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TRADITIONAL AND ROBUST PREDICTOR-BASED CONTROL FOR MIXING SYSTEMS IN CEMENT PLANTS

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Abstract: This paper presents a rational matrix represented model of homogenizing processes and their disturbances in a cement plant and also general features as a multivariable stochastic system. A control method and actually applied results are presented, which is composed of PI-controllers with Smith predictors with an optimum mixing calculation. From robustness performances necessary for the process, this paper also reports performance comparison results by simulation experiments when applying a robust Smith predictor based two-degree of freedom controller with the traditional control and also with the extended horizon adaptive control. *Copyright ©2000 IFAC*

Keywords: Predictive control, Delay compensation, Multivariable systems, Stochastic systems, Robust performance, Adaptive control, Cement plant, Process model

1. INTRODUCTION

A typical process flow diagram from a quarry to the inlet of a kiln in a cement manufacturing plant is shown in Fig. 1. In this plant, it is important to manage and control fluctuations of chemical compositions at the inlet of a kiln in order to obtain good quality of product and to maintain its stable and efficient operation. For manufacturing Portland cement in Japan, three moduli of hydraulic modulus *HM*, silica modulus *SM* and iron modulus *IM* are used for quality control.

It is usual to keep the mean values and standard deviations of these moduli of raw meal at a kiln inlet such as; HM=2.10, SM=2.60 and IM=1.60, s_{HM}=0.027, s_{SM}=0.070 and s_{IM}=0.080 respectively (Cement Association of Japan, 1978). The heat dissipation in a typical kiln of 5,000 ton/day capacity, for example, will be expected to decrease around 7,500 Mcal/day when the standard deviation of *HM* could be reduced by 0.01. For these surroundings, a cement plant should be exclusively equipped with installations such as homogenizing beds and blending silos for homogenizing raw material compositions. Also in a raw grinding mill process, a raw material mixing control system is provided to minimize variances that come especially from low frequency components of fluctuations. The system controls three mixing ratios of four kinds of raw materials at the mill inlet, which are limestone, clay, silica sand and iron ore, according to the results of on-line X-ray analysis of raw meal at the mill outlet.

In this paper, the authors will indicate that chemical composition fluctuations of raw materials will affect as stochastic disturbances and also presents transfer function models of homogenizing processes. As a consequence, the mixing control system is represented as a stochastic system with three input and three output variables.

The general features of this system as a multivariable control system are successively summarized. The actually applied results of a control method are also presented. The actual controller consists of digital PI-controllers with Smith predictor and of optimum mixing calculation. This mixing calculation part can be recognized as a decoupling pre-compensator.

Moreover, the robust performances of the mixing control system are notified to be necessary. The performances of a robust Smith predictor based digital controller (Landau, 1995) is examined comparing with the traditional PI-controller and also with the extended horizon adaptive control by simulation experiments.

2. MODELING FOR DISTURBANCE AND HOMOGENIZING PROCESSES

2. 1. Assumption for modeling

The following assumptions are introduced for modeling:

AP-1; Homogenizing effects in each process can be characterized by linear time-invariant models. The mixing and three modulus calculations of plural materials can be also approximated by linear calculation on around steady state values.

AP-2; The arriving process of each raw material from a quarry to a plant site is a Poisson arrival process and their chemical composition distributions in each arrival can be independently characterized by normal distributions which are obtained by chemical analysis data of bored samples.

AP-3; Variation of the secondary components of each raw material are expressed by a first order regression formula with the variation of each major component.

AP-4; The homogenizing effects including its dynamics in the grinding mill have same characteristics among all kinds of raw material.

2.2. Multivariable transfer function model of process

The examinations for the assumptions and transfer function models for each composed process including disturbance model have been presented (Ozaki et al, 1996). As a consequence, the overall block diagram of the process has been shown in Fig.2. with the traditional control schema.

