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EXPERIMENTAL STUDY ON VIBRATION CHARACTERISTICS OF AN AC SYNCHRONOUS MOTOR AND THEIR ENVIRONMENTAL IMPACT

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ABSTRACT: Electric machinery serves as a fundamental driving force in various industrial production processes. The three-phase synchronous motor is the most widely recognized type of electric machinery used in industrial plants due to its robust structure, high power output, and ease of maintenance. However, unexpected motor failures can lead to production disruptions. Since one of the key factors contributing to motor failure is vibration, this article presents an analysis of the vibration characteristics of an AC motor and examines its environmental impact. Since moving machinery inherently generates vibrations, this study specifically investigates the vibrations occurring both at the motor itself and at its mounting base. These vibrations can significantly affect the surrounding physical environment, including the buildings and facilities where the motor is installed. Experimental comparisons of vibration levels reveal that the vibration characteristics of an AC motor vary at different positions, including drive end, non-drive end, and motor base. Measurements indicate that the non-drive end exhibits the highest vibration levels under all load conditions, since the rotor shaft extends the farthest from the stator at the non-drive end, leading to increased oscillations. In contrast, the motor base experiences the lowest vibration levels since it is not directly attached to the motor. The findings from this study will contribute to the development of predictive maintenance strategies. The failures are typically detected after they occur, resulting in repair delays, downtime, and production losses. Identifying potential motor failures in advance can reduce operational disruptions, minimize maintenance costs, and improve overall efficiency.

Keywords: AC Motor, Synchronous Motor, Environmental Impact, Vibration Signal Analysis, Fast Fourier Transform

1. INTRODUCTION

Vibration and noise are intrinsic dynamic phenomena in industrial manufacturing systems, predominantly arising from rotating machinery and mechanically coupled components. These effects represent not only unavoidable byproducts of operation but also critical indicators of mechanical integrity, structural stability, and system-level performance. Excessive vibration accelerates material fatigue, promotes mechanical looseness and misalignment, and significantly shortens equipment service life. In parallel, vibration-induced noise contributes to environmental pollution and occupational health risks, particularly in densely integrated industrial facilities. As a result, vibration and noise analysis has become a cornerstone of modern condition monitoring and sustainable industrial operation [1, 2].

Electric motors, especially three-phase AC synchronous motors, function as indispensable prime movers in a wide range of industrial applications, including automated production lines, HVAC systems, energy conversion units, and precision manufacturing equipment. Their popularity stems from high power density, operational reliability, and favorable efficiency characteristics. Nevertheless, the electromechanical energy conversion process inherently generates dynamic excitation forces due to electromagnetic interactions, rotor imbalance, bearing dynamics, and load variations. These forces induce structural vibrations that propagate through the motor housing and mounting interface, potentially affecting adjacent machinery, foundation structures, and the surrounding built environment [1–3].

The magnitude and spectral distribution of motor-induced vibration are governed by a complex interaction of design parameters, such as rotor–stator geometry, electromagnetic force harmonics, shaft stiffness, bearing configuration, load characteristics, and installation conditions. Inadequate mounting stiffness or improper foundation design may amplify vibration transmission and excite structural resonances, thereby increasing noise radiation and structural stress. As industrial systems continue to evolve toward higher power densities and compact layouts, the mitigation of vibration and its environmental impact have emerged as a critical design and operational challenge [2–5].

Dynamic characterization and vibration-based diagnostics have long been established as fundamental tools for assessing mechanical system health. Prior studies have demonstrated that accurate identification of natural frequencies and modal properties is essential for avoiding resonance-induced performance degradation and improving operational stability in machine tools and rotating machinery [3, 6]. Complementary diagnostic approaches, including acoustic-based fault detection and high-resolution spectral analysis, have further expanded the scope of condition monitoring, offering non-invasive alternatives for fault identification in electric motors [4, 7]. Despite these advances, vibration signals remain the most direct and information-rich representation of mechanical excitation and structural response.

Recent research has placed increasing emphasis on reducing electromagnetic vibration and noise through motor design optimization. Investigations into permanent magnet and high-speed motors have shown that targeted modifications to electromagnetic force distribution and winding configuration can substantially reduce vibration and acoustic emissions without compromising performance [5, 8]. In parallel, system-level analyses of coupled mechanical structures have highlighted the importance of asymmetrical boundary conditions and stiffness distribution in vibration amplification and transmission phenomena [7, 9]. These findings collectively underscore the need for integrated analysis of motor dynamics and structural interaction.

