Enrichment effects at different control algorithms in jig in the presence of feed flow rate changes

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Abstract. The article describes selected PI digital control algorithms. The phenomenon of windup and its influence on the quality of control have been described. Selected methods of compensating this phenomenon are presented. A comparative analysis of algorithms was made in terms of their impact on the quality of control in the presence of changes in the feed flow rate. As a criterion, the relative value of the integral from the error square and the relative production value were presented, illustrating the impact of the considered algorithms on the economic effects of enrichment.

1. Introduction
One of the main goals of coal processing is to obtain products of a given quality determined by the measured ash content in coal. In the case of coal enrichment in a jig, this goal can be achieved by appropriate adjustment of the process parameters. From the process control point of view, there are no sufficiently accurate models, although many theories have been developed describing the phenomena of material distribution in the pulsating bed of the jig [1–5]. There are many variables depending on each other, which should be controlled: the shape and frequency of pulsation, the amount of top and bottom water, collector air pressure, material loosening in the bed, the flow rate of the underflow product. The enrichment of coal in the jig is therefore a very complex process. An extensive description of the jigging control at the current stage of process knowledge is given in [6]. Currently, industrial programmable controllers are commonly used to control technological processes, including coal enrichment. They are characterized by high computing power, enabling the design of comprehensive measurement and control systems. This paper is a description of a fragment of work related to the study of the influence of selected control algorithms on enrichment effects.

2. Jig discharge zone model
In simulation studies model of jig discharge zone [6] has been used.
Figure 1. Jig discharge zone [7].

The model assumes that the material in jig bed consists of known amount of layers with known densities $\rho_i$, that get to the discharge zone at certain velocities $v_i$ and flow rates $q_i$. Position of the layer below the overflow can be designated from the formula:

$$h_i(t) = \frac{1}{A} \cdot \int_0^t \sum_{i=1}^n q_i - \left( q_d + q_g \right) \cdot dt + h_{i0}$$

(1)

where:
- $A$ – area of discharge zone, m$^2$,
- $q_i$ – flow rate of layer, m$^3$/h,
- $q_d$ – flow rate of the underflow product, m$^3$/h,
- $q_g$ – flow rate of the overflow product, m$^3$/h,
- $h_{i0}$ – initial position of layer, m.

Wherein:

$$h_{i0} = \frac{1}{b \cdot v_s} \cdot \sum_{i=1}^n q_i$$

(2)

where:
- $b$ – width of the jig bed, m,
- $v_s$ – average movement velocity of layer, m/s.

For layers above the overflow equation is modified by including velocity of each layer:

$$h_i(t) = H + \Delta h_i(t)$$

(3)

where:
- $H$ – height of the overflow threshold, m.

$$\Delta h_i(t) = \frac{v_i}{v_s} \cdot \left[ \Delta h_i(v=v_s) (t) - \Delta h_{i-1(v=v_s)} (t) \right]$$

(4)

where:
- $v_i$ – movement velocity of the layer, m/s.

$$\Delta h_i(v=v_s) (t) = \frac{1}{A} \cdot \int_0^t \sum_{i=1}^n q_i - \left( q_d - q_g \right) \cdot dt - H$$

(5)
In model described by these equations every layer has its density, which is decreasing from the bottom to the Surface of the jig bed. It allows to designate separation density. It is assumed that separation density corresponds to the density at the overflow level. Block diagram of the model is presented on figure 2.

![Block diagram of the jig discharge zone model](image)

**Figure 2.** Block diagram of the jig discharge zone model [6].

3. Considered control algorithms

In the jig, the distribution of the concentrate feed and the bottom product (waste) takes place in the discharge zone, the material is delaminated in terms of density. By changing the flow rate of the bottom product, the amount and density of the product that above the overflow threshold changes. Thus, the density of the separation is changed, which is one of the output values of the jig. In order to measure the position of the fraction with the desired density, a float sensor is used [8]. As shown in [9], the discharge zone model is non-linear. The dynamic parameters of the object are different for different changes in the input quantity, i.e. the flow rate of the bottom product.

In the simulation tests of the jig discharge zone control system, a closed loop system was used, as shown in figure 3.

![Block diagram of control system](image)

**Figure 3.** Block diagram of control system.

In this system, the input signals are: flow rate of the underflow product $Q_d$ and feed characteristics. Output signals are: location of the float $h$, and ash content in product $A_k$, which is the basic parameter defining the quality of the product.

In the simulation tests, a digital PI algorithm was used, described by the formula (6).

$$u(n) = k_p \left\{ e(n) + \frac{T_s}{T_i} \sum_{k=1}^{n} e(k) \right\}$$

(6)
where:
- $u(n)$ – control signal,
- $e(n)$ – control error,
- $k_p$ – controller amplification,
- $T_i$ – integration time, s,
- $T_s$ – sampling period, s.

Digital algorithms consisting of integrating element are characterized by the occurrence of windup phenomenon – rise of the integrator output signal to high values, which cause an extended recovery time of the control signal to a level below its physical limit (usually from 0 to 100%, which usually corresponds to a current signal in the range of 4 to 20 mA). This may lead to a deterioration in the quality of regulation, and in extreme cases to instability of the entire system. In order to limit this phenomenon, modifications of the algorithm are used, which were described, among others, in [10–14]. In this paper, a comparative analysis of two such modified algorithms with reference to the algorithm without windup compensation has been made. The first method is to stop the integration when the control signal exceeds the lower or upper limit. The block diagram of this compensation method (hereinafter referred to as AWC1) is shown in Figure 4.