In Fig. 2, the point "*Mi*" means "mill inlet" and in this point, perturbations of three moduli can be expressed as the following equation.

$$\left[DHM_{Mi}, DSM_{Mi}, DIM_{Mi}\right]^T \cong \boldsymbol{M}\cdot diag\left[G_{HB}^{Lime}, G_{HB}^{Clay}, G_{HB}^{Silica}, G_{HB}^{Iron}\right]\cdot G\cdot D\boldsymbol{Z}_p(s)\cdot\overline{\boldsymbol{u}} + \boldsymbol{M}\cdot\overline{\boldsymbol{Z}}_{Mi}\cdot D\boldsymbol{u}(s) \qquad (1)$$

where, in general, $\overline{X}$ is used for mean value, $\boldsymbol{\Delta} X$ is for perturbation, $\boldsymbol{Z}$ means chemical composition matrix and $\boldsymbol{u}$ is a control input vector composed of four mixing ratios. Matrix representation is used that $\boldsymbol{Z}_p$ is major components' matrix, $\boldsymbol{M}$ is a conversion matrix between three moduli and four chemical composites, G is a regression coefficient matrix calculated with chemical analysis data of bored samples. The notation of G_{HB}^{Lime}, for example, means a transfer function model of bed blending equipment for limestone. According to the assumption AP-2, each diagonal component of $D\boldsymbol{Z}_p(s)$ is represented as a Gaussian white noise passing a shaping filter whose time constant corresponds to the mean arrival time of raw material to the plant site (Ozaki et. al. 1996).

The transfer function of bed blending installation (for example, G_{HB}^{Lime}) can be approximated as the following transfer function.

$$G_{HB}^{Lime}(s) = \frac{1+\dfrac{\sqrt{N_{Lime}}}{2}T_{Lime}\cdot s}{1+\dfrac{N_{Lime}}{2}T_{Lime}\cdot s} \qquad (2)$$

where T_{Lime} is a stacking period and N_{Lime} is a number of stacking layers. In Eq. (1), the first term of the right hand expresses the disturbance come from fluctuations of chemical compositions and the second one is corresponding to the corrective term by the control action. For this control system, the process is a raw grinding mill whose transfer function $G_{GM}(s)$ is expressed as the following equation which has been derived by experiments in the actual plant under several operation conditions, i.e. different values of L_C. (Ozaki 1999a).

$$G_{GM}(s) = \frac{\exp\left\{-\left(l_x + 1/(30\times L_C)\right)\right\}}{(1+L_C)\left(1+\dfrac{T_B}{5}s\right)^5 - L_C} \qquad (3)$$

where T_B is mean residence time in a mill itself, L_C is a positive feedback ratio called as a circulation load factor of return meal from a separator and l_x is sample transporting time to the X-ray analyzer.

3. FEATURES OF MULTIVARIABLE SYSTEM

The general features for designing a raw material mixing control system are summarized as the followings with referring Fig. 2 (Ozaki, K. 1999a);

(1). This control system should be a digital control system with a sample period of 20-30 minutes because the capacity of sampling and sample transportation equipment will belong with this period and also the multi-purpose analysis is indispensable for the X-ray spectrometer.

(2). The controlled object is a 3-input and 3-output multivariable stochastic system activated by four independent Gaussian processes passing shaping filters and pre-homogenizing transfer functions. These processes interact to the process as input disturbances.

(3). If the assumption AP-4 is valid, the interactor matrix of the process will be a scalar and only static decoupling is necessary to save any interactions between three mixing ratios and three observed moduli.

(4). If the assumption is violated, the dynamic characteristics of four materials will be different and it leads to have the rational polynomial element on the non-diagonal part of the interactor matrix, that is a general multivariable system. But in actual, even though in this case, the deviations of dynamic characteristics such as mean residence time in the mill can be expected small compared with their average values over four kinds of raw material. As a result, process gain interaction can be considered as the major interaction.

