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Fuzzy Controller in the Products Collecting System of the Jig for Minerals Beneficiation

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Abstract: The fuzzy controller of the bottom product collecting system of the pulsating jig is presented. The primary purpose of the research work was to design and properly adapt the fuzzy controller so that it would enable the correct operation of the jig with appropriate control properties in all compartments of the jig. The results of industrial tests, in which selected indicators of regulation quality were considered, were analyzed. A comparative analysis of the tested fuzzy controller and the classic PID controller was also performed.

Keywords: jig; control system; fuzzy controller; PID; coal mine

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1. Introduction

The energy crisis caused by shortages in gas supplies to the EU countries, including Poland, delays the implementation of energy transformation and requires a return to fossil fuels. The efficient use of coal resources is very important in the present. Gravitational classification, which uses the difference in coal grain density depending on the content of minerals in this grain, plays a significant role in the coal production process. The beneficiation process separates the coal feed into a concentrate with low ash content and high calorific value and waste with the lowest possible content of a combustible substance [1]. A pulsating jig is one of popular devices commonly used in processing plants in Polish mines [2]. Its popularity is related to its reliability and a wide range of grain classes that can be used as feed for beneficiation. Pulsating jigs are devices with a very wide range of applications in the processing of mineral raw materials. In addition to the beneficiation of hard coal, they are also often used in the processing of metal ores, cleaning of mineral aggregates, and recovery of coal from mine dumps [3]. Moreover, they are used in many other fields, such as the recovery of building materials, soil purification, separation of electronic scrap and processing of car scrap [4,5]. Further research work will enable a continuous increase in the efficiency of these devices, both in terms of design solutions and the technology of the beneficiation process. The purpose of the experiments described in this article was to increase the efficiency of the production of high-quality carbon products in pulsating jigs.

Beneficiation in the jig consists of, e.g., loosening and transport of the material and is a complex, non-linear process with parameter fluctuations and the non-stationary nature of disturbances. Separation density, which determines the efficiency of the process, is the basic stabilized parameter [6].

Disturbances in the jig system require using automatic control systems with stabilization of the separation density [6]. This task consists of stabilizing, at a given level, the height of the separating layer in the final part of the working channel of the jig, which has a decisive impact on the process efficiency. This article suggests replacing the commonly used classic PID controller with the fuzzy control of the bottom product collecting system. In fuzzy control systems, signals are represented by linguistic variables [7]. Due to this, a set of rules in the form of conditional sentences is used to control the object. In the PID control, the dynamic model of the system should be well reproduced. The system parameters can be selected, regarding the dynamic properties, by using optimization algorithms or modeling [8,9]. The linearity of the system around a specific operating point is assumed. This makes the system susceptible to interference. Since fuzzy controllers do not require a good representation of the model, they seem to be more suitable for a non-linear system such as a pulsating jig.

This is a new approach to controlling the bottom product collecting process in jigs with float measurement of the separating layer height that has not yet been tested and implemented in machines operating in processing plants in Poland, or maybe even in the world. The conducted research shows that the use of fuzzy control can improve the control over the process and its effectiveness.

The following chapters of the paper present the principle of operation of the pulsating jig and discuss the bottom product collecting system, which is the object of the regulation. The next part presents the results of the research on the fuzzy controller and the results of the experiment in which a comparative analysis of the operation of the automatic control system with a fuzzy controller was carried out in relation to the classic solution with a PID controller. The article ends with conclusions from the conducted research.

2. Principle of Jig Operation

The pulsating jig is one of the popular machines commonly used in the processing plants in Polish mines, (Figure 1).

