machines

Article

Dynamic Properties of Chain Drive in a Scraper Conveyor under Various Working Conditions

Shoubo Jiang [1], Shuan Huang [1], Qinghua Mao [2], Qingliang Zeng [1,3,*], Kuidong Gao [1] and Jinwang Lv [1]

[1] College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China; jiangshoubo@sdust.edu.cn (S.J.); huangshuan21@163.com (S.H.); gaokuidong22@163.com (K.G.); lvjinwang559@163.com (J.L.)
[2] Shaanxi Key Laboratory of Mine Electromechanical Equipment Intelligent Monitoring, Xi'an University of Science and Technology, Xi'an 710054, China; maoqh@xust.edu.cn
[3] College of Information Science and Engineering, Shandong Normal University, Ji'nan 250358, China
* Correspondence: qlzeng@163.com

Abstract: A scraper conveyor is important in coal mining. During operation, its working performance is affected by chain speed fluctuations, terrain fluctuations, and load changes. Thus, evaluating the influence of these factors on the dynamic properties of a scraper conveyor is important. This study first built a dynamic property test bench. Then, the vibration signals of the reducer output shaft were measured under various chain speed, terrain, and load conditions. Finally, the dynamic properties of a scraper conveyor were evaluated by conducting a frequency domain analysis of the measured vibration signals. The results show that the output shaft of the motor, the second shaft, and the second-stage meshing gear of the reducer are sensitive to external factors. Under the terrain conditions of "horizontal + vertical" bending, the middle chute was the most sensitive to the meshing frequency of the sprocket chain. This type of condition had a significant influence on the scraping phenomenon of the scraper and the middle chute. Under various load conditions, the amplitude of each shaft of the reducer decreased, especially the amplitude of the motor output shaft, but the scraping amplitude of the scraper and middle chute greatly increased. This study is of great significance for improving the dynamic properties and structural optimization of scraper conveyors.

Keywords: scraper conveyor; dynamic properties; vibration signals; various working conditions

check for updates

Citation: Jiang, S.; Huang, S.; Mao, Q.; Zeng, Q.; Gao, K.; Lv, J. Dynamic Properties of Chain Drive in a Scraper Conveyor under Various Working Conditions. *Machines* **2022**, *10*, 579. https://doi.org/10.3390/machines10070579

Academic Editor: Radosław Zimroz

Received: 13 June 2022
Accepted: 13 July 2022
Published: 18 July 2022

1. Introduction

Coal is the primary energy source in China. Longwall mining technology is the most efficient and widely used technology in coal mining today [1–4]. The longwall fully mechanized mining face comprises hydraulic support, a scraper conveyor, a shearer, and other auxiliary equipment [5]. The scraper conveyor is the only coal transportation equipment and the running track of the shearer and the fulcrum of the hydraulic support [6–8].

In the coal mining process, the scraper conveyor will face the complex working condition of the middle chute bending, which is caused by fluctuation of the terrain under the scraper conveyer's bottom plate and the hydraulic support pushing the scraper conveyer's middle chute [9,10]. The large coal cut by a shearer causes a dynamic load on the scraper conveyor, making the working environment relatively bad [11–13]. Simultaneously, problems such as chain speed fluctuations and load changes also affect the dynamic properties of the chain drive of the scraper conveyor, thereby affecting the stability of the scraper chain. Therefore, studying the chain drive according to chain speed fluctuations, terrain properties, and load changes is necessary.

Scholars have conducted considerable research to improve the dynamic properties of scraper conveyors. These properties are different during start-up and when transporting coal. Given the polygon effect of the chain drive system, its inertia, and other factors, the dynamic properties fluctuate more drastically during start-up. Thus, some scholars have improved the dynamic properties of scraper conveyors from the perspective of a soft start. Lu et al. [14], based on a mathematical model of the permanent-magnet synchronous motor and a dynamic model of scraper conveyors, established an electromechanical coupling model of a permanent-magnet direct-drive system and a scraper conveyor. The performance of the composite sliding-mode controller was studied using numerical simulation. The results showed that the composite sliding-mode controller can realize the smooth start and stable operation of scraper conveyors. Li et al. [15] proposed an optimization evaluation system for the soft start of viscous fluid transmission for scraper conveyors, based on the analytic hierarchy process. Through the joint simulation platform of MATLAB and Isight, a dual-parameter control model of soft-start time was established using experimental design and a simulated annealing algorithm, and the best start-up time under different conditions was determined. Zhang et al. [16] constructed a dynamic differential equation of scraper conveyors based on the finite element method. The dynamic properties under different working conditions were simulated and analyzed. The dynamic properties when starting and restarting after braking were determined. The correctness of the relevant dynamic properties was verified through experimental tests. Wang et al. [17] established a rigid–flexible coupling dynamic analysis model and a contact calculation model for the tail chain drive system of a heavy scraper conveyor, and they carried out a simulation and contact calculation. The results showed that the load start-up of the chain drive system produced large impact stress and load deformation on the ring chain and sprocket. The above scholars analyzed the dynamic properties at start-up and optimized the soft-start mode and time of scraper conveyors. Finally, the feasibility of the proposed method was verified. However, given that a scraper conveyor is a nonlinear and strong coupling mechanical system, the above scholars still have room for improvement in the reduction of real coal conveying conditions when verifying the feasibility of the proposed method. Therefore, the correctness of the proposed theory should be verified using experiments closer to actual working conditions.

Some scholars have studied the dynamic properties of scraper conveyors in the coal conveying process. If a scraper conveyor fails in the working process, it will seriously reduce the efficiency of coal and carbon mining and even cause casualties. Therefore, studying abnormal working conditions and predicting failure are essential. Xie et al. [18] analyzed the dynamic properties of the chain drive system under the single-side-chain-clamping condition by establishing a dynamic model of torsional pendulum vibration. The torsional pendulum vibration speed, acceleration, and tension of the chain drive system under different chain-clamping conditions were determined using simulations. Experiments to verify the correctness of the theoretical analysis were carried out. Jiang et al. [19] used discrete element and multi-body dynamics co-simulations to study the dynamic properties of the chain drive system when subjected to impact load, which provided a theoretical basis for the optimization of the chain drive system. Wang et al. [20] established a dynamic tension model based on the time-varying dynamic analysis method and determined the dynamic chain tension. The crack initiation properties of the chain ring under the action of time-varying load were studied, and a prediction model of the crack initiation life was established using the multiaxial fatigue strength theory. Zhang et al. [21] proposed a novel strategy for the fault detection of scraper chains based on a vibration analysis of the chute. Zhao et al. [22] proposed a local gear fault diagnosis method based on a bispectral analysis of signal envelopes obtained from stator current processing under time-varying load. The results showed that this method can successfully diagnose the failure of scraper conveyor gear. Based on the research results of the above scholars, making corresponding adjustments by making predictions about the scraper conveyor before it fails is possible, which greatly reduces failure and improves the coal handling efficiency and intelligence of scraper conveyors.

Furthermore, the operation status of scraper conveyors under normal working conditions determines its reliability and stability, which are important factors when measuring its performance. Thus, some scholars study the dynamic properties of scraper conveyors under these conditions. Jiang et al. [23] established rigid and rigid–flexible coupling models of scraper conveyors based on the multi-body dynamics theory, and they carried out a simulation analysis on the two models under full, half, and no-load conditions. They determined the dynamic properties of the scraper conveyor chain drive under different working conditions. Ren et al. [24] established a coupling analysis model of a scraper conveyor based on the discrete element method and the multi-body dynamics theory. They conducted a simulation analysis of the coal conveying process under various eccentric loads. The simulation results showed that the transverse vibration of the chain is positively correlated with the coal handling capacity, whereas the longitudinal vibration is negatively correlated with the coal handling capacity. Jiang et al. [25] established the finite element model of the chain drive system of a scraper conveyor based on the translation and rotation models of the Vogit model. A contact analysis was carried out on the model using the meshing properties of the chain drive system. The dynamic properties of the chain drive system were determined by comparing the Von Mises stress and contact pressure curves. Shprekher et al. [26,27] studied the dynamic properties of the motor and found that using a frequency converter to regulate the speed of a double-motor-driven scraper conveyor causes uneven motor power. Thus, a driving method that can realize the power balance of the two motors was proposed, and a simulation model was established with Matlab/Simulink to verify its feasibility. Given the particularity of scraper conveyors, most studies use simulation analyses. However, a scraper conveyor is a complex and highly coupled multi-body dynamics system. Only the chain drive system of a scraper conveyor is composed of sprocket–chain engagement and chain–scraper–middle chute coupling friction. Thus, Wojnar et al. [28] built an experimental bench for a scraper conveyor reducer to study the vibration of the reducer gear. Meanwhile, a dynamic test study of a single subsystem cannot fully reflect the real dynamic properties of a scraper conveyor, especially in the various complex and harsh working conditions in coal mines. Therefore, simulating the actual working condition of a scraper conveyor and testing the dynamic properties of the whole scraper conveyor are necessary.

In this study, a test bench is built to determine the dynamic properties of a scraper conveyor, and a dynamic properties test is performed. The dynamic properties of the scraper conveyor are determined by collecting and analyzing the vibration signals of the reducer output shaft under different working conditions. This study is significant for improving a scraper conveyor's dynamic properties and structural optimization.

The remainder of this article is organized as follows: Section 2 introduces the dynamic properties test bench and test scheme. Section 3 analyzes the vibration signals under three different conditions. Section 4 provides the conclusions.

2. Dynamic Properties Test

2.1. Construction of the Test Bench

A scraper conveyor dynamic properties test bench is built based on an SGD320/17B scraper conveyor, as shown in Figure 1 [29]. The dynamic properties test bench of the scraper conveyor includes a mechanical module, an electrical control module, a measuring module, and supporting software.

