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Shearer Height Adjustment Based on Mechanical-Electrical-Hydraulic Cosimulation

KUIDONG GAO[1], ZHAOSHENG MENG[2], KAO JIANG[1], HAIZHONG ZHANG[1], AND QINGLIANG ZENG[1,3]

[1]College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[2]State Key Laboratory of Mining Disaster Prevention and Control Co-Founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao 266590, China
[3]College of Information Science and Engineering, Shandong Normal University, Jinan 250014, China

Corresponding author: Zhaosheng Meng (skdmzs@163.com)

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ABSTRACT The automatic height adjustment of a shearer cutting drum is a key technology for shearer automation. However, a fundamental and important requirement for underground electronic products is explosion-proof rating, which creates great challenges to the research on the control method of the shearer height adjustment system. To address this problem, a novel shearer height adjustment control method was proposed based on basic fuzzy control, and the feasibility of the height adjustment method was studied with the help of multisoftware cosimulation technology. First, the drum cutting coal model was established using Finite Element Method (FEM) software LS-DYNA, the mechanical model of the gear transmission system model and the height adjustment system were constructed with the multibody dynamics software ADAMS, the hydraulic height adjusting system model was constructed with AMESim, and a fuzzy controller for shearer height adjustment was developed in Simulink. Then, the data conversion interface between the mentioned models was constructed using MATLAB, to obtain the cosimulation model for the shearer automatic height adjustment. Finally, with the help of fuzzy control method, the feasibility of the cosimulation model used in the adaptive control method of the shearer drum height adjustment was verified. The results show that the cosimulation model can adequately describe the height adjustment process of a shearer, which lays a foundation for the optimization of adaptive height adjustment method. At the same time, the proposed model is also applicable for studying the dynamic characteristics of the mechanical-electrical-hydraulic coordination in the process of shearer adaptive height adjustment.

INDEX TERMS Mechanical-electrical-hydraulic cosimulation, height adjustment, shearer cutting system, fuzzy control.

I. INTRODUCTION

A. BACKGROUND

Energy is the key factor driving economic development. Although China's economic growth has slowed in recent years, China is still the world's largest energy consumer. In 2018, China's energy consumption and growth accounted for 24% of global energy consumption and 34% of global energy consumption growth, respectively. Coal still plays a leading role in China's energy consumption pattern, accounting for more than 55% of the overall energy consumption [1], [2]. Therefore, underground coal mining automation and intelligent mining technology are inevitable directions of coal industry development.

A drum shearer is a key piece of equipment for fully mechanized mining that is responsible for cutting coal and transporting the coal to the scraper conveyor. A typical drum shearer is a complex system that usually consists of traction,

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cutting, electronic control, and hydraulic height adjustment systems. The cutting drum of the shearer is connected to the rocker arm by a rotational joint. The hydraulic height adjustment cylinder lifts the rocker arm while the electric motor, usually installed on the arm, drives the cutting drum. Under ideal conditions, the shearer is in a state of high stress caused by drum cutting coal. During the cutting process, the drum is always in dynamic equilibrium with the surrounding rock under the combined action of electrical, hydraulic, and mechanical systems. When the floor or roof is uneven or when the occurrence height of coal seam varies greatly, the shearer is prone to cut the roof rock or floor rock. Then, this kind of equilibrium state is broken. At this time, cutting resistance of the drum increases suddenly, which results in pick wear and overload of the cutting motor, causing damage to the shearer [3]–[5]. Therefore, the automatic height adjustment behavior of the shearer is of great significance to reduce the wear of picks and improve the efficiency of coal mining.

B. RELATED WORKS

To solve the problem of shearer cutting rock and improve the cutting adaptability of the shearer, scholars have made great efforts to keep the shearer in the state of cutting coal. The most direct solution is the coal–rock interface identification technology [6], which can guide the shearer to automatically track the coal–rock interface. To achieve this, the direct sensors method [7]–[10], the traditional memory cutting method [11]–[13], the Hidden Markov Model method, and the multisensor data fusion method have been successively developed [4], [14], [15]. However, due to the complicated underground mining environment, it is almost impossible to develop a height adjustment system that is applicable to all geological conditions. Therefore, to ensure reasonable and effective shearer selection, researchers often need to carry out a large number of industrial tests. As underground conditions are poor and the tests are expensive, developing an effective mechanical-electrical-hydraulic cosimulation platform to achieve a pretest of the dynamic cutting performance and the height adjustment ability is of great significance [16].

In recent years, with the rapid development of computer technology, cosimulation technology has been widely used for solving multidomain problems [17], [18]. For instance, the cutting vibration behavior of the continuous miner [19], nonlinear motion behavior of the robot [20]–[23], complex fluid dynamics analysis and structural optimization design of variable displacement pump [24]–[26], fuel system design and fuel economy analysis of hybrid cars [27]–[30], and other mechanical–hydraulic cosimulations have been performed [31]–[34]. There are few literature reports focusing on cosimulation problems with three or more domains.

C. DESCRIPTION OF THE COSIMULATION MODEL

According to previous research, a method for judging the cutting state of the shearer was proposed based on the cutting force response. A MG650/1620-WD-type shearer was taken as an example, and its mechanical-electrical-hydraulic cosimulation model was established. The dynamic response and height adjustment behavior of the shearer during the cutting process were simulated, and the feasibility of the scheme was tested. First, a Finite Element Method (FEM) model of the shearer drum cutting coal was established using LS-DYNA to predict the cutting load on the cutters. Then, a mechanical-electrical-hydraulic cosimulation model based on ADAMS/MATLAB/AMESim software was established to simulate the whole dynamic response of the shearer during the cutting process. Specifically, the dynamic model of the shearer mechanical transmission system was constructed using ADAMS software, and the dynamic model of the cutting unit electrical driving system and hydraulic model of shearer height adjustment system were constructed using AMESim software. Finally, a load servo type height adjustment fuzzy controller was developed using Simulink and applied to the cosimulation model to test its rationality. Data transmission and co-simulation of these three models were implemented with MATLAB software as shown in Fig.1.

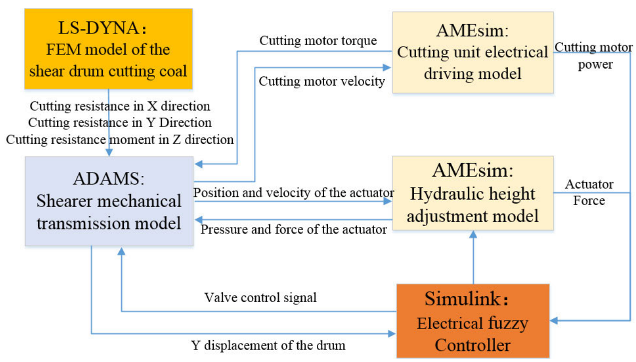


FIGURE 1. Data flow within the mechanical-electrical-hydraulic cosimulation model.

