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Research Article

On the Investigation of the Energy Efficiency Using PID and Fuzzy Logic Controllers in a Marble Machine

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Abstract

Energy consumption is the main cost item in the cutting machines with diamond segmented circular sawblade. Therefore, there are many benefits of taking measures for reducing the energy consumption. The aim of presented experimental study is to develop control methods to reduce energy consumption in marble cutting process. In the study, cutting experiments were performed with a fully computer controlled test rig for three natural rocks (Burdur beige and Usak green marbles and Afyon travertine). The experiments were carried out on two modes (manual and automatic). While travel speed is kept fixed in manual mode as usual in industry, it is controlled by a controller embedded closed control loop during the cutting process in automatic mode. Other machine parameters, such as sawblade rotation speed, cutting depth and flowing speed of cooling water, are kept fixed in all experiments. In designed closed control loop, PID and FL controllers widely used in industry were used to control travel speed. Obtained results show that if the travel speed is controlled during cutting process, energy saving can be ensured by of controllers for the three rocks.

Keywords: PID controller, Fuzzy logic controller, Energy saving, Marble cutting, Applied control

1. Introduction

Afyon is one of the most important marble supplier cities of Turkey and of the world with its plenty of marble mines and factories. To separate the block marbles taken from mine as plaques, block cutting machines segmented diamond circular sawblade are used. There exist many parameters effecting the cutting operation in these machines. They include two parts: first one is machine parameters (sawblade rotation speed, travel speed, cutting depth, flowing speed of cooling water, cutting mode (down-cutting or up-cutting), metallurgic and mechanic features of diamond sockets, sawblade thickness etc.), second one is rock parameters (mineralogical and physical-mechanical features) [1–4]. Many studies have been realized to examine the effects of the said parameters [1–5, 7]. Specific energy is defined as energy consumed per unit volume and it can be used to monitor efficiency of marble cutting process [6]. The sawblade rotation and travel speeds have significant effects on specific energy. In [4], it is observed that the travel speed effect is more than the sawblade rotation speed effect.In industry, block cutting machines called as stripper-trimmer (ST) are widely used for separating block marble to plaques [1, 3, 4, 10, 11]. In the ST machines, sawblade rotation speed is adjusted with wheel-belt systems and it is fixed during cutting process. The travel speed is changed by machine operator and it is commonly held on fixed value. However, marble is not homogeneous material and it can contain regions with different hardness. Because of these fixed parameters, efficiency decreases in cutting process. For adjusting the sawblade rotation speed, motor drivers were recently used in ST machines but not widely. On the other hand, for changing travel speed, the drivers are almost used in whole of ST machines. So, if travel speed is controlled by a controller embedded in closed control loop, energy saving is possible. In previous studies, travel speed has been controlled by floating and PID controllers [9, 10]. In these studies, approx. 10% and 15% saving amounts are obtained. The studies showed that classical control methods are not satisfying enough to control the cutting process. So, it is well known that fuzzy logic (FL) control can be used to handle unexpected behavior of the cutting process, model uncertainty, and time delay (dead time) of mechanical system. In the presented study, PID and FL controllers are examined to control travel speed in the cutting process. Three natural rocks (Burdur beige marble, Usak green marble and Afyon travertine) are used as work piece for cutting experiments. The experiments were performed with a fully computer controlled test rig designed just as ST machine [4, 6]. Full details of the test rig can be found in [4, 8–10]. A graphical user interface providing control of the test rig was designed with NI LabVIEW programming language which is widely used for academic and industrial applications [9]. In addition, NI PID toolset packet program was used for designing PID and fuzzy controllers [12]. Below, firstly, control loop and the controllers are presented. Then, the results obtained from experiments are given. Finally the results and future researches are discussed.

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2. Control loop and controllers

In the marble processing industry, the specific energy can be used to monitor efficiency of cutting process and to predict required energy [6]. The sawblade rotation speed, travel speed, cutting depth, cooling water flow speed, cutting mod, metallurgic features of diamond sawblade segment and marble features are directly connected with the specific energy. The travel speed effect is the most important among these parameters [4, 7].There is adverse proportion between travel speed and the specific energy. In Figure 3, an experimental result performed for Usak green marble is seen. In graphs, error signal (e) is used instead of the specific energy. The error signal is derived from the equation (2.1);

$$e = y_{sp} - y \tag{2.1}$$

This experiment is started with 0,7m/min. travel speed and after the sawblade entering completely into the marble, travel speed is gradually increased. With increase in the travel speed, a decrease is observed in error signal. The error signal drops to approx. $0 \mathrm{Ws/mm^3}$ value for 1,4m/min. travel speed. Although travel speed is increased to 1,5m/min., error is nearly fixed to $0 \mathrm{Ws/mm^3}$ value. If travel speed is continued to be increased, increasing trend is expected in error signal. This extreme point is called optimum amount of the specific energy.

