

Advanced Vibration Analysis in Smart Factories

Susmita Mistri^{1*}, Souradip Roy², Hao-Chung Kuo³

¹ International Ph.D. Program in Photonics, Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering, National Yang - Ming Chiao Tung University, Hsinchu, 30010 Taiwan, Republic of China.

² General interface Solution (GIS), Foxconn, No.2, Houke S. Road, Houli District, Taichung City – 42152, Taiwan, Republic of China.

³ Semiconductor Research Center, Hon Hai Research Institute, Taipei, 11492 Taiwan, Department of Photonics, Institute of Electro-Optical Engineering, National Yang - Ming Chiao Tung University, Hsinchu, 30010 Taiwan, Republic of China.

DOI : <https://doi.org/10.51583/IJLTEMAS.2025.140400053>

Received: 16 April 2025; Accepted: 17 April 2025; Published: 10 May 2025

Abstract: In the development of smart factories, advanced vibration analysis is essential since it allows for real-time machinery and equipment monitoring and diagnostics. Smart sensor integration signifies continuous collection, processing, and analysis of vibration data to identify early indications of mechanical failures and maintain maximum performance in intricate industrial systems. With a focus on how artificial intelligence (AI) is revolutionizing conventional diagnostic approaches, this chapter examines the most recent developments in vibration analysis techniques. Machine learning and deep learning algorithms are used in AI-driven vibration diagnostics to identify complex defect patterns that traditional techniques could overlook. On top of that, that combine vibration data from several sources improves diagnostic precision and resilience, making it possible to identify problems in big, networked systems. By integrating sensor data with advanced signal processing techniques like wavelet transformation and Fast Fourier Transform (FFT), a complete image of system health is produced, allowing for predictive maintenance and minimizing downtime. This chapter shows how as we go toward Industry 5.0, AI, sensor technology, and vibration data fusion work together to improve smart factory operations, increase overall system reliability, and facilitate the long-term growth of manufacturing sectors.

Keywords: Advanced Vibration Analysis, Industrial Internet of Things (IIOT), Industry 5.0 & 4.0, Artificial Intelligence, Predictive maintenance (PDM), Smart Manufacturing, Monitoring system, Signal Processing, Smart Sensor, Digital Twin Technology.

I. Introduction

Industry 4.0 has completely changed the manufacturing scene by integrating automation, intelligence, and connection into production systems. A new age in manufacturing has begun with the introduction of Industry 4.0, which is distinguished by data-driven decision-making, intelligent automation, and networked systems[1]. Advanced technologies have been embedded in factory processes as an extension of the drive for more automation, efficiency, and dependability in the modern-day industrial landscape. Vibration analysis has become a vital tool in the Industry 4.0 revolution for maintaining the health of machinery, enhancing performance, and reducing unscheduled downtime[2]. Vibration analysis is one of the key technologies supporting this revolution and is essential for achieving operational excellence, especially in smart factories[3]. Predictive maintenance, process optimization, and accurate machinery health monitoring are made possible by utilizing modern vibration analysis techniques, which guarantee dependability and effectiveness[4]. The use of real-time smart sensors, AI-driven diagnostic tools, and data fusion techniques has greatly improved vibration monitoring approaches, which previously frequently depended on manual analysis and periodic checks. These developments make it possible for equipment to be continuously and predictively monitored, which helps manufacturers spot possible problems before they become expensive failures[5].

The foundation of this change is real-time vibration analysis driven by smart sensors[6]. Smart sensors built into machinery provide continuous vibration signature monitoring, in contrast to traditional vibration monitoring systems that need manual data collecting[7]. With wireless connection, edge processing, and self-calibration characteristics, these sensors can identify changes in vibration patterns quickly and provide real-time notifications when anomalies are found. By empowering factory operators to take prompt corrective action, this continuous feedback loop keeps minor problems from turning into significant failures. By keeping an eye on a variety of vibration frequencies, smart sensors can detect issues like imbalance, misalignment, and bearing wear and offer important insights into a machine's state[8]. Real-time equipment monitoring enhances the possibilities of advanced maintenance planning. Figure 1 represents the operational architecture for Industrial Metaverses, defining a layered framework that integrates physical and digital systems to enhance industrial operations through immersive technologies.

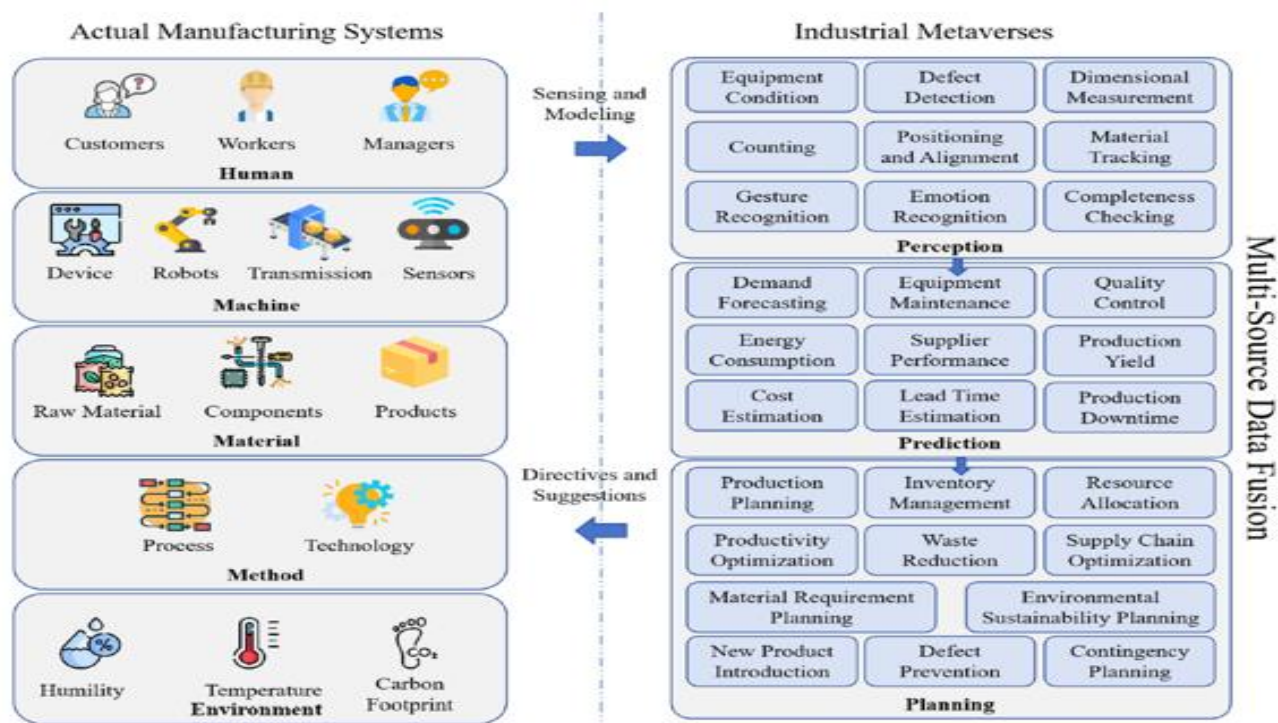


Figure 1. Operational architecture for Industrial Metaverses[8].

Artificial intelligence (AI) has revolutionized the diagnostic process by offering powerful instruments for analyzing vibration data, which extend beyond vibration monitoring. Traditional vibration analysis methods relied on expert interpretation, which was effective but also bound by time limits and human error. Artificial intelligence (AI)-driven vibration diagnostic solutions combine machine learning (ML) and deep learning (DL) algorithms to automatically evaluate large volumes of data, identify trends, and identify anomalies that can indicate impending ruptures. Since these artificial intelligence (AI) systems have been trained on historical vibration data to comprehend the typical operating signatures of machines, they are able to detect even the smallest deviations in vibration patterns[9]. AI systems are becoming more adept in identifying problem conditions such as misalignment, bearing strain, and gear wear before they result in catastrophic failures[10]. AI-driven vibration analysis is capable of more than just identifying defects; it can also predict a component's remaining usable life (RUL). By accurately scheduling maintenance chores, it is possible to anticipate when a part may break, which lowers the possibility of unplanned interruptions and unnecessary downtime[11].

Vibration analysis has advanced significantly with the introduction of data fusion techniques, particularly in complex systems where machine health is influenced by several interrelated components. Many parts, including motors, gears, bearings, and shafts, combine to form machinery in a typical manufacturing setting, ensuring optimal performance[6]. When a vibration problem occurs in one area of the system, it frequently affects the entire machine, making it difficult to identify the source of the issue. To overcome this difficulty, data fusion integrates vibration data from several sensors positioned at different positions throughout the system. Apart from vibration data, the study also considers other operating characteristics including temperature, pressure, and speed. A more accurate diagnosis is made possible by this holistic approach, which considers the interactions between many systemic components. When combined with temperature and speed data, vibration data from a motor, for example, may show imbalance, but the cause may be identified as a thermal problem impacting the motor's parts[12]. More accurate diagnostics and focused maintenance plans result from data fusion's ability to identify intricate fault patterns that would be challenging to identify with separate data sources. Combining data from multiple sources allows for real-time machinery optimization in addition to improving diagnostic accuracy. Manufacturers can dynamically modify machine settings to reduce component stress, avoid failures, and enhance overall performance by examining vibration patterns in combination with other operating parameters[13]. In complex systems, where interactions between several components can produce subtle or delayed effects that might otherwise go undetected, this ongoing feedback loop is essential. For instance, data fusion can assist in identifying problems that emerge from the interplay between the motion of the conveyor and the robotic arm on a production line with high-speed conveyors and robotic arms[14]. This enables proactive modifications to avert malfunctions.

