A reference-optimizing antiwindup control for input-constrained systems

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***Abstract*— Control limits due to saturation constraints may result in the directionality problem in addition to the controller windup effect. In solving the directionality problem, this paper explores the concept of modifying the reference signal to be an element of the maximal output admissible set of the closed-loop dynamics. This is achieved by an online constrained optimization of a tracking-related cost function associated with the closed-loop system. The design procedure for this reference-optimizing directional compensator is applicable to most existing antiwindup schemes. The effectiveness of the proposed control structure is demonstrated via simulation of benchmark case study examples.**

I. Introduction

All practical systems are inherently non-linear. Most commonly, the nonlinearities are as a result of saturation constraints and switching modes. This due to the fact that many industrial applications and processes are subject to hard physical constraints on their inputs. Examples include constraints on valve openings (0%-100%), limited speed of motors, and safety limits. These input constraints cause a mismatch between the controller output and the plant input which makes the feedback loop to run as open-loop. This mismatch leads to accumulation of a significant error that would then require errors of opposite sign for a long period before the feedback closed-loop is active and the controller action returns to normal. This undesired phenomenon, called the ”windup effect”, results in large transients, oscillating or unstable behaviour of the system.

In [2], a formal definition of anti-windup problem was given. An important aspect of this definition was that the recovery of linear performance (a concept also discussed in [3]) was stated in terms of non-linear $\mathcal{L}_2$ gains involving the unconstrained and actual response of the system [5]. Various anti-windup schemes (e.g. reset anti-windup, [4], [5]) can be considered as particular special cases of the unified coprime-factor framework put forward by Kothare et al [6]. The a posteriori design strategy of anti-windup control is a two-step approach in which a linear control design satisfying all nominal performance specifications is performed first, then an additional *anti-windup compensator* to the linear controller is designed to minimize the undesirable effects of windup which can occur during saturation [1].

In multivariable systems, due to directional change in the computed control vector, input-constrained systems may exhibit directionality issues in addition to standard “windup effects” [7]. The directionality problem is a performance degradation effect that is associated with input-constrained systems. The directional change in control signal leads to degradation of output performance. A more precise definition of directionality is given in [8] as:

> *“A process exhibits directionality when the saturated controller output $v(t)$ yields a process response that is not the ’closest’ (in the process output space) to the process response of unconstrained controller output $u(t)$”*

A common strategy to address the directionality problem in multivariable input-constrained systems is to insert an artificial nonlinearity (AN) before the saturation. As noted in [9], [10], direction preservation of the controller output $u(t)$ by scaling with factor σ (see σ below) is not necessarily optimal. Furthermore, the optimal active set of constraints might not necessarily preserve the direction of the controller output $u(t)$. The use of optimal *directionality compensators* have been reported to compensate for directionality by solving constrained optimization problems. In [8], [11], the objective cost is $\|(y^c-y)^{\mathrm{T}}\mathcal{Q}^{\mathrm{T}}\mathcal{Q}\,(y^c-y)\|$ where $y^c, y, \mathcal{Q}$ are the output response to the constrained plant input, the output response to the unconstrained plant input and a weighting matrix respectively.

The bottom line of the ideas in [8], [9], [11] involve defining the AN as a quadratic optimization

$$v^* = \arg\min_{v} \|\mathcal{T}v - \mathcal{F}u\|^2_{\mathcal{Q}^{\mathrm{T}}\mathcal{Q}} \,:\, v_{min} \leq v \leq v_{max} \qquad (1)$$

so that the saturation nonlinearity is never active,

- Clipping: $\mathcal{T} = I_n,\ \mathcal{F} = I_n$
- Soroush et al [8]: $\mathcal{T} = \mathcal{F} = \mathcal{PC}$
- Direction Preservation [9]: $\begin{cases} \mathcal{T} = I_n,\ \mathcal{F} = I_n & \text{if } v_{min} \leq u_i \leq v_{max} \\ \mathcal{T} = I_n,\ \mathcal{F} = \sigma I_n & \text{if otherwise} \end{cases}$
- Heath et al [11]: $\mathcal{T} = \mathcal{F} = \mathcal{K}_p$

where $\sigma = \min_i |\frac{sat(u_i)}{u_i}|$, $sat(\cdot) = \min\left(v_{max}\,, \max(v_{min}, \cdot)\right)$ $\mathcal{P}$ is a diagonal matrix whose diagonal elements depend on the relative orders of the controlled outputs, $\mathcal{K}_p$ is the steady-state gain, and $\mathcal{C}$ is the characteristics matrix of the plant that defines the plant’s behaviour over a short time horizon.

