Research on Vibration Patterns and Online Monitoring System of Heavy-Haul Railway Catenary

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Abstract: This study aims to address the issue of severe vibration in the catenary induced by heavy-haul railways - characterized by large transport volume and high axle load - when trains traverse bridge sections. Such vibrations significantly increase the risk of cumulative fatigue damage to catenary components. The research focuses on developing accurate methods for load identification and analysis. By precisely capturing and evaluating the dynamic loads sustained by the catenary during operation, this work provides essential data support and a theoretical basis for assessing the operational status of the system, predicting the service life of key components, and optimizing structural design.

Research conclusions: (1) This study successfully developed an integrated online monitoring system capable of multi-parameter acquisition, wireless transmission, and intelligent analysis. The system adopts an integrated mast design, complies with IP65 protection standards, and features wide-temperature operational capability, ensuring stable performance in harsh railway environments. Its vehicle-triggered automatic activation and low-power sleep mechanism significantly enhance engineering application efficiency and reliability.(2) Through multi-sensor collaborative data acquisition and Kalman filter-based data fusion, this study accurately characterized the dynamic response of the catenary system. Field measurements revealed that the contact wire uplift fluctuates within ±5 mm under wind load when no train is present, while the peak uplift during pantograph passage ranges between 20 and 25 mm. This work represents the first quantitative characterization of the operational load spectrum for heavy-haul trains.(3) Utilizing deep learning algorithms, this research achieved intelligent recognition of pantograph abnormal states. Integrated with train number identification, a "one-pantograph-one-file" management system was established. The structured correlation of multi-source data and response spectrum analysis significantly improved the safety management level of the power supply system.(4) This study provides valuable references and a solid foundation for further investigation into vibration patterns and intelligent maintenance of heavy-haul railway catenary systems.

Keywords:Railway Communication; Online Monitoring; Sensors; Heavy-Haul Railway; Catenary

1. Introduction

Heavy-haul railways, characterized by large transport capacity and high axle loads, are prone to inducing intense vibrations when traversing bridge sections, posing severe challenges to the durability of the Overhead Contact System (OCS). The severe dynamic loads significantly increase the risk of fatigue damage to OCS components, affecting their service safety and operational life. Therefore, accurately acquiring the dynamic loads borne by the OCS during actual operation is crucial for system operational condition assessment, critical component life prediction, and structural optimization. Accurate identification and quantification of OCS loads serve as the key prerequisite for conducting fatigue characteristic research and condition evaluation. Through load analysis, not only can a data foundation be provided for the safe operation and maintenance of the OCS, but theoretical bases can also be established for vibration control and structural improvement, holding significant engineering value for enhancing the power supply reliability of heavy-haul railways. Consequently, this paper focuses on investigating the vibration patterns of heavy-haul railway OCS and online monitoring systems.