(5). The pseudo-decoupling using a static pre-compensator calculated using bored sample data can be expected to eliminate the greater part of the interactions. Using actual boring data for two districts, non-diagonal elements of the product of the pre-compensator matrix and the process gain matrix are less than 15% of the corresponding diagonal elements. This example shows that the static pre-compensation is actually sufficient for decoupling of the multivariable system.

The above-mentioned feature of the multivariable system is most important characteristic of the mixing system and also it can be expected to be generalized for the other process control based on the same philosophy as the literature (Yamamoto and Shah, 1999).

4. TRADITIONAL CONTROL METHOD AND ITS RESULTS

The traditional control method was designed based on the features of the process mentioned in the previous section. The schematic diagram of the control method is shown in Fig. 2. A digital PI-controller with a Smith predictor is applied for dynamical compensation of an error signal of each modulus. For simplicity, a SISO block diagram of this control method is shown in Fig. 3 and the pulse transfer function of $G_C^*(z^{-1})$ in Eq. (4) is derived for the approximated transfer function of the process as $\frac{\exp(-l_0 s)}{1+T_0 s}$.

$$G_C^*(z)=\frac{C^*(z)}{E^*(z)}=\frac{Z\left[\frac{1-e^{-T_C s}}{s}\times K_P\left(1+\frac{1}{T_i s}\right)\right]}{1+Z\left[\frac{1-e^{-T_C s}}{s}\times f_0 K_P\left(1+\frac{1}{T_i s}\right)\times\frac{1-e^{-ls}}{1+T_0 s}\right]}$$

$$=\frac{K_P\left(1+\frac{T_c}{T_i}\frac{z^{-1}}{1-z^{-1}}\right)\left(1-hz^{-1}\right)\left(1-z^{-1}\right)}{\left(1-hz^{-1}\right)\left(1-z^{-1}\right)+f_0K_p\left(1-z^{-d}\right)z^{-1}\left[\left(1-\frac{T_0}{T_i}\right)(1-h)\left(1-z^{-1}\right)+\frac{T_c}{T_i}\left(1-hz^{-1}\right)\right]} \tag{4}$$

where T_C is a sampling interval, $h=\exp\left(-T_c/T_0\right)$, f_0 is a process gain, K_P and T_I are a proportional gain and integral time of continuous PI-controller and the time delay is discretized as $l_0/T_C=d$ (d is an integer).

The output variable of this controller corresponds to the corrective target for each modulus. Using these targets expressed as ΔHM_T, ΔSM_T, ΔIM_T, static mixing calculation is carried out in order to get new mixing ratios in consideration of the interactions between three mixing ratios and three output moduli. In the mixing calculation, the following optimization calculation is applied taking into account of the limits of one-step corrective action.

$$\mathop{Min}_{\Delta u}\left[\begin{array}{c}K_1\left(\Delta HM_T-\Delta HM\right)^2+K_2\left(\Delta SM_T-\Delta SM\right)^2\\+\left(\Delta IM_T-\Delta HM\right)^2\end{array}\right] \tag{5}$$

$$with \sum_{i=1}^{4}\Delta u_i=0 \;\; and \;\; \left|\Delta u_i\right|\le\Delta_{\max}(i),$$

$$where \quad \Delta HM=\sum_{i=1}^{4}\left(\frac{\partial HM}{\partial u_i}\right)\cdot\Delta u_i, etc.$$

If all perturbations are small and the mean compositions at the raw mill inlet will be same as the ensemble mean of overall boring data $\overline{\boldsymbol{Z}}_0$, the optimum mixing ratios can be given with the following linear matrix calculation.

$$\begin{aligned}\boldsymbol{J}\cdot\boldsymbol{\Delta u}&\equiv[\Delta u_1,\Delta u_2,-(\Delta u_1+\Delta u_2+\Delta u_3),\Delta u_3]^T\\&=\boldsymbol{J}\cdot\left(\boldsymbol{M}\cdot\overline{\boldsymbol{Z}}_0\cdot\boldsymbol{J}\right)^{-1}[\Delta HM_T,\Delta SM_T,\Delta IM_T]^T\end{aligned} \tag{6}$$

where the ratio of silica sand is considered as a subordinate variable within four ratios and then the conversion matrix $\boldsymbol{J}=\begin{bmatrix}1&0&0\\0&1&0\\-1&-1&-1\\0&0&1\end{bmatrix}$ is applied.

