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Enhanced IMC-based Load Disturbance Rejection Design for Integrating Processes with Slow Dynamics

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Abstract: By revealing the deficiency of existing internal model control (IMC) based methods for load disturbance rejection for integrating processes with slow dynamics, a modified IMC design is proposed to deal with step or ramp type load disturbance as often encountered in practice. The controller parametrization is based on a two-degree-of-freedom (2DOF) control structure which allows for independent regulation of load disturbance rejection from the setpoint tracking. Analytical controller formulae are given based on classification of the ways by which such load disturbance seeps into the process. It is an obvious merit that there is only a single adjustable parameter in the controller design, which in essence corresponds to the time constant of the closed-loop transfer function for load disturbance rejection, and can be monotonically tuned to meet a trade-off between disturbance rejection performance and closed-loop robust stability. Robust tuning constraints are given correspondingly to accommodate for process uncertainties. An illustrative example is given to show the effectiveness and merits of the proposed method.

Keywords: Integrating process, internal model control (IMC), load disturbance rejection, slow dynamics, asymptotic tracking, robust stability.

1. INTRODUCTION

Integrating processes are difficult to be manipulated in engineering practices, e.g., heating-up sections of various industrial reactor tanks and distillation columns, due to the fact that a balance relationship between the input and the output of such a process may be easily destroyed by load disturbance. In addition, time delay is usually associated with practical applications, which brings more challenge to effective control of integrating processes (Huzmezana et al, 2002). It has been widely recognized that if the conventional unity feedback control structure is used, the water-bed effect between the setpoint response and the load disturbance response is unavoidably severe for integrating and unstable plants (Zhou, Doyle, and Glover, 1995). A number of two-degree-of-freedom (2DOF) control schemes have therefore been developed in recent years for independent regulation of setpoint tracking and load disturbance rejection. By using the Smith predictor (SP), Tian and Gao (1999) demonstrated that a double-controller scheme can significantly improve system capacity of load disturbance rejection for chemical integrating processes with dominant time delay. Further enhanced SP schemes can be seen in the recent references (Kwak, Whan, and Lee, 2001; Chien, Peng, and Liu, 2002; Hang, Wang, and Yang, 2003; Normey-Rico and Camacho, 2002, 2009; Liu et al, 2005; Zhang, Gu, and Rieber, 2008). Owing to that the standard SP control structure is in essence equivalent to the internal model control (IMC) structure for time delay processes (Morari and Zafiriou, 1989), Kaya (2004) proposed an alternative 2DOF IMC scheme in terms of user-specified gain and phase-margin specifications. By comparison, a few papers (Torrico and Normey-Rico, 2005; Garcia and Albertos, 2008) recently presented discrete-time domain 2DOF control methods for advanced regulation of integrating processes. With a focus on closed-loop performance for disturbance rejection in the framework of the unity feedback control structure, IMC-based PID tuning methods have been elaborated in the recent references (Lee et al, 1998; Wang and Yang, 2001; Skogestad, 2003; Lee and Edgar, 2004; Jose, Rosendo, and Alejandra, 2004; Shamsuzzoha and Lee, 2007). Visioli (2001) developed an optimization algorithm for PID tuning in terms of the integral-time-squared-error (ITSE) criterion. Wang and Cai (2002) gave another PID tuning method for disturbance rejection based on using expected closed-loop gain and phase margin specifications.

