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Research on abrasive belt wear monitoring for the rail grinding

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Abstract: *A comprehensive analysis of an abrasive belt wear monitoring scheme for rail grinding was conducted, focusing on the generation mechanisms of sound and current signals during the sanding process. Initially, we establish a theoretical model linking the sound of belt grinding with its corresponding current generation mechanism. This model also integrates the patterns of abrasive belt wear, laying the groundwork for subsequent signal feature extraction and state recognition. Our approach not only guides the extraction and recognition processes but also ensures the general applicability of our findings, making them more relevant for real-world rail grinding scenarios. The study then delves into an empirical investigation of the characteristics of actual sound and current signals obtained during rail belt grinding. By analyzing these signals across time, frequency, and time-frequency domains, we extract multidimensional signal features. These extracted features serve as crucial inputs for identifying the wear state of the abrasive belt in subsequent chapters. Our methodical approach provides a robust framework for understanding and monitoring the condition of abrasive belts in rail grinding applications, with potential implications for improving efficiency and quality in industrial practices.*

Keywords: *Wear analysis, Abrasive belt condition monitoring, Rail grinding*

1. Introduction

Abrasive belt grinding for rail maintenance offers numerous advantages, but it's undeniable that it also poses some challenges, with the most significant being the short lifespan issue caused by the abrasive belt's single-layer grain structure [1]. The lifespan of an abrasive belt is related to its performance and effective grinding area. To extend its service life, it's essential to select belts with stable grinding performance and high durability that meet grinding requirements, and to optimize the grinding process to enhance the wear ratio. Additionally, designing special belt grinding mechanisms to increase the effective grinding area of the belt is necessary [2]. However, the former is limited by abrasive belt manufacturing technology, and the latter by the spatial constraints of grinding equipment, both having certain limitations. Therefore, it's crucial to accurately determine the service life of abrasive belts based on the above measures, to avoid prematurely replacing belts that still have grinding capacity, and to prevent the use of expired belts that could damage the rails [3].

The material removal layer for defective rails is generally uneven, leading to differences in the process parameters of abrasive belts for different grinding units on the grinding vehicle [4]. Rail grinding takes into account various factors such as the type of grinding, characteristics of track defects, and the available "window" time for grinding operations, resulting in varying process parameters for different tracks. Due to the single-layer grain structure of abrasive belts, their grinding performance varies significantly at different stages of wear. The same belt will employ different process parameters at various stages of its service life. Consequently, the service life of each abrasive belt varies due to different process parameters [5]. The subject of rail grinding is the rail itself, and the primary defects and distribution characteristics of different tracks vary.

Longitudinal wave grinding of rails results in different cross-sectional profiles at various locations along the track, as shown in Figure 1. The grinding depth varies significantly at different cross-sections even with the same grinding angle, with differences reaching up to 0.5mm. This results in varying depths and widths of the grinding area, not only across different tracks but also varying over time on the same track. Compared to conventional machine tools, the reference for the grinding vehicle is not fixed, as it experiences longitudinal vibrations, lateral swaying, and "snaking" movements while in motion. These unique conditions affect the wear of the abrasive belts and consequently their service life [6].

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Based on the analysis above, the service life of each abrasive belt varies depending on the service conditions [7]. If a lenient strategy is used to set the service life threshold for abrasive belts, some that have reached their lifespan might continue to be used. This can lead to irreparable grinding defects, necessitating rail replacement, which is costly in terms of labor and resources and affects normal track operations. To ensure the safety of rail grinding operations, a conservative strategy could be adopted to set the service life threshold for abrasive belts. However, this could waste the limited grinding capability of the belts, increase the frequency of stops for belt replacements, raise grinding costs, and reduce operational efficiency. Therefore, accurately determining the service life of abrasive belts is both crucial and challenging [8].

In rail wheel grinding, the lifespan of grinding wheels can be determined by setting a minimum thickness for use. However, this method cannot be applied to abrasive belt grinding. Especially in rail abrasive belt grinding, where multiple grinding units operate simultaneously under the vehicle, it is virtually impossible for operators on the vehicle to monitor the wear condition of each belt while operating the equipment [9]. The high reliability requirements of rail grinding operations also do not allow for such an approach [10]. Therefore, it is essential to monitor the wear condition of abrasive belts online and predict their remaining lifespan, which is a very important issue to be addressed in abrasive belt grinding for rail maintenance.

