Multiple-Model Control Strategy of a one Chamber Ball Mill

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Key Words: *Multiple-model adaptive control; cement grinding; Robust stabilization; time-variant nonlinear plants.*

Abstract. *This paper presents a method for multiple-model (MM) control of a cement-milling circuit. The approach presented is based on the experimentally justified model developed by Breusegen. The results from the MM control (using multiple proportional-integral (PI) controller) are compared to results from robust stabilization of a nonlinear cement mill model (by two single PI controllers).*

1. Introduction

Nonlinear behavior, uncertainties and the appearance of internal disturbances are often met when studying many of the industrial plants. This imposes a necessity of advanced methods for designing control systems in particular for in particular mill systems.

One chamber ball mill with recycle is a strongly nonlinear industrial plant. The first results of this system have been presented in Breusegen [2] which system is based on on-site experimentation and can be described with equations ($1 \div 3$). The results constitute a basis for the dynamic model presented in Magni [9]. It has been shown in Breusegen that linear quadratic control scheme based on the minimization of several system specific performance criteria could lead to an admissible results about behavior of the closed loop system, but did not guarantee robust stabilization. In Magni et al [9] the nonlinear predictive control of the cement mill is studied, and in [7] a robust control scheme is studied when the plugging phenomenon appears caused by bigger hardness of the feed for grinding material.

In this paper the author proposes the control of the one chamber ball mill to be realized with the multiple-model approach. It is shown that this control method is applicable for this nonlinear time varying plant. This is proved by the comparison of the results from the multiple-model strategy and the robust stabilization approach described in the literature [7].

The paper consists of the following sections. In the second section the mathematical description of the plant (ball mill) is presented. In the third section a brief description of the multiple-model control strategy and its application towards the described plant are given. The structure scheme used for control as well as the information about control channels is shown. The purpose is to guarantee stable functioning of the plant in different regimes. The experimental part is presented in section 4. The conclusions are exposed is section 5.

2. Plant Description

Control of the cement mill can be realized by classical PI law for the circulation loading of the mill through the influence on the speed rotation of the separator and/or through the influence on the quantity of the material feed for grinding [7]. Linear controllers based on the linear approximation of the processes are stable and effective only in a limited area around the work point. In some cases disturbances appear caused by the specific process and push the plant (the mill) to the work area in which the controller can not stabilize its work. A typical example for a similar situation is the plugging phenomenon of the mill when the material hardness is changed.

For solving this problem the following nonlinear model for description of the plant is used [4, 5, 6]:

(1) $T_f \dot{y}_f = -y_f + (1-\alpha(\upsilon))\varphi(z,d)$;

(2) $T_r \dot{y}_r = -y_r + \alpha(\upsilon)\varphi(z,d)$;

(3) $\dot{z} = -\varphi(z,d) + y_r + u$,

where $T_f, T_r [\min]$ are time constants; $z[t]$ is quantity of the material inside of the mill (loading); d — hardness of the clinker; $\alpha(\upsilon)[rpm]$ — separation function; $\varphi(z,d)\ [t/\min]$ — quantity of the material outside of the mill; $\upsilon\ [rpm]$ — speed of the separator; $y_r\ [t/\min]$ quantity of the material which is returned for grinding; $y_f\ [t/\min]$ — quantity of the finely ground material.

The values of the variable coefficients in this nonlinear model are tuned so that the model control variable coincides with the plant control one when the reference is step signals [3].

The dynamic model of the system consists of three nonlinear differential equations. The regimes of the system can be characterized by z, y_f and y_r. The system has maximum two control actions u and υ. Usually the control is realized only through the channel of u. The speed of the separator υ is constant.

