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Brief Paper

Analysis of dual-rate inferential control systems☆

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Abstract

For a dual-rate control system where the output sampling interval is an integer multiple of the control interval, we propose a model-based inferential control scheme which uses a fast-rate model to estimate the intersample outputs and then supply them to a controller at the fast rate. Comparing such an inferential controller with the corresponding fast single-rate controller, we conclude that the former is no better in disturbance rejection capability; however, in the presence of model-plant mismatch, the former is advantageous in stability robustness of the closed-loop system. © 2002 Published by Elsevier Science Ltd.

Keywords: Robustness; Stability; Multirate systems; Digital control; Inferential control

1. Introduction

Multirate systems are common in the chemical process industry because many property or quality variables are not available fast enough: for example, in a polymer reactor, the composition, density or molecular weight distribution measurements typically take several minutes of analysis time, while the control signals can be adjusted at relatively fast rates, the only limitation being the load on the distributed computer control system. In such cases, it makes sense to configure the control systems so that several sample rates co-exist to achieve better tradeoff between performance and implementation cost. This paper is concerned with a dual-rate case where the output is measured at a relatively slow rate, whereas the control signal is adjusted faster.

Research on multirate systems started in the early 1950s. The first important work was Kranc's switch decomposition (Kranc, 1957); this was further developed into the lifting technique by Friedland (1960), Khargonekar, Poolla, and Tannenbaum (1985). The lifting technique converts a periodic discrete-time system into a time-invariant system and is now one of the main tools for studying multirate systems. The advantages of lifting are that it preserves norms of the signals and that the lifted systems are linear time invariant (LTI). We will use lifting for our subsequent analysis in this paper.

In dual-rate systems where the output sampling period is an integer multiple of the control period, it is possible to identify fast single-rate models based on multirate input–output data (Li, Shah, & Chen, 2001a). In this paper, we propose a simple and practical control scheme, referred to as *dual-rate inferential control*, in which the fast single-rate models are used to estimate the missing output samples at the fast rate, and then single-rate control algorithms are implemented at the fast rate. We comment that such a dual-rate inferential control scheme has been applied to an industrial continuous catalytic reforming (CCR) unit for octane quality control (Li, Shah, Chen, & Qi, 2001b), resulting in significant reduction in octane quality variance; the industrial partner involved was Shell Canada. In this work, we will focus on performance and stability robustness analysis of such an inferential control scheme.

In the process control literature, multirate systems have also been studied a great deal: Lu and Fisher (1988) studied the intersample output estimation and inferential control for dual-rate systems and developed a method for output estimation based on the past control and output measurements; Guilandoust, Morris, & Tham (1986, 1988) considered more general multirate systems with primary outputs sampled at a slow rate and showed that the intersample outputs can be estimated using a fast sampled secondary output; Lee and

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Morari (1992) developed a state-space framework called the generalized inferential control scheme for multirate systems and discussed various LQG/$\mathscr{H}_2$ optimal design techniques; and finally, Gudi, Shah, and Gray (1993) developed an enhanced observability estimation method for multirate processes.

In this paper, we focus on inferential control systems using fast sampled models. The contribution of the paper is as follows:

- We propose a simple and practical inferential control scheme for dual-rate systems using fast single-rate models, and develop a lifted framework for analysis of performance and stability robustness.
- We compare the proposed inferential controller with the corresponding fast single-rate controller, and conclude that the former is no better in disturbance rejection capability; however, surprisingly, the former is advantageous in stability robustness in the presence of model–plant mismatch (MPM).

Briefly, this paper is organized as follows: In Section 2 we introduce the dual-rate inferential control scheme. In Section 3 we look at performance of the inferential control scheme in the absence of MPM. In Section 4 we discuss stability robustness of inferential control systems in the presence of MPM. In Section 5 we discuss some extension to the result given in Section 4.

