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Continuous-Time Anti-Windup Generalized Predictive Control of an MIMO Boiler System

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***Abstract*— This paper deals with a continuous-time anti-windup generalized control to a multivariable boiler experimental system. Water temperature and water level of the experimental system need to be controlled, but the heater and water flow of the experimental system are limited, namely, the experimental system is a multivariable system with control input constraints. For this system, a multivariable continuous-time anti-windup generalized predictive controller is designed. The effectiveness of the proposed design scheme is confirmed by experiment.**

Index Terms- Constrainted control, Anti-windup, Generalized predictive control, Multi-input multi-output process experimental system.

I. Introduction

For real process control system, control input must deal with some constraints such as actuator output limitation. In this paper, we consider a control problem of multivariable boiler system with heater and water flow limitation. The merit of the proposed design scheme is explained as follows.

Multivariable continuous-time generalized predictive control (MCGPC) is a popular technique of process control [1]. However, this technique does not consider input constraints, so stability of the controller is not always guaranteed. Recently, a continuous-time anti-windup generalized control system design scheme for uncertain process with input constraints and time delay is designed by using coprime factorization [2], and the control system design for non-minimum phase processes with input constraints is also considered [3]. The above design schemes are obtained by using the results in [6], [7] and are extended to multivariable case with known parameters [4]. Most recently, based on the result in [4], a simulation study is shown for multivariable process control with input constraints [9]. However, the detailed design issues for real process control system has not been shown. In this paper, we introduce a modelling method of a boiler system which parameters of the system are estimated by extended Kalman filter [9]. Based on the above model, a multivariable continuous-time anti-windup generalized predictive controller (MCAGPC) is considered. Further, the proposed control scheme is applied to the boiler system.

II. Problem statement

The boiler system modelling based on extended Kalman filter is shown in Appendix. Based on the result, we consider the multivariable process as follows.

$$A(s)\underline{Y}(s) = B(s)\underline{U}(s) + C(s)\underline{V}(s) \tag{1}$$

Then, $\underline{Y}(s)$, $\underline{U}(s)$, $\underline{V}(s)$ are $p \times 1$ output, $p \times 1$ input, $p \times 1$ disturbance vectors. $B(s)$ is a $p \times p$ polynomial matrix, $A(s)$ and $C(s)$ are $p \times p$ diagonal polynomial matrix. The control inputs $u_j(t)$ has following constraint.

$$u_{min,j} \le u_j(t) \le u_{max,j} \tag{2}$$

$$\underline{u}(t) = \begin{pmatrix} \sigma(u_{11}(t)) \\ \vdots \\ \sigma(u_{1p}(t)) \end{pmatrix} \tag{3}$$

$$\sigma_j(v) = \begin{cases} u_{max,j} & if \quad v > u_{max,j} \\ v & if \quad u_{min,j} \le v \le u_{max,j} \\ u_{min,j} & if \quad v < u_{min,j} \end{cases} \tag{4}$$

The problem considered in this paper is to design a multivariable continuous-time anti-windup generalized predictive control system to the boiler system.

III. Multivariable continuous-time anti-windup generalized predictive control system design

The design of MCAGPC is based on [4], and it considers control input constraints. The proposed controller for the process with input constraints is given by the following Youla-Kucera parametrization.

$$\begin{aligned} R(s) &= (Y(s) - Q(s)\tilde{N}(s))^{-1}K(s) & (5)\\ U(s) &= X(s) + Q(s)\tilde{D}(s) & (6)\\ V(s) &= Y(s) - Q(s)\tilde{N}(s) & (7) \end{aligned}$$

where $Q \in RH_\infty$ is a design parameter matrix for ensuring a strongly stable feedback controller. RH_∞ is the whole of stable and proper real rational function.

$$RH_\infty = \{f(s) \in R(s) | \sup_{s \in C_{+e}} |f(s)| \le \infty\} \tag{8}$$

