

Received August 20, 2020, accepted September 1, 2020, date of publication September 11, 2020, date of current version September 24, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3023551

# Dynamic Characteristics of the Chain Drive System of Scraper Conveyor Based on the Speed Difference

SHOUBO JIANG<sup>1</sup>, RUIBO LV<sup>1</sup>, LIRONG WAN<sup>1</sup>, QINGHUA MAO<sup>2</sup>,  
QINGLIANG ZENG<sup>1,3</sup>, KUIDONG GAO<sup>1</sup>, AND YANG YANG<sup>1</sup>, (Member, IEEE)

<sup>1</sup>College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China

<sup>2</sup>Shaanxi Key Laboratory of Mine Electromechanical Equipment Intelligent Monitoring, Xi'an University of Science and Technology, Xi'an 710054, China

<sup>3</sup>College of Information Science and Engineering, Shandong Normal University, Jinan 250358, China

Corresponding author: Qingliang Zeng (qlzeng@sdust.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 51674155 and Grant 51974170, in part by the Natural Science Foundation of Shandong Province under Grant ZR2019BEE066, in part by the Applied Basic Research Project of Source Innovation Program in Qingdao under Grant 19-6-2-68-cg and Grant 18-2-2-20-jch, in part by the Shandong Provincial Key Research and Development Project under Grant 2019SDZY01, in part by the Project of Shaanxi Key Laboratory of Mine Electromechanical Equipment Intelligent Monitoring, Xi'an University of Science and Technology, under Grant SKL-MEEIM201906, and in part by the Project of Shandong Province Higher Educational Young Innovative Talent Introduction and Cultivation Team (Performance enhancement of deep coal mining equipment).

**ABSTRACT** The scraper conveyor is the unique transport equipment in coal mining face. Its chain drive system is the core subsystem. The dynamic characteristics of the chain drive system need monitoring for a safe mining. Existing monitoring methods include controlling the chain tension, chain speed and motor current. However, the above-mentioned methods have many disadvantages, such as difficult and costly to implement in mining face, due to the poor working environment and the limitations of the scraper conveyor's structure. This study proposes a monitoring method for the dynamic characteristics of the scraper conveyor on the basis of the speed difference between the head and the tail sprockets. Such an initiative is carried out to study the dynamic characteristics of the scraper conveyor under real working conditions and describe its running state. The speed difference of the head and tail sprockets under different chain speeds, terrains, and loads is monitored and studied. Research results show that the average and maximum speed differences are 0.797% and 0.990%, respectively. Due to the complex terrain, the tighter the scraper chain gets, the smaller the difference of the rotational speed is, compared with the flat working condition. The speed difference under load greatly increases compared with no load. Research results provide data support for the research of the chain drive system dynamics of the scraper conveyor. These results will also provide a new idea for the monitoring of the operating state of the scraper conveyor.

**INDEX TERMS** Scraper conveyor, dynamic characteristics, speed difference, chain drive system.

## I. INTRODUCTION

The scraper conveyor is a type of continuous action transport machinery with flexible body as traction mechanism [1], [2]. This machinery is mainly used in other places, such as underground mining face or channel, and mainly consists of a head frame, middle part, and tail frame. The traction mechanism is an infinitely closed scraper chain that circulates through the sprockets of the head and tail (or drum). The bearing mechanism is the middle slot. The drive motor drives the

scraper chain continuous operation through the transmission device and sprocket. Finally, the cargo in the middle tank is transported from the tail to the head for unloading and transfer.

The scraper conveyor is the only transportation equipment of the long-wall coal mining face at present. Accordingly, the stable operation of the scraper conveyor is the prerequisite for the smooth underground coal mining work. On this basis, the main research contents of scholars worldwide are to study the dynamic characteristics of the scraper conveyor and monitor its running state. Świder *et al.* [3]–[5] analyzed the causes of uneven load under the starting condition of the

The associate editor coordinating the review of this manuscript and approving it for publication was Hamid Mohammad-Sedighi<sup>1</sup>.

scraper conveyor on the basis of the average current of the scraper conveyor motor. They used MATLAB/SIMULINK software to analyze the developed model and compare the simulation results with the experimental results. During the operation of the scraper conveyor, its load is difficult to be directly measured, and the variation of load can affect the voltage fluctuation frequency of the driving motor. The dynamic characteristics of the entire chain drive system can be obtained by monitoring the voltage or current of the driving motor. The results of the numerical analysis and experimental verification indicated that the installation inclination of scraper conveyor has an important influence on the change of chain tension during operation. The change of tension is an important cause of dynamic load, chain clamping, and chain breaking faults. Dolipski *et al.* [6]–[8] recorded in detail the uneven distribution of load on a single drive motor during the actual operation of the scraper conveyor. They also introduced the load distribution coefficient to represent the uneven distribution of load. A dynamic model of conveyor is proposed to describe the nonuniform state of load in each driving motor. The aforementioned authors also studied the chain automatic tensioning system of the scraper conveyor. They also proposed ASTEN follow-up algorithm to respond to the chain elongation change and the load change caused by the shearer under different operating conditions of diverse conveyors. The effectiveness of the algorithm is verified by numerical simulation and experiment. The wear of the sprocket and chain in the chain drive system will increase the chain pitch and decrease the wheel pitch. Finally, the physical and mathematical models for simulation software research of the conveyor are established to determine the dynamic characteristics of the chain gear teeth and head frame. Stecuła and Brodny *et al.* [9] proposed a complete machine equipment efficiency model through monitoring the current waveform of the scraper conveyor drive motor. The actual running state and fault mode of the conveyor are described according to the current waveform signal of each driving motor. Sobota [10] analyzed the wear phenomenon of the sprocket teeth during the operation of the scraper conveyor and determined the mode of power loss. Stoićuta *et al.* [11] introduced and analyzed a coal flow control system for the longwall scraper conveyor. They also realized load monitoring and real-time control of the scraper conveyor drive motor and improved the dynamic characteristics of the whole machine. Zhang *et al.* [12] introduced a strain distribution estimation method for the loop chain drive system of the scraper conveyor on the basis of the multibody dynamic theory and linear state observer. The multibody dynamic model of the chain drive system is established by using ADAMS dynamic design software. The mathematical model of the chain drive system is solved by using MATLAB function. Finally, the system performance of the dynamic model is verified by comparing the simulation results. Wang *et al.* [13] designed the dynamic tension test and intelligent coordinated control system of the scraper conveyor. Such a system is used to monitor the dynamic tension of the heavy scraper conveyor and realize