In this test bench, a vibration sensor is initially used to collect the vibration signal of the scraper conveyor during operation. A Donghua DH5905 dynamic signal wireless receiving device is used for data transmission. The vibration sensor is attached to the outer surface of the reducer output shaft to obtain the vibration signal of the scraper conveyor and analyze its vibration spectrum. It is placed on the cover to prevent displacement during high-speed operation, which may affect the test results or cause dangerous situations. The research idea of this study is shown in Figure 2, and the main technical parameters of the test bench are shown in Table 1.

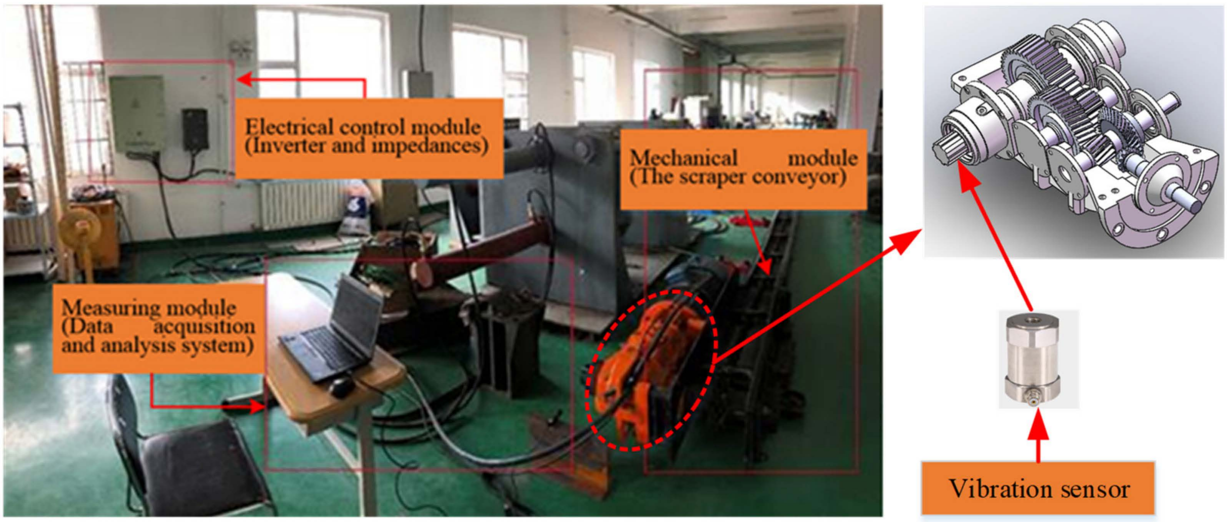


Figure 1. Test bench of dynamic properties for the scraper conveyor.

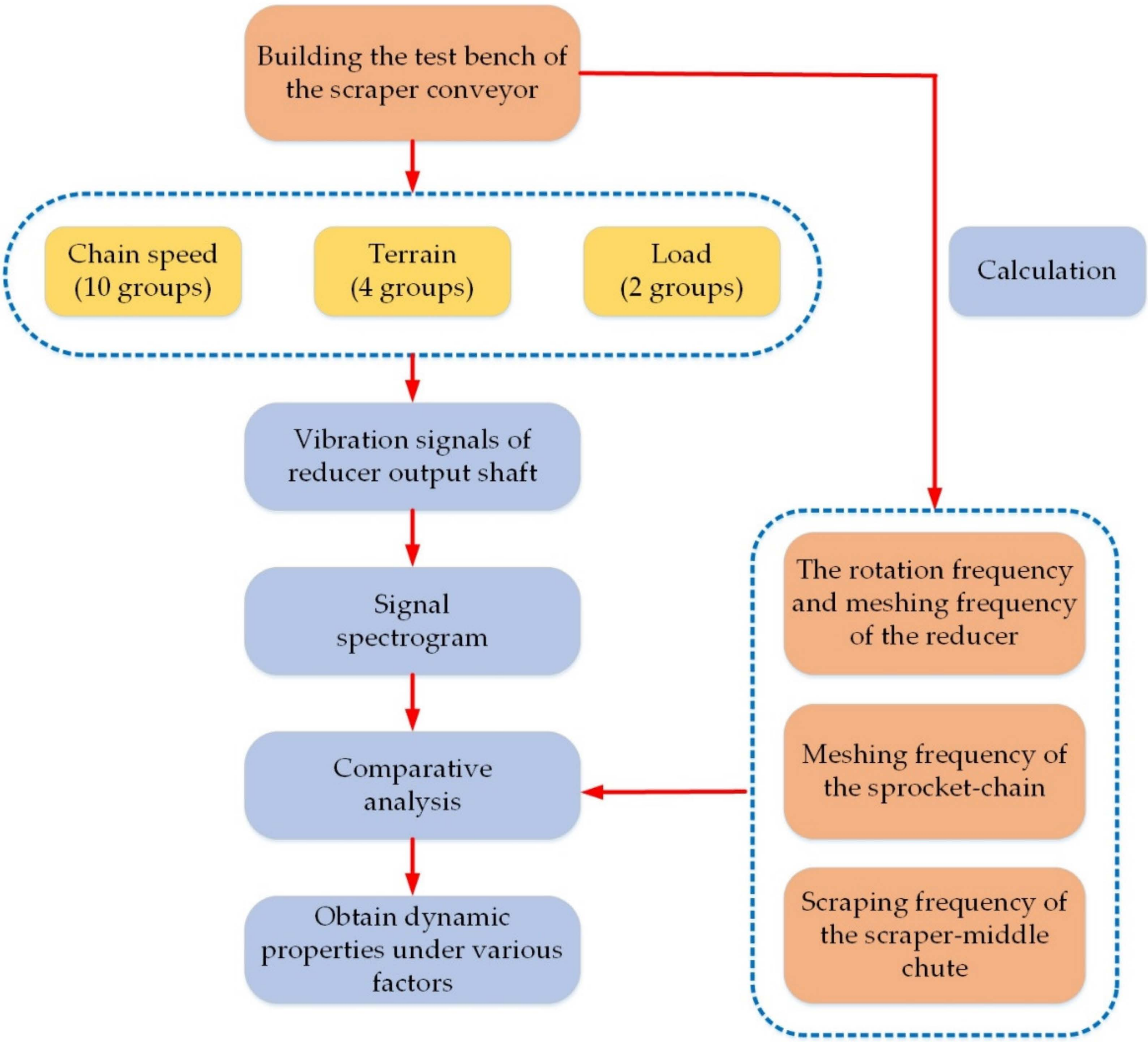


Figure 2. The research idea of this study.

Table 1. Technical parameters of the test bench.

Improved SGD320/17B	Technical Parameter
Rated power of motor (kW)	18.5
Speed of variable frequency motor (rpm)	1470
Working length of scraper (m)	12
Middle chute size (length × width × height, mm)	600 × 320 × 156
Rated chain speed (m/s)	0.59
Chain specification	Φ14 × 50
Breaking force of ring chain (kN)	>250
Transmission ratio of reducer	24.95
Working voltage (V)	380
Adjusting height of hydraulic jack (mm)	85~350
Maximum horizontal bending angle of scraper conveyor (°)	3

2.2. Test Scheme

Based on existing research and simulation analyses, chain speed, terrain, and load are the most important factors affecting the dynamic properties of a scraper conveyor. Therefore, this test mainly aims to test the above three factors.

2.2.1. Chain Speed

Based on the speed regulation properties of the frequency converter, the chain speed is changed by changing the frequency of the frequency converter. The tests are carried out at the frequencies of 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 Hz to determine the change in the output shaft vibration of the gear reducer.

2.2.2. Terrain

In the actual working process, the scraper conveyor will bear the pushing force of the hydraulic support pushing the jack in the horizontal direction, resulting in horizontal bending. Undulations are observed on the working surface of the bottom plate of the scraper conveyor. Vertical bending occurs in the vertical direction. Therefore, in actual working conditions, a scraper conveyor works in the composite terrain of horizontal and vertical bending.

Based on the above analysis, in the design of the test scheme, four kinds of experimental working conditions are considered, and these are shown in Table 2. The corresponding data are collected for analysis.

Table 2. Four typical terrain conditions of the scraper conveyor test bench.

1	straight working condition
2	horizontal bending (3°) working condition
3	vertical bending (3°) working condition
4	horizontal bending + vertical bending working condition

2.2.3. Load

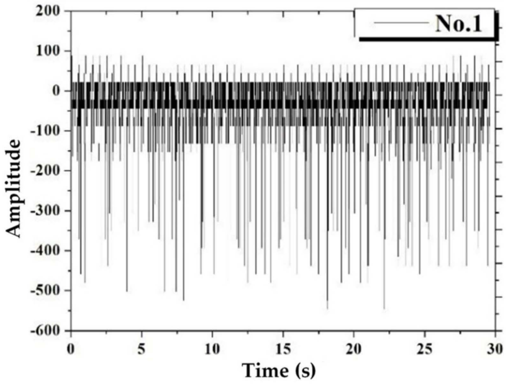
Given that this test bench increases the power of the SGD320/17B scraper conveyor from 17 to 18.5 kW and adjusts the working length from 80 m to 12 m, simulating 40 t/h full-load operation conditions in the test is difficult. Thus, only the dynamic properties data under no-load and load conditions are collected for a comparative analysis.

In the load condition, artificial, uniform loading coal blocks simulate the shearer cutting and loading coal blocks, as shown in Figure 3 [29].