Note that most of existing IMC-based methods as aforementioned for load disturbance rejection have been devoted to optimizing the closed-loop sensitivity function, $S = 1 - T_r$, where T_r denotes the closed-loop transfer function, based on the H_2 optimal performance objective, $\min \|e\|_2^2 = \min \|(1 - T_r)/s\|_2^2$. For an integrating process, an additional asymptotic tracking constraint of $\lim_{s \to 0} dS/ds = 0$ is required for controller design to reject a step type load disturbance that seeps into the process at its input side (Morari and Zafiriou, 1989). However, for an integrating process with slow dynamics, that is, the process transfer function, G, has slow pole(s), it can be seen from the load disturbance transfer function, $H_d = GS$, that the load disturbance response is inevitably subject to a long 'tail', i.e., sluggish load disturbance suppression. So is for the presence of a deterministic load disturbance that seeps into the process with slow dynamics. A modified IMC filter design was proposed in the recent papers (Liu and Gao, 2008b, 2009b) to cope with this problem for stable processes with time delay, inspired by the early idea of Horn, Arulandu and Braatz (1996) for cancelling the slowest pole of a delay-free process. In view of that significant improvement for load disturbance rejection can thus be obtained, this paper extends the approach for integrating processes with time delay, based on a 2DOF control structure as introduced in Zhang et al (2004) and Liu et al (2005a, b). For the load disturbance types of step and ramp as often encountered in practice, modified IMC controller designs are proposed in terms of classification of the ways by which such load disturbance seeps into the process. It is therefore clarified that different IMC filter structures should be developed for controller design to reject different types of load disturbance that may result in steady output offset.

2. CONTROL STRUCTURE AND CLASSIFICATION OF LOAD DISTURBANCE

To allow for independent regulation of both setpoint tracking and load disturbance rejection, a 2DOF control structure is adopted to present the proposed controller design, which is shown in Fig.1,

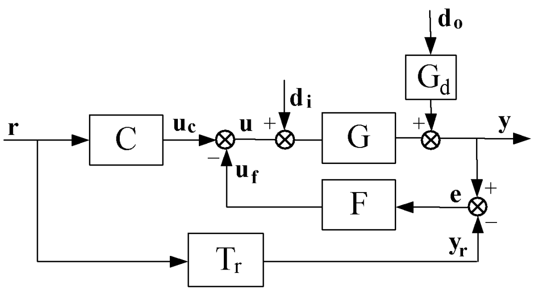

Fig. 1. Two-degree-of-freedom control structure

where G denotes the process, C the feedforward controller for setpoint tracking, F the feedback controller for load disturbance rejection, T_r the desired transfer function for setpoint tracking; r is the setpoint, y the process output, y_r the referential output, d_i load disturbance that seeps into the process at its input side, d_o load disturbance that seeps into the process at its output side with a transfer function, G_d. Note that the standard 2DOF IMC structure cannot guarantee internal stability of the closed-loop system for integrating processes (Morari and Zafiriou, 1989). The above control structure was originally proposed by Zhang et al (2004), and essentially, is equivalent to the 2DOF control structure given by Liu et al (2005a, b), as can be verified from the nominal transfer functions for setpoint tracking and load disturbance rejection.

Without loss of generality, an integrating process is described in the form of

$$G_m = \frac{k_p}{s(\tau_p s+1)} e^{-\theta s} \tag{1}$$

where k_p denotes the proportional gain, θ the process time delay, τ_p a time constant reflecting the inertial characteristics. It should be noted that the above model can effectively be used to represent a wide variety of higher-order integrating processes (Liu and Gao, 2008a).

Following the IMC-based controller design method for setpoint tracking given by Liu and Gao (2005a), the setpoint tracking controller can be derived using (1) as

$$C = \frac{s(\tau_p s+1)}{k_p(\lambda_c s+1)^2} \tag{2}$$

along with

$$T_r = \frac{1}{(\lambda_c s+1)^2} e^{-\theta s} \tag{3}$$

where λ_c is an adjustable parameter for setpoint tracking. Note that the above design can lead to the aforementioned H_2 optimal performance for the nominal case of $G = G_m$, corresponding to a smooth output response with no overshoot for step change of the setpoint.

Hence, the proposed controller design is herein concentrated on F for load disturbance rejection. Among different types of load disturbance, step or ramp type disturbance may result in steady offset of the process output, which is generally not allowed in practical applications. Note that unlike the case for a stable process, a step or ramp type load disturbance may result in apparently different response characteristics according to the ways by which the disturbance seeps into an integrating process. Also note that unlike stochastic disturbances, in many practical applications step or ramp type load disturbance can be elementally conjectured from the process mechanism or observed from the steady output error. For instant, temperature drop arising from the load disturbance of air convection in a heating barrel for injection molding (Liu, Yao and Gao, 2009a). From a practical view, the ways of such load disturbance seeping into an integrating process is herein classified as two for study, as shown in Fig.1, one from the process input side, and the other from the process output side with a transfer function,

$$G_d = \frac{k_d}{\tau_d s+1} \tag{4}$$

where k_d denotes the magnitude of such a deterministic load disturbance while the disturbance itself is normalized as the unity, and τ_d is a modeled time constant roughly reflecting the disturbance dynamics.