$X(s)$ and $Y(s)$ satisfy the following Bezout identify.

$$\tilde{N}(s)\tilde{X}(s) + \tilde{D}(s)\tilde{Y}(s) = I_p \tag{9}$$

$$X(s)N(s) + Y(s)D(s) = I_p \tag{10}$$

$$\tilde{X}(s), \tilde{Y}(s), X(s), Y(s) \in RH_\infty \tag{11}$$

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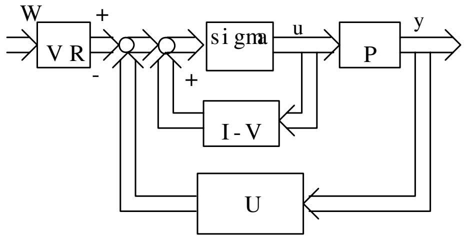

Fig. 1. The proposed MIMO control system

then, the coprime factorization presentation N(s) and D(s) of the process can be chosen as follows.

$$P(s) = N(s)D^{-1}(s) = \tilde{D}^{-1}(s)\tilde{N}(s) \tag{12}$$

Defining the stable closed-loop characteristic polynomial matrix of the system without input constraint as T(s), we chose N(s), D(s) as follows.

$$\tilde{N}(s) = T^{-1}(s)B(s) \tag{13}$$
$$\tilde{D}(s) = T^{-1}(s)A(s) \tag{14}$$

$$\begin{aligned} \tilde{T}(s) &= (I_p + K_e C_e(s)G(s))\tilde{A}(s) \\ &+ (K_e R_e + K_e C_e(s)F(s))\tilde{B}(s) \qquad (15) \\ T(s) &= A(s)(I_p + K_e C_e(s)G(s)) \\ &+ B(s)(K_e R_e + K_e C_e(s)F(s)) \qquad (16) \end{aligned}$$

X(s) and Y(s) are designed as follows.

$$X(s) = K_e R_e + K_e C_e(s)G(s)F(s) \tag{17}$$
$$Y(s) = I_p + K_e(s)C_e(s)G(s) \tag{18}$$
$$K(s) = K_e R_e \tag{19}$$

C_e(s), G(s) and F(s) are obtained as

$$C_e(s) = diag\left\{\frac{I_{N_y+1}}{C_1(s)}, \ldots, \frac{I_{N_y+1}}{C_p(s)}\right\} \tag{20}$$
$$G(s) = [G_1^T(s) \ldots G_p^T(s)] \tag{21}$$
$$G_i(s) = \begin{bmatrix} 0 & \ldots & 0 \\ G_{i11}(s) & \ldots & G_{ip1}(s) \\ \vdots & \ldots & \vdots \\ G_{i1N_{yi}}(s) & \ldots & G_{ipN_{yi}}(s) \end{bmatrix} \tag{22}$$
$$F(s) = \begin{bmatrix} F_1(s) & & 0 \\ & \ddots & \\ 0 & & F_p(s) \end{bmatrix} \tag{23}$$
$$F_i(s) = [0F_{i1}(s) \ldots F_{iN_y}(s)] \tag{24}$$

N_y is predictor order, and G_i(s), F_i(s) are given by

$$\frac{s^k C_i(s)}{A_i(s)} = \frac{F_{ik}(s)}{A_i(s)} + E_{ik}(s) \tag{25}$$
$$\frac{E_{ik}(s)B_{ij}(s)}{C_i(s)} = \frac{G_{ij}(s)}{C_i(s)} + H_{ijk}(s) \tag{26}$$
$$(j = 1, \ldots, m) \tag{27}$$

K_e is the matrix form from the rows of the matrix K corresponding to the inputs $u_1(t), u_2(t), \ldots, u_p(t)$. R_e is the matrix form of the $\underline{r}_i = [r_{i0} \ldots r_{iN_{yi}}]^T$ and they are the Markov parameters of the transfer function $R_{ni}(s)/R_{di}(s)$ of the reference output.