D. MOTIVATION FOR THIS WORK

The main contributions of this paper are as follows: 1) Due to the environment, cost, and other factors, the industrial test of shearer height adjustment is very expensive. The proposed mechanical-electrical-hydraulic cosimulation method lays a foundation for the virtual development of shearer's adaptive height adjustment system. 2) The height adjustment of the shearer is essential not only to reduce cutter wear and improve mining efficiency but also to effectively promote the intelligent control of the shearer and finally help improve the intelligence level of coal mining. 3) The mechanical-electrical-hydraulic cosimulation method proposed in this paper is suitable not only for shearers but also for other equipment with the characteristics of mechanical-electrical-hydraulic cooperation, such as hydraulic support.

E. ORGANIZATION OF THIS PAPER

This paper is arranged as follows. In Section II, the dynamic sub models of a shearer height adjusting system are constructed. This includes the FEM model of the shearer drum cutting system, the multi-body dynamic mechanical model

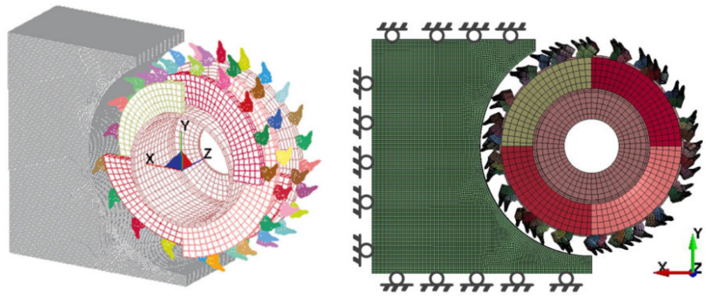


FIGURE 2. FEM model and boundary conditions of the drum cutting coal.

of the shearer transmission system, the dynamic mechanical model of the cutting unit driving system, and the hydraulic model of shearer height adjustment system. In Section III, mechanical-electrical-hydraulic cosimulation models of the shearer based on both artificial control and fuzzy control are established. In Section IV, the results of the cosimulation models are analyzed. Finally, the conclusions are presented in Section V and the future work is discussed in Section VI.

II. DYNAMIC SUB MODELS OF THE SHEARER CUTTING SYSTEM

A. FEM MODEL OF THE SHEARER DRUM CUTTING COAL

There are two primary methods to predict the pick cutting force, namely: the static analytical method and the dynamic analysis based on the finite element method. The static analytical method can estimate the average cutting force of pick cutting, while the dynamic analysis method can provide a true representation of the coal or rock cutting process and obtain the random dynamic load of the pick cutting process [35]. Thus, the FEM method was adopted in this paper. Structures of the shearer drum and picks are shown in Fig. 1. The system consisted of one shearer drum and the coal seam, as shown in Fig. 2. The FEM model was meshed using hexahedral elements, and rigid body constraints were applied among the picks, vanes, and hub to confirm their similar movement. The movement degree of freedom (DOF) in the Y and Z directions and the rotational DOF around the X and Y directions of the drum are constrained, so that it can only move along the X axis and rotate around the Z axis.

Given that the constitutive model of the coal material has a significant influence on the simulation results, multiple constitutive models are provided by LS-DYNA, such as the Holmquist-Johnson-Cook, Drucke-Prager, and Brittle-Damage models [36]–[39]. The Brittle-Damage model and eroding failure of material were selected in this study because of the brittle characteristics of coal [38], [39]. The contact between the pick and coal was defined as surface to surface penetration contact (*CONTACT_ERODING_SURFACE_TO_SURFACE). The pick was defined as the master face, and the coal was defined as the slave face. When the maximum principal strain of coal element reaches 0.02, the coal element will be removed from the coal model.

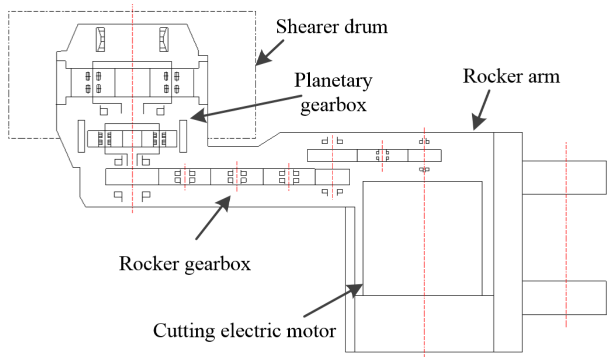


FIGURE 3. Mechanical transmission system of shearer cutting part.

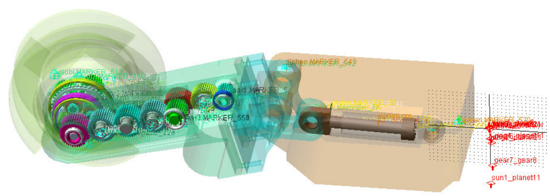


FIGURE 4. Dynamic model of shearer mechanical transmission system.

Rigid hourglass type 5 control was adopted to define the coal element, and the hourglass coefficient was set as 0.04. The main material parameters of the coal and drum model are shown in Table 1.

B. MULTI-BODY DYNAMIC MODEL OF THE SHEARER MECHANICAL TRANSMISSION SYSTEM

The cutting motor-rocker arm reducer-planetary gearbox-drum transmission system was adopted in MG650/1620-WD, as shown in Fig. 3. The rocker arm reducer consists of a 2-stage spur gearbox with a transmission ratio of 2.486. The planetary gear reducer consists of 2 stage planetary transmission with a transmission ratio of 23.0785.

The digital model of the shearer mechanical transmission system was prepared using Solidworks, and the data were transferred to ADAMS in parasolid format. The established multibody dynamic model of the transmission system is shown in Fig. 4. The shearer body was mounted on the ground with a fixed joint. The rocker arm and the shearer body, the rod of height adjustment cylinder and the rocker arm, the cylinder barrel and the shearer body were connected with

TABLE 1. Main parameters of the coal and drum.

Coal	Density (t/mm^3)	Elastic modulus (MPa)	Poisson's ratio	Tensile strength (MPa)	Compressive strength (MPa)	Shear strength (MPa)	Fracture judgment (MPa/mm^2)
	1.3e-9	3100	0.3	1.2	37	9	0.2
Drum	Density (t/mm^3)	Elastic modulus (MPa)	Poisson's ratio	Translation constraint	Rotational restraint	Translational velocity (m/min)	Rotational velocity (m/min)
	7.85e-9	2×10^5	0.3	Y, Z	X, Y	10.4	25.83

rotational joints. Displacements of the rod drove the swing angle of the rocker arm, and then the drum cutting height was adjusted to cut the coal seam with different thicknesses. Taking the impact and collision characteristics of the transmission system into consideration, the contact among the gears and the splines was defined using an impact-function-based contact algorithm, which was provided by ADAMS. As the contact force between the gears produces friction force, soaking lubrication was adopted in gear transmission. According to the material contact properties table proposed by ADAMS, the static friction coefficient was defined as 0.23, the dynamic friction coefficient was 0.16, and the rebound coefficient was 0.9 [40].