coordinated control of the chain wheel drive of the scraper conveyor under heavy load conditions. Jiang *et al.* [14] established the finite element model of the chain drive system of the scraper conveyor. They obtained Von Mises stress and contact pressure curves of the dangerous positions (horizontal and vertical) of the sprocket wheel by using LS-DYNA software. The analytical and comparison results indicated that the chain link and sprocket have different failure forms. Such finding provides guidance for overcoming the problem of chain breaking and sticking of the scraper conveyor. Wang and Wang [15] proposed the coordinated speed planning strategy of the scraper conveyor and the shearer. They established the load analytical model of the scraper conveyor on the basis of the two-way mining process of the shearer. Moreover, these authors combined the load analysis with the multi-objective particle swarm optimization algorithm to construct a reasonable method. Finally, the effectiveness of the proposed method was verified by simulation examples and application experiments. The results showed that the load fluctuation of scraper conveyor is much smaller than that of the traditional solutions. Ju *et al.* [16] established a torsional vibration mechanical model for the main drive system of the scraper conveyor driven by high-power permanent magnet synchronous motor. A nonlinear feedback controller is designed, and the effectiveness of the controller is demonstrated by simulation. Lu *et al.* [17] designed a compound synovium velocity controller for the permanent magnet synchronous motor. They used Kellin-Vogit model to describe the chain characteristics of the scraper conveyor and used discrete element method to establish the overall dynamic model of the scraper conveyor system. The electromechanical coupling simulation model is established by using MATLAB/Simulink module according to the coupling relationship between the permanent magnet direct drive system and the scraper conveyor. The simulation results showed that the composite sliding mode controller of the permanent magnet direct drive system can realize the smooth start of scraper conveyor. Grinschgl *et al.* [18] proposed a chain drive modeling strategy combined with multibody simulation and finite element method. They also compared the simulation and experiment of a simple double-chain drive. The simulation results are in good agreement with the measured results. Ma and Li [19] analyzed the structure of the scraper chain drive system and simulated its service life and reliability. The authors found that the order of reliability of the vibration system from high to low is lignite, coking coal, anthracite, and gangue when the scraper chain system transmits different materials. Suvanjumrat *et al.* [20] used multibody dynamic simulation method to study the large displacement of the chain parts during rotation in the symmetric model. The validity of the simulation model is verified by comparing the MBD simulation and the physical experiment of the conveyor chain drive system. Wang *et al.* [21] studied the influences of chain speed, static friction coefficient, particle size, and laying angle on the transport efficiency of the scraper conveyor. They used discrete and finite element methods to

study the stress and deformation characteristics of the chute during transportation. The results show that the mass flow significantly varies with the chain velocity and the coefficient of static friction. The loose coal is large, and the chute wear is serious when the chain velocity is high. The large stresses are mainly concentrated in the direct contact area and the area subjected to the impact load of the bulk coal. Liu *et al.* [22] established a dynamic model of the longitudinal torsional coupled vibration of the scraper chain system. They also studied the longitudinal torsional vibration characteristics of the scraper chain system under load excitation. Theoretical and experimental results show that the maximum fluctuations of the scraper speed and tension force are 119.5% and 78.6% respectively.

In summary, most research results on the dynamic characteristics of the chain drive system and the scraper conveyor under ideal working conditions are just simulation studies without experimental verification. The methods for monitoring the dynamic characteristics of the scraper conveyor in the research results include direct monitoring of the scraper chain tension and the physical quantities, such as the inverter current, that indirectly reflect the scraper chain tension. However, the existing monitoring methods have some disadvantages, such as difficulty in practical implementation and high cost, due to the structural characteristics of the chain drive system and the limitations of the harsh working environment of the scraper conveyor. Based on experience, the scraper conveyor's head and tail sprockets have different degrees of speed difference under various working conditions. This work proposes a research and monitoring method for the dynamic characteristics of the chain drive system of the scraper conveyor on the basis of the speed difference between the head and the tail sprockets. The speed difference under different working conditions was monitored by setting up an experimental platform for the dynamic characteristics of the scraper conveyor. Finally, the experimental results indicated that the speed difference under various complicated working conditions is analyzed. The dynamic characteristics and working state of the chain drive system of the scraper conveyor are evaluated on the basis of the speed difference.