Advanced signal processing techniques based on vibration and acoustic measurements have demonstrated strong diagnostic capabilities across various mechanical systems. FFT-based intrinsic factor analysis and correlation methods have been successfully applied to internal combustion engines for fault discrimination and operational characterization under varying conditions [8–11]. The robustness and adaptability of these techniques motivate their extension to AC motor vibration analysis, particularly in the context of predictive maintenance and environmental impact assessment.

2. RESEARCH SIGNIFICANCE

Despite extensive studies on vibration and noise in electric motors, important gaps remain. Most research focuses on internal dynamics or isolated measurement points, providing limited understanding of vibration distribution across different motor locations. In addition, vibration transmission from the motor to its mounting base and surrounding structures, which is essential for evaluating environmental impact, has not been systematically quantified. Furthermore, industrial maintenance is still largely reactive, with vibration-related faults often detected only after failure, causing unplanned downtime and increased costs. These issues highlight the need for a comprehensive vibration analysis framework addressing both machine health and environmental vibration transmission.

3. MATERIAL AND METHODS

3.1 Contributions of This Study

To address the aforementioned limitations, this study makes the following key contributions:

Multi-location vibration characterization: Vibration signals are systematically measured and analyzed at the drive end, non-drive end, and mounting base of an AC synchronous motor, enabling a detailed comparison of spatial vibration characteristics under varying load conditions.

Quantification of vibration transmission to the foundation: The study explicitly evaluates vibration levels at the motor base to assess the extent of vibration propagation to supporting structures, thereby providing insight into the environmental impact of motor operation.

FFT-based analytical framework with customized feature extraction: A frequency-domain analysis framework based on the Fast Fourier Transform is developed and enhanced with tailored feature extraction techniques adapted from established intrinsic factor analysis methodologies, improving sensitivity to load-dependent vibration behavior.

Implications for predictive maintenance strategies: By identifying location-specific vibration characteristics and transmission patterns, the proposed approach supports early detection of abnormal operating conditions and contributes to the development of robust predictive maintenance strategies aimed at reducing downtime and lifecycle costs.

Relevance to sustainable industrial systems: The findings provide practical guidance for motor installation, vibration isolation, and foundation design, supporting environmentally compatible and sustainable operation of industrial motor-driven systems.

3.2 Operating Principle of AC Synchronous Motor

The operating principle of an AC synchronous motor is fundamentally governed by the electromechanical interaction between a rotating magnetic field (RMF) produced by the stator windings and a magnetic field established within the rotor through DC excitation. When a balanced three-phase alternating current is supplied to the stator, spatially displaced windings generate a sinusoidally distributed magnetic field that rotates at a constant angular velocity, known as the synchronous speed. This speed is directly determined by the supply frequency and the number of stator poles, and it remains invariant under steady-state operating conditions. The resulting RMF forms the primary mechanism by which electromagnetic torque is produced in synchronous machines.

The rotor of a synchronous motor is excited by a DC current supplied either through slip rings and brushes or via a brushless excitation system incorporating rotating rectifiers. This excitation establishes a constant magnetic field within the rotor reference frame. When the stator's RMF intersects with the rotor field, a magnetic coupling is formed between the stator and rotor poles. Unlike induction motors, where torque is generated through induced currents and slip, torque production in synchronous motors arises from the tendency of the rotor magnetic field to align with the rotating stator field. This magnetic alignment produces a steady electromagnetic torque that drives the rotor at the same angular velocity as the stator RMF once synchronism is achieved [14].

At standstill, the stator's rotating magnetic field alternates polarity relative to the stationary rotor, subjecting it to a rapidly oscillating torque with zero average value over a complete electrical cycle. As a result, synchronous motors inherently lack self-starting capability. To overcome this limitation, auxiliary starting mechanisms are employed to accelerate the rotor to a speed sufficiently close to the synchronous speed. Common starting techniques include the incorporation of damper (amortisseur) windings embedded in the rotor poles, which function analogously to the squirrel-cage rotor of an induction motor during startup. Alternatively, external prime movers or variable-frequency drives (VFDs) may be used to gradually increase rotor speed. Once the rotor speed approaches the synchronous value, the DC excitation is applied, and the rotor magnetic field becomes magnetically locked with the stator RMF, establishing synchronism [14].