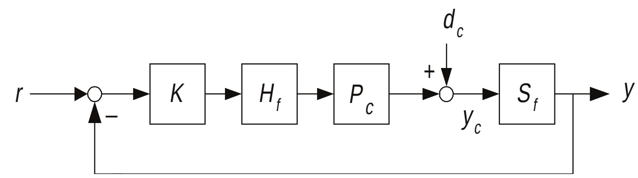

Fig. 1. The sampled-data single-rate control system.

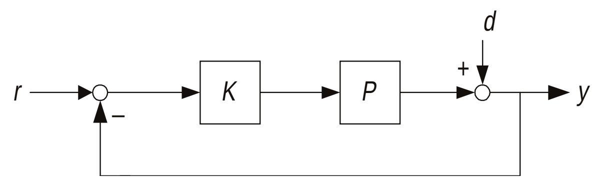

Fig. 2. The discrete-time single-rate control system.

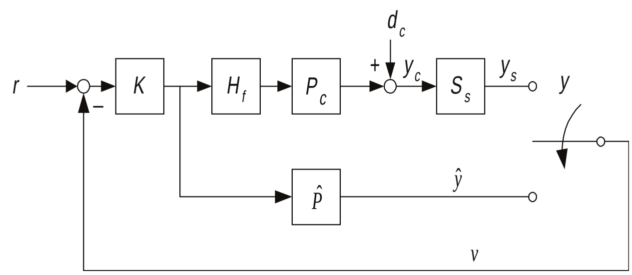

Fig. 3. The sampled-data inferential control system.

2. Dual-rate inferential control scheme

First, let us consider a single-input, single-output single-rate control system shown in Fig. 1, where P_c is a continuous-time LTI plant and K a digital controller. The two systems P_c and K are interfaced by the A/D and D/A converters, modeled by S_f, the ideal sampler, and H_f, the zero-order hold (ZOH), respectively, both operating with the *fast* period T. This is a single-rate sampled-data control system which involves two exogenous signals, the discrete-time reference $r(k)$ and the continuous-time disturbance $d_c(t)$. The measured continuous-time output is $y_c(t)$. Define P as the ZOH equivalent model of P_c ($P = S_f P_c H_f$) and discretize $d_c(t)$ at the fast rate: $d(k) = d_c(kT)$. Thus Fig. 1 is equivalent to a pure discrete-time control system in Fig. 2, which involves only discrete-time signals (Chen & Francis, 1995).

Suppose that due to physical constraints, we cannot sample the output as fast as we wish and thus we have to replace S_f in Fig. 1 by a *slow* sampler S_s with a sampling period nT, where n is a positive integer: $n > 1$. In order to maintain single-rate control, one option is to adopt a slow zero-order hold H_s with period nT and obtain a single-rate control system operating at the slow rate; however, the disadvantage is that performance degradation could be significant. The option that we propose is the inferential control scheme shown in Fig. 3, where the output sampling is now slow (S_s), but the fast zero-order hold H_f and the fast single-rate controller K are still in place. For such a scheme to work, we assume that a model $\hat{P}$ for the fast single-rate system P is available. In order to feed back to the controller K a fast rate signal $v(k)$, representing the output $y(k)$, we use the slow sampled output ($y_s(k) = y_c[k(nT)]$) every nT period, giving $y(0)$, $y(n)$, and $y(2n)$, etc., and use the model $\hat{P}$ to get the estimated output $\hat{y}(k)$ to fill in the missing samples in $y(k)$. Such a process is depicted in Fig. 3 by a periodic switch which connects to y_s at times $=j(nT)$, and connects to $\hat{y}(k)$ at $t = j(nT) + iT$, $i = 1, 2, \ldots, n-1$. Thus the output of the switch is a fast rate signal given by

$$v(k) = \begin{cases} y_s(j), & k = jn, \\ \hat{y}(jn+i), & k = jn+i,\ 0 < i < n. \end{cases}$$