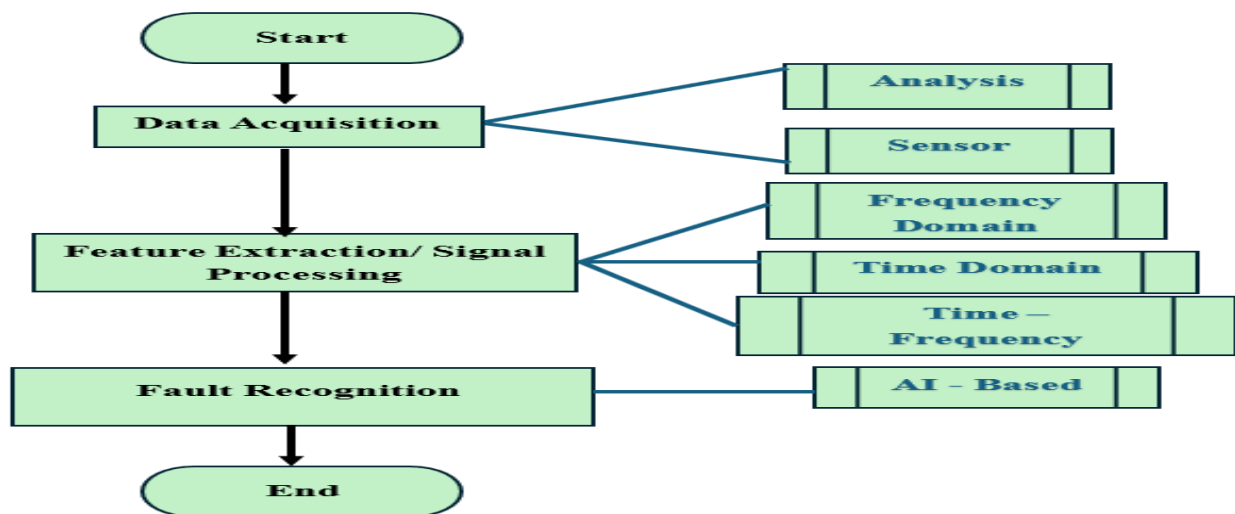


Figure 2. The framework of data acquisition stage is discussed first, followed by feature extraction techniques, and AI-based fault recognition algorithms[2].

Figure 2 shows the flowchart of AI based fault recognition system. Real-time smart sensor integration, data fusion in vibration analysis, and AI-driven diagnostics represent significant advancements in the maintenance and operation of machinery in smart factories. These technologies provide more accurate and proactive maintenance schedules in addition to early detection defects and ongoing monitoring[9, 15]. Smart factories can employ advanced vibration analysis to increase machine efficiency, extend equipment life, and decrease downtime all of which lead to more efficient, cost-effective, and ecologically friendly production processes[16]. These technologies will become increasingly significant in defining the future path of industrial automation and maintenance to develop smarter, more robust production environments[8]. Figure 3 shows the real-time control and dynamic scheduling of the invention management.

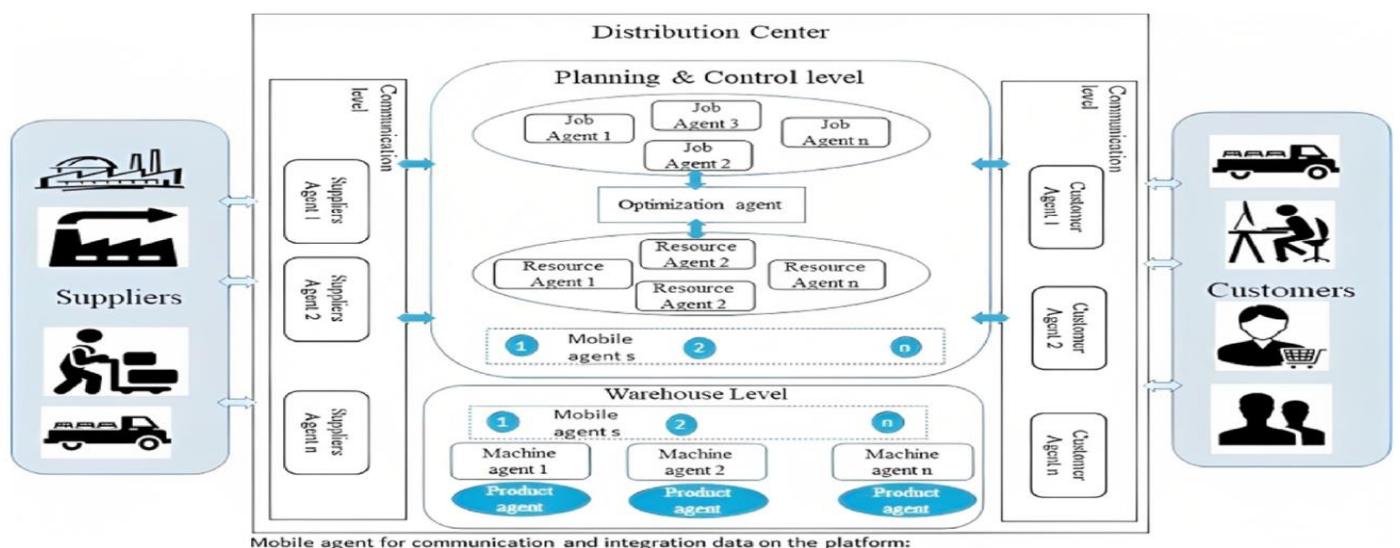


Figure 3. Real-time control and dynamic scheduling of the inventory management[9].

Principles of Vibration Analysis

Vibration analysis is the methodology of utilizing vibrations to monitor and assess the condition of machinery and equipment. Vibrations are measured and analyzed to find abnormalities, flaws, or indications of wear and tear in machine parts. A method for measuring and assessing the vibrations of industrial machinery or structural elements is vibration analysis[14]. This diagnostic tool is essential for identifying irregularities that can point to equipment or system problems. The foundation of vibration analysis is an understanding of how mechanical systems behave when in motion and how vibrations appear when parts are stressed, worn out, or fail.

Traditional Methods vs. Modern Technology

Traditional Vibration Analysis Techniques

To identify machine defects, traditional vibration analysis techniques measure and evaluate vibration signals. Time-domain analysis, which examines the vibration signal as a function of time, is among the most popular techniques. Engineers can identify anomalies such as abrupt spikes or oscillations by using this technique to visualize the vibration waveform. The overall energy of the vibration is frequently measured using the Root Mean Square (RMS) value, which serves as a helpful gauge of the condition of the equipment. Potential problems including misalignment, imbalance, or bearing failures are indicated if the RMS value rises over specific criteria. Frequency-domain analysis is another conventional technique that breaks down vibration signals into their component frequencies using methods such as the Fast Fourier Transform (FFT). This assists in determining the fault frequencies connected to. This makes it easier to find fault frequencies linked to certain mechanical problems, such as unbalance, bearing flaws, or gear meshing. To determine the extent of mechanical issues, peak-to-peak displacement is also monitored, particularly for low-frequency vibrations. Though successful, these conventional methods are typically less dynamic than contemporary approaches that use machine learning and real-time data analytics since they are more labor-intensive and require expert interpretation.

Advancements in Vibration Analysis Technology

Advancements in vibration analysis technology have significantly enhanced the ability to monitor and diagnose machinery health compared to traditional methods. Traditional techniques, such as time-domain analysis and frequency-domain analysis using tools like Fast Fourier Transform (FFT), have served as the backbone for identifying mechanical faults by observing vibration patterns over time and frequency[17, 18]. These methods are reliable, but they often require manual intervention and expert knowledge to interpret the data, making them more time-consuming and less efficient for real-time monitoring. Additionally, traditional methods typically rely on fixed threshold values for fault detection, which can lead to missed early warning signs or false alarms if the threshold is not set correctly.

In contrast, modern vibration analysis technology uses cutting-edge instruments such as machine learning algorithms, wireless sensors, and Internet of Things (IoT) integration to deliver more accurate, automated, and real-time diagnosis[16]. IoT devices enable vibration sensors to continuously gather data from machinery and send it for analysis in real time. With the ability to adjust to the circumstances of every machine, machine learning algorithms can analyze enormous volumes of data to find trends and forecast breakdowns with a far better degree of precision. Additionally, centralized data collecting made possible by cloud-based platforms makes it possible for several sites to receive predictive maintenance and ongoing remote monitoring. By offering more proactive and preventive maintenance techniques, these developments drastically lower maintenance expenses and downtime. Overall, while traditional methods remain foundational, modern vibration analysis technology offers faster, more accurate, and scalable solutions, driving the shift toward smarter, data-driven maintenance practices in industry[19].

Benefits of New Technology in Vibration Analysis

Improved Accuracy and Sensitivity

The improved accuracy and sensitivity provided by new technology in vibration analysis bring significant benefits to industrial maintenance and performance optimization. Traditional vibration analysis methods often rely on manual interpretation of signals, which can be prone to human error or limitations in detecting subtle faults. New technologies, such as advanced sensors, IoT integration, and machine learning algorithms, have greatly enhanced the ability to capture and analyze minute variations in vibration data, leading to higher sensitivity and precision in detecting early signs of mechanical issues[18].