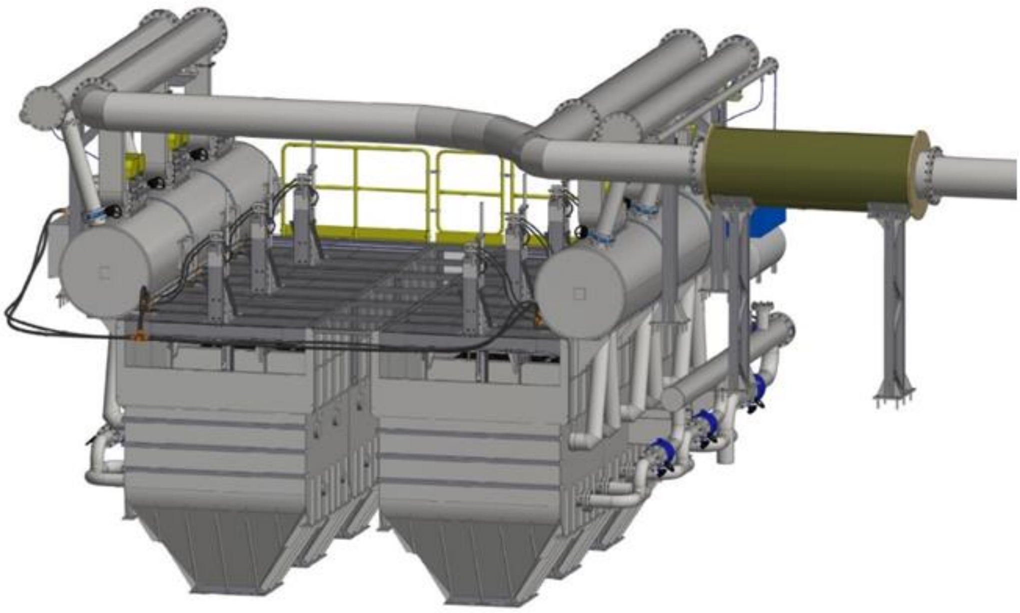


Figure 1. Pulsating jig.

Beneficiation in pulsating jigs consists of two basic operations. The first one is separation of the material in a pulsating water stream. The grains of the material moved in the water medium are grouped according to density, forming layers. The upper layer is made of run-of-mine with a lower density and with a lower content of waste rock and ash. The lower layer, on the other hand, is made of grains with a higher density, which are waste or a semi-product. The second operation is product collection by discharging the upper layer to the concentrate collecting system and the lower layer to the adjacent wastes collection compartment. It should be mentioned that the effectiveness of the jig's operation is greatly influenced by hydrodynamic factors, which include the characteristics of the pulsating cycle, working air pressure and the flow rate and method of feeding the bottom water.

The control of the bottom product collection consists of stabilizing the position of the separation layer in the final part of the working trough [10]. Most often, it is realized using the PID controller, and the height of the layer is measured using a float sensor [11]. PID controllers are particularly applicable in automatic control systems, where process dynamics and operational requirements are of special importance [12]. The selection of settings must depend on the purpose of the control. The optimization of the dynamics of the control system eliminating the impact of the disturbance and maintaining the zero error is of key importance [13,14]. The use of fuzzy sets makes the controller less sensitive to interferences in input signals [15]. A change in the input signal due to interferences or incorrect measurement does not immediately eliminate the impact on the output signal level. A disturbance may reduce or increase the share of the rule in the final value, but the rule will still be taken into account in the control calculation [16]. Controllers built on the basis of such logic are inherently resistant to interferences [17].

The aim of the research work was to check the possibility of improving the efficiency of the jig by using the fuzzy controller.

3. Object of the Control

The separation of the material in the jig takes place at the end of the jig's compartment, in the so-called bottom product collection zone (Figure 2).

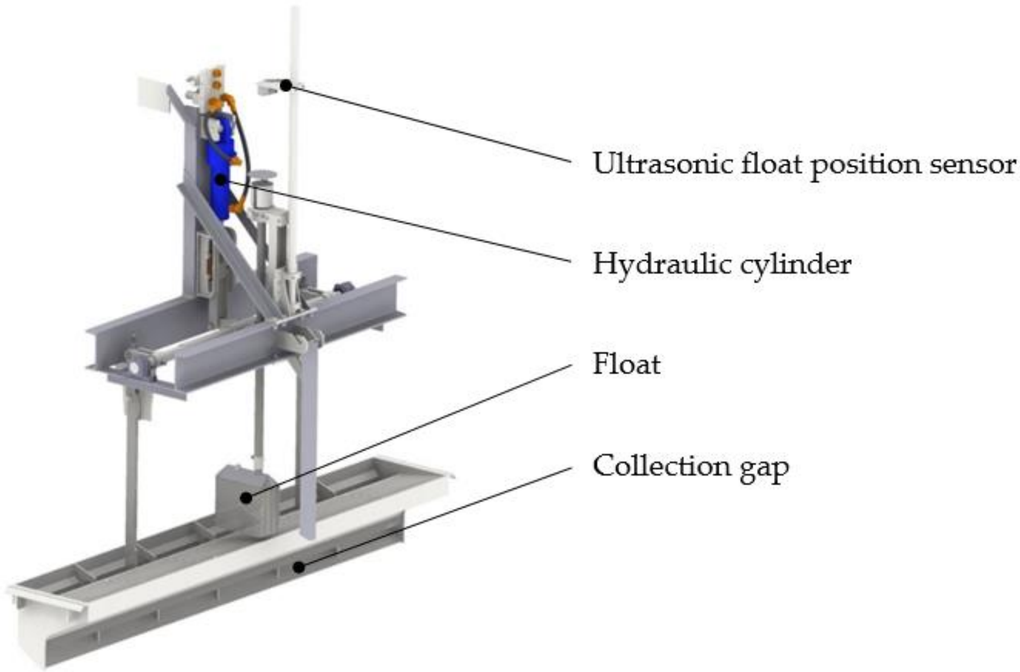


Figure 2. Culvert system in jigs.