Another approach is to modify the reference signal in such a way that the closed loop system does not violate the plant input constraints [12]–[14]. In the reference optimization approach presented in [15], the effect of the directional change in control on the process output can be interpreted as the performance degradation of the output when the modified set-point is used instead of the original set-point. In other

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words, as shown in [15], the directional change in the set-point is an indication of the output performance degradation.

In this paper, the control design of *reference-optimizing directionality compensators* in the framework of internal model control (IMC) is considered. The design procedure is formulated as a constrained optimization problem whose solution is a realizable reference trajectory. Section III presents an overview of the realizable reference optimization problem and discusses how it differs from the concept of achievable steady-state optimization. In Section IV, the modified IMC anti-windup (MIA) framework of [4] is used to develop the theoretic framework of realizable references, while Section V illustrates the performance of the proposed control structure through three benchmark examples. Finally, the conclusions are summarized in Section VI of the paper.

II. Notation

Let $\mathcal{U}(=\mathbb{R}^n)$ be the space of all control signals and $\mathcal{D}_u$ be the domain of all admissible control signals. Thus, any calculated control signal $u(t) \in \mathcal{U}$ is mapped to $\mathcal{D}_u$ by the input constraints of the plant $G(s)$. Let $T(s)$ denote the combined closed-loop dynamics of the plant and a stabilizing controller. Define the maximal output admissible set $\mathcal{O}_\infty$ [16] of $T(s)$ as the set of all initial states x_0 and reference inputs $\bar{r}$ such that, if the constant input $\bar{r}$ is applied to the system, the response y satisfies the output constraints,

$$\mathcal{O}_\infty = \left\{ \left(x_0, \bar{r}\right) \;:\; y\left(x_0, \bar{r}\right) \in Y \subset \mathbb{R}^n, \;\; \forall t \geq 0 \right\}.$$

Typically, by an appropriate choice of matrices C and D and a set Y, all constraints such as plant input constraints may be summarized by a single set inclusion [17],

$$Cx(t) + Du(t) \in Y. \tag{2}$$

Subsequently, for brevity sake, signal dependence on t is omitted but implied.

III. Realizable Reference Optimization

The use of set-point filters to modify the reference signal so as to meet some system performance criteria had been introduced in the context of two degree-of-freedom (DOF) control structures [18]–[20], and set-point trajectories in the context of model predictive control (MPC) [21]. This section expatiates on the concept of solving an optimization problem to compute a modified reference signal as introduced by [22] in the context of anti-windup [15], [23], [24].

When $u \notin \mathcal{D}_u$, there is an inconsistency between the controller output u and the plant input v, that is, $u \neq v$. Then the optimal solution to the directionality problem reduces to finding the active set of constraints that yield a process response that is close in some sense to the process response of unconstrained controller output.

The basic idea of realizable reference optimization is to modify the set-point r with the aim of restoring the consistency between controller output and the plant input. The modified set-point, called realizable reference r_r, is such that if the realizable reference r_r had been applied to the system in Figure 2, then the saturation nonlinearity would not be active. Here, the objective cost is chosen as $\frac{1}{2}\|(r^r - r)\|^2_{\mathcal{Q}^{\mathrm{T}}\mathcal{Q}}$ where r^r, r, $\mathcal{Q}$ are the realizable reference, actual reference and a weighting matrix respectively. The matrix $\mathcal{Q}$ is chosen such that the elements of matrix $\mathcal{Q}$ and $\mathcal{Q}^{\mathrm{T}}\mathcal{Q}$ have the same sign as that of the steady-state matrix.

