Research Article

Multifactor Analysis of Roadheader's Body Pose Responses during the Horizontal Cutting Process

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Based on the Lagrange equation in system dynamics, aiming at the horizontal cutting process, the dynamical coupling model of boom-type roadheader's body pose was established. According to input problem of solving the model, a calculation method of the cutting head load was proposed, and the relationship between the cutting head load and pressure of the driving cylinders and swing angle of the cutting arm was obtained through simulating analysis. The simulation model was established to solve the dynamical coupling model. The cutting head load, horizontal swing angle of the cutting arm, and dip angle of coal seam were regarded as independent variables to perform changing parameter analysis in variations of the body pose. The field experiment was carried out, and the measured data is basically consistent with the simulation values. The results show that lateral displacement of the body can reach up to 6.5 cm, backward displacement can reach up to 5.2 cm, floor-based quantity can reach up to 11 cm, pitch angle of the body can reach up to 7.8°, and roll angle can reach up to 2.1°. Variations of the body pose parameters are influenced greatly by the cutting head load, while the influence from horizontal swing angle of the cutting arm and dip angle of coal seam is slighter. Among the pose parameters, floor-based quantity and pitch angle of the body vary relatively greatly, which tend to seriously influence forming quality of the roadway and should be mainly considered in deviation rectification of the roadheader's body pose.

1. Introduction

Coal is the main energy source in China, accounting for 65% of China's primary energy consumption, which supports sustainable development of national economy and society. At present, the depth of coal mining in China keeps increasing, and some coal mines have exceeded 1000 m; therefore coal mining faces more and more difficulty. The mining and excavating operation are the most important and difficult production links. There are high risk factors in deep coal seam, so it is very significant to study the key basic problems of the fully mechanized excavation face [1–6].

Boom-type roadheader is the most important equipment in the fully mechanized excavation face, mainly used for excavation of the roadway to prepare the working face for coal mining. Due to the complexity and changeableness of the occurrence condition and physical mechanical properties of coal and rock in roadway cross-section, the hardness of

coal and rock during cutting process is changing constantly and randomly; therefore the cutting head load is also continuously changing during the cutting process [7–12]. The complex and changeable cutting head load, different dip angles of coal seam, and constantly changing horizontal swing angle of cutting arm cause constant change of roadheader's body pose during the horizontal cutting process, which seriously influences the positioning and orienting excavation of the roadheader and leads to reduction in forming quality and drive efficiency of the roadway [13–16]. Therefore, study on the regularities of roadheader's body pose responses during the horizontal cutting process has great significance in improvement of forming quality and drive efficiency of the roadway, realization of robotized automatic cutting, and ultimately realization of “unmanned” operation in the fully mechanized excavation face.

Some domestic and international scholars have done some researches on related aspects of roadheaders. Ergin

and Acaroglu and Acaroglu and Erdogan established the mathematical model of the cutting system of a longitudinal axial roadheader during the horizontal cutting process and obtained the three-dimension forces on the cutting head through theoretical calculation and field test methods, then analyzed stability of the cutting system during cutting process and the influencing factors through simulations, and finally ascertained the maximum working range of the cutting system under stable state [17, 18]. Jang et al. and Chen et al. analyzed dynamical behaviors of the execution system of a boom-type roadheader during cutting process through the method of multi-rigid-body dynamics modeling and simulation and designed the attachments of the cutting head in order to improve the cutting performance of roadheader [19, 20]. Li et al. and Zhao et al. established the overall dynamical model of a boom-type roadheader based on the Lagrange equation, constructed the theoretical virtual cutting head load, and analyzed the vibration characteristics of the overall unit system during the horizontal process and obtained the results of vibration frequency and amplitude responses [21, 22]. Du et al. and Fu et al. built a measurement system based on the intersectional lasers, laser target, and calculation method of roadheader's body pose to carry out real-time measurement of roadheader's body pose when it moves in the roadway during the cutting process, and verified the system and method through experiment [23, 24].

In conclusion, some researches conducted on dynamical behaviors of key mechanisms of the boom-type roadheader during cutting process, vibration characteristics of the overall unit, and measurement of the body pose have been certainly achieved. However, research on the regularities of roadheader's body pose responses under influence of various factors during cutting process is still vacant. Based on EBZ-160 type roadheader, aiming at the horizontal cutting process and the three factors of the cutting head load, horizontal swing angle of cutting arm, and dip angle of coal seam, this paper is going to analyze the regularities of roadheader's body pose responses through overall unit dynamical modeling and simulation.