3. PROPOSED CONTROLLER DESIGN

3.1 Step Type Load Disturbance

It can be seen from Fig.1 that the transfer functions relating d_i and d_o to y can be derived respectively as

$$\frac{y_{di}}{d_i} = \frac{G}{1+GF} \tag{5}$$

$$\frac{y_{\mathrm{do}}}{d_{\mathrm{o}}}=\frac{G_{\mathrm{d}}}{1+GF} \quad (6)$$

Note that the complementary sensitivity function of the closed-loop structure between the process input and output can be formulated as

$$T_{\mathrm{d}}=\frac{GF}{1+GF} \quad (7)$$

which is actually equivalent to the transfer function from d_{i} to the controller output, u_{f}. Therefore, (5) and (6) can be rewritten as

$$\frac{y_{\mathrm{di}}}{d_{\mathrm{i}}}=G(1-T_{\mathrm{d}}) \quad (8)$$

$$\frac{y_{\mathrm{do}}}{d_{\mathrm{o}}}=G_{\mathrm{d}}(1-T_{\mathrm{d}}) \quad (9)$$

For an integrating process, as modeled in (1), it is easy to see that two asymptotic tracking constraints to reject a step type load disturbance occurring at the process input side are required as

$$\lim_{s\to 0}(1-T_{\mathrm{d}})=0 \quad (10)$$

$$\lim_{s\to 0}\frac{d}{ds}(1-T_{\mathrm{d}})=0 \quad (11)$$

Following the IMC-based design procedure given by Liu and Gao (2005a), a desired closed-loop transfer function for load disturbance rejection can be obtained as

$$T_{\mathrm{d\text{-}IMC}}=\frac{(3\lambda_{\mathrm{f}}+\theta)s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s} \quad (12)$$

where λ_{f} is an adjustable parameter for tuning closed-loop performance for disturbance rejection.

According to the nominal case of $G=G_{\mathrm{m}}$, the feedback controller can be inversely derived from (7) as

$$F=\frac{1}{G_{\mathrm{m}}}\cdot\frac{T_{\mathrm{d}}}{1-T_{\mathrm{d}}} \quad (13)$$

Substituting (12) into (13), we obtain the IMC-based controller form of

$$F_{\mathrm{IMC}}=\frac{s(\tau_{\mathrm{p}}s+1)[(3\lambda_{\mathrm{f}}+\theta)s+1]}{k_{\mathrm{p}}(\lambda_{\mathrm{f}}s+1)^3}\cdot\frac{1}{1-\dfrac{(3\lambda_{\mathrm{f}}+\theta)s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s}} \quad (14)$$

Note that the second multiplier in (14) satisfies

$$\lim_{s\to\infty}\frac{1}{1-\dfrac{(3\lambda_{\mathrm{f}}+\theta)s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s}}=1 \quad (15)$$

$$\lim_{s\to 0}\frac{s}{1-\dfrac{(3\lambda_{\mathrm{f}}+\theta)s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s}}=\infty \quad (16)$$

$$\lim_{s\to 0}\frac{s^2}{1-\dfrac{(3\lambda_{\mathrm{f}}+\theta)s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s}}=6\lambda_{\mathrm{f}}^2+6\lambda_{\mathrm{f}}\theta+\theta^2<\infty \quad (17)$$

which imply that this multiplier can be viewed as a special bi-proper integrator with a double zero at $s=0$. Note that it was analytically approximated together with the first multiplier into a PID form for implementation by Liu and Gao (2005a), by means of the mathematical Taylor series. In fact, it may be practically implemented using the closed-loop unit shown in Fig.2, such that no approximation error will be caused.