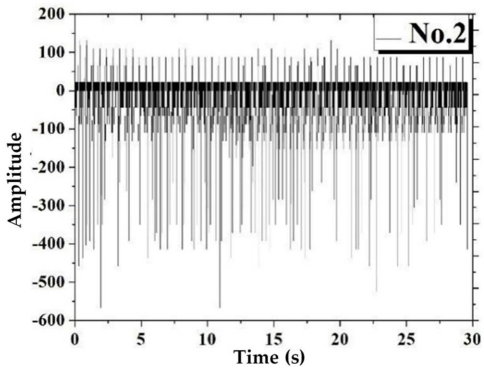
Figure 3. Loaded condition of the test bench.

2.3. Test Stability Analysis

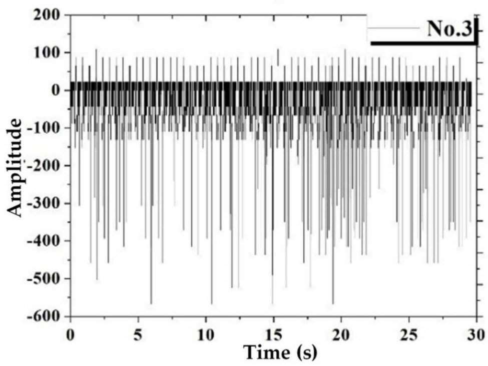
To verify the stability of the data acquisition module and ensure the accuracy of the test results, the sampling frequency of the data acquisition module is set to 2000 Hz for data acquisition, and the acquisition time is 30 s. Ten groups of vibration signals on the output shaft of the reducer are collected for comparison and analysis, as shown in Figure 4. The standard deviation, root mean square, skewness, and kurtosis of each group are summarized in Table 3.



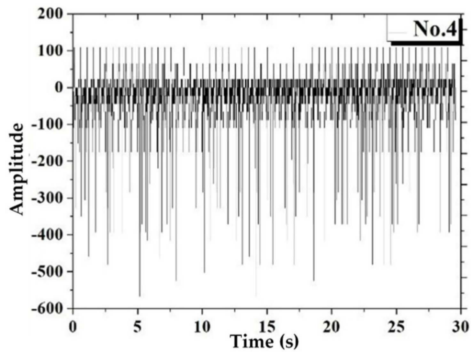
(**a**) Group 1



(**b**) Group 2



(**c**) Group 3



(**d**) Group 4

Figure 4. *Cont.*

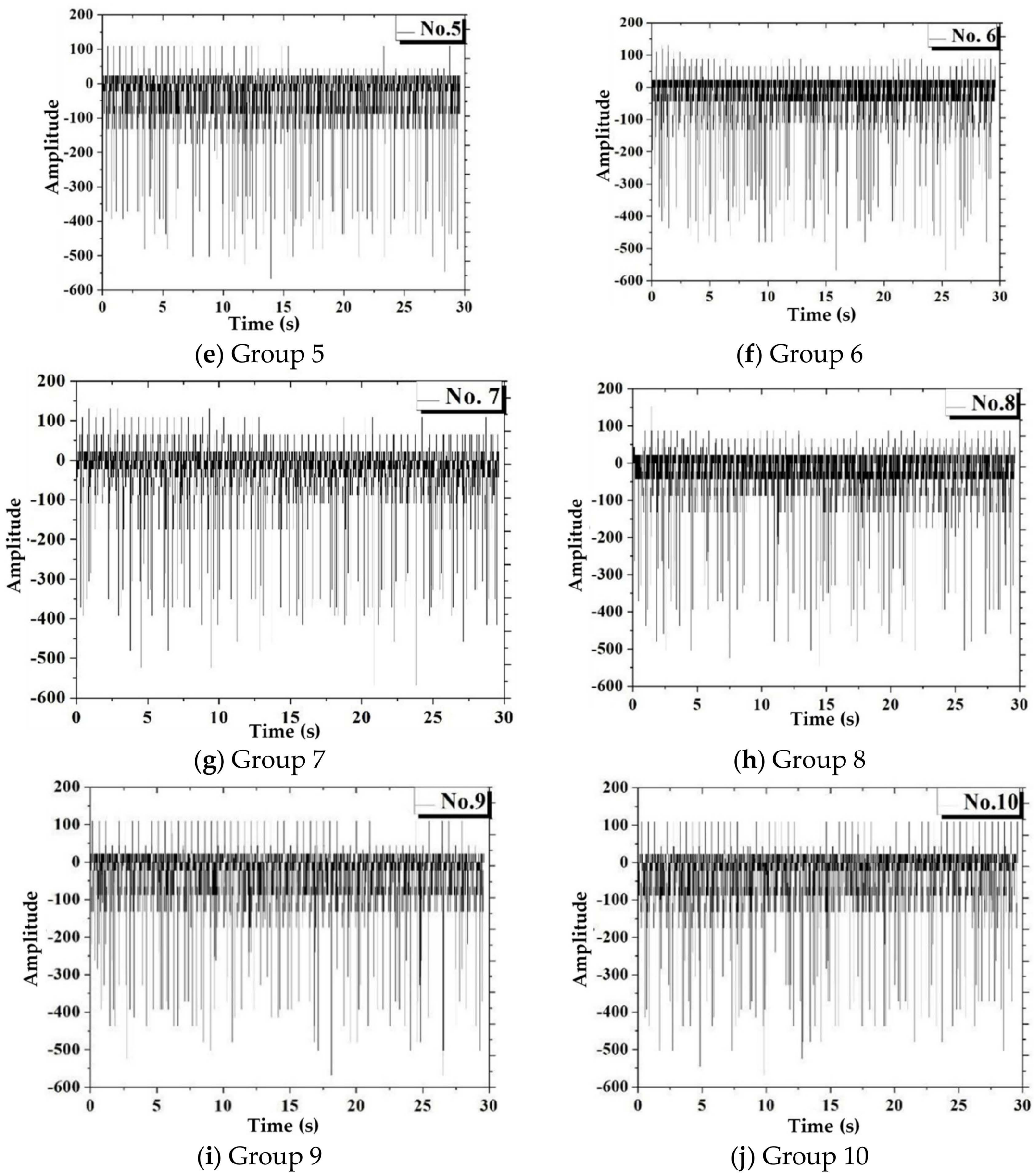


Figure 4. Collected 10 groups of vibration signals (before filtering).

Table 3. Stability table of collected 10 groups of vibration signals.

Number	Standard Deviation	Root Mean Square	Skewness	Kurtosis
1	54.99	63.9	−1.87	10.42
2	53.08	54.99	−1.25	5.67
3	56.45	63.59	−1.28	6.74
4	50.29	53.96	−1.67	11.77
5	54.4	60.98	−2.03	9.89
6	55.36	58.62	−2.16	11.6
7	49.4	53.08	−2.36	16.49
8	51.55	55.05	−1.79	10.13
9	54.19	59.23	−1.95	9.17
10	53.38	57.82	−1.69	7.01

The data in Table 3 show that, among the 10 groups of vibration data measured, the standard deviation is stable between 49.4 and 56.45, and the root mean square is stable between 53.08 and 63.9. Various statistical data indicators show that the collected vibration data are relatively stable, proving the reliability of the vibration signal acquisition module of this test bench.

3. Test Results

According to the test scheme, the vibration signals of the output shaft of the scraper conveyor reducer were collected under different chain speeds, terrains, loads, and no-load conditions. Through the analysis of the vibration signal, the influence of three factors on the dynamic properties of the scraper conveyor was determined.

3.1. Calculation of Frequency Value

The fluctuation of the vibration signal measured in the test is closely related to various frequency signals in the operation of the scraper conveyor, such as the rotation frequency of the motor, the rotation frequency of each shaft in the reducer, the meshing frequency of the gears at all stages, the scraping frequency of the scraper and the middle chute, and the meshing frequency of the scraper and the sprocket. Therefore, calculating the frequency value of each component in the scraper conveyor is necessary to further analyze the measured signal first.

The reducer in the test bench is a three-stage gear drive, as shown in Figure 5. The first stage is spiral bevel gear transmission, the second is helical cylindrical gear transmission, and the third is straight cylindrical gear transmission. Table 4 shows that the total reduction ratio of the reducer is 24.95. The number of teeth and modulus of gears at all stages.

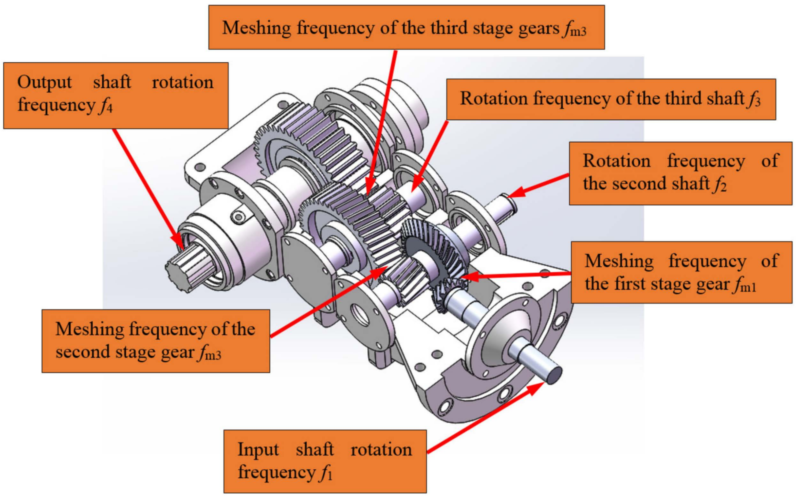


Figure 5. Three gear transmissions in the gear reducer.

Table 4. Gear parameters in the gear reducer.

