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Article

Cite This: Ind. Eng. Chem. Res. 2018, 57, 6947−6955

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Dual SIMC-PI Controller Design for Cascade Implement of Input Resetting Control with Application

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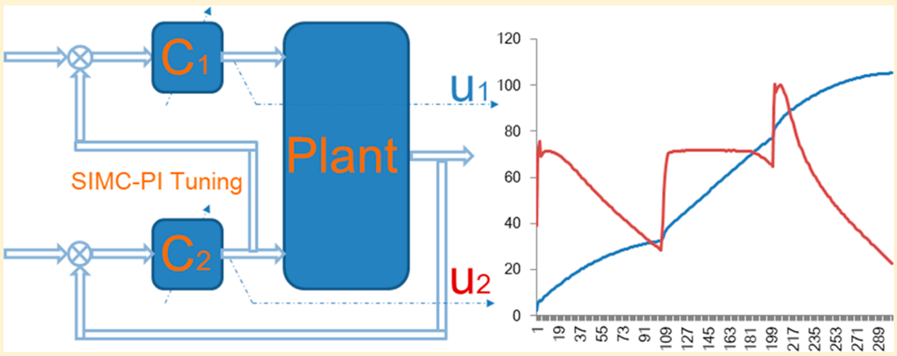

ABSTRACT: Input resetting control (IRC) is an economical and effective approach to achieve good closed-loop behavior for systems with extra inputs. The paper investigates use of the cascade IRC implementation. A SIMC-based controller tuning rule is proposed for first-order plus time delay (FOPTD) processes in the two-input−single-output (TISO) structure. Satisfactory regulatory capacities for both set-point tracking and input resetting are obtained. Both of the controllers are analytically derived with proportional-integral (PI) forms by proposing the equivalent transfer functions. The resulting tuning guideline shows how the adjustable parameters should be changed to balance a trade-off between performance specifications and levels of robustness. Numerical simulations have been carried out to demonstrate the effectiveness of the proposed method. Moreover, the feasibility of implementing the proposed control strategy in practice is verified by a light intensity control experiment.

1. INTRODUCTION

There are typically equal numbers of manipulated inputs and controlled outputs for process control systems encountered in industrial applications. However, in many situations, improved closed-loop performance can be obtained by introducing additional input variables. Input resetting control (IRC) refers to a class of control problems where there are more manipulated inputs than outputs to be controlled.[1] The approach is known under many names, including valve position control, midranging control, and habituating control.[2−4] The last name is because the human body has such a scheme in controlling blood pressure. In many chemical and biological control systems, this structure is preferred for manipulating inputs to effectively regulate output behaviors with efficient cost of control action.[5] Meanwhile, the presence of additional controllers for IRC also brings challenges to researchers and engineers because more parameters need to be selected to achieve multiple control objectives such as input resetting response, set-point tracking, and external disturbance rejection. To address this issue, it is considered to extend controller tuning rules developed for single-input−single-output (SISO) systems to IRC systems because fruitful achievements have been received in the past decades on the design of SISO systems. With the availability of plant models, the internal model control (IMC) has been recognized as one of the most effective model-based strategies.[6] After the first attempt of IMC methodology to controller design for stable plants, a number of articles in terms of the IMC principle were developed to obtain good load disturbance rejection performance both for open-loop stable and for unstable plants.[7−9] By virtue of controller order reduction techniques, IMC-based PI/PID tuning rules were developed for different types of time delay processes.[10−14] There is growing concern on the balancing tunings of input and output disturbances.[15] The control schemes for both stable and unstable plants were developed by appropriately selecting the weighting function and minimizing the peak of the magnitude frequency response.[16−19] Recently, a number of articles were proposed to reject load disturbances for integrating processes with time delay.[20−22] The SIMC rule for model-based PI/PID tunings has appeared to be popular since it was published by Skogestad.[23] The main reason for the success is that it provides simple controller forms with satisfactory closed-loop performance for time delay processes. Meanwhile, another feature is

Received: December 5, 2017
Revised: April 12, 2018
Accepted: April 13, 2018
Published: April 13, 2018

DOI: 10.1021/acs.iecr.7b05047
Ind. Eng. Chem. Res. 2018, 57, 6947−6955

that the robustness and performance specifications can be adjusted quantitatively with the parameter. Verification of the SIMC tuning rule has been studied by comparing the performance of the SIMC rule to the optimal method for a given robustness constraint.[24]

Note that conventional practice for systems with an extra manipulated variable is to select controller parameters by trial and error.[2] But this may not be optimal as there is a lack of systematic tuning procedures for IRC controllers. Available advanced approaches to IRC, including the model-based control and the direct synthesis control, were reviewed.[25] A direct synthesis IRC control scheme for stable processes was proposed where improved input resetting performance was achieved. An adaptive IMC-based tuning rule for discrete-time IRC systems with internal saturation conditions was presented.[26] It is worth noting that a majority of the existing methods for IRC were not suitable for processes with time delays, especially for those with large ones. Analysis of the trade-off between the performance and robustness was also neglected in most studies. The intention of the article is to extend the SIMC tuning rule to the cascade IRC situation. It is desirable to provide analytic tuning expressions for both controllers without loss of their simplicities. Based on model approximation techniques, the derivation of dual SIMC-PI controllers is carried out for first-order plus time delay (FOPTD) processes. The proposed tuning rule involves two adjustable parameters that are closely related to the design specifications. The parameter tuning guideline is allowed to be established with the balanced performance/robustness consideration.

The outline of the paper is as follows. Section 2 introduces the cascade IRC implementation. In section 3, a two-step SIMC controller design strategy is provided and dual analytic PI controllers are derived. In section 4, the proposed method is tested on simulation examples by comparing it to alternative approaches. Experimental results from a light intensity control device are also included to verify the effectiveness of the method in practice. Finally, section 5 summarizes the main ideas and makes the concluding remarks.