The ability of modern sensors to detect vibrations at much finer resolutions, for example, makes it possible to identify problems that traditional methods could have missed. These sensors have a wider frequency range, which enhances the ability to detect faults in a range of mechanical parts, including gears, bearings, misalignment, and imbalance[20]. These advanced technologies are more sensitive and can identify anomalies or departures from typical operating patterns far in advance of them becoming catastrophic failures. This allows predictive maintenance tactics that were previously challenging to execute with the same degree of precision.

Through the automation of fault pattern recognition, the combination of artificial intelligence and machine learning enhances vibration analysis even more. The likelihood of false positives and negatives is decreased by these algorithms' ability to learn from past data and continuously enhance their diagnostic capabilities. Additionally, based on changing vibration data, machine learning models can forecast probable breakdowns, enabling proactive maintenance teams to minimize downtime and increase equipment longevity[19, 21, 22]. The enhanced precision and sensitivity made possible by contemporary vibration analysis technology, in summary, give producers more dependable, real-time diagnostics that are critical for maximizing maintenance plans, cutting expenses, and averting unscheduled downtime. In industrial contexts, the transition from reactive to proactive maintenance procedures has advanced significantly with this technological leap.

Real-time Monitoring and Alerts

Real-time monitoring and alerts have revolutionized vibration analysis by enabling continuous, dynamic tracking of machinery health. Unlike traditional methods that require periodic checks or manual inspections, modern vibration analysis systems equipped with IoT sensors provide constant, real-time data on equipment condition. These sensors continuously measure vibrations, sending data to centralized monitoring systems where it can be processed and analyzed in real-time. The ability to identify any problems as they appear rather than awaiting planned maintenance inspections is one of the fundamental advantages of real-time monitoring[19, 21]. This makes it possible to quickly identify any unusual vibrations, whether they are caused by imbalance, misalignment, or bearing wear. This lowers unplanned downtime and increases overall operational efficiency by enabling maintenance teams to react more quickly to stop minor problems from developing into catastrophic failures or expensive repairs.

This feature is further enhanced with notifications that are immediate. Technology instantly alerts users via dashboard alerts, emails, or SMS when vibration data exceeds preset thresholds or shows unusual trends. This automated alert system allows maintenance workers to respond quickly even when they are far away and not physically near the gear[5, 16, 23]. In increasingly complex systems, machine learning algorithms can enhance these alerts by distinguishing between distinct flaws, lowering false positives,

and ensuring that only problems that can be fixed are indicated. Figure 4 shows the steps involved in real-time fault diagnosis process.

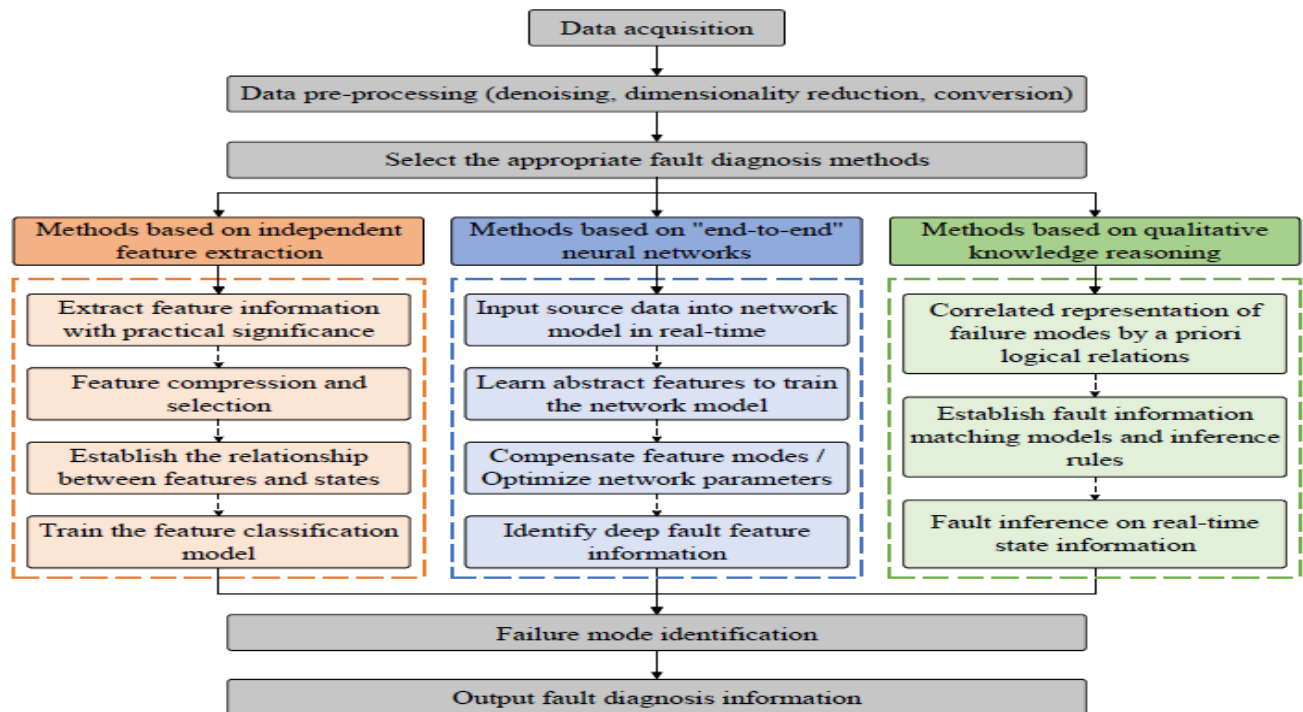


Figure 4. Real – Time fault Diagnosis process[15]

More importantly, continuous data collecting over time is made possible via real-time monitoring and alarms, which supports predictive maintenance. This constant stream of data makes it easier to spot aberrations that may indicate the start of a malfunction and contributes to a more precise profile of the machine's normal operating circumstances[16]. Eventually, these technologies can help optimize maintenance schedules by reducing unnecessary interventions and focusing resources on machines or parts that require upkeep. Overall, the accuracy and speed of defect diagnosis are improved by vibration analysis's real-time monitoring and warnings, which also make more effective preventative maintenance methods possible. These technologies enable quick decisions based on real-time data, extending the lifespan of critical equipment, reducing downtime, and lowering maintenance expenses.

Integration with Industry 4.0 and 5.0

Traditional industrial processes are transformed into extremely effective, intelligent, and flexible systems through the integration of modern vibration analysis with Industry 4.0 and 5.0 technologies[1, 8, 9]. Advanced vibration analysis supports the digital technologies, automation, and data-driven decision-making that are key to both Industry 4.0 and Industry 5.0.

Industry 4.0 Integration

The Fourth Industrial Revolution, or Industry 4.0, is centered on the creation of intelligent and networked production environments using cloud computing, big data, IoT (Internet of Things), and cyber-physical systems. Because it allows for real-time machine monitoring and data gathering that can be transmitted to centralized cloud platforms for processing and analysis, advanced vibration analysis is essential to this integration[12]. Predictive maintenance techniques and machine efficiency optimization are made possible by the constant evaluation of equipment performance and condition made possible by this data.

IoT Connectivity:

Real-time feedback and remote monitoring are made possible by vibration sensors integrated into devices that transmit data via Internet of Things networks[7]. Because of this connectivity, maintenance staff are guaranteed to be informed immediately of any anomalies, which speeds up reaction times and reduces downtime.

Big Data and Analytics:

Factories can use big data analytics to identify trends, anticipate possible breakdowns, and improve maintenance schedules by gathering enormous volumes of vibration data[10, 24]. This predictive strategy prolongs the life of machines, boosts productivity, and decreases unscheduled downtime.

Cloud Integration:

Cloud-based platforms allow factory managers and maintenance teams to remotely monitor machine health and make informed decisions based on the most recent information by storing and making vibration analysis data accessible from any location[11].

Industry 5.0 Integration

With an emphasis on customization, innovation, and human involvement in the production process, Industry 5.0 places more emphasis on human-machine collaboration than Industry 4.0, which is more focused on automation and efficiency. Advanced vibration analysis in this situation facilitates a closer bond between people and machines in addition to improving operational efficiency[7, 11, 13, 17].

Collaborative Robots (Cobots):

Collaborating with human operators, cobots can incorporate Precise vibration analysis. By utilizing vibration data to adjust their movements in real time, cobots may maximize safety and production quality by guaranteeing that humans and machines collaborate.

Human-Centric Systems:

Human operators can make well-informed decisions on production and maintenance plans with the aid of vibration data that has been evaluated and displayed on user-friendly dashboards. Operators can receive visual feedback regarding the health of their machinery through the integration of AI-driven insights and augmented reality (AR), enabling them to make necessary adjustments to production processes or take preventative measures.

Customization and Flexibility:

Manufacturing systems in Industry 5.0 are becoming more and more individualized and customized. When vibration analysis and AI are combined, they can help modify machine settings for individual production runs, guaranteeing peak performance even when the business produces tiny quantities of bespoke goods.