![Figure 4. Block diagram of PI controller with integration stopping.](image)

The second method (AWC2) consists of introducing additional negative feedback between the control signal and the error signal after its integration. The signal difference from the integrator signal is subtracted from the signal system before the system limiting its value and the control signal (output) of the controller, after multiplying it by a suitably selected gain factor (Fig. 5.). In the case at hand, this coefficient is 0.01.

![Figure 5. Block diagram of PI controller with additional feedback.](image)
4. Quality criteria
In order to assess both the quality of control and economic effects, which are affected by the considered algorithms, two indicators were adopted:

- The relative integral square error, described by the formula:
  \[ J_{ISE} = \int_0^\infty e^2(t) \, dt \]  
  (7)
where:
  \( e(t) \) – control error.

- The relative production value [15]:
  \[ WP = M_k \cdot \left( C_{bas} \cdot \frac{Q_i}{21} - w_S \cdot (S_i^r - 0.9) - w_A \cdot (A^r - 22) \right) \]  
  (8)
where:
  \( M_k \) – mass of the product, Mg,
  \( C_{we} \) – calculated price of the product, zł/Mg,
  \( C_{bas} \) – adopted base price of normative coal, zł/Mg,
  \( Q_i \) – coal heating value, MJ/kg,
  \( S_i^r \) – sulfur content in coal, %,
  \( w_S \) – price-correcting factor due to the sulfur content,
  \( w_A \) – price-correcting factor due to the ash content.

In the case of the second indicator, the values of \( C_{bas} = 165 \) PLN / Mg, \( w_S = 10 \), \( w_A = 0.5 \) were assumed. As already mentioned, both indicators have been presented in relative terms. For the integral of the error square, the reference value is the largest value of this indicator, while for the value of production - the lowest.

5. Results
In the case studies feed characteristics shown in Table 1 were adopted.

| Fraction density g/cm³ | Ash content % | Sulfur content % | Heat value kJ/kg |
|-----------------------|--------------|-----------------|-----------------|
| < 1,30                | 12,15        | 4,67            | 0,84            | 30 680 |
| 1,30-1,35             | 17,96        | 7,40            | 0,86            | 29 630 |
| 1,35-1,40             | 10,95        | 10,99           | 0,97            | 27 300 |
| 1,40-1,50             | 8,47         | 17,92           | 1,10            | 25 750 |
| 1,50-1,60             | 7,43         | 26,61           | 1,24            | 22 550 |
| 1,60-1,70             | 7,02         | 35,81           | 1,25            | 19 160 |
| 1,70-1,80             | 3,95         | 43,81           | 1,13            | 16 220 |
| 1,80-1,90             | 4,04         | 51,03           | 1,12            | 13 560 |
| 1,90-2,00             | 2,57         | 57,08           | 1,39            | 11 330 |
| ≥ 2,00                | 25,45        | 75,84           | 2,75            | 4 420  |

In order to select the controller’s settings, the control object was identified using the step response method. It was assumed that the jig discharge zone can be described as a first-order inertial object with a time delay:

\[ K_0(s) = \frac{k_o e^{-s\tau}}{1 + s\tau} \]  
(9)
where:
\[ k_o \] – amplification,
\[ \tau \] – time delay, s,
\[ T \] – time constant, s.

Based on the identification experiment, the values of the object parameters were determined:
- \( k_o = 0.014 \),
- \( \tau = 8 \) s,
- \( T = 39.24 \) s.

The selection of settings was made according to the modified Ziegler-Nichols method, described by equations (10) and (11).

\[
\begin{align*}
    k_p &= 0.7 \frac{\tau}{k_o \tau} \quad (10) \\
    T_i &= 0.3T + \tau \quad (11)
\end{align*}
\]

Otrzymano w ten sposób wartości nastaw:
- \( k_p = 245 \),
- \( T_i = 19.8 \) s.

Sampling time of \( T_s = 1 \) s was assumed.

The simulation was carried out for 1500 s, with a given ash content of 12.5% (which corresponds to a distribution density of 1.55 g/cm³). The change in the flow rate of the feed was assumed every 300 seconds, from 100 to 400 Mg / h and from 400 to 100 Mg / h. Based on the recorded values of the product quality parameters, the values of the adjustment indicators were calculated. The values of the relative integral square error are shown in Figure 6, while the relative production value - in table 2.

| Algorithm       | without AWC | AWC1     | AWC2    |
|-----------------|-------------|----------|---------|
| WP, %           | 100         | 112.77   | 108.95  |
6. Conclusion
The conducted simulation tests allowed to formulate the following conclusions:

- In the algorithm without *anti-windup* compensation, the integral square error has the highest value, which results from the fact that after a change in the flow rate of the feed there are large overshoots of the controlled parameter.
- Application of the *anti-windup* compensation in algorithm allows to reduce the overshoots, and thus – reduce the value of the integral from the square of the error.
- Application of the digital PI algorithm with a *windup* compensation system leads to an increase in the production value – this effect is obtained when the feed parameters change, such as its flow rate or its characteristics.
- In this paper it was assumed that the system works with sudden changes in the feed flow rate. These changes to some extent reflect the actual cycle of changes of this parameter. It is reasonable to carry out tests using the measurement data of the actual control object. Such research will be carried out in further scientific work.

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