Regarding the research status of heavy-haul railways at home and abroad, Bardhan [1] introduced a hybrid reliability analysis framework combining Multi-gene Genetic Programming (MGGP) and the First-Order Second-Moment Method (FOSM). This method automatically constructs explicit performance functions through GP and efficiently quantifies the influence of soil parameter variability on slope stability based on FOSM, achieving a reasonable assessment of failure probability for heavy railway track embankments and providing a new pathway for efficient slope reliability analysis. Eckert [2] proposed a novel method for multi-objective optimization of heavy-haul train electrical braking systems utilizing optimizable fuzzy control. Preliminary findings indicate that directly replacing pneumatic control valves with electropneumatic valves without significant modifications to control schedules fails to substantially improve vehicle dynamic behavior. This method employs multi-objective optimization to simultaneously minimize energy consumption during braking and reduce force peaks in freight car traction gears. The optimized fuzzy braking controller outperforms standard procedures, demonstrating its potential to enhance heavy-haul train efficiency while adhering to safety standards. Li Lihua [3] noted that in research on subgrade reinforcement technologies for heavy-haul railways, geosynthetic reinforcement has garnered widespread attention due to its effectiveness in improving soil mass integrity and reducing deformation; existing studies have confirmed the role of geogrids in improving load transfer and restraining lateral displacement in soft ground treatment and pile-net composite foundation applications. Some scholars have also conducted analyses on the dynamic performance of reinforced embankments under flood immersion conditions or cyclic freeze-thaw environments in seasonal frost regions, pointing out that three-dimensional reinforcement forms such as geocells demonstrate comparative advantages in suppressing settlement and increasing stiffness. To further quantify the dynamic response patterns of different reinforcement configurations, this study systematically compares axial deformation, pore water pressure development, and damping characteristics of plain soil, geogrid-reinforced soil, and geocell-reinforced soil under simulated heavy-haul cyclic loading through large-scale dynamic triaxial tests, clarifying the significant effects of geocell reinforcement in controlling cumulative strain and delaying pore pressure growth, thereby providing experimental basis for the optimization of heavy-haul railway subgrade reinforcement schemes. Zhang Yahui [4] proposed that in research on foundation reinforcement of loess tunnels for heavy-haul railways, jet grouting pile technology demonstrates remarkable effectiveness. Studies indicate that after jet grouting pile reinforcement, the tunnel invert heave decreased from 16.3 cm to 5.66 cm, displacement amplitude during the operation period reduced by 72.5%, and acceleration peak decreased by 36%, effectively enhancing the dynamic stability of the tunnel foundation.

Currently, the intense vibrations induced when heavy-haul railways operate on bridge sections pose significant fatigue damage risks to OCS components. However, existing technical means struggle to achieve accurate detection of OCS dynamic loads, and no relevant research exists. To address this, this study proposes an online monitoring device installed on the mast, aiming to simultaneously satisfy the needs for OCS operational safety monitoring in engineering practice and the precise acquisition of load parameters at the research level.

2. Online Monitoring Scheme for Vibration Parameters

2.1 System Composition and Characteristics

Investigate the operational conditions and failure cases of Overhead Contact System (OCS) equipment in typical sections such as bridge sections and wind gap sections of heavy-haul railways, screen sections with deteriorated OCS service states, and conduct vibration and electrical parameter measurements of the OCS foundation, mast, and overhead catenary under complex operating conditions of the coupled system of heavy-haul trains/track/bridge/fully enclosed noise barrier. Compare wireless communication technologies such as Local Area Network (LAN), Wi-Fi, and 5G [5] to achieve collaborative acquisition and wireless real-time monitoring of multiple vibration parameters. Through time-frequency analysis of vibration parameters, propose response spectra of OCS foundation, mast, and overhead catenary under coupled system excitation, thereby realizing online monitoring of the actual service state of the OCS.

To effectively monitor and analyze the impact of heavy-haul trains on the OCS during operation, vibration measurement sensors and supporting acquisition equipment were deployed on masts, bridges, and contact wires at three target OCS sections identified through screening, to achieve collaborative acquisition of vibration parameters, as shown in Figure 1. The measurement accuracy of contact wire vibration displacement shall be no less than ±1 mm; the sampling frequency shall be ⩾200 Hz, used to monitor the dynamic uplift generated when the pantograph passes through registration points, with the acquired dynamic data of the contact wire used in conjunction with static data from the three-dimensional spatial coordinate database of the OCS.

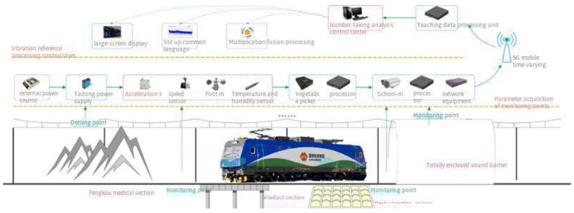

Figure 1. Schematic Diagram of Collaborative Acquisition of Multi-vibration Parameters.

Three typical target OCS sections were selected, with one set of mast and bridge vibration measurement devices and OCS service condition video monitoring equipment deployed at each section. For vibration measurement, tri-axial acceleration sensors are proposed, with measurement accuracy no less than ±1 g and sampling frequency no lower than 200 Hz, used to measure the acceleration variation of masts when trains pass through. The sensor and equipment layout is shown in Figure 2.