By combining Industry 4.0 and 5.0 technologies with advanced vibration analysis, smart factories may increase their automation, efficiency, and flexibility. Manufacturers may lower costs and downtime while simultaneously improving product quality, increasing operational efficiency, and establishing more adaptable, human-centered production environments by utilizing real-time data, predictive maintenance, and AI-driven insights[6, 11, 12]. A major step toward developing more intelligent, responsive, and sustainable production systems is the convergence of these industrial revolutions with improved vibration analysis.

Smart Sensor and IIOT

The Industrial Internet of Things (IIoT) and smart sensor integration are essential for improving vibration analysis in modern manufacturing settings. Increased operational efficiency, less downtime, and better decision-making result from these technologies' improved capacity to track the condition of equipment, identify problems, and facilitate predictive maintenance[8].

Smart Sensors in Vibration Analysis

Recent advances in smart sensor technology have greatly improved vibration analysis's potential for use in manufacturing industries. These days, smart sensors can detect even the smallest vibrations that could be signs of an equipment failure because they have advanced characteristics including increased sensitivity, enhanced accuracy, and integrated processing capabilities[24]. Increasingly, these sensors have inherent intelligence that allows them to interpret raw data locally and remove unnecessary noise before sending it. This lessens the strain on central systems and guarantees that only important, superior data is forwarded for additional examination. Additionally, vibration monitoring systems are now more flexible and scalable thanks to the introduction of wireless smart sensors, which permits their deployment across a variety of equipment without requiring significant infrastructure or wiring changes. These sensors can now be mounted on machines in confined spaces or difficult-to-reach places owing to advancements in simplifying. Incorporating IoT capabilities into smart sensors also enables real-time data transfer, giving operators instant access to information on the condition of their equipment. Modern factories may now employ more effective, predictive maintenance tactics that decrease downtime, improve equipment life, and improve overall operational efficiency thanks to recent advancements in smart sensor technology, which are revolutionizing vibration analysis[11–13]. Fig. 5 shows the sensors and analytical techniques used for different mechanical quality assessment measures.

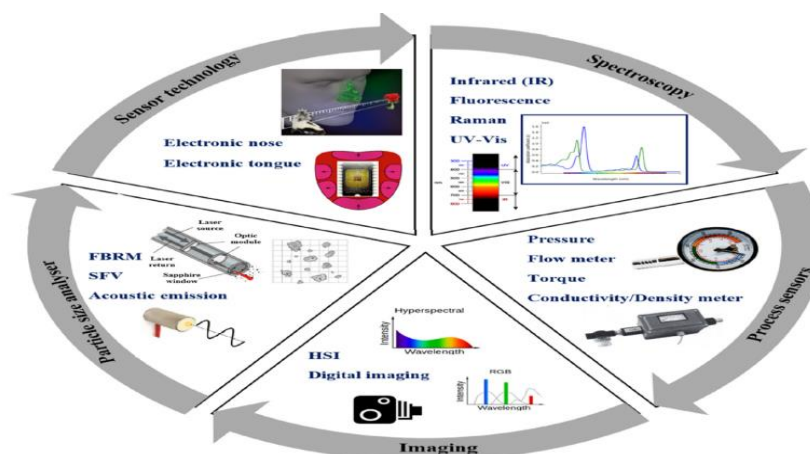


Figure 5. Sensors and analytical techniques used for quality assessments[13]

Industrial Internet of Things (IIoT) in Vibration Analysis

Through the smooth integration of sensors, machinery, and centralized data systems, the Industrial Internet of Things (IIoT) has revolutionized vibration analysis by providing real-time monitoring and predictive maintenance capabilities. To ensure that any anomalous vibrations are identified early, IIoT enables the continuous gathering of vibration data from machines, which is then sent to cloud-based platforms for analysis. By detecting possible problems before they result in equipment failure, this data-driven method lowers unscheduled downtime and expensive repairs. The IIoT also makes remote monitoring possible, which enables operators to keep tabs on the condition of their machines at any time and from any location and base decisions on the most recent data[6, 9, 25, 26]. IIoT systems provide thorough insights into machine performance by combining vibration analysis with other operational data, which enhances maintenance plans and boosts overall factory productivity. IIoT systems improve problem detection, decrease downtime, and facilitate more proactive, data-driven decision-making with cloud computing and predictive analytics, which results in enhanced operational reliability and significant cost savings. AGV applications, sensors, supply management, inventory management, delivery management, and 6G-based IoT-based smart factory of the industry 4.0 system are demonstrated in Fig. 6.

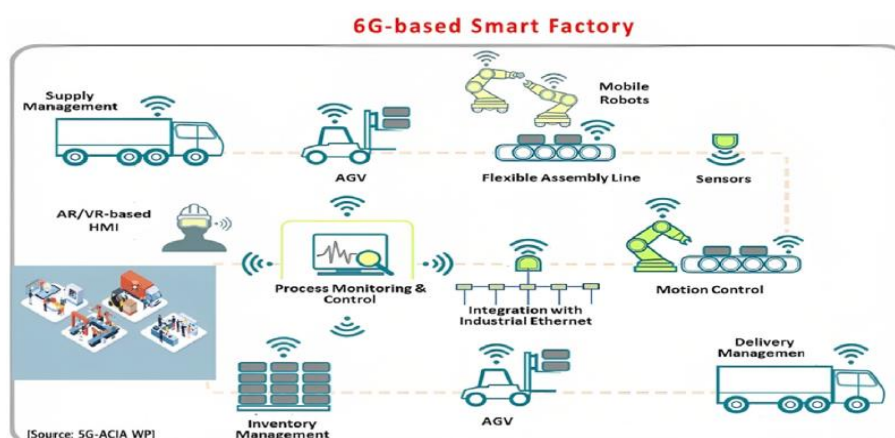


Figure 6. IOT in 6G based factory of the industry 4.0 system[9]

Data Analysis and Fault Diagnosis

Modern data analysis and defect detection techniques, especially when it comes to vibrational analysis, are essential for improving Industry 4.0 performance and moving toward Industry 5.0. The way vibrational data is gathered and processed has been completely transformed into Industry 4.0 by the combination of sensors, Internet of Things (IoT) devices, and real-time data analytics. Advanced signal processing methods like wavelet analysis, machine learning algorithms, and Fast Fourier Transform (FFT) allow manufacturers to identify equipment breakdowns early on, limiting downtime and guaranteeing predictive maintenance[17, 23]. With the advent of Industry 5.0, human-centric methods are the focus. In smart factories, collaborative robots, or cobots, operate alongside humans, and vibrational analysis is increasingly utilizing artificial intelligence (AI) and big data analytics.

A defect detection system that is more intelligent and adaptive is made possible by these advancements; it can recognize error in real time, learn from historical data, and even recommend optimization tactics. This change is intended to increase industrial processes' accuracy, effectiveness, and adaptability so that businesses may swiftly adjust to shifting demands, boost output, and establish safer working conditions[16, 23, 27]. The next frontier for vibrational analysis in smart factories will be the smooth fusion of AI-driven diagnostics and human intuition, made possible by ongoing advancements in sensor technology, data processing, and computing power.

Key Components of Vibrational Analysis

Vibration analysis is an advanced diagnostic technique used to evaluate the condition of equipment and identify mechanical issues. To monitor, measure, analyze, and interpret vibration data, a few components must cooperate[2]. Vibration analysis's essential elements include the following:

Vibration Sensor and Data Acquisition

Vibration Sensor

The vibration sensor serves as the main part for recording vibration data. These sensors translate the motion of vibrating machinery into electrical signals to detect and quantify mechanical vibrations. Typical kinds of vibration sensors are as follows:

Accelerometers:

The most often used sensors in vibration analysis are these ones. They can detect vibrations at high frequencies and quantify the acceleration of an object in one or more axes. There are several uses for accelerometers, ranging from tracking structural health to identifying imbalances.

Velocity Transducers:

These sensors measure the velocity of vibration and are generally used for low-frequency vibrations. They are particularly useful for identifying faults like misalignment, imbalance, and bearing wear.

Displacement Probes:

These sensors measure the displacement or distance traveled by an object due to vibration. Displacement probes are typically used for detecting large amplitude oscillations or low-frequency vibrations, such as those associated with unbalance in rotating machinery.

Strain Gauges:

These sensors measure the strain or deformation that occurs in a structure due to mechanical stress or vibration. Strain gauges are often used in structural monitoring to detect stresses that may indicate cracks or material fatigue.

Data Acquisition System (DAQ)

The Data Acquisition System (DAQ) is an essential part that gathers and analyzes the vibration sensors data. The sensors are connected to it, and the analog signals are amplified and converted into digital formats before being sent to a processing unit for analysis. The DAQ system is made up of various essential components:

Signal Conditioning:

Signal conditioning equipment is used to make sure the data is in the right format for analysis because sensor raw data is frequently in analog form. Analog-to-digital converters (ADCs) are devices that transform analog signals into digital form, filters to eliminate noise, and amplifiers to increase signal intensity.

Real-Time Data Transmission:

Wireless communication and real-time data transfer to central monitoring systems are supported by a large number of contemporary DAQ systems. This makes it possible to continuously monitor the condition of the equipment without requiring user intervention and guarantees that data is accessible for prompt analysis and decision-making.

Storage and Processing:

After digitization, the data is sent to a computer or cloud-based system for storage and subsequent analysis. Long-term data tracking and remote access are made possible by the DAQ system's integration with cloud platforms or built-in storage options.