## II. EXPERIMENTAL BENCH CONSTRUCTION

We have improved the body of the scraper conveyor on the basis of the SGD320/17B scraper conveyor. The length of the middle slot and the distance between the scraper are shortened. The supporting steel plate and the height adjusting jack are installed at the bottom of the middle slot to simulate the topographic relief characteristics. The motor is changed from an ordinary motor to a variable frequency motor, and its power is appropriately increased. We installed a frequency converter to adjust the chain speed of the scraper conveyor. This task is conducted to study the difference between the front and the rear sprocket speed of the scraper conveyor at different chain speeds. Finally, a speed measuring device was installed on the head and tail sprocket shafts to simulate

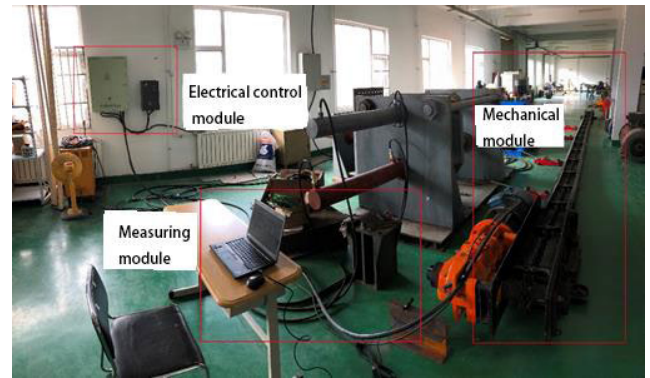


FIGURE 1. Dynamic characteristics test bench of the scraper conveyor.



FIGURE 2. Mechanical module of the test bench.

the velocity fluctuation and difference of the front and rear sprockets under different working conditions.

The dynamic characteristics of the test bed of the scraper conveyor built in this study are shown in Fig. 1. The test bed is mainly composed of the following: mechanical module (scraper conveyor test bed body), electrical control module (realizes stepless speed regulation and positive and negative rotation controls of the scraper conveyor), and measurement module (collects the speed of the machine head and tail). The building of the test bed and the functions of each module are described in detail as follows.

The mechanical module of the scraper conveyor dynamic characteristic test bed is shown in Figs. 2 and 3.

The test bed mainly includes the SGD-320/17B scraper conveyor, hydraulic adjustment jack, support plate, and other auxiliary components. An 18.5 kW variable-frequency motor matching qBN9000-30 type high-performance general vector inverter produced by Shanghai QIBIAN Company is adopted in the test bed. This device is used to simulate the influence of different chain speeds on the speed difference of the scraper conveyor's head and tail sprockets. Such an inverter realizes stepless speed regulation and positive and negative rotation controls of the scraper conveyor speed.

The measurement module is mainly used for the installation of the rotational speed measuring device.

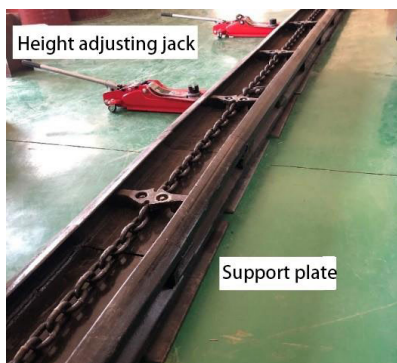


FIGURE 3. Adjustable jacks and bottom plates.



FIGURE 4. Positions of the head reflective film.



FIGURE 5. Positions of the rear reflective film.

The reflector is fixed on the head sprocket shaft and tail sprocket tooth because the speed change and difference of the head and tail should be simultaneously measured. The pulse frequency of the reflector is collected with a laser transmitter. Eight reflective plates (pulse number is 8) are installed on the sprocket shaft of the head at an interval of 45° to ensure the acquisition accuracy (Fig. 4). Six reflective plates (pulse number 6) are installed on the tail sprocket shaft at 60° (Fig. 5).

In the work of the dynamic signal wireless acquisition sensor, the acquisition module will automatically transmit the

TABLE 1. Correspondence table of frequency, rotational speed, and chain moving speed.

Frequency setting of inverter (Hz)	Motor speed (rpm)	Theoretical speed of head sprocket (rpm)	Chain speed (m/s)
2	58.8	2.36	0.0236
4	117.6	4.71	0.0471
6	176.4	7.07	0.0707
8	235.2	9.43	0.0943
10	294	11.78	0.1178
12	352.8	14.14	0.1414
14	411.6	16.50	0.1650
16	470.4	18.85	0.1885
18	529.2	21.21	0.2121
20	588	23.57	0.2357

wireless signal after the power is switched on. After the wireless hotspot is connected through a laptop, the collected strain signals can be received in the supporting DH5905 dynamic test software. Given that only one speed channel can be collected by one acquisition module, the speed signals of the head and tail can be simultaneously measured by two speed channels. The fluctuation and speed difference of the head and tail sprockets in various running projects can be obtained by analyzing and processing the measured speed.

### III. EXPERIMENTAL SCHEME

Existing theories and simulation analyses indicated that chain speed, terrain, and load are the most prominent factors that affect the dynamic characteristics of the scraper conveyor among others. Therefore, the test and analysis of the speed difference between the front and the rear sprockets of the scraper conveyor under these three factors are carried out.

#### A. CHAIN SPEED

The test was carried out at frequencies of 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 Hz on the basis of the speed control characteristics of the frequency converter. The speeds of the head and tail sprocket wheels were collected simultaneously. The motor speed, theoretical speed of sprocket head, and chain speed corresponding to each frequency are shown in Table 1.