Remark 1. *In the context of secondary-level control, the achievable steady-state optimization recently reported by the authors of [25], [30] seeks an optimal steady-state reference r^*_{ss} that should be applied in Figure 2 instead of the actual reference r such that the steady-state output response y_{ss} is as close as possible to r subject to only the plant input satisfying $v \in \mathcal{D}_u$. That is,*

$$r^*_{ss} = \arg\min_{y_{ss}} \|y_{ss} - r\|^2_{\mathcal{Q}^{\mathrm{T}}\mathcal{Q}} \tag{3}$$

subject to steady-state input (v_{ss}) constraints of the plant.

In contrast, it is noted that the realizable reference optimization seeks an optimal feasible reference r^*_r such that r^*_r is close in some sense to r subject to the control signals satisfying $v = u_r \in \mathcal{D}_u$. Consequently, the realizable reference optimization concept is clearly distinct and independent from the achievable steady-state optimization concept.

The achievable steady-state optimization concept is more relevant in hierarchical supervisory control [26], [27]. The achievable steady-state targets r^*_{ss} do not coincide with the actual reference r if and only if the actual reference is such that $\{x_0, r\} \notin \mathcal{O}_\infty$ in steady-state. In these situations, one has to make structural changes to the plant input constraints for the control problem to be well-posed [10].

In the next Section, the modified IMC anti-windup (MIA) framework of [4] is used to develop a proposed directionality compensator using the theoretic framework of optimal realizable references.

IV. Proposed Control Structure

A. Internal Model Control (IMC)

The standard internal model control (IMC) is a model-based linear controller design structure introduced by [28] as shown in Figure 1 where $Q(s)$, $G(s)$ and $\tilde{G}(s)$ denote the IMC controller, the plant and the plant model respectively.

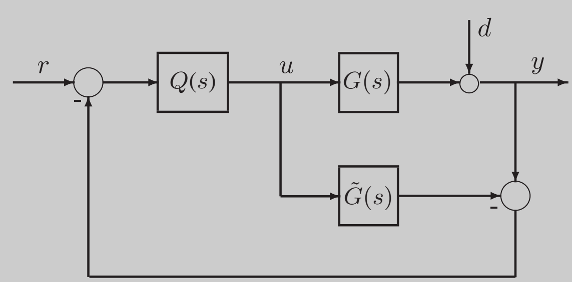


Fig. 1. Internal Model Control (IMC)

With the assumption of perfect model i.e. $G(s) = \tilde{G}(s)$, the stability of $G(s)$ and $Q(s)$ guarantees nominal stability of the unsaturated closed loop system [28] which makes the IMC structure attractive for anti-windup designs. The modified IMC structure [4] in Figure 2 was presented as an anti-windup scheme to deal with undesirable effects associated with the standard IMC structure in event of a saturation.

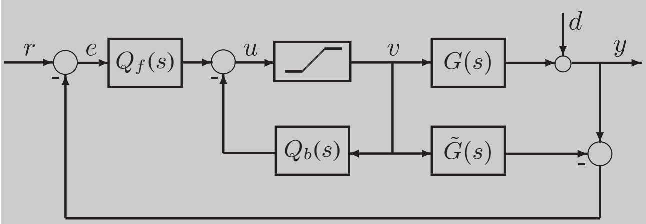


Fig. 2. Modified IMC Antiwindup (MIA)

Here, the IMC controller $Q(s)$ is factorized as:

$$Q(s) = (\mathrm{I} + Q_b(s))^{-1} Q_f(s), \tag{4}$$

where $Q(s)$ is assumed bi-proper minimum-phase stable and therefore $Q_f(s)$ is minimum-phase stable to guarantee internal stability of the closed-loop system. Consequently, $Q_b(s)$ is strictly proper and ensures that Figure 2 is free of algebraic loops. The choice of $[Q_f(s),\, Q_b(s)]$ as $[Q(s),\, 0]$ corresponds to standard IMC: $\min_v |u - v|_1)$ while $[Q(\infty),\, Q(\infty)Q(s)^{-1} - \mathrm{I}]$ corresponds to Hanus' conditioning technique: $\min_v |Q_f(e - e')|_1$, where $e' = Q^{-1} * v$.