Upon reaching synchronous operation, the rotor rotates at exactly the synchronous speed with zero steady-state slip, regardless of load variations within the rated operating range. This defining characteristic distinguishes synchronous motors from induction motors and makes them particularly suitable for applications requiring precise speed regulation and constant angular velocity. Any increase in mechanical load is accommodated by an increase in the torque angle, defined as the angular displacement between the rotor magnetic axis and the stator RMF, while the rotational speed remains unchanged. However, excessive load or sudden disturbances may cause the torque angle to exceed a critical stability limit, potentially leading to loss of synchronism.

In addition to precise speed control, synchronous motors offer significant advantages in terms of power factor regulation. By adjusting the magnitude of the DC excitation current, the motor can operate at lagging, unity, or leading power factor conditions. Over-excitation enables the motor to supply reactive power to the electrical network, effectively functioning as a synchronous condenser, while under-excitation results in reactive power absorption. This capability is particularly valuable in industrial environments where power factor correction and voltage regulation are essential for efficient energy utilization and compliance with grid requirements [14].

From a mechanical and structural perspective, the electromagnetic forces generated during synchronous operation are periodically distributed around the stator periphery and transmitted through the rotor, shaft, bearings, and mounting structure. Although the rotational speed remains constant, these electromagnetic forces can introduce time-varying radial and tangential force components, which act as excitation sources for mechanical vibration. Variations in load, excitation level, or structural stiffness can alter the magnitude and frequency content of these forces, thereby influencing the vibration behavior of the motor. Consequently, a thorough understanding of the operating principle of AC synchronous motors is essential for interpreting vibration signals and identifying abnormal operating conditions.

In the context of condition monitoring and predictive maintenance, the synchronous relationship between electrical frequency and mechanical speed provides a clear spectral reference for vibration analysis. Characteristic vibration frequencies associated with electromagnetic excitation, rotor dynamics, and mechanical imperfections can be directly correlated with the synchronous speed and its harmonics. This property facilitates the identification of faults such as rotor eccentricity, misalignment, bearing degradation, and electromagnetic imbalance. Therefore, the operating principle of the AC synchronous motor not only underpins its functional advantages but also forms the theoretical foundation for advanced vibration signal analysis and environmental impact assessment, as explored in the subsequent sections of this study.

3.3 Vibration Phenomena in AC Synchronous Motors

Vibration phenomena in AC synchronous motors originate from a combination of electrical and mechanical excitation mechanisms, and their presence often reflects deviations from ideal operating conditions. These vibrations not only degrade mechanical integrity and acoustic performance but also serve as critical indicators of incipient faults affecting motor efficiency, reliability, and service life. Compared to induction motors, synchronous machines operate at a strictly constant rotational speed under steady-state conditions, which makes them inherently more sensitive to disturbances arising from load fluctuations, excitation irregularities, and structural misalignments. As a result, even minor perturbations can produce measurable vibration responses, particularly in high-power or high-speed applications [15].

From an electrical perspective, vibration in synchronous motors is primarily associated with electromagnetic force variations acting on the stator and rotor. Ideally, these forces are symmetrically distributed around the air gap; however, imperfections in winding distribution, magnetic material properties, or excitation control can introduce spatial and temporal asymmetries. Such asymmetries give rise to unbalanced magnetic pull, which manifests as periodic radial forces acting on the rotor. These forces may excite structural resonances within the motor housing, shaft, or mounting base, thereby contributing to increased vibration levels. In addition, harmonic components in the stator current and DC excitation can generate time-varying electromagnetic forces at characteristic frequencies, further enriching the vibration spectrum.

Mechanical sources of vibration are equally significant and often dominate the overall vibration response. Among these, rotor unbalance is recognized as the most prevalent cause of vibration in synchronous motors, particularly in large-scale or high-speed machines. Rotor unbalance arises when the mass center of the rotor does not coincide with its geometric axis of rotation. This condition may result from manufacturing imperfections, assembly tolerances, uneven wear, or the accumulation of contaminants such as dust, oil, or mechanical debris on the rotor surface. Even a small mass eccentricity can produce substantial centrifugal forces at high rotational speeds, leading to pronounced vibration amplitudes and elevated bearing loads [15].

