}sin0.1t$. In addition, $h = 1.2s$, and the initial conditions of those two sections are $x_{01} = [-0.1\ -0.2\ 0.8]^T$ and $x_{02} = [0.2\ 0.3]^T$, respectively.

Assuming the index of network QoS varies from 0.2 to 0.8, we divide it into 2 parts as $(0.2\ 0.6]$ and $(0.6\ 0.8]$. From (7), we have $\bar{\varepsilon}_{t_k}^1 = 0.4$ and $\bar{\varepsilon}_{t_k}^2 = 0.7$ then one can obtain the control gains of the networked SSTCS $K_i(\bar{\varepsilon}_{t_k}^j)$ and the parameter $M_{\bar{\varepsilon}_{t_k}^i}$ $(i = 1, 2$ and $j = 0, 1)$ from Theorem 2 with $\gamma = 2.0$.

Fig. 6-7 show the state responses of the network-based SSTCS by using the proposed event-triggered data-releasing mechanism, where the red circles denote instants when packets are released into the network. The output responses of the leading section and internal section are shown in Fig. 8 together with releasing instants and theirs releasing period. From Fig. 6-7 and Fig. 8, one can see that the amount of released packets are tremendous reduced by using the proposed event-generator before the sampled-data entering the network, only 17% of the sampled data need to be released into the network.

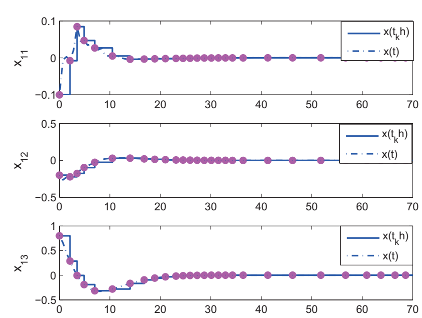

Figure 6: State responses of the leading section using event-triggered mechanism

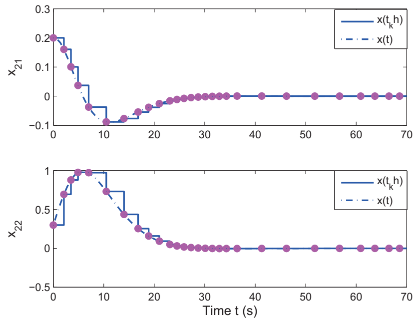

Figure 7: State responses of the inertial section using event-triggered mechanism

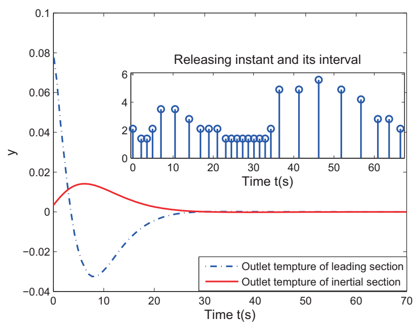

Figure 8: Control input and its corresponding releasing instant by using event-triggered mechanism

5 Conclusion

In this paper, we have presented a new network data-transmitting mechanism for the network-based SSTCS. By comparing the current sampled signals with the last released data, a new event-triggered mechanism is proposed. Based on LMI approach and Lyapunov stability theory, an H_∞ cascade control strategy for the network-based SSTCS under the new data-transmitting mechanism is developed. The H_∞ controllers and theirs corresponding data-transmitting protocol parameters can be easily obtained by LMIs without requiring a complicated artificial parameter tuning. Simulation results demonstrate the effectiveness of the proposed methods.

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