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MULTIVARIABLE LINEAR QUADRATIC CONTROL OF A CEMENT MILL: AN INDUSTRIAL APPLICATION

V. van Breusegem*, L. Chen*, V. Werbrouck**, G. Bastin* and V. Wertz*

*Centre for Systems Engineering and Applied Mechanics, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium

**S.A Slegten, B-1348 Louvain-la-Neuve, Belgium

Abstract. The paper presents the design procedure of a model-based control algorithm for the regulation of tailings and product flowrates in a cement mill The control variables are the feeding rate and the classifier speed Experimental results of a full-scale industrial application are reported and discussed with a view to the control of the fineness of the cement

Keywords. Cement industry, Multivariable control systems, Industrial control

1 INTRODUCTION AND PROCESS DESCRIPTION

Cement production processes are well-known to require a high energy consumption A large part of this energy is consumed during milling of the cement clinker and raw materials. It is therefore of interest to optimize this operation in order to decrease the energy consumption by unit of final product but also to enhance the quality of the final product Such a process optimization can be achieved by using feedback control strategies that aim at maintaining the process at efficient operating levels

In a recent paper, "State of the art in the control of milling circuits" (Hulbert, 1989), one of the main conclusions of the author is that · "there is a tendency for simple single variable control schemes to be replaced by multivariable control strategies, which are more suited for the task"

The concern in this paper is precisely to present the design of a "Linear Quadratic Multivariable (LQ-MV)" controller for cement mills and to illustrate its performance with the experimental results obtained on a mill of the company "Cimenteries d'Obourg" (Belgium) where the controller has now been in operation for more than one year

The schematic lay-out of a cement milling circuit is shown in Fig 1 The mill is fed with raw material and cement clinker (feed) After grinding, the material is introduced into a high-efficiency classifier and separated into two classes The tailings (refused part) are fed back to the mill while the finished product (accepted part) exits the milling circuit The classification of the material is driven by the rotational speed and by the air flow rate of the classifier

Traditionally, the application of feedback control techniques to cement milling circuits is limited

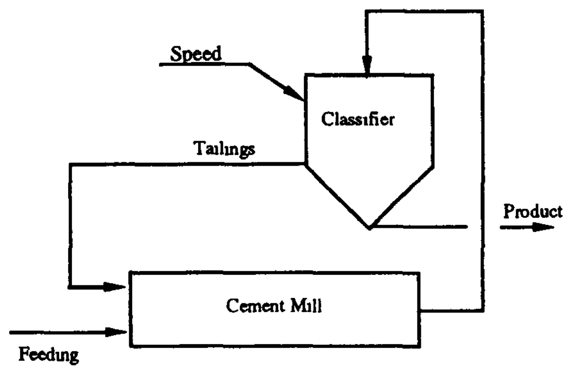

Figure 1 Milling circuit principle

to monovariable classical PI control of the tailing flowrate (or of the circulating load) with either the feed flow rate or the classifier speed as control action A typical example can be found in (Ciganek and Kreysa, 1991)

This paper presents a *multivariable* model based linear-quadratic control strategy where two outputs are simultaneously controlled (tailings and finished products) by using the two available inputs (feed and classifier speed) together Other multivariable model based control studies using either the internal model control principle (Lanthier *et al*, 1989) or the inverse Nyquist array method (Hulbert, 1989; Niemi *et al*, 1989) have been published These contributions however apply to wet milling circuits for the metallurgical industry and contain only simulation results (with the noticeable exception of (Hulbert, 1983) where interesting experimental results are reported). To the authors' knowledge, this paper is the first industrial application of multivariable control to a cement milling circuit giving rise to a genuine routine operation

2 CONTROL OBJECTIVES

In steady-state operation, it is clear that the product flow rate is necessarily equal to the feed flow rate while the tailing flow rate may take any arbitrary constant value Too high a level of the circulating load (fresh feed plus tailing flow rate) leads to the obstruction of the mill while too low a circulating load contributes to fast wear of the mill internal equipment It follows that the circulating load must be controlled at a well chosen level in order to avoid the above-mentioned behaviour and hence to optimize the grinding efficiency and, consequently, to minimize the energy consumption of the mill (i e the ratio Energy per Unit Product) A usual approach is to control the tailings flowrate by using the feed flowrate as control input This control strategy is however not fully satisfactory since it indirectly induces a loss of the control of the product flowrate

