



Model-Oriented Intelligent Diagnosis of the Technical Condition of Metalworking Equipment

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ABSTRACT: This paper presents a model-oriented intelligent approach for diagnosing the technical condition of metalworking equipment. The method integrates model-based state estimation and neural networks to identify faults under variable operating conditions. Diagnostic decisions are based on the analysis of operational signals, including vibration, current, rotational speed, torque, acoustic emission, and temperature. A mathematical model and Kalman filter are used to generate residual signals characterizing deviations from normal operation, while neural networks perform feature extraction and fault classification. Experimental results demonstrate high diagnostic accuracy and efficiency, confirming the applicability of the proposed approach for online condition monitoring of metalworking equipment.

KEY WORDS: Metalworking Equipment, Intelligent Diagnosis, Neural Networks, Technical Condition Monitoring, Fault Detection

I. INTRODUCTION

The application of modern diagnostic methods for metalworking equipment improves operational efficiency, productivity, and system reliability by enabling timely detection of faults [1]. A key challenge in this area is the continuous monitoring and analysis of sensor data that reflect the technical condition of equipment components and influence product quality.

Recent advances in intelligent data analysis, machine learning, and neural networks have significantly enhanced condition monitoring and fault diagnosis systems [2]. Model-oriented diagnostic approaches, which combine mathematical models with measured operational signals, allow deviations from normal operating conditions to be detected under variable loads and external disturbances.

In this study, a model-oriented intelligent diagnostic approach integrating state estimation and neural networks is proposed. The approach provides reliable fault detection and technical condition monitoring of metalworking equipment and is suitable for online diagnostic applications [3–7].

II. SIGNIFICANCE OF THE SYSTEM

The significance of the proposed model-oriented intelligent diagnostic system lies in its ability to ensure reliable and timely assessment of the technical condition of metalworking equipment under variable operating conditions. By integrating mathematical modeling, state estimation, and neural network-based analysis, the system enables early detection of faults and reduces the risk of unexpected equipment failures.

The use of diagnostic residuals generated from a model-based approach allows deviations from normal operation to be identified even in the presence of measurement noise and external disturbances. This enhances diagnostic accuracy compared to conventional threshold-based methods. In addition, the application of neural networks provides effective feature extraction and nonlinear fault classification, improving the adaptability of the system to complex fault patterns.



The proposed system supports online condition monitoring and predictive maintenance, contributing to reduced downtime, optimized maintenance scheduling, and increased reliability of metalworking equipment in industrial environments.

III. LITERATURE SURVEY

Existing studies on fault diagnosis of metalworking equipment focus on condition monitoring based on the analysis of vibration, electrical, acoustic, and thermal signals. Traditional diagnostic approaches rely on signal processing techniques in the time and frequency domains, including spectral analysis, envelope detection, and statistical feature extraction. These methods are effective for detecting well-defined faults but show limited performance under variable operating conditions and in the presence of noise.

Model-based diagnostic methods have been widely investigated as a means of detecting deviations between measured signals and reference values generated by mathematical models. Approaches based on state estimation, such as Kalman filtering, enable robust fault detection by accounting for system dynamics and measurement uncertainty. However, the accuracy of these methods strongly depends on the quality of the mathematical model.

Recent research highlights the growing role of intelligent diagnostic techniques, particularly machine learning and neural networks, in fault identification and classification. Neural networks provide powerful tools for nonlinear feature extraction and data-driven fault recognition. Hybrid approaches that combine model-based residual generation with neural network-based analysis demonstrate improved diagnostic accuracy and adaptability, making them a promising direction for intelligent condition monitoring of metalworking equipment.

