Influence of grinding media movement on the throughput of dry grinding circuit with electromagnetic mill

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Abstract. The paper investigates how the movement of grinding media affects the throughput of dry grinding circuit with the innovative electromagnetic mill. General structure of the grinding circuit, control system and its advantages are presented. Three air flows are critical for determining material throughput and providing proper operating conditions of the installation: flow through the working chamber of the mill, through the main classifier and in the recycle stream. They are affected by the moving grinding media. To assess this influence, air speed measurements were taken for different positions of dampers in air streams, for several masses of grinding media and frequencies of the rotating electromagnetic field. For each air stream, a set of polynomial models was identified. Control scheme for the air flows was proposed, including compensation for grinding media movement. Introduction of hierarchical control and distribution of particular control tasks on different layers was necessary.

1. Introduction

In order to produce fine particles, it is necessary to use technological installations equipped with comminution machines (crushers and mills) and classifiers (pneumatic, hydraulic, mechanical) that are able to produce various types of mineral powders, filling aggregates or fine aggregates used in many industries [1-6]. The usefulness of products is determined by physical and chemical properties of raw materials as well as features newly created as a result of mechanical, thermal, chemical or even biological processing. Development is based on searching for faster, cheaper, energy-efficient, more accurate and multifunctional comminution methods [7]. The electromagnetic mill meets all of the specified requirements. It is an innovative solution in the field [8-10]. Its main application is grinding of loose materials. The process can be carried out in dry or wet conditions, i.e. transport medium may be gas or liquid [11]. Working in a closed circuit allows to overcome the disadvantages of conventional devices.

2. Dry grinding circuit with electromagnetic mill

Figure 1 presents the electromagnetic mill system in the version for dry grinding [12]. The electromagnetic mill is a grinding device in which a rotary electromagnetic field is used to move ferromagnetic grinding media in a working chamber. The fixed, vertical position of the working chamber means that there are energy savings since there is no need to move the chamber, which is the case in conventional mills. The working chamber is filled at around 20% to 25% of its capacity with grinding media, the shape and size of which depends on the type of material and final product particle size distribution [13]. Thanks to the rotary electromagnetic field, the grinding media circulate at a certain speed in the working chamber – depending on the frequency of the field.

Figure 1. Diagram of the grinding system with the electromagnetic mill.
The material is comminuted due to collisions between grinding media and the material. The grinding efficiency is also raised thanks to the heat generated in the process, whose main task is to dry the material. The material movement in the system is caused by an air blower. The feed is supplied directly to the working chamber with a screw feeder – due to this solution we gain control over the loading speed of the feed. The air flow allows the ground material to move up, where the pre-classifier (directly above the working chamber) returns the unground particles back to the working chamber, while particles of smaller size pass through [14]. Then the material goes to the main classifier (much more accurate) – which separates the grains into the product stream (particles of the desired size) and the recycle stream (where particles of coarse size get). The material in the recycle stream returns to the working chamber, where it is subjected to grinding again. The material in the product stream goes to the cyclone, where the material is separated from the air and goes into the final product container. Thanks to the use of many technologies that make up the system with the electromagnetic mill, we get a huge advantage over conventional solutions. Faster grinding time results in a decrease in energy demand and in increased process efficiency. Other advantages include a reduction in the cost of replaceable parts of the mill, the ability to control the product (eg. size, shape, humidity) or finally the possibility of grinding various materials [15].

3. Model identification

From a technological point of view, three air flows play the major roles in ensuring proper operating conditions of the milling installation: flow through the working chamber \( F_W \), through the main classifier \( F_C \), and in the recycle stream \( F_R \). They are controlled by setting desired openings (0–100%) of three air dampers installed at air inlets (see Fig. 1). Due to cross-couplings, the positions of all air dampers: main \( P_M \), recycle \( P_R \) and additional \( P_A \) nonlinearly affect air streams in inlets: main \( F_M \), recycle \( F_R \) and additional \( F_A \) [16-18]; thus,

\[
F_x = f_x(P_M, P_R, P_A), \quad x = \{M, R, A\}. \tag{1}
\]

These streams in turn influence the remaining two key air flows:

\[
F_W = w_M F_M + w_R F_R = f_W(P_M, P_R, P_A),
F_C = c_M F_M + c_R F_R + c_A F_A = f_C(P_M, P_R, P_A), \tag{2}
\]

where \( w_M = w_R = 1.12, c_M = c_R = c_A = 0.2 \) are constants related to pipe diameters [16]. As it has already been stated, only flows \( F_W, F_C, F_R \) will be further considered as they are the targets of control algorithms during the milling process.