Suppose the plant model $\tilde{G}(s)$ can be factorized as $\tilde{G}_+(s)\tilde{G}_-(s)$ where $\tilde{G}_+(s)$ contain time delays and unstable zeros of $\tilde{G}(s)$ while $\tilde{G}_-(s)$ has a realizable stable inverse, see [29, §12.2.2]. In addition, it is required that $\tilde{G}_+(0) = 1$. A suitable choice of $Q_f(s)$ and $Q_b(s)$ [4] is

$$Q_f(s) = F_A(s)\tilde{G}(s)Q(s) \tag{5}$$
$$Q_b(s) = F_A(s)\tilde{G}(s) - I \tag{6}$$

where the non-causal diagonal filter $F_A(s)$ is chosen such that $\lim_{s\to\infty} [F_A(s)\tilde{G}(s)] = I$. The IMC controller is given by,

$$Q(s) = \tilde{G}_-(s)^{-1} F(s) \tag{7}$$

where the IMC filter $F(s)$ is

$$F(s) = \mathrm{diag}\left(\frac{1}{(\lambda_i s + 1)^p}\right),\ i = 1 \cdots n \tag{8}$$

and p is is selected such that $Q(s)$ is biproper. The speed of response can be improved by choosing the parameter λ_i so as to minimize some weighted sensitivity functions. In addition, the adjustable parameter λ_i provides the tradeoff between performance and robustness to model inaccuracies.

B. Reference-Optimizing IMC Antiwindup Control

The proposed control structure incorporates the reference optimization concept discussed in § III into the modified IMC anti-windup of Figure 2. Assume no plant-model mismatch in Figure 2, i.e. $G(s) = \tilde{G}(s)$, then the plant input v is related to the actual controller-output u by:

$$u = \begin{bmatrix} C_f & -C_b \end{bmatrix} \begin{bmatrix} x \\ q \end{bmatrix} + \begin{bmatrix} D_f & -D_b \end{bmatrix} \begin{bmatrix} (r-d) \\ v \end{bmatrix}, \tag{9}$$

where C_f, D_f, x and C_b, D_b, q are the state-space matrices and states of $Q_f(s)$ and $Q_b(s)$ respectively. For the same states $[x,\, q]$, the realizable reference concept assumes that there exists a realizable reference r_r such that there is consistency between the realizable controller-output u_r and the plant input v (i.e. $v = u_r$). Therefore, from Figure 2,

$$u_r = \begin{bmatrix} C_f & -C_b \end{bmatrix} \begin{bmatrix} x \\ q \end{bmatrix} + \begin{bmatrix} D_f & -D_b \end{bmatrix} \begin{bmatrix} (r_r-d) \\ v \end{bmatrix}. \tag{10}$$

It then follows from (9) and (10) that,

$$u_r = D_f(r_r - r) + u. \tag{11}$$

Now, the controller's state equation evolves with $\{r_r, x_r, q_r\}$, and the controller output originally given by (9) is redefined to also evolve with r_r as follows.

$$u = \begin{bmatrix} C_f & -C_b \end{bmatrix} \begin{bmatrix} x_r \\ q_r \end{bmatrix} + \begin{bmatrix} D_f & -D_b \end{bmatrix} \begin{bmatrix} (r_r-d) \\ v \end{bmatrix}. \tag{12}$$

Hence, the controller dynamics remains the same but with an input r_r satisfying (11) as shown in Figure 3.

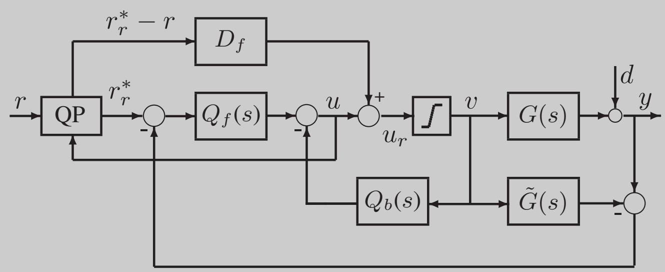


Fig. 3. Reference-Optimizing IMC Antiwindup, $v = u_r$.