To reduce the influence arising from the slow dynamics of G or G_{d} to load disturbance response of y_{di} or y_{do}, it is ideal to eliminate the corresponding pole from the characteristic equation of (8) or (9). It is thus expected that $1-T_{\mathrm{d}}$ has the

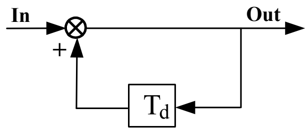

Fig. 2. Positive feedback control unit

corresponding zero to cancel the slow pole of G_{m} or G_{d}, such that the characteristic equation is governed only by the time constant of T_{d}. The numerator of $1-T_{\mathrm{d}}$, however, is unavoidably involved with time delay factor(s) for a time delay process, so it cannot be factorized to make exact zero-pole cancellation with the denominator of G_{m} or G_{d}. The following asymptotic constraint is therefore proposed to realize the above idea,

$$\lim_{s\to -1/\tau}(1-T_{\mathrm{d}})=0 \quad (18)$$

where $\tau=\tau_{\mathrm{p}}$ (or τ_{d}).

Hence, for an integrating process with slow dynamics, we propose a rectified closed-loop transfer function to reject a step type load disturbance occurring at the process input side,

$$T_{\mathrm{di\text{-}step}}=\frac{\eta_2 s^2+\eta_1 s+1}{(\lambda_{\mathrm{f}}s+1)^4}e^{-\theta s} \quad (19)$$

where η_1 and η_2 are used to satisfy the asymptotic constraints in (11) and (18).

Substituting (19) into (11) and (18), we obtain

$$\begin{cases}\eta_1=4\lambda_{\mathrm{f}}+\theta\\ \eta_2=\tau_{\mathrm{p}}\eta_1+\tau_{\mathrm{p}}^2[(\lambda_{\mathrm{f}}/\tau_{\mathrm{p}}-1)^4e^{-\theta/\tau_{\mathrm{p}}}-1]\end{cases} \quad (20)$$

Accordingly, substituting (19) into (13), we obtain the feedback controller,

$$F_{\mathrm{di\text{-}step}}=\frac{s(\tau_{\mathrm{p}}s+1)(\eta_2 s^2+\eta_1 s+1)}{k_{\mathrm{p}}(\lambda_{\mathrm{f}}s+1)^4}\cdot\frac{1}{1-\dfrac{\eta_2 s^2+\eta_1 s+1}{(\lambda_{\mathrm{f}}s+1)^4}e^{-\theta s}} \quad (21)$$

It is seen that there is essentially one adjustable parameter, λ_{f}, in the controller, which may be monotonically tuned to obtain desirable disturbance rejection performance.

To reject a step type load disturbance occurring at the process output side with a slow transfer function of G_{d}, we propose the closed-loop transfer function as

$$T_{\mathrm{do\text{-}step}}=\frac{\eta_1 s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s} \quad (22)$$

Substituting (22) into (18), we obtain

$$\eta_1=\tau_{\mathrm{d}}[(\lambda_{\mathrm{f}}/\tau_{\mathrm{d}}-1)^3e^{-\theta/\tau_{\mathrm{d}}}+1] \quad (23)$$

Substituting (22) and (23) into (13), we obtain

$$F_{\mathrm{do\text{-}step}}=\frac{s(\tau_{\mathrm{p}}s+1)(\eta_1 s+1)}{k_{\mathrm{p}}(\lambda_{\mathrm{f}}s+1)^3}\cdot\frac{1}{1-\dfrac{\eta_1 s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-\theta s}} \quad (24)$$

3.2 Ramp Type Load Disturbance

To reject a ramp type load disturbance occurring at the process input side, which may be described in the form of a double integrator, an additional asymptotic constraint along with (10) and (11) to guarantee no steady offset of the process output is required accordingly as

$$\lim_{s\to 0}\frac{d^2}{ds^2}(1-T_{\mathrm{d}})=0 \tag{25}$$

Hence, for an integrating process with slow dynamics, we propose the closed-loop transfer function as

$$T_{\text{di-ramp}}=\frac{\eta_3 s^3+\eta_2 s^2+\eta_1 s+1}{(\lambda_{\mathrm{f}}s+1)^5}e^{-\theta s} \tag{26}$$