2. Dynamical Coupling Model of the Body Pose

2.1. Overall Mechanical Analysis during the Horizontal Cutting Process. Theoretically, due to the extremely complex working environment of coal mine, the boom-type roadheader should be a system with infinite degree of freedom during the horizontal cutting process. Therefore, in order to establish the dynamical coupling model of roadheader's body pose, it is necessary to make reasonable and appropriate simplification and assumption for the working state of roadheader [25–27].

According to the actual structure and working environment of roadheader, its working state is simplified and assumed as follows.

(1) In general, the quality distribution of the parts of roadheader is relatively uniform and the elasticity is small, so the elasticity can be ignored and the overall unit can be simplified as concentrated quality: quality of cutting head m_1 ,

FIGURE 1: The coordinate system in vertical view of the overall machine.

FIGURE 2: The coordinate system in left view of the overall machine.

quality of the cutting arm m_2 , and quality of the body m_3 (including the travelling mechanism).

(2) Assuming that the parts of roadheader are connected by massless elastic element, the rigidity coefficient between the cutting head and the cutting arm is expressed by K_1 , the rigidity coefficient between the cutting arm and the body is expressed by K_2 , and the rigidity coefficient between the body and the bottom ground is expressed by K_3 .

(3) Assuming that the damping between all parts of roadheader is viscous damping, the damping between the cutting head and the cutting arm is expressed by C_1 , the damping between the cutting arm and the body is expressed by C_2 , and the damping between the body and the bottom ground is expressed by C_3 .

(4) The cutting head load can be simplified as three-dimension forces, namely, the force in the horizontal direction, the force in the vertical direction, and the force perpendicular to the coal wall.

Take the initial position of roadheader's center of gravity as the origin to establish a three-dimensional fixed rectangular coordinate system OXYZ, and take the roadheader's center of gravity as the origin to establish a moving coordinate system O'X'Y'Z' fixed on the body and moving with the body, as shown in Figures 1 and 2. The x -axis is in the horizontal direction, the y -axis is perpendicular to the coal wall, and the z -axis is in the vertical direction.

In Figure 1, λ is the horizontal swing angle of the cutting arm relative to the body, θ_2 is the roll angle of the body, S_X is displacement of the body in the x -axis direction, and S_Y is displacement of the body in the y -axis direction; R_X is the component force of the cutting head load in the horizontal direction, R_Y is the component force of the cutting head load perpendicular to the coal wall, and F_X is the friction force

between the crawler and the bottom ground in the x -axis direction. F_Y is the friction force between the crawler and the bottom ground in the y -axis direction. In Figure 2, γ is the vertical swing angle of the cutting arm relative to the body, θ_1 is the pitch angle of the body, S_Z is displacement of the body in the z -axis direction, R_Z is the component force of the cutting head load in the vertical direction, and φ is the dip angle of coal seam.

2.2. Dynamical Coupling Model. Since a roadheader can be considered as a complete system during cutting process, the differential equations of roadheader's body pose can be established based on the Lagrange equation in system dynamics, so as to accurately describe the overall unit dynamical behaviors of roadheader during the horizontal cutting process.

The second-kind Lagrange equation in system dynamics [28] is

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} = Q_i. \quad (1)$$

Considering viscous resistance, Rayleigh dissipation function D is introduced into the Lagrange equation:

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i. \quad (2)$$

Separating the potential forces from the right side of (2), which is to introduce the energy function $U(q_i)$, (2) can be furtherly transformed into:

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} + \frac{\partial U}{\partial q_i} = Q_i. \quad (3)$$

In (3), T is the kinetic energy of the system, D is the dissipative energy, U is the potential energy, q_i is the generalized coordinate, i is the number of generalized coordinates, and Q_i is the generalized force.

Based on the Lagrange equation (3), the dynamical coupling model of roadheader's body pose is going to be established through energy method in following part:

$$\begin{aligned} \frac{d}{dt} \left(\frac{\partial T}{\partial \dot{S}_X} \right) &= (m_1 + m_2 + m_3) \ddot{S}_X - (m_1 L + m_2 L_y) \cos \gamma (\ddot{\lambda} \cos \lambda - \dot{\lambda}^2 \sin \lambda), \\ \frac{\partial T}{\partial S_X} &= 0, \\ \frac{\partial D_H}{\partial \dot{S}_X} &= C_1 \frac{\sin^2 \theta_2}{\cos^2 \gamma} \dot{S}_X + C_1 \frac{\sin \theta_2 [\dot{S}_Y \sin(\varphi - \theta_1) + \dot{S}_Z \cos(\varphi - \theta_1)]}{\cos^2 \gamma}, \\ \frac{\partial U_H}{\partial S_X} &= (m_1 + m_2 + m_3) g \sin \theta_2 + K_1 \frac{\sin^2 \theta_2}{\cos^2 \gamma} S_X \\ &\quad + K_1 \frac{\sin \theta_2 [L \sin(\gamma + \varphi - \theta_1) - L \sin(\gamma + \varphi) - b \sin \theta_2 + S_Y \sin(\varphi - \theta_1) + S_Z \cos(\varphi - \theta_1)]}{\cos^2 \gamma}. \end{aligned} \quad (4)$$

