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VIBRATION-BASED INTELLIGENT DIAGNOSTICS OF METAL CUTTING MACHINE TOOLS USING FFT AND CNN ALGORITHMS

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Abstract

Modern manufacturing systems require highly reliable and accurate metal cutting machine tools to ensure stable machining quality and production efficiency. One of the major problems in industrial practice is the early detection of defects in spindle units, bearings, and gear transmission systems. This paper presents an intelligent vibration-based diagnostic methodology for evaluating the technical condition of machine tools using Fast Fourier Transform (FFT) and Convolutional Neural Network (CNN) algorithms. Experimental investigations were conducted on an HT-250M lathe machine under various operating conditions. Vibration signals were processed using FFT spectral analysis to identify characteristic defect frequencies. A CNN model was developed for automatic classification of machine conditions based on vibration spectra. The obtained results demonstrated that the proposed methodology allows accurate identification of bearing and gearbox defects at early stages, improves machine reliability, and reduces maintenance costs. The developed system can be effectively applied in predictive maintenance and Industry 4.0 manufacturing environments.

Keywords: machine tools, vibrodiagnostics, FFT, convolutional neural network, predictive maintenance, spindle dynamics, vibration analysis.

Introduction

Metal cutting machine tools are widely used in modern manufacturing industries and play a critical role in determining machining accuracy, surface quality, and production productivity. During long-term operation, machine components such as spindle units, bearings, and gear transmission systems are subjected to dynamic loads and wear processes, leading to increased vibration levels and deterioration of operational stability.

Traditional maintenance methods based on periodic inspection often fail to detect defects at early stages. Therefore, vibration diagnostics has become one of the most effective non-destructive techniques for monitoring machine tool condition. Vibrodiagnostic methods enable fault identification without stopping the machine and significantly reduce maintenance costs and downtime.

In recent years, artificial intelligence and deep learning technologies have been increasingly applied in technical diagnostics. Convolutional Neural Networks (CNN) have demonstrated high efficiency in automated defect recognition and vibration signal classification. Combined with FFT spectral analysis, CNN-based diagnostic systems provide reliable and intelligent monitoring of machine conditions.

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The objective of this research is to develop an intelligent vibration-based diagnostic system for assessing the technical condition of metal cutting machine tools using FFT and CNN algorithms.

The scientific novelty of the study includes:

- development of informative vibration frequency ranges for defect detection;
- integration of FFT spectral analysis with CNN classification;
- determination of relationships between vibration parameters and machine technical condition;
- improvement of predictive maintenance efficiency.

Materials and Methods

1 Experimental Setup

Experimental investigations were carried out on an HT-250M metal cutting lathe operating under industrial workshop conditions. The spindle unit, gearbox assembly, and rolling bearings were selected as the main objects of investigation.

The experimental setup included:

- piezoelectric accelerometers;
- digital vibration acquisition system;
- FFT signal processing software;
- industrial computer workstation.

Sensors were mounted near spindle bearings and gearbox housing surfaces to capture vibration signals under different spindle rotational speeds and loading conditions.

2 FFT-Based Signal Processing

The Fast Fourier Transform (FFT) method was used to convert time-domain vibration signals into frequency-domain spectra.

The FFT transformation is expressed as:

$$X(k) = \sum_{n=0}^{N-1} x(n)\, e^{-j2\pi kn/N}$$

where:

- $x(n)$is the discrete vibration signal;
- $X(k)$is the frequency-domain representation;
- $N$is the number of samples.

FFT spectra enabled identification of:

- spindle rotational frequencies;
- bearing defect frequencies;
- gear mesh frequencies;
- resonance zones.

The RMS vibration parameter was determined using:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

where:

- $x_i$is vibration amplitude;
- $N$is the number of signal samples.

3 CNN-Based Diagnostic Model

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A Convolutional Neural Network (CNN) was developed for automatic defect classification. FFT vibration spectra were transformed into two-dimensional feature maps and used as input data for the network.
The CNN architecture consisted of:
- convolution layers;
- pooling layers;
- fully connected layers;
- Softmax output classifier.

The convolution operation is defined as:

$$y(i,j) = \sum_m \sum_n x(i-m, j-n)k(m,n)$$

where:
- $x$is the input feature map;
- $k$is the convolution kernel;
- $y$is the output feature map.

The model was trained using labeled vibration datasets corresponding to healthy and defective machine conditions.

Results and Discussion

Experimental investigations showed that healthy machine components produce stable harmonic vibration spectra with low amplitudes. In contrast, defective bearings and gear systems generated increased harmonic peaks and sideband frequency components.
The resonance frequency of the spindle system was determined according to:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where:
- $f_r$is resonance frequency;
- $k$is dynamic stiffness;
- $m$is equivalent system mass.

The obtained results demonstrated that increasing bearing wear reduces system stiffness and increases resonance vibration amplitudes.
Characteristic defect frequencies for rolling bearings were identified using theoretical relationships. Experimental FFT spectra confirmed the presence of outer race and inner race defects.
The developed CNN model successfully classified machine conditions with high accuracy. The obtained diagnostic performance was:
- overall classification accuracy — 96.4%;
- bearing defect detection accuracy — 97.1%;
- gearbox fault detection accuracy — 95.8%.

Compared with conventional threshold-based methods, the proposed intelligent diagnostic system demonstrated higher robustness under noisy industrial conditions.
The developed methodology provides several practical advantages:
- early defect identification;
- reduction of maintenance costs;

- improved operational reliability;
- implementation of predictive maintenance strategies.

The obtained results also indicate strong potential for integration into Industry 4.0 smart manufacturing systems.

Conclusion

This study presented an intelligent vibration-based diagnostic methodology for metal cutting machine tools using FFT spectral analysis and convolutional neural network algorithms.

The developed approach enables:

- accurate assessment of spindle and gearbox condition;
- identification of bearing defects at early stages;
- automated vibration signal classification;
- improvement of predictive maintenance efficiency.

Experimental investigations conducted on the HT-250M lathe confirmed the effectiveness of the proposed system under industrial operating conditions.

The developed methodology improves machine reliability, reduces maintenance costs, and increases operational stability of manufacturing equipment.

Future studies will focus on hybrid artificial intelligence models and real-time cloud-based diagnostic systems for smart industrial applications.

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