The matrix $\boldsymbol{K}_{Pre}=\left(\boldsymbol{M}\cdot\overline{\boldsymbol{Z}}_0\cdot\boldsymbol{J}\right)^{-1}$ can be considered as the pseudo-decoupling precompensator explained in the previous section.

The traditional control method has been applied for several plants and representative results are shown in Table. 1. For Iraq and Indonesia plants, the standard deviations of three moduli have been calculated with X-ray analysis results during manual operation and computer controlled operation and compared in the table. The standard deviation of hydraulic modulus (HM) under control, for example, is around one by two or three of the figure under manual operation. Moreover, all standard deviations under control are much less than the average values of manufacturing plants in Japan already shown in the section one. These results show that the designed control method has good performances and can be expected to contribute the efficient operation of kilns.

5. ROBUST SMITH PREDICTOR-BASED DIGITAL CONTROL

The traditional control method has fairly good performances for actual plants, but the homogenizing processes have time-varying and non-linear characteristics. Especially for a raw grinding mill, as shown in Eq. (3), its dynamics including time delay will change with the circulation load factor changing time to time according to grindability of raw material. And also, non-linear characteristics of a grinding rate function will affect the overall dynamics of the closed-circuit grinding mill (Ozaki, 1999a). Moreover, the gain matrix will change caused of fluctuation of mean chemical compositions at the mill inlet. These characteristics request robust performances of the mixing control system. In this sections, a robust control method is examined to apply for improving the performances.

5. 1 Multivariable ARMAX model of the process

The process can be expressed by the following ARMAX model.

$$A(z^{-1})\cdot \boldsymbol{I}\cdot \boldsymbol{y}(k) = z^{-d}\cdot \boldsymbol{B}(z^{-1})\cdot \boldsymbol{u}(k)+\boldsymbol{C}(z^{-1})\cdot \boldsymbol{w}(k) \quad (7)$$

where;

$$\boldsymbol{y}(k) = [DHM_m, DSM_m, DIM_m]^T,$$

$$\boldsymbol{u}(k) = [Du_1, Du_2, Du_3]^T, \ \boldsymbol{w}(k) = [w_1, w_2, w_3, w_4]^T,$$

The vector $\boldsymbol{w}(k)$ composes of independent Gaussian random series which represent major components' fluctuation of raw material,

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-n},$$

$$\boldsymbol{B}(z^{-1}) = \boldsymbol{B_0}\cdot B'(z^{-1}) = \boldsymbol{B_0}\cdot\left(1 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_n z^{-n+1}\right) \text{ and}$$

$$\boldsymbol{C}(z^{-1}) = \boldsymbol{I} + \boldsymbol{C_1} z^{-1} + \boldsymbol{C_2} z^{-2} + \cdots + \boldsymbol{C}_{n-1} z^{-n+1}.$$

The scalar polynomials $A(z^{-1})$ and $B'(z^{-1})$ compose a discrete time representation of a raw grinding mill dynamics. The matrix $\boldsymbol{B}_0$ has static gain elements. The polynomial matrix $\boldsymbol{C}(z^{-1})$ has 3x4 elements and defines input disturbance. If the conversion such that $\boldsymbol{u}'(k)=\boldsymbol{B_0}\cdot\boldsymbol{u}(k)$ is applied in Eq. (7), the expression can be of a decoupled form from an input vector $\boldsymbol{u}'(k)$ to a measured vector $\boldsymbol{y}(k)$.