In equations (1 ÷ 3) $\varphi(z,d)$ and $\alpha(\upsilon)$ are equal to:

$$\varphi(z,d) = 20 * z * \exp\left(-\frac{d*z}{80}\right);$$

$$\alpha(\upsilon) = 9\left(\frac{\upsilon}{\upsilon_{\max}}\right)^3 - 13.5\left(\frac{\upsilon}{\upsilon_{\max}}\right)^4 + 5.4\left(\frac{\upsilon}{\upsilon_{\max}}\right)^5;$$

$$\upsilon_{\max} = 200, \quad \alpha_{\max} = 0.9, \quad T_f = 18[\text{min}], \quad T_r = 0.6[\text{min}].$$

In the steady-state operation, it is clear that the product flow rate $y_f[t/\min]$ is necessarily equal to the feed flow rate while tailings flow rate y_r and the load in the mill z may take any arbitrary constant values. The load in the mill depends on the input feed and on the output flow rate that depends in a nonlinear way on the load in the mill z and the hardness of the material d, which is a time varying parameter. Sometimes this nonlinearity can also cause instability of the system and obstruction of the mill. The load in the mill must be controlled at a well chosen level, because too high level of the load in the mill leads to the obstruction of the mill, while too low circulating load contributes to too fast wear of the mill internal equipment. A usual approach is to control [9] the tailings flow rate y_r by using the feed flow rate as control input. This strategy is, however, not fully satisfactory since it indirectly induces a loss of control of the product flow rate y_f.

One of the approaches for solving the problem with plugging phenomenon, when the hardness of the feed material changes, is the method of global robust stabilization described in details in [7]. The control objective is to control the mill load z and the production rate y_f at desired set points z_{ref} and $y_{f\,ref}$ by acting on the feed rate u and the separator speed ν. The most important control goal is constant value of z to be guaranteed. The controller must prevent the mill from plugging and achieve global stabilization. Moreover, the controller must be robust against modeling uncertainties. The control inflow rate u and the control separation speed υ are physically constrained to be positive and saturated.

The control law derived in [7] is:

(4) $u = m(\psi)$;

(5) $\psi = -y_r + k_1(z_{ref} - z) + \theta$;

(6) $\dot{\theta} = k_2(z_{ref} - z) + k_2(m(\psi) - \psi)$;

(7) $\upsilon = l(\eta)$;

(8) $\dot{\eta} = k_3(k_2(y_f - y_{f\,ref}) + k_2(l(\eta) - \eta))$,

where $m(\psi) = sat[0, u_{\max}](\psi)$ и $l(\eta) = sat[0, \upsilon_{\max}](\eta)$.

The equations (4 ÷ 8) present a very simple control law made up of two saturated PI controllers with anti wind-up. Block diagrams of the two controllers are presented in *figure 1*.

The closed loop system is:

(9) $T_f \dot{y}_f = -y_f + (1-\alpha(\upsilon))\varphi(z,d)$;

(10) $T_r \dot{y}_r = -y_r + \alpha(\upsilon)\varphi(z,d)$;

(11) $\dot{z} = -\varphi(z,d) + y_r + u$;

(12) $\dot{\theta} = k_2(z_{ref} - z) + k_2(m(\psi) - \psi)$;

(13) $\dot{\eta} = k_3(k_2(y_f - y_{f\,ref}) + k_2(l(\eta) - \eta))$;

(14) $\psi = -y_r + k_1(z_{ref} - z) + \theta$;

(15) $\upsilon = l(\eta)$.

For a more precise understanding of the presented above method in *figure 2* the structure scheme of the control system is shown.