Because rotor unbalance directly influences vibration magnitude, mechanical stress, and bearing life, it is typically the primary parameter monitored in vibration-based condition diagnostics. The vibration signature of rotor unbalance is characterized by a dominant frequency component at the fundamental rotational frequency, often accompanied by harmonics depending on the severity and distribution of the imbalance. Persistent unbalance can accelerate bearing degradation, shaft fatigue, and structural loosening, ultimately increasing the risk of catastrophic failure if left unaddressed.

Another significant vibration mechanism in AC synchronous motors is rotor eccentricity, which may be classified as static, dynamic, or mixed eccentricity. Static eccentricity occurs when the rotor is displaced from the stator center but rotates around its own axis, while dynamic eccentricity arises when the rotor centerline rotates around the stator center. Mixed eccentricity combines both effects. Eccentricity alters the air-gap magnetic field distribution, leading to fluctuating electromagnetic forces that excite vibration at characteristic frequencies related to both rotational speed and electrical supply frequency. These effects are particularly critical in synchronous motors, where air-gap uniformity is essential for stable operation.

Misalignment between the motor shaft and the driven load constitutes another major source of vibration. Misalignment may be angular, parallel, or a combination of both, and is often introduced during installation or as a result of thermal expansion and foundation settling. In synchronous motors, misalignment induces periodic bending moments on the shaft and bearings, generating vibration components at the fundamental rotational frequency and its multiples. Over time, misalignment contributes to increased mechanical losses, bearing wear, and coupling failure.

A distinct vibration phenomenon observed in synchronous machines is hunting, also referred to as oscillatory instability. Hunting arises from transient disturbances such as sudden load changes, excitation fluctuations, or grid disturbances, which cause the rotor to oscillate about its equilibrium torque angle. These oscillations occur at low frequencies relative to the synchronous speed and may persist if insufficient damping is present. While damper windings are typically employed to suppress hunting, residual oscillations can still contribute to low-frequency vibration and torque ripple, particularly in lightly damped systems or under fluctuating load conditions.

Bearing-related vibrations also play a critical role in the overall vibration behavior of synchronous motors. Bearing defects, lubrication degradation, or excessive preload introduce characteristic vibration frequencies associated with rolling element dynamics. These mechanical excitations can interact with electromagnetic forces, leading to complex vibration patterns that require advanced signal processing techniques for accurate diagnosis.

From a system-level perspective, vibrations generated within the motor are transmitted through the shaft, bearings, housing, and mounting structure to the foundation and surrounding environment. The dynamic stiffness and damping properties of the mounting base significantly influence vibration transmission and amplification. Consequently, vibration phenomena in synchronous motors cannot be fully understood without considering the coupled motor–foundation system.

In the context of condition monitoring and predictive maintenance, each vibration mechanism exhibits distinct spectral features that can be identified through frequency-domain analysis. The synchronous nature of motor operation provides well-defined reference frequencies, enabling precise correlation between observed vibration components and their underlying physical causes. By analyzing vibration signals at multiple locations and operating conditions, it becomes possible to distinguish between electrical and mechanical excitation sources, detect early-stage faults, and assess their potential environmental impact.

Overall, a comprehensive understanding of

Fig.1 The synchronous motor used in the experiment.

(a) (b) (c)

Fig.2 Sensor's allocation: (a) the drive end, (b) the non-drive end, and (c) the motor base.

vibration phenomena in AC synchronous motors is essential for reliable fault diagnosis, effective predictive maintenance, and the mitigation of vibration transmission to surrounding structures. This understanding forms the foundation for the experimental measurements and signal processing methodology presented in the subsequent sections of this study.

3.4 Sensor Allocation

Appropriate sensor allocation is a critical aspect of vibration measurement and condition monitoring in AC synchronous motors, as the diagnostic sensitivity and interpretability of the acquired data are strongly influenced by sensor placement. In a synchronous motor, as schematically illustrated in Fig. 1, the rotor assembly comprising the shaft, bearings, and associated rotating components is inherently the most susceptible to vibration over a wide frequency range. This susceptibility arises from the direct exposure of these components to both mechanical excitations, such as unbalance and misalignment, and electromagnetic forces generated within the air gap. Consequently, vibration signatures associated with incipient faults tend to manifest most prominently in the vicinity of the rotor–bearing system.