$$K = (H^T T_y H + T_u)^{-1} H^T T_y \tag{28}$$
$$H = \begin{bmatrix} H_{11} & \ldots & H_{1p} \\ \vdots & \ldots & \vdots \\ H_{p1} & \ldots & H_{pp} \end{bmatrix} \tag{29}$$
$$H_{ij} = \begin{bmatrix} 0 & \ldots & \ldots & 0 \\ h_{ij1} & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ h_{ijN_{yi}} & \ldots & h_{ij1} & 0 \end{bmatrix} \tag{30}$$
$$T_y = diag\{T_{y1}, \ldots, T_{yp}\} \tag{31}$$
$$T_{yi} = \int_{T_{1i}}^{T_{2i}} \underline{T}_{N_{yi}}^T \underline{T}_{N_{yi}} dT \tag{32}$$
$$\underline{T}_{N_{yi}} = [1T \ldots (T^{N_{yi}/N_{yi}!})] \tag{33}$$
$$T_u = diag\{\lambda_1 T_{u1}, \ldots, \lambda_p T_{yp}\} \tag{34}$$
$$T_{uj} = \int_0^{T_{ci}} \underline{T}_{N_{uj}}^T \underline{T}_{N_{uj}} dT \tag{35}$$
$$\underline{T}_{N_{ui}} = [1T(T^2/2!) \ldots (T^{N_{uj}/N_{ui}!})] \tag{36}$$
$$R_e = \begin{bmatrix} \underline{r}_1 & & 0 \\ & \ddots & \\ 0 & & \underline{r}_p \end{bmatrix} \tag{37}$$

N_{uj}, T_{1i}, T_{2i}, T_{cj} are control horizon, minimum prediction horizons, maximum prediction horizons, control horizons.
Two design polynomial matrices U_n(s) and U_d(s) for Q(s) are selected for satisfying

$$Q(s) = U_d(s)^{-1} U_n(s) \tag{38}$$

Applying the controllers Q(s), R(s), U(s), V(s) to the process having constraints in input values, control performance can be improved. And Q(s) gives strongly stability to the system [2], [3]. When the process is with uncertainties, we can use the results in [2, 8] to design the control system so that the robust stability of the resulted control system is ensured.

IV. Experiment

Using the modeling method shown in Appendix, actual experiment for estimating boiler parameters is undertaken. The parameters in (1) are obtained by using the estimated parameters, where the estimated parameters are obtained by using extended Kalman filter (see Table 1) for Tank1's temperature and water level. Experiment using the proposed method is based on (1) with the estimated parameters. However, the obtained estimation parameters by extended Kalman filter are discrete-time system parameters, we must transform the parameters into continuous-time system parameters. The mean value of parameters is transformed into continuous-time equation parameters, and the parameters are used in the design of the proposed MCAGPC controller. A(s) and B(s) in (1) are estimated as the following equations.

Table 1: Extended Kalman filter	
Estimation init value	$\hat{Z_{t_0}} = 0$
Init estimation error covariance matrix	$p_{00} = [0]$
Input1(Heater)	u_1=1.125[KWH]
Input2(Inflow of water)	u_2=4.8[L/min]

$$
\begin{aligned}
A_{ii}(s) &= s^3 + 8.5s^2 + 31s + 20 \\
B_{11}(s) &= 0.12s^2 + 0.9s + 0.7 \\
B_{12}(s) &= 5.5 \times 10^{-8}s^2 + 3.8 \times 10^{-7}s - 3.9 \times 10^{-7} \\
B_{21}(s) &= -0.12s^2 - 0.84s + 0.86 \\
B_{22}(s) &= 4.8 \times 10^{-5}s^2 + 3.7 \times 10^{-4}s + 1.2 \times 10^{-3} \\
C_{ii}(s) &= 1.5s^2 + 9.65s + 15.5 \\
(i &= 1, 2)
\end{aligned}
$$

Design parameters of the proposed MCAGPC are displayed in the table below.