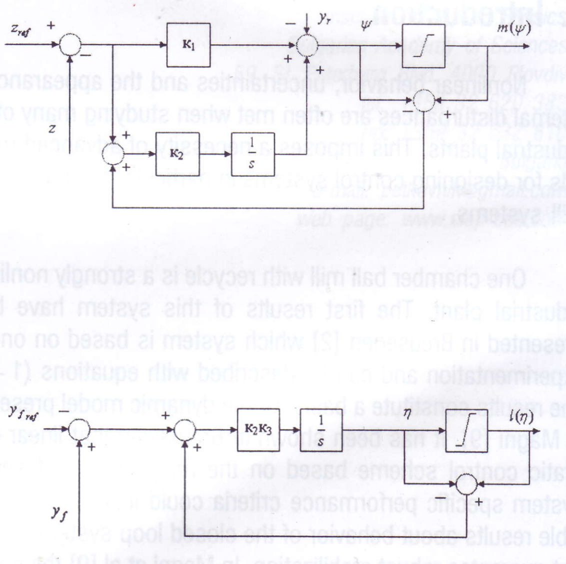


Figure 1. Structure diagram of the two PI Controllers

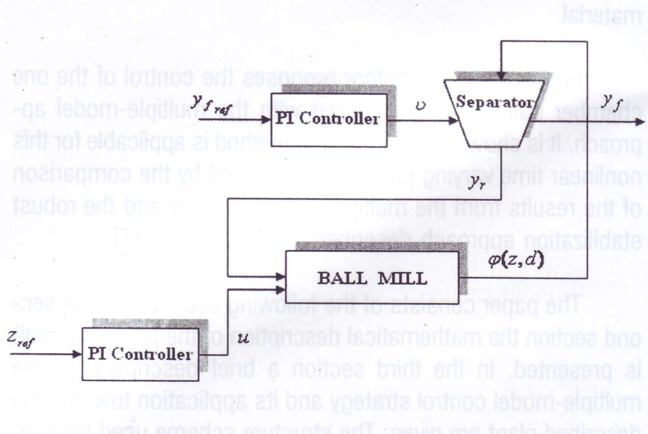


Figure 2. Block diagram of the control system of the one chamber ball mill

3. Multiple-Model Control Strategy

One of the adaptive control strategies, which is not based on the recursive parameter estimation of the model, in contrast with the classical adaptive control, is the multiple-model control strategy of one chamber ball mill. The behavior identification of the plant is based on the weighted behavior of a set of preliminary identified models (bank of models) for the different operating regimes [11, 12] (*figure 3*). The models can appear in result of identification in an open loop for each of the regimes when prior knowledge about the operating area of the plant is available. The design of the model bank has essential significance for good quality control. The selected models number is usually related to the operating conditions number over which the control system is expected to work. The number of the models into the bank is also important.

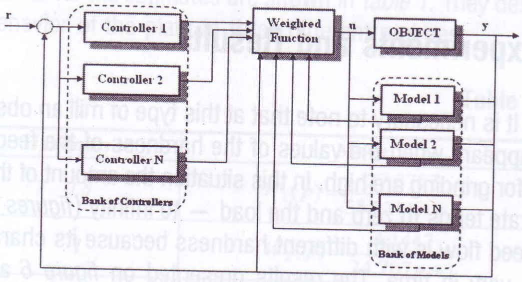


Figure 3. Basic structure diagram of multiple model adaptive control

It is confirmed by numerical experiments, existing in the literature statements [8] that after determined number of models into the model bank the quality control can change for the worse. It is possible a large set of models to be used and for each regime only one model is chosen among them which is the closest to the real model in the current moment. The number of the models in the model bank determines the number of the controllers in the bank of controllers — multiple controller. The essential property of this type of controller is its robustness for the changing area of parameters which is covered from the model bank.

The basic discrete multiple-model adaptive algorithm for control of the continuous input-output object proposed from Garipov [13] and finally formulated in [6, 14] consists of the following steps:

Step 1. The number N of operating regimes has to be specified. The plant is expected to be known or identified off-line in these N operating points. The reference signal is given.

Step 2. The sample time T_0 is specified and all multiple-model adaptive control (MMAC) signals in time range Ò $= MT_0$ are observed at the moments kT_0, $k = 0,1,\ldots,M$. A bank of N discrete-time models for sample time T_0 is formed.