In conventional vibration diagnostics, sensors are therefore commonly mounted near the motor bearings, where vibration energy is directly transmitted from the rotating elements to the stationary structure. Bearing locations provide access to rich vibration information related to rotor dynamics, bearing health, shaft alignment, and electromagnetic force interactions. Moreover, measurements taken near bearings typically exhibit high signal-to-noise ratios, facilitating the detection of characteristic frequency components associated with common fault mechanisms.

In the present study, sensor placement was strategically selected to capture both the intrinsic vibration behavior of the synchronous motor and the vibration transmitted to the surrounding environment. To this end, vibration sensors were installed at three critical locations: the drive end, the non-drive end, and the motor base, as illustrated in Fig. 2. This multi-location measurement strategy enables a comprehensive assessment of vibration generation, transmission, and attenuation across the motor–foundation system.

The drive end, which is mechanically coupled to the external load through a shaft or coupling, is a primary location for capturing vibration components associated with torque transmission, load-induced stress, and coupling misalignment. Vibrations measured at the drive end are particularly sensitive to variations in mechanical loading conditions and can reveal abnormalities related to shaft deflection, torsional oscillations, and load-induced resonance. As a result, the drive-end sensor provides valuable information on the interaction between the motor and the driven equipment.

The non-drive end represents a distinct dynamic region of the motor, often characterized by a longer shaft overhang and different bearing support conditions compared to the drive end. This configuration makes the non-drive end more susceptible to transverse vibration and bending modes, especially in synchronous motors where electromagnetic forces act periodically along the rotor length. Consequently, vibration amplitudes at the non-drive end are frequently higher than those observed at the drive end, particularly under variable load or excitation conditions. Measurements at this location are therefore essential for capturing vibration phenomena associated with rotor eccentricity, electromagnetic asymmetry, and hunting behavior.

The motor base serves as the interface between the motor structure and its supporting foundation, and it plays a crucial role in the transmission of vibration to the surrounding environment. Although the motor base is not directly connected to the rotating components, it acts as a conduit through which vibration energy propagates into the building structure. By placing a sensor at the motor base, the study directly evaluates the extent to which motor-generated vibrations are transmitted to the foundation. This information is particularly relevant for assessing environmental impact, structural integrity, and compliance with vibration and noise regulations in industrial installations.

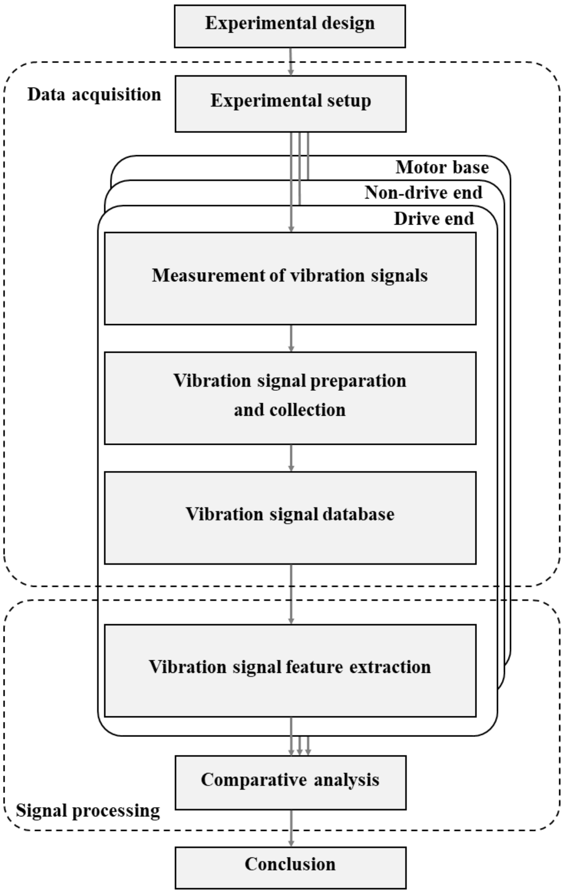

Fig.3 Experimental Procedure.

From a measurement perspective, the selected sensor locations also enable comparative analysis of vibration attenuation and amplification across the motor structure. Differences in vibration amplitude and frequency content among the drive end, non-drive end, and motor base provide insight into structural stiffness, damping characteristics, and boundary conditions. Such comparisons are instrumental in identifying dominant vibration transmission paths and assessing the effectiveness of mounting and isolation strategies.