A correct fineness of the product is also of great importance The fineness depends on the composition of the mill feed, but also on the rotational speed and on the air flow rate of the classifier A natural control objective would therefore be to keep the fineness as close as possible to a desired value by acting for example on the rotational speed of the classifier However, in cases where on-line fineness measurements are not available, an indirect control strategy can be of interest

These observations have led to consideration of the following control objective

- To regulate the product and tailing flow rates at desired levels (setpoints) by acting on the feed flow rate and on the rotational speed of the classifier

The achievement of this control objective clearly requires a multivariable control approach since two outputs (tailings and product flow rates) must be regulated by simultaneous actions on two inputs (feed flow rate and rotational speed) in the presence of important cross-coupling effects The air flow rate in the classifier is kept constant for long periods of operation and is not available here for control purpose

Moreover, it is obvious that in a milling circuit such as that in Fig 1

- For a given feed composition, the fineness will be constant if *both* the product and the tailings flow rates are kept constant

- Similarly the energy consumption of the process (ratio Energy/UnitProduct) will be fully under control if *both* the product and tailings flow rates are regulated together at suitable set points

This clearly implies that an overall control of both the fineness and the energy consumption can be achieved at a supervisory level in the control system, by manipulating and optimizing the tailing or product set points, using for instance off-line laboratory measurements of the fineness

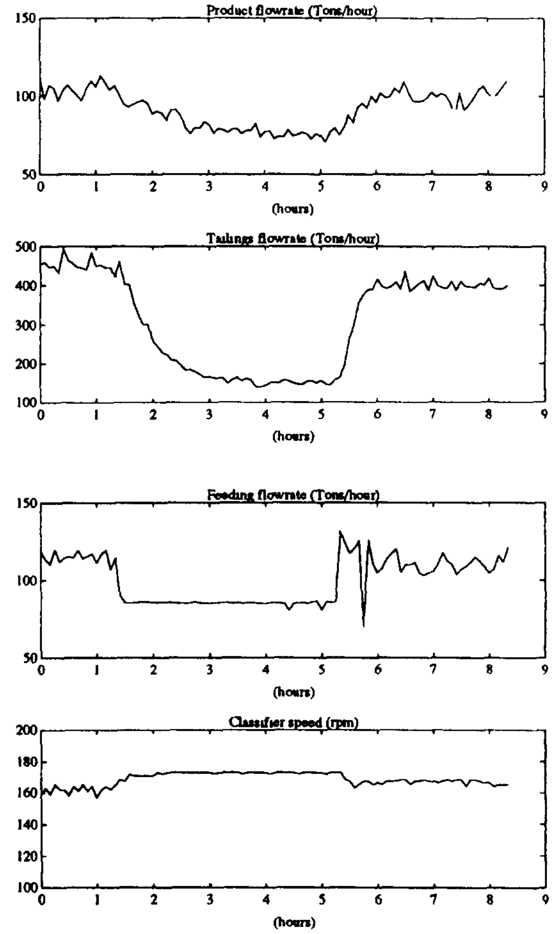

Figure 2a Experimental data of September 19, 1990

3 MATHEMATICAL MODELLING

It is well known that the design of an efficient multivariable control system requires a model The first step in the control algorithm design consists in obtaining a mathematical model of the cement milling process

3 1 Black-box model

Roughly speaking, there exist two modelling options (Hulbert, 1989) a mechanistic model which tends to describe in detail the physics of the whole process and a "black-box" model which aims at reproducing the input/output behaviour of the milling process Generally, the first approach leads to complex models which can hardly be used directly for the design of a controller The second approach, followed in this paper, provides models which can be made just complex enough for the description of the main process dynamics while remaining tractable for control design