Substituting (26) into (11), (25) and (18), we obtain

$$\begin{cases}\eta_1=5\lambda_{\mathrm{f}}+\theta\\ \eta_2=(5\lambda_{\mathrm{f}}+\theta)\eta_1-5\lambda_{\mathrm{f}}\theta-15\lambda_{\mathrm{f}}^2-\theta^2/2\\ \eta_3=\tau_{\mathrm{p}}\eta_2-\tau_{\mathrm{p}}^2\eta_1+\tau_{\mathrm{p}}^3[(\lambda_{\mathrm{f}}/\tau_{\mathrm{p}}-1)^5e^{-\theta/\tau_{\mathrm{p}}}+1]\end{cases} \tag{27}$$

Substituting (26) and (27) into (13), we obtain the feedback controller,

$$F_{\text{di-ramp}}=\frac{s(\tau_{\mathrm{p}}s+1)(\eta_3 s^3+\eta_2 s^2+\eta_1 s+1)}{k_{\mathrm{p}}(\lambda_{\mathrm{f}}s+1)^5}\cdot\frac{1}{1-\dfrac{\eta_3 s^3+\eta_2 s^2+\eta_1 s+1}{(\lambda_{\mathrm{f}}s+1)^5}e^{-\theta s}} \tag{28}$$

For the case of rejecting a ramp type load disturbance occurring at the process output side with a slow transfer function of G_{d}, it is similar to the case for rejecting a step type load disturbance occurring at the process input side. The controller formulae of (20) and (21) can be correspondingly adopted, except for that τ_{p} should be substituted by τ_{d} in (20) for computation.

4. ROBUST TUNING CONSTRAINTS

For analysis simplicity, it is practical to lump multiple sources of process uncertainty into a multiplicative form to treat with (Skogestad and Postlethwaite, 2005). According to the standard $M-\Delta$ structure for robustness analysis (Zhou, Doyle and Glover, 1995), the transfer function connecting the input and output of the multiplicative uncertainty can be derived in terms of the closed-loop structure between the process input and output as shown in Fig.1, which is exactly equivalent to the closed-loop complementary sensitivity function, T_{d}. Hence, it follows from the small gain theorem that the perturbed closed-loop structure with the multiplicative uncertainty hold robust stability if and only if

$$\|T_{\mathrm{d}}\|_\infty<\frac{1}{\|\Delta\|_\infty} \tag{29}$$

where $\Delta=(G-G_{\mathrm{m}})/G_{\mathrm{m}}$ denotes the process multiplicative uncertainty. Note that for a single-input-single-output (SISO) system, there exist $\|T_{\mathrm{d}}\|_\infty=\sup(|T_{\mathrm{d}}(j\omega)|)$ and $\|\Delta\|_\infty=\sup(|\Delta(j\omega)|)$, $\forall\omega\in[0,+\infty)$. Denote $|\Delta|_{\mathrm{m}}=\sup(|\Delta(j\omega)|)$ hereafter for simplicity.

Substituting (19) into (29), we obtain a closed-loop tuning constraint for rejecting a step type load disturbance occurring at the process input side as

$$\frac{(\lambda_{\mathrm{f}}^2\omega^2+1)^2}{\sqrt{(\eta_2\omega^2-1)^2+\eta_1^2\omega^2}}>|\Delta|_{\mathrm{m}} \tag{30}$$

Substituting (22) into (29), we obtain a closed-loop tuning constraint for rejecting a step type load disturbance occurring at the process output side as

$$\frac{(\lambda_{\mathrm{f}}^2\omega^2+1)^{3/2}}{\sqrt{\eta_1^2\omega^2+1}}>|\Delta|_{\mathrm{m}} \tag{31}$$

Substituting (26) into (29), we obtain a closed-loop tuning constraint for rejecting a ramp type load disturbance occurring at the process input side as

$$\frac{(\lambda_{\mathrm{f}}^2\omega^2+1)^{5/2}}{\sqrt{(\eta_3\omega^3-\eta_1\omega)^2+(\eta_2\omega^2-1)^2}}>|\Delta|_{\mathrm{m}} \tag{32}$$

Note that a closed-loop tuning constraint for rejecting a ramp type load disturbance occurring at the process output side is the same as that for rejecting a step type load disturbance occurring at the process input side as shown in (30), except for that τ_{p} should be substituted by τ_{d} when using (20) for computation.