Synchronization:

The DAQ system guarantees precise synchronization of data from various sensors in applications with many sensors, allowing for the examination of the entire spectrum of vibrations and their effects on machinery.

In conclusion, vibration sensors and data acquisition systems are essential components in the process of monitoring and analyzing machinery health. Together, they enable continuous, real-time collection of vibration data, which can be used for diagnosing faults, predicting failures, and optimizing the performance and lifespan of equipment[1, 2, 6, 9, 26]. With advancements in sensor technology and DAQ systems, the future of vibration analysis is set to become even more powerful and automated, allowing for smarter, more efficient industrial operations.

Signal Processing and Analysis

In vibration analysis, signal processing and analysis are essential because they convert unprocessed data into useful information for defect finding and maintenance. Signal acquisition is the first step in the process, during which vibration signals from machinery are captured by sensors such displacement probes, accelerometers, and velocity transducers. These analog signals, which are frequently weak or noisy, show the equipment's dynamic behavior[10, 26]. Signal conditioning, which involves boosting the signal,

removing noise or unnecessary frequencies, and transforming the analog signals into digital form using an analog-to-digital converter, is used to make sure the data is appropriate for analysis. Following data conditioning, signal transformation is the next stage, during which time-domain and frequency-domain analysis techniques are used. Time-domain analysis helps identify abrupt spikes or abnormalities by analyzing how vibration amplitude varies over time. The Fast Fourier Transform (FFT), which is frequently used in frequency-domain analysis, separates the signal into its component frequencies and makes it possible to identify certain fault frequencies associated with problems like imbalances or bearing failures. By precisely interpreting the vibration data, this thorough signal processing methodology makes it possible to identify possible mechanical faults and support predictive maintenance plans.

Condition Monitoring

Condition monitoring is the practice of testing the operational performance of machinery and equipment on a regular or periodic basis to identify possible problems before they result in failure. It is a crucial part of predictive maintenance plans and entails evaluating the condition of machinery using a variety of monitoring methods, including vibration analysis, temperature monitoring, pressure measurement, and oil analysis. Condition monitoring helps detect abnormal conditions like wear, misalignment, imbalance, or lubrication issues by regularly monitoring these signs. This enables maintenance personnel to take early action and prevent expensive unscheduled downtime. Installing sensors (such as accelerometers) on crucial pieces of machinery to measure vibrations and track their trends over time is a common practice in vibration analysis condition monitoring[15, 22, 25]. After the data is gathered, it is processed and examined to look for any variations in standard operating procedures.

Real-time monitoring systems give constant input, and maintenance staff are alerted by alarms or messages when vibrations surpass a preset level. This makes it possible to take prompt maintenance measures, such fixing or replacing parts, to stop equipment failure[15]. In addition to increasing machine dependability, condition monitoring also helps to prolong equipment life, optimize maintenance plans, and lower operating expenses. By switching from reactive to proactive maintenance, it improves overall operating efficiency and guarantees that equipment operates safely, smoothly, and with few disruptions.

In summary, the key components of vibration analysis include sensors to capture vibrations, signal conditioning equipment to process the data, a data acquisition system to collect and transmit the data, analysis software to interpret the information, fault detection algorithms, and real-time monitoring systems to provide alerts. These components work together to provide an integrated system for identifying and diagnosing mechanical issues in machinery, ultimately improving predictive maintenance and operational efficiency.

Benefits of advanced Vibrational Analysis in Smart Factories:

Smart factory performance and efficiency are greatly enhanced by advanced vibrational analysis. Using extensive vibrational analysis in smart manufacturing has some major advantages as shown in Figure 7.

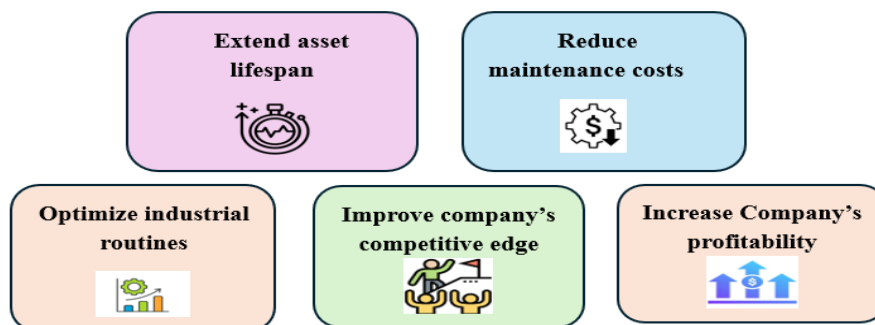


Figure 7. Benefits of Vibration Analysis

Predictive maintenance (PdM)

PdM is a cutting-edge method of managing industrial machinery that anticipates possible faults before they happen by utilizing real-time data and analytics. Using sensors that measure variables like vibration, temperature, pressure, and rotational speed, this approach depends on ongoing equipment health monitoring. PdM systems can evaluate this data and identify trends and anomalies that point to wear or imminent failure by combining technologies such as IoT, AI, and machine learning. Advanced vibrational analysis is one of the most important PdM tools[5, 16]. It monitors vibration frequencies to help find problems like misalignment, imbalance, or bearing wear. Maintenance can be planned before a failure occurs since these systems can predict when a part will fail through continuous trend analysis. This proactive approach reduces downtime, extends the life of equipment, and minimizes unnecessary maintenance, leading to improved efficiency and cost savings for industries. Figure 8 shows the architecture of a predictive maintenance planning model.

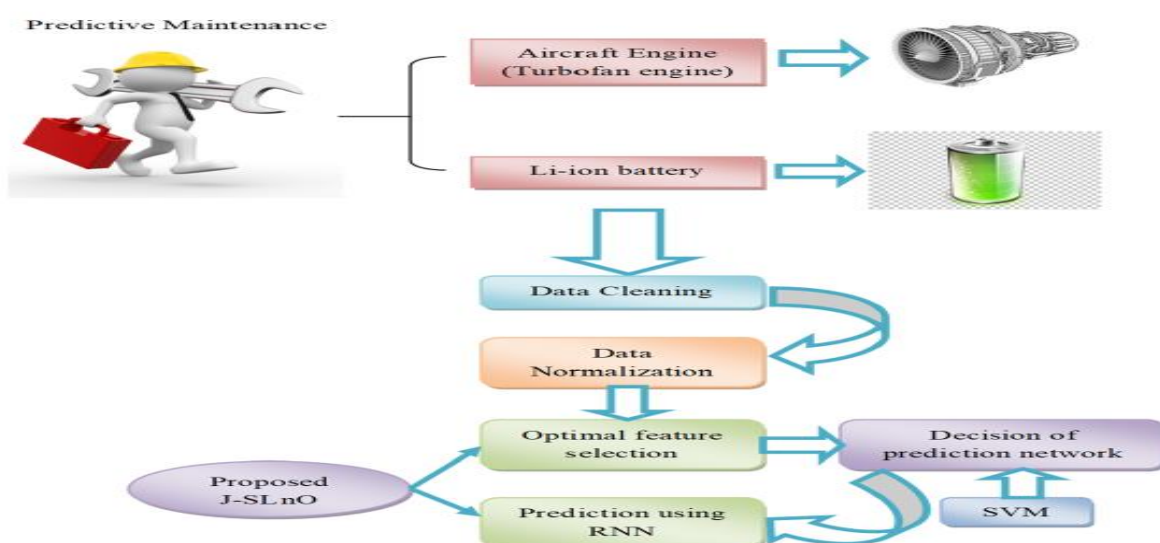


Figure 8. Architecture of proposed predictive maintenance planning model[21]

Real-Time Monitoring and Remote Diagnostics:

Remote diagnostics and real-time monitoring are crucial elements of present industrial processes, especially in smart factories. Real-time monitoring makes it possible to continuously observe manufacturing processes and machines by combining IoT sensors with sophisticated data analytics. By seeing possible problems like misalignment, wear, or inefficiencies as they arise, this offers insightful information on the functionality and health of equipment. This is further improved by remote diagnostics, which allow engineers or operators to examine and troubleshoot issues from any place without having to be physically present on-site[15, 23]. By resolving problems early before they worsen, this capability reduces operational downtime in addition to expediting the problem-solving process. Additionally, machine learning algorithms and remote diagnostics can be used to forecast faults and suggest remedial measures, guaranteeing timely and economical maintenance. A more responsive and effective manufacturing environment results from the combination of remote diagnostics and real-time monitoring.

Data-Driven Decision Making

Advanced vibration analysis systems collect and analyze large volumes of data over time, providing insights into equipment performance and health trends. This data supports better decision-making, enabling factories to implement proactive maintenance strategies and allocate resources more effectively. Figure 9 represents the schematic representation of the relationship between big data analytics and smart factories.