5. 2 Multi-loop SP-RST digital controller

For the mixing control system, delay compensation is most important design point as explained in the section three. Landau has proposed a robust control design for the Smith predictor-based two degree freedom controller, named as SP-RST, using "modulus margin" and "delay margin". These margins have more adequate representation of robust stability than gain and phase margins, that has been introduced in a topic of recent robust control (Kwakernaak, 1995).

This design procedure firstly considers the function of Smith predictor in the digital control design. The diagrams of two-degree-freedom RST controller shown in Fig. 4(a) can be converted into Fig. 4(b) when using the predictor. Moreover, the following two Bezout equations can be separately applied for the later diagram.

$$A(z^{-1})S_0(z^{-1}) + B(z^{-1})R_0(z^{-1}) = P_0(z^{-1}) \quad (8)$$

$$A(z^{-1})E(z^{-1}) + z^{-d}F(z^{-1}) = P_P(z^{-1}) \quad (9)$$

where S_0, R_0 are pole placement polynomials when designing without time delay, P_0 is a closed loop pole polynomial as a result of the design and P_P can be interpreted as a dynamics of the predictor with the same philosophy as the Smith predictor (Åstrom and Wittenmark, 1997) (Landau, 1995).

Introducing integral action in S_0 and having the polynomial of $A(z^{-1})$ in R_0 , following explicit representations for S and R can be obtained (Landau, 1995) (Landau et. al. 1998)

$$S(z^{-1}) = P_0(z^{-1}) - \frac{z^{-d}B(z^{-1})H_R(z^{-1})P_0(1)}{B(1)H_R(1)} \quad (10)$$

$$R(z^{-1}) = \frac{A(z^{-1})H_R(z^{-1})P_0(1)}{B(1)H_R(1)} \quad (11)$$

where H_R is a polynomial which can be used as the robust design.

The robust control design can be succesively introduced such that using free-selection part of P_0 and R_0, the sensitivity function could be shaped to cope with the predefined modulus margin and delay margin. The example of a robust design for a SISO mixing control system is as the followings. Let's approximate the process as a discrete form of a first order system with time delay and take the modulus margin of 5dB and the delay margin with one sample interval which are generally sufficient figures in the mixing control system. According to the definition of the modulus margin, the sensitivity function $S_{yp}(e^{-jw})$ should be upper-bounded by the following.

$$DM = \frac{1}{2} = \left|1 + L(e^{-jw})\right|_{\min} = \left(\left|S_{yp}(e^{-jw})\right|_{\max}\right)^{-1} = \left(\left\|S_{yp}\right\|_{\infty}\right)^{-1}$$

where $L(e^{-jw})$ is a loop transfer function. Also in consideration of the multiple uncertainty figure for one sample interval of the delay margin and then applying robust stability condition, the complementary sensitivity function $S_{yb}(e^{-jw})$ should be bounded as the followings.

$$\left|S_{yb}(z^{-1})\right| \le \left|(1 - z^{-1})\right|^{-1}$$

Moreover using the trade-off relation, the following inequality can be obtained for the sensitivity function.

$$1 - \left|1 - z^{-1}\right|^{-1} < \left|S_{yp}(z^{-1})\right| < 1 + \left|1 - z^{-1}\right|^{-1} \quad (12)$$

Applying most simple design example such that $P_0(z^{-1})=1$ and $H_R(z^{-1})$ for the mixing process approximated as the first order discrete system with time delay of $d=2$, the resulting multi-loop control schema can be shown in Fig. 5. The sensitivity function for the representative HM control loop is shown in Fig. 6 comparing with the function of the traditional control. It shows that the modulus margin shapes the sensitivity function for the low frequency range and the delay margin for the high frequency region. Robust performances with these two margins can have the good performance margin even though the process characteristics including its time delay would fairy remarkably change.