IV. METHODOLOGY

The proposed methodology for diagnosing the technical condition of metalworking equipment is based on a model-oriented intelligent approach that integrates mathematical modeling, state estimation, signal processing, and neural network-based analysis. Operational data from internal control signals and external sensors are continuously collected and preprocessed to ensure reliable input. A mathematical model combined with a Kalman filter is used to predict system states and generate diagnostic residuals reflecting deviations from normal operation. Informative features are then extracted from residual and vibration signals in the time and frequency domains. Finally, a neural network performs nonlinear fault identification and classification, enabling accurate diagnosis and supporting online condition monitoring and predictive maintenance of metalworking equipment. Diagnostic data can be classified into two categories depending on the acquisition method and signal sources. Among the considered diagnostic parameters, vibration signals are most commonly used for fault analysis of metalworking equipment. Characteristic frequency components can be described as:

$$Fd = |fs \pm nfr|$$

The instantaneous motor torque is expressed as:

$$T(t) = T_0 + \Delta T(t)$$

Kalman filter prediction equations:

$$\begin{aligned} \hat{z}\{k+1\} &= A\hat{z}k + Bvk \\ P\{k+1\} &= APk + W \end{aligned}$$

Correction equations:

$$\begin{aligned} G_k &= P\{k+1\}HT(HP_{k+1}HT + V)^{-1} \\ \hat{z}k &= \hat{z}\{k+1\} + Gk(yk - H\hat{z}\{k+1\}) \\ Pk &= (I - GkH)P\{k+1\} \end{aligned}$$

The methodology for diagnosing faults in induction motors involves systematic procedures for data acquisition, processing, and fault identification. Diagnostic procedures convert measurements of machine parameters and collected data into actionable information about potential faults. The process includes analysis and synthesis of specific physical quantities, enabling short- and long-term evaluations of motor reliability. The main objectives are fault detection, localization, and identification, preferably without intrusive inspections.

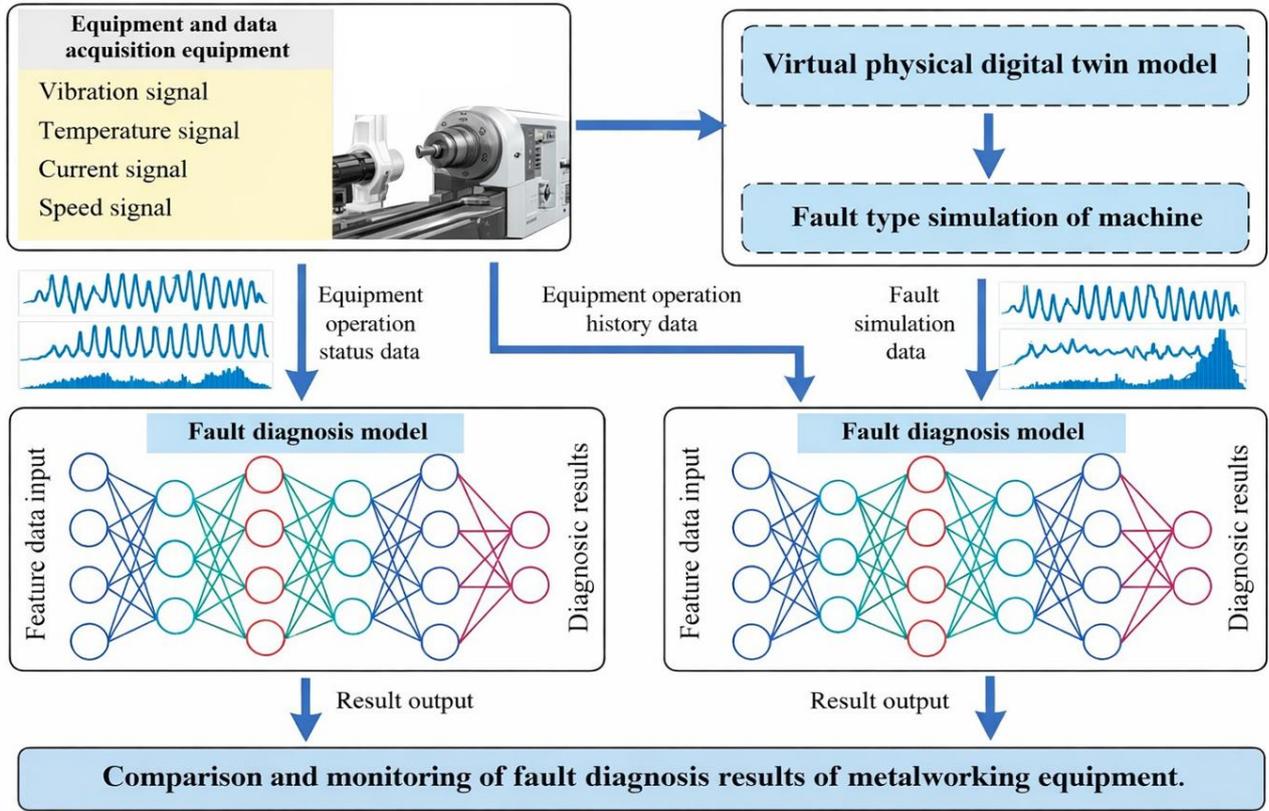


Fig. 1. Model-Oriented Intelligent Diagnostic System for Monitoring the Technical Condition of Metalworking Equipment

