DETERMINATION OF THE TECHNICAL CONDITION OF LOCOMOTIVE BEARING ASSEMBLIES USING VIBRATION DIAGNOSTIC METHODS

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Abstract: *This paper investigates the determination of the technical condition of locomotive bearing assemblies using vibration diagnostic methods. The major types of bearing faults, methods for identifying their characteristic vibration signatures, and modern diagnostic technologies are comprehensively analyzed. Particular attention is given to the analysis of vibration signals in both the time and frequency domains, highlighting the diagnostic capabilities of advanced signal-processing techniques such as the Fast Fourier Transform (FFT), Envelope Analysis, and the Wavelet Transform. Furthermore, the paper discusses the improvement of maintenance strategies based on the concepts of Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM), as well as the advantages of artificial intelligence-based diagnostic systems for automated fault detection and condition assessment. The research findings demonstrate that vibration diagnostics is an effective tool for the early detection of defects in locomotive bearing assemblies, enhancing operational reliability, reducing maintenance costs, and improving the overall efficiency of railway rolling stock maintenance.*

Keywords: *locomotive, bearing assembly, vibration diagnostics, vibration analysis, Fast Fourier Transform (FFT), Envelope Analysis, Wavelet Transform,* *Condition-Based Maintenance (CBM), Predictive Maintenance (PdM), technical condition diagnostics, artificial intelligence.*

Introduction

The reliable and uninterrupted operation of railway locomotives largely depends on the technical condition of their critical mechanical components. In particular, the bearing assemblies used in traction electric motors, gearboxes, and wheelsets operate under severe dynamic loads, high rotational speeds, continuous vibration, and varying climatic conditions. Consequently, continuous monitoring of the technical condition of locomotive bearings has become one of the key factors in ensuring operational safety, improving system reliability, and reducing the risk of unexpected failures. [2,3] Under the traditional scheduled preventive maintenance system, locomotive components are repaired or replaced after a predetermined service interval regardless of their actual technical condition. However, this maintenance strategy is not always economically efficient, as components with sufficient remaining service life may be removed prematurely, while hidden defects in other components may remain undetected until failure occurs. To overcome these limitations, modern railway maintenance practices increasingly adopt the concepts of Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM), which enable maintenance activities to be planned according to the actual health condition of equipment rather than fixed maintenance schedules. [4] Among the available condition monitoring techniques, vibration diagnostics has proven to be one of the most effective methods for assessing the technical condition of bearing assemblies. Vibration signals are generated directly by the mechanical processes occurring within bearings and contain valuable diagnostic information regarding the initiation and progression of defects. Changes in vibration characteristics often appear at an early stage of fault development, allowing defects to be detected well before catastrophic failure occurs. Therefore, vibration-based condition monitoring has become an essential component of modern locomotive maintenance systems, contributing to improved operational reliability, enhanced traffic safety, reduced maintenance costs, and increased availability of railway rolling stock. Bearing assemblies are among the most heavily loaded components of a locomotive. Their failure can lead to overheating of the traction electric motor, increased vibration levels, higher energy consumption, accelerated wear of adjacent components, and, in severe cases, operational failures or safety-critical accidents. Therefore, the reliable operation of bearing assemblies is essential for ensuring the safe and efficient performance of railway rolling stock. [2,3]

During both the manufacturing and operational stages of rolling-element bearings, several common defects may occur, including:

- damage to the inner raceway;
- wear or spalling of the outer raceway;
- defects in rolling elements (balls or rollers);
- cage (separator) deformation or failure;
- lubrication system deficiencies;
- corrosion;
- electrical erosion;
- fatigue-induced microcracks in the bearing material;
- rotor imbalance;
- shaft misalignment; and
- shaft bending.