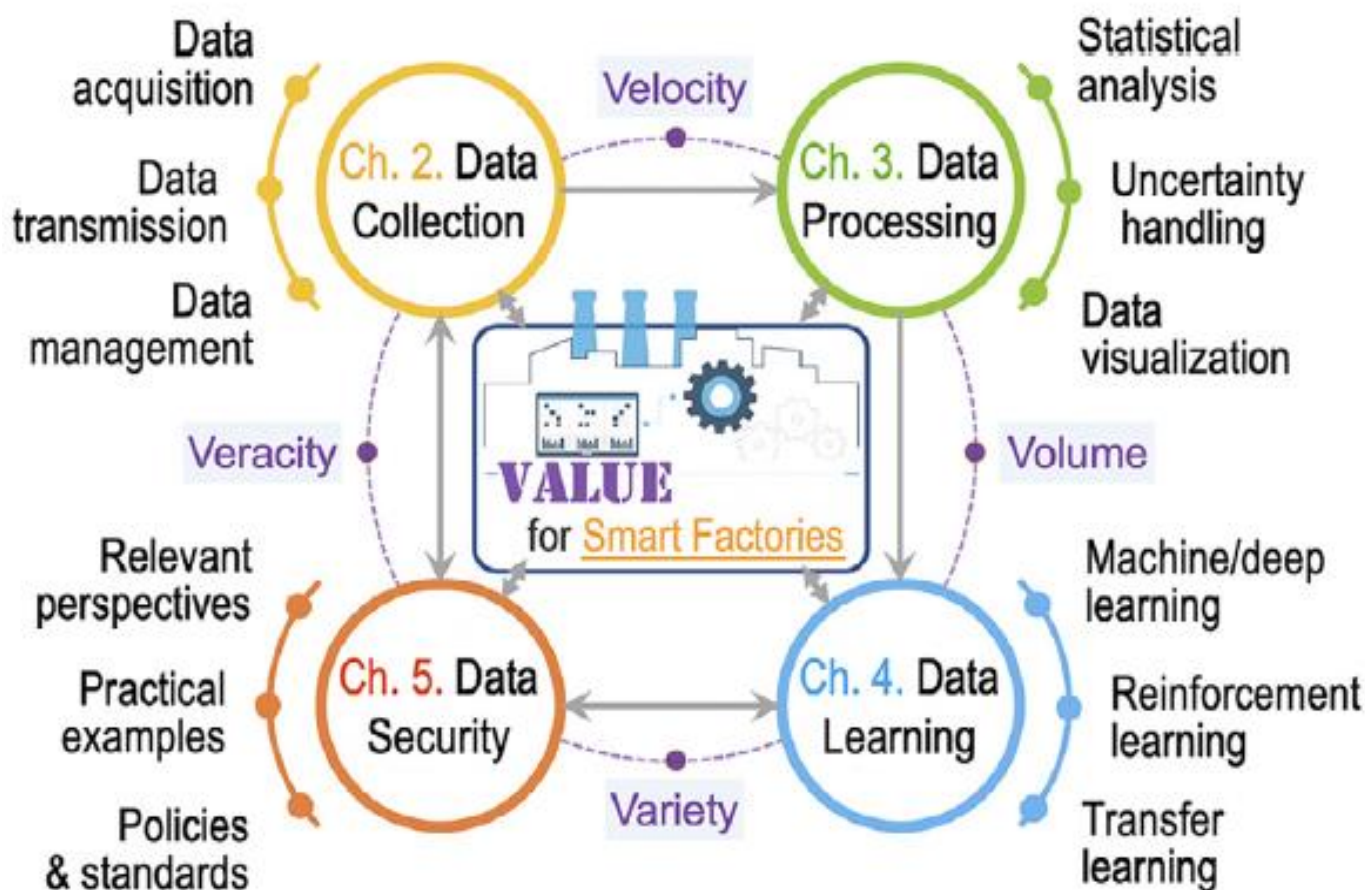


Figure 9. Schematic relationship among key elements in big data analytics and smart factories[24]

Improved Operational Efficiency

In smart factories, advanced vibration analysis greatly improves operational efficiency by reducing production processes and averting unplanned machinery failures. Businesses may identify and fix possible issues before they result in expensive downtime by using real-time equipment health monitoring. By ensuring that equipment runs at optimal efficiency, this proactive strategy lowers production delays and permits continuous workflows. Furthermore, by using predictive insights to optimize maintenance plans, wasteful repairs and interventions are reduced, freeing up resources for other important duties[7]. In addition to helping companies regularly fulfill production goals, these upgrades also increase overall productivity, which guarantees more efficient operations and higher profitability in highly competitive manufacturing contexts.

Reduced downtime and cost

The two biggest advantages of improved vibration analysis in smart factories are decreased downtime and cost. Vibration analysis allows for the real-time, continuous monitoring of machinery health, allowing for the early identification of possible problems like imbalance, wear, or misalignment before they become serious failures. Unplanned downtime is mostly caused by unplanned breakdowns, which are reduced by this proactive strategy. Factories can prevent expensive production halts by scheduling repairs or part replacements during scheduled maintenance periods with predictive maintenance[7, 9, 13, 26].

Advanced vibration analysis also contributes to minimizing maintenance costs by decreasing the frequency of unscheduled shutdowns and emergency repairs. By ensuring that maintenance activities are focused only when required, it also improves resource allocation by cutting down on needless labor, parts, and equipment use. By reducing the interruptions and inefficiencies brought on by downtime, factories can increase their bottom line in addition to saving money on direct repair expenses. In conclusion, sophisticated vibration analysis contributes to increased uptime, reduced operating expenses, and enhanced financial performance in smart factories.

Technologies Enhancing Vibration Analysis in Smart Factories

Enhancing vibration monitoring, detection, and analysis through a variety of cutting-edge technologies has been the focus of recent research on vibration analysis in smart factories. These technologies enhance overall system efficiency, maximize equipment performance, and identify issues early. One of the smart developments that can be incorporated in vibration analysis for smart factories is depicted in Figure 10.

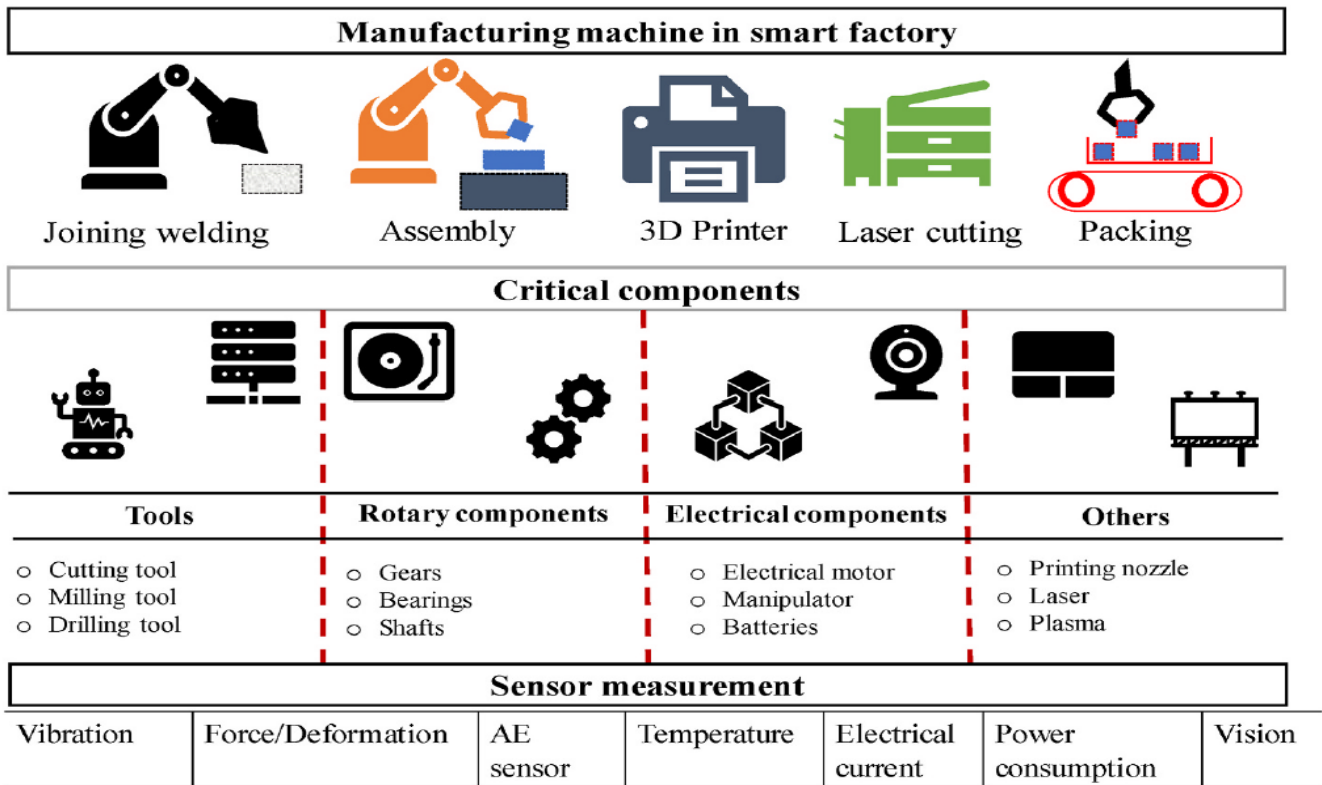


Figure 10. Different machines, key components, and sensor measurement types used in the Smart Factory[7].

Industrial Internet of Things (IIoT)

By connecting machinery via networks of sensors and actuators, the IIoT has revolutionized vibration analysis. IIoT-enabled sensors send information to edge or centralized processing systems while continuously monitoring vibration levels. These systems make it possible to monitor in real time, which speeds up the identification of irregularities and the implementation of preventative measures. While edge computing minimizes latency by processing data close to the source, cloud integration further improves the scalability and accessibility of vibration data. A motor that exhibits odd vibration patterns, for example, can immediately send out alerts, requiring fast repair to prevent catastrophic failures[1, 3, 26].