Relationships (1, 2) were investigated e.g. by Ogonowski et al. [16] for test conditions with the mill turned off; however, when moving grinding media are present in the working chamber, they introduce extra pneumatic resistance to the system and modify the air flows. This means that models (1, 2) need to be extended.

To simplify model structure and improve goodness of fit of model outputs to measured data, modelling procedure was decomposed with respect to position of additional damper \( P_A \) [16]. Decomposition with respect to \( f \) and \( m \) was also done, to make the models consistent with the ones already used by air flow control algorithms. (For operating conditions when \( f \) or \( m \) do not fall into the tested set of values, interpolation of model coefficients or model outputs may be used.) Moreover, the models were transformed to incremental form, to enable design of compensators suitable for the existing control scheme (see next section of the paper). Consequently, for each output signal a set of models was identified, one model per each tested triple of \( P_A, f \) and \( m \) values:

\[
\Delta F_x \equiv F_x - F_{x0} = f_x(P_M, P_R), \tag{3}
\]

where \( x = \{W, C, R\} \), and \( F_{x0} \) is flow \( F_x \) measured for no milling case \((f = 0, m = 0)\).

To identify relationships (3), polynomial approximation was used:

\[
\Delta F_x = \sum_{i=0}^{N_x} \sum_{j=0}^{N_y} a_{ij} \cdot P_M^i \cdot P_R^j, \tag{4}
\]

where: \( a_{ij} \) – polynomial coefficients to be identified; \( N_x, N_y \) – maximum degrees of individual variables, selected as 4; also, only terms up to degree 4 were allowed \((i+j \leq 4)\), to minimize the risk of overfitting the model to noisy data. Prior to estimation, input and output signals were scaled by 0.01 and 100, respectively, to have the same order of magnitude equal to 1, which provides better numerical properties of matrix equations to be solved. Then, coefficients \( \hat{a}_{ij} \) of the full model (with 15 terms) and of simpler structures (that exclude some of the terms) were estimated with least squares method. Finally, adjusted coefficient of determination \( AR^2 \) was calculated for each model (18-23):

\[
AR^2 = 1 - (1 - R^2) \frac{N - 1}{N - p - 1}, \tag{5}
\]

where: \( N \) – number of observations in the data set; \( p \) – number of model coefficients (excluding the free coefficient, if present); \( R^2 \) – coefficient of determination, that is [28-30]:
\[ R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \]

with: \( y_i \) – measured output signal; \( \hat{y}_i \) – output signal calculated from the model; \( \bar{y} \) – mean value of the measured output. High values of \( AR^2 \) (close to 1) indicate a well fitted model. Selection of best model structure was performed according to the following criteria:

- the model has high value of \( AR^2 \) (good fit);
- the model does not have many terms (low complexity);
- for one air stream, model structure is the same for all decomposed models, i.e. for all values of \( P_A, f \) and \( m \) (needed for compensator design).

As a result, the following seven-parameter model was chosen:

\[ \Delta F_c = a_0 + a_1 P_A + a_2 P_A^2 + a_3 P_A^3 + a_4 P_B + a_5 P_B^2 + a_6 P_B^3 + a_7 P_B^4. \]

This structure turned out the best for all air flows (\( \Delta F_W, \Delta F_{cW}, \Delta F_R \)); identical model structure for all outputs was not an assumption during model creation, but it followed from satisfying the above selection criteria a)–c) individually for each output signal. Exemplary model response is shown in Figure 2.

Figure 2. Output of the identified model compared to measured data: recycle air stream, \( P_A = 30\%, f = 60 \text{ Hz}, m = 500 \text{ g} \).

4. Control system design

The control system of the electromagnetic mill is designed as layered, as shown in Figure 3. Its individual components are controlled by a SCADA system [13]. The task of the optimization layer is to determine the operating points of the electromagnetic mill. The most important point of the mill’s operation is its load, i.e. mass stream of the feed. For the supervisory and direct control layers, the feed stream is the leading value, which is the basis for design of the functional structure of control systems in these layers.

Figure 3. Layered control system of the electromagnetic mill.