Furthermore, the multi-point sensor allocation enhances the robustness and reliability of the experimental data. By capturing vibration signals from multiple locations, the approach reduces the likelihood of misinterpretation caused by localized anomalies or measurement noise. It also enables cross-validation of diagnostic indicators, thereby improving confidence in fault identification and condition assessment.

In the context of predictive maintenance, the chosen sensor allocation supports early detection of abnormal vibration patterns and facilitates the differentiation between electrical and mechanical excitation sources. When combined with frequency-domain analysis techniques such as the Fast Fourier Transform, the spatial distribution of vibration measurements provides a powerful diagnostic framework for monitoring motor health and evaluating vibration-related environmental impact.

Overall, the sensor allocation strategy adopted in this study is designed to balance diagnostic sensitivity, environmental relevance, and experimental practicality. By integrating measurements at the drive end, non-drive end, and motor base, the proposed approach offers a comprehensive perspective on vibration behavior in AC synchronous motors and establishes a solid foundation for the subsequent signal processing and analysis presented in this work.

3.5 Experimental Procedure

The experimental procedure was designed to ensure repeatable, high-fidelity vibration measurements and to facilitate a systematic analysis of the relationship between motor operating conditions and vibration characteristics. As illustrated in Fig. 3, the overall methodology was divided into two primary phases: data acquisition and signal processing. This structured approach allows for clear separation between experimental measurement and analytical interpretation, thereby enhancing the reliability and transparency of the results.

The experimental workflow commenced with the setup and calibration of a high-frequency vibration sensing system, including accelerometers, mounting accessories, signal conditioning modules, and a data acquisition computer. The particular attention was paid to secure sensor mounting and cable management to minimize measurement artifacts and electromagnetic interference. The sensors were rigidly attached to the motor surfaces at the predefined locations described in the previous section, ensuring consistent orientation and contact conditions throughout the experiment.

During the data acquisition phase, vibration signals were recorded under six distinct load conditions to capture the motor’s dynamic response across its operating range. Measurements were initially conducted under no-load conditions, corresponding to a supply voltage of 380 V and a line current of 3.5 A. For this operating state, a total of 50 individual measurement instances were acquired to establish a statistically representative baseline. Subsequently, vibration signals were collected under five additional load conditions of 20%, 40%, 60%, 80%, and 100% of the rated load, while maintaining the same supply voltage. The corresponding electrical currents measured at these load levels were 4.16 A, 4.48 A, 5.48 A, 6.14 A, and 6.80 A, respectively, reflecting the increasing mechanical demand imposed on the motor.

All vibration data were recorded using the DigivibeMx M20 software platform, which provided real-time signal visualization and ensured synchronized multi-channel data acquisition. The sensors operated at a fixed sampling frequency of 24,000 Hz, selected to adequately capture both low-frequency mechanical vibrations and higher-frequency components associated with electromagnetic excitation and bearing dynamics. This sampling rate satisfies the Nyquist criterion for the frequency range of interest and enables accurate spectral analysis.

To improve temporal consistency and facilitate subsequent analysis, the raw vibration signals were segmented at the input stage using a standardized segmentation protocol. This process ensured that each signal segment had a uniform duration and time alignment, thereby reducing variability associated with transient effects and enabling direct comparison across different load conditions.

In addition to measurements taken at the drive end of the motor, vibration data were simultaneously collected at the non-drive end and the motor base. This multi-point sensing configuration was implemented to capture spatial variations in vibration behavior and to evaluate the transmission of vibration energy through the motor structure and mounting interface. By acquiring data from multiple locations under identical operating conditions, the experimental design enables a comprehensive characterization of vibration generation, propagation, and attenuation within the motor–foundation system.

The inclusion of the motor base as a measurement point is particularly significant for assessing environmental impact, as vibrations detected at this location represent those transmitted to the supporting structure and surrounding infrastructure. Comparisons among the drive end, non-drive end, and motor base measurements provide insight into structural stiffness, damping characteristics, and the effectiveness of vibration isolation.

Following data acquisition, the collected vibration signals were organized into six distinct data sets corresponding to the predefined load conditions. Each data set consisted of multiple time-domain signal segments acquired under identical electrical and mechanical conditions. In the signal processing phase, a feature extraction procedure was applied to characterize the vibrational behavior associated with each load level.

