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Improving the Multivariable Control of the OreGrinding System using Disturbance Observer Mechanism and the PI Controller

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ABSTRACT

Ore grinding system is a multivariable mechanism which is used in mining industry, metallurgy, cement production, chemicals, pharmaceuticals, ceramics and various research laboratories. Previous control methods of this system include open multi-loop PID controller, Model Predictive Control (MPC), adaptive control and robust control. The mentioned techniques do not show proper performance, when exposed to intense disturbances. In this research, an iron ore grinding system with intensive internal and external disturbances has been considered. Here, we have used a multivariable control method based on disturbance observer with two inputs and two outputs in the leading loop, and a PI controller for tracking the reference input in the closed loop. This method includes a controller for the product size loopand a controller for circulating load loop. In contrast to traditional disturbance observer systems which are more suitable for minimum phase systems, here the disturbance observer is improved to be used to estimatethe disturbance in a non-minimum phase system as well. To show the efficiency of the proposed control method, the iron ore grinding system circuit has been simulated in the Simulink environment and the designed controller has also been applied to it. The simulation results prove the proper performance of the suggested technique in the presence of various external disturbances in different practical situations.

Keywords: *Process Control, Multivariable Control, Disturbance Observer, Iron Ore Grinding System, PI controller.*

INTRODUCTION

Introducing the Process

Ore grinding system is a size reduction process that is used in the mining industry to increase the usable minerals extracted from ores. It's obvious that product size is highly influential in the recovery of valuable minerals. The components constituting ore grinding machine include ball mill, pump sump, fresh ore feed and cyclone. According to the raw material and its hardness, this system changes the ore or the raw material to a desired size. Anore grinding system should have a stableuniform distribution of the product size, maximum productivity and minimum loss (non-grinded pieces).

The Process Controller

Controlling an ore grinding system is naturally difficult due to its multi-input/output and interference structure. In a single-input/single-output system, the effect of a change in the input can be easily tracked in the output,and it is easy to determine the attributes of the input signal to achieve the desired output. But in a multivariable system exposed to disturbance, a small change in a single input will change the entire output, and it's notpossible to individually track the effect of inputs on outputs. Also, the ore grinding system involves excessive interference and it's not possible to design a separate controller for each pair of input/output. So the problem of interference should be solved first and then the controller should be designed.

Another problem in this system is the external intensive disturbance that renders the controller inefficient. The existence of disturbance in industrial processes is inevitable, but it's possible to eliminate it by identifying it in the controller. In the process of the ore grinding, disturbances have a great effect in the productivity of a closed loop system with a controller. The product size and circulating load are highly sensitive towards internal and external disturbances, which make the designing of the controller hard and inefficient. External disturbances include changes in the hardness of ore and the product injection to the

system, and internal disturbance is created due to the existence of interference and the mismatch of the model. For example when the primary input is changed to adjust the primary output to the desired size, and simultaneously the secondary input is manipulated to control the secondary output, the effect that the primary input puts on the secondary output due to interference, is considered as disturbance. On the other hand, some of the system behaviors cannot be described by the model, and that is considered as disturbance which can even result in system instability. The present research uses observer to eliminate disturbance, so it can identify the dimension and type of disturbance and consider disturbance control in the control algorithm and signal calculation, and prevent inappropriate effect on the output by a quick elimination scheme.
In practice, ore grinding system is controlled by extensive control systems or SCADA systems in which, the controllers, control the process variables on the reference size which is usually determined by the operator. Therefore, if the control algorithm is properly applied in the tracking of the reference input, the output in the ore grinding system will be tracked properly.

Review of the Previous Researches

Due to the difficulties and complexities of the ore grinding system control, the attention of many scholars has been directed to this subject. In [1] it has been proposed to control the grinding circuit by multi-loop PID controllers. Despite the simplicity of the control settings, the outcome of this controller is low and has little robustness against changes in the system parameters. Also if the system parameters are changed, the control parameters should be adjusted as well. One of the other common methods for the grinding system control is to use the Model Predictive Control, which has a high ability in dealing with interference and delay[2]. In [3] a solution for model predictive control based upon modified disturbance observer has been offered for the controlling of industrial systems. Also many control algorithms such as robust control [4], adaptive control, and neuro-control [6], have been used to control the grinding process in mines, and a review of these methods is listed in [7]. Advanced feedback control for the optimal performance of grinding process is usually done based upon the dynamic optimization of model predictive control.
In the majority of processes or industrial systems, the presence of disturbance and uncertainty is an inevitable problem. For example, in ore grinding system, the performance of this process is highly sensitive to various disturbances such as changes in the hardness of the ore and its size, model uncertainties and interference effects. These disturbances and process changes have great influence on the efficiency of the control in a closed loop system. Many advanced control methods such as model predictive control, usually can't have proper outcomes in delayed complex multivariable processes in the presence of strong disturbances and various uncertainties. To solve this problem, control systems can asymptomatically and slowly reduce the effect of these factors to the minimum by adjusting the feedback. This issue can reduce the performance of the control system when encountering strong disturbances and great uncertainties in the process [8].
To improve the performance of the disturbance elimination in these cases, it's possible to use hardware sensors to gather information about disturbances which will certainly lead to greater costs in production and higher system complexity. The proper method to overcome the disturbance problem is introducing leading compensating partfor disturbances into the control system beside the feedback part. A direct method to extract the disturbance model is to directly analyze the mechanism and remove the disturbance in the controller design. Nevertheless, it's not generally possible to extract the disturbance model in real systems [8].
A more effective method is to use disturbance observer method that can estimate and eliminate the effects of the disturbance without changing the input/output behavior [8]. Disturbance observer method was first introduced by Ohishi in 1987 [9] and today, due to its simple structure and high ability in removing disturbance and compensating the uncertainties of process, it's widely used in industrial systems and processes such as robot arm, hard disk drive systems, process mining industry, and magnetic suspension systems [8]. This method has a good ability in rejecting large external disturbances and model uncertainty, since it is not dependent on the accurate disturbance model, and actually estimates it. Disturbance observer is usually a double input-single output system whose inputs are control variable and controlled output, and its output is an estimation of the disturbance that is used in the leading compensator to remove disturbance.
In [10], an advanced feedback control that is based upon model predictive control and disturbance observer is suggested for the optimized performance of grinding system. In [11], a fractional disturbance observer is offered for the control of grinding system. In this method, a low-pass fractional filter has been used in the disturbance observer to add a degree of freedom in tracking the reference input and disturbance rejection.