(16) $A_j(\theta;q^{-1})y(k) = B_j(\theta;q^{-1})u(k) + e_j(k)$, $(j=1,2,\ldots,N)$,

where $A_j(q^{-1}) = 1 + a_{j,1}q^{-1} + \ldots + a_{j,na}q^{-j,na}$ and are polynomials of the operator q^{-1}. These models correspond to the continuous-time descriptions of the plant at the N operating points. The larger number of models will result in harder numerical complexity of the algorithm, but more accurate plant identification.

Step 3. The multiple model controller consists of a bank of N discrete controllers.

(17) $R_j(q^{-1})u_j(k) = S_j(q^{-1})y(k) + T_j(q^{-1})r(k)$, $(j=1,2,\ldots,N)$,

where the polynomials R_j, S_j and T_j have a specific description according to the design method.

Each of the single controllers is tuned for the exact model from the bank (16) of N discrete-time models using the multiple-model adaptive control system (MMACS) error e as an input. The rules of tuning depend on the desired control and the design method.

Step 4. The weighted mechanism is a procedure in a supervisory level to calculate the weights of each control signal in MMACS. Usually it is suggested that the current values of weights are functions of the prediction model errors in each sample time interval with index k and duration T_0, $\mu_i(k+1) = F_1[\hat{e}_i(k+1)]$ and they can be calculated according to:

(18) $\hat{e}_i(k+1) = \{y(k+1) - \hat{y}_i(k+1/k)\}$, $\quad k = 0,1,\ldots,M$.

At the moment $(k+1)$ the prediction model output depends on the weight of the control signal at the moment k, i.e. $\hat{y}_i(k+1/k) = F_2[\mu_i(k)]$, $\mu_i(0) = \mu(0)$.

The following idea is applied in the paper: let F_1 express the inverse proportional dependence of each weighted control coefficient on the corresponding prediction model error by:

(19) $\mu_i(k+1) = J_i^{-1}(k+1)\left[\sum_{i=1}^{N} J_i^{-1}(k+1)\right]^{-1}$, $k = 0,1,\ldots,M$,

where

(20) $J_i(k+1) = \hat{e}_i^2(k+1)$ and $\sum_{i=1}^{N}\mu_i(k+1) = 1$

A numerical problem with the implementation of the described algorithm arises from the possible underflow and overflow in the calculation of the model probabilities. This problem usually exists when the true system mode is very different from one or more models used in the algorithm.

A common technique to circumvent the numerical problems of the standard implementation is to place a lower bound on the model probabilities to prevent any model probability from becoming too small. Although this technique enables each model to be practically activated quickly, it is only an ad hoc trick without solid theoretical justification [10].

Step 5. Start of the described algorithm. All initial values of the weighted coefficients in MMACS can be assumed equal as $\mu(0) = 1/N$, i.e. the weighting mechanism starts with an equal weight of each controller in MMAC.

The block diagram of the multiple-model control system presented in *figure 1* is developed further and specified for the described in section 2 plant.

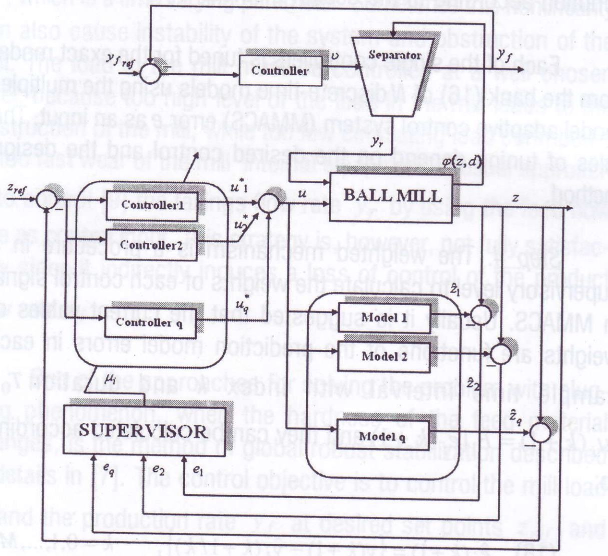


Figure 4. Structure diagram of the multiple-model control system of ball mill with recycle

The special feature of the plant requires two channel controls to be realized. The first channel is: controlled value — load z of the mill, control action — feed flow rate u. Controlled value for the second channel is finely ground material y_f and control action is speed of the separator υ.