The above equations are plugged into (3), and then the differential equation of motion to describe S_X was derived as

$$\begin{aligned} &(m_1 + m_2 + m_3) \ddot{S}_X + C_1 \frac{\sin^2 \theta_2}{\cos^2 \gamma} \dot{S}_X + K_1 \frac{\sin^2 \theta_2}{\cos^2 \gamma} S_X + (m_1 + m_2 + m_3) g \sin \theta_2 - (m_1 L + m_2 L_y) \cos \gamma (\ddot{\lambda} \cos \lambda - \dot{\lambda}^2 \sin \lambda) \\ &+ \frac{\{C_1 \sin \theta_2 [\dot{S}_Y \sin(\varphi - \theta_1) + \dot{S}_Z \cos(\varphi - \theta_1)] + K_1 \sin \theta_2 [L \sin(\gamma + \varphi - \theta_1) - L \sin(\gamma + \varphi) - b \sin \theta_2 + S_Y \sin(\varphi - \theta_1) + S_Z \cos(\varphi - \theta_1)]\}}{\cos^2 \gamma} \\ &= R_X + F_X. \end{aligned} \quad (5)$$

In the same way, the differential equations of motion to describe S_Y , S_Z , θ_1 , and θ_2 were derived as follows:

$$\begin{aligned}
& (m_1 + m_2 + m_3) \ddot{S}_Y + C_1 \frac{\sin^2(\varphi - \theta_1)}{\cos^2 \gamma} \dot{S}_Y + K_1 \frac{\sin^2(\varphi - \theta_1)}{\cos^2 \gamma} S_Y + (m_1 + m_2 + m_3) g \sin(\varphi - \theta_1) - (m_1 L + m_2 L_y) \cos \gamma (\ddot{\lambda} \sin \lambda - \dot{\lambda}^2 \cos \lambda) \\
& + \frac{\{C_1 \sin(\varphi - \theta_1) [\dot{S}_Z \cos(\varphi - \theta_1) + \dot{S}_X \sin \theta_2] + K_1 \sin(\varphi - \theta_1) [L \sin(\gamma + \varphi - \theta_1) - L \sin(\gamma + \varphi) - b \sin \theta_2 + S_Z \cos(\varphi - \theta_1) + S_X \sin \theta_2]\}}{\cos^2 \gamma} = R_Y \\
& + F_Y, \\
& (m_1 + m_2 + m_3) \ddot{S}_Z + \left[2C_3 + C_1 \frac{\cos^2(\varphi - \theta_1)}{\cos^2 \gamma} \right] \dot{S}_Z + \left[2K_3 + K_1 \frac{\cos^2(\varphi - \theta_1)}{\cos^2 \gamma} \right] S_Z - (m_1 L + m_2 L_y) (\ddot{\lambda} \sin \lambda - \dot{\lambda}^2 \cos \lambda) + (m_1 + m_2 + m_3) g \\
& \cdot \cos(\varphi - \theta_1) + aK_3 \theta_2 + bK_3 \theta_1 + aC_3 \dot{\theta}_2 + bC_3 \dot{\theta}_1 \\
& + \frac{\{C_1 \cos(\varphi - \theta_1) [\dot{S}_Y \sin(\varphi - \theta_1) + \dot{S}_X \sin \theta_2] + K_1 \cos(\varphi - \theta_1) [L \sin(\gamma + \varphi - \theta_1) - L \sin(\gamma + \varphi) - b \sin \theta_2 + S_Y \sin(\varphi - \theta_1) + S_X \sin \theta_2]\}}{\cos^2 \gamma} = R_Z \\
& + N + G, \\
& J_X \ddot{\theta}_1 + b^2 C_3 \dot{\theta}_1 + b^2 K_3 \theta_1 + (m_1 + m_2 + m_3) g [S_Z \sin(\varphi - \theta_1) - S_Y \cos(\varphi - \theta_1)] - (m_2 + m_3) g L_\alpha \cos(\alpha + \varphi - \theta_1) - (m_1 L + m_2 L_y) g \cos(\gamma + \varphi - \theta_1) \\
& + K_1 \\
& \cdot \frac{[L \sin(\gamma + \varphi - \theta_1) - L \sin(\gamma + \varphi) - b \sin \theta_2 + S_Y \sin(\varphi - \theta_1) + S_Z \cos(\varphi - \theta_1) + S_X \sin \theta_2] [S_Z \sin(\varphi - \theta_1) - L \cos(\gamma + \varphi - \theta_1) - S_Y \cos(\varphi - \theta_1)]}{\cos^2 \gamma} \\
& + bC_3 \dot{S}_Z + bK_3 S_Z = M_{\theta_1}, \\
& J_Y \ddot{\theta}_2 + a^2 C_3 \dot{\theta}_2 + a^2 K_3 \theta_2 + [(m_1 + m_2 + m_3) g S_X - (m_1 + m_2) gb] \cos \theta_2 + K_1 \\
& \cdot \frac{\cos \theta_2 (S_X - b) [L \sin(\gamma + \varphi - \theta_1) - L \sin(\gamma + \varphi) - b \sin \theta_2 + S_Y \sin(\varphi - \theta_1) + S_Z \cos(\varphi - \theta_1) + S_X \sin \theta_2]}{\cos^2 \gamma} + aC_3 \dot{S}_Z + aK_3 S_Z = M_{\theta_2}.
\end{aligned} \tag{6}$$