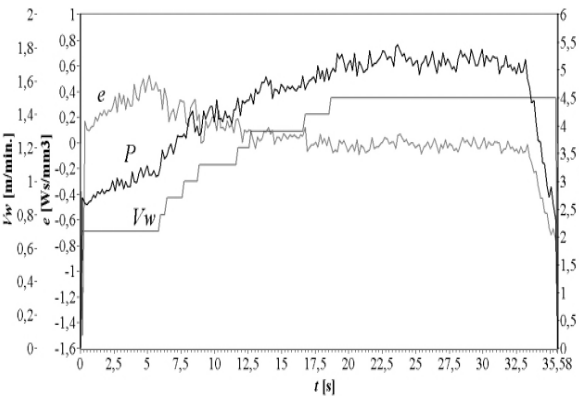


Fig. 1. Relationship between travel speed and error signals

In control loop, single input single output (SISO) and multi input single output (MISO) controllers were used. SISO PID and MISO FL controllers were tested to control travel speed in the cutting process. Below, architecture FL controller is presented. Full details of PID controller are given in [10], therefore, details of PID controller are not duplicated in this paper. But, PID controller and control loop are only presented in Figure 2.

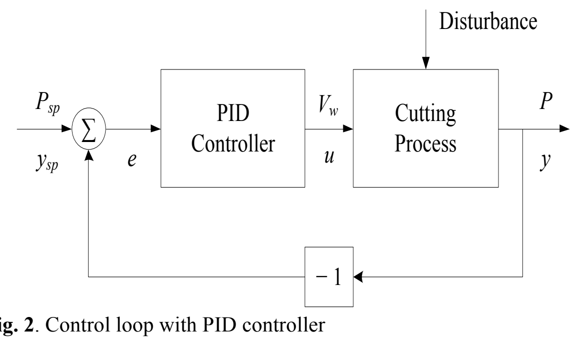


Fig. 2. Control loop with PID controller

FL was first introduced by Zadeh in 1960 and it has been rapidly growing in recent years [13]. Designing powerful controllers are possible with FL method. Process must be mathematically described in traditional controllers, but it does not need to be mathematically described in FL controller. FL controller has capability to process with missing or exactly unknown knowledge. Pioneering application of FL controller is implemented by Mamdani in 1974 to control the steam machine [14]. Recent applications of FL controller are seen in water quality control, automatic train operation systems, fluid or gas flowing control, elevator control, chemical and physical process control, etc. FL controller is classified on expert systems and expert knowledge can be directly used in designing controller [15-19].

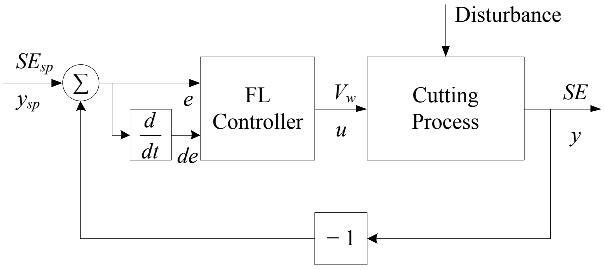


Fig. 3. Control loop with FL controller

FL controller designed in this study is MISO type and it has two inputs and one output variable (Figure 3). The error and its derivative are input variables and travel speed is output variable. Input/output (I/O) variables are described with linguistic variables (e, de and V_w). Linguistic variables are represented to linguistic terms. A linguistic variable usually have an odd number of linguistic terms, with a middle linguistic term and symmetric linguistic terms at each extreme [12]. Generally, three to seven linguistic terms are used to categorize the values of a linguistic variable. It is defined linguistic terms of negative big–NB, negative medium–NM, negative small–NS, zero–Z, positive small–PS, positive medium–PM and positive big–PB for linguistic variables e, de and V_w Linguistic variables are illustrated as membership functions. Standard functions include triangular shape, trapezoidal shape, singleton-type (vertical line shape), Sigmoid-type (wave shape), and Gaussian-type (bell shape) membership functions. Membership functions of travel speed designed with NI PID Toolset are seen in figure 4 [20, 21].