Disturbance observers do not show proper efficiency in non-minimum phase systems with delay. An improved disturbance observer is proposed in [12]that is used as a leading compensation along with feedback.The gain of the feedback is calculated in an online form by using model predictive control method. Also in [13], multivariable disturbance observer has been offered to improve the performance of disturbance rejection in the advanced feedback control methods. All the stable and implementable disturbance observers are categorized in this reference based upon delay times and non-minimum phase of open loop zeroes.

The control algorithms discussed in the previous section, do not directly consider disturbance and have limited control ability in the presence of great disturbances, since they consider the effect of disturbance on output through feedback and try to reject it, and ultimately reduce the speed of disturbance rejection. Ore grinding system disturbances are large and cause damages to the system and should not have durable effects on the output and the previous methods are not proper due. A method is to use leading control in the disturbance path, so it would cut the disturbance before its effect reaches the output. But to do that, the disturbance model should be exactly calculated through the disturbance channel mechanism analysis which is not possible in the case of ore grinding system. The solution for this system is to use the disturbance estimation technique, which estimates the disturbance before entering the system and considers it in the controller design so the controller can quickly and without much control expense, reject the disturbances.

The Contributions of this Research

One of the important issues in multivariable control is the selection of proper pairs between input and output. It means that amongst the inputs and outputs, each output should be paired with the input that has the highest effect on it. The relative gain array matrix method, is used for the selection of pairs. Then to compensate the effect of the interference, a compensator that equals the reverse of the direct gain of the system matrix is placed in the leading path to reduce the effect of the interference. The most important contribution of the present research is that, the designed controller can remove the effect of interference and internal and external disturbances in the output, without any separate compensators. In this paper, a hybrid control algorithm is introduced that uses the combination of multi-loop multivariable control algorithm and disturbance-based multivariable observer. The controller designed for the ore grinding system, includes a loop to control the product size, which consists of a feedback control with proportional-integral controller, and a leading control to compensate the estimated disturbance with disturbance observer. The second control loop is intended to control the circulating load that uses the proportional-integral lead controller as the first loop does. The problem with the disturbance observer introduced by Ohishi is that it is not possible to use it in delayed cases. So we have improved the disturbance observer structure to deal with it here.

Paper structure

We discuss the primary definitions and concepts in the second section. The ore grinding process is introduced in the third section. The fourth section, describes the ore grinding machine's multivariable control structure with the use of improved disturbance observer-based control. Controller design and simulation results are also given in this section. The fifth section provides the conclusions.

Primary definitions and concepts

The processes, in which an output is controlled by a changeable variable, are categorized as single input-single output. In spite of that, many industrial processes have more than one control loop. In fact, in any industrial complex, at least two variables of product size and quality should be controlled. Therefore there are usually at least two control loops in industrial processes. Systems having more than one control loop, are known as multivariable systems.

Multi-Input Multi-Output System models

For systems having more than one output, input-output models are shown as in figure 1.

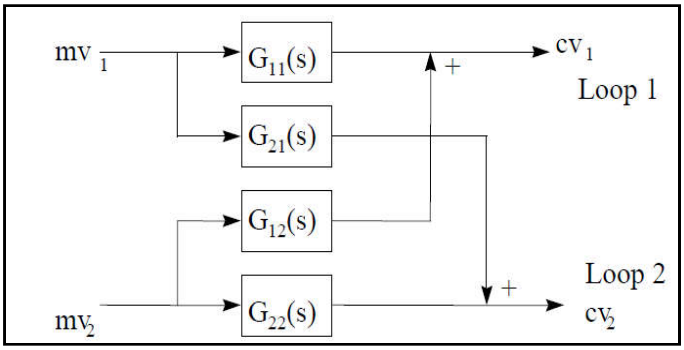

Figure (1): Multi-Input Multi-Output model structure

In the above figure, $G_{11}(s)$, showsthe leading path dynamics between the variables of $mv_1$and cv_1; while $G_{22}(s)$ shows the response method of cv_2 after making a change in the input mv_1. The effect of interference has been modeled using the transfer functions of $G_{21}(s)$and $G_{12}(s)$. The$G_{21}(s)$shows the relation between the input variable mv_1 and output cv_2, and the transfer function $G_{12}(s)$shows the relation between the variables of mv_2 and cv_1.