In general, the task of the optimization layer is to determine mill operation parameters that minimize energy consumption with constraints resulting from the required quality of the product, expressed through its particle size. The optimization task can also take into account other limitations: product temperature and humidity as well as particle's geometric...
properties. If the mill is powered by a frequency converter, its output frequency and base frequency can be changed. In addition, the mass of grinding media inside the working chamber may change. The tests confirmed that the output frequency, base frequency and mass of grinding media have the greatest influence on the active power of the mill [27, 28].

To manage all the control tasks on different layers, an HMI/SCADA control system was created. It consists of two controllers – the main one is SIMATIC S7-300 with analogue input/output and the other is SIMATIC S7-1200, responsible for inverter control (operating in the MODBUS network). Intra-system communication between S7-300, S7-1200 and SIMATIC Industrial PC (IPC) is possible thanks to the PROFINET network, and displayed thanks to the IFIX SCADA. There is a large number of sensors and actuators in the system [24]. As a result, the measurement of the following parameters can be obtained in the system: air velocity, temperature and underpressure in streams; air humidity at intake and exhaust; temperature of various sections of the system; position of air dampers; feed moisture; the loading speed of the feed; fill level of the working chamber; mass of the product; quality of the product.

From the technological point of view, the most important task for the control system is to stabilize the air flows in each part of the circuit. These air flows are changed on purpose or are disturbed with different time horizons, based on the production requirements changes, dynamics and cross-coupling of different direct control loops and safety loops, and other factors. This fact requires hierarchical control and distribution of particular control tasks on different layers [25]. As described by Ogonowski et al. [24], the hierarchical structure of the control system determines certain flow of the control decisions. Optimisation layer calculates required set points of air flows in particular parts of the circuit and passes them to the supervisory layer. Then, dedicated algorithm (see Figure 4) calculates the set point for the particular dampers positions. Since not all possible values of $F_{\text{ref}}$, $F_{\text{set}}$ and $F_{\text{ref}}$ (required by optimisation layer) may be simultaneously set in the system, the first task of the supervisory control algorithm is to check whether the required values are reachable. The task is achieved by solving the models of working chamber and separator for empty, not working mill [16]. If the required parameters are not reachable, the algorithm terminates with the response: operating points are not reachable. Otherwise the first step is completed with the set of the solutions ($P_{\text{set}}, P_{\text{set}}, P_{\text{set}}$). Then the constraint for $F_{\text{ref}}$ is verified and if there is more than one solution, the one with minimum $F_{\text{ref}}$ is chosen. If no solution satisfies the $F_{\text{ref}}$ constraint, then the restriction on $P_{\text{set}}$ interval is performed and the whole algorithm is repeated.

The above steps completely neglect the influence of the grinding media mass and rotation frequency on the transport air flow, that was pointed out in Section 3. Since this influence changes more frequently than the decisions of optimization layer, instead of model modification in supervisory layer, one of the solutions would be to introduce non-linear static compensation in the direct control layer. If one assumes the structure as in Fig. 5, then $y$ represents the steady state of the controlled air flow and $d$ represents the set point of frequency or grinding media mass.
Since models (4) are incremental, the compensator formula can be obtained by proper choice of the function $g(d)$ that will satisfy the following equation:

$$h(g(d), d) = 0. \tag{8}$$

Two separate compensators should be used: one to correct for the effect of varying field frequency and the other to react to changing mass of grinding media. Such choice is due to different time horizons for these compensators' operation. The output of the frequency compensator needs to be recalculated each time when setpoint for $f$ changes, which may happen quite often, as $f$ is the control variable for minimizing energy consumption. On the other hand, setpoint for $m$ is constant for normal operating conditions of the milling circuit and is equal to $m = 500$ g. This setpoint is maintained by a separate direct control loop and its change is rather unlikely; it could be caused only by some special technological requirements or an emergency situation (e.g. lack of grinders in the supply tank or hardware damage in this control subsystem). So, it is reasonable to design separate compensators for the influence of mass and frequency; moreover, it is justifiable to base the latter on models for constant $m = 500$ g.

5. Summary
Grinding circuit with electromagnetic mill is characterized by multiple good features among the systems for fine milling, but it requires compound control system to work efficiently. Because of numerous input and output signals in the milling process, and many interactions (in different time horizons) between them, control must be hierarchical. This also applies to control of flow of transport air, which determines maximum throughput, target particle size, grinding efficiency and other parameters of the process. The paper suggests a layered control strategy for the key air flows, that takes into account the openings of dampers at air inlets and the influence of mass and frequency of grinders rotating in the mill chamber. The control algorithm is based on polynomial models of air flows estimated from experimental data.

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