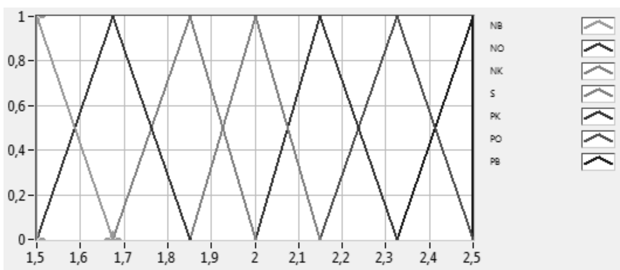


Fig. 4. Membership functions for travel speed

Rules represent the relationships between input and output linguistic variables based on their linguistic terms. A rule base is the set of rules for a fuzzy system. To create a rule, it must be specified the antecedents (IF parts), and consequents (THEN parts), of the rule. An input linguistic variable is associated with a corresponding linguistic term to form an antecedent. An output linguistic variable is associated with a corresponding linguistic term to form a consequent [12]. The total number N of possible rules is defined by the following equation (2.2);

$$N = n^m \tag{2.2}$$

where n is the number of linguistic terms for each input linguistic variable and m is the number of input linguistic variables. In this study, designed rule base consists of total 49 rules for two linguistic variables and seven linguistic terms. Rule base is designed according to $V_w - e$ characteristic given in Figure 1. If a rule has more than one antecedent, it must be specified an antecedent connective to determine how to calculate the truth value of the aggregated rule antecedent. In this study, antecedents are connected to AND operator (AND connective). The rules are defined by the following.

1. Rule: IF e is NB, and de is NB, THEN V_w is NM
2. Rule: IF e is NB, and de is NM, THEN V_w is NM
49. Rule: IF e is PB, and de is PB, THEN V_w is PB

The rule base is modified in experiments and it is designed in matrix form (Table 1). It is seen that, if error is under zero and there is a decreasing trend (or de is under zero), travel speed (V_w) decreases.

Table 1. Rule base for FL controller

V_w	de						
	NB	NM	NS	Z	PS	PM	PB
NB	NM	NM	NM	NM	NS	Z	Z
NM	NM	NM	NM	NS	Z	Z	PS
NS	NM	NM	NS	Z	Z	PS	PM
Z	NM	NS	Z	Z	PS	PM	PB
PS	NS	Z	Z	PS	PM	PB	PB
PM	Z	Z	PS	PM	PB	PB	PB
e PB	Z	PS	PM	PB	PB	PB	PB

A fuzzy controller uses a consequent implication method to scale the membership functions of each output linguistic variable before performing defuzzification [12]. Some implication methods are Mamdani max-min, Mamdani max-prod, Takagi-Sugeno, and Tsukamoto etc. For all rules, Mamdani minimum implication method was used in the study. Defuzzification is the process of converting the degrees of membership of output linguistic variables within their linguistic terms into crisp numerical values. In a FL controller, it can be used one of several mathematical methods to perform defuzzification. These methods are center of area, center of sums, center of maximum, or mean of maximum etc. In the study, center of area method is used for defuzzification. The controller surface of designed FL controller is seen in Figure 5.Since rule base of FL controller is designed according to cutting process characteristic, rule base is used for all rock types. Also, error and its derivative signals have same range. However, range of travel speed signal shows difference for any rock and its range must be adjusted considering rock type. This adjusting is automatically carried out by an algorithm embedded in graphical user interface (Figure 6). When rock type is changed by user, the algorithm is run and range of travel speed is precisely determined.

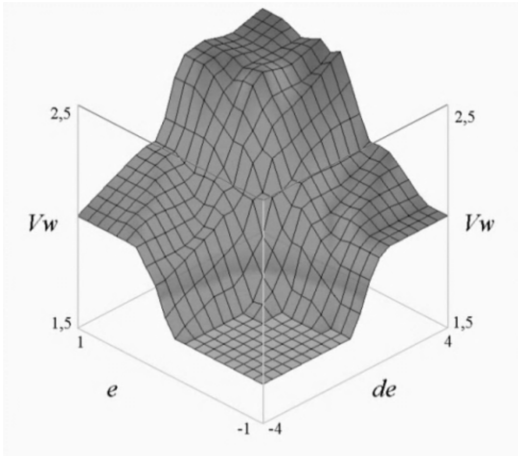


Fig. 5. Controller surface for designed FL controller

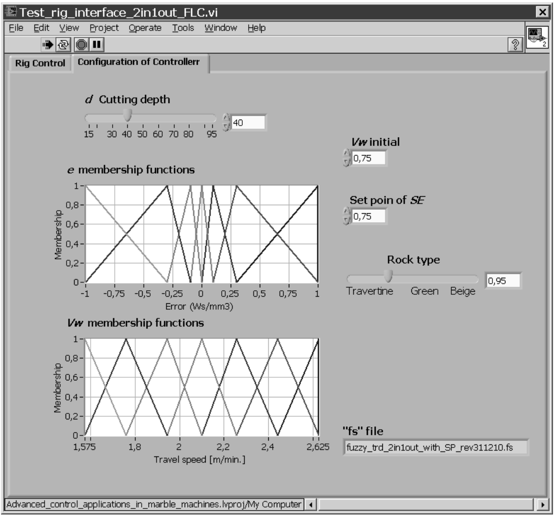


Fig. 6. Controller configuration tab

Nowadays the renewable energy plays a very important role. There are some types of renewable energy which were successfully implemented: the solar thermal energy, the wind energy, the photovoltaic energy, the biomass, the hydropower energy and others. The photovoltaic energy became one of the most important types of renewable energy.