Hence, given a specified upper bound of $|\Delta|_{\mathrm{m}}$ in practice, the admissible tuning range of λ_{f} in F can be graphically determined by checking the magnitude plots of the above tuning constraints, respectively. Owing to that λ_{f} is the only time constant of the closed-loop structure as shown in Fig.1 for load disturbance rejection, tuning λ_{f} to a small value will result in a faster load disturbance response, but at the risk of closed-loop robust stability in the presence of the process uncertainties. In the opposite, increasing λ_{f} to a large value will improve the closed-loop robust stability, but at the cost of slower load disturbance response. Therefore, by monotonically varying λ_{f} in the process operation, a good trade-off between disturbance rejection performance and the closed-loop robust stability can be conveniently obtained.

5. ILLUSTRATION

Consider an integrating process recently studied by Normey-Rico and Camacho (2009),

$$G=\frac{0.1e^{-5s}}{s(5s+1)}$$

The IMC-based design method (Liu et al, 2005a) gives the feedforward and feedback controllers shown in Fig.1 as

$$C=\frac{s(5s+1)}{0.1(\lambda_{\mathrm{c}}s+1)^2}$$

$$F_{\mathrm{IMC}}=\frac{s(5s+1)[(3\lambda_{\mathrm{f}}+5)s+1]}{0.1(\lambda_{\mathrm{f}}s+1)^3}\cdot\frac{1}{1-\dfrac{(3\lambda_{\mathrm{f}}+5)s+1}{(\lambda_{\mathrm{f}}s+1)^3}e^{-5s}}$$

Note that the second multiplier in F_{IMC} is herein implemented using the closed-loop unit shown in Fig.2 for simulation comparison.

Using the proposed method in this paper, the controller formulae of (20) and (21) for rejecting a step type load disturbance occurring at the process input side gives

$$F_{\text{di-step}} = \frac{s(5s+1)(\eta_2 s^2 + \eta_1 s + 1)}{0.1(\lambda_f s+1)^4} \cdot \frac{1}{1 - \dfrac{\eta_2 s^2 + \eta_1 s + 1}{(\lambda_f s+1)^4} e^{-5s}}$$

$\eta_1 = 4\lambda_f + 5$, $\eta_2 = 5\eta_1 + 9.197(0.2\lambda_f - 1)^4 - 25$

By adding a unity step change to the setpoint and to the process input at $t = 50$ (s), and taking $\lambda_c = 3$ and $\lambda_f = 3.6$ for comparison, we obtain the output responses shown in Fig.3.