The minimization of the cost function $\frac{1}{2}\|(r_r - r)\|^2_{\mathcal{Q}^{\mathrm{T}}\mathcal{Q}}$ can then be expressed as a quadratic programming (QP):

$$r_r^* = \arg\min_{r_r} \frac{1}{2} r_r^T \mathcal{Q}^T \mathcal{Q} r_r + f^T r_r \,:\, v_{min} \le u_r \le v_{max} \tag{13}$$

where $f = -\mathcal{Q}^T\mathcal{Q}r$ and u_r is as given by (11). The optimization problem (13) aims to make r_r as close as possible to r while not violating the plant input constraints. Here, the weighting matrix $\mathcal{Q}$ is chosen as the steady-state gain of the plant i.e. $\mathcal{Q} = G(0)$, see § III. This choice allows the optimization to take into account the plant's steady-state characteristics while computing the optimal realizable reference r_r^*. The optimal controller output u_r^* that ensures consistency ($v = u_r$) can then be obtained from (11) as

$$u_r^* = D_f(r_r^* - r) + u. \tag{14}$$

Remark 2. *It is noted that, unlike [23], the controller output equation* (12) *also evolves with r_r in the above formulation. Consequently a key advantage of this formulation is that the designed directional compensator can easily be plugged into an existing controller with little or no modification to that existing controller.*

V. CASE STUDY EXAMPLES

In this section, the performance of the proposed reference-optimizing IMC antiwindup control (see Figure 3) is demonstrated via simulation of three benchmark examples. Its' performance is compared with those of the *directionality compensators* of [8] and [30] as listed below,

- MIA [4]
- TMIA [25], [30] with $\mathcal{Q} = I_n$[1]
- Souroush et al [8] with $\mathcal{Q} = \mathcal{K}_p = G(0)$
- Proposed Compensator, with $\mathcal{Q} = \mathcal{K}_p = G(0)$.

The *quadprog* solver in MATLAB-SIMULINK was used to solve the quadratic programming (QP).

Example 1 [4]. Consider the following plant,

$$G(s) = \frac{10}{100s+1}\begin{bmatrix} 4 & -5 \\ -3 & 4 \end{bmatrix} \quad (15)$$

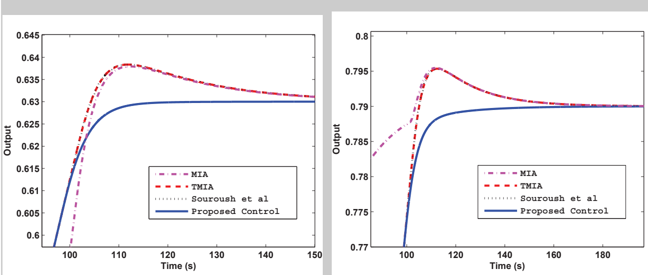
with $|u_i| \leq 1,\ i = 1,2$ and a set-point change of $[0.63, 0.79]^T$. The standard IMC controller for a step input is designed as,

$$Q(s) = \frac{100s+1}{10(20s+1)}\begin{bmatrix} 4 & 5 \\ 3 & 4 \end{bmatrix}. \quad (16)$$

Following the development in § IV.A, the factorization of the IMC controller $Q(s)$ is obtained using (5) and (6), where

$$\tilde{G}(s) = \frac{10}{100s+1}\begin{bmatrix} 4 & \frac{-5}{0.1s+1} \\ \frac{-3}{0.1s+1} & 4 \end{bmatrix};\ F_A(s) = 2.5(s+1)I$$

The structural matrices are obtained as $\mathcal{K}_p = \begin{bmatrix} 40 & -50 \\ -30 & 40 \end{bmatrix}$, $\mathcal{C} = \begin{bmatrix} 0.4 & -0.5 \\ -0.3 & 0.4 \end{bmatrix}$ and $Q_f(\infty) = \begin{bmatrix} 2 & 2.5 \\ 1.5 & 2 \end{bmatrix}$.