Two sets of experimental data shown in Figures 2a (Experiment 1 of September 19, 1990) and 2b (Experiment 2 of October 17, 1990) were used initially for the black box identification of the building process This data (like all the data presented in this paper) has been obtained from experiments performed in the milling circuit ♯3 of the company "Cimenteries d'Obourg", Belgium It consists of product and tailing flow rate responses to steps in feed flow rate

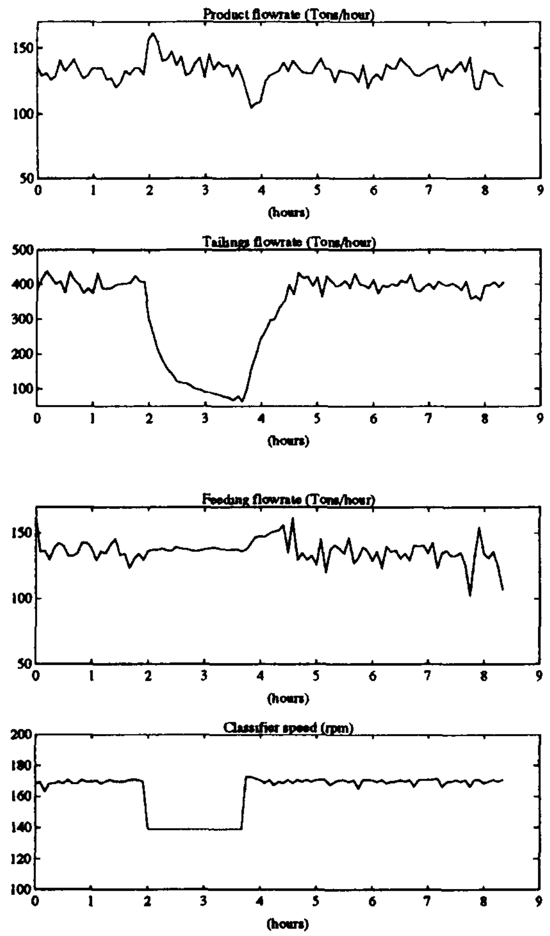

Figure 2b Experimental data of October 17, 1990

and classifier speed, respectively In Fig 2a, the feed flow rate has been decreased from 120 tons/hour to 90 Tons/hour producing variations of the product flow rate (of similar amplitude) and of the tailings flow rate (from 450 Tons/hour to 150 Tons/hour) In Fig 2b, the classifier speed is decreased from 170 rpm to 135 rpm while the feed flow rate is kept constant That produces a decrease in the tailings flow rate and an impulse-like response of the product flow rate These experimental data confirm the multivariable nature of the milling process Indeed, it is clearly shown that a variation of one of the inputs induces significant variations of both outputs

From these data, using standard identification techniques of the Matlab Identification Toolbox (Ljung, 1988), the following dynamical model has been obtained in the form of a set of four first-order differential equations

$$(t_{11}\frac{d}{dt}+1)y_p = k_{11}u_f \qquad (1)$$

$$(t_{12}\frac{d}{dt}+1)y_p = k_{12}\frac{du_s}{dt} \qquad (2)$$

$$(t_{21}\frac{d}{dt}+1)y_t = k_{21}u_f \qquad (3)$$

$$(t_{22}\frac{d}{dt}+1)y_t = k_{22}u_s \qquad (4)$$

where y_p, y_t, u_f and u_s denote the product flow rate ($Tons/hour$), the tailings flow rate ($Tons/hour$), the

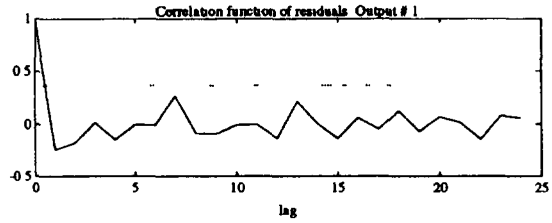

Figure 3 Whiteness of residuals for the product/feeding relation (Experiment 1)

feed flow rate ($Tons/hour$) and the classifier speed (rpm), respectively It must be pointed out that in the model described by equations (1)-(4) , the variables y_p, y_t, u_f and u_s represent variations around the following nominal point

$$\bar{y}_p = 120\,Tons/hour\ ,\ \bar{y}_t = 450\,Tons/hour\ ,$$
$$\bar{u}_f = 120\,Tons/hour\ ,\ \bar{u}_s = 170\,rpm$$