C. DYNAMIC MODEL OF THE CUTTING UNIT ELECTRICAL DRIVING SYSTEM

A flameproof three-phase servo motor (YBCS-650) was equipped on the MG 650/1620-WD as the cutting motor. The motor was transversally arranged in the rocker arm box. The torque of the motor was transmitted to the torque shaft through a spline and then output to the external gear transmission system. The main parameters of YBCS-650 are shown in Table 2.

TABLE 2. Main parameters of YBCS-650 flameproof three phase asynchronous motor for a shearer.

Parameters	Value	Parameters	Value
Rated power	650 kW	Operation mode	S1
Rated voltage	3300 V	Connection mode	Y
Rated current	136 A	Rotor rated current	5.5 A
Rated frequency	50 Hz	Efficiency	96%
Rated speed	1486 r/min	Power factor	0.86

In this study, based on the sub model of EMDIMSC01 in AMESim, the electrical driving system for the motor reducer considering load and viscous friction was established, as shown in Fig. 5.

D. HYDRAULIC MODEL OF SHEARER HEIGHT ADJUSTMENT SYSTEM

The hydraulic height adjustment system of the shearer is shown in Fig. 6. The system was mainly composed of a pump station motor, an oil leach, a double gear pump, two solenoid

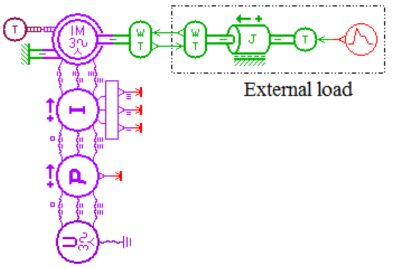


FIGURE 5. Electrical driving model of the shearer cutting motor.

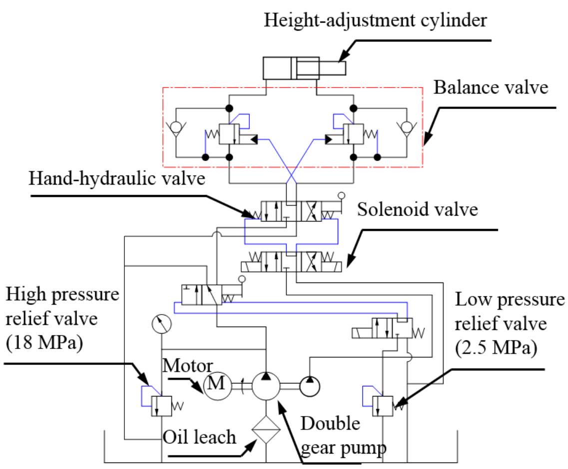


FIGURE 6. Schematic of shearer height adjustment hydraulic system.

valves, oil pipes, a balance valve (bidirectional hydraulic lock) and a height-adjustment cylinder. The black lines are the main oil pipes, and the blue lines are the control oil pipes. The pump used in the system was a double gear pump with 1465 r/min rotational velocity and 92% volumetric efficiency. The rated flow rate and working resistance of the large pump and small pump were 28 mL/r and 4 mL/r and 18 MPa and 2.5 MPa, respectively. The balance valve was used to lock the hydraulic circuit and maintain the hydraulic cylinder in the same position. It consisted of two CBEA-LAN type counterbalance valves, as shown in Fig. 7, and the flow capacity of the balance valve was 150 L/min. As a simulation platform to establish and analyze the complex systems, AMESim software was selected to construct the model of the balance valve, as shown in Fig. 8. In the pilot valve, mass and displacement limit of the spool were 0.02 kg and -3.5∼0 mm, respectively.

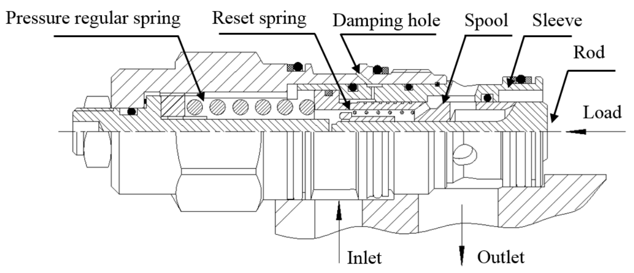


FIGURE 7. Schematic of the CBEA-LAN type balance valve.

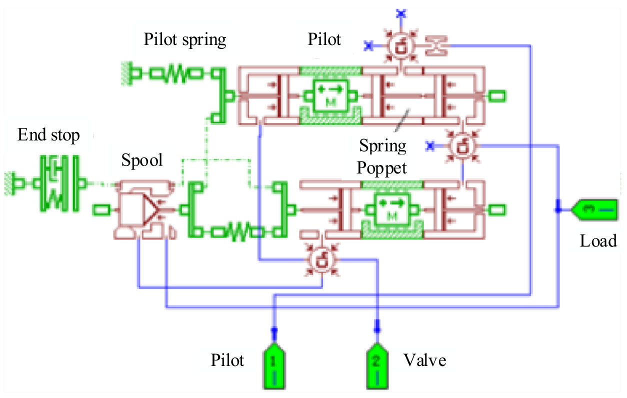


FIGURE 8. Hydraulic model of the balance valve in AMESim.

The spring stiffness was 150 N/mm, and the preload was 1500 N. The piston and rod diameters were 16 mm and 12 mm. In the main valve, the mass and displacement limit of the spool were 0.01 kg and 0∼3.5 mm. The spring stiffness was 1 N/mm. The diameters of cone valve, hole and rod were 12 mm, 10 mm and 4 mm, respectively. The clearance of end stop was 0.5 mm.

The simplified hydraulic system model is shown in Fig. 9. The balance valve model was packaged into a super component. The flow capacity of the solenoid valve was 150 L/min. The piston diameter, rod diameter, and working stroke of the cylinder were 278 mm, 150 mm, and 740 mm, respectively. The oil pressure was 18 MPa. The inner diameter and length of tubing 2 were 25 mm and 0.5 m, while those of tubing 3 were 13 mm and 5.5 m. The external load was the random load obtained in Section II. A.

III. MECHANICAL-ELECTRICAL-HYDRAULIC COSIMULATION MODEL OF THE SHEARER HEIGHT ADJUSTMENT SYSTEM

A. COSIMULATION MODEL WITH ARTIFICIAL HEIGHT ADJUSTMENT SIGNAL

Based on the sub models of the cutting system established in Section II, the mechanical-electrical-hydraulic cosimulation model with artificial height adjustment signal was constructed using software interfaces, as shown in Fig. 10. The main purpose of this model was to test the rationality of the cosimulation model. The multibody dynamic mechanical model of the shearer was exported from ADAMS using A/Control plug tool. The models were compiled into an

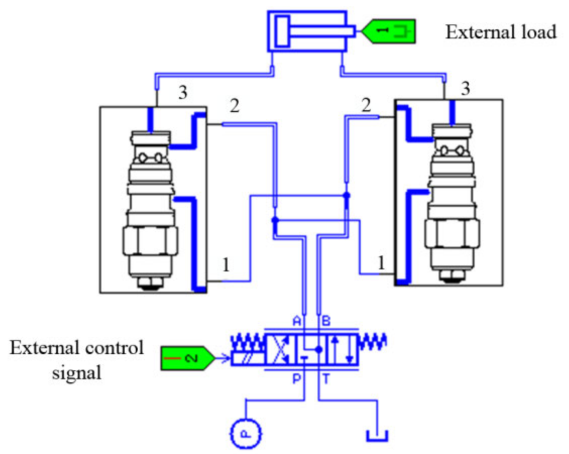


FIGURE 9. AMESim model of the hydraulic height-adjustment system.