Equations (5) and (6) are the dynamical coupling model of roadheader's body pose. In the equations, L is the distance between the center of gyration of the cutting arm and the center of gyration of the cutting head, L_y is the distance between the center of gravity of the cutting arm and its center of gyration, J_X is the moment of inertia of the body about the x -axis, J_Y is the moment of inertia of the body about the y -axis, a is 1/2 of the width of the body, b is 1/2 of the length of the body f , G is the gravity of roadheader, N is the bearing reaction on roadheader from the bottom ground, M_{θ_1} is the resultant moment of the system corresponding to θ_1 , and M_{θ_2} is the resultant moment of the system corresponding to θ_2 .

3. Calculation Method of the Cutting Head Load

According to (5) and (6), the cutting head load must firstly be obtained as the initial input quantity to solve the dynamical coupling model of the roadheader's body pose. With the complexity and changeableness situation of the cutting head load, it is difficult to obtain the cutting head load spectrum directly in the field, and the spectrum obtained by individual researchers is too complex and irregular to process and utilize efficiently. Aiming at the present situation, a method is proposed to calculate the cutting head load in this paper.

The cutting arm of roadheader is driven by a pair of angling cylinders during the horizontal cutting process and driven by a pair of lifting cylinders during the vertical cutting process. The pressure of angling cylinders and lifting cylinders is changing with different hardness of coal and rock,

and there is a positive correlation between them [22, 29]. The pressure of angling cylinders and lifting cylinders can be accurately measured by sensors; therefore, the breaking forces of the cutting head to the coal wall can be calculated according to the pressure of cylinders. According to Newton's third law, the breaking forces are equal to the cutting head load.

3.1. The Component Force in the Horizontal Direction. The cutting arm is fixedly connected to the revolving platform and driven by a pair of symmetrically arranged cylinders. The cylinder pole is connected to the revolving platform and the cylinder barrel is connected to the frame. At work, the cylinder on one side is elongated and the cylinder on the other side is shortened synchronously, and the synergistic motion drives the revolving platform to revolve, leading the cutting arm to swing around its center of gyration. As shown in Figure 3, the center of gyration of the revolving platform is point O , the hinge point of the cylinder pole and the revolving platform is point A , the hinge point of right cylinder barrel and the frame is point B , the hinge point of left cylinder barrel and the frame is point C , the hinge point of left cylinder pole and the revolving platform is point D , and the force bearing point of the cutting head is point R . The gyration radius of the revolving platform is $OA = OD = r$, $OB = OC = l_1$, $OR = L_1$, and $\angle AOB = \angle COD = \alpha$. After the cutting arm swings beyond a certain angle λ , point A has moved to point A' , point D has moved to point D' , $CD' = l_2$, and $A'B = l_3$.

Take the horizontal swing process towards the right side as an example. As the cutting arm swinging horizontally

FIGURE 3: Two-dimensional diagram of the cutting arm during the horizontal swing process.

towards the right, the component force of the cutting head load in the horizontal direction presents towards the left. During this process, the hydraulic oil is entering into the head port of the left cylinder to push the revolving platform, and the hydraulic oil is entering into the rod port of the right cylinder to pull the revolving platform. When the cutting arm swings towards the left, the force condition is oppositely symmetrical to the above analysis.