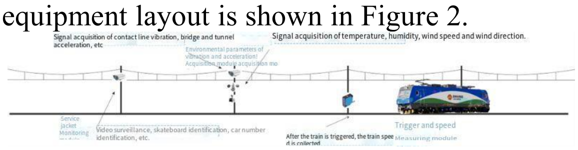

Figure 2. Schematic Diagram of Sensor and Measurement Monitoring Equipment Layout (1 Set).

During collaborative data acquisition, a multi-channel data acquisition [6] device is employed to synchronously collect multi-directional vibration signals and environmental parameters. With its high sampling rate, it precisely captures instantaneous vibrations and features local storage to ensure data security. All data undergo rigorous time synchronization processing to ensure accurate matching.

This system achieves time synchronization and data transmission among measurement points in different sections through wireless communication. For overhead catenary vibration measurement, a multifunctional measurement and control device integrating data preprocessing, video recording, power supply, and control is adopted to realize integrated functions of monitoring, control, and transmission.

Wireless transmission and data processing utilize 5G wireless communication technology to achieve collaborative acquisition of multi-point vibration parameters. Each sensor node packages vibration data through built-in 5G modules and transmits it to the central processing system via base stations, featuring high transmission rate, multi-node synchronization, and wide coverage capabilities, ensuring real-time and stable data upload in complex environments. The system employs algorithms such as Kalman filtering [7] to fuse acceleration, velocity, and environmental parameters, enhancing measurement accuracy; identifies vibration characteristics and mutation points through spectrum and time-domain analysis, and generates vibration response spectra.

Regarding data statistics and display, the data analysis software configured in this system possesses functions of data processing, display, analysis, early warning, and report output. It can automatically associate spatiotemporal information for data storage, generate quantitative results through analysis, and perform anomaly judgment. The system has self-diagnostic capabilities, enabling real-time monitoring of equipment status and reporting of major faults. All detection results are named according to elements such as line, location, train number, pantograph number, and detection date/time, and stored on computer hard drives. It supports flexible retrieval of data and images by mileage post, registration point, time, train number, and other conditions, while also supporting backup copying of historical data. The software operation interface is intuitive, allowing users to select any retrieval benchmark to view data curves and display video feature information corresponding to each point.

The design of the online monitoring system for heavy-haul railway OCS vibration fully considers the stringent requirements of railway field conditions. All monitoring equipment is integrally installed on masts, ensuring no infringement of structure gauge and compliance with electrical safety clearances. The system exhibits good electromagnetic compatibility and anti-electromagnetic interference capability, with its operation not affecting the normal operation of trains or other ground equipment. Field equipment is securely fastened, meeting IP65 protection rating. Key fasteners adopt anti-loosening design. Metal structure surfaces undergo galvanization and plastic spraying treatment for corrosion resistance, and satisfy mechanical strength requirements for tensile and shear resistance.

The system integrates multiple monitoring modules capable of real-time monitoring of OCS vibration parameters. Core monitoring contents include the uplift amount at OCS registration points, acceleration of mast and bridge/tunnel foundation vibrations, and synchronous recording of video images when pantographs pass through, train number, operating speed, as well as ambient temperature, humidity, wind speed, and wind direction. Monitoring data undergoes preliminary processing and synchronization association in the field analysis host before being transmitted to the ground data processing center via a data transmission module with 4G/5G wireless transmission capability. The data transmission process incorporates network security protection measures to ensure data security.

The system features high automation and reliability. Its train arrival identification module can automatically trigger system startup for data acquisition when trains enter the monitoring area, and enter low-power sleep mode when no trains are present, effectively saving energy and extending equipment service life. Field devices adopt industrial-grade design, capable of long-term stable operation with external power support. Their storage capacity can satisfy the requirement of storing all-weather monitoring data for no less than 30 days. Under normal maintenance conditions, the system design service life is no less than 240 months, with explicit maintenance response time commitments established for failures such as critical monitoring function loss, ensuring system maintainability and availability.