Since S_s is the same as S_f followed by the periodic switch shown in Fig. 3, it is easy to see that the equivalent discrete-time model for Fig. 3 is Fig. 4. Here, P, d and y are as before. Due to the periodic switch, the fictitious fast rate signal $y(k)$ is fed back only once every n samples. Therefore

$$v(k) = \begin{cases} y(jn), & k = jn, \\ \hat{y}(jn+i), & k = jn+i,\ 0 < i < n. \end{cases}$$

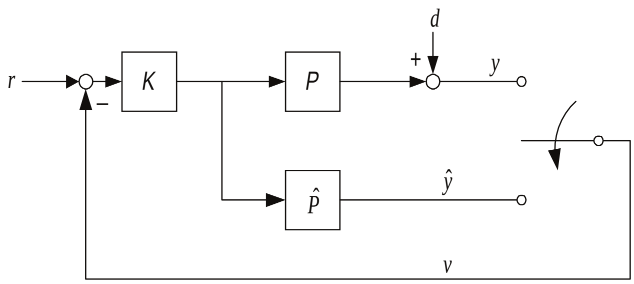

Fig. 4. The discrete-time inferential control system.

To summarize, the dual-rate inferential control scheme uses a fast-rate plant model, a fast single-rate controller, and a periodic switch. It is conceptually simple, easy to implement in digital computers, and practical for industry. Later we will show that in comparison with the fast single-rate control system in Fig. 1, we may lose some performance; but we will gain robustness.

Note that the inferential control scheme assumes availability of a fast single-rate model $\hat{P}$. There are two ways of obtaining $\hat{P}$: (1) if a model for the continuous-time plant P is available, $\hat{P}$ can be computed easily by discretization; (2) if not, we need to invoke the results by Li et al. (2001a) to identify such a fast model based on multirate input–output data.

Next we will compare the inferential control system in Fig. 4 with the single-rate system in Fig. 2 in tracking and disturbance rejection performance (Section 3) and in stability robustness (Section 4).

3. Nominal performance

Consider the dual-rate inferential control system in Fig. 4. Assume in this section that there is no MPM; thus $\hat{P}=P$. If furthermore there is no disturbance in the system, i.e., $d(k)=0$, then $\hat{y}(k)=y(k)$ and hence $v(k)\equiv y(k)$. Thus the dual-rate system is equivalent to the single-rate system in Fig. 2; we conclude

- Without MPM, closed-loop stability of the dual-rate system in Fig. 4 is equivalent to that of the single-rate system in Fig. 2.
- Without MPM and disturbance, the tracking performance (y following r) of Fig. 4 is the same as that of Fig. 2.

This is the main reason why the proposed dual-rate inferential control scheme is attractive: In the ideal situation, we can expect to recover the performance of the fast single-rate system.

When disturbance is present ($d\neq 0$), we now examine the disturbance rejection capability of the two system involved. First, let us look at the single-rate system in Fig. 2. Defining the system from d to y as G_{sr}, we get

$$G_{sr}=(I+PK)^{-1}.$$

We can use the $\mathscr{H}_\infty$ norm to quantify the effect of d on y as follows: Suppose the significant frequency components in d are captured by the pass-band of a pre-filter W_2; the quantity $\|G_{sr}W_2\|_\infty$ is then appropriate as a worst-case measure of the effect of disturbance. The best achievable disturbance rejection performance, denoted γ_{sr}, is obtained by minimizing $\|G_{sr}W_2\|_\infty$ over the class of controllers providing closed-loop stability—a standard $\mathscr{H}_\infty$ optimization problem. In the special case when P is already stable, we can parametrize the set of stabilizing controllers via

$$K=(I-PQ)^{-1}Q \tag{1}$$

with Q stable and LTI. Thus we arrive at the following model-matching problem:

$$\begin{aligned}\gamma_{sr}&=\min_Q\|G_{sr}W_2\|_\infty\\&=\min_Q\|(I-PQ)W_2\|_\infty.\end{aligned} \tag{2}$$

The minimization is done over the class of stable and LTI Q's. The quantity γ_{sr} can be thought of as a measure of disturbance rejection capability of the single-rate system in Fig. 2.