To this end, this paper conducts research on the monitoring and remaining lifespan prediction of abrasive belt wear in rail grinding. Considering the patterns of abrasive belt wear and the demands of rail grinding operations, we propose reasonable methods for evaluating the degree of abrasive belt wear and determining their lifespan. By comparing various monitoring methods, grinding sound and current are selected as monitoring signals, and their monitoring mechanisms are analyzed in depth [11]. Based on the changes in monitoring signals with abrasive belt wear, methods for signal feature extraction and abrasive belt wear state identification are studied [12]. According to the wear patterns of abrasive belts under different process parameters, methods for predicting the remaining lifespan of abrasive belts are researched. The findings of this paper will enhance the intelligence level of rail grinding equipment and play an important role in the following aspects.

2. Abrasive Belt Grinding Sound Generation Mechanism

In this section, we combine insights from existing literature with sound signals captured from rail abrasive belt grinding sites to provide a detailed analysis of the origins and characteristics of sound signals generated during rail grinding.

2.1. Experiment for Abrasive Belt Grinding Sound Signal Acquisition

The rail grinding vehicle used in the experiment is depicted in Figure 1. The abrasive belt grinding unit, mounted at the bottom of the carriage, primarily consists of a contact wheel, drive wheel, and tension wheel. A transducer is installed near the abrasive belt grinding area, directly facing the grinding zone. The abrasive belt used has a grain size of 36#, and the belt speed is set at 23 m/s. The operation speed is maintained at 1 km/h, with a tension force of 500 N and a grinding pressure of 600 N. This configuration facilitates the accurate capture of sound signals during the grinding process.

Figure 1: The rail abrasive belt grinding equipment.

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2.2. Sound Generation Mechanism in Abrasive Belt Grinding

The sounds associated with rail abrasive belt grinding can be classified into three primary categories: environmental noise, noise from the operation of the grinding vehicle, and the actual grinding sound. Environmental noise refers to ambient sounds in the vicinity of the railway tracks. In urban track sections, environmental noise predominantly includes sounds like highway traffic and other urban living noises. In contrast, environmental noise in rural track sections mainly consists of noises from railway infrastructure and sounds produced by wildlife adjacent to the tracks. Compared to the other two types of noise, environmental noise sources are typically located further away from the transducer. Consequently, the sound pressure undergoes divergence and attenuation during its transmission, leading to an inverse relationship between sound pressure levels and the distance of propagation. Furthermore, high-frequency components within environmental noise experience significant absorption and attenuation during transmission. Additionally, rail grinding operations are often conducted at night when environmental noises are relatively subdued. Therefore, the proportion of environmental noise, especially its high-frequency components, is considerably lower in the overall sound signal captured during rail grinding activities.

The noise generated by the grinding vehicle can be divided into stationary noise and operational noise. During operation, the internal combustion engines in power equipment generate impact noise, rotational noise, and friction noise. Motors produce electromagnetic noise, rotational noise, and friction noise. In transmission equipment, gears and pulleys produce impact and friction noise during meshing, and rotational noise during operation. Bearings generate rolling noise and friction noise. Additionally, the wheel system of the grinding unit emits rotational noise during its operation. Among these noises, those caused by rotation and meshing are periodic, leading to peaks in the frequency spectrum corresponding to the rotational frequency. Noise caused by friction has a broader frequency band and is not periodic.

Operational noise primarily includes wheel-rail noise, bridge noise, and aerodynamic noise. Research both domestically and internationally indicates that when train speeds are below 200 km/h, wheel-rail noise accounts for more than 60% of the total noise energy, while aerodynamic noise constitutes less than 6%. Wheel-rail noise mainly comprises impact sounds, rolling noise, and squealing. Impact sounds arise from rail defects like uneven weld joints and significant flaking, causing instantaneous changes in the vertical speed of the train; rolling noise is due to the tangential forced vibrations caused by the unevenness of the wheel treads; and squealing originates from friction between the wheel and rail when the train traverses curves or brakes. The intensity of these noises is closely related to the speed of the train. Compared to regular trains, the speed of a rail grinding vehicle is relatively low, hence this part of the noise is less significant.

Grinding sound refers to the noise produced by vibrations in the abrasive belt, rail, and their connected components, caused by fluctuations in the grinding force during the abrasive belt grinding of the rail. Notably, when grooves are present on the contact wheel, the contact stiffness changes significantly during rotation, leading to vibrations. In the grinding process, the abrasiveness of the grains is random; as grains enter and exit the contact area, the contact stiffness changes, resulting in vibrations. Different grinding behaviors occur throughout the entire process of grain engagement and disengagement: friction, plowing, and cutting. The friction process generates noise due to frictional vibration, while the sound emissions from the plowing and cutting processes cause vibrations on the rail surface, leading to noise. The wear of the abrasive belt affects both the time-varying characteristics of contact stiffness and the grinding behavior of the grains, thereby altering the grinding sound.