The receiving trough is located upstream of the overflow threshold, used to segregate the grains in the bed. An element controlling the size of the discharge gap is moved in this trough. The float ends with a plate which reflects the ultrasonic signal from the sensor measuring its position. On the basis of the information from the sensor, the opening of the discharging slit increases/decreases and the underflow intensity changes, which alters the position of the separation layer (separation density). The aim is to maintain the separation layer at the level of the overflow threshold. Changes in the feed amount and its densiometric composition cause fluctuations in the separation density. The control system minimizes these fluctuations. It should be noted that the dynamic parameters of the collecting system change with the change in the feed parameters, they are also different for a different flow rate of the bottom product [1].

The block diagram of the system for the automatic control of the bottom product collection from the jig, using the fuzzy controller, is shown in Figure 3.

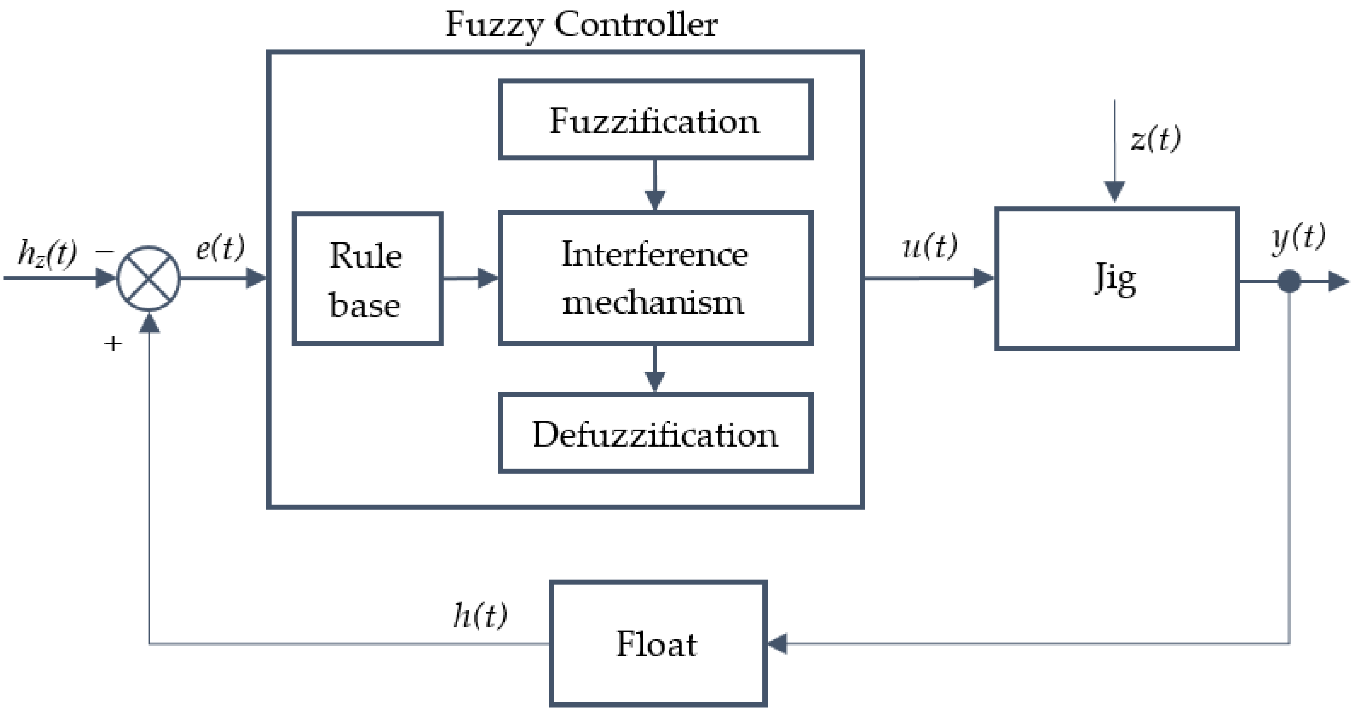


Figure 3. Control system.

The collecting system affected by disturbances $z(t)$ is subjected to control. This system is equipped with a hydraulic cylinder, which allows changing an opening of the discharge slot, thereby changing the intensity of the bottom product collection. An electronic sensor measures the degree of opening the slot. The second sensor controls the position of the metal float, which determines the location of the separation layer. The sensor sends a feedback signal $h(t)$. This signal is compared with the set separation layer height $h_z(t)$, corresponding to the set separation density. The signal $e(t)$ from the comparing system, called the deviation, is transferred to the controller, which converts it into a control signal $u(t)$, which is the basis for changing the degree of opening of the discharging slot.

For the proper operation of the fuzzy controller, it is important to correctly prepare the knowledge base. So far, no systematic procedure for determining fuzzy rules [7] has been developed, therefore, they are most often created on the basis of the practical experience of a human operator. It is a subjective method, but it leads to satisfactory results.