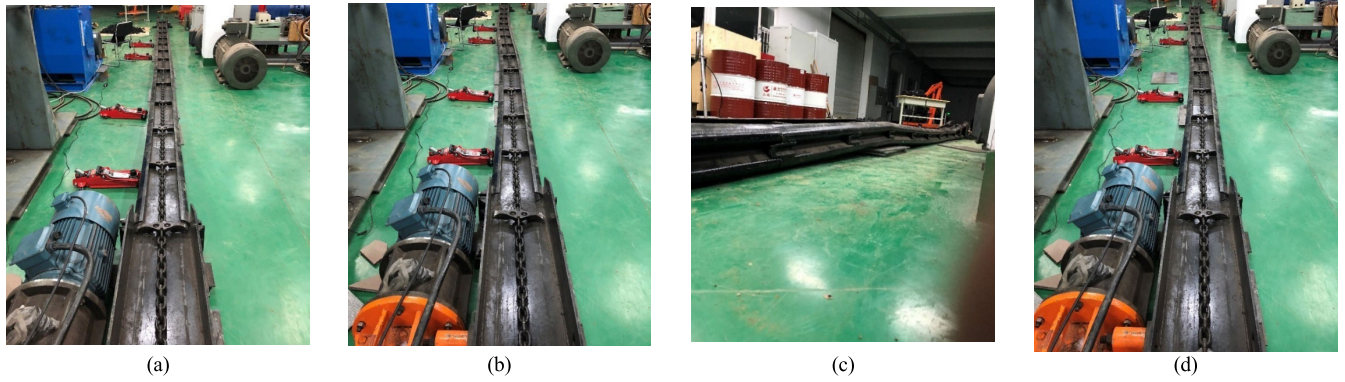
#### B. TERRAIN

During the working process of the scraper conveyor, horizontal bending occurred due to the passage of the jack at the bottom of the hydraulic support in the horizontal direction. Vertical bending occurred due to the fluctuation of the working face bottom plate in the vertical direction. In actual working conditions, scraper conveyors often work under the composite terrain of horizontal bending + vertical bending. On this basis, the experiment simulated the flat, horizontal bending (3°), vertical bending (3°), and horizontal bending + vertical bending conditions. The corresponding data were then collected for analysis. The test bed configuration of scraper conveyor under various working conditions is shown in Figs. 6 (a-d).

#### C. LOAD

Fig. 7 shows the load condition of the scraper conveyor.

The prototype SGD320/17B scraper conveyor has a design power of 17 kW, working length of 80 m, and volume



**FIGURE 6.** Four typical terrain conditions of the scraper conveyor test bench. (a) Working condition of flat. (b) Horizontal bending condition. (c) Vertical bending condition. (d) Horizontal + vertical bending composite condition.



**FIGURE 7.** Loaded condition of the scraper conveyor test bench.

of 40 T/h. The test bench shortens the working length of the conveyor to 12 m and increases the motor power to 18.5 kW. We only collect the dynamic characteristic data under no-load and load conditions for comparative analysis because the full-load operation is difficult to simulate in the test. Under the load condition, artificial coal shoveling is adopted during the operation of the scraper conveyor to simulate the coal cutting of the shearer to complete the load loading. The experimental scheme variables are shown in Table 2.

**IV. RESULT DISCUSSION**

The designed test scheme demonstrates that the speed signals of the head and tail sprockets are collected under different chain speeds (realized by adjusting the frequency of the frequency converter), terrains, and loaded and no-load conditions. The test results of the speed difference between the front and the rear sprockets of the scraper conveyor under various working conditions are analyzed and discussed.

**A. CHAIN SPEED**

The speed of the sprocket in the head and tail is monitored at different chain speeds. The results are shown in Figs. 8 (a-j).

The data in the figure show that the polygon effect of chain meshing transmission becomes gradually obvious with the improvement of chain speed. The sprocket speed fluctuation

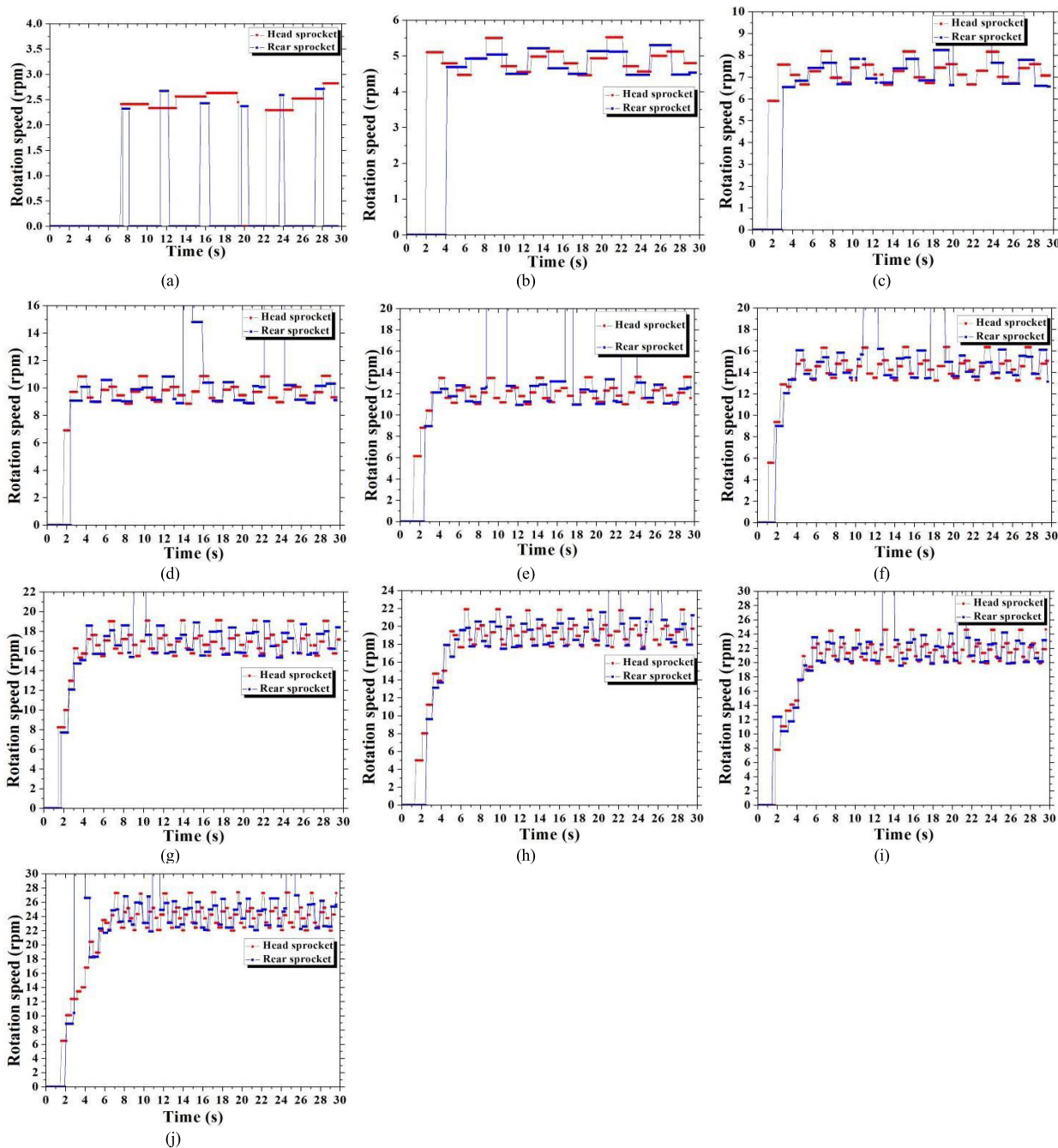
**TABLE 2.** Summary of the experimental program variables.