Mathematical Model in the Vector-Matrix Form

The elements in the blocks of figure 1 are transfer functions that show the relation between the corresponding input/output couples. According to the figure, the relation between each input and output in each loop can be described as follows:

$cv_1 = G_{11}mv_1 + G_{12}mv_2$ (1)
$cv_2 = G_{21}mv_1 + G_{22}mv_2$ (2)

The above equations can be rewritten in the vector-matrix form as shown below:
$cv = Gmv$ (3)

In the above equation, each matrix and vector is defined as follows:

$$cv = \begin{bmatrix} cv_1 \\ cv_2 \end{bmatrix} mv = \begin{bmatrix} mv_1 \\ mv_2 \end{bmatrix} G = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}$$

Inserting the Disturbance into the System Model

In section 1-2, only the main part of the process is considered. But in many cases, various processes are influenced by external factors such as changes in environmental temperature, material quality and performance environment. These factors are considered as *disturbance* in the system model. External disturbances are defined as unwanted inputs, while internal disturbances are actually the uncertainties of the system model. In modeling the real systems, the part of system behavior that cannot be described by model, or the mismatch of the model with the real world, can be considered as uncertainty. These uncertainties that have great influence in system behavior, are created in the system due to various reasons, one of which to mention is the changes of system parameters while functioning. To model the disturbance in multivariable systems model, the input-output relation is considered as below:

$cv = Gmv + G_d dv$ (4)

In the above equation, G_d matrix, which shows the effect of disturbance inputs on system outputs, is described as follows:

$G_d = \begin{bmatrix} G_{d1} & 0 \\ 0 & G_{d2} \end{bmatrix}$(5)

Disturbance input is considered as below:

$dv = \begin{bmatrix} dv_1 \\ dv_2 \end{bmatrix}$ (6)

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The illustration of the multivariable system block diagram with disturbance is as follows:

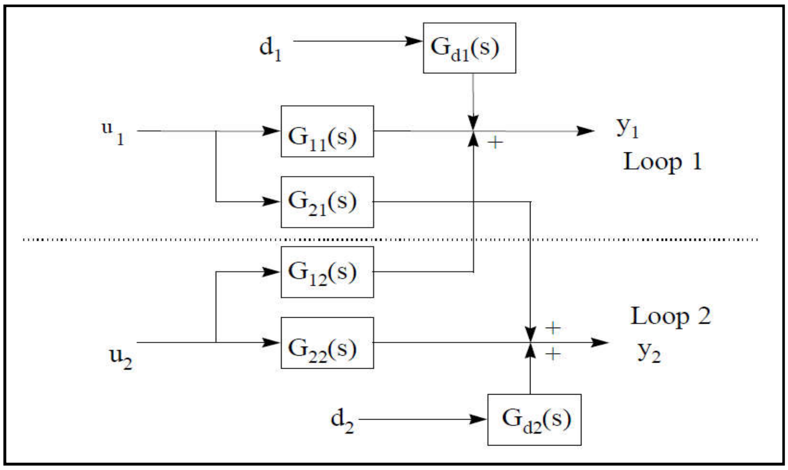

Figure (2): The illustration of multivariable system block diagram with disturbance

The Ore Grinding Process

Given that mining industry is one of the important industries in our country, Iran, and it's the most important financial resource after oil, increasing the productivity in this industry has been a concern for many years in this area.

According to the Ministry of Industry and Mines of Iran, about 5% of ores turn into waste due to improper efficiency of the ore grinding machines. Moreover, due to improper performance of the control system of these machines, the cost of energy consumption also increases. Product reduction factors includetype of grinding material, rotation speed and grinding mechanism, which will be briefly described.

Generally, there are three grinding materials: steel and other mineral metals, metal objects called cylpeb, and regular or high density ceramic stones.

Steel and other mineral metals with various component sizes from 10 to 15 mm, are mostly used in the ore grinding industry. Clypeb objects are used to grind ores without edges and with equal lengths and diameters from 8×8 to 45×45 mm. Their form has been evolved due to high density and special surface for the maximization of the ore grinding performance. Mineral ceramics with approximately equal densities are usually used for the initial clearing of ores, and mineral ceramics with high densities are used for ores containing aluminum oxide.

In terms of rotation speed, ore grinding processes are categorized in three performance modes of slow, fast and very fast. Each performance mode has a different charging path and different grinding objects collection. Ore grinding process can also act in *dry* or *wet* modes depending on whether the raw materials become wet or not. Size reduction of the final product depends on the following factors:

- Input material properties (mass, volume, hardness, density and size distribution)
- Mineral grinding material properties (mass, density, and size distribution)
- Rotation speed of the grinding part
- The density level of the slurry material in the wet mode

One of the important attributes of the industrial grinder is the production capacity of it, which is measured in tons per hour. Production capacity depends on the dimensions, type and loading of ores, rotation speed, material index, shaft power, and specific covalent bond of minerals.

Size reduction is the result of three main grinding mechanisms. *Abrasion* occurs when local stresses with low compression are applied to extract themain part of the original rock, as shown in figure 3.

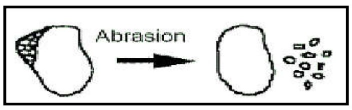

Figure (3) Abrasion of the ore parts

Cleavage happens when compressing forces are exerted to produce parts with 50% to 80% of the original part size, as shown in figure 4.