6. SIMULATION RESULTS

Based on pseudo-decoupling possibility of the system, the several performances as a SISO system has been firstly verified by computer simulation. And then the above-mentioned two control methods are compared and also with an adaptive control method of the extended horizon adaptive control (EHAC) (Ydstie, 1984) (Ozaki, 1999b) under the multivariable schema. The sampling interval T_C is of

30 minutes uniformly for three control methods. In Fig. 7 the disturbance response for traditional control and SP-RST is firstly compared especially for the robust performance when changing the time delay from the nominal value of 1 hour (2xT_C) to 2.5xT_C and 3xT_C. Secondary. the regulation performances under stochastic disturbances as a SISO mixing system using three methods are shown in Fig. 8 with open loop and closed loop performances. Finally, multi-loop regulation performances under stochastic disturbances are summarized in Table 2, in which the standard deviations during 240 sampling times corresponding to 5 days operation have been compared when changing process gain matrix and also changing time delay. The EHAC has the adaptive property to get the quasi-minimum variance result for a stochastic disturbance (Dugard. et al 1984), so its results can be recognized as the most preferable performance. Nevertheless the simplicity of the control configuration is also very important for application purposes. The control schema of robust SP-RST control is quite simple and can overcome the anxious of application engineers for the adaptive control which has delicate mechanism and the possibility to be unstable under an extremely ill condition of the process. As these consequences, robust SP-RST control can be expected to be an effective applicable schema to the advanced mixing control system.

7. CONCLUSIONS

The linear multivariable model including stochastic representation of disturbance has been presented. Based on these analysis and modeling, the general properties of a mixing control system have been clarified especially for the multivariable control design. The traditional Smith predictor based digital PI-controller with optimum mixing calculation has been presented and also good performances have been reported using actual operational data in three factories. Moreover, a Smith predictor based two degree of freedom digital control method is compared with the traditional control and also an adaptive control method. This control method has been confirmed that it can improve the control performances under when the process characteristics including time delay will fairly change.

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Table 1 Control results in actual plants

Delivery Plant	Mode	σ_{HM}	σ_{SM}	σ_{IM}
Factory A In Columbia	Auto	0.079	0.085	0.079
Factory B	Manual	0.083	0.062	0.057
In Iraq	Auto	0.047	0.027	0.056
Factory C	Manual	0.039	0.073	0.089
In Indonesia	Auto	0.011	0.033	0.041
Average values in Japanese factories	Auto or Manual	0.07	0.093	0.086

(Note): All σ are calculated using X ray analysis results.

Table2 Multi-loop regulation comparison result with standard deviations under changing the model parameter

Control method		Change in model parameters		
		Nominal ($\boldsymbol{B}_0$, d=2)	Gain Matrix (1.2 $\boldsymbol{B}_0$)	Time delay (d=3)
Traditional	σ_{HM}	0.0291	0.0287	0.0325
PI + Smith	σ_{SM}	0.0612	0.0586	0.0700
Predictor	σ_{IM}	0.0302	0.0362	0.0345
Multi-loop	σ_{HM}	0.0256	0.0258	0.0292
EHAC	σ_{SM}	0.0377	0.0376	0.0400
	σ_{IM}	0.0302	0.0215	0.0221
Multi-loop	σ_{HM}	0.0240	0.0221	0.0248
Robust	σ_{SM}	0.0449	0.0452	0.0491
SP-RST	σ_{IM}	0.0227	0.0338	0.0264