Next, we look at the dual-rate system in Fig. 4. Define G_{dr} as the closed-loop system from d to y in Fig. 4. Thus

$$\gamma_{dr}=\min\|G_{dr}W_2\|_\infty \tag{3}$$

represents the disturbance rejection capability of the dual-rate system in Fig. 4. Note that G_{dr} is not LTI; the norm used in (3) is interpreted as the $\mathscr{L}_2$ induced operator norm.

Because of the presence of the switch, the system in Fig. 4 is linear periodically time-varying. In order to derive a model for G_{dr}, we use the standard lifting technique (Khargonekar et al., 1985).

Let $x(k)$ $(0\leqslant k<\infty)$ be a discrete-time signal. The lifted signal $\underline{x}$ is defined as

$$\underline{x}=\left\{\begin{bmatrix}x(0)\\x(1)\\\vdots\\x(n-1)\end{bmatrix},\begin{bmatrix}x(n)\\x(n+1)\\\vdots\\x(2n-1)\end{bmatrix},\ldots\right\}.$$

The map from x to $\underline{x}$ is defined as the lifting operator L. Note that after lifting the signal dimension is increased by a factor of n, so is the underlying period. The inverse lifting operation, L^{-1}, is from $\underline{x}$ to x, defined in the obvious way.

Lifting all the signals involved in Fig. 4 to get $\underline{y}$ for y, $\underline{\hat{y}}$ for $\hat{y}$, etc., we can derive a simple model for the periodic switch which relates v to y and $\hat{y}$ in the lifted domain

$$\underline{v}=R_1\underline{y}+R_2\underline{\hat{y}}. \tag{4}$$

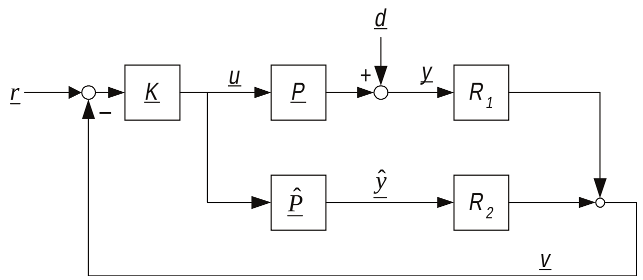

Fig. 5. The lifted inferential control system.

Here R_1 and R_2 are static systems given by the following matrices:

$$R_1 = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}_{n\times n},$$

$$R_2 = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{n\times n}. \tag{5}$$

The lifted systems

$$\underline{K} = LKL^{-1}, \quad \underline{P} = LPL^{-1}, \quad \underline{\hat{P}} = L\hat{P}L^{-1},$$

together with (4) give rise to the lifted closed-loop system in Fig. 5, which is the equivalent model under lifting for the dual-rate structure in Fig. 4. The advantage is that we are now dealing with an LTI system.

Proposition 1. *When P is stable and there is no* MPM, *the disturbance rejection capability of the dual-rate system in Fig.* 4 *is no better than that of the single-rate system in Fig.* 2, *i.e.*, $\gamma_{dr} \geqslant \gamma_{sr}$.