2. BRIEF DESCRIPTION OF INPUT RESETTING CONTROL

The IRC design refers to the control problems for systems with extra manipulated inputs compared to outputs. The most common case of IRC is the two-inputs−single-output (TISO) system with the framework in Figure 1. Consider a plant with a single controlled output y with set-point r and two manipulated inputs u_1 and u_2. u_1 is the “main” input and has a larger effect on y than u_2, but it cannot be used to achieve sufficiently fast control of y. Thus, we use u_2 as an extra input to improve the fast control of y. However, u_2 does not have sufficient power or is too costly to use for long-term control. Thus, u_1 should be used for longer (steady-state) control of y, whereas u_2 at steady-state should be reset to its desired resetting value r_{u_2}.

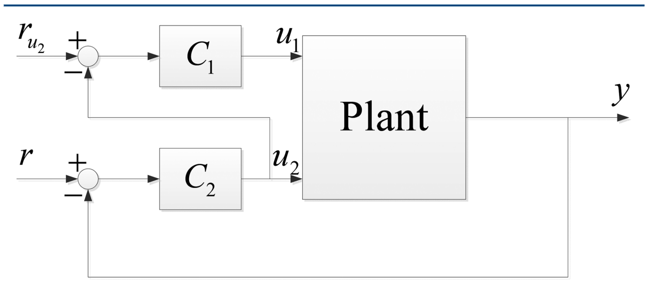

Figure 1. General cascade implement of input resetting conrol.

Figure 2 is a block diagram showing the architecture in which the control problem of the paper is discussed. r is the set-point input and r_{u_2} is the extra reference signal for u_2. G_1 and G_2 are identified processes. As mentioned above, they are modeled as FOPTD processes

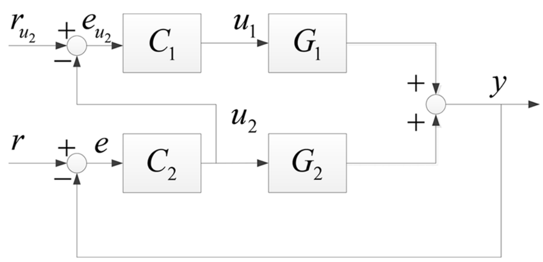

Figure 2. Two inputs and single output cascade implement of input resetting control.

$$G_1 = \frac{k_1}{\tau_1 s + 1} e^{-\theta_1 s} \qquad G_2 = \frac{k_2}{\tau_2 s + 1} e^{-\theta_2 s} \tag{1}$$

Assume that G_1 and G_2 have different dynamic features, where typically G_1 has a larger gain, time constant, and time delay constant than G_2.

$$k_1 > k_2 \qquad \tau_1 > \tau_2 \qquad \theta_1 > \theta_2 \tag{2}$$

C_1 and C_2 are controllers and both of them are designed to be PI forms

$$C_1 = k_{C_1}\left(1 + \frac{1}{\tau_{I_1} s}\right) \qquad C_2 = k_{C_2}\left(1 + \frac{1}{\tau_{I_2} s}\right) \tag{3}$$

where k_{C_i} $(i = 1, 2)$ is the proportional gain and τ_{I_i} $(i = 1, 2)$ = is the integral time.

The characteristic equation is $1 + G_2C_2 - G_1C_1C_2 = 0$. The sensitivity function S and the complementary sensitivity function T of the overall system are given below:

$$S = \frac{1}{1 + G_2C_2 - G_1C_1C_2} \qquad T = \frac{G_2C_2 - G_1C_1C_2}{1 + G_2C_2 - G_1C_1C_2} \tag{4}$$

The sensitivity function S is employed as the measurement to evaluate the system robustness level in the simulation section. The controller design can be understood to asymptotically eliminate the error between the output and the reference. To achieve both the set-point tracking and input resetting objectives, the following conditions must be fulfilled:

$$\lim_{t\to\infty} e(t) = 0 \qquad \lim_{t\to\infty} e_{u_2}(t) = 0 \tag{5}$$

where

$$e = \frac{1}{1 + G_2C_2 - G_1C_1C_2} r - \frac{G_1C_1}{1 + G_2C_2 - G_1C_1C_2} r_{u_2} \tag{6}$$

DOI: 10.1021/acs.iecr.7b05047
Ind. Eng. Chem. Res. 2018, 57, 6947−6955

$$e_{u_2} = \frac{1 + G_2C_2}{1 + G_2C_2 - G_1C_1C_2} r_{u_2} - \frac{C_2}{1 + G_2C_2 - G_1C_1C_2} r \quad (7)$$

Given two linear time-invariant FOPTD processes to form the considered cascade IRC system, the aim of the article is to derive SIMC-PI controllers C_1 and C_2 such that (1) the satisfactory set-point tracking response is yielded, (2) the input resetting response is achieved, and (3) the robustness requirement is met.

3. SIMC-PI CONTROLLER DESIGN FOR CASCADE IRC

3.1. Fast Process Controller Design. As the set-point tracking response is mainly regulated by the controller C_2 in terms of G_2, C_2 is developed with respect to G_2. Followed by the SIMC controller tuning rule, the corresponding PI controller is

$$k_{C_2} = \frac{1}{k_2} \frac{\tau_2}{\tau_{c2} + \theta_2} \quad (8)$$

$$\tau_{I_2} = \min\{\tau_2, 4(\tau_{c2} + \theta_2)\} \quad (9)$$

where τ_{c2} is the adjustable parameter and a recommended choice of τ_{c2} is equal to the pure time delay part of G_2 that $\tau_{c2} = \theta_2$. Thus, the controller is given as

$$k_{C_2} = \frac{1}{k_2} \frac{\tau_2}{2\theta_2} \quad (10)$$

$$\tau_{I_2} = \min\{\tau_2, 8\theta_2\} \quad (11)$$

3.2. Slow Process Controller Design. The next step is to design C_1 when the secondary-loop controller C_2 is addressed. Denote the open-loop transfer function from u_1 to u_2 as G_{12}. The control structure yields

$$G_{12} = \frac{u_2}{u_1} = -\frac{G_1C_2}{1 + G_2C_2} \quad (12)$$

The closed-loop structure of the equivalent control process G_{12} is shown in Figure 3. Observe that the objective of resetting the input u_2 to the desired value r_{u_2} can be regarded as designing C_1 in terms of G_{12} to achieve set-point tracking response. Thus, on simplifying and rearranging eq 12, the following equation is obtained