Stage	Gear Module	Helix Angle (°)	Number of Teeth of Driving Gear	Number of Teeth of Driven Gear	Gear Ratio
1	5	33.75	14	36	2.57
2	5	10	13	44	3.38
3	6	0	15	43	2.87

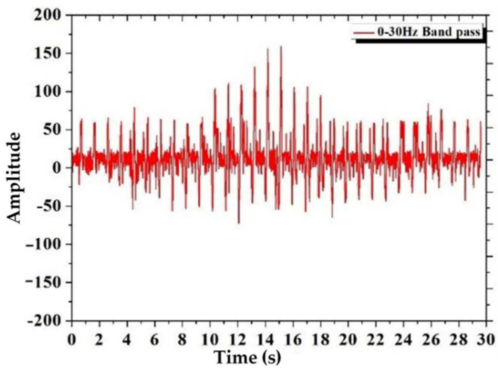
The rotation frequency of each shaft and the meshing frequency of each gear level of the reducer at different chain speeds are calculated, as shown in Table 5.

Table 5. Frequencies of various parts in the test bench.

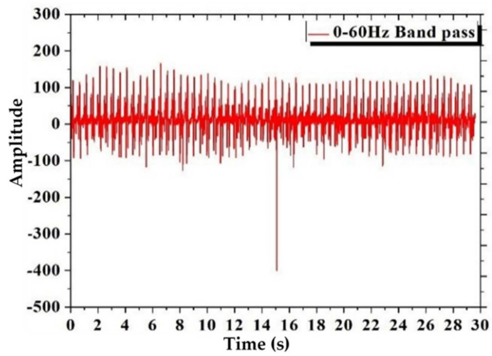
Chain Speed (m/s)	Motor Rotation Frequency (Rotation Frequency of Reducer Input Shaft) (Hz)	Meshing Frequency of Primary Gear (Hz)	Rotation Frequency of the Second Shaft (Hz)	Meshing Frequency of Secondary Gear (Hz)	Rotation Frequency of the Third Shaft (Hz)	Meshing Frequency of Third Gear (Hz)	Rotation Frequency of Output Shaft (Head Sprocket) (Hz)
0.0236	0.98	13.72	0.3811	4.9544	0.1126	1.6890	0.0393
0.0471	1.96	27.44	0.7622	9.9089	0.2252	3.3780	0.0786
0.0707	2.94	41.16	1.1433	14.8633	0.3378	5.0670	0.1178
0.0943	3.92	54.88	1.5244	19.8178	0.4504	6.7561	0.1571
0.1178	4.9	68.6	1.9056	24.7722	0.5630	8.4451	0.1964
0.1414	5.88	82.32	2.2867	29.7267	0.6756	10.1341	0.2357
0.1650	6.86	96.04	2.6678	34.6811	0.7882	11.8231	0.2750
0.1885	7.84	109.76	3.0489	39.6356	0.9008	13.5121	0.3142
0.2121	8.82	123.48	3.4300	44.5900	1.0134	15.2011	0.3535
0.2357	9.8	137.2	3.8111	49.5444	1.1260	16.8902	0.3928

3.2. Chain Speed

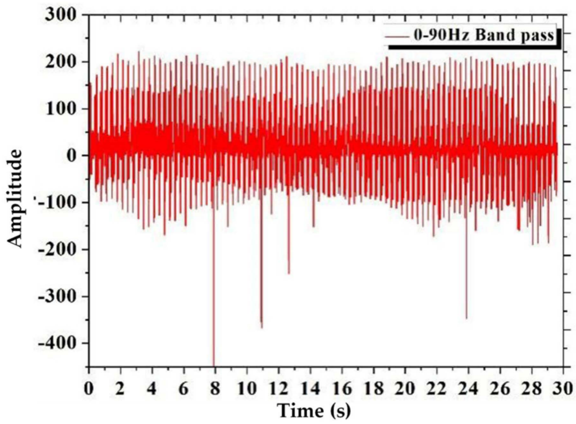
Based on the above discussion, according to the frequency of each group of tests, 10 groups of vibration signals measured at different frequencies are processed using fast Fourier filtering to filter out redundant interference signals. After filtering, the vibration signals of each group are collected, and they are shown in Figure 6.