Proof. Specializing to our discussion here, we set $\underline{r} = 0$ and $\underline{\hat{P}} = \underline{P}$ in Fig. 5. The lifted system $\underline{G}_{dr} := LG_{dr}L^{-1}$, or equivalently, the system from $\underline{d}$ to $\underline{y}$ in Fig. 5, can be derived as follows. First, compute the system from $\underline{d}$ to $\underline{u}$ (noting that $R_1 + R_2 = I$):

$$\underline{u} = -(I + \underline{K}\,\underline{P})^{-1}\underline{K}R_1\underline{d}.$$

Then since $\underline{y} = \underline{d} + \underline{P}\,\underline{u}$, we have

$$\underline{G}_{dr} = I - \underline{P}(I + \underline{KP})^{-1}\underline{K}R_1. \tag{6}$$

If P is stable, we use (1) for controller parametrization; the lifted version is

$$\underline{K} = (I - \underline{PQ})^{-1}\underline{Q}.$$

Substitute this into (6) and simplify

$$\underline{G}_{dr} = I - \underline{PQ}R_1.$$

Since lifting preserves norms, we have

$$\gamma_{dr} = \min \|\underline{G}_{dr}\underline{W}_2\|_\infty = \min \|(I - \underline{PQ}R_1)\underline{W}_2\|_\infty, \tag{7}$$

where the latter minimization is over the class of stable and LTI Q's.

In order to compare γ_{sr} and γ_{dr}, we lift the systems involved in (2) to get

$$\gamma_{sr} = \min \|(I - \underline{PQ})\underline{W}_2\|_\infty. \tag{8}$$

Now suppose Q^* is the optimal solution for the minimization in (7), i.e.,

$$\gamma_{dr} = \|(I - \underline{P}\,\underline{Q}^*R_1)\underline{W}_2\|_\infty.$$

(If γ_{dr} is not attainable, we can use a sequence of Q^*s so that the performance converges to γ_{dr}, and the argument to follow is similar.) Define $\underline{Q}_1 = \underline{Q}^*R_1$ to get

$$\gamma_{dr} = \|(I - \underline{PQ}_1)\underline{W}_2\|_\infty.$$

This looks like the norm involved in (8), but Q_1 is not LTI (it is stable); it is in fact linear and periodic with period n (because R_1 does not correspond to an LTI system before lifting). However, since for LTI plants, linear periodic control does not offer any advantage over LTI control in $\mathscr{H}_\infty$ optimization (Khargonekar et al., 1985), and the underlying plant (P and W_2) is LTI, we have

$$\|(I - \underline{PQ}_1)\underline{W}_2\|_\infty \geqslant \min \|(I - \underline{PQ})\underline{W}_2\|_\infty.$$

Hence $\gamma_{dr} \geqslant \gamma_{sr}$, which complete the proof. □

Proposition 1 perhaps makes sense intuitively; but it is not clear if it is still valid when P is unstable. In the next section, we give a somewhat surprising result on stability robustness.

4. Stability robustness

In this section we assume that there is MPM in the dual-rate system in Fig. 4, and hence $\hat{P} \neq P$. We will study issues related to stability robustness. We treat P as uncertain and $\hat{P}$ as the nominal plant model; we assume a standard additive uncertainty model (Doyle, Francis, & Tannenbaum, 1992), i.e., P belongs to the uncertainty class given by

$$\{\hat{P} + \Delta W_1\colon \|\Delta\|_\infty < 1\}.$$

The MPM is represented by ΔW_1, where Δ is the perturbation, assumed to be stable and LTI, with norm less than 1 (normalized), and W_1 is a fixed frequency weighting filter which is stable and LTI. The inferential control system with this uncertain structure is depicted in Fig. 6. Our goal is to find a condition under which the closed-loop system is stable for all admissible Δ.

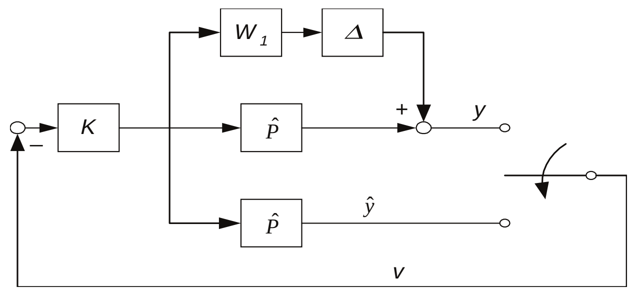

Fig. 6. The inferential control system with additive uncertainty.