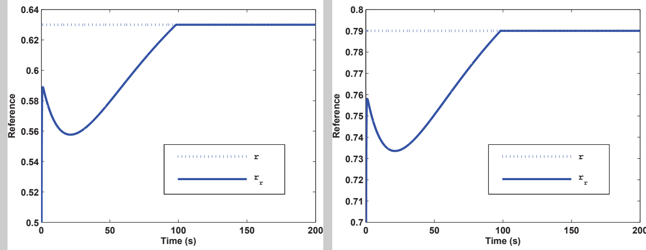


(a) Output Response y_1. (b) Output Response y_2.

Fig. 4. Output Responses of Example 1.

In this example, it can be observed from Figure 4 that the proposed compensator eliminates the overshoot inherent in the other directional compensators for both outputs y_1 and y_2. The plots in Figure 5 show the realizable reference signals computed by the proposed compensator.

[1] This yields same response as the "Souroush et al [8] with $\mathcal{Q} = I_n$" since the achievable steady-state is equivalent to the actual reference for well-posed control problems (see Remark 1).



(a) Reference Signals r_r^1, r^1. (b) Reference Signals r_r^2, r^2.

Fig. 5. Actual and Realizable Reference Signals of Example 1.

Example 2 [8]. Consider the plant, G(s), given by

$$\frac{1}{s^2+0.04s+0.0002}\begin{bmatrix} 0.25(s+0.03) & -0.0008 \\ -0.125 & 4(s+0.01) \end{bmatrix}$$

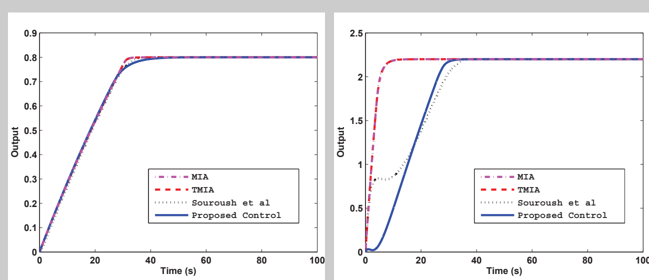
with $|u_i| \leq 0.12,\ i = 1,2$ and set-point change of $[0.8, 2.2]^T$. The standard IMC controller for a step input is designed as,

$$Q(s) = \begin{bmatrix} \frac{4s+0.04}{5s+1} & \frac{0.0008}{2s+1} \\ \frac{0.125}{5s+1} & \frac{0.25s+0.0075}{2s+1} \end{bmatrix}. \quad (17)$$

Following the development in § IV.A, the factorization of the IMC controller $Q(s)$ is obtained using (5) and (6), where

$$F_A(s) = \begin{bmatrix} 4(s+1) & 0 \\ 0 & 0.25(s+1) \end{bmatrix};\ \tilde{G}(s) = G(s). \quad (18)$$

The structural matrices are obtained as $\mathcal{K}_p = \begin{bmatrix} 37.5 & -4 \\ -625 & 200 \end{bmatrix}$, $\mathcal{C} = \begin{bmatrix} 0.25 & 0 \\ 0 & 4 \end{bmatrix}$ and $Q_f(\infty) = \begin{bmatrix} 0.8 & 0 \\ 0 & 0.125 \end{bmatrix}$.



(a) Output Response y_1. (b) Output Response y_2.

Fig. 6. Output Responses of Example 2.

In this example, it is observed from Figure 6 that all the responses are identical to the MIA response for output y_1. However, the performance of the proposed compensator performs slightly better than the "Souroush et al [8] with $\mathcal{Q} = G(0)$" for output y_2.

Example 3 [31]. The non-minimum phase plant in [31] is modified as a minimum-phase plant having complex poles and complex zeros. The modified plant, $G(s)$, is given by

$$G(s) = \begin{bmatrix} \frac{1.5}{63s+1} & \frac{1}{2s^2+s+1} \\ \frac{1}{5096s^2+147s+1} & \frac{1.6}{91s+1} \end{bmatrix} \quad (19)$$