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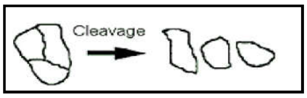

Figure (4): Parts cleavage in the ore grinding system

Fracturing is the result of the rapid usage of the compressive tensions to produce parts with small sizes and extensive size distribution, as shown in figure 5.

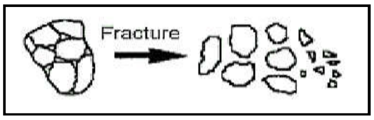

Figure (5): Fracturing the parts in the ore grinding system

In practice, none of the three above mentioned mechanisms happen alone, and size reduction of parts happens in all of them. The precedence for the occurrence of these mechanisms depends on the type of the rotary part, performance conditions and mineral material type.

Ore grinding is a size reduction process which is used in mining industry to increase the amount of usable materials extracted from ores. Figure 6 shows the ore grinding process that includes a ball mill, pump sump, fresh ore feed and cyclone.

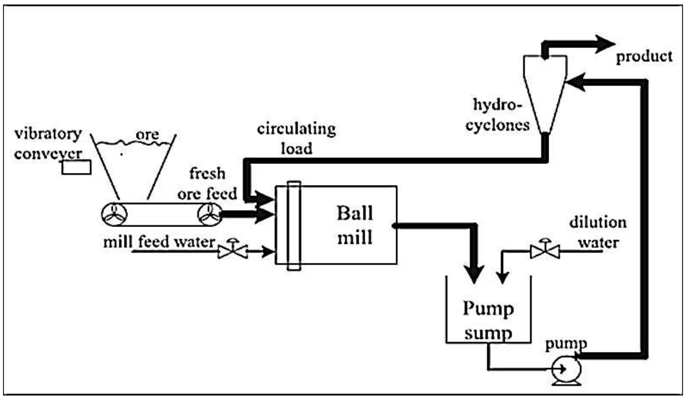

Figure (6): Ore grinding machine

When the ball mill operates, raw stones along with waterenter the process. Raw stones circulation together with milling in the ball mill turns them into ores with smaller size. The material obtained from combining the dilution water with product oresexit the mill in proper sizes and enter the pump sump. Afterwards, water is injected into pump to dilute the product, and then pump it into the hydro cyclones so they would be divided into two flows; a flow including granulations with desired size which goes towards the exit, and a flow with big granulations that re-enters the process as circulating load.

Designing an Improved Disturbance Observer for the Ore Grinding System

Ore grinding system has two inputs and two outputs, and a separate disturbance observer should be designed for each loop. In this research, to control the ore grinding system, a new algorithm based on Disturbance Observer Control Method (DOCM)is introduced, where each controller includes a PI feedback and a leading compensator for disturbances using an observer. At the end, the simulation results will confirm the efficiency of the designed controller.

The Structure of the Controller

Large external disturbances such as changes in the size of granulations and the hardness level of the ore can cause continuous fluctuations in the final product size. These changes, affect the product size and the amount of circulating load through delayed channels and elements with inertia. So the goal is to control and preserve the sustainability of the hardness level of ore and particle size, by determining the proper amount for the dilution water and fresh ore feed rate. The relation between inputs and outputs is shown in figure 7.

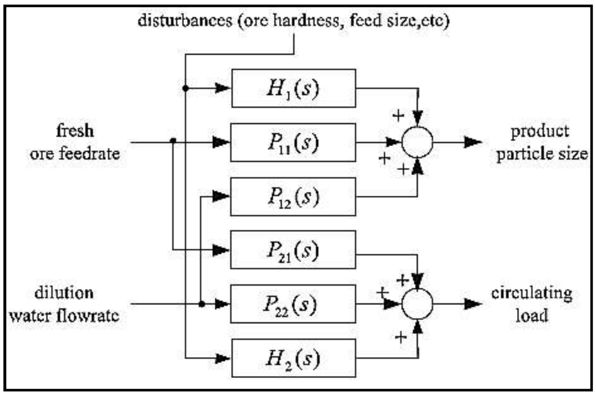

Figure (7): Block connection between the process inputs and outputs

In the figure above, it is shown that the u_1 (fresh ore feed rate) input with the transfer functionP_{11}, affects y_1 (product particle size) output. But the y_1 output also is influenced by u_2 input (dilution water flow rate) with the transfer functionP_{12} and disturbance with the transfer functionH_1, and this influence, makes it difficult to control the output. The y_2 output (circulating load) is also influenced by u_2 with the transfer functionP_{22}, u_1 input with the transfer functionP_{21} and disturbance with theH_2transfer function. To control the output, the factors affecting them should be controlled. The disturbance cannot be controlled among them, and only the effect of it on the outputs can be removed. It should be noted that the interference phenomenon, is clearly observed in this process, and to design an efficient controller, a separation scheme should be used. Also, given that the input of disturbance is not controllable, the controller should be designed to minimize the effect of the disturbance on the system output.
The first stage to design a controller for the multi input-multi output systemic to select input-output pairs. Note that the ore grinding system is a multi-input/multi-output system, which means the observers should be designed for different disturbances for each control loop between inputs and outputs. We use the improved disturbance observer to overcome the problem of interference and the mismatch of the model with the real system in the presence of intense external disturbances. In the ore grinding system considered in this paper, changeable variables (input variables), are the ratio of fresh ore to be fed into the system ($u_1(t)$) and the ratio of dilution water ($u_2(t)$). The controlled variables (output variables) are the product size (y_1) and the amount of circulating load (y_2). In this research, we pair the $u_1$input, with the $y_1$output, and the u_2 input, with the y_2 output.By this selection, the structure of the DOMC controller will be as figure 8.