Frequency of the down converter at different chain speeds (Hz)					Scrapers conveyor configuration under different terrains		Loaded lotus	
2	4	6	8	10	Flat	Horizontal bending	No-load	Load
12	14	16	18	20	Vertical bending	Horizontal bending + vertical bending		

**TABLE 3.** Average rotational speed of the head and rear sprockets under various chain speeds.

Chain speed (m/s)	Theoretical value of the sprocket speed (rpm)	Average speed of the head sprocket (rpm)	Mean value of the sprocket speed (rpm)	Speed difference (rpm)	Speed difference/head sprocket speed ×100%
2.358	2.394	2.394	2.376	0.018	0.763
4.716	4.752	4.752	4.71	0.042	0.891
7.068	7.17	7.17	7.104	0.066	0.934
9.426	9.48	9.48	9.534	-0.054	-0.573
11.784	11.892	11.892	11.802	0.09	0.764
14.142	14.418	14.418	14.31	0.108	0.764
16.5	16.566	16.566	16.656	-0.09	-0.545
18.852	19.23	19.23	19.104	0.126	0.668
21.21	21.768	21.768	21.558	0.21	0.990
23.568	23.922	23.922	23.79	0.132	0.560

of the head and tail is also highly obvious. Except for the first three groups, the speed of the tail sprocket in the other seven groups took a step at a certain time point, characterized by a sharp increase in the speed to tens of times of the normal value in a short time. This phenomenon is explained as follows: the sharp friction with the middle slot and sprocket resulted in the surface grinding of the scraper during the operation of the scraper. The reflective signal produced when the laser pointer irradiated interfered with the normal speed signal collected by the laser pointer. After the interference value in the tail speed is filtered out, the average speed of the head and tail during the smooth operation of each chain speed was counted. The speed difference of the head and tail sprockets was then calculated (Table 3).



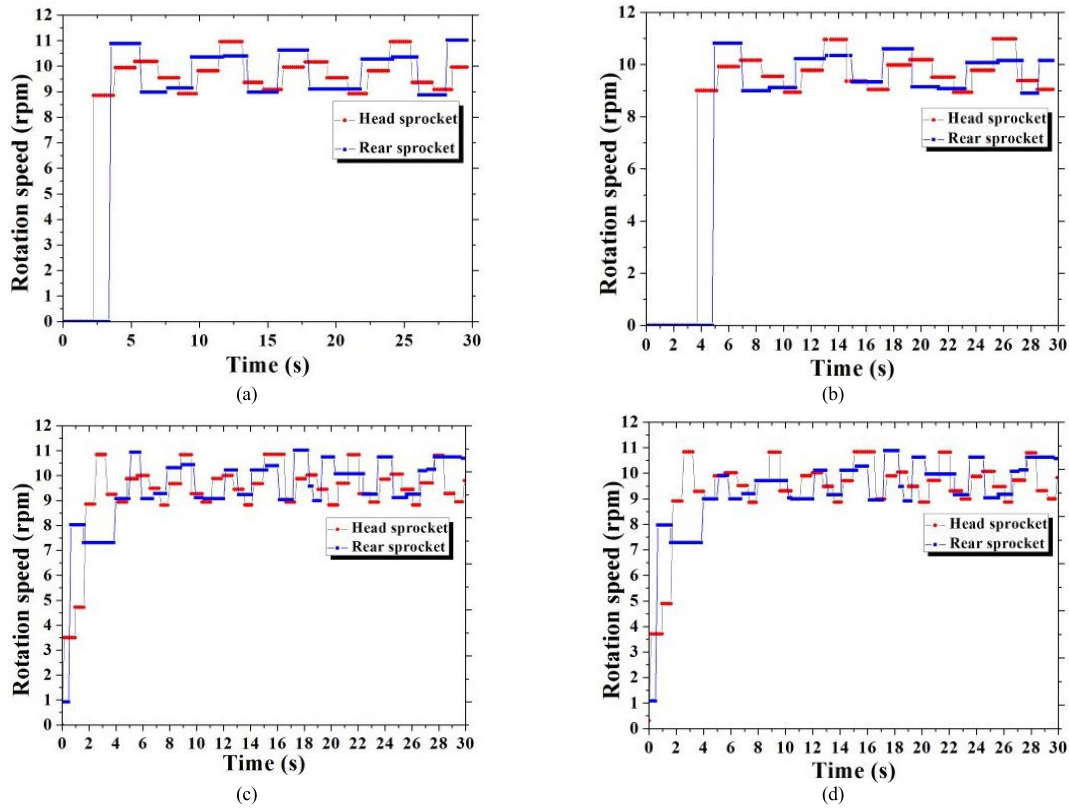
**FIGURE 8.** Fluctuation of the collected sprocket rotational speed under different chain speeds. (a) Chain speed = 0.0236 m/s. (b) Chain speed = 0.0471 m/s. (c) Chain speed = 0.0707 m/s. (d) Chain speed = 0.0943 m/s. (e) Chain speed = 0.1178 m/s. (f) Chain speed = 0.1414 m/s. (g) Chain speed = 0.1650 m/s. (h) Chain speed = 0.1885 m/s. (i) Chain speed = 0.2121 m/s.