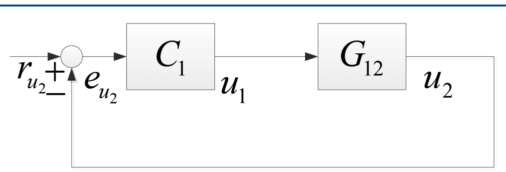

Figure 3. Diagram of the equivalent closed-loop for G_{12}.

$$G_{12} = \frac{u_2}{u_1} = -\frac{G_2C_2}{1 + G_2C_2} \cdot \frac{G_1}{G_2} = -T_2G_1{G_2}^{-1} \quad (13)$$

T_2 is the complementary sensitivity function of the G_2C_2 channel. Equation 13 indicates that T_2 is a high-order complex function because of the existence of the time delay part in the denominator. A low-order controller is desired for ease of implementation. Therefore, T_2 is approximated by

$$T_2 \approx \frac{e^{-\theta_2 s}}{\tau_{c2}s + 1} \quad (14)$$

and we get

$$G_{12} = -\frac{k_1}{k_2} \frac{\tau_2 s + 1}{\tau_{c2}s + 1} \cdot \frac{e^{-\theta_1 s}}{\tau_1 s + 1} \quad (15)$$

Provided that τ_{c2} is relatively small compared to τ_1, we can make further approximation of G_{12} as

$$G_{12} \approx -\frac{k_1}{k_2} \frac{\tau_2 s + 1}{\tau_1 s + 1} e^{-(\theta_1 + \tau_{c2})s} \quad (16)$$

For eq 16, it is reasonably assumed that τ_2 is smaller than $(\theta_1 + \tau_{c2})$ and the zero approximation rule[27] is adopted

$$G_{12} \approx -\frac{k_1}{k_2} \frac{1}{(\tau_1 - \tau_2)s + 1} e^{-(\theta_1 + \tau_{c2})s} \quad (17)$$

The SIMC tuning rule is applied to G_{12} in eq 17 to design C_1. The controller of C_1 is given as

$$k_{C_1} = \frac{k_2}{k_1} \frac{\tau_1 - \tau_2}{\tau_{c1} + \tau_{c2} + \theta_1} \quad (18)$$

$$\tau_{I_1} = \min\{\tau_1 - \tau_2, 4(\tau_{c1} + \tau_{c2} + \theta_1)\} \quad (19)$$

τ_{c1} is an adjustable parameter. A recommended choice of τ_{c1} is equal to the pure time delay part of G_{12}. Because of the minus sign (−) in G_{12}, it is mentioned that the final form of C_1 is

$$C_1 = -k_{C_1}\left(1 + \frac{1}{\tau_{I_1}s}\right) \quad (20)$$

Finally, for the resetting reference r_{u_2}, its value is always determined by the set-point reference, it is recommended to select it to be no more than 20% of r. Meanwhile, it is concluded that the proposed IRC tuning is applicable to a class of FOPTD models when the normalized dead times (θ_1/τ_1 and θ_2/τ_2) approximately belong to 0.1−3.

3.3. Guideline for Selection of Tuning Parameters. The proposed controller tuning rule involves two free parameters, τ_{c1} and τ_{c2}. They can be tuned to adjust the change speeds of controlled variables and therefore be utilized to make a compromise in terms of performance and robustness. To clearly illustrate the selection procedure of tuning parameters, several standard indices are adopted to evaluate the dynamic performance: overshoot (OS), setting-time (ST), regulatory control maximum error (ME), and integrated absolute error (IAE). Maximum sensitivity (Ms) is also employed as a measurement tool to quantitatively evaluate the robustness level of the closed-loop system. Ms is a standard index and defined as $\mathrm{Ms} = \max_{\omega} |S(i\omega)|$ for feedback control structures, where S is the sensitivity function of the system. For the configuration in Figure 2, the sensitivity function S is given in eq 4. In the present work, initial choices of τ_{c1} and τ_{c2} are suggested to be $\tau_{c2} = \theta_2$ and $\tau_{c1} = \theta_1 + \tau_{c2}$. Toward the proposed choice, there is a 2-fold consideration. On one hand, this combination of τ_{c1} and τ_{c2} could be able to achieve the set-point tracking and the input resetting response for most of cases. On the other hand, the parameter tunings around this point are clear that the robustness is improved monotonically with their increase. For engineering purposes, a simple and effective

DOI: 10.1021/acs.iecr.7b05047
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tuning is desired and hence the first step is to select τ_{c2} to obtain a set-point tracking response that satisfies the design requirements in terms of performance specifications. Then, the second step is to select τ_{c1} to make the closed-loop system meet the robustness requirement. On the basis of experience gained from many simulations, for stable processes, the guideline for selection of tuning parameters is recommended as $\tau_{c2} \in [\theta_2, 3\theta_2]$, $\tau_{c1} \in [0.5(\theta_1 + \tau_{c2})\ 2(\theta_1 + \tau_{c2})]$. The closed-loop system can obtain Ms from about 1.3 to 2.0, which is a widely adopted range to design a robust system.[28] The resulting closed-loop system is guaranteed to obtain sufficient magnitude and phase margins as well as acceptable dynamic performance. Meanwhile, it also needs to be mentioned that there exists a class of parameter combinations to obtain the same level of robustness. A direct way of finding the best obtainable specification to a certain degree of robustness level is to calculate all the possible results. Obviously, this is not preferred since it is a tough and time-consuming procedure. Instead, an effective method has been proposed that all the possible points can be approximately represented by the use of the linear fitting technique, which is illustrated in Example 1 in the following section.