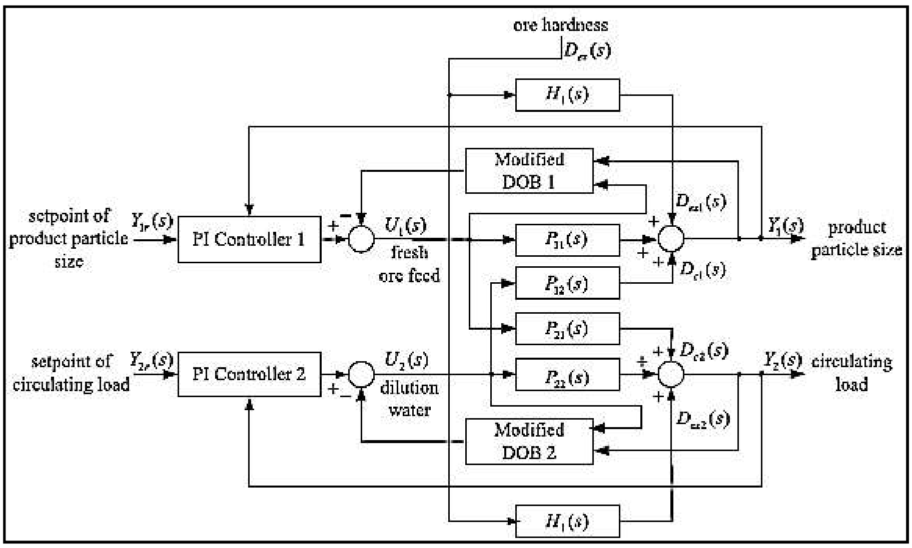

Figure (8): The structure of the controller with the improved DOMC

As is clear from figure 8, in the DOMC controller, two PI controllers and the two improved DOBs are used. Here we have considered the Q filter, to be low-pass of the first degree with a steady state gain of 1.

$$Q(s) = \frac{1}{\lambda s+1} \quad (7)$$

After designing the observer for external disturbances, it is time to design the PI controller. This controller has this advantage over the previous versions that it gives accurate estimation of external disturbances, while the model predictive control models disturbance based upon the previous behavior of the system, and (probably inaccurately) estimates it.
Ziegler-Nichols control method for systems with great disturbances has a proper performance. This method, considers a low value for proportional coefficient so there will be no instability problem. But concerning the ore grinding system that is naturally stable and slow, a large proportional coefficient can be chosen without any instability problem. But attention should be paid that this direct increase in gainis only possible in the first controller from the u_1 input to the $y_1$output. Considering the transfer function from u_2 input to the $y_2$output, it should be noticed that due to the delay of the system itself, it is not possible to add proportional gain to the system, sinceit will cause costs in the control signal and overshoot, and can be harmful to system drivers. So our goal is that despite the existence of external disturbance, the system response should have a proper speed and the overshoot must be removed.

Simulation results

To evaluate the efficiency of the designed controller, first a condition is considered in which the reference input of the product size, y_1, changes; The output of the ore grinding system in response to this change in the reference input, is given in the following figure.

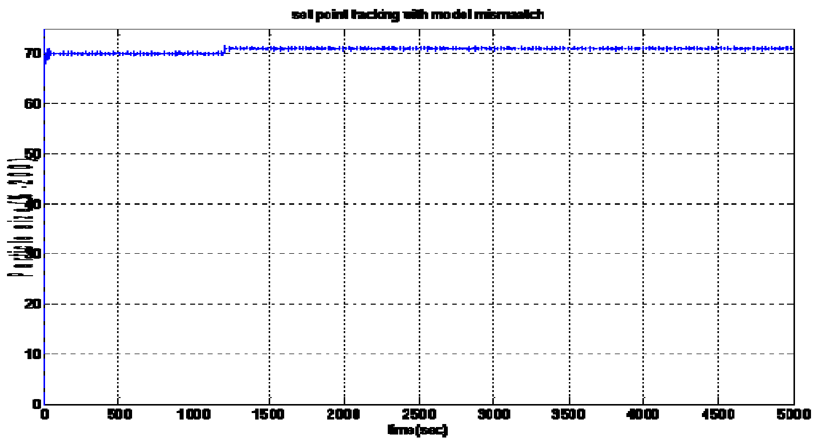

Figure (9): The output of the product size, in response to the size change of the reference product with DOMC

In the figure above, the reference input for the final size of the product, is primarily set to 70%, and it is shown that the controller takes the system output to the reference input without steady state error and with good transient behavior. There are different criteria for the analysis of the transient behavior of system, and given the attributes of ore grinding system, the maximum overshoot and setup time are considered as the comparison parameters. Then, the reference input is changed from 70% to 71%, 20 minutes after the simulation starts, and it is seen that the controller, has taken the output to the desired input without high overshoot. In this condition, the reference input for the amount of circulating load, has been set as a step signal with the value of 150 tons per hour, and no change has been made to it.
In figure 10, it is seen that the controller is able to track this reference input without error, and with the change of the first input, no change has happened in the output of the circulating load of the grinding system, and the effect of internal disturbances (change in product size) has reached its least amount.