The first channel is designed to eliminate the mill obstruction when the characteristics of the feed material are changed and for improving the work of the load disturbance when the hardness d is changed. This is the reason of proposing the multiple-model approach for control which can deal with abrupt changes in the operating regimes. This is the situation when the hardness of the feed flow rate changes from d_1 to d_2 ($d_1 \le d_2$ or $d_1 \ge d_2$).

The load z of a mill is desired to remain equal to constant preliminary set values $z_{ref} = const$. Using a multiple-model control scheme this condition is satisfied but only for hardness values lower or equal to 1 ($d \le 1$). When $d > 1$ and for the purposes to prevent abrupt changes of the mill, it is needed to decrease the load z at other equal conditions $\upsilon = const$. The decrease of z is one decision of the mentioned problem but on the other hand the decrease of z, which for $d = 1.33$ is with $22.4[t]$, leads to a rapid wear of the inner equipment because of the direct contact between it and the grinding balls. Therefore, it is necessary also to control one of the two parameters y_f or y_r, aiming at increasing values of z. This is possible to be realized by impact on speed of the separator ν.

4. Experiments and Results

It is necessary to note that at this type of mill an obstruction appears when the values of the hardness of the feed material for grinding are high. In this situation the amount of the out flow rate tends to zero and the load — to infinity (*figures 5, 6*). The feed flow is with different hardness because its characteristics vary in time. The results presented on *figure 6* are for constant values of υ.

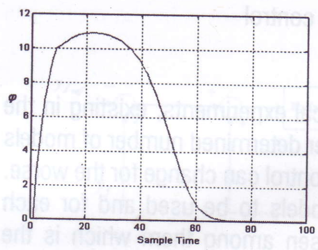


Figure 5. Behavior of φ

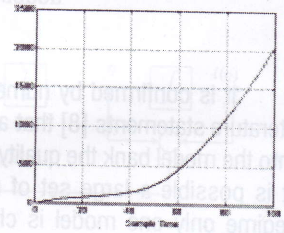


Figure 6. Behavior of z

The multiple-model control strategy needs models for each of the probable regimes. For the particular task these are the models for different hardness values. The experimental results show that only one model for description of the behavior of the mill for hardness to 0.8 in relative scale can be used.

The tasks that have to be solved can be separated commonly in two:

- Modeling;
- Control.

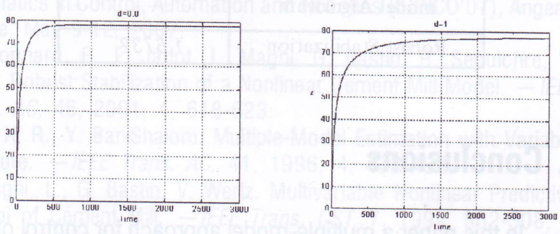
The first task — identification of the set of models and proof of their applicability for the control purposes of the corre sponding regime. Second task — design of multiple-model control system, which includes: design of the model bank, design of robust multiple-model controller, basic algorithm for operation of the supervisor. At the end a controller is necessary to control the separator, so that the load z has constant values.

The models for different values of d are identified for channel u-z. The response of the plant z when the control action is u_{ref} is a process which can be approximated with a first order lag. Table presents identified analytical models for d=0.8; 1; 1.33.