2.2 Detection Principle

The core components of this system include the OCS registration point uplift detection module, mast and bridge/tunnel foundation vibration acceleration detection module, pantograph high-definition video module, ambient temperature and humidity measurement module, wind speed and direction measurement module, train number identification module, train arrival identification module, field analysis host, and field multifunctional control box. It employs non-contact measurement methods, aiming to monitor OCS vibration in real time, and synchronously record pantograph passage video images, train number, passing speed, and weather conditions.

2.2.1 Train Arrival Identification Module

As shown in Figure 3, the train arrival identification module is installed beside the track and used for real-time detection of whether trains enter the monitoring area. When a train is detected entering, the module outputs a train arrival signal, triggering the monitoring system to start data acquisition and image capture operations. When no trains are passing, various system modules can automatically enter sleep mode, significantly reducing standby power consumption, effectively decreasing equipment operating duration, and contributing to extending the service life of the entire system. The module also features data statistics functions, capable of recording key information such as daily train passage quantity, passage time, and frequency.

Figure 3. Schematic Diagram of Train Arrival Identification Module.

2.2.2 Train Speed Detection Module

As shown in Figure 4, a Doppler radar speed detector is installed on the line mast for monitoring the speed of passing trains. Its core principle is based on the Doppler effect: the radar emits microwaves toward the vehicle and receives reflected waves. When relative radial motion exists between the target and the radar, the reflected wave frequency shifts relative to the transmitted wave frequency. This frequency shift is proportional to the target radial velocity, and the radar calculates the vehicle speed by detecting this frequency difference.

Main Technical Parameters:

Detection lane: Single lane

Speed detection accuracy: ±1 km/h

Speed detection range: 10-250 km/h

Communication interface: Standard RS-232

Operating environment: Operating temperature -30℃~+70℃, operating humidity 10%~90%.

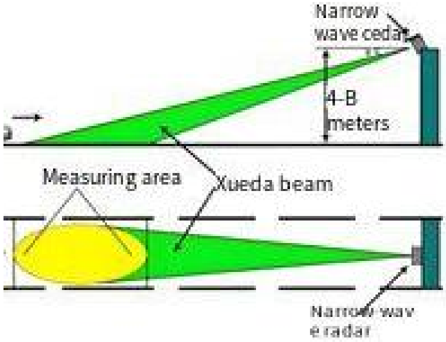

Figure 4. Train Speed Detection Principle.

2.2.3 OCS Uplift Detection Module

The OCS uplift detection module employs a high-definition industrial camera with infrared supplementary lighting equipment to acquire contact wire vibration images at a sampling rate of 200 Hz when the pantograph passes through. Through image recognition algorithms, the pixel coordinate variations of contact wire feature points are extracted. Combined with pre-calibrated camera parameters, the vertical vibration displacement of the contact wire in actual space is calculated. The results are shown in Figure 5.

Figure 5. Waveform Diagram of Registration Point Uplift Before and After Pantograph Passage.

2.2.4 Mast and Bridge/Tunnel Foundation Vibration Acceleration Detection Module

As shown in Figure 6, the vibration acceleration is acquired using a high-precision tri-axial acceleration sensor installed at the upper part of the selected mast, and is real-time acquired through the signal amplification and acquisition module, with synchronization storage together with other data.

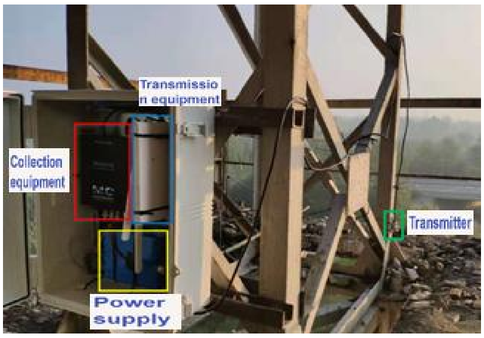

Figure 6. Vibration Acceleration Monitoring Module.