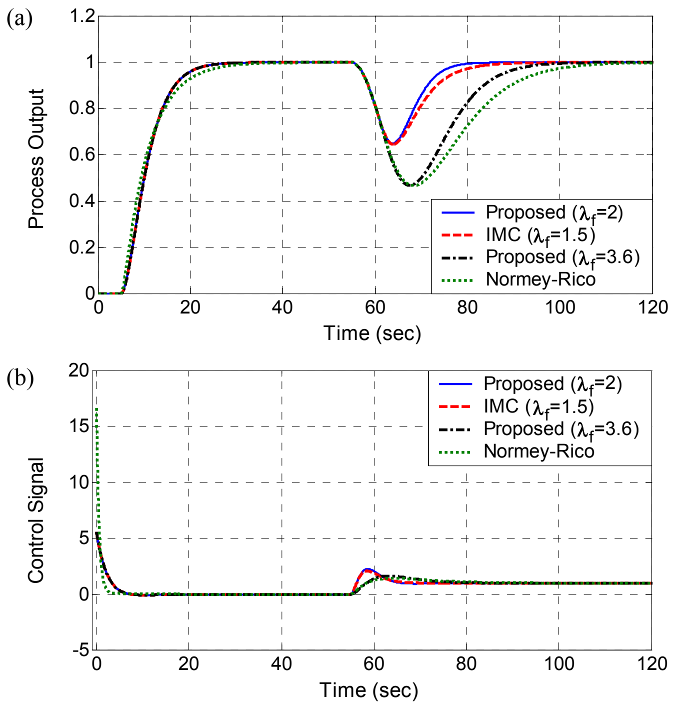

Fig. 3. Nominal output responses

It is seen that the load disturbance response is recovered more quickly by the proposed method, in terms of the similar setpoint tracking speed and the same magnitude of disturbance response peak. The IMC-based method given by Liu et al (2005a) results in a very close response with the proposed method when using the above control parameters. If $\lambda_f = 2$ is tuned to improve the load disturbance response, it is seen from Fig.3 that $\lambda_f = 1.5$ is needed by the IMC-based method (Liu et al, 2005a) to obtain the same disturbance response peak, but still with a longer recovery time.

Now assume that the process time constant is actually 30% larger. The perturbed output response is shown in Fig.4, indicating good robust stability of the proposed method.

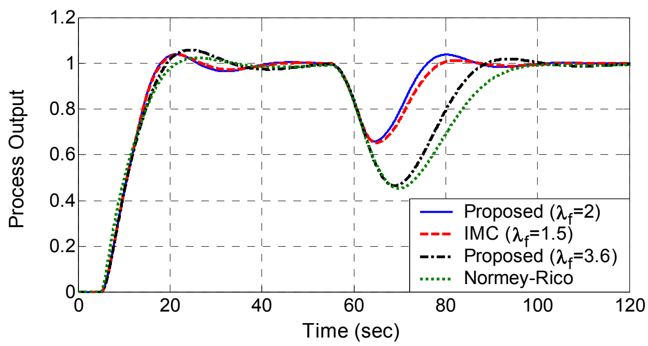

Fig. 4. Perturbed output responses

To demonstrate the achievable performance for rejecting load disturbance from the process output side with a slow dynamics, assume that the load disturbance transfer function is $G_d = 1/(10s+1)$, but is actually estimated with 20% error for control design, i.e., $\hat{G}_d = 1/(8s+1)$. The proposed controller formulae of (23) and (24) for such case gives

$$F_{\text{do-step}} = \frac{s(5s+1)(\eta_1 s + 1)}{0.1(\lambda_f s+1)^3} \cdot \frac{1}{1 - \dfrac{\eta_1 s + 1}{(\lambda_f s+1)^3} e^{-5s}}$$

$\eta_1 = 4.2821(0.125\lambda_f - 1)^3 + 8$

By adding a unity step change of the load disturbance at $t = 60$ (s), and taking $\lambda_f = 2$ for comparison, the results are shown in Fig.5.

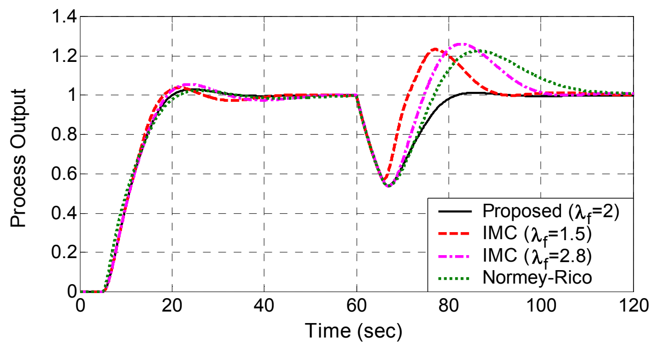

Fig. 5. Responses for a slow load disturbance at the output side

It is seen that apparently improved disturbance response is obtained by the proposed method, which demonstrates that based on assessment of the deterministic load disturbance characteristics, further enhanced disturbance rejection performance can therefore be obtained.

6. CONCLUSIONS

To overcome sluggish load disturbance rejection associated with integrating processes with slow dynamics, a modified IMC design for controller parametrization has been proposed based on a 2DOF control structure which allows for separate optimization of load disturbance rejection. For step or ramp type load disturbance as often encountered in practice, controller formulae have been analytically derived based on classification of the ways by which such load disturbance seeps into the process. Simulation comparisons have evidently demonstrated that the disturbance type based controller design can give noteworthy performance improvement for load disturbance rejection.

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