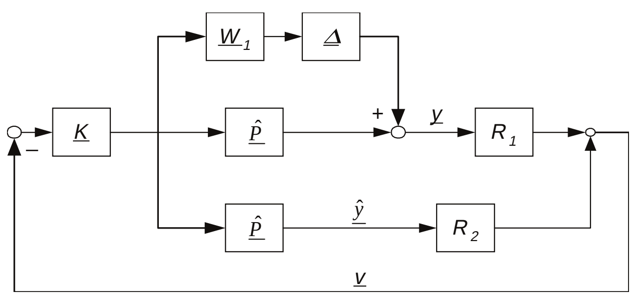

Fig. 7. The lifted inferential control system with additive uncertainty.

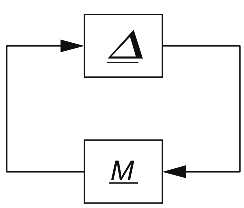

Fig. 8. The equivalent system of Fig. 7.

Proposition 2. *Assume that K stabilizes $\hat{P}$ (nominal stability). Let $\underline{W}_1$, $\underline{K}$, and $\underline{\hat{P}}$ be the lifted systems of W_1, K, and $\hat{P}$, respectively. The dual-rate system in Fig. 6 is closed-loop stable for all admissible Δ if*

$$\|\underline{W}_1(I+\underline{K}\underline{\hat{P}})^{-1}\underline{K}R_1\|_\infty < 1, \tag{9}$$

where the matrix R_1 was defined in (5).

Proof. Similar to what we did in Section 3, we lift the system in Fig. 6 to get Fig. 7. Isolating $\underline{\Delta}$, we can reconfigure Fig. 7 into Fig. 8, where $\underline{M}$ is given by

$$\underline{M} = -\underline{W}_1(I+\underline{K}\,\underline{\hat{P}})^{-1}\underline{K}R_1.$$

It follows easily from the nominal stability assumption that $\underline{M}$ is a stable system. Applying the small-gain condition to the feedback system in Fig. 8, we conclude that the closed-loop system is stable for all admissible Δ if

$$\|\underline{\Delta}\|_\infty \cdot \|\underline{M}\|_\infty < 1,$$

which is true for all admissible Δ ($\|\underline{\Delta}\|_\infty < 1$) if $\|\underline{M}\|_\infty < 1$. □

The condition given in Proposition 2 is sufficient for robust stability of the dual-rate system; however, if we allow the perturbation Δ to be n-periodic instead of time-invariant, the condition becomes necessary (Zhou, Doyle, & Glover, 1996; Dullerud, 1996). In the sequal, we need just the sufficiency in Proposition 2.

Now we compare the robustness condition in Proposition 2 with that for the single-rate system of Fig. 2. Such a condition was well-known (Doyle et al., 1992): The closed-loop system in Fig. 2 is stable for all admissible Δ if and only if (Doyle et al., 1992; Zhou et al., 1996)

$$\|W_1(I+K\hat{P})^{-1}K\|_\infty < 1,$$

which is equivalent to the following after lifting:

$$\|\underline{W}_1(I+\underline{K}\underline{\hat{P}})^{-1}\underline{K}\|_\infty < 1.$$

The quantity on the left, denoted β_{sr}, can be used as a measure of stability robustness for the single-rate system (Doyle et al., 1992): The smaller the β_{sr} is, the more robust the system is. Similarly, the quantity on the left of (9), denoted β_{dr}, is a robustness measure for the dual-rate inferential control system.

Corollary 1. *The fast single-rate control system is no more robust than the dual-rate inferential control system, i.e.,* $\beta_{dr} \leqslant \beta_{sr}$.