S-function in MATLAB. As shown in Fig. 10, the valve control signal (external control signal in Fig. 9) was generated by using an artificial signal builder. Both the solvers in AMESim and Simulink software were defined as the variable-step solvers. In addition, the time interval for data communications between the mentioned software was defined as 0.001 s.

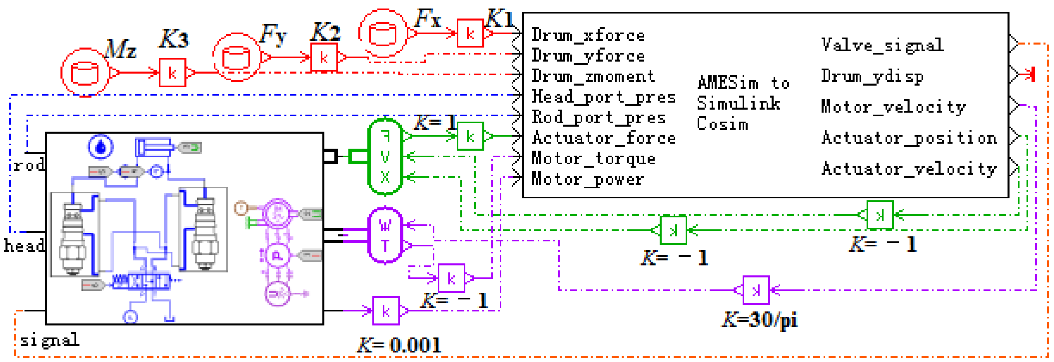
B. FUZZY CONTROLLER MODEL OF THE SHEARER HEIGHT ADJUSTMENT

As mentioned in Section I, the height-adjustment process of a shearer is highly nonlinear. It is difficult to establish a precise mathematical model for this behavior. Therefore, the traditional modeling theory is not applicable for this work. In this study, the intelligent fuzzy control method was selected to develop the height-adjustment controller because it can achieve the precise control of a complex system [41], [42].

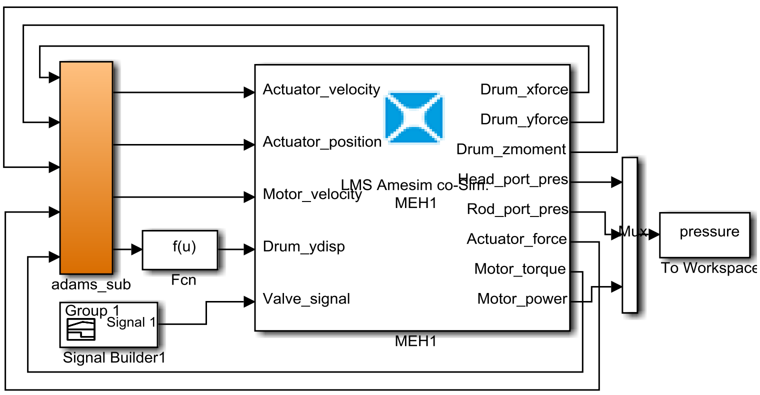
The actual output power of the shearer cutting motor was calculated with equation (1). During the shearer cutting process, the supplied voltage remains almost unchanged. Assuming that the efficiency and power factor of the motor are constants, the current variations of the cutting motor can reflect the power variations of the shearer cutting part.

$$\boldsymbol{P}_s = \sqrt{3}\eta UIcos\varphi \tag{1}$$

Here, η is the efficiency of the cutting motor, U is the line voltage of stator winding, I is the line current of the stator winding, cos φ is the power factor of the cutting motor, φ is the phase difference between the stator phase current and phase voltage, and P_s is the power of the cutting motor. The resultant force of the height adjustment cylinder is positively correlated with the cutting load. Therefore, the variations in the cutting motor power and the cylinder resultant force can be used to accurately determine the shearer working conditions. The control logic of the rocker arm height adjustment of the shearer is usually determined according to the experience of the technicians. Hence, this study used a Mamdani-type fuzzy controller [43], which typically consists of the



(a) Cosimulation model of the cutting system in AMESim.



(b) Cosimulation model of the cutting system in MATLAB.

FIGURE 10. Mechanical-electrical-hydraulic cosimulation model of shearer cutting system.

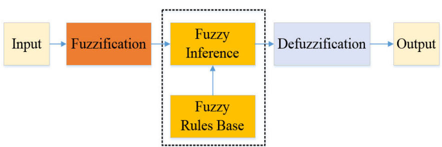


FIGURE 11. Mamdani-type fuzzy controller.

following three stages, as shown in Fig. 11: fuzzification, fuzzy inference, and defuzzification [44].

1) FUZZIFICATION OF THE INPUT VARIABLES

In the fuzzification stage, input and output variables are converted into fuzzy values. In this study, the rated power of the cutting motor and the maximum resultant force of the cylinder were defined as input variables, marked as P_e and F_e. The rated voltage of the valve controller was defined as the output variable, marked as U_f. Accordingly, the real power of the cutting motor, the real-time resultant force of the cylinder, and the real-time voltage of the valve controller were defined as P_s, F, and u, respectively. Then, the quantization factors $\text{k1} = P_s/P_e$, $\text{k2} = F/F_e$, and $\text{ku} = u/U_f$ were introduced to transfer P_s, F, and u from the fundamental domain to the fuzzy domain, namely, X, Y, and Z, respectively. Finally, X was divided into 5 levels, and its fuzzy subset was defined as {xVS, xS, xM, xB, xVB}. Y was divided into 6 levels, and its fuzzy subset was defined as {yVS, yS, yM, yB, yVB, yVVB}. Z was divided into 11 levels, and its fuzzy subset was defined as {NVB, NB, NM, NS, NVS, ZO, PVS, PS, PM, PB, PVB}. Trapezoidal and triangular membership functions were selected to fuzzy the variables and the results are shown in Fig. 12.

2) FUZZY RULE BASE

A fuzzy if-then rule base was chosen based on experiences of the experts to make an informed decision [45], [46]. It is known that the hardness of the rock is greater than that of the coal wall. Therefore, when the shearer cuts the roof rock or the floor rock, the two input variables increase significantly. Then, the controller needs to send a control signal to adjust the height of the drum to avoid cutting the rock for a long period. Thus, the fuzzy rule can be expressed by equation (2).

$$R^{j,i}: \text{If X is } x_i \text{ and Y is } y_j, \text{ then Z is } z_{j,i} \tag{2}$$

Here, $R^{j,i}$ is the fuzzy control rules, x_i and y_j belong to X and Y, respectively. Based on the above, the fuzzy rule base for the fuzzy controller was established, as shown in Table 3.