4. EXAMPLE STUDIES

This section is devoted to test the proposed method through numerical simulations and a light intensity control experiment. By comparing it to reported methods in the literature, we aim to obtain conclusions regarding the performance and robustness of the provided method. In this paper, for fair comparison among different methods, all the controllers are tuned to have the same Ms value in each work.

4.1. Example 1. Consider two stable processes as follows:

$$G_1 = \frac{1}{5s + 1}e^{-s} \qquad G_2 = \frac{0.1}{0.5s + 1}e^{-0.1s} \tag{21}$$

The configuration is shown in Figure 2. The effectiveness of the proposed IRC method is verified by comparing it to the method by Allison et al.[25] and the SISO SIMC tuning with G_1. The step square wave with unit magnitude is sent as the reference signal r. The resting reference value r_{u_2} is a step response with 20% magnitude of the reference input ($r_{u_2} = 0.2$). For the proposed method, the tuning procedure begins with the attempt $\tau_{c2} = 0.1$ and $\tau_{c1} = 1.1$ with respect to the guideline in the above section. The initial response achieves the set-point tracking and input resetting control objectives with the robustness level Ms = 1.83. Thus, the parameters need small adjustments to enhance the robustness to the desired degree with Ms = 1.8. The first step is to increase the value of τ_{c2} to obtain a smooth setting response without an overshoot. Then, τ_{c1} is adjusted in terms of the value of Ms. For this case, we finally have $\tau_{c2} = 0.13$ and $\tau_{c1} = 0.565$ to ensure the closed-loop system with the robustness level Ms = 1.8. The controller parameters are calculated in Table 1, and the nominal closed-loop responses to set-point tracking and controlled actions are shown in Figures 4–6. The performance index summary is listed in Table 2. Simulation results show that both of the IRC methods achieve set-point tracking and input resetting control objectives with smooth responses. Compared with the SISO structure, the IRC implementation can obviously reduce input usage by effectively decreasing the maximum value of u_1. It is responsible to consider that improved performance is obtained with the proposed method since it has quicker responses to the output y and manipulated variable u_2 when compared to the method.[25] It also needs to be pointed out that excessive overshoots in responses to u_1 and u_2 yielded by the proposed method are the cost of improved set-point tracking and input resetting actions. To analyze the robustness, perturbations in process constants are considered and the process models of the uncertain case are $G_1 = 1.61e^{-1.15}/(8.18s + 1)$ and $G_2 = 0.14e^{-0.15}/(0.68s + 1)$. The corresponding closed-loop responses are shown in Figures 7–9. A certain degree of overshoots appearing for input resetting responses indicates

Table 1. Controller Parameters with the Robustness Level for Example 1

	C_1		C_2		
methods	k_{C_1}	τ_{I_1}	k_{C_2}	τ_{I_2}	Ms
proposed	0.27	4.5	21.74	0.5	1.8
SISO SIMC	2.941	5.0			1.8
Allison[25]	23.46	10.8	0.91	0.5	1.8

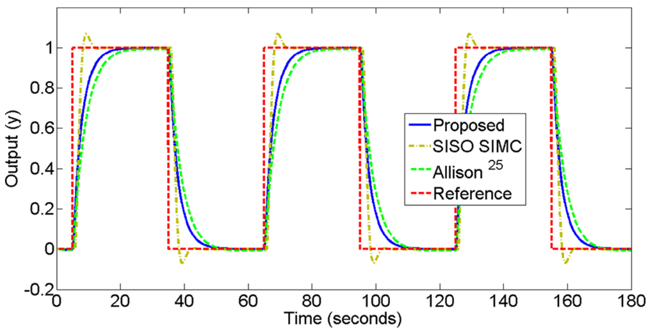

Figure 4. Nominal output response in y to unit step square wave reference for Example 1.

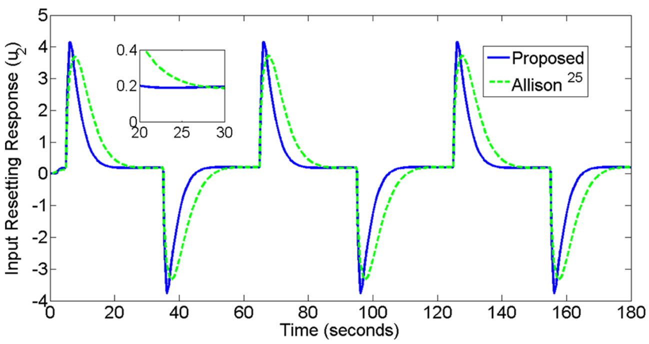

Figure 5. Nominal input resetting response in u_2 for Example 1.

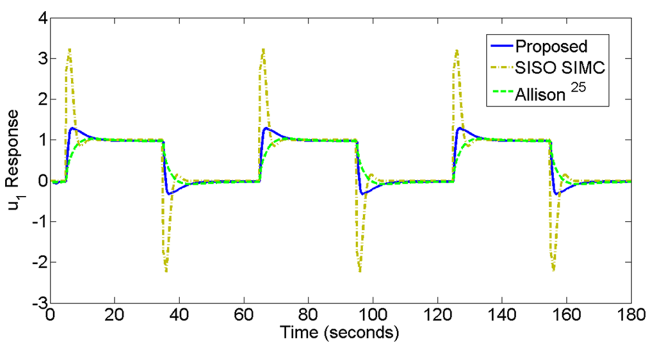

Figure 6. Nominal manipulated variable response in u_1 for Example 1.