3. Abrasive Belt Grinding Sound Signal Analysis

3.1. Sound Signal Analysis in the Time Domain

The time-domain waveform of the sound signal from the rail grinding test is shown in Figure 2. The grinding vehicle starts grinding 40 seconds after commencing movement, finishes grinding after 105 seconds, and then idles for 110 seconds before stopping. As can be seen in Figure 2 a), there is a clear difference in the amplitude of sound across different states of the grinding vehicle, with the lowest amplitude occurring during stationary phases. At this time, the sound mainly consists of the operational noise of various mechanical components, and Figure 2 b) shows that low-frequency periodic components predominate in the sound.

When the grinding vehicle is in motion, the sound pressure amplitude is slightly higher than when stationary, primarily due to the addition of wheel-rail noise. Since the grinding speed is low, the increase in amplitude is modest. Figure 2 c) indicates a significant increase in high-frequency components, which is attributed to the wheel-rail noise caused by rolling contact and friction that tend to have higher frequencies. During the grinding process, the sound pressure amplitude increases significantly compared to non-grinding periods. Figure 2 d) reveals a notable increase in high-frequency components. This part of the sound is closely related to abrasive belt wear, and the following section will focus on discussing its generation causes and characteristics.

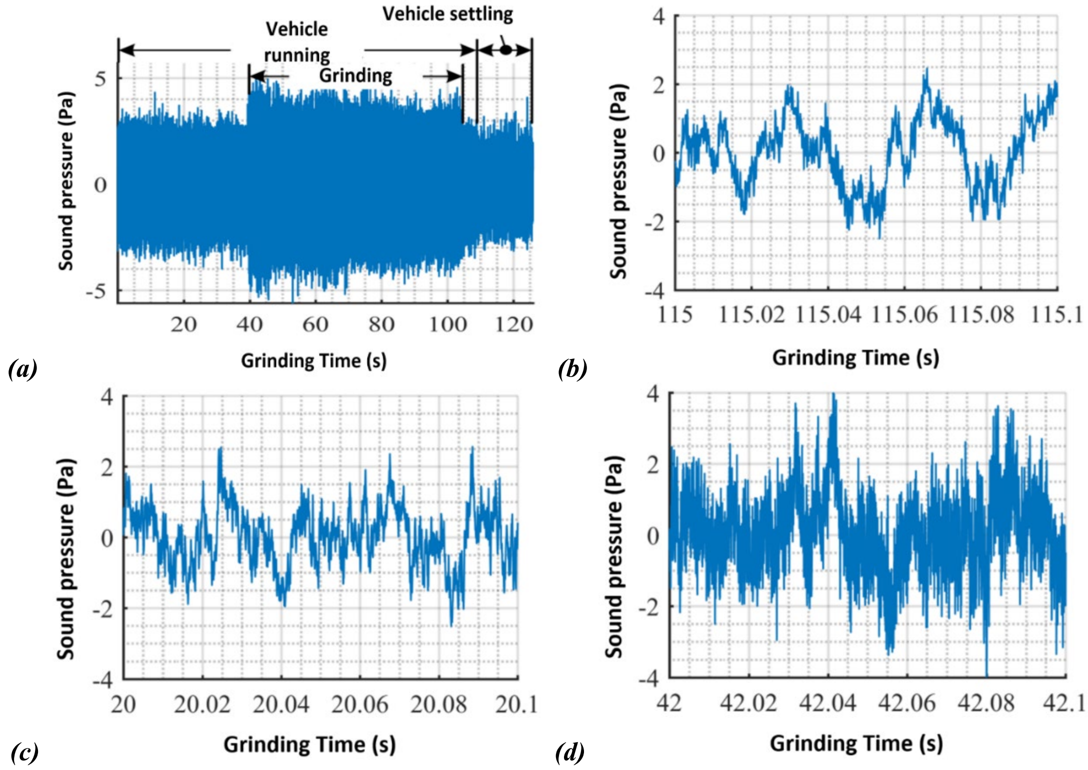

Figure 2: The sound signal of rail grinding experiment (a) a complete grinding cycle (b) Vehicle setting (c) Vehicle running (d) Vehicle grinding.

3.2. Sound Signal Analysis in the Time-frequency Domain

The plowing action of the abrasive grains causes plastic deformation within the rail material, while the cutting action of the grains leads to shear fractures. During this process, the release of internal strain energy in the material generates stress waves. When these stress waves propagate to the surface of the rail, they induce mechanical vibrations in the rail surface, which then radiate outwards as sound waves.