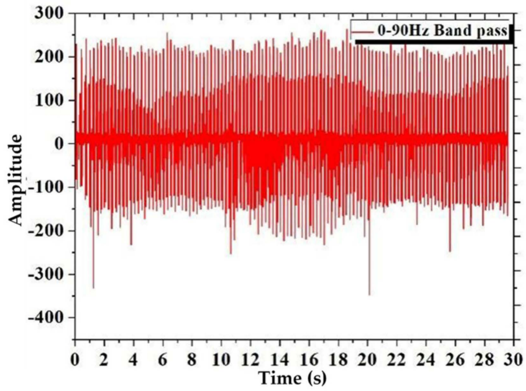
(**a**) 0.0236 m/s



(**b**) 0.0471 m/s

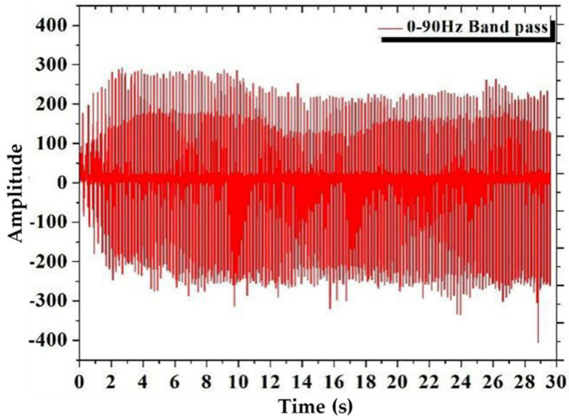


(**c**) 0.0707 m/s

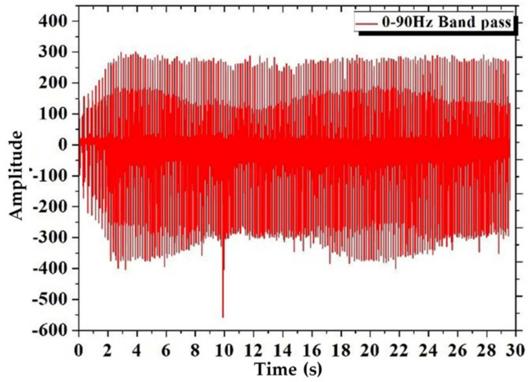


(**d**) 0.0943 m/s

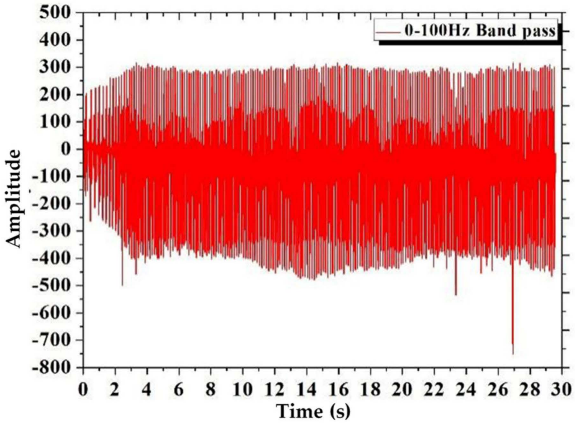
Figure 6. *Cont.*



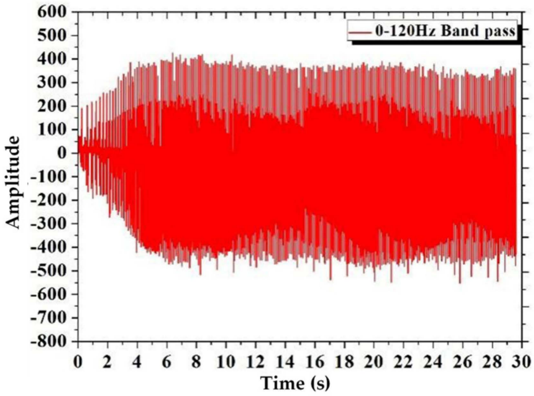
(**e**) 0.1178 m/s



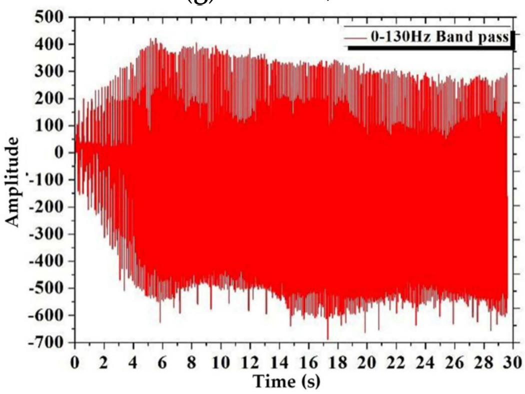
(**f**) 0.1414 m/s



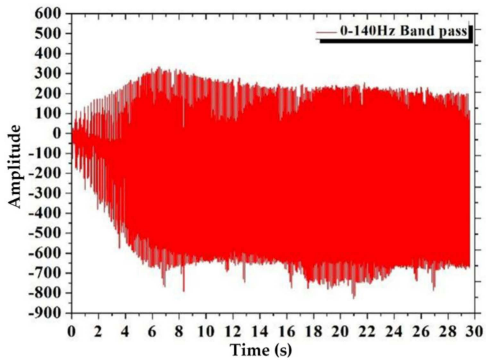
(**g**) 0.1650 m/s



(**h**) 0.1885 m/s



(**i**) 0.2121 m/s

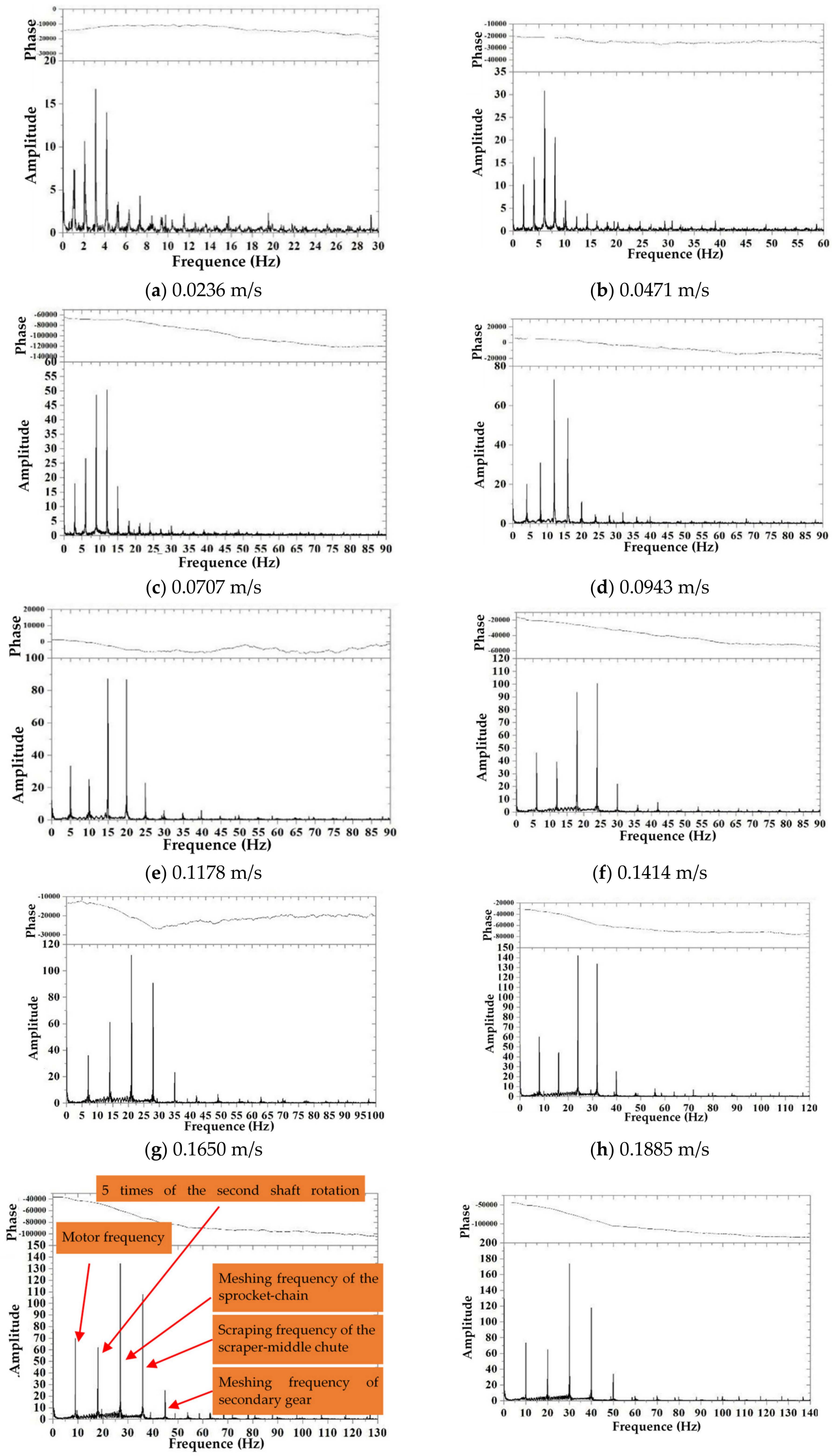


(**j**) 0.2357 m/s

Figure 6. Vibration signals of 10 groups under different chain speeds.

The influence of each frequency signal in the test bench system on the dynamic properties of the scraper conveyor is analyzed. FFT transformation is performed on each signal in Figure 6 to obtain and analyze spectrograms of each group of signals, as shown in Figure 7. Figure 7 shows that five fixed frequencies in different chain speeds greatly influence the scraper conveyor's dynamic properties.

Taking Figure 7i as an example, combined with the meshing frequency of each shaft and gear at all stages calculated in Table 5, among the shafts of the reducer, the rotation frequency of the second shaft and the rotation frequency of the input shaft (that is, the motor rotation frequency) have a greater impact on the signal.



(**a**) 0.0236 m/s (**b**) 0.0471 m/s
(**c**) 0.0707 m/s (**d**) 0.0943 m/s
(**e**) 0.1178 m/s (**f**) 0.1414 m/s
(**g**) 0.1650 m/s (**h**) 0.1885 m/s
(**i**) 0.2121 m/s (**j**) 0.2357 m/s

Figure 7. Spectrograms of vibration signals under different chain speeds.

The motor's output shaft relates to the reducer's input shaft through a coupling. The coupling used in the test bench is connected by elastic connecting pins, which is a non-rigid connection. Given the small gap between the connecting pin and the coupling hole, the vibration occurs at the connecting pin during operation. With an increase in the chain speed, the amplitude of the input shaft rotation frequency increases gradually, and the maximum amplitude can reach 70. In all stages of gear meshing frequency, the meshing frequency of the second-stage gear has the greatest impact on the vibration signal compared with the other gear meshing frequencies.

After the analysis, the remaining two frequencies are the scraping frequency of the scraper–middle chute and the meshing frequency of the chain sprocket. The length of the middle chute of the test bench is 0.6 m, with 13 sections; the scraper spacing is 0.75 m, with 32 scrapers in total; and the chain length is 24 m. The meshing frequency of the chain and the sprocket is approximately 27 Hz, and the scraping frequency of the scraper and the middle chute is 36 Hz.

3.3. Terrain

According to the design of the test scheme, the system's vibration signals are collected and analyzed under the conditions of straight, only horizontal bending, only vertical bending, and horizontal + vertical bending.

Figure 8 shows the vibration signals collected by the acquisition module under four different terrain conditions. The amplitude of the vibration signal is the largest under the combined horizontal and vertical bending condition, followed by the vertical bending condition. The small difference between the horizontal bending and straight conditions indicates that the fluctuation of the vibration signal is greatly affected by terrain fluctuations.

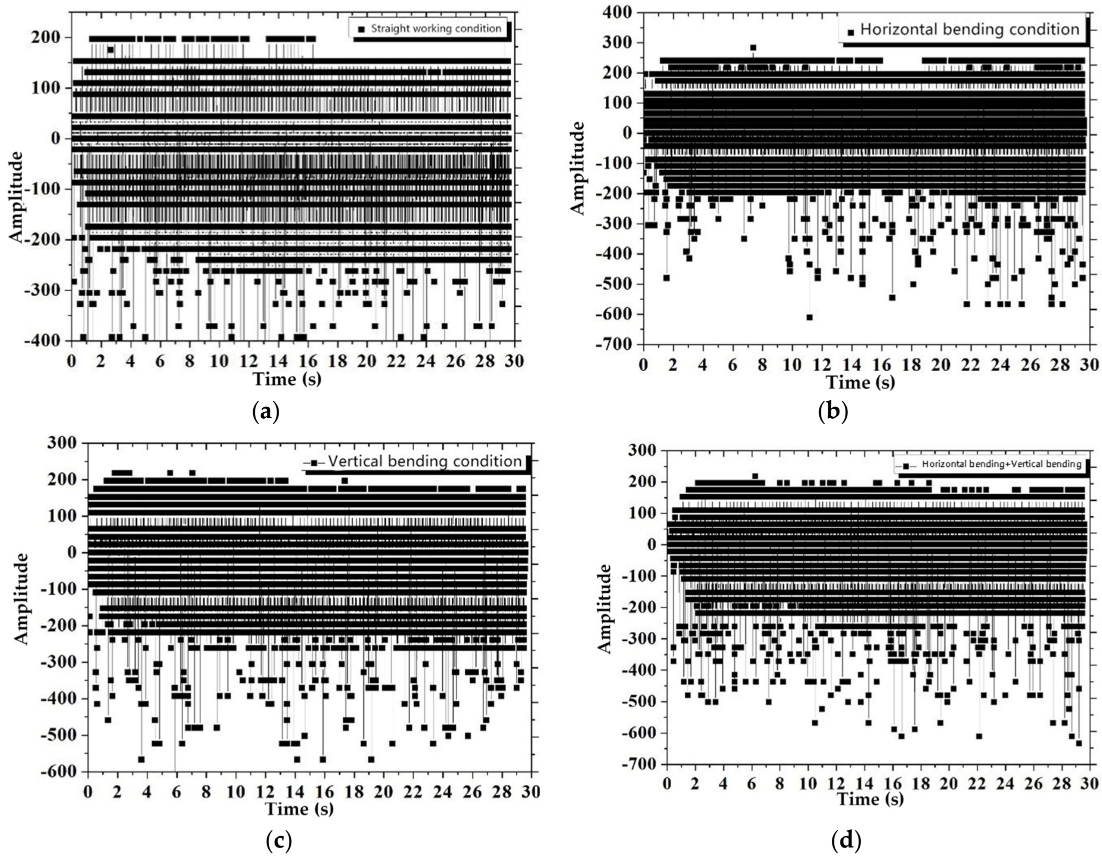


Figure 8. Vibration signals under four various terrain conditions. (**a**) Straight working condition. (**b**) Horizontal bending condition. (**c**) Vertical bending condition. (**d**) Combined working condition of horizontal and vertical bending.

FFT filters the vibration signals under four different terrains, and the high-frequency components higher than 60 Hz are filtered, as shown in Figure 9.