Proof. Since R_1 is a projection matrix with $\|R_1\| \leqslant 1$, we have

$$\begin{aligned}\beta_{dr} &= \|\underline{W}_1(I+\underline{K}\underline{\hat{P}})^{-1}\underline{K}R_1\|_\infty \\ &\leqslant \|\underline{W}_1(I+\underline{K}\underline{\hat{P}})^{-1}\underline{K}\|_\infty \cdot \|R_1\| \\ &\leqslant \|\underline{W}_1(I+\underline{K}\underline{\hat{P}})^{-1}\underline{K}\|_\infty,\end{aligned}$$

the last quantity on the right being β_{sr}. The proof is complete. □

This result still leaves room for doubt: Can the dual-rate control structure be *better* in stability robustness than the fast single-rate one? The answer is positive; and we illustrate this with an example.

Example. Consider a nominal plant $\hat{P}$ with a PI controller K

$$\hat{P}(z) = \frac{0.15}{z-0.9}, \quad K(z) = 3 + \frac{0.5}{1-z^{-1}}.$$

Suppose the actual plant P, different from $\hat{P}$, is given by

$$P(z) = \frac{0.13}{z^3(z-0.92)}.$$

With this P in place, it can be shown that the fast single-rate system (Fig. 2) is closed-loop unstable, while the dual-rate inferential control system (Fig. 4) with $n=4$ is closed-loop

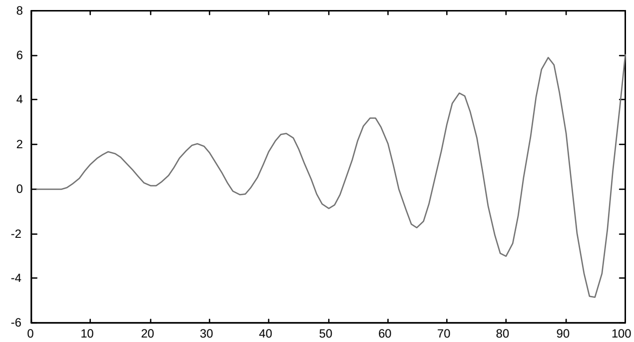

Fig. 9. Step response in y for the fast single-rate system.

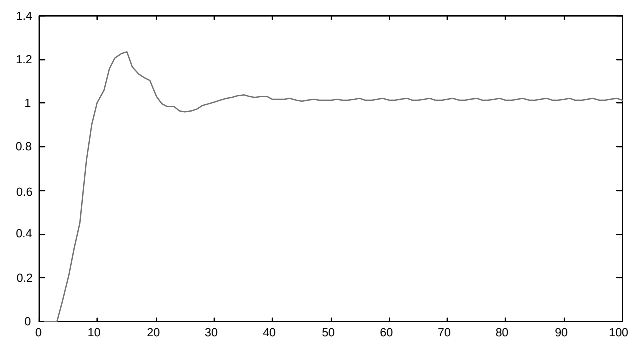

Fig. 10. Step response in y for the dual-rate inferential control system.

stable, see the closed-loop step responses in Figs. 9 and 10. This shows that the dual-rate inferential system is indeed more robust than the corresponding fast single-rate system!

5. Concluding remarks

In the preceding section, we studied stability robustness of the dual-rate inferential control system assuming an additive uncertainty model. We point out here that similar result holds if a multiplicative uncertainty model is used; in this case P belongs to the class

$$\{(I + \Delta W_1)\hat{P}\colon \|\Delta\|_\infty < 1\}.$$

Similar to the condition in (9) in Proposition 2, the robust stability condition for this case is

$$\|\underline{W}_1\underline{\hat{P}}(I + \underline{K}\underline{\hat{P}})^{-1}\underline{K}R_1\|_\infty < 1.$$

Based on this, we can make the same conclusion that the dual-rate inferential control scheme is advantageous in stability robustness over the fast single-rate control scheme.

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