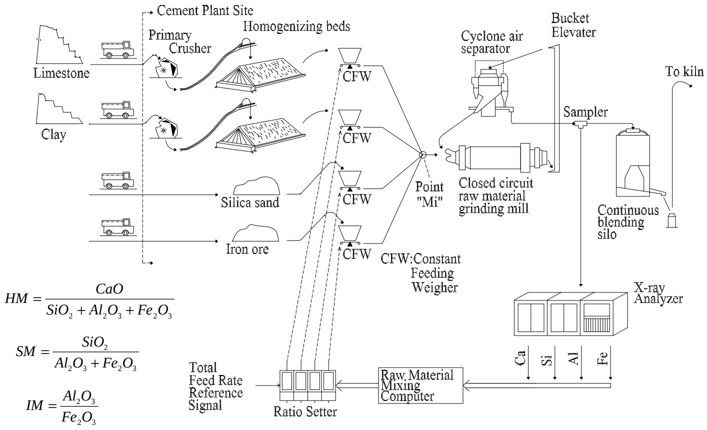

Fig.1 Schematic process flow-diagram

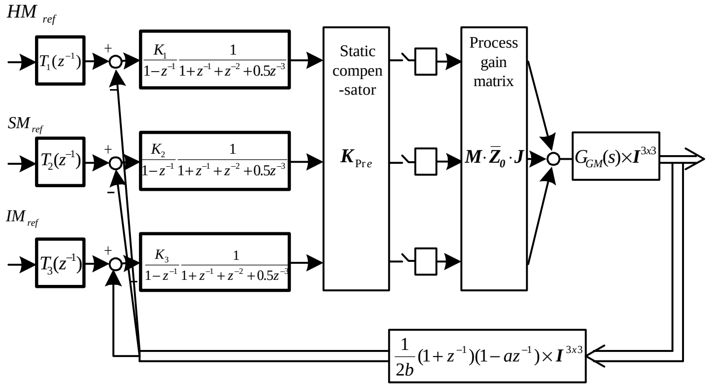

Fig.5 Configuration of multi-loop robust mixing control system

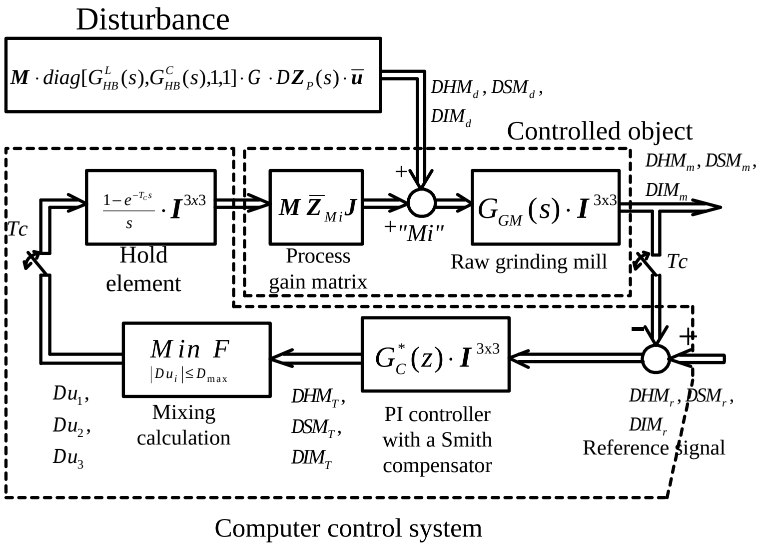

Fig.2 Overall block diagram

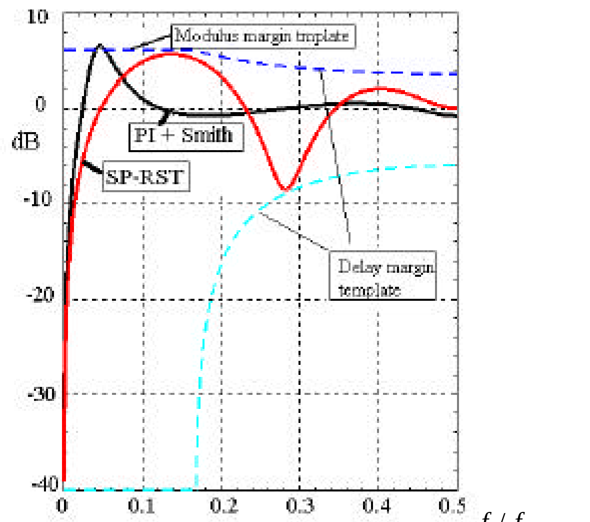

Fig.6 Sensitivity functions / robust RST vs traditional controller

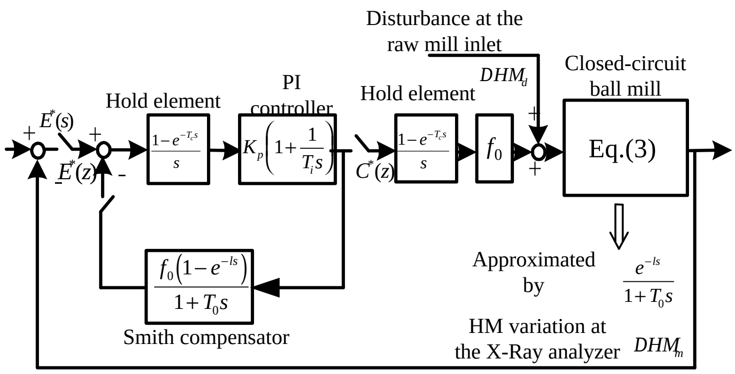