The values of the coefficients of the model (1)-(4) are given in Table 1 Each coefficient is either the time constant (t_{ij}) or the static gain (k_{ij}) of one of the transfer functions relating each input (feed flow rate and classifier speed) to each output (product and tailings flow rate)

Table 1 : *Values of the coefficients of the model (1)-(4)*

Time constant	Static gain
$t_{11} = 0\ 9\,hour$	$k_{11} = 1\frac{Tons}{Tons}$
$t_{12} = 0\ 42\,hour$	$k_{12} = -25\frac{Tons}{hour\ rpm}$
$t_{21} = 0.65\,hour$	$k_{21} = 8\ 6\frac{Tons}{Tons}$
$t_{22} = 0.35\,hour$	$k_{22} = 11\frac{Tons}{hour\ rpm}$

3 2 *Model validation*

Although the model (1)-(4) may appear quite simple (first-order transfer functions without dead time) the validation tools described below show that it nevertheless captures the essential features of the milling circuit

The first validation test which has been applied is a whiteness test on the residuals of each of the four relations This test is satisfied for all the relations as illustrated in Fig 3 with the correlogram of the residuals for the product/feed relation (Experiment 1) The model has also been validated by simulation Fig 4 shows the good agreement of the experimental results and the simulation on the data of Experiment 2

An a posteriori additional validation of the model has also been performed It consists of a comparison of the values of the parameters of the model (1)-(4) with those obtained on a later experiment (number 3) performed on April 25, 1991 Both parameter values are given in the following table

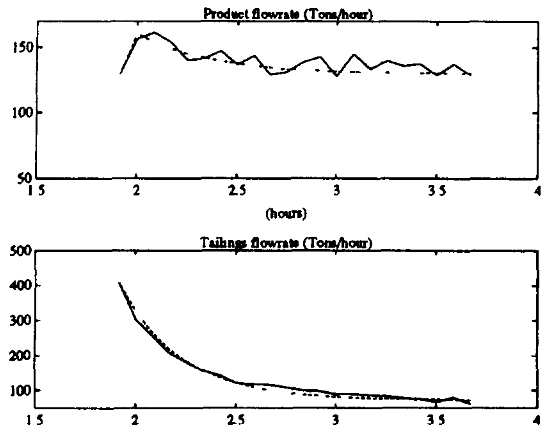

Figure 4 Comparison between experimental and simulated data (Experiment 2)

Table 2 :*Comparison between the values of the parameters identified from Experiments 1 and 3*

Experiment	t_{11} (min)	k_{11}	t_{21} (min)	k_{21}
1	54	1	39	8 6
3	54	1	32	9 8

4 CONTROL DESIGN

Recall that the objective is to regulate both the product and the tailing flow rate at desired levels (setpoints) by acting on the feed flow rate and on the classifier rotational speed The model being linear, one can directly apply a multivariable LQ control design which consists of the following steps discretisation of the continuous model, introduction of integral actions in the discrete model and computation of the gain matrix of the LQG controller For each of these steps, the Matlab functions from the Matlab Control Systems Toolbox (Grace *et al*, 1990) have been used

4 1 Discretization

With a view to the implementation of the control algorithm on a digital control system, a discrete time *LQ* controller is sought This implies that the model of the process obtained in the previous section has to be discretized