Taking the center of the revolving platform as the base point O, the moment of push force of the left cylinder about the point O is

$$M_T = P_1 S_1 \frac{r l_1 \sin(\alpha + \lambda)}{l_2}. \quad (7)$$

The moment of pull force of the right cylinder about the point O is

$$M_L = P_1 (S_1 - S_2) \frac{r l_1 \sin(\alpha - \lambda)}{l_3}. \quad (8)$$

The moment of the cutting head load about the point O is

$$M_1 = R_{f1} L_1 \cos \gamma. \quad (9)$$

The revolving platform bears a large unilateral pressure while the roadheader is drilling into the coal wall, but the pressure to the revolving platform is very small and relatively dispersed during the section cutting process. The revolving platform and its support are connected with sufficiently lubricated rolling bearing. Therefore, the friction moment of the revolving platform itself is negligible relative to the driving force of the cylinder and the resistance of the coal wall to the cutting head.

According to (7), (8), and (9), the circumferential force of the cutting head in the horizontal direction is

$$R_{f1} = \frac{P_1 r l_1 [l_3 S_1 \sin(\alpha + \lambda) + l_2 (S_1 - S_2) \sin(\alpha - \lambda)]}{l_2 l_3 L_1 \cos \gamma}. \quad (10)$$

In the above formula, P_1 is the pressure of the angling cylinders, S_1 is the cross-sectional area of the cylinder diameter, and S_2 is the cross-sectional area of the pole diameter.

FIGURE 4: Two-dimensional diagram of the cutting arm during the vertical swing process.

The component force of the cutting head load in the horizontal direction is

$$R_x = R_{f1} \cos \lambda = \frac{P_1 r l_1 \cos \lambda [l_3 S_1 \sin(\alpha + \lambda) + l_2 (S_1 - S_2) \sin(\alpha - \lambda)]}{l_2 l_3 L_1 \cos \gamma}. \quad (11)$$

3.2. The Component Force in the Vertical Direction. The cutting arm is driven by a pair of lifting cylinders arranged parallelly and symmetrically to each other during the vertical swing. The cylinder pole is connected to the cutting arm and the cylinder barrel is connected to the revolving platform. At work, lifting cylinders are elongated or shortened synchronously, driving the cutting arm to swing up or down. As shown in Figure 4, the hinge point between the cutting arm and revolving platform is point O', the hinge point of the cylinder barrel and the revolving platform is point E, the hinge point of the cylinder pole and the cutting arm is point F, and the force bearing point of the cutting head is point R. The distance between the center of gravity of the cutting arm and point O' is L_G , $O'E = l_4$, $O'F = l_5$, $O'R = L_2$, and $\angle EO'F = \beta$. After the cutting arm swings beyond a certain angle γ , point F has moved to point F', and $EF' = l_6$.

Take the vertical upward swing process as an example. With the cutting arm swinging vertically upward, the component force of the cutting head load in the vertical direction presents downward, and the hydraulic oil is entering into the head port of the lifting cylinders to push the cutting arm to swing upward. When the cutting arm swings downward, the force condition is oppositely symmetrical.

Taking the hinge point O' between the cutting arm and revolving platform as the base point, the moment of the cutting head load about the point O' is

$$M_2 = R_{f2} L_2 \cos \lambda. \quad (12)$$

The moment of the gravity of the cutting arm about the point O' is

$$M_G = (m_1 + m_2) g L_G \cos \lambda \cos \gamma. \quad (13)$$

The moment of push force of the lifting cylinders about the point O' is

$$M_S = 2P_2S_3 \frac{l_4l_5 \sin(\gamma + \beta)}{l_6}. \quad (14)$$

According to (12), (13), and (14), the circumferential force of the cutting head in the vertical direction is

$$R_{f2} = \frac{2P_2S_3l_4l_5 \sin(\gamma + \beta)}{l_6L_2 \cos \lambda} - \frac{(m_1 + m_2)gL_G \cos \gamma}{L_2}. \quad (15)$$

In the above formula, P_2 is the pressure of the lifting cylinders, and S_3 is the cross-sectional area of the cylinder diameter.