2.2.5 Pantograph High-Definition Video and Pantograph Anomaly Identification Module

The pantograph high-definition video monitoring module consists of a high-definition camera and infrared supplementary lighting equipment. The camera resolution is no less than 5 megapixels, capable of real-time acquisition and video recording of high-definition video of pantographs passing through the monitoring point at a sampling frequency of 25 Hz. During the recording process, the system can automatically overlay subtitle information of key parameters including monitoring time, OCS vibration uplift amount, mast acceleration, train speed, ambient temperature and humidity, and wind speed.

Meanwhile, this module integrates deep learning algorithms, enabling real-time analysis of acquired pantograph images and intelligent identification of abnormal states such as obvious damage, fracture, and attached foreign objects on the collector strips.

The high-definition video monitoring effect when trains pass through is shown in Figure 7.

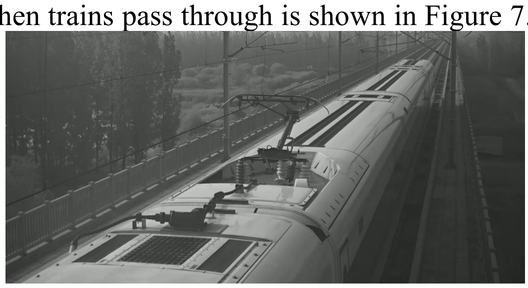

Figure 7. Schematic Diagram of High-definition Monitoring Effect When Train Passes Through.

The pantograph fault detection results by the system are shown in Figure 8.

2.2.6 Train Number Identification Module

The train number identification module consists of a high-speed camera and infrared supplementary lighting equipment, capable of real-time acquisition of train number images under dynamic train operating conditions, and

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automatic extraction of train number information and recording data based on intelligent image recognition algorithms. The images acquired by the train number identification module and the recognition effect are shown in Figure 9.

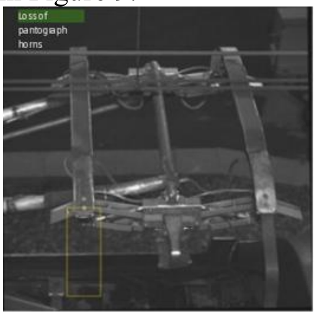


Figure 8. Schematic Diagram of Intelligent Identification Detection Effect for Collector Strip Chunking and Horn Missing.

Figure 9. STrain Number Identification Test Effect.

2.2.7 Wind Speed/Direction and Ambient Temperature/Humidity Acquisition Module

This system real-time acquires wind speed and direction data through a two-dimensional ultrasonic anemometer installed above the mast, while monitoring ambient temperature and humidity through high-precision temperature and humidity sensors. When trains pass through, the system continuously and synchronously acquires these parameters and transmits them together with other monitoring data to the ground data processing center for analysis. The wind speed measurement principle is shown in Figure 10.

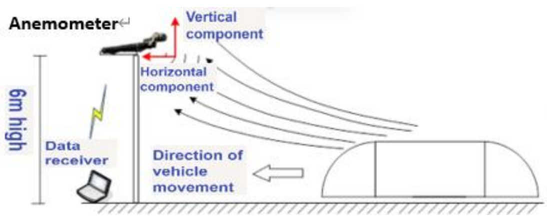


Figure 10. Schematic Diagram of Wind Speed Measurement.

2.2.8 Field Analysis Host and Field Multifunctional Control Box

The field multifunctional control box provides functions such as centralized power supply, acquisition module connection, remote and timed switch control for the monitoring system. It is designed with a high protection rating (no less than IP65), effectively resisting dust and low-pressure water jets; supports a wide temperature operating range of -40℃~+70℃, adapting to harsh environments; adopts hot-swappable hard disk storage design for convenient data transfer; all structural designs comply with IEC vibration and shock standards, possessing good anti-vibration and anti-impact performance; power supply and interfaces all meet industrial-grade lightning protection levels, providing reliable protection for equipment.

The field acquisition host is responsible for integrating various monitoring data and video images, performing synchronized storage and correlation analysis, and uploading data to the ground server according to network conditions.

