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Predictive Fault Diagnosis of Spindle Overload and Axis Overload in CNC Machine Tools Using Operational Data Analytics

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***Abstract*—Computer Numerical Control (CNC) machine tools are fundamental to modern manufacturing industries where uninterrupted operation and machining precision are essential for productivity. Among various failure conditions, spindle overload and axis overload are major causes of unexpected machine stoppage, job failure, and increased maintenance cost. Conventional monitoring systems generally rely on alarm-based detection that identifies faults only after abnormal conditions occur. This paper presents a study and conceptual framework for predictive fault diagnosis of overload conditions in CNC machine tools using operational data analytics. Industrial machine data obtained through machine drivers and stored in structured datasets are utilized to analyse load behaviour patterns. A data-driven methodology integrating preprocessing techniques and multiple machine learning models is proposed to enable early overload warning and maintenance prediction. The proposed framework focuses on improving machine reliability, minimizing downtime, and supporting intelligent maintenance decisions. Experimental validation using real industrial datasets is considered as future work.**

Keywords*—CNC Machine Tools, Predictive Maintenance, Spindle Overload, Axis Overload, Machine Learning, Industrial Data Analytics, Fault Diagnosis

I. INTRODUCTION

Computer Numerical Control machines have become an essential component of automated manufacturing systems due to their capability to achieve high precision, repeatability, and productivity. Continuous operation of CNC machines depends heavily on the stable functioning of spindle systems and axis feed drives. Any abnormal loading condition affecting these components can interrupt machining operations and result in production losses.

Spindle overload commonly occurs when excessive cutting forces or improper machining parameters increase mechanical and electrical stress on the spindle drive. Such conditions may lead to sudden machine stoppage and possible tool damage. Similarly, axis overload conditions arise when feed drives experience excessive resistance or abnormal load variations, causing positioning errors or job failure. In industrial environments, these failures directly impact productivity and increase maintenance requirements.

Traditional maintenance practices rely mainly on reactive monitoring systems that generate alarms only after overload conditions are reached. With the advancement of data-driven manufacturing and Industry 4.0 concepts, predictive fault diagnosis has emerged as an effective strategy for identifying abnormal behaviour before failure occurs. By analysing operational machine data, it becomes possible to estimate future machine conditions and provide early warnings.

This work presents a study of overload-related problems in CNC machines and proposes a predictive diagnostic framework based on industrial operational datasets and machine learning techniques. The objective is to enable early overload detection and intelligent maintenance planning to enhance operational efficiency.

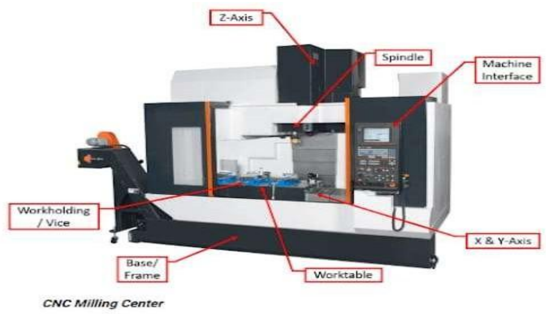


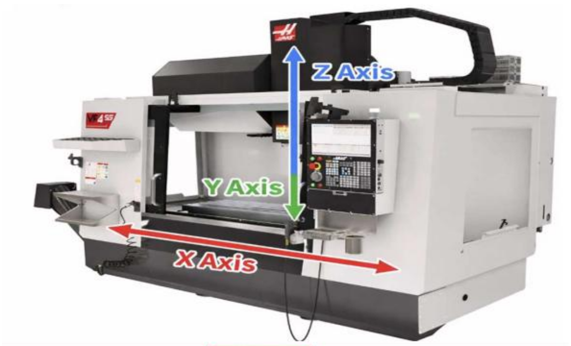
Fig No 1.CNC Machine Structure

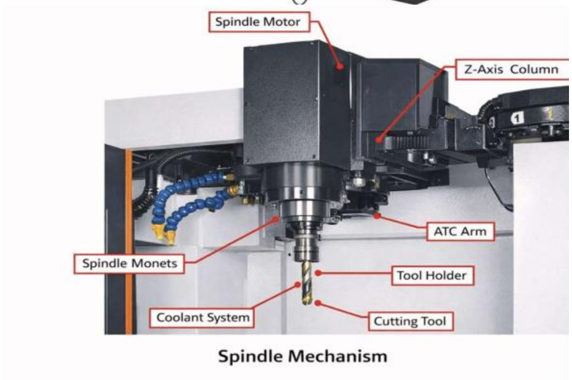
II. BACKGROUND OF SPINDLE AND AXIS OVERLOAD

The spindle unit is responsible for rotational motion and cutting energy transfer during machining. Variations in cutting load, tool wear, or improper feed parameters can increase spindle current and torque demand, resulting in overload conditions. Continuous overload may lead to overheating, vibration increase, or emergency shutdown.