The efficiency of photovoltaic systems depends primarily on the solar cell efficiency and the cell selection in function of its parameters. The latter has a very important influence for the lifetime of photovoltaic panels.

A system which allows determining quickly and accurately the solar cell parameters will ensure a good selection of the cells and will ensure the conditions to build a very good and reliable photovoltaic panel.

The determination of photovoltaic cells parameters was, is and will be a domain of interest for researchers. As now there are many types of photovoltaic cells it is necessary to find the suitable methods and solar cell testers which allow determining the important parameters of the solar cell: the photo generated current, the series and shunt resistances, the maximum power, the ideality factor of diode, the reverse saturation current, the fill factor and the efficiency.

There are some measurement systems which allow determining the parameters of photovoltaic cells [1-2].

To realize the measurements the test bench system for solar cells must contain: the light source, the I-V characteristic module, the thermostat, the mobile part, the acquisition and control system and the dedicated software. In industrial applications, the solar simulator is built using halogen lamps, even if the matching between the spectrum of the halogen lamp and the solar spectrum is not very good. This happens due to the lower cost on the illuminated surface [1]. The module for measuring I-V characteristics has to permit the measurement in a very short time (seconds), and the number of measurement points has to be large enough to allow a good data processing.

Characteristics' measurement can be done through various techniques: the use of an electronic load, of a capacitor as a variable load, of a MOSFET or a digital potentiometer [3]. The variation of the illumination levels can be done by varying the distance between the solar cell and the light source. A thermostat can be used to maintain the temperature constant during the measurement time. The levels of illumination can be determined using the photo detectors.

3. Experımental results

In the circular cutting process, there are many parameters effecting energy consumption and each of these parameters is research subject. Because parameters except for travel speed are out of this study, they are fixed. Fixed parameters are sequentially; sawblade rotation speed $V_s = 1500\text{rpm}$, cutting dept $d = 50\text{mm}$, flowing speed of cooling water $V_f = 10\text{l/min.}$ and sawblade produced by UNIMAS has 24 diamond segments. Moreover, cutting mode is vital parameter in cutting process. In the circular cutting process, there are two cutting modes, such as up-cutting and down-cutting. In this study, as it is more suitable for cutting natural rocks, down-cutting mode is selected [3]. In the study, cutting experiments were performed for three natural rocks (Burdur beige and Usak green marbles and Afyon travertine). In cutting experiments, work pieces having a length 900mm, 70mm, and 200mm section are used. First, manual experiment is performed in fixed travel speed to determine PID and FL controller parameters. The automatic experiments are carried out for PID and FL controllers. Below, experimental results performed with manual, PID and FL control methods are presented. In addition, effecting control methods in specific energy and energy saving amount achieved in each control methods are given.

3.1 Results of manual cutting

In manual cutting mode, the motor has been operated 10% below its nominal power for secure cutting process. Specific energy values obtained for each rock as follows; $1{,}308\text{Ws/mm}^3$ for Burdur beige marble in $1{,}1\text{m/min.}$, $0{,}985\text{Ws/mm}^3$ for Usak green marble in $1{,}6\text{m/min.}$, $0{,}918\text{Ws/mm}^3$ for Afyon travertine in $1{,}7\text{m/min.}$. The amounts of travel speed and specific energy show that while soft rocks, such as Afyon Travertine, are fast cut, hard rocks like Burdur beige marble are not.