The data in the table demonstrate that the actual speed of the sprocket at the head of the scraper is higher than its theoretical speed. The difference between the tail and the head sprocket speeds is basically unchanged with the increase in chain speed. The average and maximum difference percentages are about 0.797% and 0.990%, respectively. The difference in speed comes from the existence of the loose and tight side chains in the chain on the one hand and the fluctuation of speed caused by the polygonal effect of the sprocket–chain meshing on the other hand.

### B. TERRAIN

The speed signals of the head and tail sprockets were collected for comparative analysis under various conditions, such as flat, horizontal bending only, vertical bending only, and horizontal + vertical bending, according to the design in the test plan.

Figs. 9 (a-d) show the sprocket speed signals of the head and tail under four different terrain conditions. The sprocket starts with a higher acceleration and takes a shorter time for the sprocket to reach its rated speed under the straight and



**FIGURE 9.** Sprocket rotational speed signals under four various terrain conditions. (a) flat condition. (b) Horizontal bending condition. (c) Vertical bending condition. (d) Horizontal + vertical bending composite condition.

**TABLE 4.** Average rotational speed of the head and rear sprockets under various terrain.

Terrain conditions	Average speed of head sprocket (rpm)	Average speed of tail sprocket (rpm)	Speed difference (rpm)	Speed difference/head sprocket speed $\times 100\%$
Flat	8.899	8.83	0.069	0.775368
Horizontal bending	8.95	8.861	0.089	0.994413
Vertical bending	8.508	8.417	0.091	1.069582
Composite bending	8.07	8.02	0.05	0.619579

horizontal bending conditions compared with the combination of vertical bending and “horizontal + vertical” bending, thereby indicating that the sprocket suffers less resistance in this process. Under the vertical and composite bending conditions, the sprocket start-up process is relatively mild, thereby indicating that the resistance encountered during the start-up process is relatively large.

Table 4. shows the speed difference of the head and tail sprockets under different terrains. The speed difference of the head and tail sprockets in horizontal and vertical working conditions is slightly different compared with that of the flat working conditions. However, the speed difference of two sprockets is greatly reduced in the combination of horizontal bending and vertical bending. The analytical result indicated that under the combined working condition of horizontal + vertical bending, the effective working length of the chain

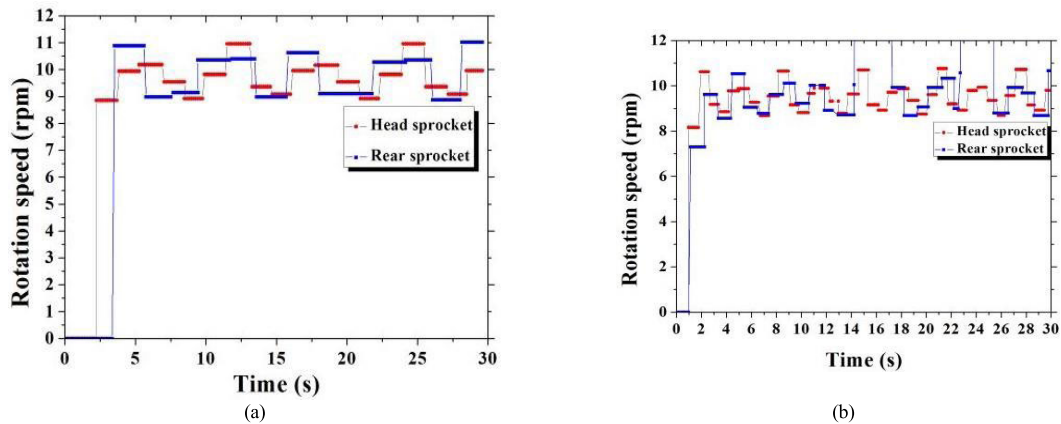
increases, and the chain state is tighter than the other three working conditions. This phenomenon leads to the decrease in the speed difference between the head and tail sprockets.

**C. LOAD**

The speed signals of the head and tail sprockets of the test rig are collected for comparative analysis under no-load and load conditions according to the design in the test scheme. Meanwhile, the speed signals of the head and tail sprockets collected under no-load and load conditions are shown in Figs. 10 (a, b).

The fluctuation degree of the sprocket speed of the head and tail of the machine significantly increases under the load condition compared with the no-load condition. On the one hand, this phenomenon is caused by the strengthening of the polygon effect of the chain drive under the load condition. On the other hand, the meshing of chain, scraper, and sprocket is greatly affected when coal passes through the sprocket of machine head. This situation results in obvious fluctuation of the speed of the machine head sprocket, thus leading to the “shaking” phenomenon of the whole chain.