To ensure the reliability and generalization capability of the proposed diagnostic approach, the neural network was trained using representative datasets obtained under both normal and faulty operating conditions. The dataset was divided into training and testing subsets to evaluate diagnostic performance. Feature normalization and dimensionality reduction were applied to improve convergence and reduce computational complexity. The effectiveness of the proposed methodology was assessed using quantitative performance indicators, including diagnostic accuracy, mean square error, and processing time, confirming its suitability for online condition monitoring applications.

V. EXPERIMENTAL RESULTS

The vibration-based diagnostic analysis was performed using time-domain and frequency-domain characteristics of the metalworking equipment under normal operating conditions and in the presence of a fault. The time-domain analysis shows that, under normal conditions, the root mean square (RMS) value of the vibration signal does not exceed **0.35–0.40**, while the maximum vibration amplitude is approximately **0.6**. When a fault occurs, the RMS value increases to **0.60–0.65**, and the maximum amplitude rises to **0.95–1.0**, indicating a significant increase in dynamic loads and mechanical disturbances.

Frequency-domain analysis reveals that, in the normal operating state, the vibration spectrum is dominated by a single peak at the fundamental spindle rotational frequency of $f_1 \approx 50$ Hz. The amplitude of this spectral component exceeds the background level by more than **eight times**, while higher-order harmonics remain below **10–15%** of the main component amplitude.