The data transmission submodule utilizes 4G/5G wireless network to real-time or periodically transmit monitoring information such as vibration data, contact wire uplift amount, video, train number, pantograph images, and equipment status to the ground data center. This module employs data encryption transmission and network security protection measures (such as encryption protocols, firewall, intrusion detection/defense systems, etc.) to ensure data security and prevent cyber attacks.

Data transmission network topology is shown in Figure 11.

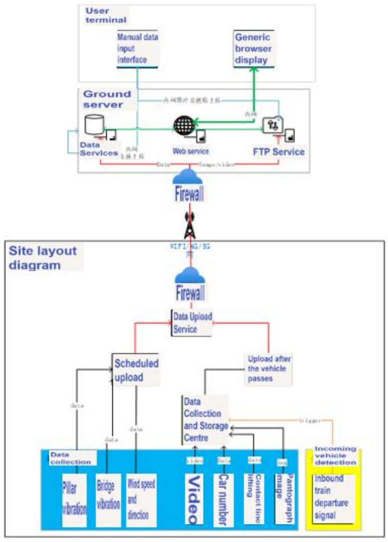


Figure 11. Data Transmission Network Topology.

3 Vibration Data Acquisition

3.1 Installation Site Selection for OCS Online

Performance Monitoring

To meet the site selection requirements for critical sections such as bridges, wind gaps, and high embankments, through field survey, full communication with OCS technical professionals, and combined with the Shenning section OCS layout plan, the following three locations were finally determined as installation points for the OCS online monitoring system:

(1) Shenning Qianluwan No. 1 Bridge downstream side, mileage post K9+089 – K9+358 section;

(2) Shenning Qianluwan No. 2 Bridge downstream side, mileage post K9+485 – K9+705 section;

(3) Shenning Wanghuzhuang No. 1 Bridge upstream side, mileage post K7+263 – K7+577 section.

All selected points are located in typical wind environment and high pier areas, with maximum wind force reaching Grade 10 in autumn and winter, abundant wind resources, and multiple wind turbine generators installed on surrounding mountains; minimum temperature in winter reaches -30℃, with some piers height up to 10 meters. The overall environment meets the bridge/tunnel vibration test conditions specified in the contract.

3.2 Hardware Deployment and Core Algorithm Development

The vibration monitoring system is deployed as follows:

(1) Vibration Monitoring System Design Finalization

Sensor deployment scheme completed: For three typical sections (bridge/wind gap/high embankment), the selection and location planning of sensors for mast vibration, contact wire uplift amount, and environmental parameters have been clarified, with all technical parameters meeting standards.

(2) Functional Division of Mast A/B/C

Mast A: Train arrival identification module;

Mast B: Integrated 7 types of modules including vibration/anemometer/train number identification;

Mast C: Pantograph high-definition monitoring.

(3) Standardization of Installation Engineering

Anti-loosening design: M16 bolts + anti-loosening nuts, tightened with torque wrenches;

Protection design: IP65 protection rating, hot-dip galvanized angle steel hoop;

Power supply scheme: Trackside distribution box (AC220V) cable.

Real-time Monitoring Algorithms are as follows:

(1) Multi-source Data Collaboration

Kalman filtering fuses vibration/environmental data, spectrum analysis generates response spectra;

Train number identification accuracy 95%, pantograph anomaly identification algorithm verified.

(2) Dynamic Compensation Mechanism

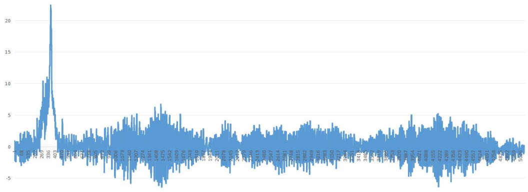
As shown in the equation (1), real-time correction of trolley vibration errors is achieved through IMU.

$$\Delta z = 21\iint (az, IMU - g)dt^2 \qquad (1)$$

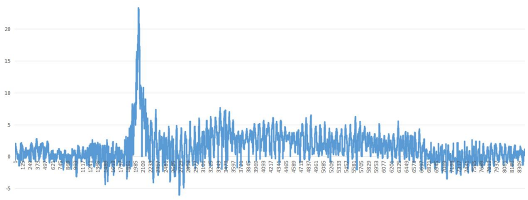
In the equation, az , IMU represents the raw acceleration reading along the z-axis, and g denotes the gravitational acceleration.