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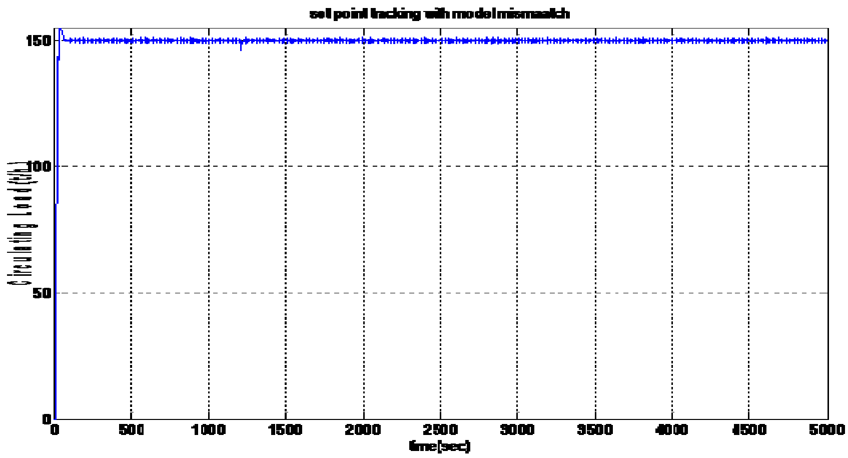

Figure (10): The output of the amount of the circulating load in response to the change in the size of the reference product with DOMC

Given that in practice, in addition to the tracking of the reference input, reducing the cost of controlis important, the control signal is shown in figure 11 to illustrate that the designed controller is able to track the reference input and reject disturbance by producing proper control signal.If the control signal does not have proper dynamic properties, it will wear out the system drivers and will be really expensive.

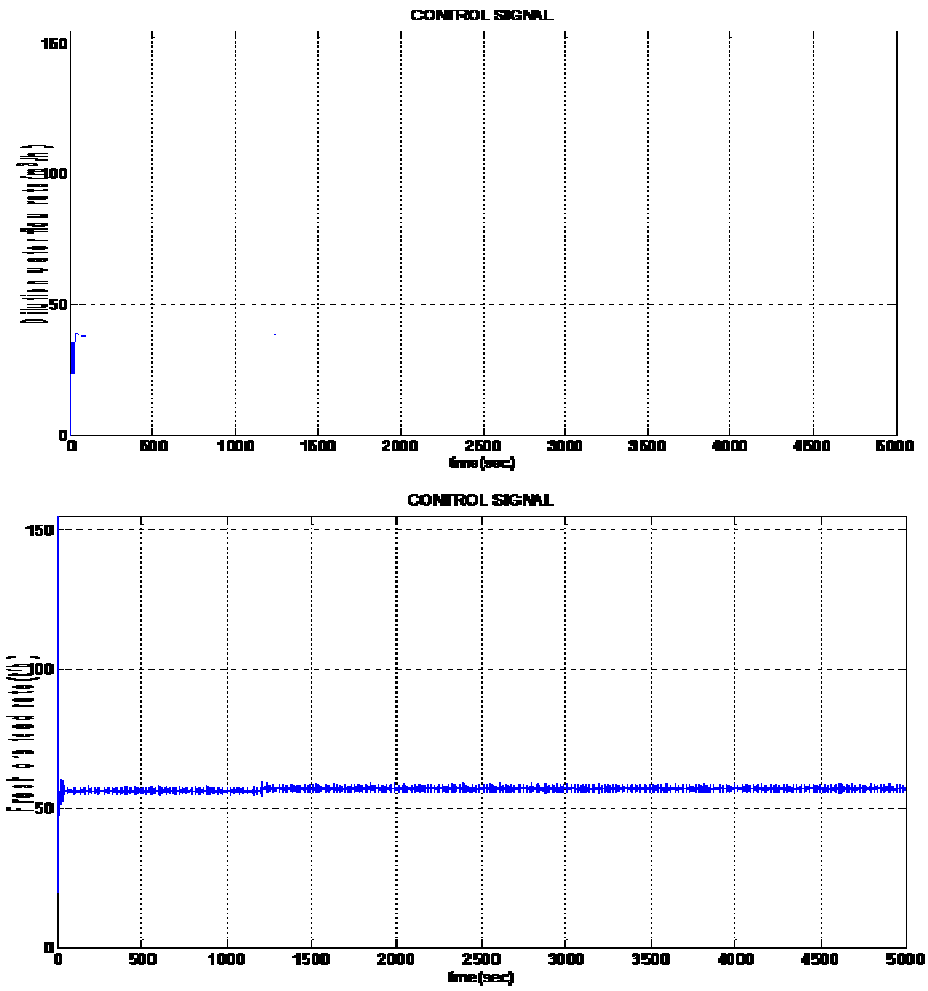

Figure (11): Control signals of u1 (right) and u2 (left) while changing the reference input of the product size

In the figure above, it is seen that the amount of the inject able ore, is about 50 tons per hour, which is physically suitable. Following the simulation, the reference input for the amount of the circulating load

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will be changed. In this condition, the reference input for the amount of the circulating load is primarily 150 tons per hour, which in the time of $t = 20\ min$, it will be changed to 155 tons per hour, and in the figures below, it is seen that the designed PI controller as well as the improved disturbance observer, has a proper performance and can track the reference inputwith a maximum overshoot of 3.2% in a short time. It should be noted that the changes in the reference input, are considered as internal disturbance and due to the presence of the improved disturbance observer, the controller can quickly capture these changes and eliminate their effect on the system output in a short amount of time. At this situation, the desired value for the product size is considered 70%. The simulation results are given in the following.