The mean and speed difference of the sprocket speed of the head and tail are calculated and then summarized in Table 5. The data in the table demonstrate that under the load condition, the speed of the head and tail sprocket decreased, and the speed difference of the head and tail sprockets greatly increased compared with the no-load condition, which was approximately two times the speed difference under the



**FIGURE 10.** Sprocket rotational speed signals under empty and loaded conditions. (a) No-load condition. (b) Load conditions.

**TABLE 5.** Average rotational speed of the head and rear sprockets under empty and loaded conditions.

Working condition	Average speed of head sprocket (rpm)	Average speed of tail sprocket (rpm)	Speed difference (rpm)	Speed difference/head sprocket speed $\times 100\%$
No-load	8.89963	8.82969	0.06994	0.7921
Load	8.76296	8.63354	0.12942	1.499037

no-load condition. This situation is due to the scraper chain that has elastic deformation under load. In the actual working condition, the excessive speed difference may cause the chain wheel and ring to have the skipping teeth, which is unfavorable to the smooth operation of the chain drive system. Therefore, the load of the scraper conveyor or the tensioning degree of the scraper chain should be controlled to prevent this accident.

## V. CONCLUSION

This work adopts the means of building the experimental platform of the dynamic characteristics of the scraper conveyor to monitor and compare the revolving speed of the front and rear sprockets under different chain speeds, landforms, and loads. This initiative is carried out to explore the dynamic characteristics of the scraper conveyor and monitor its working state under real working conditions. Finally, the following conclusions are drawn by analyzing the variation of the speed difference between the front and the rear sprocket wheels of the scraper conveyor under different complex working conditions:

1) The actual speed of the head sprocket is higher than the theoretical speed at different chain speeds. The difference between the speeds of the tail and head sprockets is basically unchanged with the improvement of the chain speed. The average and maximum difference percentages are about 0.797% and 0.990%, respectively.

2) In the face of different terrain conditions under actual working conditions, the scraper conveyor will produce diverse degrees of bending. Under the horizontal and vertical bending conditions, the speed difference between the head and the tail sprockets is slightly different from that of the

flat condition. However, under the combined conditions of horizontal and vertical bending, the speed difference between the head and the tail sprockets is greatly reduced due to the obvious increase in the effective working length of the chain and the tighter scraper chain.

3) In the case of load, the fluctuation degree of the scraper conveyor's head and tail sprocket's rotational speed increases compared with that in the no-load condition. The difference of the rotational speed significantly increases, which is approximately twice that in the no-load condition.

In summary, the scraper conveyor is located in different terrain conditions or load and the head and tail sprocket speed difference varies. The study of the speed difference under different working conditions provides a new idea for monitoring the working state of the scraper conveyor. The experimental data have certain auxiliary and reference significance for the study of the dynamic characteristics of the chain drive system of the scraper conveyor under real working conditions.

## REFERENCES

- [1] S. Hao, S. Wang, R. Malekian, B. Zhang, W. Liu, and Z. Li, "A geometry surveying model and instrument of a scraper conveyor in unmanned longwall mining faces," *IEEE Access*, vol. 5, pp. 4095–4103, 2017.
- [2] C. Luo, X. Fan, J. Ni, H. Yang, X. Zhang, and W. Li, "Positioning accuracy evaluation for the collaborative automation of mining fleet with the support of memory cutting technology," *IEEE Access*, vol. 4, pp. 5764–5775, 2016.
- [3] J. Świder, K. Herbuś, and K. Szezerda, "Analysis of load unevenness of chain conveyor's driving motors on the basis of numerical simulations," *J. Achievements Mater. Manuf. Eng.*, vol. 73, no. 2, pp. 165–175, 2015.
- [4] J. Świder, K. Herbuś, and K. Szezerda, "Dynamic analysis of scraper conveyor operation with external loads," presented at the 4th Int. Conf. Comput. Solutions Manuf. Eng., Nov. 4, 2016.
- [5] J. Świder, K. Herbuś, and K. Szezerda, "Analysis of impact of longitudinal inclination of a chain conveyor on dynamical phenomena during operation," presented at the 4th Int. Conf. Comput. Solutions Manuf. Eng., Nov. 4, 2016.
- [6] M. Dolipski, E. Remiorz, and P. Sobota, "Dynamics of non-uniformity loads of AFC drives," *Arch. Mining Sci.*, vol. 59, no. 1, pp. 155–168, Mar. 2014.
- [7] M. Dolipski, E. Remiorz, and P. Sobota, "Follow-up chain tension in an armoured face conveyor," *Arch. Mining Sci.*, vol. 60, no. 1, pp. 25–38, 2015.
- [8] M. Dolipski, E. Remiorz, and P. Sobota, "Determination of dynamic loads of sprocket drum teeth and seats by means of a mathematical model of the longwall conveyor," *Arch. Mining Sci.*, vol. 57, no. 4, pp. 1101–1119, 2012.