The Fast Fourier Transform (FFT) was employed to convert the time-domain vibration signals into the frequency domain, yielding amplitude spectra that reveal the dominant frequency components of motor vibration. Frequency-domain analysis is particularly well suited for synchronous motors, as characteristic vibration frequencies can be directly correlated with rotational speed, supply frequency, and their harmonics.

From each frequency spectrum, five prominent peaks along the frequency axis were identified based on their amplitude significance. These peaks correspond to the dominant vibration components generated by internal moving parts, electromagnetic forces, and structural interactions within the motor. The frequencies and magnitudes associated with these peaks were extracted as diagnostic features for subsequent analysis.

To enhance robustness and reduce the influence of random noise and measurement variability, the extracted features were averaged across multiple measurements for each load condition and sensor location. This averaging process improves statistical reliability and ensures that observed trends reflect consistent vibration behavior rather than isolated anomalies.

Following feature extraction, a comparative analysis was conducted to examine the relationship between motor load conditions and the corresponding spectral characteristics. The analysis focused on identifying systematic variations in dominant frequencies and vibration amplitudes as a function of load, sensor location, and operating condition. The analytical approach was adapted from established methodologies reported in [11–13], which have demonstrated effectiveness in correlating vibration and acoustic signal features with machine operating states and fault conditions.

The outcomes of this analysis provide insight into load-dependent vibration mechanisms and vibration transmission pathways. These findings serve as the basis for evaluating motor health, assessing environmental impact, and supporting predictive maintenance decision-making. Detailed interpretations of the experimental results and their practical implications are presented and discussed comprehensively in the concluding section of this paper.

4. EXPERIMENTAL RESULTS

The experimental results are presented through a comparative analysis framework based on spectral features extracted from vibration signals acquired under varying load conditions. To facilitate quantitative comparison and visual interpretation, statistical averaging was applied to the extracted spectral features, and the results were summarized using comparative bar charts, following established analytical approaches reported in the literature [16, 17]. This visualization strategy enables clear identification of load-dependent trends in vibration amplitude and dominant frequency behavior across different sensor locations.

Specifically, the comparative vibration analysis focuses on the average magnitudes of the first through fifth prominent peaks identified in the frequency spectra of the vibration signals. These peaks correspond to dominant vibration components

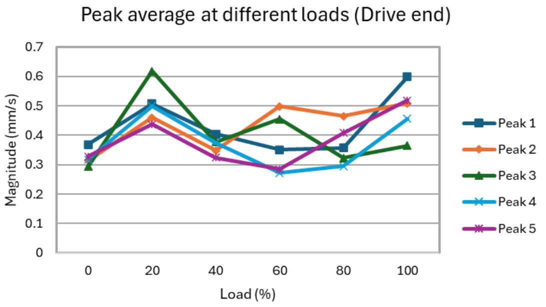

Fig.4 The averaged magnitudes of the 1st to 5th peaks of the frequency spectrum of the vibration signal at the motor’s drive end with distinct load conditions.

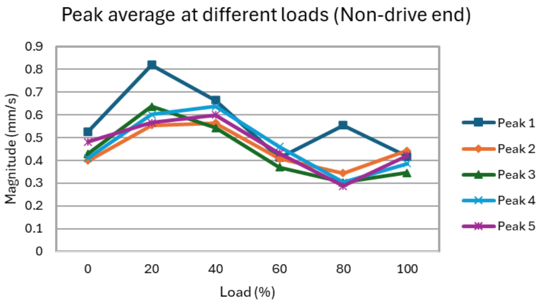

Fig.5 The averaged magnitudes of the 1st to 5th peaks of the frequency spectrum of the vibration signal at the motor’s non-drive end with distinct load conditions.

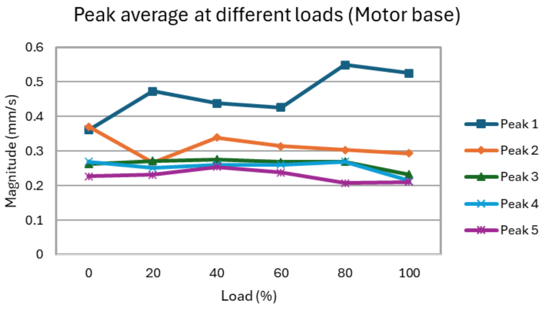

Fig.6 The averaged magnitudes of the 1st to 5th peaks of the frequency spectrum of the vibration signal at the motor base with distinct load conditions.