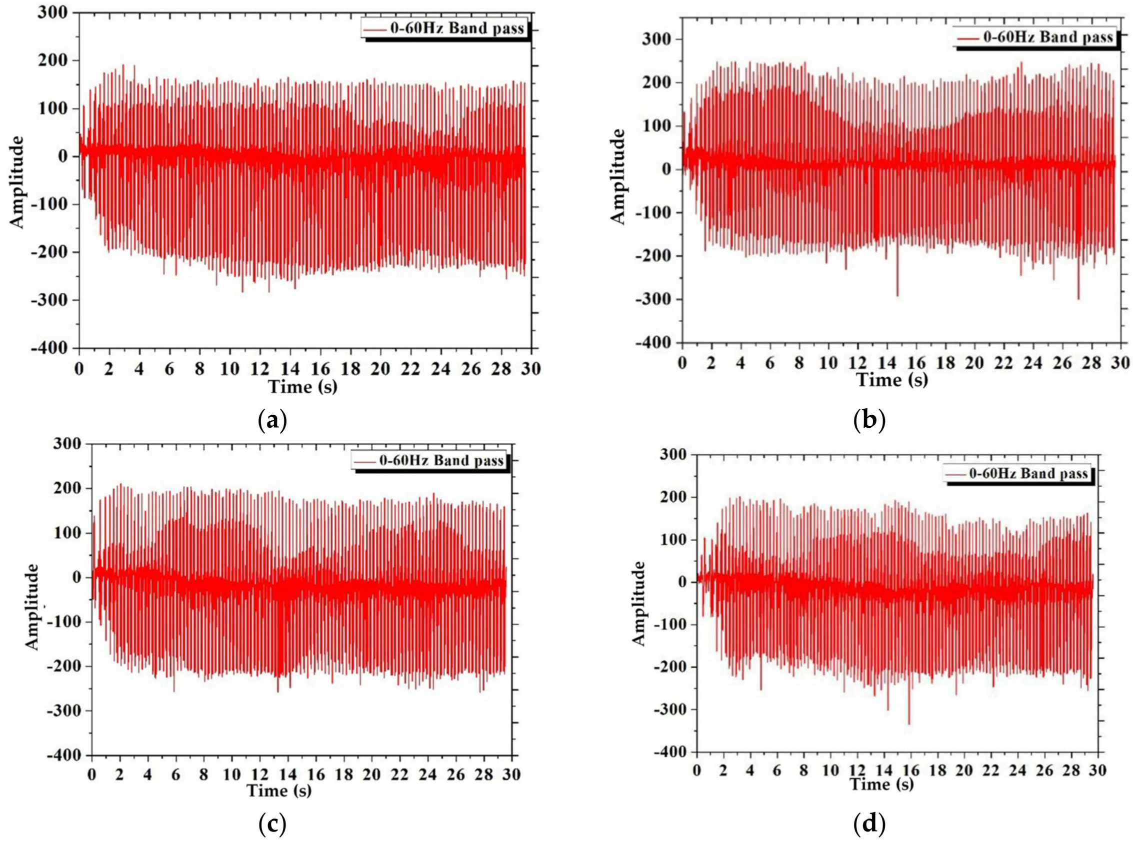
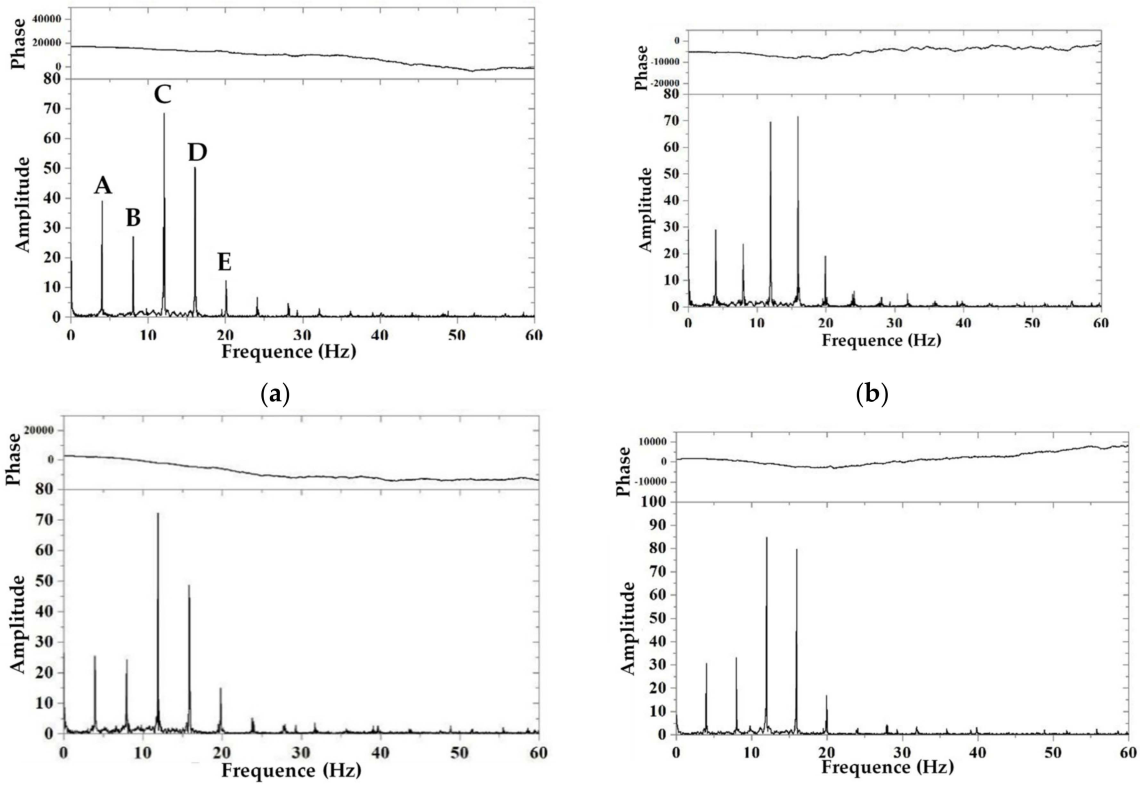


Figure 9. Vibration signals under four various terrain conditions after FFT filtering. (**a**) Straight working condition. (**b**) Horizontal bending condition. (**c**) Vertical bending condition. (**d**) Combined working condition of horizontal and vertical bending.

FFT changes are performed on the filtered signal to obtain vibration signal spectrograms under four working conditions, as shown in Figure 10. According to the above analysis and calculation, the meanings of each frequency in Figure 10a are as follows: A—motor (input shaft of the reducer) rotation frequency, B—five times of the second shaft rotation frequency of the reducer, C—the meshing frequency of the sprocket and the chain, D—the scraping frequency of the scraper–middle chute, and E—the meshing frequency of the second-stage gear of the reducer.

Figure 10 shows that, with the transition of the scraper conveyor from the straight working condition to horizontal bending, vertical bending, and horizontal + vertical bending terrains, the amplitude of the motor rotation frequency, the rotation frequency of the second shaft of the reducer, and the meshing frequency of the secondary gear remain unchanged. Therefore, the frequency properties of each shaft of the reducer have little effect on the dynamic properties of the scraper conveyor in the process of terrain change. The amplitude of the meshing frequency between the sprocket and the chain is maintained at approximately 70 under the three working conditions of straight, horizontal, and vertical bending. However, the amplitude increases to 85 under the combined working condition of horizontal bending + vertical bending. For the scraper and the middle chute, no significant difference is found in the amplitude of the scraping frequency between the straight and vertical bending conditions. The amplitude increases significantly in the horizontal bending and the combination of horizontal + vertical bending.



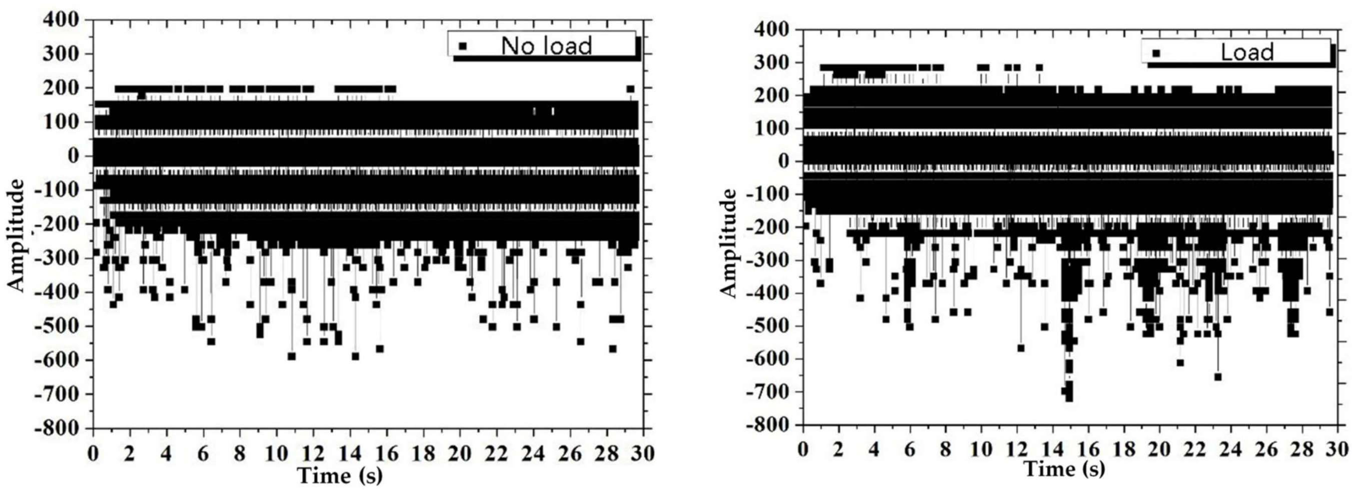
(**a**) (**b**)

(**c**) (**d**)

Figure 10. Spectrograms of vibration signals under four various terrain conditions. (**a**) Straight working condition. (**b**) Horizontal bending condition. (**c**) Vertical bending condition. (**d**) Combined working condition of horizontal and vertical bending.