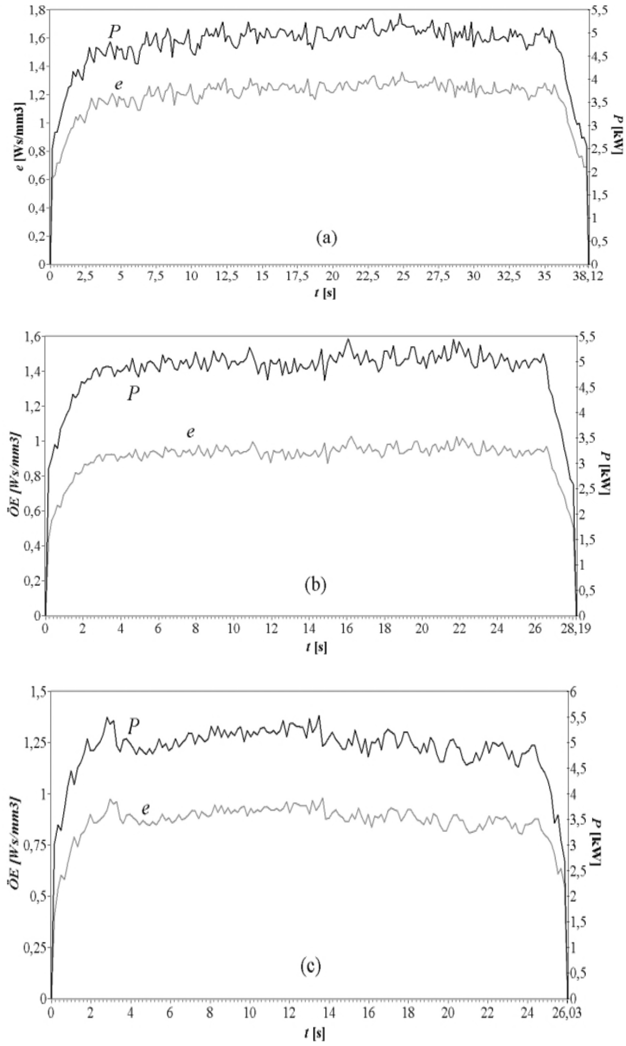


Fig. 7. Results for manual mode experiments
a) Burdur beige marble
b) Usak green marble
c) Afyon travertine

Experimental results show that although travel speed is fixed, oscillations are seen in sawblade power and error curves for Burdur beige marble and Afyon travertine (Figure 7). But, these curves are almost fixed for Usak green marble. This shows that while Usak green marble is homogenous contents, other rocks are not. Parameters of PID and FL controllers are selected according to these results.Configured PID controller parameters are sequentially; saturation range of control variable ($u = V_w$), set point of controlled variable ($y_{sp} = P_{sp}$), controller gain (K_c), controller integral time (T_i), controller derivative time (T_d).The saturation range of control variable shows difference for rock type. Minimum value of control variable is fixed $V_{w\min} = 0\text{m/min.}$ for all rock. Maximum values are determined $V_{w\max} = 1{,}8\text{m/min.}$ for Burdur beige marble, $V_{w\max} = 2{,}2\text{m/min.}$ for Usak green marble, $V_{w\max} = 2{,}4\text{m/min.}$ for Afyon travertine. The set point of controlled variable is selected $P_{sp} = 5{,}5\text{kW}$. The controller parameters (K_c, T_i and T_d) are seen in Table 2. The parameters given in table 2 are determined with try and error method [10].

Table 2. Parameters for PID controller

Rock type	K_c	T_i	T_d
Burdur beige	1,3	0,04	0,000015
Usak green	0,9	0,03	0,000015
Afyon travertine	1,2	0,04	0,000015

Configured of FL controller parameters are sequentially; range of control variable ($u = V_w$), set point of controlled variable ($y_{sp} = SE_{sp}$).The FL controller parameters are seen in table 3.

Table 3. Parameters for FL controller

Rock type	SE_{sp}	Range of V_w
Burdur beige	$1{,}03 \text{Ws/mm}^3$	$[1{,}2 - 2]$
Usak green	$0{,}83 \text{Ws/mm}^3$	$[1{,}5 - 2{,}5]$
Afyon travertine	$0{,}75 \text{Ws/mm}^3$	$[1{,}575 - 2{,}625]$

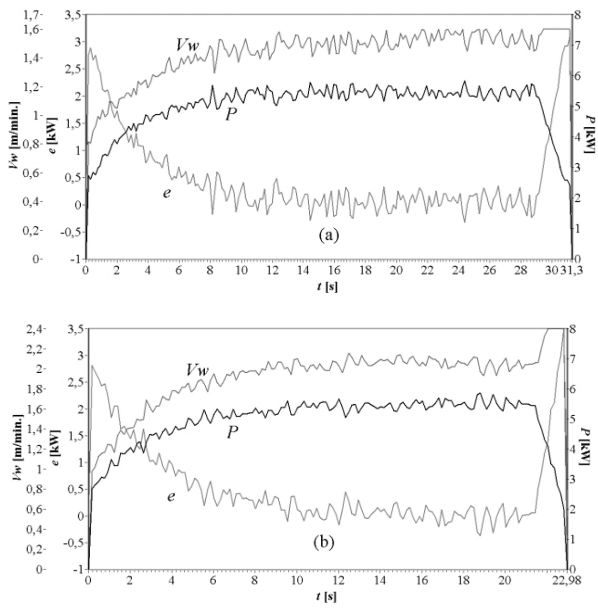
In addition travel speed is started at initial values given in Table 4 for PID and FL controllers

Table 4. Initial values of V_w

Rock type	Initial value of V_w
Burdur beige	0,8m/min.
Usak green	1m/min.
Afyon travertine	1,1m/min.