The component force of the cutting head load in the vertical direction is

$$\begin{aligned} R_Z &= R_{f2} \cos \gamma \\ &= \frac{2P_2S_3l_4l_5 \cos \gamma \sin(\gamma + \beta)}{l_6L_2 \cos \lambda} \\ &\quad - \frac{(m_1 + m_2)gL_G \cos^2 \gamma}{L_2}. \end{aligned} \quad (16)$$

3.3. The Component Force Perpendicular to the Coal Wall.

The component force of the cutting head load perpendicular to the coal wall can be calculated through addition of the component forces of the circumferential forces in the horizontal and vertical direction. As shown in Figure 3, the circumferential force of the cutting head in the horizontal direction is R_{f1} , and its component force perpendicular to the coal wall is

$$\begin{aligned} R_{Y1} &= R_{f1} \sin \lambda \\ &= \frac{P_1rl_1 \sin \lambda [l_3S_1 \sin(\alpha + \lambda) + l_2(S_1 - S_2) \sin(\alpha - \lambda)]}{l_2l_3L_1 \cos \gamma}. \end{aligned} \quad (17)$$

As shown in Figure 4, the circumferential force of the cutting head in the vertical direction is R_{f2} , and its component force perpendicular to the coal wall is

$$\begin{aligned} R_{Y2} &= R_{f2} \sin \gamma \\ &= \frac{2P_2S_3l_4l_5 \sin \gamma \sin(\gamma + \beta)}{l_6L_2 \cos \lambda} \\ &\quad - \frac{(m_1 + m_2)gL_G \sin \gamma \cos \gamma}{L_2}. \end{aligned} \quad (18)$$

FIGURE 5: The pressure of the angling cylinders.

In summary, the component force of the cutting head load perpendicular to the coal wall is

$$\begin{aligned} R_Y &= R_{Y1} + R_{Y2} \\ &= \frac{P_1rl_1 \sin \lambda [l_3S_1 \sin(\alpha + \lambda) + l_2(S_1 - S_2) \sin(\alpha - \lambda)]}{l_2l_3L_1 \cos \gamma} \\ &\quad + \frac{2P_2S_3l_4l_5 \sin \gamma \sin(\gamma + \beta)}{l_6L_2 \cos \lambda} \\ &\quad - \frac{(m_1 + m_2)gL_G \sin \gamma \cos \gamma}{L_2}. \end{aligned} \quad (19)$$

3.4. The Calculation Results of the Cutting Head Load. Based on underground engineering experiment, the pressure data of angling cylinders and lifting cylinders on the EBZ-160 type roadheader was acquired by the BYD-60 type mining explosion-proof pressure transmitter, and the experiment data was processed. During the cutting process, the pressure of angling cylinders is changing in the range of 5~21 MPa, as shown in Figure 5. According to the pressure of angling cylinders and horizontal swing angle of the cutting arm, the component force R_X of the cutting head load in the horizontal direction was simulated and calculated, and the result is shown in Figure 6. The pressure of lifting cylinders is changing in the range of 8~21 MPa, as shown in Figure 7. According to the pressure of lifting cylinders and vertical swing angle of the cutting arm, the component force R_Z of the cutting head load in the vertical direction was simulated and calculated, and the result is shown in Figure 8. According to the pressures of angling cylinders and lifting cylinders, the component force R_Y of the cutting head load perpendicular to the coal wall was simulated and calculated, and the result is shown in Figure 9.

4. Simulation and Analysis

4.1. Simulink Model and Initial Conditions Setting. According to the dynamical coupling model of roadheader's

FIGURE 6: The component force R_x of the cutting head load in the horizontal direction.

FIGURE 7: The pressure of the lifting cylinders.

FIGURE 9: The component force R_y of the cutting head load perpendicular to the coal wall.

FIGURE 8: The component force R_z of the cutting head load in the vertical direction.

body pose during the horizontal cutting process, namely, (5) and (6), the simulation model to solve the differential equations was established in *Simulink*, as shown in Figure 10.

The horizontal swing process of EBZ160 type roadheader's cutting arm has the characteristic of axial symmetry, and the maximum of the swing angle is 28° in both left and right side. In coalfields of different areas, the dip angle of coal seam is different, but it is no more than 15° in most areas [30], and the maximum of the dip angle of coal seam adapted for EBZ160 type roadheader is 18° . Therefore, five positions of the cutting arm and five dip angles of coal seam are selected to perform changing parameter analysis of roadheader's body pose responses during the horizontal cutting process. The five positions of the cutting arm are expressed by $\lambda = 0^\circ$, $\lambda = 8^\circ$, $\lambda = 14^\circ$, $\lambda = 20^\circ$, and $\lambda = 28^\circ$, and the five dip angles of coal seam

(a) The simulation system to solve roadheader's body pose

(b) The simulation model to solve S_X (c) The simulation model to solve S_Y

FIGURE 10: Continued.

(d) The simulation model to solve S_Z (e) The simulation model to solve θ_1 (f) The simulation model to solve θ_2

FIGURE 10: The simulation model to solve roadheader's body pose during the horizontal cutting process.