4. Fuzzy Controller

The suggested controller consists of two inputs and one output. The inputs are the control deviation $e(t)$ and the derivative approximated by the first-order difference, which represents the rate of change of the control deviation:

$$e' = \frac{\mathrm{de}}{\mathrm{dt}} \tag{1}$$

where:

$$e = e(t) = h_z(t) - h(t) \tag{2}$$

The deviation is a difference between the set value $h_z(t)$ and the actual value $h(t)$ of the controlled quantity in successive time steps.

The output of the $u(t)$ controller is the increase in the degree of opening of the discharge slot through which the heavy product is discharged, described by the two-dimensional control surface:

$$u = f(e,\ e') \tag{3}$$

The deviation is differentiated in each time step before entering the fuzzy part of the controller.

The standardized input and output membership functions are shown in Figure 4. To obtain a digital controller, continuous time was replaced with discrete time:

$$t \approx kT,\ (k = 0, 1, 2, \ldots\ ) \tag{4}$$

(**a**) (**b**) (**c**)

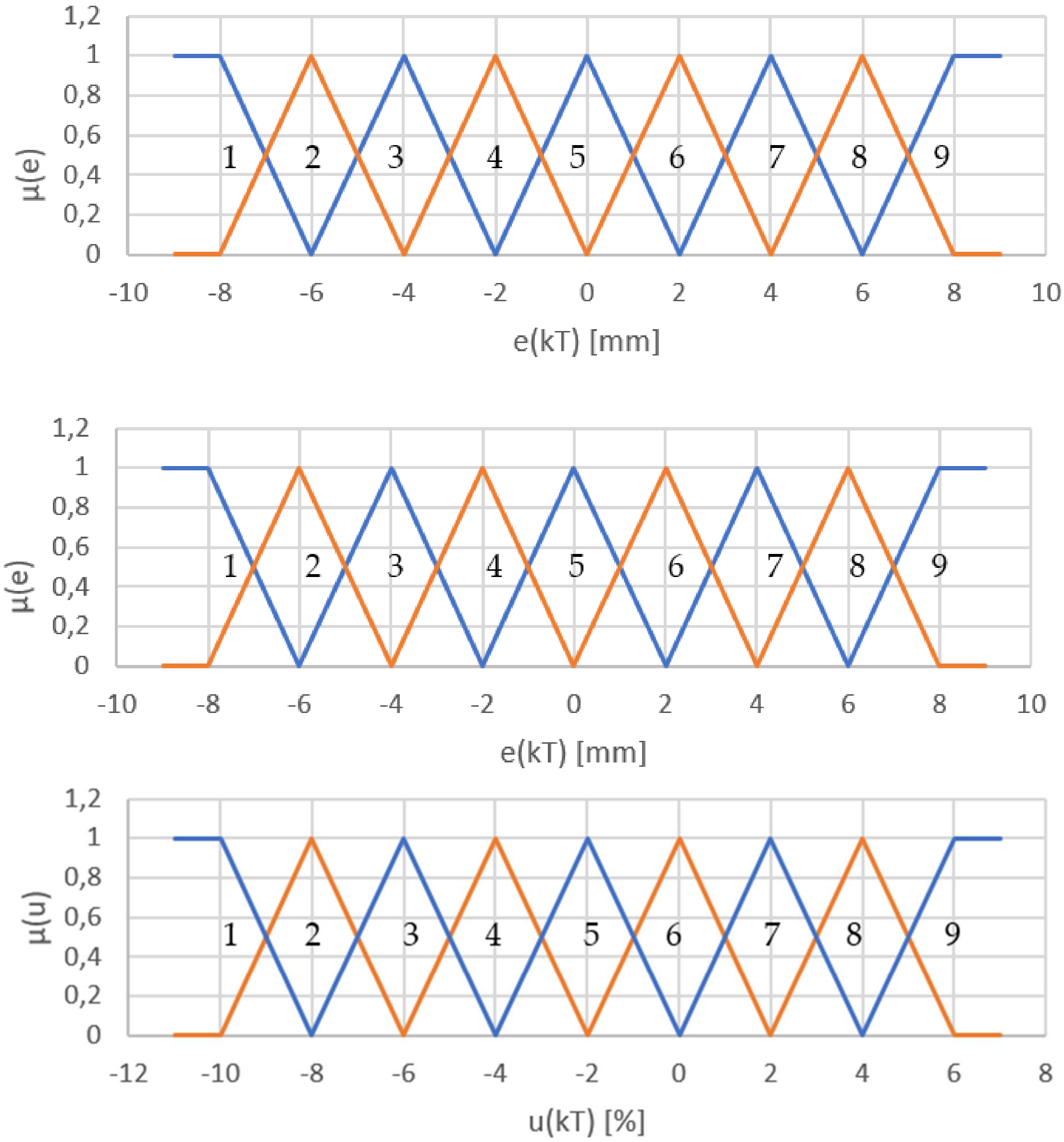


Figure 4. Membership functions for (**a**) $\mu(e)$, (**b**) $\mu(e')$, (**c**) $\mu(u)$.