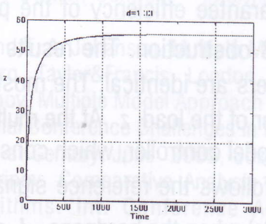
In *figure 7* the load of the mill with different amount of material with different hardness d is shown (open loop). Three models are estimated out of the presented characteristics in *figure 7*, by identification using an optimization approach, and the results for the estimates are shown in *table 1*. They describe the behavior of the plant in three different regimes.

Table 1

Hardness d	Model
0.8	$W_1(p)=\dfrac{27.3757}{55.9211p+1}$
1	$W_2(p)=\dfrac{4.1447}{24.707p+1}$
1.33	$W_3(p)=\dfrac{31.2646}{80.5556p+1}$



a) b)



c)

Figure 7. Behavior of z at different hardness of the feed flow

From *figure 7c* it is noticed that z does not accept the desired value — 78 tons. The reason is that the experiments are performed with a constant value of υ.

A multiple-model algorithm for control of z by influencing on u — amount of feed flow material, by setting of three single PI controllers in the bank of controllers, and control of angular speed of the separator υ by one PI controller which ensures constant load by correction in υ. The reference signal z_{ref} is equal of 78 tons all the time.

The successful realization of the described control scheme of that nonlinear plant leads to the prevention of the mill obstruction when the values of hardness d are high.

The discrete analogues of the models presented in table 1 are found. They are used for design of the model bank and multiple-model controller. After a set of experiments it is determined that with a set of three models, respectively three controllers, the range of d from 0.5 to 1.33 is covered.

For stabilization of z on the desired value the process for channel $\upsilon - y_f$ has to be identified. The result of the identification is a model which is used for design of the controller that realizes a correction of the separator speed υ.

The initial conditions for operation of the closed loop system are defined as follows:

- $z_{ref} = 78[t]$ and $y_{f_{ref}} = 141.5[rpm]$;
- material with hardness $d = 0.8$ is feed to put the mill in nominal regime (reaching nominal load 78 [*t*]).
- all controllers which form multiple-model controller are with equal weights $\mu_i = 1/3; i = 1,2,3$ in weighted control action.

When the parameters settle down on the reference signals the hardness d is changing according to the profile presented in *figure 8* with which the feed of the fresh material with different characteristics is simulated.

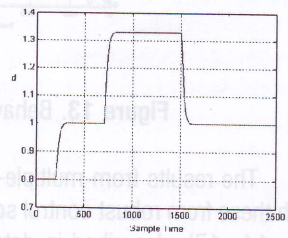


Figure 8. Profile of hardness d

From *figure 4* it is seen that the multiple-model approach is used for control of the mill load z, and the speed of the separator is needed to be corrected in order to be guaranteed constant value of z.

The results from the operation of the system presented in *figure 4* after reaching the desirable regime are shown in *figures 9 ÷ 12*. In *figure 13* the behavior of the weights for the whole operating interval of the plant is presented.