3.3 Field Acquisition of Contact Wire Dynamic Uplift

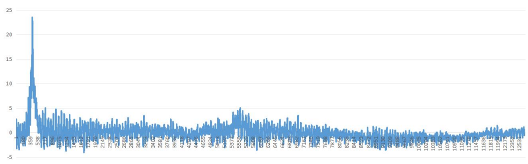
As shown in Figure 12, the contact wire vibration measurement curves for the downstream Qianluwan No. 2 Bridge and upstream Wanghuzhuanggou No. 1 Bridge from November 15 to November 16, 2025 are enumerated.



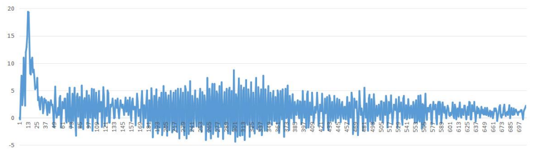
(a)Dynamic Uplift Curve of Contact Wire at Downstream Qianluwan No. 2 Bridge（2025-11-1515:44）



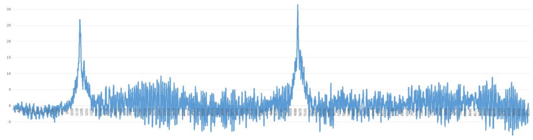
(b)Dynamic Uplift Curve of Contact Wire at Downstream Qianluwan No. 2 Bridge（2025-11-1610:25）



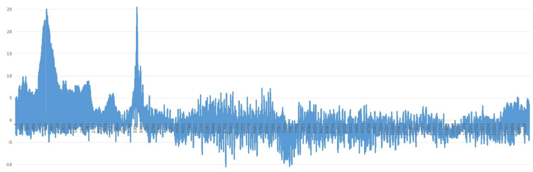
(c)Dynamic Uplift Curve of Contact Wire at Downstream Qianluwan No. 2 Bridge（2025-11-1615:11）



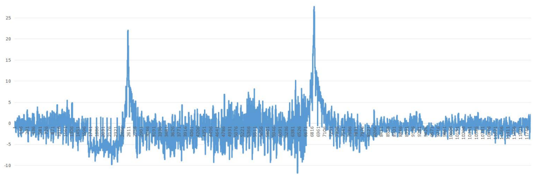
(d)Dynamic Uplift Curve of Contact Wire at Downstream Qianluwan No. 2 Bridge（2025-11-1620:21）



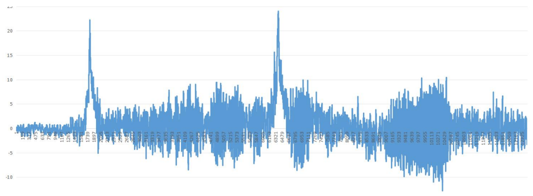
(e)Dynamic Uplift Curve of Contact Wire at Upstream Wanghuzhuanggou No. 1 Bridge（2025-11-1613:37）



(f)Dynamic Uplift Curve of Contact Wire at Upstream Wanghuzhuanggou No. 1 Bridge（2025-11-1613:59）



(g)Dynamic Uplift Curve of Contact Wire at Upstream Wanghuzhuanggou No. 1 Bridge（2025-11-1614:10）



(h)Dynamic Uplift Curve of Contact Wire at Upstream Wanghuzhuanggou No. 1 Bridge（2025-11-1614:21）

Figure 12. Vibration Measurement Curves of Contact Wire at Downstream Qianluwan No. 2 Bridge and Upstream Wanghuzhuanggou No. 1 Bridge.

Statistics show that: when no pantograph passes through, due to external factors such as wind speed at wind gaps, the contact wire uplift fluctuates within the ±5 mm range; when a pantograph passes through, the average peak value of contact wire uplift is in the range of (20 mm, 25 mm).