FIGURE 11: The response results of displacement of the body in the x -axis direction S_X .

are $\varphi = 0^\circ$, $\varphi = 5^\circ$, $\varphi = 10^\circ$, $\varphi = 15^\circ$, and $\varphi = 18^\circ$. The initial parameters of simulation are shown in Table 1 [31, 32].

4.2. Analysis of the Simulation Results. The dynamical coupling model was simulated and solved in the simulation model. The cutting head load, horizontal swing angle of the cutting arm, and dip angle of coal seam were regarded as independent variables to perform changing parameter analysis in variation of the five body pose parameters, which are displacement of the body in the x -axis, y -axis, and z -axis direction, pitch angle, and roll angle of the body, and the results are shown in Figures 11–15.

According to Figure 11, displacement of the body in the x -axis direction S_X , namely, the lateral displacement, is in the minus x -axis direction, and its maximum can reach up to 6.5 cm. At different horizontal swing angles of the cutting arm and dip angles of coal seam, with the increase of the

cutting head load R_X , S_X basically increases linearly at first, then slightly decreases, and reaches up to the maximum when the cutting head load is in the range of 70~90 kN. With the increase of horizontal swing angle of the cutting arm, S_X increases parabolically, and, with the increase of the dip angle of coal seam, S_X increases parabolically as well.

According to Figure 12, displacement of the body in the y -axis direction S_Y , namely, the backward displacement, is in the minus y -axis direction, and its maximum can reach up to 5.2 cm. At different horizontal swing angles of the cutting arm and dip angles of coal seam, with the increase of the cutting head load R_Y , S_Y basically increases at first and then decreases linearly. The horizontal angle of the cutting arm has no influence on the maximum point of S_Y , and, at different horizontal swing angles of the cutting arm, S_Y reaches up to the maximum when the cutting head load is about 40 kN. But the dip angle of coal seam has great

FIGURE 12: The response results of displacement of the body in the y -axis direction S_Y .

TABLE 1: Initial parameters of simulation.

Parameters	Value	Unit
m_1	1600	Kg
m_2	5700	Kg
m_3	37700	Kg
K_1	6.31×10^7	$\text{N} \cdot \text{m}^{-1}$
K_2	7.45×10^6	$\text{N} \cdot \text{m}^{-1}$
K_3	1×10^4	$\text{N} \cdot \text{m}^{-1}$
C_1	400	$\text{N} \cdot \text{s} \cdot \text{m}^{-1}$
C_2	3.49×10^4	$\text{N} \cdot \text{s} \cdot \text{m}^{-1}$
C_3	10	$\text{N} \cdot \text{s} \cdot \text{m}^{-1}$
J_x	118123	$\text{Kg} \cdot \text{m}^2$
J_y	25381	$\text{Kg} \cdot \text{m}^2$
a	1.15	m
b	2.95	m
L	3.9	m
L_y	1.75	m

influence on the maximum point of S_Y , and, at different dip angles of coal seam, the cutting head load R_Y corresponding to the maximum point of S_Y is in the range of about 40~95 kN, and as the dip angle of coal seam is greater, the cutting head load R_Y corresponding to the maximum point of S_Y is smaller. With the increase of horizontal swing angle of the cutting arm, S_Y decreases linearly, and, with the increase of the dip angle of coal seam, S_Y decreases parabolically.

According to Figure 13, displacement of the body in the z -axis direction S_Z , namely, the floor-based quantity, is in the minus z -axis direction, and its maximum can reach up to 11 cm. At different horizontal swing angles of the cutting arm and dip angles of coal seam, when the cutting head load R_Z is less than 70 kN, with the increase of the cutting head load R_Z , S_Z increases linearly, and when the cutting head load R_Z is more than 70 kN, S_Z still increase linearly, but the gradient is significantly decreased. With the increase of horizontal swing angle of the cutting arm, S_Z increases

FIGURE 13: The response results of displacement of the body in the z-axis direction S_Z .

parabolically, and, with the increase of the dip angle of coal seam, S_Z increases parabolically as well, but its amplitude of variation is smaller.

According to Figure 14, pitch angle of the body θ_1 is in the $-ZOY$ plane and its maximum can reach up to 7.8° . At different horizontal swing angles of the cutting arm and dip angles of coal seam, with the increase of the cutting head load R_Z , θ_1 decreases linearly. With the increase of horizontal swing angle of the cutting arm, θ_1 increases linearly, but its amplitude of variation is relatively small, and, with the increase of the dip angle of coal seam, θ_1 decreases parabolically.