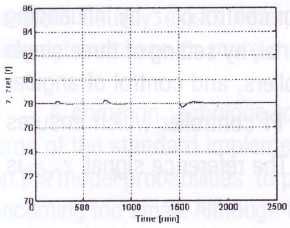


Figure 9a. z and z_{ref}

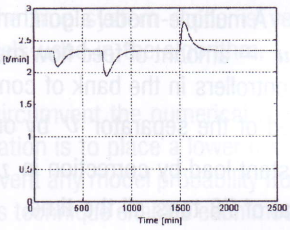


Figure 9b. Weighted u

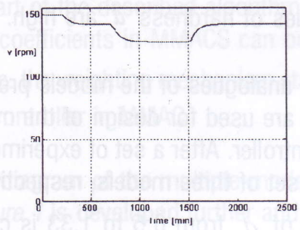


Figure 10. Behavior of the separator speed v

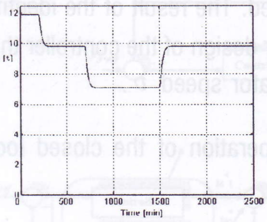


Figure 11. Behavior of $\varphi(z,d)$

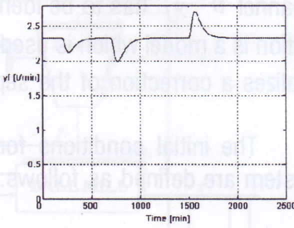


Figure 12. Behavior of y_f

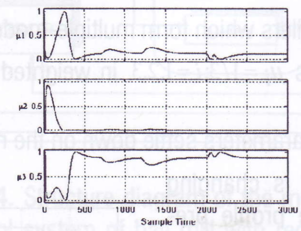


Figure 13. Behavior of the weights μ_i

The results from multiple-model approach are compared with these from robust control scheme proposed in the literature. (fig. 14÷17), described in details in [7].

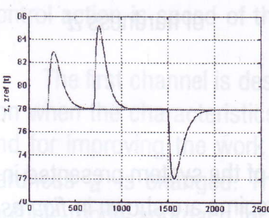


Figure 14a. z and z_{ref}

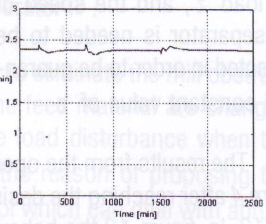


Figure 14б. Behavior of u

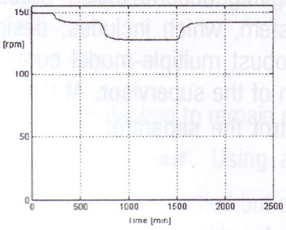


Figure 15. Behavior of the separator speed v

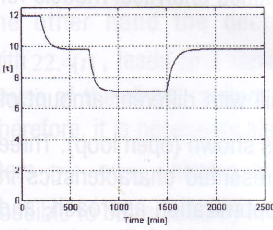


Figure 16. Behavior of $\varphi(z,d)$

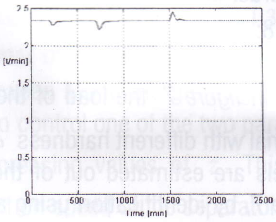


Figure 17. Behavior of y_f

The *least squares of the estimated time-variant plant control error* are used as accuracy criterion – for the two approaches shown in *table 2*.

Table 2

Algorithm Type	*Error Value*
Input-Output Multiple-model Algorithm	*0.0193*
Robust Stabilization	*1.6732*

5. Conclusions

In this paper a multiple-model approach for control of one chamber ball mill is proposed. The obtained results are compared with results obtained from a approach proposed in the literature. The comparison of the results shows that the two approaches guarantee efficiency of the plant when $d=1$ and without $d=1.33$ obstruction. The results for more of the observed parameters are identical. The most essential difference is in the behavior of the load z. At the multiple-model approach with multiple-model controller, which consists of three single PI controllers, z follows the reference signal with smaller oscillations (*figure 9a*) when the hardness d changes. This behavior of z guarantees longer „life" of the mill because this working regime of the mill is close to the optimal. At the described in the literature approach for control with only two single PI controllers the oscillations of z are significant (*figure 14a*). This is confirmed with results from *table 2*. The result for Input-Output Multiple-model Algorithm Error is achieved by insignificant higher values of control action u.

When the behavior of u (*figures 9b and 14b*) is compared there can be made the following conclusion. There is a smooth change in the value of u (*figure 9b*) generated by the multiple-model control strategy, while at control with two PI controllers (*figure 14b*) u has smaller values but it changes quickly and the deviation from the reference signal is insignificant. Physically, this corresponds to an approximately constant amount of fed fresh material. This is the reason about significant oscillation in the behavior of z at the described in the literature robust algorithm for stabilization.

This study showed the applicability of the multiple-model strategy for control of the one chamber ball mill.

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