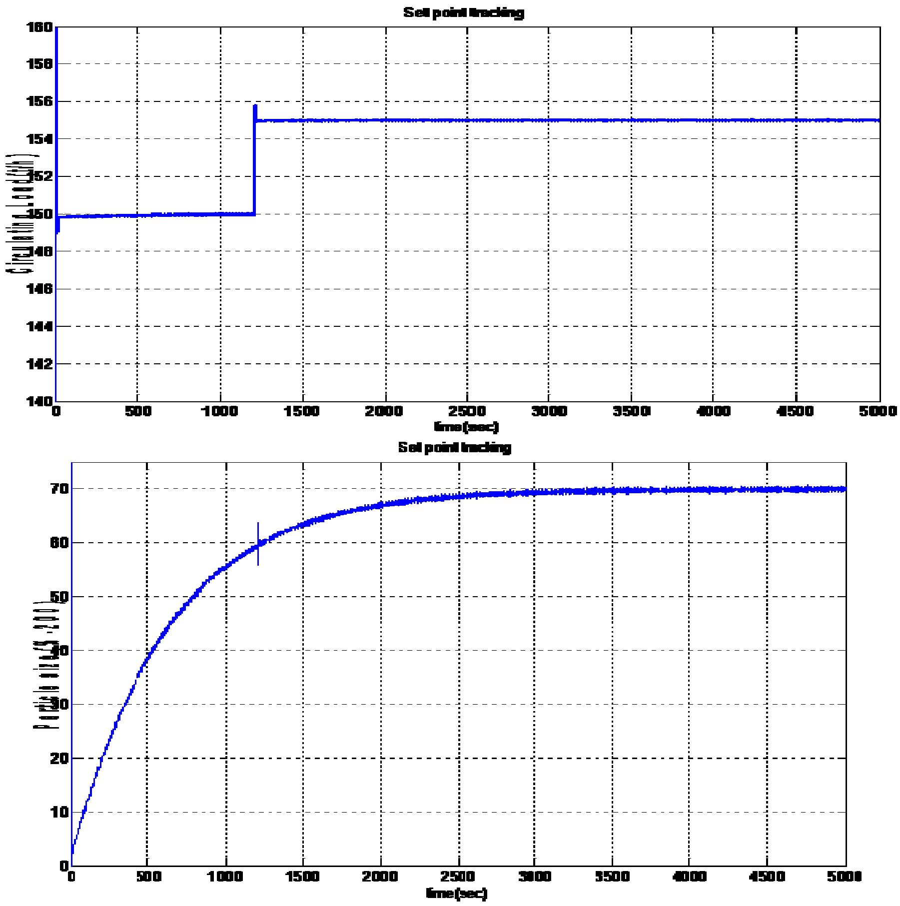

Figure (12): The output of the product amount (right) and the amount of circulating load (left) in the closed loop system with the PI controller and DOMC

It is seen in the above figures that the effect of disturbance is finally removed in this condition, and the output has reached the desired size which is 70%.On the other hand, despite the rapid change in the desired circulating load size, the designed controller can quickly and efficiently track these changes.
To simulate the external disturbance, the hardness level of the injectable ore in time $t = 20min$, is increased by 10%. In the following, the response of the closed loop product size and the amount of circulating load in the presence of external disturbance are given, which reflect the proper ability of the designed controller in rejecting the large external disturbances.