The fuzzy space of linguistic variables was divided into nine linguistic values constituting the set: {1, 2, 3, 4, 5, 6, 7, 8, 9}.

In fuzzy controllers, empirical knowledge is memorized and stored in a fuzzy rule base. For the considered fuzzy controller consisting of two inputs and one output, each fuzzy rule takes the following form:

$$\begin{array}{l} \textbf{IF } (e \text{ is } Ei\ ) \textbf{ AND } (e' \text{ is } E_i{}'\ ) \textbf{ THEN} \\ \cdots\cdots (u \text{ is } U_i) \\ \textbf{END\_IF} \end{array} \tag{5}$$

where:

E_i, E_i—linguistic values defined as fuzzy sets from the universe $E\ i\ E'$

On the basis of functions and observation of the dynamic characteristics of the controlled process and on the basis of analyses of the preliminary tests, a fuzzy rule matrix was established, presented in Table 1.

Table 1. Rule matrix.

Δu		*E*								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
E'	**1**	1	1	2	3	4	6	6	6	7
	2	1	1	2	3	5	6	6	6	7
	3	1	2	2	4	5	6	6	7	8
	4	1	2	3	4	6	6	6	7	8
	5	2	2	4	5	6	6	6	7	8
	6	2	3	5	5	6	6	7	7	8
	7	2	3	5	5	6	6	7	8	9
	8	3	4	5	5	6	7	7	8	9
	9	4	4	5	5	7	7	7	8	9

The rule matrix created on the basis of expert knowledge is a key element of the fuzzy controller as it contains information about the behavior of the controller for various combinations of input signals. On its basis, the central process of the controller operation, which is reasoning, consists of determining the weights assigned to each rule and the way of interpreting these weights [18]. Mamdani's type of reasoning, who proposed to determine the weight of the rule as [19]:

$$w_1 = min[\mu_1(e_0), \mu_1(e_{0'})] \tag{6}$$

$$w_2 = min[\mu_2(e_0), \mu_2(e_{0'})] \tag{7}$$

where:

e_0—the argument of the membership function of number to the sets E_i

e_0—the argument of the membership function of number to the sets $E_i{}'$ was used.

Decision is the fuzzy matrices U_1 and U_2 of the following membership functions:

$$\mu_1(u) = min[w_1, \mu_1(u)] \tag{8}$$

$$\mu_2(u) = min[w_2, \mu_2(u)] \tag{9}$$

Conclusion from both rules is a fuzzy matrix U of the following membership function [19]:

$$\mu_z = max[\mu_1, \mu_2] = max[min[w_1, \mu_1(u)], min[w_2, \mu_2(u)]] \tag{10}$$

In the present solution, it is required that the result of the operation of the fuzzy system is a precise numerical value. It was determined on the basis of the COG center of gravity method (ang. Center Of Gravity) [19].

$$\mathrm{u_{COG}} = \frac{\sum_{i=1}^{n}(\mu_z(u_i)\cdot u_i)}{\sum_{i=1}^{n}\mu_z(u_i)} \tag{11}$$

5. Testing

Testing within the task concerned the comparison of the operation of a fuzzy controller with a classic PID controller. The tests were carried out on an industrial three-product coal fine jig, beneficiating the material in the grain class 30-2. The same rule matrix presented above was used in all jig compartments. The results were compared with the results obtained from a twin jig working in parallel, using a classic PID controller. Both jigs operated on similar feed parameters and the same pulsation cycle settings. The sampling frequency of the signals was equal to the frequency of the pulse cycle and was 0.92 Hz.

Before testing, the designed fuzzy controller was adjusted. As part of this adjustment, the amplification on the inputs and outputs of the controller was determined and the shape of the membership function and the mutual position for each variable of the control process were modified. As a consequence, the development procedure was allowed to shape the non-linear control surface of the controller to the final version, presented in the previous chapter. Five minutes after entering the final settings, the process of recording the operating parameters of both jigs was started. Figures 5–7 show the waveforms of the distribution layer position recorded during the operation of the jig with a classic PID controller, while Figures 8–10 show the waveforms of the distribution layer position recorded during the operation of the jig with a fuzzy controller.

The set height of the separation layer in each compartment was as follows:

compartment 1–110 mm,

compartment 2–100 mm,

compartment 3–80 mm.

To analyze the operation of the controllers, control error signals were compared. Integral of absolute error (IAE) was the first adopted measure of controlling the quality. It is required that in the steady state of the system, this value is as small as possible:

$$\mathrm{minIAE} = \sum_{i=0}^{n} |e(i)| \tag{12}$$

where:

e(i)—a discrete string of values is an error in the control signal.