Most of these defects originate at the microscopic level and cannot be detected through conventional visual inspection. However, as the defects develop, they generate characteristic impulsive vibration signals during bearing operation. These vibration signatures contain valuable information about the type, location, and severity of the defect, making vibration diagnostics one of the most effective non-destructive techniques for the early detection of bearing faults. Early identification of such defects enables timely maintenance interventions, preventing secondary damage and improving the reliability and service life of locomotive equipment. [2]

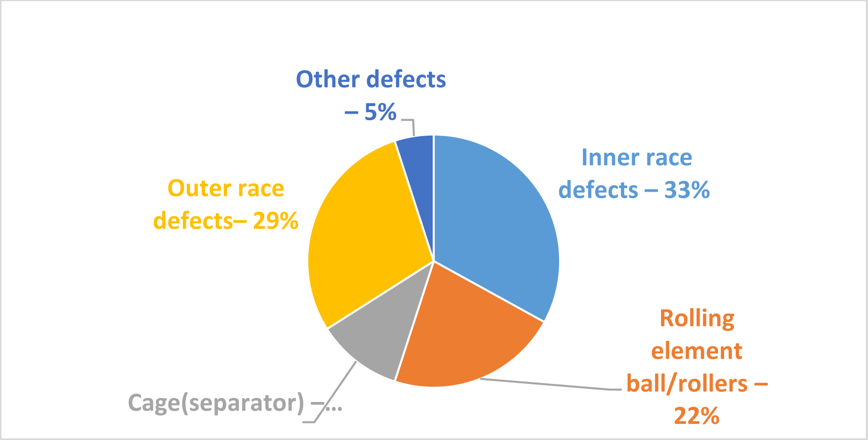

Figure 1. Percentage Distribution of Detected Defects by Bearing Component

Vibration Diagnostic Methods for Bearing Assemblies

Several vibration-based diagnostic techniques are widely employed to assess the technical condition of locomotive bearing assemblies. Each method provides specific diagnostic information depending on the nature and severity of the defect. [3,4]

One of the simplest approaches is **Time Domain Analysis**, in which the vibration signal is evaluated using statistical indicators such as the **Root Mean Square (RMS)**, **Peak Value**, **Crest Factor**, and **Kurtosis**. These parameters are effective for assessing the overall health condition of a bearing and detecting abnormal operating behavior. However, although time-domain analysis is sensitive to the presence of faults, it generally cannot accurately determine the exact location or type of the defect. [3]

One of the most widely used techniques is the **Fast Fourier Transform (FFT)**, which converts vibration signals from the time domain into the frequency domain to produce a vibration spectrum. Frequency-domain analysis enables the identification of characteristic frequencies associated with different mechanical faults, making

FFT an essential tool in bearing diagnostics. Using this method, the following defects can be effectively detected: [3,4]

- rotor imbalance;
- shaft misalignment;
- shaft bending;
- mechanical resonance.

The FFT method is particularly effective for diagnosing periodic vibration components and has become a standard technique in modern locomotive condition monitoring systems. However, because bearing defects often generate non-stationary and impulsive vibration signals, FFT is frequently combined with advanced signal-processing techniques, such as **Envelope Analysis** and the **Wavelet Transform**, to improve diagnostic accuracy during the early stages of fault development.

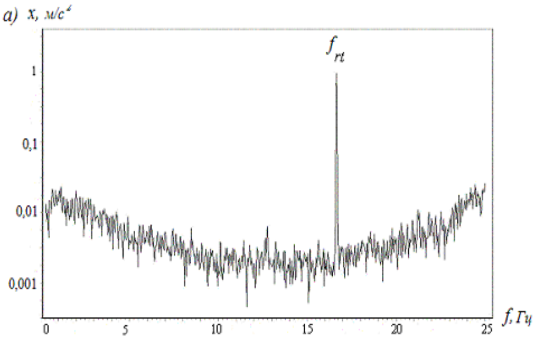

Figure 2. Frequency Spectrum of the Vibration Signal Obtained Using the Fast Fourier Transform (FFT)

As illustrated in **Figure 2**, the FFT spectrum represents the vibration signal in the frequency domain, allowing characteristic frequency components associated with mechanical faults to be identified. Peaks appearing at specific frequencies indicate abnormalities such as rotor imbalance, shaft misalignment, shaft bending, or resonance. Although FFT analysis is highly effective for detecting periodic vibration components, its diagnostic capability is limited when identifying weak impulsive signals generated during the early stages of bearing defect development.