- [9] K. Stecula and J. Brodny, "Application of the OEE model to analyze the availability of the mining armored face conveyor," presented at the 3rd World Multidisciplinary Earth Sci. Symp., Sep. 15, 2017.
- [10] P. Sobota, "Determination of the friction work of a link chain interworking with a sprocket drum," *Arch. Mining Sci.*, vol. 58, no. 3, pp. 805–822, 2013.
- [11] O. Stoicuta, T. Pana, and C. Mandrescu, "The control system analysis of the coal flow on the scrapers conveyor in a longwall mining system," presented at the Int. Conf. Appl. Theor. Electr., Oct. 8, 2016.
- [12] X. Zhang, W. Li, Z. Zhu, W. Ren, and F. Jiang, "Tension monitoring for the ring chain transmission system using an observer-based tension distribution estimation method," *Adv. Mech. Eng.*, vol. 9, no. 9, pp. 1–16, Sep. 11, 2017.
- [13] H. Wang, Q. Zhang, and F. Xie, "Dynamic tension test and intelligent coordinated control system of a heavy scraper conveyor," *IET Sci., Meas. Technol.*, vol. 11, no. 7, pp. 871–877, Oct. 2017.
- [14] S. B. Jiang, Q. L. Zeng, G. Wang, K. D. Gao, Q. Y. Wang, and K. Hidenori, "Contact analysis of chain drive in scraper conveyor based on dynamic meshing properties," *Int. J. Simul. Model.*, vol. 17, no. 1, pp. 81–91, Mar. 2018.
- [15] Y. P. Wang and S. Y. Wang, "Coordinated speed planning strategy of scraper conveyor and shearer based on scraper conveyor loads analysis," presented at the Int. Workshop Renew. Energy Develop. (IWRED), Guangzhou, China, Mar. 10, 2019.
- [16] J. Ju, W. Li, Y. Wang, M. Fan, and X. Yang, "Dynamics and nonlinear feedback control for torsional vibration bifurcation in main transmission system of scraper conveyor direct-driven by high-power PMSM," *Nonlinear Dyn.*, vol. 93, no. 2, pp. 307–321, Jul. 2018.
- [17] E. Lu, W. Li, X. Yang, and S. Xu, "Composite sliding mode control of a permanent magnet direct-driven system for a mining scraper conveyor," *IEEE Access*, vol. 5, pp. 22399–22408, 2017.
- [18] M. Grinschgl, F. Reich, R. Abeltshauser, M. Eder, and T. Antretter, "New approach for the simulation of chain drive dynamics with consideration of the elastic environment," *Proc. Inst. Mech. Eng. K, J. Multi-body Dyn.*, vol. 231, no. 1, pp. 103–120, Mar. 2017.
- [19] Q. P. Ma and J. X. Li, "Research on reliability of scraper chain drive system," presented at the 6th Annu. Int. Conf. Mater. Sci. Eng., Jun. 24, 2018.
- [20] C. Suvanjumrat, W. Suwannahong, and S. Thongkom, "Implementation of multi-body dynamics simulation for the conveyor chain drive system," presented at the 3rd Int. Conf. Mechatronics Mech. Eng., Oct. 23, 2016.
- [21] X. Wang, B. Li, S. Wang, Z. Yang, and L. Cai, "The transporting efficiency and mechanical behavior analysis of scraper conveyor," *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, vol. 232, no. 18, pp. 3315–3324, Sep. 2018.
- [22] Z. X. Liu, C. X. Xie, J. Mao, and M. Xie, "Analysis of longitudinal and torsional pendulum coupling vibration of scraper conveyor under material loading condition," *Zhendong Ceshi Yu Zhenduan J. Vibrat.*, vol. 39, no. 1, pp. 147–152, Feb. 2019.



**LIRONG WAN** received the Ph.D. degree from the Shandong University of Science and Technology, in 2008. She is currently a Professor with the Shandong University of Science and Technology. Her research interests include virtual prototype, concurrent engineering, computer integrated manufacturing, electromechanical integration, and hydraulic transmission and control.



**QINGHUA MAO** received the B.S., M.S., and Ph.D. degrees from the Xi'an University of Science and Technology, in 2007, 2010, and 2012, respectively. He is currently an Associate Professor with the School of Mechanical Engineering, Xi'an University of Science and Technology. His main research interests include nondestructive testing, fault diagnosis, intelligent testing, and control of coal mine mechanical equipment.



**QINGLIANG ZENG** received the Ph.D. degree in machine design and theory from the China University of Mining and Technology, in 2000. He is currently a Professor with the Shandong University of Science and Technology and Shandong Normal University. He has participated in more than 40 projects funded by the National Sci-Tech Support Plan, the National 863 Program, and the Natural Science Foundation of China. He has published more than 100 articles as the Principle Person. His research interests include electromechanical integration, condition monitoring and fault diagnosis, and virtual prototype.



**KUIDONG GAO** was born in Zaozhuang, Shandong, China, in 1986. He received the B.S. degree from Central South University, Changsha, Hunan, in 2008, and the Ph.D. degree in mechanical engineering from the China University of Mining and Technology, Xuzhou, Jiangsu, China, in 2014. From 2014 to 2018, he was an Assistant Professor with the Department of Mechanical Engineering, Shandong University of Science and Technology. Since 2019, he has been an Associate Professor. 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, and simulation and application of mechatronic hydraulic systems.



**YANG YANG** (Member, IEEE) received the Ph.D. degree in mechanical and electronic engineering from the Shandong University of Science and Technology, in 2020. He is currently a Lecturer with the College of Mechanical and Electronic Engineering, Shandong University of Science and Technology. His research interests include contact mechanics, coal gangue interface recognition, signal processing, mechanical design electromechanical integration, and intelligent control.



**SHOUBO JIANG** was born in Shandong, China, in 1988. He received the B.S., M.S., and Ph.D. degrees in mechanical engineering from the Shandong University of Science and Technology, Qingdao, China, in 2011, 2014, and 2018, respectively. He is currently a Lecturer with the College of Mechanical and Electronic Engineering, Shandong University of Science and Technology. His research interests include gear transmission, chain drive, and CG.



**RUIBO LV** received the B.S. degree in mechanical and electrical engineering from the Shandong University of Science and Technology, in 2018, where he is currently pursuing the M.S. degree in mechanical engineering. His current research interests include advanced manufacturing technology and electromechanical hydraulic transmission control.

...