The input and output surfaces of the height adjustment fuzzy controller were produced as shown in Fig. 13.

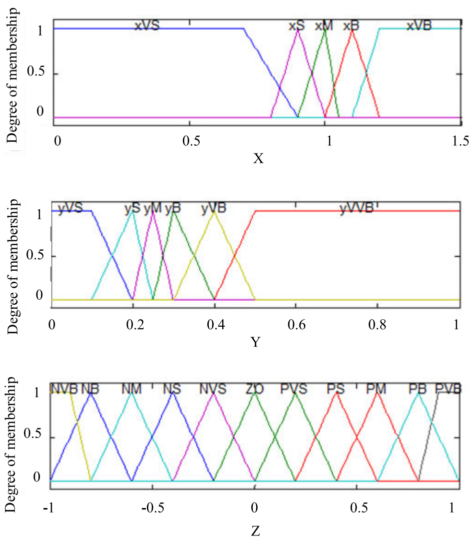


FIGURE 12. Membership functions of the fuzzy variables.

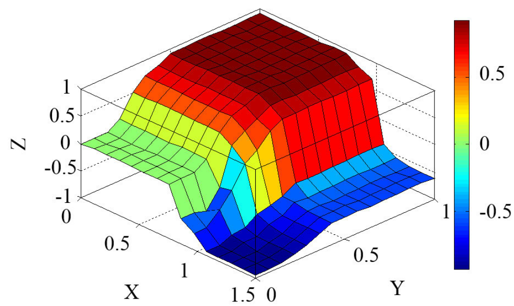


FIGURE 13. Input and output surfaces of the height adjustment fuzzy controller of the shearer.

TABLE 3. Fuzzy controller rule base.

Y \ X	xVS	xS	xM	xB	xVB
yVS	ZO	NVB	NM	NVB	NVB
yS	ZO	NB	ZO	NB	NVB
yM	PS	PVS	ZO	NB	NB
yB	PM	PS	ZO	NM	NB
yVB	PB	PM	PS	NM	NM
yVVB	PVB	PB	PM	NS	NM

3) DEFUZZIFICATION

Defuzzification is the last stage for a fuzzy controller, which can be performed by many different methods. In this study, a center of gravity defuzzifier was chosen to complete the defuzzification [47], [48].

Fig. 14 shows the model of the fuzzy control subsystem based on the aforementioned fuzzy control rules by using MATLAB/Simulink. Scale transformation of the corresponding variables was performed by using the gain modules, and the input and output of the fuzzy controller were limited in the range of fuzzy domain by using the saturation modules. Moreover, a three-order BW low pass filter with the cutoff frequency of 20 rad/s was added to the model to filter the variable signals (i.e., to filter out the high frequency parts of the motor power and actuator force to prevent excessive system vibration).

The initial operating height of the rocker arm in the mechanical model was set as the lowest. For the rocker arm to swing up and down, the signal builder needs to output a valve control signal to raise the rocker arm first. The signal builder stops working after 2 s, and the valve control signal is determined by the fuzzy controller. Moreover, to cut the roof and the floor evenly, there should be a limitation in the vertical motion direction of the drum. In consideration of this, a logic control of the drum motion range was added into the designed fuzzy control subsystem. If the vertical displacement of the drum was less than 450 mm, the valve control signal was set as -10 so the drum moved upward. If the vertical displacement was greater than 750 mm, the valve control signal was set as 10 so the drum moved downward. Otherwise, the valve control signal was given by the fuzzy controller.

C. COSIMULATION MODEL WITH FUZZY CONTROL HEIGHT ADJUSTMENT SIGNAL

In Section III. A, the valve control signal for the mechanical-electrical-hydraulic cosimulation model was generated by an artificial signal builder. In this section, the artificial signal builder was replaced by the fuzzy controller built in Section III. B to test the height adjustment fuzzy control method (Fig. 15). The mechanical-electrical-hydraulic cosimulation model in AMESim was the same as that in Fig. 10 (a).

IV. NUMERICAL SIMULATIONS AND RESULTS

A. COAL CUTTING SIMULATION RESULTS

Fig. 16 (a) shows the three-directional force loads of the drum during the coal cutting process. It can be observed that the Y direction force R_y is significantly greater than the X direction force R_x. This is clearly explained in Fig. 17, where the cutting resistance of the vane pick (Z_i) is along the tangential direction of the drum, while the advancing resistance of the drum (Y_i) is pointed towards the center of the drum. ω is the rotation angular speed of the drum and v_q is the traction speed of the shearer. The values of forces R_x, R_y, and R_z can be determined using the following equations:

$$R_x = \sum_{i=1}^{n_p}(-Y_i \sin\theta_i - Z_i \cos\theta_i) \quad (3)$$

$$R_y = \sum_{i=1}^{n_p}(-Y_i \cos\theta_i + Z_i \sin\theta_i) \quad (4)$$

$$R_z = \sum_{i=1}^{n_p} X_i \quad (5)$$

Here, X_i is the average lateral force, θ_i is the vertical angle of Y_i, and n_p is the number of cutting picks. When Z_i and Y_i

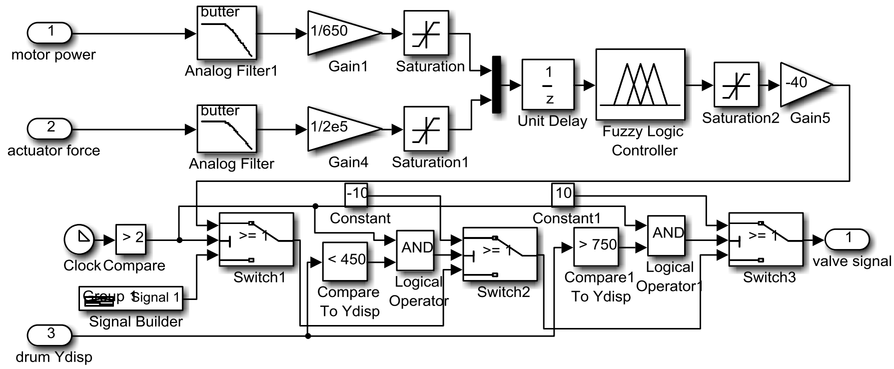


FIGURE 14. Model of the electrical fuzzy control subsystem.