DOI: 10.1021/acs.iecr.7b05047
Ind. Eng. Chem. Res. 2018, 57, 6947–6955

Table 2. Performance Indices for Example 1[a]

methods	responses: indexes:	servo-control OS	servo-control ST	servo-control IAE	input resetting (u_2) OS	input resetting (u_2) ST	input resetting (u_2) IAE	u_1 response OS	u_1 response ST	u_1 response IAE
proposed		**0**	6.7s	8.005	4.16	**13.5s**	**17.746**	0.29	0.72	**6.996**
SISO SIMC		0.15	**2.3s**	**5.743**				3.5	**0.56**	10.297
Allison[25]		**0**	9.1s	9.376	**3.68**	20.1s	28.974	**0.03**	3.66	7.359

[a]The data are calculated for a single period, and bold type in each column means the better performance of the criterion.

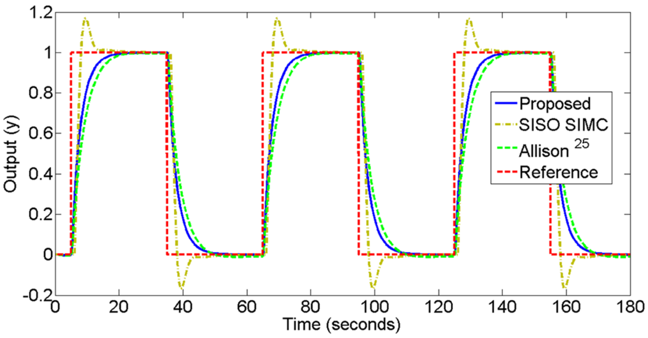

Figure 7. Uncertain output response in y to unit step square wave reference for Example 1.

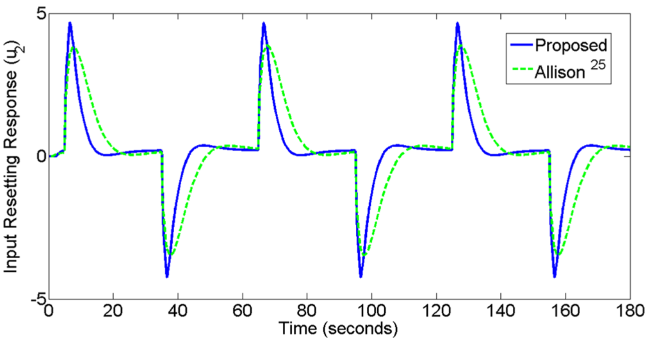

Figure 8. Uncertain input resetting response in u_2 for Example 1.

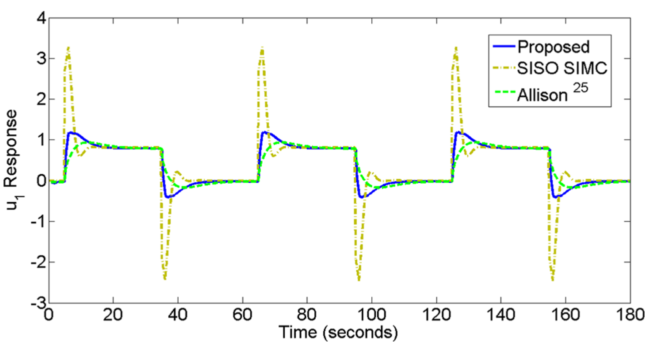

Figure 9. Uncertain manipulated variable response in u_1 for Example 1.

that uncertainties degrade the performance for both of the methods. Finally, it is possible to include a filter to modify the set-point response, resulting in two degrees of freedom (2DoF) for controllers. For the considered PI controller, it is recommended to introduce a first-order filter. This may be used, for example, to get smoother manipulated input signals.

In order to obtain the optimal performance in terms of the target robustness level, we first study the relationship between the parameters (sweeping over the ratio range from 1 to 3 for τ_{c2}/θ_2, and from 0.5 to 2 for $\tau_{c1}/(\theta_1 + \tau_{c2})$) and the robustness. The Ms value versus τ_{c1} and τ_{c2} graph is shown in Figure 10. For Figure 10d, we find two points $\tau_{c2}/\theta_2 = 1$, $\tau_{c1}/(\theta_1 + \tau_{c2}) =$

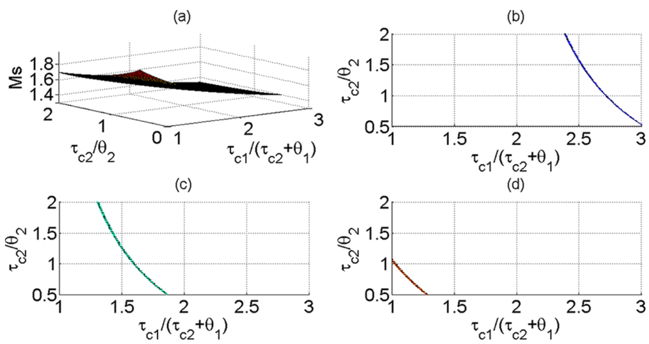

Figure 10. (a) Surface of Ms value to parameters τ_{c1} and τ_{c2}. (b) Region of the combination of τ_{c1} and τ_{c2} with Ms = 1.4. (c) Ms = 1.6. (d) Ms = 1.8.

1.1 and $\tau_{c2}/\theta_2 = 1.3$, $\tau_{c1}/(\theta_1 + \tau_{c2}) = 0.5$ with Ms = 1.8. The linear fitting technique is utilized to form the equation $[\tau_{c1}/(\theta_1 + \tau_{c2})] = -2(\tau_{c2}/\theta_2) + 3.1$. All the points that satisfy the equation can be considered to make the closed-loop system obtain Ms = 1.8. Four points are selected as (1, 1.1), (1.1, 0.9), (1.2, 0.7), and (1.3, 0.5). Their Ms values are 1.8, 1.79, 1.79, and 1.8, respectively. Thus, the proposed linear fitting method can be regarded as an effective way to express the collection of all the points with the same robustness level in terms of Ms. The next step is to find the optimal performance according with the selected indices. Their setting times are 6.617, 6.6223, 6.638, and 6.665, respectively. It can be seen that for the considered performance specification the point (1, 1.1) achieves the best set-point tracking response. How to obtain the best performance when different values of parameters hold the same level of robustness can be summarized as (1) find two points with the desired Ms value, (2) adopt the linear fitting method to form the equation, (3) select several points to calculate the selected performance specification, and (4) keep searching until you obtain the point with the best value.