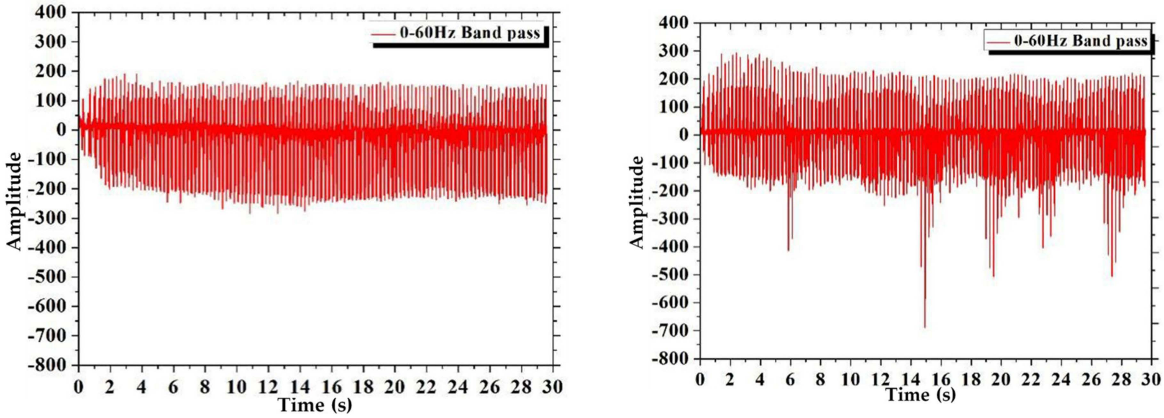
3.4. Load

The original signal collected is shown in Figure 11, and FFT filtering is carried out to filter out the high-frequency components above 60 Hz, as shown in Figure 12.



(**a**) No-load condition (**b**) Load condition

Figure 11. Vibration signals under no-load and load conditions.

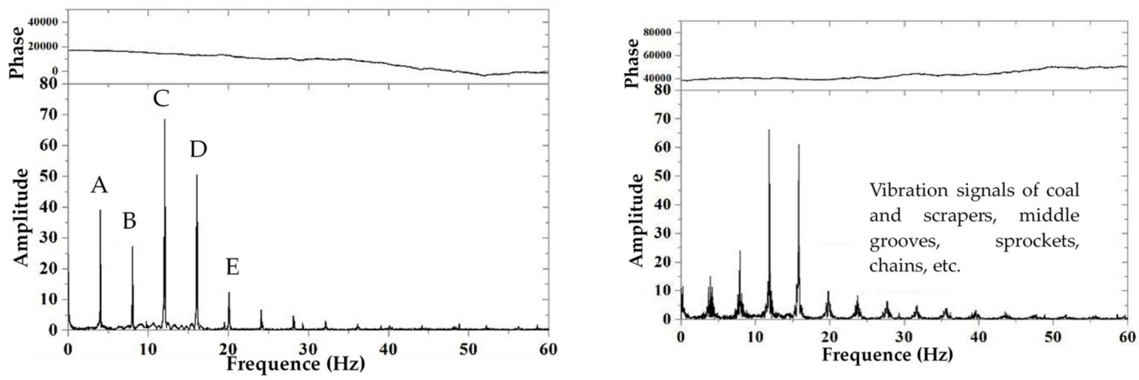


(**a**) No-load condition (**b**) Load condition

Figure 12. Vibration signals under no-load and load conditions after FFT filtering.

Figure 12 illustrates that the vibration signal changes smoothly after FFT filtering under no-load conditions. Furthermore, under load conditions, the amplitude of the vibration signal in the time domain increases significantly, and the time when the amplitude occurs is irregular.

Figure 13 shows the FFT spectrum of the filtered signal. Its shows (A) the motor (input shaft of the reducer) rotation frequency, (B) five times of the second shaft rotation frequency of the reducer, (C) the meshing frequency of the sprocket and the chain, (D) the scraping frequency of the scraper–middle chute, and (E) the meshing frequency of the secondary gear of the reducer. Compared with the no-load condition, the amplitude of the motor output shaft rotation frequency, the second shaft rotation frequency of the reducer, and the meshing frequency of the secondary gear all decrease under the load condition. The amplitude of the motor rotation frequency decreases most notably, from 40 to 15. The amplitude of the meshing frequency of the sprocket and chain remains stable, whereas the amplitude of scraping between the scraper and the middle chute increases from 48 to 60. At the same time, compared with the no-load condition, many high-frequency signals exist in the load condition spectrum. These vibration signals are higher than the scraping frequency of the scraper and the middle chute, and the meshing frequency of the scraper and the sprocket.



(**a**) No-load condition (**b**) Load condition

Figure 13. Spectrograms of vibration signals under no-load and load conditions.

4. Analysis and Discussion

In order to study the dynamic properties of a scraper conveyor, a test bench to determine the dynamic properties of a single-chain scraper conveyor is built. Three working conditions that have been found to have the greatest impact on the dynamic properties of a scraper conveyor are simulated [29]: different chain speeds, different terrains, and no-load/loaded conditions. The effect of different frequencies on its dynamic properties is studied.

Because the structure of a scraper conveyor is complex and the test cost is high, some scholars use the simulation method to study the dynamic properties of its single subsystem [18–20]. However, a scraper conveyor is a highly coupled multi-body dynamic system, and there are certain limitations when only studying a single subsystem. Therefore, in this paper, the dynamic properties of the entire drive system of a scraper conveyor are studied from the perspective of a spectrum analysis by means of experiments.

Our studies serve as a proof of concept that, in the drive system of a scraper conveyor, there are five main frequencies that affect its dynamic performance: motor rotation frequency, reducer second shaft rotation frequency, reducer secondary gear meshing frequency, sprocket–chain meshing frequency, and scraper–middle chute scraping frequency. Among the shafts of the reducer, the rotation frequency of the second shaft has a greater impact on the signal. The reason for this is that the second shaft of the reducer is driven by spiral bevel gears. The spiral bevel gear generates axial and radial forces during operation, affecting the scraper conveyor's dynamic properties. Based on the above analysis, it can be observed that ensuring the machining accuracy of the spiral bevel gear and helical cylindrical gear in the reducer can improve the dynamic properties of a scraper conveyor. From our results, we can conclude that, with an increase in chain speed, the amplitude of the motor rotation frequency gradually increases, with a maximum value as high as 70, and the influence on the dynamic properties of the scraper conveyor gradually increases.

Compared with other terrain conditions, the composite working condition of horizontal bending + vertical bending significantly impacts the meshing frequency of the sprocket–chain, and the amplitude increases to 85. This indicates that the combined working condition significantly influences the sprocket–chain meshing properties. The scraping phenomenon between the scraper and the middle chute greatly influences the dynamic properties of the scraper conveyor in the horizontal bending condition. The reason for this is that the gap between the middle chutes is large when the scraper conveyor is horizontally bent. When the scraper runs to the gap between the middle chutes, the running resistance increases, which increases the amplitude of the vibration signal. Therefore, during scraper conveyor use, the horizontal bending angle should be reduced as much as possible, and the connection between the middle chutes should be strengthened to reduce the running resistance of the scraper.

Compared with the no-load condition, under the load condition, the rotational frequency amplitude of the motor output shaft is significantly smaller, reducing from 40 to 15, which indicates that the influence of the motor output shaft rotation frequency on the dynamic properties of the scraper conveyor decreases with an increase in load. However, the influence of the scraping frequency of the scraper–middle chute on the dynamic properties is increased. When some scholars studied the load condition, they found that the speed difference of the head and tail sprockets of the scraper conveyor increased significantly compared with the no-load condition [29], indicating that the scraper conveyor subsystem chain transmission system dynamic properties become worse. In this paper, from the perspective of a spectrum analysis, it is found that the scraping frequency of the scraper–middle chute is one of the main factors affecting the dynamic properties under the load condition. The phenomenon that one side of the scraper moves out of the middle chute in the process of transporting coal by the scraper appears many times in the load test, which proves that the amplitude of the scraping frequency between the scraper and the middle chute increases. Some additional high-frequency signals will affect the dynamic properties of the scraper conveyor and increase wear. During the process of the scraper conveying coal, the coal frequently collides with the scraper, the middle chute, the sprocket, and the chain, which results in a vibration signal, finally affecting the dynamic properties of the entire scraper conveyor.

Considering the cost problem, the designed test bench is based on single-chain scraper conveyors, but double-chain scraper conveyors are currently the most used in mines. Therefore, the test results have certain limitations, but they still have a certain reference value. In this case, a double-chain scraper conveyor can be used in future research.

In this study, the dynamic properties of a scraper conveyor under different working conditions are studied by building a test bench, which is of great significance for improving the scraper conveyor's dynamic properties and structural optimization design. Based on this study, the dynamic properties of the chain drive system under multi-source excitation can be analyzed from the perspective of vibration energy transfer.

5. Conclusions

This study builds a test bench for the overall dynamic properties of a scraper conveyor to examine the dynamic properties of different chain speeds, different terrains, and no-load/load conditions. A frequency spectrum analysis of the vibration signal of the reducer's output shaft collected under different working conditions leads to the following conclusions:

(1) Given that carrying out research in mines is unsuitable, a scraper conveyor test bench is built to comprehensively analyze the vibration of the output shaft of the reducer under different chain speeds, different terrains, and no-load/load conditions from the perspective of vibration. According to the frequency domain spectrum of the vibration signal, the dynamic properties of the drive system of the scraper conveyor are analyzed, and the overall health status of the scraper conveyor is inferred.

(2) In the drive system of the scraper conveyor, five main frequencies affect its dynamic performance: the motor rotation frequency, reducer second shaft rotation frequency, reducer secondary gear meshing frequency, sprocket–chain meshing frequency, and scraper–middle chute scraping frequency. With an increase in chain speed, the amplitude of the motor rotation frequency gradually increases, with a maximum value as high as 70, and the influence on the dynamic properties of the scraper conveyor gradually increases.