4. Conclusions

This paper addresses the core issue that heavy-haul railways, due to their characteristics of large transport capacity and high axle loads, are prone to inducing intense vibrations in the Overhead Contact System (OCS) when traversing special sections such as bridges, thereby causing cumulative fatigue damage to components. A comprehensive online monitoring system for OCS vibration, integrating data acquisition, transmission, analysis, and early warning, has been successfully designed, developed, and deployed. Through engineering implementation of the system scheme, field data acquisition and analysis, and application verification of core algorithms, this study draws the following main conclusions:

(1) This research has successfully integrated multiple monitoring modules onto OCS masts, forming a complete solution. The system design fully considers the stringent requirements of railway field conditions. All equipment installations ensure no infringement of structure gauge and compliance with electrical safety clearances. Its anti-electromagnetic interference capability, IP65 protection rating, anti-loosening and anti-corrosion design, and wide-temperature operating characteristics demonstrate the feasibility of this scheme for long-term stable operation in harsh environments. The system deployment, including train arrival identification on Mast A, integration of seven types of modules such as vibration/anemometer/train number identification on Mast B, and pantograph high-definition monitoring on Mast C, achieves fully automated data acquisition from "sleep mode without trains" to "triggered by train arrival," significantly reducing energy consumption and operation and maintenance costs. This solid hardware foundation provides unprecedented platform support for real-time, continuous perception of OCS service states.

(2) The core breakthrough of this system lies in transcending the limitations of single-parameter monitoring and constructing a multi-dimensional information synchronized acquisition and fusion analysis framework. Through collaborative operation of modules including train arrival identification, Doppler radar speed measurement, contact wire image recognition ranging, tri-axial acceleration sensing, pantograph video monitoring, and environmental parameter acquisition, the system can synchronously record panoramic

data for each train passage event. On this basis, the Kalman filtering algorithm is employed to fuse vibration, speed, and environmental parameters, effectively improving measurement accuracy; through spectrum and time-domain analysis, vibration characteristics and mutation points are successfully identified, and vibration response spectra of the OCS are generated. This multi-source data correlation analysis can effectively separate train operation loads from environmental background loads, providing high-quality, high-value data sources for precise load identification and vibration pattern analysis.

(3) Field acquisition data from typical wind environment and high pier sections such as Shenning section Qianluwan Bridge and Wanghuzhuanggou Bridge hold significant value. Statistical analysis indicates that: when no pantograph passes through, affected by environmental factors such as strong wind at wind gaps, the contact wire uplift fluctuates within the ± 5 mm range, revealing the existence of environmental factors as continuous background loads; when a pantograph passes through, the peak value of contact wire dynamic uplift averages in the range of 20 mm to 25 mm. This quantitative load spectrum is the most critical input condition for assessing cumulative fatigue damage of OCS components and predicting their service life, holding direct guiding significance for formulating scientific predictive maintenance strategies.

(4) The pantograph high-definition video module integrated in this system, combined with deep learning algorithms, enables real-time analysis of acquired pantograph images and intelligent identification of abnormal states such as obvious damage, fracture, and attached foreign objects on collector strips, with high accuracy. The train number identification module can automatically extract and associate train information, laying the foundation for refined management and traceability analysis of "one pantograph, one file." All these data are synchronously stored and associated in a structured manner according to elements such as line, location, train number, and time, supporting flexible retrieval by multiple conditions and making data-based decision-making possible. This marks the transformation of OCS operation and maintenance from traditional "scheduled maintenance" or "post-failure repair" to real-time condition-based "predictive maintenance," greatly enhancing the safety and reliability of heavy-haul railway power supply systems.

Acknowledgments

This work was supported by the 2024 Key Technology Development Project for Service Safety Assurance of Heavy-Haul Railway Overhead Contact System Based on Digital Model of Guoneng Shuohuang Railway Development Co.,LTD. (Grant No. Shuo Service [2024] No. 247). (Corresponding author: Yicheng Xiang.)

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