Table 2: MCAGPC	
Reference input 1	w_1=30[℃]
Reference input 2	w_2=40[cm]
Predictor order	N_y=2
Control horizon	N_u=1
Control weighting 1	λ_1=0.08
Control weighting 2	λ_2=0.1
Min. prediction horizon	T_1=0
Max. prediction horizon	T_2=9
Min. calorific value	0[KW]
Max. calorific value	3[KW]
Min. inflow water value	1[L/min]
Max. inflow water value	10[L/min]
Design parameters 1	u_{n1}=-1 u_{d1}= $s^3 + 17s^2 + 82s + 120$
Design parameters 2	u_{n2}=-1 u_{d2}= $s^3 + 17s^2 + 82s + 120$

Experimental results are shown in Figs. 2 and 3, In Fig. 2, maximum calorific value limitation and maximum inflow water value limitation are re-described by maximum current values. In the experiment, initial water temperature of Tank 1 is 27 [℃], initial water level of Tank 1 is 35 $[cm]$, and outside temperature of the boiler is 30 [℃]. Fig. 3 gives the desired trajectory, where the desired water temperature is 30 [℃] and the desired water level is 40 $[cm]$.

V. CONCLUSION

Multi-variable continuous-time anti-windup generalized predictive control system design of a boiler system was proposed. Experimental result confirmed the effectiveness of the proposed design scheme.

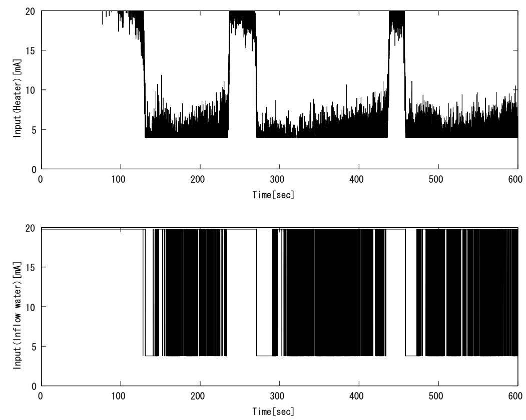

Fig. 2. Experimental results of control input with constraint

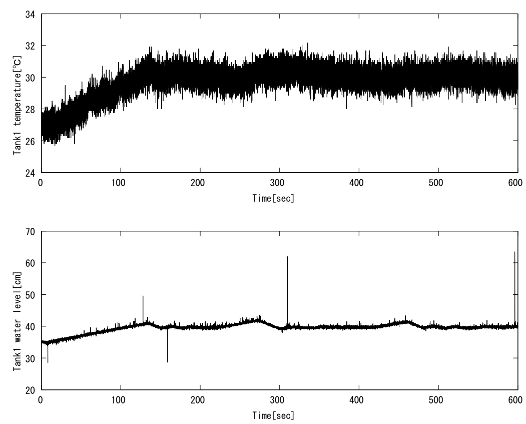

Fig. 3. Experimental results of process output

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Fig. 4. The boiler experimental system