Axis systems control linear movement through servo motors and feed mechanisms. Load imbalance, mechanical resistance, or machining disturbances can produce abnormal stress in axis drives. Axis overload events often result in interrupted machining cycles or workpiece defects.

Understanding load behaviour in these subsystems is essential for developing predictive monitoring strategies.





III. LITERATURE SURVEY

Research on CNC machine condition monitoring has significantly increased with the adoption of intelligent manufacturing systems. Earlier studies primarily focused on detecting spindle abnormalities using vibration and load monitoring techniques. These approaches monitored mechanical behaviour to identify irregular operating conditions; however, most systems depended on threshold-based detection, which reacts only after abnormal conditions appear.

Recent developments introduced data-driven fault diagnosis methods where machine signals are analyzed using artificial intelligence techniques. Deep learning and machine learning models have been applied to recognize fault patterns automatically from operational signals. These methods improve detection capability compared to traditional monitoring approaches, but they often require controlled datasets and may face performance challenges under real industrial environments where noise and parameter variation are common.

Several researchers also proposed hybrid diagnostic models combining feature extraction techniques with classification algorithms to improve accuracy. Although these methods demonstrate promising results, the majority of studies concentrate on spindle-related vibration faults or bearing failures. Limited attention has been given to overload conditions that directly affect machining continuity and production efficiency.

Furthermore, most existing works analyze individual machine components separately. Integrated monitoring of both spindle and axis subsystems using operational machine data remains insufficiently explored, especially in real industrial applications.

IV. RESEARCH GAP IDENTIFICATION

Despite advancements in intelligent fault diagnosis, important challenges remain unresolved. Many existing monitoring systems identify faults only after measurable degradation occurs, reducing the opportunity for preventive action. Current research predominantly emphasizes vibration-based fault classification rather than early overload prediction. In addition, combined analysis of spindle and axis overload behaviour is rarely addressed. Several studies rely on laboratory-generated datasets, which may not accurately represent industrial machining conditions. As a result, practical implementation of predictive maintenance strategies in real manufacturing environments remains limited.

Therefore, a predictive framework capable of utilizing real operational CNC data to identify overload trends before machine failure is required.

V. IMPROVEMENTS OFFERED BY THE PROPOSED WORK

The proposed research introduces multiple improvements compared with existing studies:

Adoption of real industrial CNC operational data instead of controlled experimental datasets.

Simultaneous monitoring of spindle overload and axis overload within a unified diagnostic framework.

Transition from reactive fault detection toward predictive overload warning.

Comparative evaluation of multiple machine learning algorithms to improve prediction reliability.

Integration of fault prediction with maintenance planning and productivity improvement objectives. These enhancements aim to make the proposed system more suitable for practical industrial deployment.

VI. RESEARCH CONTRIBUTIONS

The primary contributions of this work are summarized as follows:

Development of a predictive diagnostic framework for identifying overload conditions in CNC spindle and axis systems.

Utilization of operational data analytics for analyzing machine behaviour under real machining conditions.

Application and comparison of multiple machine learning techniques for overload prediction.

Design of an early warning strategy to reduce machine downtime and prevent production interruption.

Establishment of a scalable methodology adaptable to intelligent manufacturing environments.

VII. IMPROVEMENT SUMMARY PARAGRAPH

Compared with conventional CNC monitoring approaches, the proposed framework emphasizes predictive analysis using operational machine data rather than post-failure diagnosis. By combining spindle and axis overload monitoring with machine learning–based prediction, the system aims to identify abnormal load patterns at an early stage. This approach supports proactive maintenance decisions and enhances overall manufacturing reliability.

VIII. LIMITATIONS OF CONVENTIONAL MONITORING APPROACHES

Existing CNC monitoring systems primarily depend on threshold-based alarms embedded within machine controllers. These approaches present several limitations:

Fault detection occurs only after overload conditions appear.