The time-frequency spectrum of the sound signal from the rail grinding test is shown in Figure 3. Compared to the time-domain waveform in Figure 2, the time-frequency spectrum more clearly reflects the frequency domain distribution of various components of the grinding sound signal. Based on the a forementioned analysis, it is known that sounds produced by grain engagement and disengagement, friction, plowing, and cutting, which are closely related to abrasive belt wear, are primarily concentrated in the high-frequency range. As shown in Figure 3, the high-frequency components ranging from 6 kHz to 20 kHz in the grinding sound signal are distinctly different from the operational noise of the grinding vehicle. Therefore, filtering can effectively minimize the influence of environmental noise and the operational noise of the grinding vehicle, significantly improving the signal-to-noise ratio of the grinding sound signal for identifying the degree of abrasive belt wear. As for the mutual influence between abrasive belt grinding units, solutions need to be developed based on the specific structure of the grinding vehicle, utilizing the attenuation characteristics of sound waves and employing unidirectional or highly directional transducers.

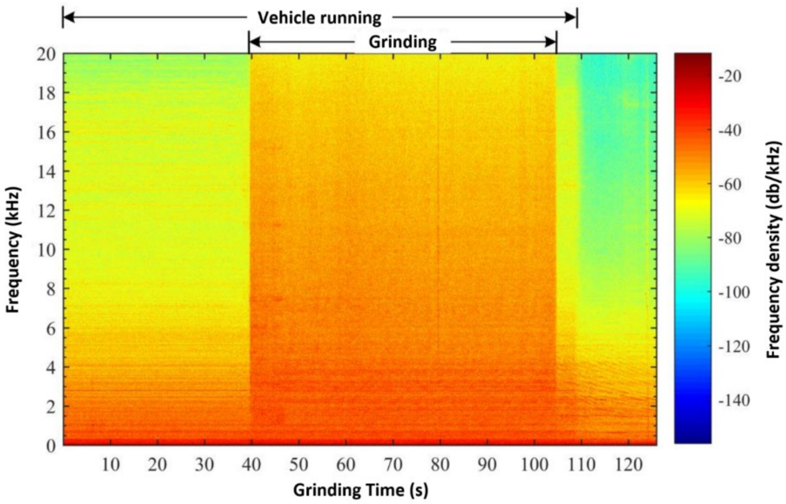

Figure 3: The spectrogram of sound signal of rail grinding experiment.

4. Modeling of Vibration and Sound Radiation in Rail Abrasive Belt Grinding

The previous section analyzed the sources of excitation forces and vibrations during the grinding process. This section will analyze and model the vibration and sound radiation processes in the grinding area. The excitation forces generated during the grinding process act simultaneously on the rail, abrasive belt, and contact wheel. The contact wheel is made of rubber, which has excellent elastic properties and low stiffness, making it an elastic damping material. As a result, compared to the rail, the vibrations produced by the abrasive belt and contact wheel under the action of excitation forces are smaller, especially the attenuation of high-frequency components is more significant, making it difficult for these vibrations to be transmitted to other structural components through the rubber layer of the contact wheel. The acoustic emission signals lose a significant amount at the contact interface, and generally, a coupling agent needs to be filled at the interface. The proportion of acoustic emissions from the rail material transmitted to the abrasive belt and contact wheel is very small. Additionally, the loss factor of rubber is tens of thousands of times greater than that of steel, hence, the vibrations of the abrasive belt and contact wheel caused by the acoustic emissions from the rail material are negligible. Therefore, the following analysis will primarily focus on the vibrations and sound radiation of the rail.

5. Conclusion

To accurately and real-time monitor the wear state of the abrasive belt during the rail grinding process, this chapter analyzes the generation mechanisms of grinding sound and current signals and extracts signal characteristics that reflect abrasive belt wear.

The sound of rail abrasive belt grinding can be categorized into environmental noise, noise from the operation of the grinding vehicle, and grinding noise. The sounds produced by grain engagement and disengagement, friction, plowing, and cutting, closely related to abrasive belt wear, are primarily concentrated in the high-frequency range above 6 kHz, distinctly different from interference noise.

A multidimensional analysis of the grinding sound signals in the time domain, frequency domain, and time-frequency domain was conducted, along with their variation patterns concerning abrasive belt wear and process parameters. The sound signals show a clear trend of decreasing as the abrasive belt wears down during the degradation phase.

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