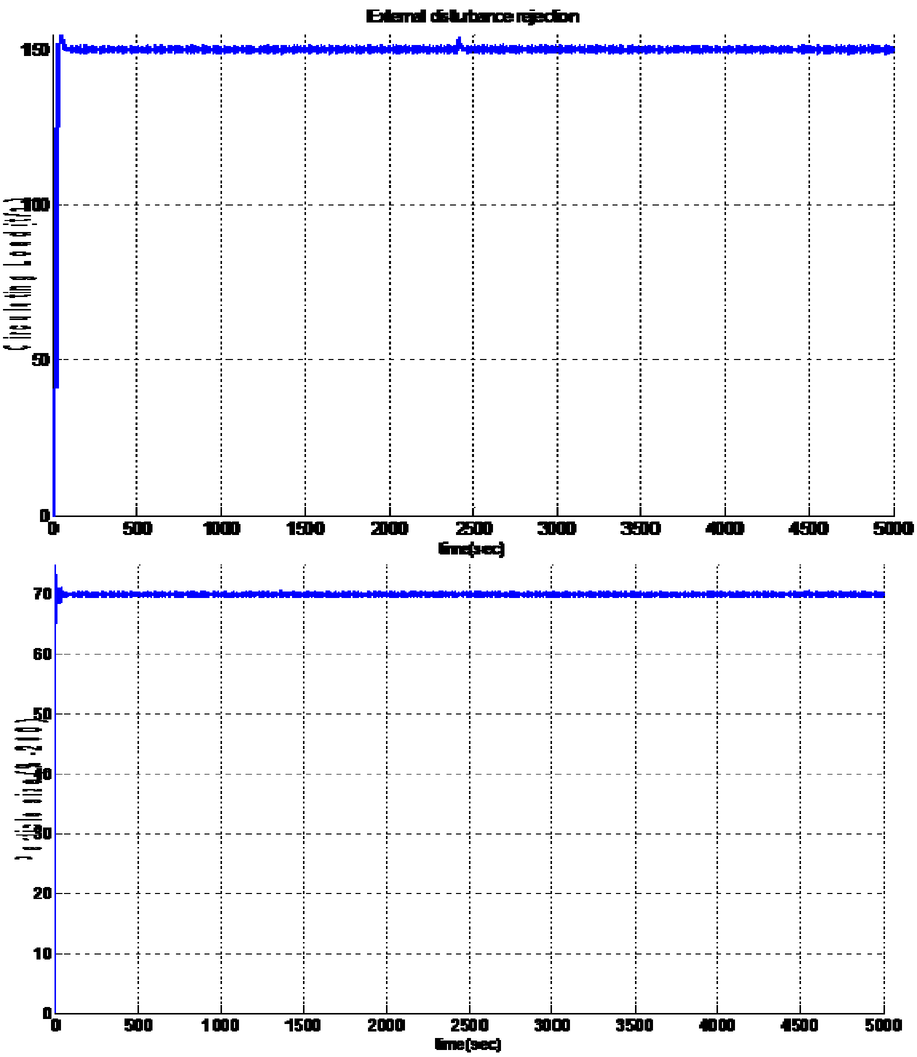

Figure (13): Product size (right) and circulating load (left) in the closed loop system at the presence of external disturbance

In figure 13, it is seen that the improved disturbance observer has performed well, and the designed controller, has properly rejected the external disturbance. In the figures it is clear that the effect of the hardness level of the ore on the outputis quickly rejected and the outputs are returned to the desired designed size.

CONCLUSION

In an ore grinding system, the existing disturbances include external disturbances (such as change in the size and the hardness level of the input ores) and internal disturbances (resulting from the mismatch with the real system and the effect of intervention among control loops). If no controller is considered for the compensation of these disturbances, the outcome of the ore grinding system will be reduced. In this paper, a multivariable control method is designed based on improved disturbance observer for the controlling of ore grinding system in the presence of different disturbances. The control method includes two controllers according to two loops, whereas each controller includes two parts of leading and feedback paths. The leading compensator part is used for the removal of disturbance by estimating it, and the PI control feedback part, is used to track the reference input.

The results of this paper can be summarized as below:

- Selection of proper loops and properly pairing the inputs/outputs
- Reduction of the interference among control loops using the direct separation method
- Designing a cheap and industrial controller for the ore grinding system with the capability of rejecting large external disturbances with the use of the improved disturbance observer

- Designing a disturbance observer to estimate the internal disturbances resulting from the incompleteness of the mathematical model of the system

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REFERENCES
1. A. Pomerleau, D.Hodouin, A.Desbiens, E. Gagnon, A survey of grinding circuit control method: from decentralized PID controllers to multivariable predictive controllers, Powder Technology 108 (2) (2000) 103–115.
2. M. Ramasamy, S. S. Narayanan, C. D. P. Rao, Control of ore grinding circuit using model predictive control scheme, Journal of Process Control 15 (2005) 273–283.
3. Xi. Chen, J. Yang, C.Guo, ad H. Wang, "Disturbance observer enhanced model predictive control with experimental studies," Automatica, Vol. 2, No.3, pp. 234-241,2011.
4. O. Galan, G. W. Barton, J. A. Romagnoli, Robust control of a SAG mill, Powder Technology 124 (2002) 264–271.
5. K. Najim, D.Hodouin, A.Desbiens, Adaptive control: state of the art and application to a grinding process, Powder Technology 82 (1) (1995) 59–68.
6. A. V. E. Conradle, C. Aldrich, Neurocontrol of a ore grinding circuit using evolutionary reinforcement learning, Minerals Engineering 14 (2001) 1277– 1294.
7. V. Manov, B. Sokolov, and S.Stoenchev, "Grinding in ores: modeling and process control," Cybernetics and information technologies, Vol. 12, No.2, pp.51-68, 2012.
8. [8] J. Yang, S. H Li, X. S. Chen, Q. Li, "Disturbance rejection of dead-time processes using disturbance observer and mode predictive control", *Chemical Engineering Research and Design*, 89(2011), 125-135.
9. K. Ohishi, M. Nakao, K. Ohnishi, K. Miyachi, Microprocessor-controlled DC motor for load-insensitive position servo system, IEEE Transactions on Industrial Electronics 34 (1) (1987) 44–49.
10. Zh. Ping, X. Bo, and Ch. Tiayou, "Improved disturbance observer based advanced feedback control for optimal operation of mineral grinding process," Chines Journal of chemical engineering, Vol. 20, No.6, pp.1206-1212, 2012.
11. E. Olivier and K. Craig, "Fractional order disturbance observer for a run-of-mine or milling circuit," proceeding in IEEE africon, Livingstone, Zambia, 13-15 Sep. 2011.
12. Wu, Dan, Ken Chen, and Xiankui Wang. "Tracking control and active disturbance rejection with application to noncircular machining. " *International Journal of Machine Tools and Manufacture* 47.15 (2007): 2207-2217.
13. Zhou, Ping, Wei Dai, and T-Y. Chai. "Multivariable Disturbance Observer Based Advanced Feedback Control Design and Its Application to a Grinding Circuit. "*Journal of Process control*, (2011), 1023-1030.

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