Wireless Sensor Networks (WSNs)

The versatility of vibration monitoring has been greatly expanded by wireless sensor networks. Unlike conventional wired systems, WSNs are simple to set up, even in intricate factory settings with gear that is hard to reach. Due to the dispersed data collection made possible by these networks, the manufacturing floor can be thoroughly monitored. Lower installation costs, simplicity in scaling, and less setup disturbance are some of its advantages. But to guarantee reliable performance, WSNs must overcome issues including signal interference and battery life.

Artificial Intelligence (AI) and Machine Learning (ML)

The use of AI and ML technologies is essential for deriving useful conclusions from vibration data. By analyzing patterns and forecasting probable equipment breakdowns, machine learning algorithms make predictive maintenance possible. For instance, an ML model may be able to identify early indicators of bearing wear by picking up on minute variations in vibration amplitude and frequency. Systems driven by AI can also categorize flaws, differentiating between problems like looseness, unbalance, and misalignment[17, 23]. These systems gradually increase their accuracy through ongoing learning, which lowers false alarms and boosts dependability.

Digital Twins

In a controlled setting, engineers can model and examine the behavior of machinery by using digital twins, which are virtual replicas of physical assets. Real-time vibration data is integrated into digital twins to forecast future circumstances and offer insights into the functioning of existing equipment. A conveyor belt system's digital twin, for example, can model different operating conditions and see possible problems before they arise[3, 25]. Not only does this proactive approach improve reliability, but it also facilitates design and maintenance decision-making.

Advanced Signal Processing Techniques

Complex signal processing techniques are used in modern vibration analysis to glean valuable information from unprocessed data. Finding frequency components using methods like the Fast Fourier Transform (FFT) aids in the detection of problems like imbalance or resonance. However, non-stationary signals, like the brief vibrations brought on by abrupt strikes, are ideally analyzed by wavelet transformations[5, 16]. An essential feature of many machines, rolling element bearings, are especially susceptible to early-stage defects that envelope analysis can detect. Together with other analytics tools, these methods offer a thorough understanding of the condition of the equipment.

Integration with Smart Devices and AR/VR

By integrating simple visualization tools, augmented reality (AR) and virtual reality (VR) technologies significantly improve vibration analysis. By superimposing real-time vibration data onto equipment, AR enables personnel to locate issues more rapidly[16, 23, 27]. Engineers may investigate and identify problems in a virtual environment thanks to VR settings, which provide realistic simulations of factory operations. These technologies lower the possibility of mistakes during repairs and expedite maintenance procedures.

Big Data Analytics

Smart factories generate enormous amounts of vibration data, which calls for advanced analytics tools. To find patterns and irregularities, these datasets are processed and analyzed using big data analytics technologies. Trend analysis, for instance, may show a motor's slow degeneration, allowing for preventative maintenance[24]. Algorithms for anomaly detection can identify

departures from typical functioning, exposing new flaws. With the use of this data, firms may more efficiently manage maintenance resources and maximize the performance of their machines.

Blockchain for Secure Data Sharing

Blockchain technology guarantees the safe exchange of vibration data between several parties in collaborative manufacturing ecosystems. Data integrity is preserved by blockchain's decentralized ledger, which guarantees authenticity and guards against manipulation. It also improves operational openness and trust by granting regulated access to critical data. To guarantee that quality requirements are fulfilled, for instance, suppliers and manufacturers can safely share vibration analysis information.

These cutting-edge technologies are incorporated with vibration monitoring to give smart factories accurate, real-time insights into the condition of their gear. With IIoT, wireless sensors, artificial intelligence, digital twins, and other advances, manufacturers can shift from reactive to predictive maintenance methods[11, 14, 16]. Even if issues like scalability, system integration, and data security still exist, new developments have the potential to increase efficiency even further. In the age of Industry 4.0, the implementation of these technologies is not only improving operational reliability but also propelling manufacturing's whole transformation.

Application of Vibration Analysis in Smart Factories

Advanced Sensing Technologies

Smaller MEMS Sensors: Contemporary MEMS sensors are small, low power consumption, and able to monitor vibrations with high resolution. Incorporating vibration analysis into IIoT frameworks requires these sensors[6].

Energy Harvesting: Sensors that use piezoelectric materials can be deployed for extended periods of time without the need for batteries. Wireless connectivity is now possible even in distant or difficult-to-reach machines thanks to high-frequency wireless sensors.

Key Study: A European research project created a self-powered MEMS sensor in 2022 that can capture vibration energy from the environment. Therefore, vibration monitoring systems are now more flexible and sustainable.

Real-Time Analysis with Edge Computing

Localized Processing: By analyzing vibration data close to the source, edge computing lowers latency. For real-time applications where a prompt reaction is required, this is especially crucial.

Scalability: By enabling dispersed monitoring of numerous machines, edge devices do away with the requirement for centralized solutions.

Key Study: In 2024, an implementation showed how to analyze industrial motor vibration in real time using microcontrollers and AI inference algorithms. Therefore, lower network bandwidth needs and quicker fault identification.

Integration with Digital Twins

Dynamic Updates: Digital twins receive real-time vibration data, which improves their precision in forecasting how equipment would behave in different scenarios.

Virtual testing of vibration patterns is made possible by digital twins, which allow for the prediction of possible problems without affecting actual machinery.

Key Study: To optimize the performance of industrial pumps, Siemens' 2023 innovation integrated digital twins and vibration analysis. Moreover, enhanced maintenance planning and improved operational reliability.

Data Fusion and Multimodal Analysis

Integrated Monitoring: To give a complete picture of the health of the machinery, vibration data is being integrated with additional signals such as thermal imaging and sound emissions.

AI Applications: To improve fault diagnosis, fusion techniques use machine learning (ML) to correlate various data kinds.

Key Study: In 2022, a study combined heat and vibration data to detect motor defects early on, finding higher detection rates than single-signal techniques. Furthermore, more accurate diagnostics and reduced equipment downtime.

Rapid developments in sensing technology, AI-driven analytics, and system integration are evident in recent studies on vibration analysis for smart factories. As a result of these advancements, smart factories are becoming robust, efficient, and adaptive spaces that can maximize operational performance and minimize downtime. Through the use of cutting-edge technologies such as edge computing, digital twins, and secure IIoT frameworks, vibration analysis remains a fundamental component of Industry 4.0's predictive maintenance and process optimization.

Challenges and Future direction

A vital tool for predictive maintenance and operational effectiveness in smart factories is vibration analysis. Businesses may anticipate breakdowns, streamline operations, and cut downtime by spotting patterns in machine vibrations. Even still, a few obstacles prevent its broad adoption, even while new developments and continuous research open intriguing new avenues for the future. With vibration sensors placed throughout smart factories, the enormous amount of data they generate is one of the biggest problems[3]. As Industry 4.0 has emerged, IoT-enabled devices that continuously gather machine performance data have proliferated. To handle, store, and analyze this enormous volume of data, powerful analytics tools and strong data infrastructures are needed. Researchers are investigating novel approaches to efficiently handle data without sacrificing speed or accuracy, such as distributed data storage and federated learning. An important obstacle is also the integration of legacy systems with contemporary vibration analysis technologies. Older machinery used in many factories is unable to easily integrate with contemporary sensors. It can be expensive and technically difficult to retrofit such systems. Recent developments aim to solve this by creating affordable, plug-and-play sensor solutions that work with different kinds of machines.

The positioning and upkeep of sensors present another difficulty. The accuracy of vibration data depends on the positioning of the sensor. Inaccurate interpretations from misplaced sensors can result in inefficiency. Additionally, sensors themselves need to be calibrated and replaced on a regular basis due to wear and failure. Self-calibrating sensors, which can adapt to shifting ambient conditions and lower maintenance needs, have shown promise in recent investigations. Concurrently, as systems become more interconnected, worries about data security and privacy have increased[17, 27]. Because smart factories are susceptible to cyberattacks, it is crucial to protect vibration data and preserve the accuracy of predictive maintenance systems. Blockchain

technology research is showing promise for improving the security of vibration monitoring systems by producing tamper-proof data logs.

Implementation issues are made worse by vibration analysis's lack of standardization. System interoperability is hampered by differences in sensor designs, data formats, and processing techniques. Currently, business and academia are working together to create universal standards that will promote higher scalability and compatibility. Furthermore, a major obstacle is the workforce's competency gap. Proficiency in domains like maintenance engineering, machine learning, and signal processing is necessary for efficient vibration analysis. To solve this, automated diagnostic tools and user-friendly interfaces have been developed, enabling non-experts to do sophisticated vibration analysis.

Future developments in machine learning and artificial intelligence (AI) are expected to completely transform vibration analysis[17, 18, 23]. AI-driven analytics may more precisely optimize maintenance plans, identify anomalies, and forecast equipment failures. Subtle patterns in vibration data that were previously invisible can now be found thanks to machine learning algorithms that have been trained on large datasets. Additionally, edge computing is becoming increasingly popular to handle vibration data nearer to the source, lowering latency and need on centralized cloud services. For edge devices, researchers are creating lightweight AI algorithms that allow for real-time monitoring and decision-making.