The process model (1)-(4) can be easily rewritten in the state-space form

$$\begin{aligned} X &= AX + BU \\ Y &= CX + DU \end{aligned}$$

where $Y = [y_p \quad y_t]^T$ is the output vector , $U = [u_f \quad u_s]^T$ is the input vector and X is the state vector The matrices A, B, C and D are the following

$$A = \begin{pmatrix} -1/t_{11} & 0 & 0 & 0 \\ 0 & -1/t_{12} & 0 & 0 \\ 0 & 0 & -1/t_{21} & 0 \\ 0 & 0 & 0 & -1/t_{22} \end{pmatrix}$$

$$B = \begin{pmatrix} k_{11}/t_{11} & 0 \\ 0 & -k_{12}/t_{12}^2 \\ k_{21}/t_{21} & 0 \\ 0 & k_{22}/t_{22} \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \quad D = \begin{pmatrix} 0 & k_{12}/t_{12} \\ 0 & 0 \end{pmatrix}$$

The corresponding state-space representation in discrete time is given by

$$X_{(k+1)T_e} = A_d X_{kT_e} + B_d U_{kT_e} \quad (5)$$

$$Y_{kT_e} = C_d X_{kT_e} + D_d U_{kT_e} \quad (6)$$

where T_e denotes the sampling period and k is an integer index. It can be easily shown that the matrices A_d, B_d, C_d and D_d have a structure which is independent of the sampling period value This structure is as follows

$$A_d = \begin{pmatrix} ad_{11} & 0 & 0 & 0 \\ 0 & ad_{22} & 0 & 0 \\ 0 & 0 & ad_{33} & 0 \\ 0 & 0 & 0 & ad_{44} \end{pmatrix}$$

$$B_d = \begin{pmatrix} bd_{11} & 0 \\ 0 & bd_{22} \\ bd_{31} & 0 \\ 0 & ad_{42} \end{pmatrix}$$

$$C_d = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \quad D_d = \begin{pmatrix} 0 & dd_{12} \\ 0 & 0 \end{pmatrix}$$

Notice finally that the values of parameters contained in the above matrices obviously depend on the values of the parameters of the model (1-4) but also on the sampling period T_e

For a sampling period Te = 1 min, the matrices of the discrete time model take the following values

$$A_d = \begin{pmatrix} 0\ 9116 & 0 & 0 & 0 \\ 0 & 0\ 8161 & 0 & 0 \\ 0 & 0 & 0\ 8797 & 0 \\ 0 & 0 & 0 & 0\ 7881 \end{pmatrix}$$

$$B_d = \begin{pmatrix} 0\ 0884 & 0 \\ 0 & 0\ 1839 \\ 1\ 0348 & 0 \\ 0 & 2\ 3306 \end{pmatrix}$$

$$C_d = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \quad D_d = \begin{pmatrix} 0 & -1 \\ 0 & 0 \end{pmatrix}$$

4.2 Introduction of integral actions

In order to introduce integral actions naturally into the controller (to guarantee zero steady-state error), according to the principle of the internal model of the perturbations, the control inputs are expressed in incremental form

$$\Delta u_{a,kT_e} = u_{a,kT_e} - u_{a,(k-1)T_e}$$
$$\Delta u_{s,kT_e} = u_{s,kT_e} - u_{s,(k-1)T_e}$$

The corresponding state space representation is obtained by augmenting the state vector size

$$X^*_{(k+1)T_e} = A^*_d X^*_{kT_e} + B^*_d \Delta U_{kT_e} \quad (7)$$
$$Y_{kT_e} = C^*_d X^*_{kT_e} + D^*_d \Delta U_{kT_e} \quad (8)$$

with

$$X^*_{(k+1)T_e} = \begin{pmatrix} X_{(k+1)T_e} \\ u_{a,kT_e} \\ u_{s,kT_e} \end{pmatrix}$$

$$\Delta U_{kT_e} = \begin{pmatrix} \Delta u_{a,kT_e} \\ \Delta u_{s,kT_e} \end{pmatrix}$$

$$A^*_d = \begin{pmatrix} A_d & B_d \\ 0 & I_2 \end{pmatrix} \quad B^*_d = \begin{pmatrix} B_d \\ I_2 \end{pmatrix}$$

$$C^*_d = \begin{pmatrix} C_d & D_d \end{pmatrix} \quad D^*_d = D_d$$

where I_2 denotes the 2×2 unit matrix

4.3 Control design

The LQ-controller has been designed from the augmented state space representation (7)-(8) using the Matlab System Control Toolbox (Grace *et al.*, 1990) Recall that the design proceeds in 3 successive steps