Single-parameter monitoring reduces diagnostic accuracy.

Lack of predictive capability prevents early maintenance planning.

Industrial operators receive warnings too late to prevent downtime.

Therefore, intelligent data-driven monitoring techniques are required to transition from reactive maintenance to predictive maintenance.

IX. PROPOSED PREDICTIVE DIAGNOSTIC FRAMEWORK

The proposed framework introduces data analytics–based approach for identifying overload behaviour patterns using operational CNC machine data.

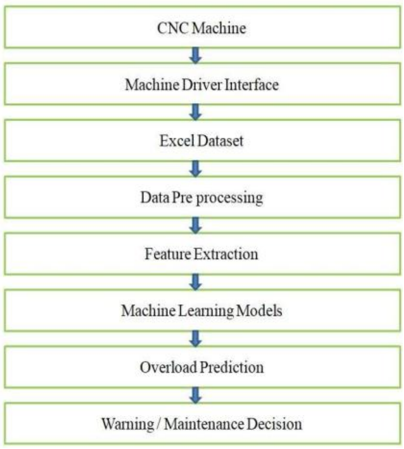


Fig No.4 Proposed System Architecture

I. System Overview

The overall workflow consists of:

CNC Machine → Data Driver Interface → Dataset Generation → Data Processing → Machine Learning Analysis → Overload Prediction Industrial operational data are collected directly from machine drivers and stored in spreadsheet format for further analysis.

II. Data Acquisition

Machine parameters associated with spindle and axis operations are extracted using industrial communication drivers. These datasets represent real operational conditions during machining processes.

III. Data Preprocessing

Collected datasets undergo preprocessing steps including:

removal of missing values normalization of parameters noise reduction

data consistency verification

These steps ensure reliable input for predictive analysis.

IV. Feature Extraction

Relevant statistical and operational features are derived from machine data to represent load behaviour trends. These features help distinguish normal and abnormal operating conditions.

V. Machine Learning-Based Prediction

Multiple machine learning algorithms are employed to analyse historical operational patterns. Model comparison enables identification of the most suitable predictive approach for overload detection. The system estimates potential overload conditions before machine alarms occur.

VI. Warning and Decision Support

Prediction outputs can be utilized to generate early maintenance warnings, allowing operators to adjust machining parameters or schedule maintenance activities.

X. PROPOSED METHODOLOGY

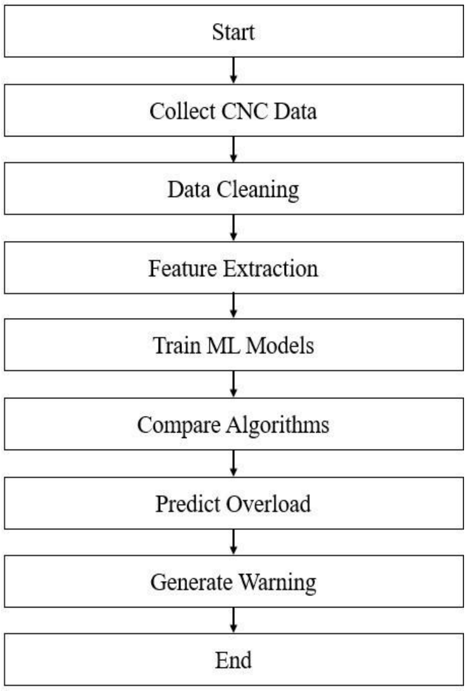


Fig No. 5 Methodology Flowchart

XI. EXPECTED OUTCOMES

I. The proposed framework is expected to provide:
II. Early detection of overload conditions
III. Reduction in unexpected machine downtime
IV. Improved spindle and axis reliability
V. Enhanced maintenance planning
VI. Increased manufacturing productivity

XII. FUTURE WORK

Future work will include implementation using real industrial datasets, experimental validation of prediction accuracy, and development of real-time monitoring interfaces integrated with CNC systems.

XIII. CONCLUSION

This paper presented a conceptual framework for predictive fault diagnosis of spindle and axis overload conditions in CNC machine tools using operational data analytics. By shifting from reactive monitoring toward predictive analysis, the proposed approach aims to enhance machine reliability and reduce production interruptions. The framework establishes a foundation for future experimental validation using real industrial data and machine learning models.

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