(3) Compared with other terrain conditions, the composite working condition of horizontal bending + vertical bending significantly impacts the meshing frequency of the sprocket–chain, and the amplitude increases to 85. In the horizontal bending condition, the amplitude of the scraping frequency of the scraper–middle chute increases significantly.

(4) Compared with the no-load condition, the rotational frequency amplitude of the motor output shaft under the load condition is significantly smaller, reducing from 40 to 15. The influence of the motor output shaft on the dynamic properties of the scraper conveyor is reduced, whereas the influence of the scraping frequency of the scraper–middle chute on the dynamic properties is increased.

(5) This study examines the dynamic properties of a scraper conveyor under different working conditions by building a test bench, which is of great significance for improving the scraper conveyor's dynamic properties and structural optimization design. Based on this study, the dynamic properties of the chain drive system under multi-source excitation can be analyzed from the perspective of vibration energy transfer.

Author Contributions: Formal analysis, S.J.; funding acquisition, Q.Z.; methodology, S.H. and S.J.; supervision, Q.M. and K.G.; writing—original draft, S.H. and J.L.; writing—review and editing, S.J. and S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Shandong Provincial Key Laboratory of Mining Machinery Engineering Open Fund (University-Enterprise Joint Funding Project), grant number 2022KLMM307; the Shandong Provincial Natural Science Foundation, grant number ZR2019BEE066; the Shandong Provincial Key Research and Development Project, grant number 2019SDZY01; the Project of Shaanxi Key Laboratory of Mine Electromechanical Equipment Intelligent Monitoring (Xi'an University of Science and Technology), grant number SKL-MEEIM201906; and the Project of Shandong Province Higher Educational Young Innovative Talent Introduction and Cultivation Team (Performance enhancement of deep coal mining equipment).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data were curated by the authors and are available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wieczorek, A.N.; Wojcicki, M. Synergism of the binary wear process of machinery elements used for gaining energy raw materials. *Energies* **2021**, *14*, 1981. [CrossRef]
2. Zhang, H.; Liao, Y.Y.; Tao, Z.; Lian, Z.S.; Zhao, R.H. Modeling and dynamic characteristics of a novel high-pressure and large-flow water hydraulic proportional valve. *Machines* **2022**, *10*, 37. [CrossRef]
3. Hao, S.Q.; Wang, S.B.; Malekian, R.; Zhang, B.Y.; Liu, W.L.; Li, Z.X. A geometry surveying model and instrument of a scraper conveyor in unmanned longwall mining faces. *IEEE Access* **2017**, *5*, 4095–4103. [CrossRef]
4. Fedorko, G.; Necas, J.; Zegzulka, J.; Gelnar, D.; Molnar, V.; Tomaskova, M. Measurement of amount for steel abrasive material transported by special scraper conveyor. *Appl. Sci.* **2021**, *11*, 1852. [CrossRef]
5. Szurgacz, D.; Zhironkin, S.; Cehlar, M.; Voth, S.; Spearing, S.; Ma, L.Q. A step-by-step procedure for tests and assessment of the automatic operation of a powered roof support. *Energies* **2021**, *14*, 697. [CrossRef]
6. Luo, C.M.; Fan, X.N.; Ni, J.J.; Yang, H.; Zhang, X.W.; Li, W. Positioning accuracy evaluation for the collaborative automation of mining fleet with the support of memory cutting technology. *IEEE Access* **2016**, *4*, 5764–5775. [CrossRef]
7. Ding, H.; Liu, Y.C.; Liu, J.C. Volumetric tooth wear measurement of scraper conveyor sprocket using shape from focus-based method. *Appl. Sci.* **2019**, *9*, 1084. [CrossRef]
8. Li, J.X.; Liang, S.W. Impact and friction of bulk material on the blanking area in the middle trough of scraper machine. *J. Coast. Res.* **2019**, *93*, 947–952. [CrossRef]
9. Dolipski, M.; Cheluszka, P.; Remiorz, E.; Sobota, P. Follow-up chain tension in an armoured face conveyor. *Arch. Min. Sci.* **2015**, *60*, 25–38.
10. Jiang, S.B.; Ren, W.J.; Mao, Q.H.; Zeng, Q.L.; Yu, P.F.; Gao, K.D.; Wang, L. Dynamic analysis of the scraper conveyor under abnormal operating conditions based on the vibration and speed characteristics. *Shock Vib.* **2021**, *2021*, 8887744. [CrossRef]
11. Liu, X.S.; Fan, D.Y.; Tan, Y.L.; Song, S.L.; Li, X.F.; Ning, J.G.; Gu, Q.H.; Ma, Q. Failure evolution and instability mechanism of surrounding rock for close-distance chambers with super-large section in deep coal mines. *Int. J. Geomech.* **2021**, *21*, 04021049. [CrossRef]
12. Liu, X.S.; Song, S.L.; Tan, Y.L.; Fan, D.Y.; Ning, J.G.; Li, X.B.; Yin, Y.C. Similar simulation study on the deformation and failure of surrounding rock of a large section chamber group under dynamic loading. *Int. J. Min. Sci. Technol.* **2021**, *31*, 495–505. [CrossRef]
13. Liu, X.S.; Fan, D.Y.; Tan, Y.L.; Ning, J.G.; Song, S.L.; Wang, H.L.; Li, X.B. New detecting method on the connecting fractured zone above the coal face and a case study. *Rock Mech. Rock Eng.* **2021**, *54*, 4379–4391. [CrossRef]
14. Lu, E.; Li, W.; Yang, X.F.; Xu, S.Y. Composite sliding mode control of a permanent magnet direct-driven system for a mining scraper conveyor. *IEEE Access* **2017**, *5*, 22399–22408. [CrossRef]
15. Li, L.; Cui, H.W.; Lian, Z.S.; Wang, Q.L. Modeling and optimization of soft start-up for hydroviscous drive applied to scraper conveyor. *Math. Probl. Eng.* **2019**, *2019*, 6131364. [CrossRef]
16. Zhang, D.S.; Mao, J.; Liu, Z.S. Dynamics simulation and experiment on the starting and braking of scraper conveyor. *Meitan Xuebao* **2016**, *41*, 513–521.
17. Wang, X.W.; Wang, S.P.; Long, R.S.; Yang, Z.J.; Liu, G.P. Rigid-flexible coupled dynamic contact analysis for a chains drive system of a heavy scraper conveyer during loading start-up. *J. Vib. Shock.* **2016**, *35*, 34–40.
18. Xie, C.X.; Liu, Z.X.; Mao, J.; Xie, M.; Lu, J.N. Analysis of torsional vibration characteristics of scraper conveyor on chain blocked condition. *Meitan Xuebao* **2018**, *43*, 2348–2354.
19. Jiang, S.B.; Huang, S.; Zeng, Q.L.; Wang, C.L.; Gao, K.D.; Zhang, Y.Q. Dynamic properties of chain drive system considering multiple impact factors. *Int. J. Simul. Model.* **2022**, *21*, 284–295. [CrossRef]
20. Wang, D.G.; Zhang, J.; Zhu, Z.C.; Gang, S.; Xiang, L. Crack initiation characteristics of ring chain of heavy-duty scraper conveyor under time-varying loads. *Adv. Mech. Eng.* **2019**, *11*, 1687814019880366. [CrossRef]
21. Zhang, X.; Li, W.; Zhu, Z.; Yang, S.; Jiang, F. Fault detection for the scraper chain based on vibration analysis using the adaptive optimal kernel time-frequency representation. *Shock Vib.* **2019**, *2019*, 6986240. [CrossRef]

22. Zhao, S.F.; Wang, P.F.; Li, S.J. Study on the fault diagnosis method of scraper conveyor gear under time-varying load condition. *Appl. Sci.* **2020**, *10*, 5053. [CrossRef]
23. Jiang, S.B.; Zhang, X.; Gao, K.D.; Wang, Q.Y.; Hidenori, K. Multi-body dynamics and vibration analysis of chain assembly in armoured face conveyor. *Int. J. Simul. Model.* **2017**, *16*, 458–470. [CrossRef]
24. Ren, W.J.; Wang, L.; Mao, Q.H.; Jiang, S.B.; Huang, S. Coupling properties of chain drive system under various and eccentric loads. *Int. J. Simul. Model.* **2020**, *19*, 643–654. [CrossRef]
25. Jiang, S.B.; Zeng, Q.L.; Wang, G.; Gao, K.D.; Hidenori, K. Contact analysis of chain drive in scraper conveyor based on dynamic meshing properties. *Int. J. Simul. Model.* **2018**, *17*, 81–91. [CrossRef]
26. Shprekher, D.M.; Babokin, G.I.; Kolesnikov, E.B.; Ovsyannikov, D.S. Research of load unbalance of a two-motor variable frequency dtive for scraper conveyor. *Izv. Vyss. Uchebnykh Zaved. Elektromekhanika* **2021**, *64*, 37–45. [CrossRef]
27. Shprekher, D.M.; Babokin, G.I.; Zelenkov, A.V.; Ovsyannikov, D.S. Universal computer model for studying the dynamics of a two-motor scraper conveyor. *Izv. Vyss. Uchebnykh Zaved. Elektromekhanika* **2021**, *64*, 56–64.
28. Wojnar, G.; Burdzik, R.; Wieczorek, A.N.; Konieczny, L. Multidimensional data interpretation of vibration signals registered in different locations for system condition monitoring of a three-stage gear transmission operating under difficult conditions. *Sensors* **2021**, *21*, 7808. [CrossRef]
29. Jiang, S.B.; Lv, R.B.; Wan, L.R.; Mao, Q.H.; Zeng, Q.L.; Gao, K.D.; Yang, Y. Dynamic characteristics of the chain drive system of scraper conveyor based on the speed difference. *IEEE Access* **2020**, *8*, 168650–168658. [CrossRef]