The operation of the system in transient states was also analyzed. For this purpose, the integral time square error (ITSE) indicator, used in constant-value systems, was implemented, in which the aim is to make the transient wave disappear as quickly as possible:

$$\mathrm{minITSE} = \min \sum_{i=0}^{n} e^2(i) \tag{13}$$

where:

e(i)—a discrete string of values is an error in the control signal.

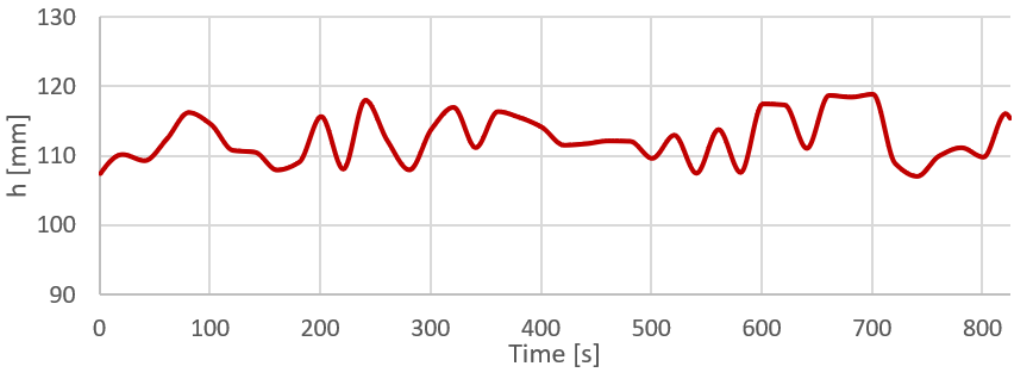


Figure 5. Waveform of changes in the position of the distribution layer in compartment 1 when using the traditional PID controller.

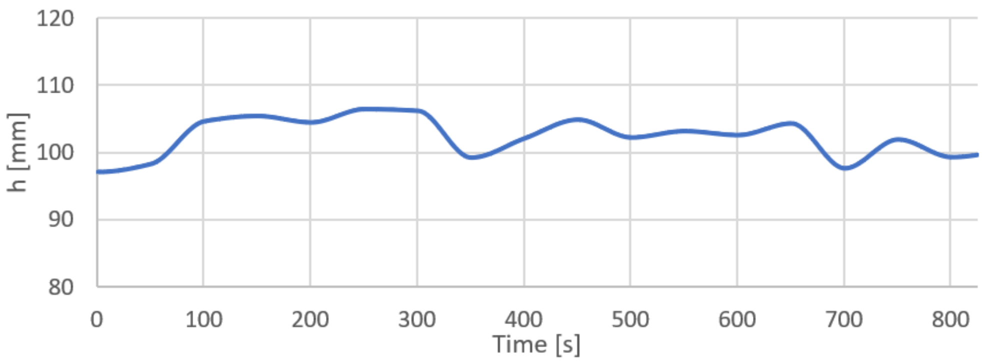


Figure 6. Waveform of changes in the position of the distribution layer in compartment 2 when using the traditional PID controller.

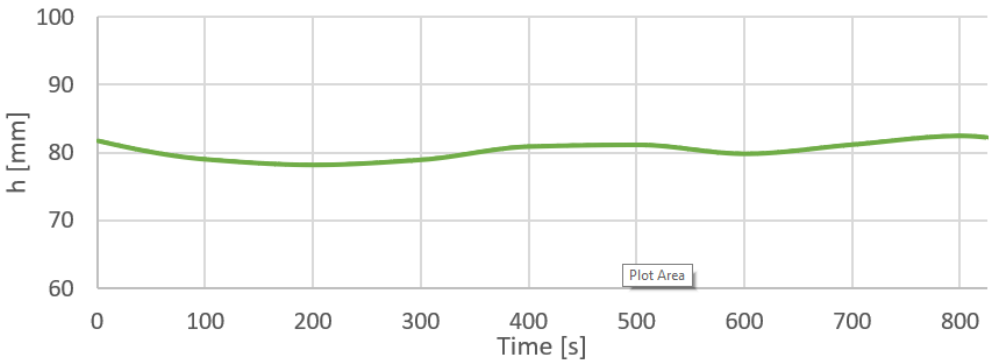


Figure 7. Waveform of changes in the position of the distribution layer in compartment 3 when using the traditional PID controller.