4.2. Example 2. In a paper mill, the pulp or stock is diluted in two steps: a coarse dilution and a fine dilution. The concentration of fibers in the slurry is called the "consistency" in industry. Consider the paper pulp consistency dilution process shown schematically in Figure 11. Identify that this block diagram is a cascade IRC case. Therefore, the controller setting strategy outlined earlier is applied to the pulp consistency control simulation.

The existence of large time delay constants in process models results in the method[25] not being suitable for the case. The PI-P tuning rule, of which parameters are tuned by trial and error, is employed as comparison. The process models are considered as

$$G_1 = \frac{3}{60s + 1}e^{-30s} \qquad G_2 = \frac{1}{10s + 1}e^{-5s} \tag{22}$$

DOI: 10.1021/acs.iecr.7b05047
Ind. Eng. Chem. Res. 2018, 57, 6947−6955

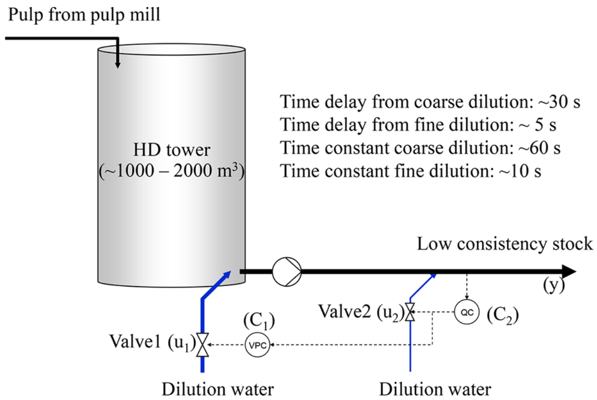

Figure 11. Paper pulp consistency control schematic.

The step square wave with unit magnitude (r = 1) is the reference signal. The resting reference value r_{u_2} is zero. A random perturbation of +20% is assumed in each parameter for the unavoidable mismatch between the actual plant dynamics and the identified model. As we mentioned, parameters of different methods should be tuned to ensure all the systems with the same robustness level. For this case, the desired value of Ms is determined to be 1.78. The initial choice of the parameters in the proposed tuning is τ_{c1} = 35 and τ_{c2} = 5, which results in a set-point tracking response with a large overshoot. By increasing the value of τ_{c2}, we can decrease the overshoot degree while the set-point response becomes slower. Nevertheless, it cannot yield a response without an overshoot. With the consideration of the overshoot and the setting-time, τ_{c2} is selected to be 6.5. After that, τ_{c1} is adjusted to be 33 so that Ms is guaranteed to be 1.78. Correspondingly, the SIMC method yields k_{C_1} = 0.3367, τ_{I_1} = 50 and k_{C_2} = 8.696, τ_{I_2} = 10. The tuning parameters for the PI-P method are τ_{c11} = 11.4286 and τ_{c12} = 2.5. The corresponding controllers are $k_{C_{11}}$ = 0.4167, $\tau_{I_{11}}$ = 50, and $k_{C_{12}}$ = 1.3334. The closed-loop responses and control effects to the perturbed plants are shown in Figures 12−14.

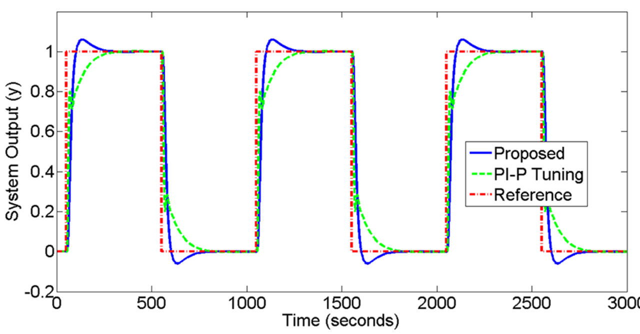

Figure 12. Uncertain output response in y to unit step squre wave reference for Example 2.

From Figure 13, the demand of input resetting control can be satisfied for both of the methods that u_2 go back to zero for the steady status. Frequency responses of sensitivity function S and complementary sensitivity function T are displayed in Figure 15. The same value of the peaks of $|S|$ shows that both of them are with the same robust stability. With these controller settings, the methods are also simulated by a unit step change in the set-point and input and output load disturbances in the G_1C_1 channel. A unit input load disturbance d_{1i} is acting at t = 350s and d_{1o} is at t = 900 s. Disturbance rejection responses are shown in Figures 16−18. The performance measures given in Table 3 indicate that better attenuation of load disturbances is

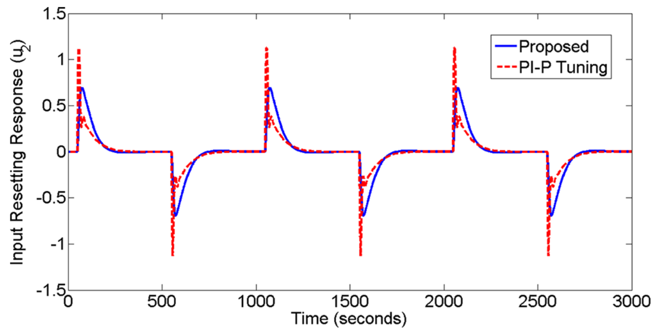

Figure 13. Uncertain input resetting response in u_2 for Example 2.