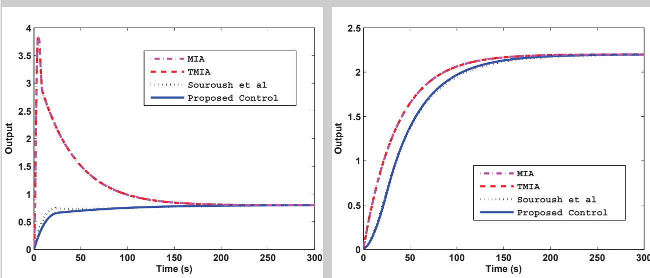
with $|u_i| \leq 7$, $i = 1, 2$ and set-point change of $[0.8, 2.2]^T$. The standard IMC controller for a step input is designed as,

$$\tilde{G}(s) = G(s)\,;\; Q(s) = \tilde{G}_{-}(s)^{-1}\begin{bmatrix}\dfrac{1}{54s+1} & 0\\ 0 & \dfrac{1}{36s+1}\end{bmatrix}.$$

Following the development in § IV.A, the factorization of the IMC controller $Q(s)$ is obtained using (5) and (6), where

$$F_A(s) = \begin{bmatrix}(63/1.5)s+1 & 0\\ 0 & (91/1.6)s+1\end{bmatrix}. \quad (20)$$

The structural matrices are obtained as $\mathcal{K}_p = \begin{bmatrix}1.5 & 1\\ 1 & 1.6\end{bmatrix}$, $\mathcal{C} = \begin{bmatrix}0.0238 & 0\\ 0 & 0.0176\end{bmatrix}$ and $Q_f(\infty) = \begin{bmatrix}0.7778 & 0\\ 0 & 1.5799\end{bmatrix}$.



(a) Output Response y_1. (b) Output Response y_2.

Fig. 7. Output Responses of Example 3.

In this example, it can be observed from Figure 7 that both the proposed compensator and "Souroush et al [8] with $\mathcal{Q} = G(0)$" yield similar responses in output y_1 and y_2. Furthermore, in output y_1, the proposed compensator eliminates the overshoot in the MIA and TMIA responses.

VI. Conclusion

A formulation of the reference-optimization concept has been presented. The computed realizable reference signals result in reference inputs that are elements of the maximal output admissible set of the plant. It has been demonstrated that the proposed control structure is effective in dealing with the directionality issues and the control windup encountered in constrained systems. A key advantage of this formulation is that the designed directional compensator can easily be plugged into an existing controller with little or no modification to that existing controller.