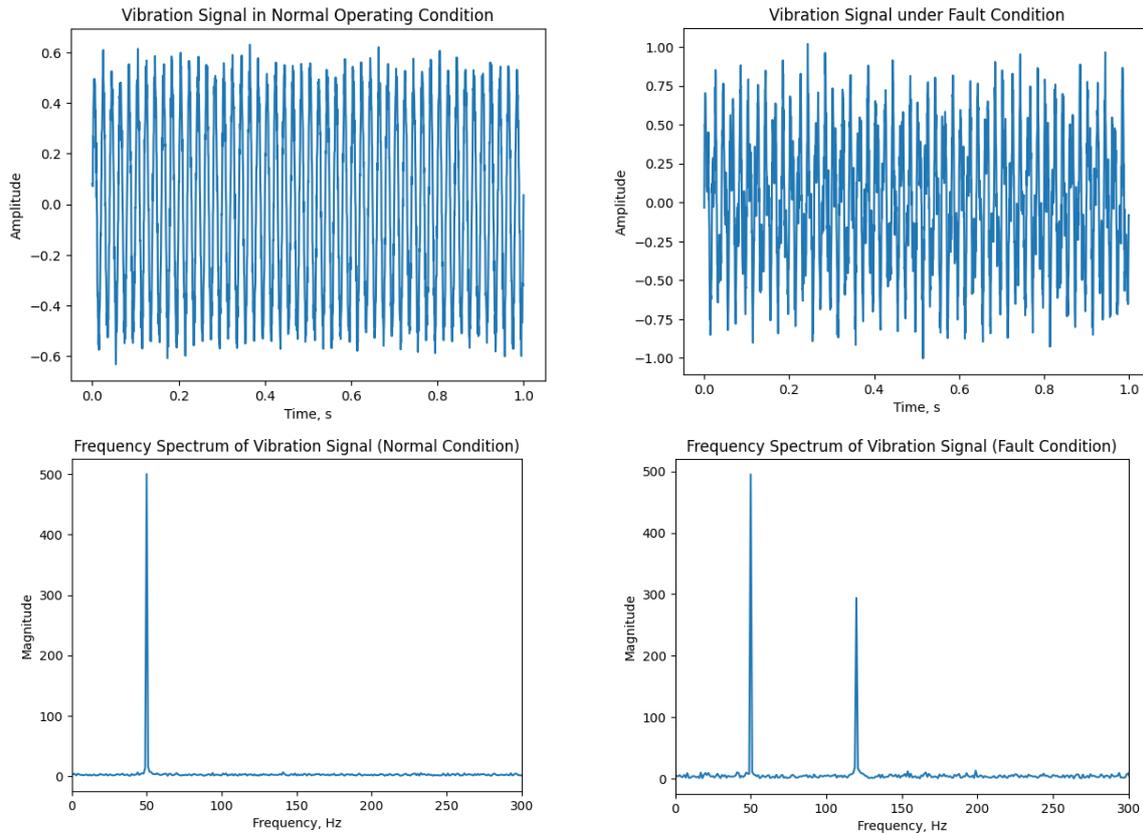


Fig. 2. Time- and Frequency-Domain Characteristics of Vibration Signals under Normal and Fault Conditions

Under faulty conditions, an additional pronounced spectral component appears at a frequency of $f_2 \approx 120$ Hz, with an amplitude reaching approximately **55–60%** of the main harmonic at 50 Hz. Furthermore, the total spectral energy in the frequency range of **80–200 Hz** increases by more than **two times** compared to the normal operating condition.

These quantitative differences between normal and faulty states confirm the high diagnostic informativeness of vibration signals. The identified time- and frequency-domain features are subsequently used as input parameters for the neural network-based diagnostic model, contributing to improved fault identification accuracy and robustness of the intelligent diagnostic system under variable operating conditions.

VI. CONCLUSION AND FUTURE WORK

This study presented a model-oriented intelligent approach for diagnosing the technical condition of metalworking equipment based on the integration of mathematical modeling, state estimation, vibration signal analysis, and neural network-based fault classification. The proposed methodology enables reliable detection of faults by analyzing deviations between measured operational signals and model-predicted values, even under variable operating conditions and measurement noise.

Experimental results demonstrated that vibration signals provide informative time- and frequency-domain features for fault identification. The analysis confirmed significant differences between normal and faulty operating states in terms of vibration amplitude, spectral energy distribution, and the presence of fault-related frequency components. These features were effectively utilized by the neural network model, contributing to improved diagnostic accuracy and robustness of the system.

Future work will focus on extending the proposed approach by incorporating additional diagnostic signals, such as acoustic emission and thermal data, and by improving the adaptability of the neural network model to a wider



range of operating modes and fault types. The integration of the diagnostic system with real-time industrial control platforms and the development of digital twin-based models are also considered promising directions for further research.

REFERENCES

- [1] R. Yousefi, R. Yusof, R. Arfa, "Fault Diagnosis of Three-Phase Induction Motors Based on Vibration and Electrical Current Signals," *Jurnal Teknologi (Sciences & Engineering)*, 2024, doi:10.11113/jt.v78.7447.
- [2] A. Chouhan, P. Gangsar, R. Porwal, C. K. Mechefske, "Artificial Neural Network Based Fault Diagnostics for Three-Phase Induction Motors under Similar Operating Conditions," *Vibroengineering Procedia*, 2020.
- [3] J. Shi, S. Li, H. Shen, "Review of Induction Motor Fault Diagnosis Technology," *Journal of Electrical Engineering*, vol. 18, no. 1, pp. 1–13, 2023.
- [4] H. Çalıř, "Vibration and Motor Current Analysis of Induction Motors to Diagnose Mechanical Faults," *Journal of Measurements in Engineering*, 2014.
- [5] U. Ali, W. Ali, U. Ramzan, "An Improved Fault Diagnosis Strategy for Induction Motors Using Weighted Probability Ensemble Deep Learning," *arXiv preprint*, Dec. 2024.
- [6] S. Kilickaya, L. Eren, "Padé Approximant Neural Networks for Enhanced Electric Motor Fault Diagnosis Using Vibration and Acoustic Data," *arXiv preprint*, Jul. 2025.
- [7] A. Pourghoraba *et al.*, "Model-Agnostic Meta-Learning for Fault Diagnosis of Induction Motors in Data-Scarce Environments," *arXiv preprint*, Dec. 2024.

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