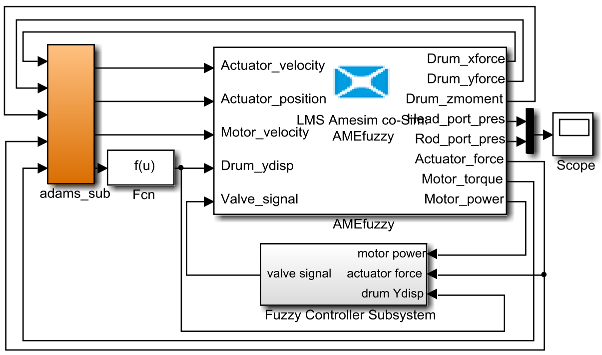
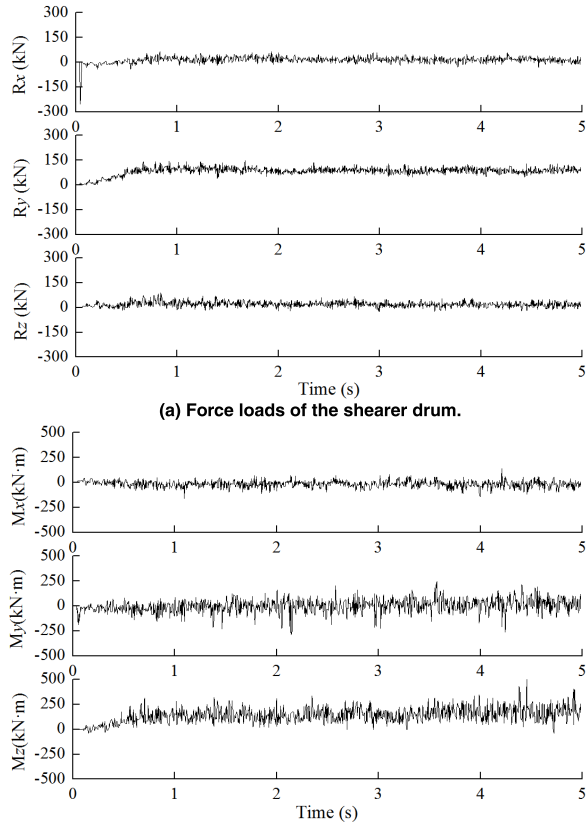


FIGURE 15. Mechanical-electrical-hydraulic cosimulation model of the height adjustment system of the shearer in MATLAB.

are decomposed along the X and Y directions, the Y direction components are always in the same direction, while the X direction components are always in the opposite direction. Thus, the synthesized force in the Y direction, R_y, is much larger than R_x. The mean value of the Z direction force is close to zero, but its fluctuation range is large. Moreover, there is a negative impact force along the X direction at the beginning of the cutting process. This is because only one pick at the upper left of the end plate of the drum contacts with the coal wall at this stage. Therefore, the X components of Z_i and Y_i are all pointed towards the negative direction of the X axis. Fig. 16 (b) shows the three directional moment loads, namely, M_x, M_y, and M_z. It can be seen that the mean values of M_x and M_y are small, while the mean value of M_z is approximately 155 kN·m.

B. RESULTS ANALYSIS OF THE COSIMULATION MODEL WITH ARTIFICIAL HEIGHT ADJUSTMENT SIGNAL

In this section, the presented simulation aimed to verify the feasibility of the mechanical-hydraulic cosimulation platform and to analyze the variation law of the variables that can reflect the cutting state of the drum. The random drum cutting load obtained in Section IV.A was applied to the model in different proportions (1, 0.8, 0.6, 0.4) to simulate different loads. At the beginning of the simulation, an initial pressure was applied in the cylinder to balance the self-weight of the



(a) Force loads of the shearer drum.

(b) Moment loads of the shearer drum.

FIGURE 16. Loads of the shearer drum.

rocker arm. Then, the simulation models were run for 10 s and the corresponding results are shown in Fig. 18.

In this simulation, the height control signal was defined artificially, which consisted of 5 stages. The first stage was the initial adjusting, where the rocker arm was adjusted to gradually enter the cutting state. To achieve this, the valve control signal was first set as 0, and the directional valve was in the center position (0-1 s). Pressure in the rodless chamber fluctuated violently under the action of cutting resistance, which established an equilibrium between the mechanical system and the hydraulic system of the shearer. Then, the pressure decreased gradually and tended to be stable. Pressure in

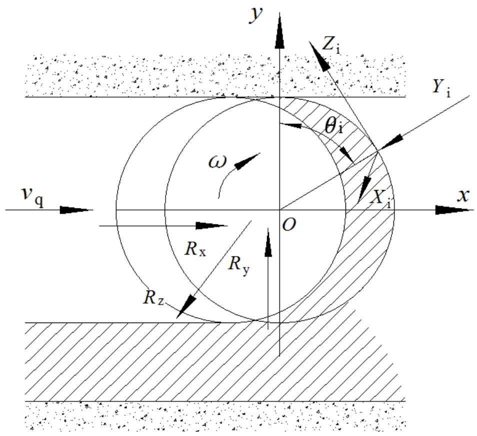


FIGURE 17. Force analysis of the shearer drum.

the rod chamber was 0 at this stage. Therefore, the piston resultant force was provided by the rodless chamber.

The second stage was the upward swing stage of the drum. The valve control signal was set as negative during this process (1-4 s). The piston rod was displaced outward and caused the drum to rise.

The third stage was the stable cutting stage of the drum (4-6 s). Both chambers exhibited large pressure fluctuations under the action of changing cutting resistance.

The fourth stage was the downward swing stage of the drum (6-9 s). At this stage, the directional valve turned on in reverse. The piston rod was displaced backward and caused the drum to fall. There was a large pressure increase in the rod chamber when the directional valve opened at 40%.

The final stage was the unloading stage. The oil supply circuit was cut off in this stage, and the pressures in both chambers decreased gradually, while the pressures in the rodless chamber exhibited a larger fluctuation.

In an evaluation of the simulation from an overall view, the pressure of the cylinder varied greatly during the height adjusting process. When the hydraulic cylinder circuit was turned on (forward or reverse), the pressures in both chambers increased significantly. The increase was more significant when the circuit was turned on reversely (the drum swung downward). When the hydraulic circuit was locked and the drum was stable at different working positions, the mean pressures of the cylinder were different. This is because the heavy moment of the rocker arm varied with the operating height of the drum. Moreover, the pressure fluctuation amplitude was large because there was no buffer in the system. The mean values of the characteristic parameters under the action of cutting loading are shown in Table 4. It can be seen that the mean resultant force of the piston rod decreased as the cutting load increased.