3.2 Results for PID controller

Since Burdur beige marble and Afyon travertine comprises different hardness regions, oscillations are seen in sawblade power curve. In order to remove these oscillations, derivative time must be adjusted. As Usak green marble has homogenous structure, PID controller creates a steady state error. For removing this error, integral time must be adjusted. Because derivative and integral time constants are multiplied with controller gain, all parameters are adjusted together.



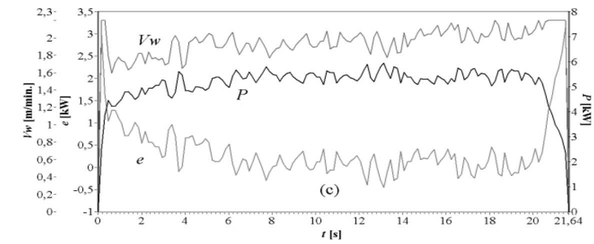


Fig. 8. Results for PID controller
a) Burdur beige marble
b) Usak green marble
c) Afyon travertine

The best results achieved with PID controller are seen for Burdur beige and Usak green marbles and Afyon travertine (Figure 8-a, b and c). Obtained specific energy values are $1{,}135 \text{Ws/mm}^3$ for Burdur beige marble, $0{,}823 \text{Ws/mm}^3$ for Usak green marble and $0{,}784 \text{Ws/mm}^3$ for Afyon travertine.

3.3 Results for FL controller

Experimental results which are given in Figure 8 and 9 for PID and FL controllers show together that FL controller is the most stable and rapid in arranging travel speed. In cutting process, as PID controller is not operated with specific energy feedback and its parameters have to adjust for each rock, using and designing this controller are difficult. Because it is quickly settled, energy efficiency increases in cutting process.

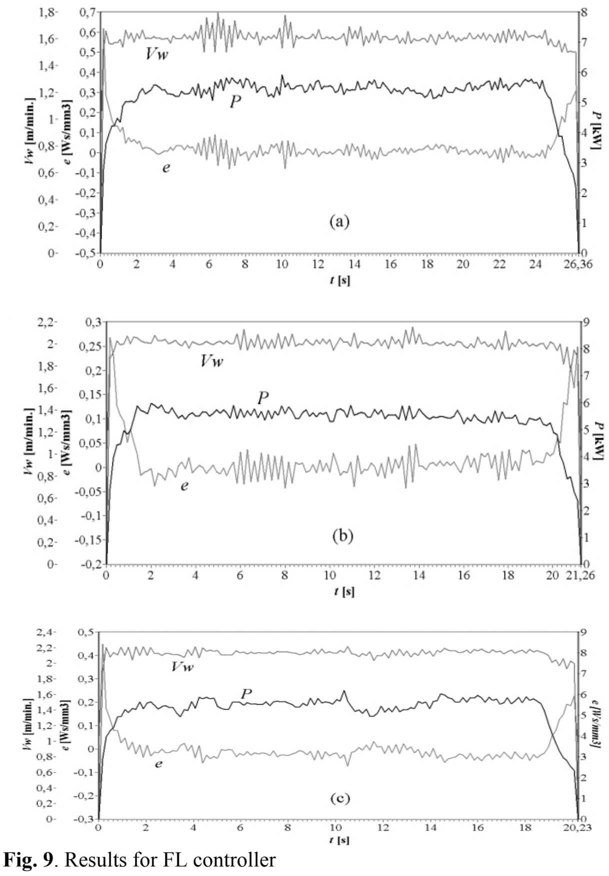


Fig. 9. Results for FL controller

a) Burdur beige marble
b) Usak green marble
c) Afyon travertine

The best results achieved with FL controller are seen for Burdur beige and Usak green marbles and Afyon travertine (Figure 8-a, b and c). Obtained specific energy values are 1,002Ws/mm^3 for Burdur beige marble, 0,784Ws/mm^3 for Usak green marble and 0,741Ws/mm^3 for Afyon travertine. Even though efficiency obtained in FL controller is more than PID controllers, it shows poor performance in Afyon travertine. When e and V_w curves given in Figure 9–c are examined, it is seen that relationship between e and V_w is different from characteristic of FL controller in 2-4s and 10-14s ranges. This results from nonlinear relationship between e and V_w. Increasing of e is not almost result from increasing of V_w. Sometimes, e shows decreasing trend due to decreasing motor load or during cutting soft regions. When e and de linguistic variables are used in FL controller, this fault appears.