1. Computation of the matrix gain L of an observer which reconstructs the unmeasured internal state X from the product and tailings flow rate measurements The gain matrix L depends on the choice of two symmetrical positive definite matrices Q_1 and R_1
2. Computation of the matrix gain K of the linear controller $\Delta U_{kT_e} = -KX^*_{kT_e}$ which minimizes the quadratic criterion
$$J = \sum_{j=0}^{\infty}(X^{*T}_{jT_e} Q_2 X^*_{jT_e} + \Delta U^T_{kT_e} R_2 \Delta U_{kT_e})$$
where Q_2 and R_2 are two symmetrical positive definite matrices
3. Computation of the state-space representation of the controller from gain matrices L and K under the following form
$$Z_{(k+1)T_e} = A_c Z_{kT_e} + B_c(Y_{kT_e} - Y^{sp}_{kT_e})$$
$$\Delta U_{kT_e} = C_c Z_k T_e + D_c(Y_{kT_e} - Y^{sp}_{kT_e})$$
where Y^{sp} denotes the set point

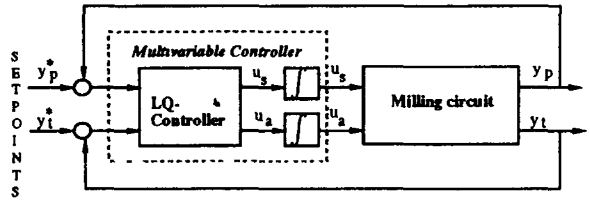

Figure 5 Control scheme

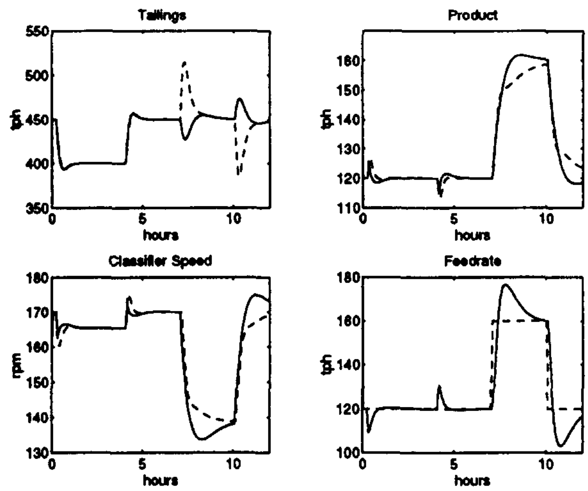

Figure 6 Comparison between the LQ-MV Controller and a PID Controller with the Classifier Speed as Control Input

The multivariable controller is finally obtained by combining in series the LQ-controller and the integral actions The proposed control scheme is shown in Figure 5

4.4 Comparison between LQ and PI control

Figures 6 and 7 show a comparison in simulation between this multivariable controller and two monovariable strategies which are common in the cement industry Usually indeed, the tailings flow rate is controlled in a monovariable loop by means either of the classifier speed or of the feed rate

The process has been simulated using the model previously described in Section 3 A multivariable controller is designed following the lines of Section 4, with the design choices presented in Section 5

In Figure 6, the multivariable controller (solid line) is compared with a monovariable *PI* controller (dashed line), using the classifier speed as control variable As shown in the first six hours of the tailings feed rate plot (Fig 6a), the monovariable controller has been tuned so as to yield a tracking performance comparable to that of the multivariable one Looking at the plots of Figures 6c and 6d (product and feed rate) one can notice that the deviation of the product flow rate (Fig 6c) with respect to its constant reference