C. RESULTS ANALYSIS OF COSIMULATION MODEL WITH FUZZY CONTROL HEIGHT ADJUSTMENT SIGNAL

The fuzzy control method was used in this paper to test the height adjustment method. Therefore, this paper mainly

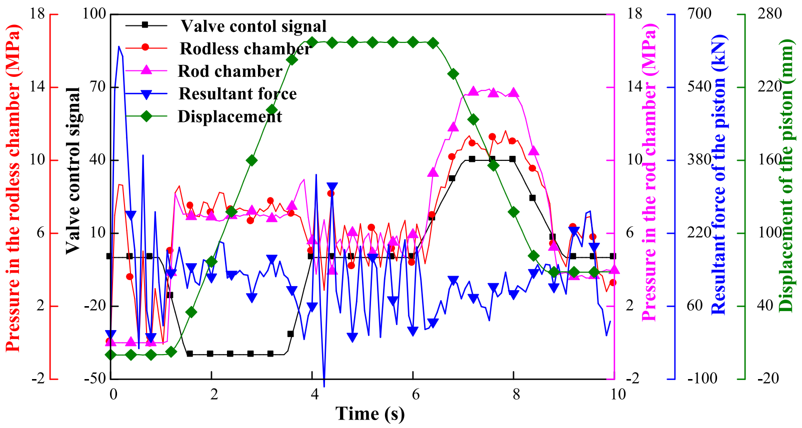
TABLE 4. The mean values of the characteristic parameters.

Load Proportion	Pressure in rodless chamber/MPa	Pressure in rod chamber/MPa	Resultant force/kN
1	5.95	5.8	105.5
0.8	6.67	5.4	177
0.6	7.5	5	246
0.4	8.3	4.9	325

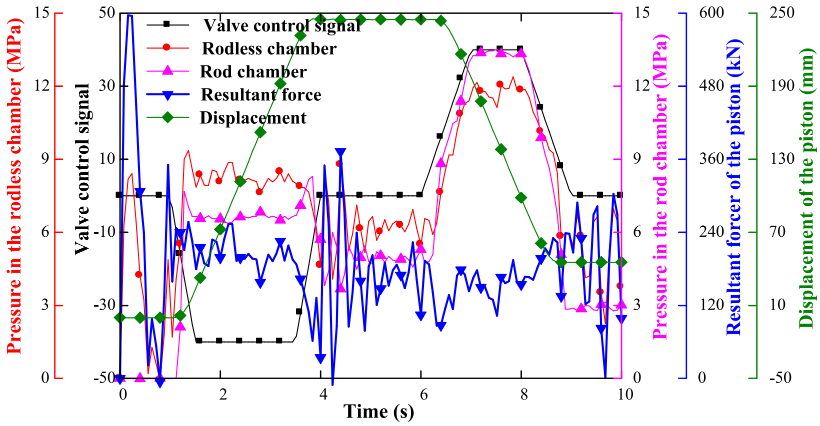
focuses on the cosimulation method and height adjustment method for shearer height adjustment. In addition, the robustness of control system can also be used to evaluate the controller performance [49], [50]. However, this paper only aims to prove the validity of the fuzzy control method and the validity of the co-simulation platform, rather than the robustness of the system. Therefore, the height adjustment method was used to evaluate the controller performance and the height adjustment performance of the system will be mainly discussed. Fig. 19 shows the results of the mechanical-electrical-hydraulic cosimulation model.

As shown in Fig.19, during the initialization stage (0-2 s), the valve control signal was set as negative. Thus, the piston rod was displaced outward and caused the drum to rise (525 mm). The motor power reached 500 kW in this stage (Fig. 19 (a)). However, due to the large self-weight of the rocker arm, there was a large impact force on the piston. The piston force reached a stable value of 270 kN at approximately 1 s (Fig. 19 (b)). After 2 s, the control signal was given by the fuzzy controller. During 2-2.5 s, the drum continued to cut the coal wall horizontally. At this stage, the drum cutting load was small, while the resultant force of the piston was large. Moreover, the motor power did not achieve the rated value. From 2.5 s to 3.95 s, the bottom coal was cut. The controller gave a negative signal to control the drum, which swung up to cut the top coal. From 3.95 s to 5 s, the controller detected that the vertical displacement of the drum had exceeded the limit height of 5 mm (750 mm). Then, a maintenance signal was given to keep the drum operating at this height. The valve control signal fluctuated constantly under the action of the movement inertia of the drum and rocker arm. When the resultant force of the piston was lower (68.6 kN) and the motor power was in the rated working state (5.17 s), the conclusion of the drum overload was obtained by the controller, and a positive signal was given to cause the drum to fall. At 6.2 s, the motor power reached 803 kW, and the cutting resistance of the drum increased continuously. Then, the controller determined that the cutting motor was in a severe overload state, and a positive control signal was given to control the drum to swing down. At approximately 7.4 s, the drum reached the minimum operating height, and the controller output a control signal to keep the drum in this state.

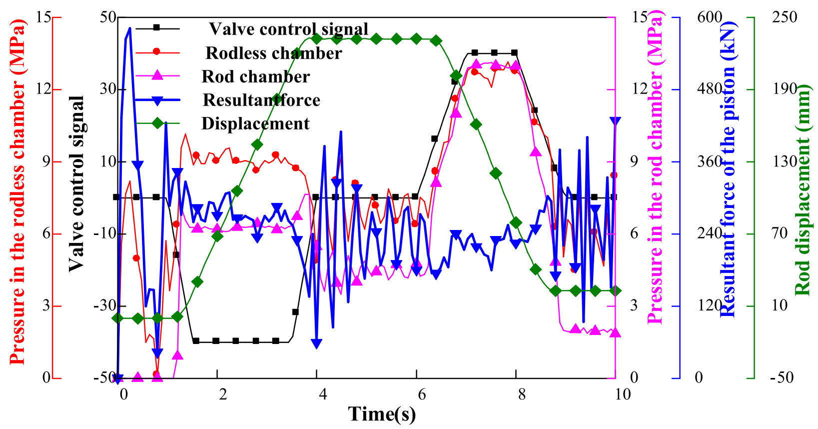
According to the above analysis, functions of the fuzzy controller in the height adjustment control system can be determined as follows: 1) When the motor power was lower



(a) Cutting load proportion is 1.0.



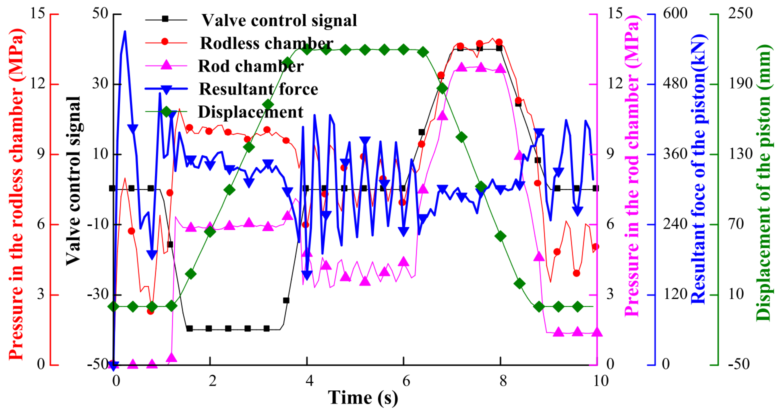
(b) Cutting load proportion is 0.8.



(c) Cutting load proportion is 0.6.