Currently, **Envelope Analysis** (Envelope Spectrum Analysis) is regarded as one of the most effective techniques for rolling-element bearing diagnostics. This method employs the **Hilbert Transform** to extract high-frequency impulsive components from the vibration signal, making it possible to identify characteristic defect frequencies with high accuracy. Envelope Analysis enables reliable detection of faults in the:

- **Inner race** (Ball Pass Frequency Inner Race – **BPFI**);
- **Outer race** (Ball Pass Frequency Outer Race – **BPFO**);
- **Rolling element** (Ball Spin Frequency – **BSF**);
- **Bearing cage** (Fundamental Train Frequency – **FTF**). [3]

Compared with conventional FFT analysis, Envelope Analysis is considerably more sensitive to incipient bearing defects because it isolates periodic impact signals generated by localized surface damage. Consequently, it has become a standard diagnostic technique in modern railway condition monitoring systems.

In addition to FFT and Envelope Analysis, several advanced signal-processing methods are widely employed in modern bearing diagnostic systems, including:

- **Wavelet Transform (WT);**
- **Spectral Kurtosis (SK);**
- **Empirical Mode Decomposition (EMD);**
- **Variational Mode Decomposition (VMD);**
- **Acoustic Emission (AE);**
- **Time–Frequency Analysis (TFA).**

These advanced techniques significantly improve the separation of useful diagnostic information from background noise and enhance the detection of incipient defects under non-stationary operating conditions. Their application increases diagnostic sensitivity and reliability, making them particularly suitable for predictive maintenance of locomotive bearing assemblies.

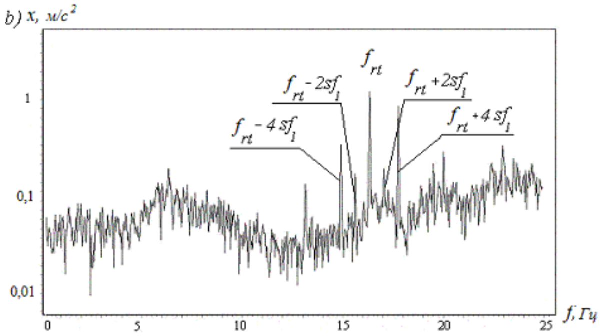

Figure 3. Flowchart of the Envelope Analysis Algorithm for Bearing Fault Diagnosis

Modern Diagnostic Technologies Used in Railway Systems

At present, leading railway manufacturers, including **Siemens Mobility**, **Alstom**, **CRRC**, and **Hitachi Rail**, employ integrated online condition monitoring systems for continuous assessment of locomotive health. These systems combine multiple sensing technologies with intelligent data processing to detect equipment degradation at an early stage and optimize maintenance scheduling.

A typical online monitoring system consists of the following components:

- vibration sensors;
- temperature sensors;
- rotational speed sensors;
- current and voltage sensors;
- acoustic emission (AE) sensors.

The acquired data are transmitted to an onboard computer or a cloud-based monitoring platform, where they are processed using advanced artificial intelligence algorithms. Based on the analyzed operating parameters, the system estimates the **Remaining Useful Life (RUL)** of bearing assemblies and recommends maintenance actions before a failure occurs. This predictive approach significantly improves maintenance efficiency, reduces unexpected downtime, and enhances operational safety.

In recent years, the application of **Machine Learning (ML)** and **Deep Learning (DL)** techniques has substantially improved the accuracy of bearing fault diagnosis. Among the most widely used algorithms are:

- **Convolutional Neural Networks (CNN);**
- **Support Vector Machines (SVM);**
- **Random Forest (RF);**
- **Long Short-Term Memory (LSTM)** neural networks.

These algorithms automatically extract diagnostic features from vibration signals, classify fault types with high accuracy, and predict defect progression under varying operating conditions. Their integration into modern railway monitoring systems represents a significant advancement toward intelligent predictive maintenance.

Conclusion

The assessment of the technical condition of locomotive bearing assemblies using vibration diagnostic methods enables the early detection of defects, supports maintenance planning based on the actual health condition of equipment, and reduces the likelihood of unexpected failures. Advanced signal-processing techniques, including the **Fast Fourier Transform (FFT)**, **Envelope Analysis**, and the **Wavelet Transform**, provide reliable identification of characteristic bearing defects under various operating conditions. Furthermore, the integration of artificial intelligence-based diagnostic algorithms significantly enhances fault detection accuracy, enables prediction of the remaining useful life of bearing assemblies, and supports intelligent maintenance decision-making. Consequently, the combined application of vibration diagnostics and artificial intelligence improves the operational reliability and safety of locomotives, reduces maintenance costs, extends the service life of bearing assemblies, and increases the overall efficiency of railway maintenance systems.

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