References

[1] S. Tarbouriech and M. Turner, "Anti-windup design: an overview of some recent advances and open problems," *IET Control Theory & Applications*, vol. 3(1), pp. 1–19, 2009.
[2] A. R. Teel and N. Kapoor, "The $\mathcal{L}_2$ anti-windup problem: Its definition and solution," in *Proceedings of the European Control Conference*, Brussels, Belgium, July 1997.
[3] S. Crawshaw and G. Vinnicombe, "Anti-windup synthesis for guaranteed $\mathcal{L}_2$ performance," in *Proceedings of the 39th IEEE Conference on Decision and Control*, Sydney, Australia, December 2000.
[4] A. Zheng, M. V. Kothare, and M. Morari, "Anti-windup design for internal model control," *International Journal of Control*, vol. 60, pp. 1015–1024, 1994.
[5] G. Grimm, J. Hatfield, A. Zheng, I. Postlethwaite, A. R. Teel, and L. Zaccarian "Antiwindup for stable linear systems with input saturation: An LMI-Based Synthesis," in *IEEE Transactions on Automatic Control*, vol. 48(9), pp. 1509–1525, 2003.
[6] M. Kothare, P. Campo, M. Morari, and C. Nett, "A unified framework for the anti-windup designs," *Automatica*, vol. 30, 1994.
[7] D. Horla, "On directional change and anti-windup compensation in multivariable control systems." *International Journal of Applied Mathematics & Computer Science*, vol. 19(2), pp. 281–289, 2009.
[8] M. Soroush and S. Valluri, "Optimal directionality compensation in processes with input saturation nonlinearities," *International Journal of Control*, vol. 72(17), pp. 1555–1564, 1999.
[9] P. J. Campo and M. Morari, "Robust control of processes subject to saturation nonlinearities," *Computers Chemical Engineering*, vol. 14(4), pp. 343–358, 1990.
[10] P. Hippe, "A solution to the problem of directionality for stable and unstable systems," in *Proceedings of the 6th IFAC Symposium on Nonlinear Control Systems (NOLCOS)*, Germany, September 2004.
[11] W. Heath and A. Wills, "Design of cross-directional controllers with optimal steady state performance," *European Journal of Control*, vol. 10(1), pp. 15–27, 2004.
[12] T. Sugie and H. Yamamoto, "Reference management for closed loop systems with state and control constraints," in *Proceedings of the 2001 American Control Conference*, Arlington, USA, June 2001.
[13] S. Oh-Hara and K. Hirata, "Experimental evaluation of on-line reference governors for constrained systems," in *SICE 2003 Annual Conference*, Fukui, Japan, August 2003.
[14] Y. Ohta, T. Taguchi, and T. Yamaguchi, "On-line reference inputs management for constrained servo systems," in *Proceedings of the Nonlinear Theory and its Applications*, Italy, September 2006.
[15] K. S. Walgama and J. Sternby, "Conditioning technique for multiinput-multioutput processes with input saturation," *IEE Proceedings on Control Theory and Applications*, vol. 140(4), pp. 231–242, 1993.
[16] E. Garone, S. D. Cairano, and I. Kolmanovsky, "Reference and command governors for systems with constraints: A survey on theory and applications," *Automatica*, vol. 75, pp. 306–328, 2017.
[17] E. G. Gilbert and K. T. Tan, "Linear systems with state and control constraints: the theory and application of maximal output admissible sets," *IEEE Transactions on Automatic Control*, vol. 36(9), Sept 1991.
[18] N. Itagaki, H. Nishimura, and K. Takagi, "Two-degree-of-freedom control system design in consideration of actuator saturation," *IEEE/ASME Transactions on Mechatronics*, vol. 13(4), pp. 470–475, August 2008.
[19] T. Hagglund, "Signal filtering in PID control," in *Proceedings of the 2nd IFAC Conference on Advances in PID Control*, Italy, July 2012.
[20] F. Padula and A. Visioli, "Set-point filter design for a two-degree-of-freedom fractional control system," *IEEE/CAA Journal of Automatica Sinica*, vol. 3(4), pp. 451–462, 2016.
[21] J. M. Maciejowski, *Predictive control with constraints*. Pearson Education Limited, First Edition, 2002.
[22] R. Hanus, M. Kinnaert, and J. L. Henrotte, "Conditioning technique, a general antiwindup and bumpless transfer method," *Automatica*, 1987.
[23] C.-Y. Chen and M.-H. Perng, "Generalized optimization-based conditioning technique for MIMO systems with input saturation," in *Proceedings of the 13th IFAC World Congress*, USA, July 1996.
[24] Y. Peng, D. Vrancic, R. Hanus, and S. S. R. Weller, "Anti-windup designs for multivariable controllers," *Automatica*, vol. 12, 1998.
[25] A. Adegbege and W. Heath, "Two-stage multivariable antiwindup design for internal model control," *Dynamics and Control of Process Systems*, Leuven, Belgium, July 2010.
[26] P. Tatjewski, "Supervisory predictive control and on-line set-point optimization," *Applied Mathematics and Computer Science*, vol. 20, 2010.
[27] P. Vega, S. Revollar, J. M. Martín, and M. Francisco, "Static and dynamic set point optimization techniques for optimal operation of wastewater treatment plants," in *European Control Conference (ECC)*, Zurich, Switzerland, July 2013.
[28] C. Garcia and M. Morari, "Internal model control I: A unifying review and some new results." *Ind. Eng. Chem. Process Des. Dev.*, 1982.
[29] D. E. Seborg, T. F. Edgar, D. A. Mellichamp, and F. J. Doyle III, *Process Dynamics and Control*. Wiley, Third Edition, 2010.
[30] A. A. Adegbege and W. P. Heath, "Internal model control design for input-constrained multivariable process," *American Institute of Chemical Engineers (AIChE) Journal*, vol. 57(12), 2011.
[31] P. Reddy, M. Pandit, and M. Chidambaram, "Comparison of multivariable controllers for non-minimum phase systems," *International Journal of Modelling and Simulation*, vol. 26(3), pp. 237–243, 2006.