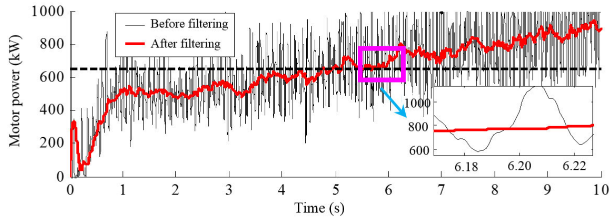
FIGURE 18. Variation curves of the characteristic parameters under different cutting loads.

and the piston resultant force was greater (cutting load of the drum was small), the controller could control the cylinder to swing up automatically to cut more coal; 2) When the motor power exceeded 1.2 times the rated value, the controller determined that the shearer was in an overloaded cutting rock state. At this stage, the controller ignored the drum cutting load signal and controlled the drum to swing down directly. Therefore, the cutting rock state and the longtime overload state were avoided effectively. 3) When the displacement of the drum reached the highest or lowest limit of the set height, the fuzzy controller could keep the drum around the set height to ensure flatness of the roof to a certain extent. In summary,

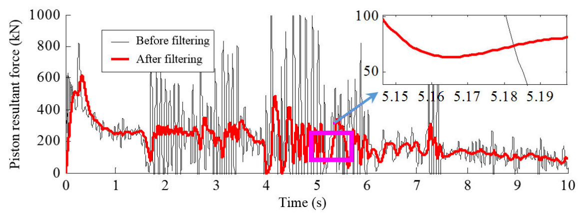


(d) Cutting load proportion is 0.4.

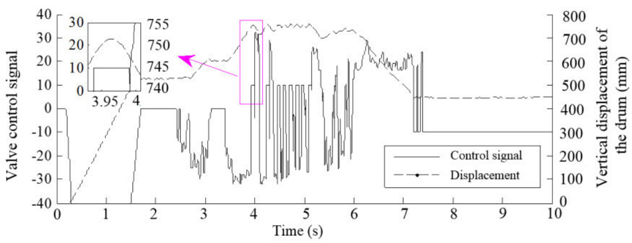
FIGURE 18. ***(Continued)*** **Variation curves of the characteristic parameters under different cutting loads.**



(a) Variations in the motor power.



(b) Variations in the piston resultant force.



(c) Variations in the valve control signal and vertical displacement of the drum.

FIGURE 19. **Results of the mechanical-electrical-hydraulic cosimulation model.**

the proposed fuzzy controller can output the corresponding control signal according to the cutting condition of the drum to realize automatic height adjustment of the shearer.

V. CONCLUSION

1) This paper employed a MG650/1620-WD shearer as the research object. First, ADAMS, AMESim, and MATLAB were used to establish the mechanical-electrical-hydraulic cosimulation model, and its rationality was tested. Subsequently, a fuzzy height adjustment controller was established. Finally, the controller was substituted into the cosimulation platform to test the rationality of the proposed height adjustment method. The variation rule of the system parameters was reasonable, which verified the feasibility of the cosimulation method.
2) The cosimulation results showed that the proposed fuzzy controller can realize the height adjustment control of the drum. Thus, a long term no-load or overload operating state of the motor can be prevented. With pressure of the hydraulic cylinder and the stator winding current of the motor as the controlling variables, the proposed fuzzy control method has a high development and application potential in the field of shearer height adjustment.
3) The cosimulation platform based on ADAMS/ MATLAB/AMESim, with the shearer height-adjustment object as the example, ran well, and the results were reasonable, which provides a theoretical basis for the subsequent experimental verification.

VI. FUTURE WORK

Due to the limitations of time and computer calculation efficiency, only the feasibility of the proposed height adjustment method and mechanical-electrical-hydraulic cosimulation was tested herein, without making too many improvements to the fuzzy control method. Therefore, the following problems still remain to be solved in the design of the mechanical-electrical-hydraulic cosimulation platform and control performance analysis for height adjustment of a shearer:

1) It is necessary to further improve the model of the shearer traction system and refine the mechanical-electrical-hydraulic cosimulation model of the shearer based on industrial tests and other means;
2) To expand the applicability of the proposed height adjustment method, more performance tests are needed according to the different characteristics of coal and rock in different coal faces. Furthermore, robustness

of the control method with different system parameters also needs to be evaluated.

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KUIDONG GAO was born in Zaozhuang, Shandong, China, in 1986. He received the B.S. degree from Central South University, Changsha, in 2008, and the Ph.D. degree in mechanical engineering from the China University of Mining and Technology, Xuzhou, China, in 2014.

From 2014 to 2018, he was an Assistant Professor with the Mechanical Engineering Department, Shandong University of Science and Technology, where he has been an Associate Professor, since 2019. He is the author of more than 40 articles and more than 20 inventions. His research interests include hydraulic transmission and control, mechanical rock breaking theory, intelligent mining technology and equipment, reliability of mining machinery, simulation, and application of mechatronic hydraulic systems.

ZHAOSHENG MENG was born in Liaocheng, Shandong, China, in 1991. He received the B.S. and Ph.D. degrees from the Shandong University of Science and Technology, Qingdao, China, in 2015 and 2019, respectively. Since 2019, he has been a Lecturer with the State Key Laboratory of Mining Disaster Prevention and Control Co-Founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology. He is the author of more than six articles and holds more than five patents. His research interests include optimum design of hydraulic support, simulation and application of mechanical-electrical-hydraulic co-simulation systems, and hydraulic transmission and control.

KAO JIANG was born in Yantai, Shandong, China, in 1993. He received the B.S. degree from the Shandong University of Science and Technology, Qingdao, China, in 2016, where he is currently pursuing the Ph.D. degree in mechatronic engineering. His research interests include dynamic analysis and control of mechanical systems and mechanical rock breaking theory.

HAIZHONG ZHANG was born in Liaocheng, Shandong, China, in 1988. He received the B.S. and M.S. degrees from the Shandong University of Science and Technology, Qingdao, China, in 2013 and 2016, respectively. His research interests include dynamic analysis and control of mechanical systems, simulation and application of mechatronic hydraulic systems, and mechanical rock breaking theory.

QINGLIANG ZENG was born in Weifang, Shandong, China, in 1964. He received the B.S. and M.S. degrees in mining machinery from the Shandong University of Science and Technology, Qingdao, China, in 1988, and the Ph.D. degree in mechanical engineering from the China University of Mining and Technology, Beijing, China, in 2000.

He joined the Shandong University of Science and Technology, as an Assistant Professor, where he has been an Associate Professor and a Professor with the Department of Mechanical Engineering, since 2002. He has also been the Director of the Innovation Team of the Ministry of Education, since 2013, and of the Shandong Collaborative Innovation Center, since 2013. He is the author of more than 60 articles and holds more than 70 patents. His research interests include monitoring and fault diagnosis system for underground equipment, computer integrated manufacturing systems, hydraulic transmission and control, and intelligent mining technology and equipment.

Dr. Zeng is a Senior Member of Chinese Mechanical Engineering Society (CMES), a member of China Simulation Federation (CSF), and an Editorial Board Member of Chinese Journal of Construction Machinery. His awards and honors include the National Science and Technology Progress Awards.