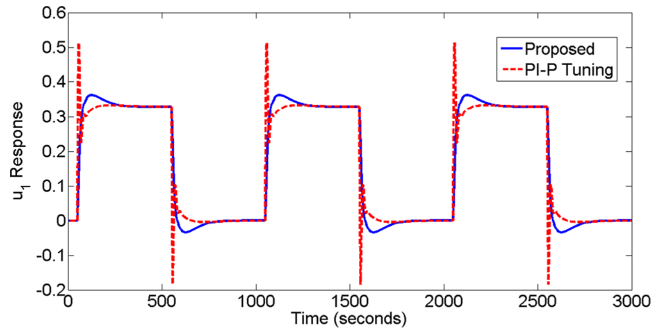

Figure 14. Uncertain manipulated variable response in u_1 for Example 2.

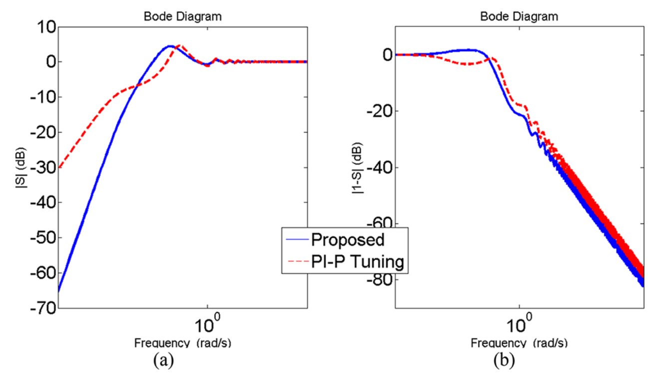

Figure 15. (a) Sensitivity function S. (b) Complementary sensitivity function T.

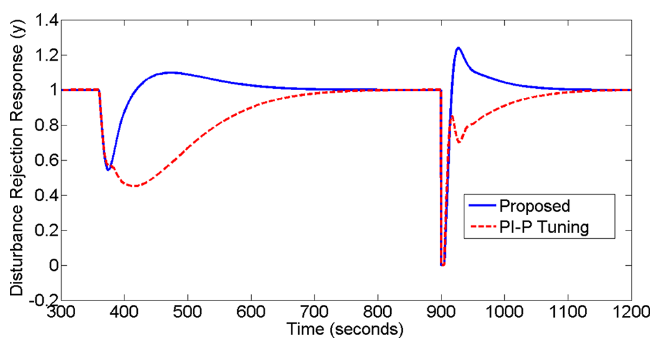

Figure 16. Response in y to input and output disturbance for Example 2.

DOI: 10.1021/acs.iecr.7b05047
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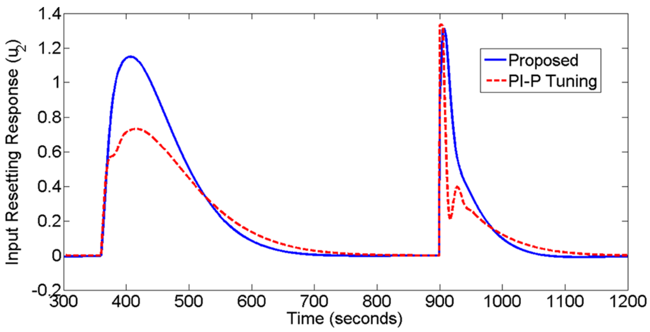

Figure 17. Input resetting response in u_2 to input and output disturbance for Example 2.

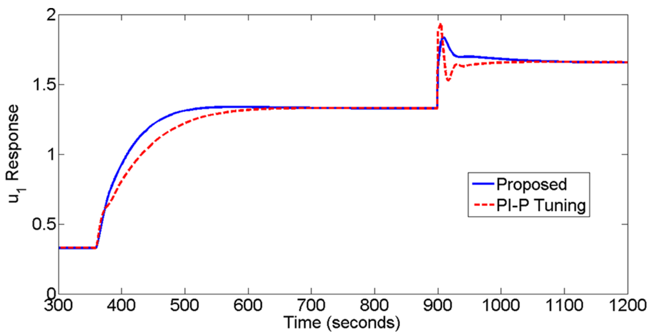

Figure 18. Manipulated variable response in u_1 to input and output disturbance for Example 2.

obtained in terms of IAE index for the proposed method compared to that for the PI-P method at the expense of the overshoot.

4.3. Example 3. A light intensity control experiment,[29] as shown in Figure 19, is carried out to evaluate the performance of the proposed control strategy. The system is made up of a computer, a monitor, and a light intensity control device. The structure of the system and the controller setup is designed through the computer. In the box, a bulb and a LED light can be manipulated to control the light intensity. Then, a light intensity sensor transmits the detected data to the computer to achieve the feedback loop. The bulb, with fast light-generating response, herein is considered as the fast process G_2 and the LED is the slow process G_1 in Figure 20.

Open-loop step response tests performed in the pilot plant are used to identify the models. Both of them are considered as FOPTD processes. The parameters are changed with the set-point value because of the variation of the working temperature. With 50% of the maximum value ($r = 15$), the process models are identified as

$$G_1 = \frac{0.5805}{13.546s + 1}e^{-5.685} \qquad G_2 = \frac{0.1516}{1.59s + 1}e^{-0.79} \tag{23}$$

The controller tuning begins with $\tau_{c2} = 0.79$ and $\tau_{c1} = 6.475$. The initial attempt achieves the set-point tracking and the input

(a) (b)

Figure 19. (a) Light intensity control experiment apparatus. (b) Light intensity control device.