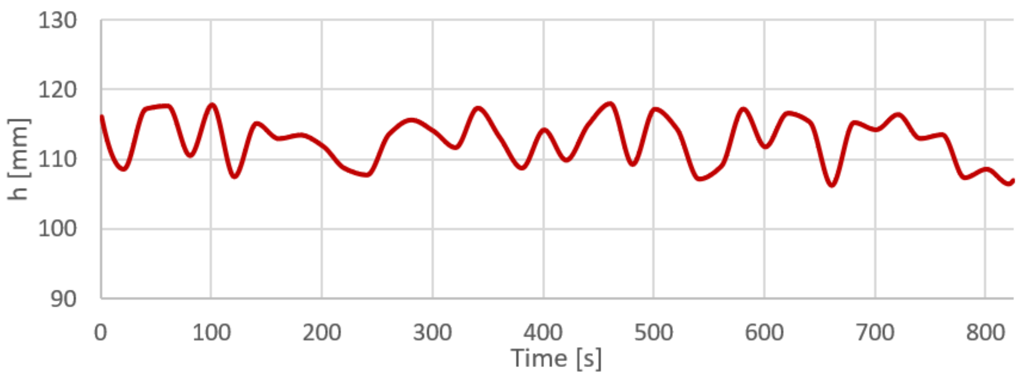


Figure 8. Waveform of changes in the position of the distribution layer in compartment 1 when using the fuzzy controller.

The results of the adopted control quality criteria are presented in Table 2.

Table 2. Results of adopted control quality criteria.

	IAE			ITSE		
Compartment Controller	**1**	**2**	**3**	**1**	**2**	**3**
PID	2552	2565	887	13,125	10,750	1302
FUZZY	2995	1728	817	13,955	5958	1384

The average values and standard deviations of the waveforms, which are presented in Table 3, were determined to compare the results of the quality of layer height adjustment in each compartment.

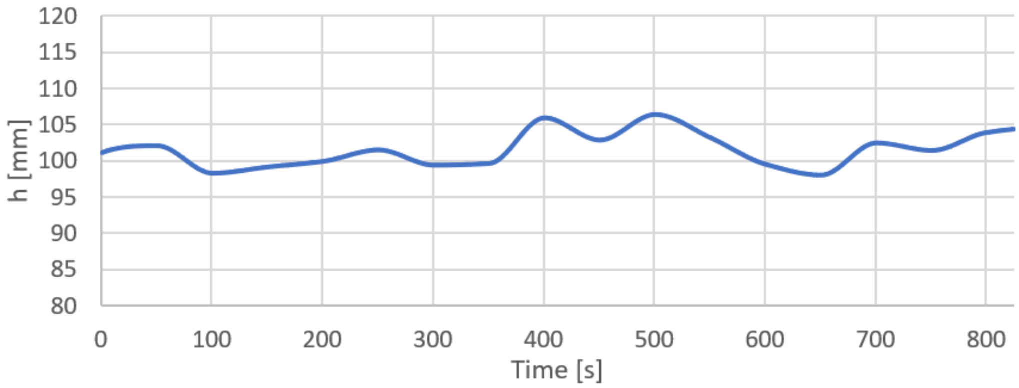


Figure 9. Waveform of changes in the position of the distribution layer in compartment 2 when using the fuzzy controller.

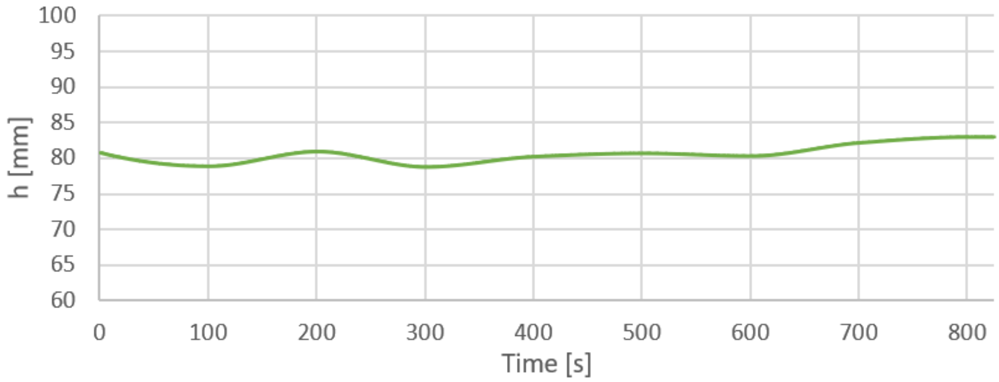
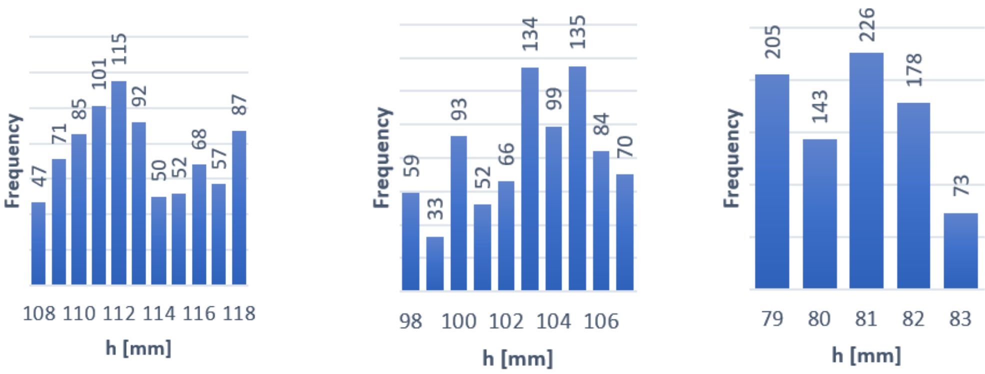


Figure 10. Waveform of changes in the position of the distribution layer in compartment 3 when using the fuzzy controller.