3.4 Analysis specific energy

SE values achieved in cutting experiments are given in Table 5. It is seen that three cutting experiments are carried out for each control method and rocks. For each method, four SE values are showed and results given with bold font are mean of other three results.

Table 5. SE values for control methods

Control methods	Burdur beige	Usak green	Afyon travertine
Manual	1,308	0,985	0,918
	1,199	0,981	0,986
	1,174	0,902	0,892
	1,227	0,956	0,932
PID	1,135	0,808	0,805
	1,092	0,823	0,784
	1,091	0,804	0,755
	1,106	0,812	0,781
FL	1,002	0,784	0,742
	0,996	0,777	0,759
	0,994	0,769	0,741
	0,997	0,777	0,751

Below mean of SE results are graphically given (Figure 10). These results show that maximum energy consumption is realized in manual mode. In case the travel speed is arranged with controller, energy consumption is reduced.

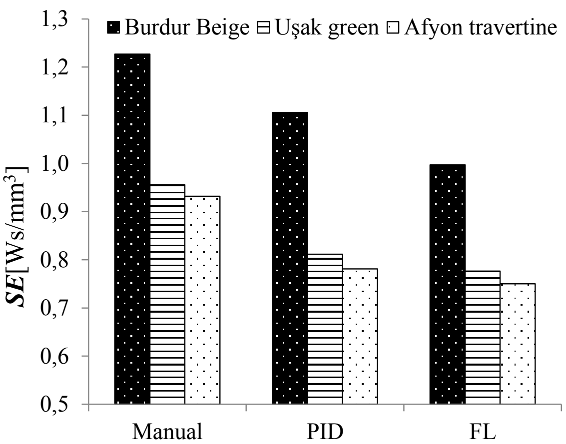


Fig. 10. Mean of SE values for control methods

3.4 Analysis duration of experiment

Duration of experiments achieved in cutting experiments are given in Table 6. While all duration values are maximum for Burdur beige marble, the values are minimum for Afyon travertine. This shows that hard rocks, such as Burdur beige marble are cut in large durations. Because of high cutting durations per unit product decreases besides high energy use in cutting of hard rocks.

Table 6. Duration of experiment for control methods

Control methods	Burdur beige	Usak green	Afyon travertine
Manual	38,116	28,193	26,028
	37,826	28,402	26,407
	35,251	29,890	23,546
	37,064	28,828	25,327
PID	31,295	23,362	23,124
	29,639	22,977	21,642
	29,479	21,156	21,310
	30,138	22,498	22,025
FL	26,356	21,258	20,247
	26,583	21,159	20,726
	26,432	20,866	20,232
	26,457	21,094	20,402

Below mean of duration of experiments are graphically given (Figure 10). These results are show that maximum durations are realized in manual mode. Minimum duration time is carried out in FL controller.

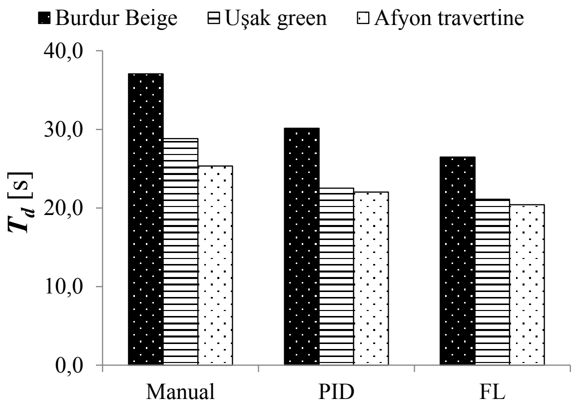


Fig. 11. Mean of durations for control methods

3.5 Analysis total absolute integral error

The quantitative criteria for measuring the controller performance are selected as the integral of absolute error (IAE). The IAE values can be found with equation (3.1). The smaller IAE values imply a better performance.

$$\text{IAE} = \int |e(t)| \cdot dt \quad (3.1)$$

The IAE values evaluated for PID and FL controllers are seen for each rocks and control methods (Table 7). The values show that FL controller has better performance than PID controller.

Table 7. IAE values for control methods

Control methods	Burdur beige	Usak green	Afyon travertine
PID	2,996	2,989	2,532
	2,574	2,412	1,676
	2,308	1,241	1,641
	2,626	2,214	2,214
FL	1,119	0,627	0,577
	1,091	0,620	0,662
	1,107	0,635	0,748
	1,106	0,627	0,620

IAE values of PID controller are over 2, but the values are under 1 for FL controller (Figure 12). Because Burdur beige marble has heterogeneous structure, controlled variable (SE) oscillates more (Figure 8–a and 9–a). Therefore, the IAE values evaluated for Burdur beige marble are more than others.