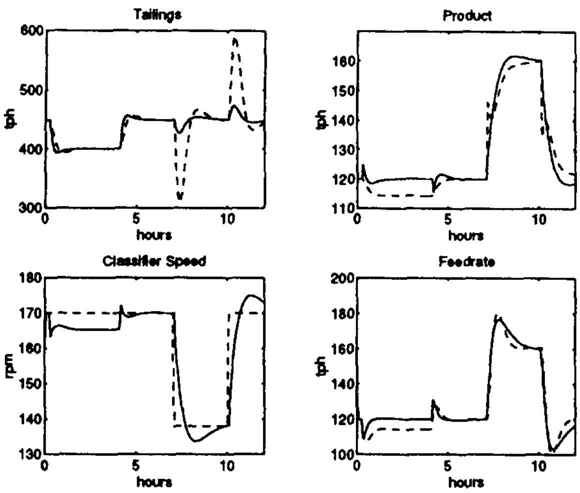

Figure 7 Comparison between the LQ-MV Controller and a PID Controller with the Feed rate as Control Input

value is significantly reduced with the LQ control at the price of some action by the feed rate, Fig 6d (this is the multivariable effect). The last six hours of these plots show what happens at constant tailings setpoint when one wants a change in product setpoint The multivariable controller handles the requested change directly In the monovariable case, one has to compute an openloop change in feed rate in order to achieve the product change However, this change in feed rate in the monovariable case produces a much larger perturbation on the tailings rate Such behaviour illustrates an advantage of the multivariable structure

Similar results can be obtained when comparing the multivariable controller (solid line) with a monovariable controller with the feed rate as control input (dashed line), as shown on Fig 7 Again, the monovariable controller has been tuned so as to yield similar performances to the multivariable controller's when controlling the tailings rate (first part of the plots) When applying a classifier speed change in order to obtain a change in product flow rate (last six hours of the plots), the results of the monovariable strategy are however much worse than in the multivariable case

5 INDUSTRIAL APPLICATION

The LQ multivariable controller described above has been implemented on the milling circuit ♯3 of the Company "Cimenteries d'Obourg", Belgium It has now been in routine operation for more than one year without interruption

The control code has been written in C-language and is running on a standard PC connected to the supervising DDC system (Texas Instruments) of the process The choice of the weighting matrices Q_1 and Q_2 has been performed according to the classical recommendations of the literature (see e g (Bitmead *et al*, 1990))

$$Q_1 = B_d^* B_d^{*T} \quad Q_2 = C_d^* C_d^{*T}$$

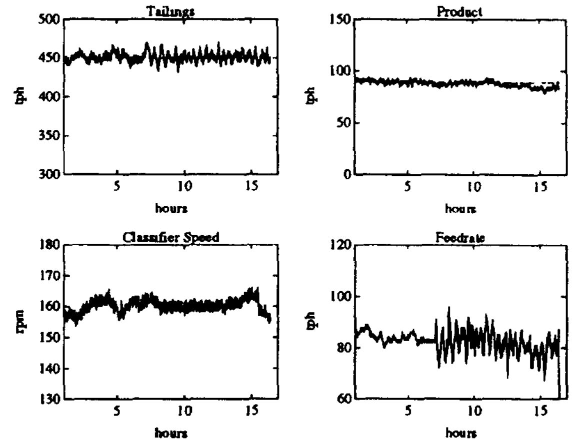

Figure 8 Experiment 5 September 1993

and the 4 remaining design parameters have been tuned on the basis of simulation studies Eventually, the following values have been chosen for R_1 and R_2

$$R_1 = \begin{pmatrix} 100 & 0 \\ 0 & 100 \end{pmatrix}, R_2 = \begin{pmatrix} 0\,1 & 0 \\ 0 & 0\,1 \end{pmatrix}$$

The behaviour of the initial system is now illustrated with selected excerpts of the data obtained in May 1992 (Experiment 4) and in September 1993 (Experiment 5)