Wireless sensor network (WSN) adoption is another encouraging trend. Traditional wired sensors frequently have issues with physical limitations and installation expenses. Battery-less sensor designs, and energy-efficient communication protocols are two recent developments in WSNs that are increasing the scalability and flexibility of vibration monitoring[4, 18]. Digital twin technology has the potential to be revolutionary as well. Businesses may improve the accuracy of diagnostics and preventive maintenance plans by simulating and forecasting how equipment will behave in different scenarios by building virtual models of their machines. To bridge the gap between theoretical and practical understanding, researchers are integrating augmented reality (AR) and digital twins for immersive maintenance training and visualization.

As businesses strive to create consistent procedures for data gathering and analysis, standardization efforts are also gaining traction. To facilitate the smooth integration of vibration analysis systems across various platforms, these projects seek to enhance interoperability. To safeguard sensitive data, more sophisticated cybersecurity solutions are being created, such as threat detection systems driven by artificial intelligence and advanced encryption methods. Future developments in vibration analysis are also being influenced by sustainability factors[17]. To ensure that the deployment of these systems is in line with international sustainability standards, researchers are concentrating on environmentally friendly materials and energy-efficient sensors. Cross-referencing vibration data with other performance measures for thorough optimization can also yield full insights into factory operations through the integration of vibration analysis with larger IoT and big data ecosystems.

In overall, even if issues like data overflow, sensor upkeep, cybersecurity, and standardization still exist, continuous research and technical developments are propelling notable breakthroughs in vibration analysis for smart factories. Digital twins, edge computing, WSNs, and AI integration hold potential for improving manufacturing processes' sustainability, dependability, and efficiency[5, 23]. The foundation of predictive maintenance and operational excellence in smart factories will continue to develop as vibration analysis overcomes current obstacles and adopts new advances.

II. Conclusion

In smart factories, vibration analysis is essential to predictive maintenance since it ensures operational efficiency, minimizes downtime, and prolongs the life of machinery. Smart factories can forecast errors before they happen, monitor equipment health, and identify anomalies by utilizing real-time data analytics and advanced sensors. In addition to minimizing unforeseen disruptions, this proactive strategy improves maintenance schedules, which lowers costs and boosts productivity. Furthermore, the incorporation of vibration analysis with AI and IoT technologies enables ongoing manufacturing process improvement. By making it possible to gather and analyze complicated data patterns with ease, these systems promote advancements in machine learning algorithms and a better comprehension of how equipment behaves. As smart factories develop, vibration analysis will remain crucial to realizing Industry 4.0's goal of redefining manufacturing through intelligent, networked systems.

In summary, vibration analysis supports sustainable and effective production systems by enabling smart factories to switch from reactive to predictive maintenance techniques. In the future, there will be even more opportunities to use vibration analysis to build robust and flexible manufacturing environments by virtue of continuous developments in sensor technology, data analytics, and artificial intelligence.

Reference

1. Cheng FT, Tieng H, Yang HC, et al (2016) Industry 4.1 for Wheel Machining Automation. *IEEE Robot Autom Lett* 1:332–339. <https://doi.org/10.1109/LRA.2016.2517208>
2. Mohd Ghazali MH, Rahiman W (2021) Vibration Analysis for Machine Monitoring and Diagnosis: A Systematic Review. *Shock and Vibration* 2021
3. Zhang J, Zhang Y, Song B, et al (2023) Vibration Detection Based on Multi-Sensor Information Fusion for Industrial Internet of Things. In: *IEEE Vehicular Technology Conference*. Institute of Electrical and Electronics Engineers Inc.
4. Pech M, Vrchota J, Bednár J (2021) Predictive maintenance and intelligent sensors in smart factory: Review. *Sensors* 21:1–39
5. Hector I, Panjanathan R (2024) Predictive maintenance in Industry 4.0: a survey of planning models and machine learning techniques. *PeerJ Comput Sci* 10:1–50. <https://doi.org/10.7717/peerj-cs.2016>
6. Singh A, Nawayseh N, Dhahi YK, et al (2024) Transforming farming with intelligence: Smart vibration monitoring and alert system. *Journal of Engineering Research (Kuwait)* 12:190–199. <https://doi.org/10.1016/j.jer.2023.08.025>
7. Kumar P, Raouf I, Kim HS (2023) Review on prognostics and health management in smart factory: From conventional to deep learning perspectives. *Eng Appl Artif Intell* 126
8. Wang X, Wang Y, Yang J, et al (2024) The survey on multi-source data fusion in cyber-physical-social systems: Foundational infrastructure for industrial metaverses and industries 5.0. *Information Fusion* 107
9. Soori M, Arezoo B, Dastres R (2023) Internet of things for smart factories in industry 4.0, a review. *Internet of Things and Cyber-Physical Systems* 3:192–204
10. Williams J (2024) Smart sensor technologies for real-time monitoring in machining: A review and prospects. ~ 22 ~ *International Journal of Machine Tools and Maintenance Engineering* 5:
11. Rehman SU, Usman M, Toor MHY, Hussaini QA (2024) Advancing structural health monitoring: A vibration-based IoT approach for remote real-time systems. *Sens Actuators A Phys* 365:. <https://doi.org/10.1016/j.sna.2023.114863>
12. Gopinath A, Teoh JW, Tagade P, et al (2023) Smart vibratory peening: An approach towards digitalisation and integration of vibratory special process into smart factories. *Eng Appl Artif Intell* 126:. <https://doi.org/10.1016/j.engappai.2023.107118>

13. Asachi M, Alonso Camargo-Valero M (2023) Multi-sensors data fusion for monitoring of powdered and granule products: Current status and future perspectives. *Advanced Powder Technology* 34:.. <https://doi.org/10.1016/j.apt.2023.104055>
14. Elsamanty M, Ibrahim A, Saady Salman W (2023) Principal component analysis approach for detecting faults in rotary machines based on vibrational and electrical fused data. *Mech Syst Signal Process* 200:.. <https://doi.org/10.1016/j.ymssp.2023.110559>
15. Yan W, Wang J, Lu S, et al (2023) A Review of Real-Time Fault Diagnosis Methods for Industrial Smart Manufacturing. *Processes* 11
16. Singh A, Nawayseh N, Samuel S, et al (2023) Real-time vibration monitoring and analysis of agricultural tractor drivers using an IoT-based system. *J Field Robot* 40:1723–1738. <https://doi.org/10.1002/rob.22206>
17. Cabal-Yepez E, Garcia-Ramirez AG, Romero-Troncoso RJ, et al (2013) Reconfigurable monitoring system for time-frequency analysis on industrial equipment through STFT and DWT. In: *IEEE Transactions on Industrial Informatics*. pp 760–771
18. Kandavalli SR, Khan AM, Iqbal A, et al (2023) Application of sophisticated sensors to advance the monitoring of machining processes: analysis and holistic review. *International Journal of Advanced Manufacturing Technology* 125:989–1014
19. Muñiz R, Nuño F, Díaz J, et al (2023) Real-time monitoring solution with vibration analysis for industry 4.0 ventilation systems. *Journal of Supercomputing* 79:6203–6227. <https://doi.org/10.1007/s11227-022-04897-3>
20. Al Mamun A, Bappy MM, Mudiyansele AS, et al (2023) Multi-channel sensor fusion for real-time bearing fault diagnosis by frequency-domain multilinear principal component analysis. *International Journal of Advanced Manufacturing Technology* 124:1321–1334. <https://doi.org/10.1007/s00170-022-10525-4>
21. Abidi MH, Mohammed MK, Alkhalefah H (2022) Predictive Maintenance Planning for Industry 4.0 Using Machine Learning for Sustainable Manufacturing. *Sustainability (Switzerland)* 14:.. <https://doi.org/10.3390/su14063387>
22. Liu Z, Xie K, Li L, Chen Y (2020) A paradigm of safety management in Industry 4.0. *Syst Res Behav Sci* 37:632–645. <https://doi.org/10.1002/sres.2706>
23. Kumar P, Shih GL, Yao CK, et al (2023) Intelligent Vibration Monitoring System for Smart Industry Utilizing Optical Fiber Sensor Combined with Machine Learning. *Electronics (Switzerland)* 12:.. <https://doi.org/10.3390/electronics12204302>
24. Gao RX, Wang L, Helu M, Teti R (2020) Big data analytics for smart factories of the future. *CIRP Annals* 69:668–692. <https://doi.org/10.1016/j.cirp.2020.05.002>
25. Gawde S, Patil S, Kumar S, et al (2024) An explainable predictive maintenance strategy for multi-fault diagnosis of rotating machines using multi-sensor data fusion. *Decision Analytics Journal* 10:.. <https://doi.org/10.1016/j.dajour.2024.100425>
26. Zhang H, Zanchetta P, Bradley KJ, Gerada C (2010) A low-intrusion load and efficiency evaluation method for in-service motors using vibration tests with an accelerometer. *IEEE Trans Ind Appl* 46:1341–1349. <https://doi.org/10.1109/TIA.2010.2049550>
27. Ooi BY, Beh WL, Lee WK, Shirmohammadi S (2020) A Parameter-Free Vibration Analysis Solution for Legacy Manufacturing Machines' Operation Tracking. *IEEE Internet Things J* 7:11092–11102. <https://doi.org/10.1109/JIOT.2020.2994395>