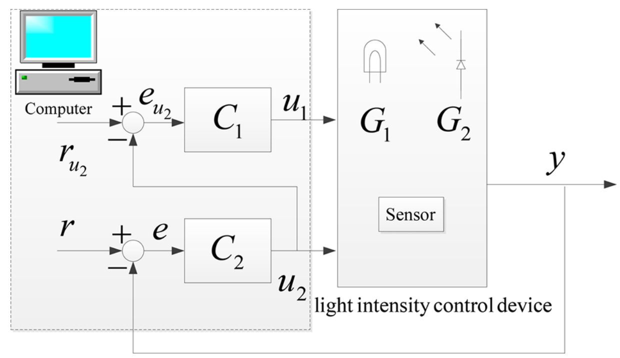

Figure 20. Light intensity control experiment schematic.

resetting responses. Therefore, only some minor adjustments are needed to further improve the performance. For engineering purposes, the tuning task is finished when the robustness index Ms is calculated to be 1.78 with respect to the identified models. The final choice is $\tau_{c2} = 0.728$ and $\tau_{c1} = 3.88$, and the corresponding controllers are given as

$$C_1 = -2.0091\left(1 + \frac{1}{13.305s}\right)$$
$$C_2 = 5.6164\left(1 + \frac{1}{1.515s}\right) \tag{24}$$

Input and output load disturbances are considered in the G_1C_1 channel. An input load disturbance d_{1i} is acting at $t = 100$ s with $d_{1i} = 30$ and d_{1o} is at $t = 200$ s with $d_{1o} = 5$. The resting reference signal r_{u_2} is 15. The standard SISO feedback control structure for G_1 with the SIMC tuning rule is employed as the comparison group. The experimental results are shown in Figure 21−23. It can be seen that the proposed method improves the performance for the set-point tracking and disturbance rejection responses. It performs a quick response and reaches the desired value smoothly. It is shown that the bulb works quickly at the beginning and the light is red in Figure 23b. Then, the output of the controller u_2 declines because of the input resetting action and the LED is active gradually in Figure 23c. Finally, the red light becomes weak enough and the white light dominates the output of the system in Figure 23d. The set-point tracking response would be achieved and the effect of both the input and the output load

Table 3. Performance Indices for Example 2

	processes:	servo-control response			input DR			output DR		
methods	indexes:	OS	ST	IAE	ME	ST	IAE	ME	ST	IAE
proposed		6%	**41.16 s**	**30.99**	**46%**	**97.8 s**	**26.21**	100%	**9.5 s**	**21.68**
PI-P tuning		**0%**	97.40 s	33.65	55%	364 s	89.96	100%	179 s	29.71

DOI: 10.1021/acs.iecr.7b05047
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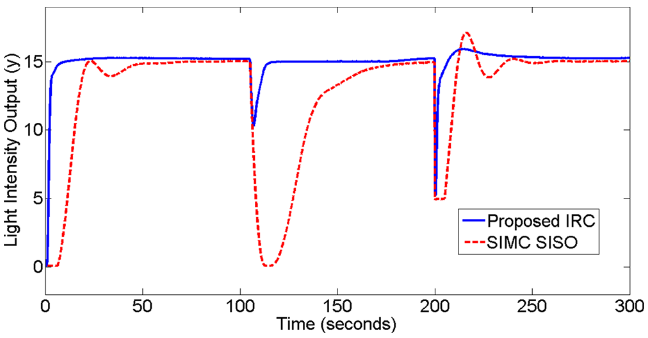

Figure 21. Measurement sensor output for the light intensity control experiment.

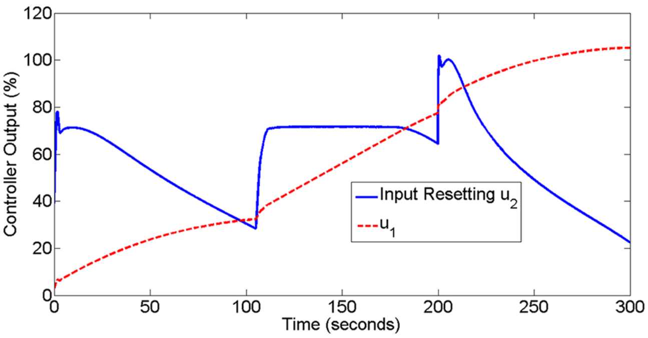

Figure 22. Outputs of the controllers for the light intensity control experiment.

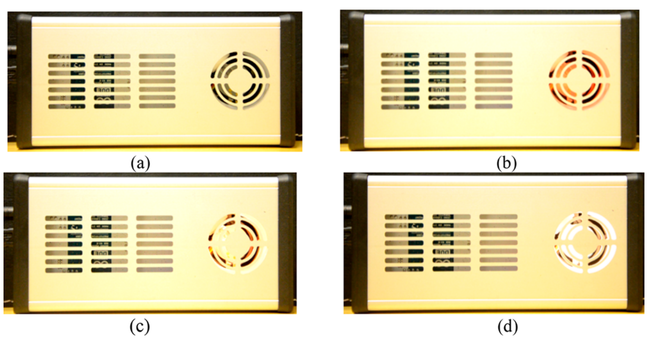

Figure 23. Performance of the light intensity control experiment: (a) t = 0 s, (b) t = 15 s, (c) t = 70 s, and (d) t = 90 s.

disturbance would be asymptotically eliminated. The closed-loop system has no steady status error with the desired input resetting value.

5. CONCLUSIONS

This paper has studied the cascade IRC problem for FOPTD processes. With the considered TISO control structure, double PI controllers have been analytically formulated. Since the final result is an effective extension of the SIMC tuning rule, an important merit of it is also acquired for the cascade IRC structure that controllers are with simple forms and result in satisfactory closed-loop behaviors. Simulation and experiment results show that the proposed controllers have also yielded good disturbance rejection responses for both input and output disturbances in terms of IAE index with a compromise of somewhat large overshoots.

Finally, as revealed by the analysis, aiming to improve the performance for high-order time delay processes and further extend the presented method to integrating and unstable processes is the next research interest.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This paper is partly supported by the National Natural Science Foundation of China under Grants 61473183 and U1509211. The work was finished at NTNU in Norway and the first author also would like to thanks for the financial support from China Scholarship Council (CSC NO. 201406230165).

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DOI: 10.1021/acs.iecr.7b05047
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