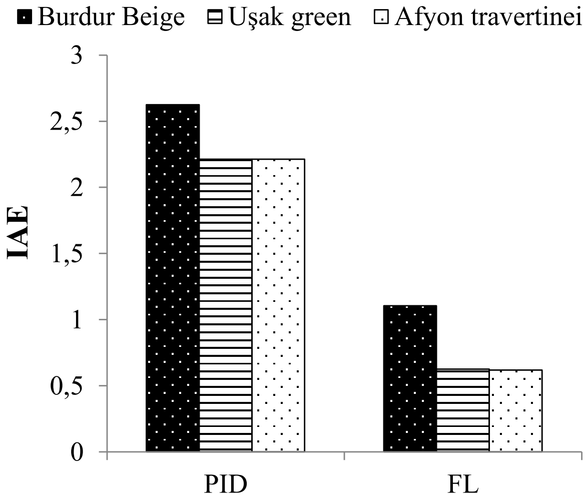


Fig. 12. Mean of IAE values for control methods

3.6 Analysis energy savings

Energy saving analysis is evaluated via different appeared manual and automating cutting results. Energy saving amounts are given as percentage (Table 8).

Table 8. Energy saving values for control methods

Control methods	Burdur beige	Usak green	Afyon travertine
PID	7,498	15,481	13,627
	11,002	13,912	15,880
	11,084	15,900	18,991
	9,861	15,098	16,166
FL	18,337	17,992	20,386
	18,826	18,724	18,562
	18,989	20,502	20,494
	18,718	19,073	19,814

Energy saving achieved for PID controller are between 10% and 15% band. For FL controller, maximum energy saving is performed approx. 20%. The surprising result is the best energy saving achieved for Afyon travertine (Figure 13).

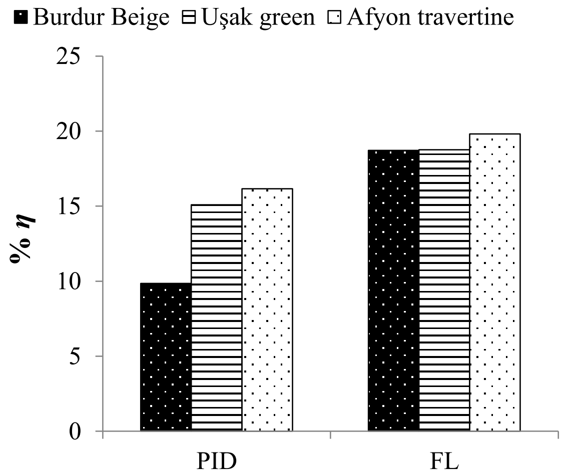


Fig. 13. Mean of energy saving values for control methods

4. Conclusıon

In this study, with arranged travel speed, energy consumed in circular cutting process is tried to be reduces. PID and FL controllers were used in control loop which is set for arranging travel speed. Cutting experiments were performed for three natural rocks (Burdur beige and Usak green marbles and Afyon travertine). Results achieved in cutting experiments are given below;In all of designed controllers, energy saving is partly provided. The best result is carried out in FL controller. PID controller which is widely used in industry is operated with sawblade power feedback. However, PID parameters should be determined to rock properties.FL controller is easily set and also it is quickly settled according PID controller. In FL controller, once rule base is composed, it is used for all rocks. Range of travel speed must be arranged in accordance with rock properties.

In this study, approx. 20% maximum energy efficiency is carried out with FL controller for Afyon travertine. In FL controller, obtained energy efficiency is about 19% for Burdur beige and Usak green marble. The reason for obtaining more energy efficiency in Afyon travertine is contains the fact that it different hardness regions. When heterogeneous rocks, such as Afyon travertine, are cut with fixed travel speed, cutting efficiency reduces. However, if travel speed is arranged according to content of cut region, cutting efficiency raises. When e and de input variables are used in FL controller, a fault reaction can occur in FL controller. The occurred fault can be solved with the addition of third input variable. Third variable may be the sawblade power signal.Though it is out of this study, fixing proportion between travel and sawblade speeds is very important in circular cutting process [3]. When travel speed is increased, more sawdust will be produced in cutting region. However, because sawblade speed is fixed, sawdust existed in cutting region will not be removed in required speed. If sawblade and travel speed can be proportionally arranged and V_w/V_s is fixed during cutting process, energy efficiency can be raised.

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