The latter experiment (Experiment 5, September 1993, Figure 8) allows one to compare the multivariable LQ controller with the former monovariable PID controller which was in operation prior to this development During the first six hours, the multivariable LQ controller is in operation and yields excellent regulation of both outputs (tailings and product flow rate) using the classifier speed and the feed rate After approximately six hours, the system is switched back to the old control structure, namely the control of the tailings using the feed flow rate The classifier speed is kept constant for most of the subsequent time, except at the end of the experiment where, in order to obtain a better fineness of the cement, the speed of the classifier has to be increased (manually), which yields a drop in product flow rate The superior performance of the multivariable control structure is obvious

The former experiment (Experiment 4, May 1992, Figure 9) covers 60 hours of production using the multivariable controller and is representative of the usual behaviour of the system A change of cement quality has occurred at the 17th hour It is characterized by a change of product setpoint (from 160 Tons/hour to 140 Tons/hour) while the tailings setpoint is maintained at 400 Tons/hour The transition has been done manually by the operators, by manipulating the feed rate while keeping the classifier speed at a constant value Because of this manual interruption of the feedback, one cannot appreciate the decoupling capability of the control algorithm in response to this big step in the product setpoint But, as a compensation, one can examine the excellent response of the controller just after the transient to this big disturbance of the closed loop

Note also that an incident has occurred around the

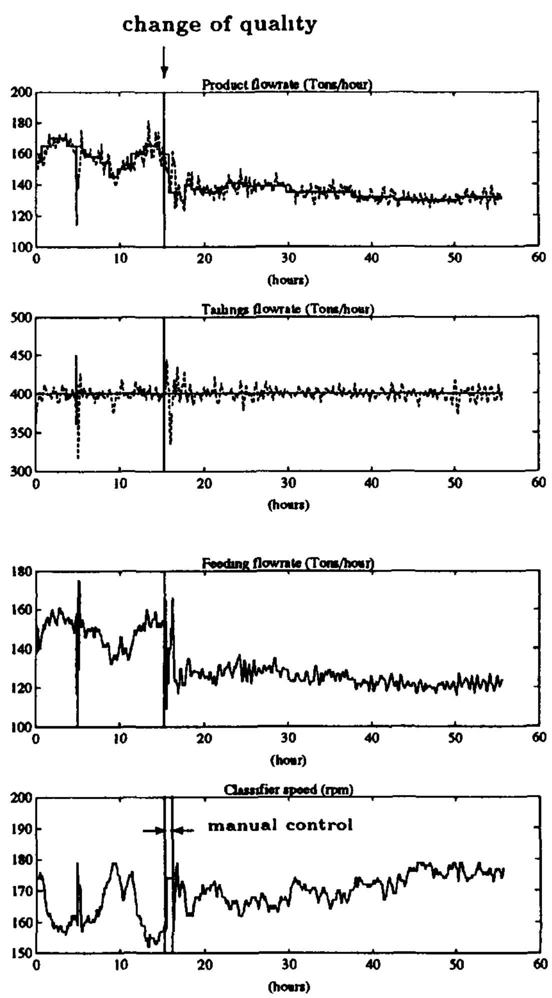

Figure 9 Experiment 4 May 1, 1992

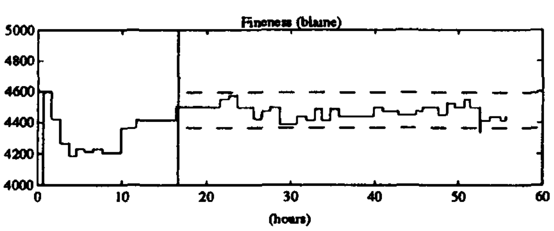

Figure 10 Fineness control during Experiment 4

6th hour the feed flow rate has been accidentally switched off This again gives the opportunity to observe that the controller allows for stable behaviour to be recovered rapidly after such a big disturbance Eventually, one notices that the operators have used the product setpoint as a means to control manually the fineness which is shown in Figure 10 to be well maintained inside the allowable range of tolerance

6 CONCLUSIONS

This paper has presented the design procedure of a model-based multivariable linear quadratic control algorithm for the regulation of tailings and product levels in a cement mill The control variables are the feed rate and the classifier speed Various experimental results on a full-scale industrial process have been presented to illustrate the behaviour of the control system

7 ACKNOWLEDGMENTS

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