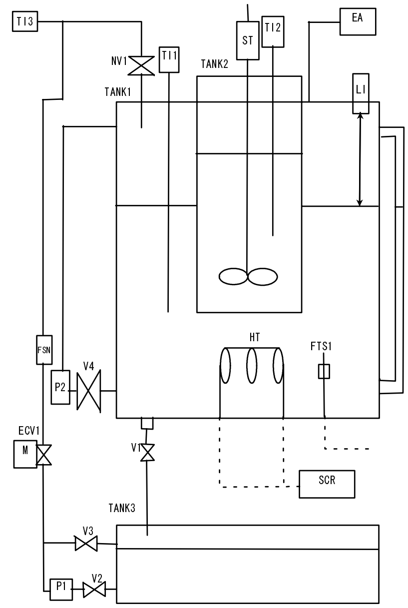

Fig. 5. The equivalent diagram of Fig. 4

Appendix

In Fig. 4, the boiler process control experimental system has double stainless tanks, the outside tank is called Tank 1 and the inside tank is called Tank 2. There is a plastic tank to store inflow and outflow of water under them, and it is called Tank 3. There is water level sensor in Tank 1, thermosensors in Tank 1 and Tank 2 and inflow control valve and circulating pump for Tank 1. And there are heater and pressure sensor on the bottom of Tank 1. The range of heater output is limited from 0 to a maximum output of 3kw. The equivalent diagram of Fig. 4 is shown in Fig. 5.

Two inputs and two outputs model about water temperature and level of process control experimental system are nonlinear state-equations as follows.

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \\ \dot{x}_4(t) \end{bmatrix} = A' \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{bmatrix} + B' \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} \tag{39}$$

$$\begin{aligned} \dot{x}_5(t) &= \frac{1}{A}u_2 - \frac{a}{A}\sqrt{2\rho g x_5(t)} \qquad (40) \\ A'_{11} &= -\frac{h_{miz}A_{w1} + h_{air}}{C_{y1}} \\ A'_{13} &= \frac{h_{miz}A_{w1}}{C_{y1}} \\ A'_{22} &= \frac{-h_{miz}(A_{w2}+A_{w3})}{C_{y2}} \\ A'_{23} &= \frac{h_{miz}A_{w3}}{C_{y2}} \\ A'_{24} &= \frac{h_{miz}A_{w2}}{C_{y2}} \\ A'_{31} &= \frac{h_{miz}A_{w1}}{C_{w1}} \\ A'_{32} &= \frac{h_{miz}A_{w3}}{C_{w1}} \\ A'_{33} &= -\frac{h_{miz}(A_{w1}+A_{w3})}{C_{w1}} \\ A'_{42} &= \frac{h_{miz}A_{w2}}{C_{w2}} \\ A'_{44} &= -\frac{h_{miz}A_{w2}}{C_{w2}} \end{aligned}$$

$$A'_{12}, A'_{14}, A'_{21}, A'_{34}, A'_{41}, A'_{43} = 0$$

Then C_{w1} and A_{w12} are represented as follows.

$$\begin{aligned} C_{w1} &= c_{miz}ro_{miz}\pi(lr_1^2 - lr_2^2)x_5(t) \\ &+ c_{miz}ro_{miz}\pi^2 lr_1^2 lh_3^2(lr_1^2 - lr_2^2) \qquad (41) \\ A_{w3} &= 2\pi lr_2 x_5(t) - \pi lr_2(2lh_3 - lr_2) \qquad (42) \end{aligned}$$

Parameters in the above equations are displayed in the following table.

Water density	$\rho[Kg/m^3]$
Gravitational acceleration	$g[m/s^2]$
Tank's cutting area	A(m^2)
Outflow entrance cutting area	a(m^2)
Water heat transfer coefficient	$h_{miz}[W/m^2$℃]
Air heat transfer coefficient	$h_{air}[W/m^2$℃]
Contacted area	A_{wi}(i=1,2,3)$[m^2]$
Heat capacity	C_{yj},C_{wj}(j=1,2)[J/℃]
Water's specific heat	C_{miz}[J/Kg℃]
Water's density	ro_{miz}[Kg/m^3]
Tank1's inside diameter	lr_1[m]
Tank2's inside diameter	lr_2[m]
Distance from Tank1 to Tank2	lh_1[m]

In this paper, parameters are estimated using extended Kalman filter based on experiment result [5]. If parameters are nonlinear, estimation values are difficult to be evaluated, so parameters are linearized around the estimation values. As a result, state-variables x_1(t), x_2(t) and x_5(t) can be observed, and their parameters are estimated by the extended Kalman filter.