According to Figure 15, roll angle of the body θ_2 is in the $-ZOX$ plane, and its maximum can reach up to 2.1° . At different horizontal swing angles of the cutting arm and dip angles of coal seam, with the increase of the cutting head load R_Z , θ_2 decreases parabolically. With the increase of horizontal swing angle of the cutting arm, θ_2 basically

increases linearly, but its amplitude of variation is relatively small, and, with the increase of the dip angle of coal seam, θ_2 decreases parabolically.

5. Experimental Research

EBZ160 type roadheader is selected to conduct field experiments in YunJiaLing mine, the depth of which is between 580 and 1200 m. Environments and conditions of the fully mechanized excavation face are highly representative, so it is suitable for experiments.

BYD-60 type mining explosion-proof pressure transmitter is selected to detect the pressure of the driving cylinders. Intrinsic safety type GUC360 mining angle sensor is selected to detect the vertical swing angle of the cutting arm. W18LD type dual speed sensor is selected to detect the horizontal swing angle of the cutting arm. TS15-A type explosion-proof automatic total station with high precision

FIGURE 14: The response results of the pitch angle of the body θ_1 .

is selected to measure the pose of roadheader. All the detected data are stored in the onboard large-capacity data recorder. The pictures of experiment equipment are shown in Figure 16.

While measuring the horizontal swing angle of the cutting arm, two arc-shaped steel racks are installed in the inside torus of the revolving platform. One rack is fixed, and the other one rotates with the revolving platform. The tooth width of the rack is 4 mm, corresponding to 1° of horizontal swing angle of the cutting arm. The sensitive surface of W18LD type dual speed sensor faces the rack, and the range of reaction is 0~2 mm, as shown in Figure 17. With rotation of the revolving platform, the dual speed sensor can directly output horizontal swing angle signal of the cutting arm.

While measuring the roadheader's body pose, a round prism was fixed on the upper surface of the body above the

center of gravity of roadheader and the automatic total station was set behind the roadheader at a certain distance. Before the cutting operation, the three-dimensional coordinate of the prism in the coordinate system of the total station was measured by the total station and expressed by $P_0(x_0, y_0, z_0)$. During the cutting process, the three-dimensional coordinate of the prism was measured and expressed by $P_i(x_i, y_i, z_i)$. A series of calculations between $P_i(x_i, y_i, z_i)$ and $P_0(x_0, y_0, z_0)$ was carried out, and variations of roadheader's body pose were obtained as follows:

$$S_X = x_i - x_0,$$

$$S_Y = y_i - y_0,$$

$$S_Z = z_i - z_0,$$

FIGURE 15: The response results of the roll angle of the body θ_2 .

$$\begin{aligned}\theta_1 &= \arctan \frac{z_i - z_0}{y_i - y_0}, \\ \theta_2 &= \arctan \frac{z_i - z_0}{x_i - x_0}.\end{aligned}\quad (20)$$

Pressure of the driving cylinders and swing angle of the cutting arm during the cutting process were detected by the sensors. According to the calculation method of the cutting head load in Section 3, the cutting head load was calculated and processed with the pose data of roadheader, as shown in Figure 18.

According to Figure 18, the experiment results of roadheader's body pose are basically consistent with the simulation results both in data and in changing trend. The

regularities of roadheader's body pose responses during the horizontal cutting process are verified experimentally.

6. Conclusions

In this paper, a calculation method of the cutting head load is proposed, and the relationship between the cutting head load and pressure of the driving cylinders and swing angle of the cutting arm was obtained. Based on the experimental data of pressure of the driving cylinders, the spectrum of cutting head load was obtained.

Based on the Lagrange equation method, the dynamical coupling model of roadheader's body pose during the horizontal cutting process and the corresponding simulation model were established. The dynamical coupling model was simulated and solved, and the regularities of roadheader's

FIGURE 16: The pictures of the experiment equipment.

FIGURE 17: Installation position of dual speed sensor and measurement schematic diagram.

body pose responses influenced by different factors during the horizontal cutting process were obtained through the processing and changing parameter analysis of the simulation results. Finally, the simulation results are verified through field experiment.

The cutting head load is calculated based on the pressure of the driving cylinders and swinging angle of the cutting arm, and pressure of the driving cylinders, swinging angle of the cutting arm, and the dip angle of coal seam can be detected and obtained in real time. Therefore, the regularities

of roadheader's body pose responses during the horizontal cutting process can provide important theoretical basis for rectification of roadheader's body pose and control of automatic cutting operation.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

FIGURE 18: The experiment results of roadheader's body pose.

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