Fig.3 Traditional digital PI controller with Smith predictor

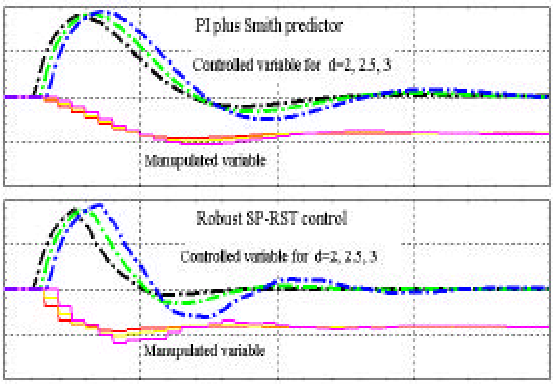

Fig.7 Disturbance response comparisons against dead time chan

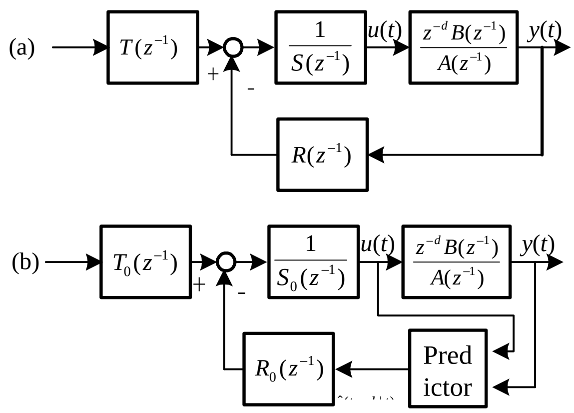

Fig.4 RST controller (a) without and (b) with Smith predictor

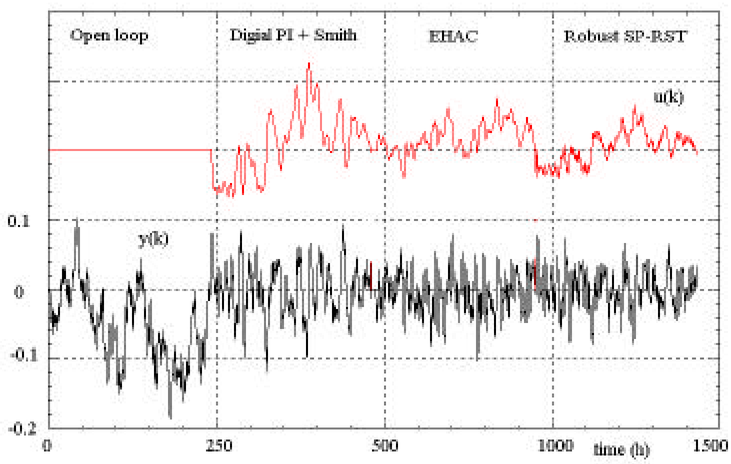

Fig.8 SISO regulation performances of three control methods