Table 3. Mean values and standard deviations of recorded waveforms.

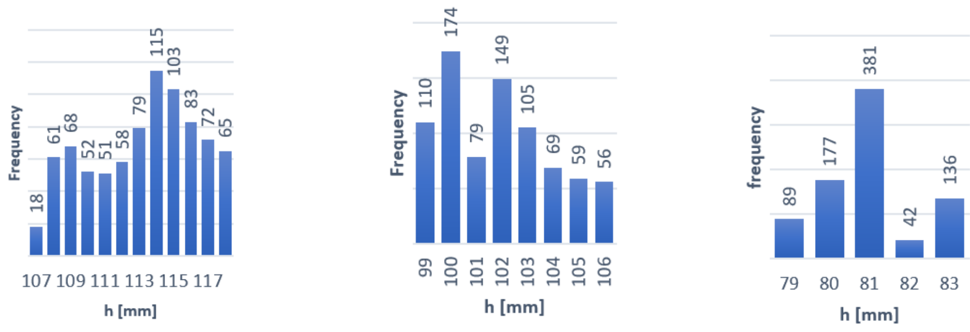
	Deviation			Average		
Compartment Controller	**1**	**2**	**3**	**1**	**2**	**3**
PID	3.14	2.60	1.24	112.47	102.5168	80.19
FUZZY	4.09	2.24	1.19	113.71	101.48	80.52

Distributions of the height of the separation layer in the case of the operation of the jig with a traditional PID controller (Figure 11) and with a fuzzy controller (Figure 12) are also presented.



(**a**) (**b**) (**c**)

Figure 11. PID Distribution, (**a**) compartment 1, (**b**) compartment 2, (**c**) compartment 3.



(**a**) (**b**) (**c**)

Figure 12. FUZZY Distribution, (**a**) compartment 1, (**b**) compartment 2, (**c**) compartment 3.

The presented separation layer heights are set at the height of the overflow threshold and are the minimum values of the layer. This means that the controller should, if possible, maintain the layer at the desired level but, at the same time, prevent the layer from falling below the set values. Any adjustments can only be made upwards. In the first compartment, where the greatest disturbances related to the introduction of material to the jig occur, the rule is to keep the separation layer above the set value, which is tantamount to transferring part of the material to the second compartment where the proper separation takes place. This procedure is designed to minimize losses in the first compartment.

6. Conclusions

Results of the research on increasing the efficiency of production of high-quality mineral raw materials in pulsating jigs are presented. The main purpose of the work was to develop and implement a new control algorithm that would increase the jig efficiency. The results of industrial tests, in which the traditional PID controller was replaced by a fuzzy controller reducing the control error in the selected compartments of the jig, were analyzed. The following conclusions may be drawn:

1. The product collection in the jig is not linear.
2. The integral quality criteria calculated in subsequent compartments are smaller and smaller, which results from smaller disturbances in each subsequent compartment. In the second compartment with the fuzzy controller, much smaller error was obtained than in the case of the PID controller. This tendency was not confirmed in compartments 1 and 3. This may indicate the need to build different reasoning rules for each compartment.
3. The integral of the squared error calculated in the third compartment of the jig does not change significantly depending on the controller used, which may indicate that the used controllers ensure similar dynamics of the control system.
4. The type of the used controller does not have much impact on the controlling time in the discussed cases.
5. With large disturbances related to feeding the material to the jig, the control signal is saturated, which causes overcontrol and worsening of the effects of control. This is visible both when using fuzzy and PID controllers. It is justified to consider correcting the saturation of the integrating signal.
6. The test results are the basis for testing the adjustment of the controller in the tested jig.
7. It is reasonable to further analyze the effects of using algorithms with various methods of compensation of unfavorable phenomena accompanying the regulation of non-linear processes.
8. The test results do not prove the superiority of the fuzzy controller over the classic one. However, they show that the fuzzy controller provides good stabilization at the set level and can be a good alternative to the PID controller.

9. In further tests, a more detailed simulation analysis of the system with a fuzzy controller is planned, taking into account such disturbances as: a change in the feed flow rate or a change in the share of each grain class, which will be the subject of a separate publication. Positive test results will allow for permanent implementation of the fuzzy controller to control the collection of the bottom product from the jig.

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