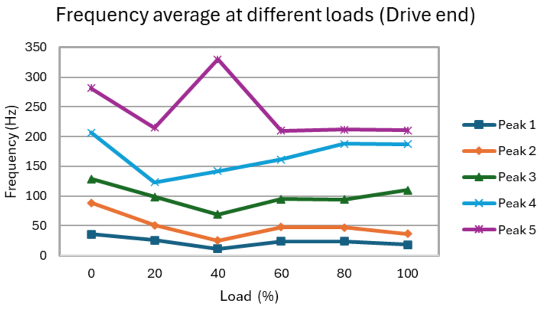

Fig.7 The averaged frequencies of the 1st to 5th peaks of the frequency spectrum of the vibration signal at the motor’s drive end with distinct load conditions.

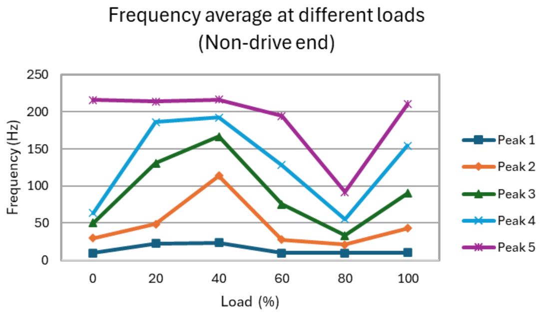

Fig.8 The averaged frequencies of the 1st to 5th peaks of the frequency spectrum of the vibration signal at the motor’s non-drive end with distinct load conditions.

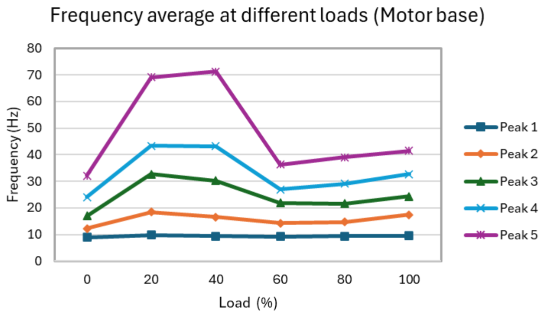

Fig.9 The averaged frequencies of the 1st to 5th peaks of the frequency spectrum of the vibration signal at the motor base with distinct load conditions.

associated with rotor dynamics, electromagnetic excitation, and structural resonances. The averaged peak amplitudes under each load condition are presented in Figs. 4–6 for the drive end, non-drive end, and motor base, respectively. In parallel, Figs. 7–9 illustrate the corresponding average frequencies of the first through fifth spectral peaks under the same operating conditions, providing insight into the stability and variability of dominant vibration frequencies as a function of load.

4.1 Vibration Amplitude Characteristics

The vibration amplitude analysis at the drive end of the motor reveals a clear dependence on mechanical load. As shown in Fig. 4, the magnitude of the dominant spectral peaks generally increases with increasing load, reaching its maximum at 100% load. This trend reflects the elevated mechanical stress and torque transmission occurring at higher load levels, which amplify vibration excitation at the motor–load interface. Notably, an anomalously high vibration amplitude is observed at the 20% load condition, exceeding those recorded at adjacent load levels. This deviation suggests the possible influence of transient dynamic effects, such as partial load-induced resonance, electromagnetic force imbalance, or coupling-related nonlinearity, which may be more pronounced under light-load operation.

At the non-drive end of the motor, the vibration amplitude behavior exhibits a markedly different trend, as illustrated in Fig. 5. The peak amplitude reaches its maximum at 20% load and subsequently decreases as the load increases. This observation indicates that the non-drive end is particularly sensitive to low-load operating conditions, where reduced damping and increased susceptibility to rotor oscillation may amplify vibration response. As the load increases, enhanced electromagnetic stiffness and mechanical constraint may contribute to the observed reduction in vibration amplitude. This behavior underscores the importance of monitoring low-load conditions, which are often overlooked in conventional maintenance strategies.

Figure 6 presents the vibration amplitude analysis at the motor base, which represents the vibration transmitted to the supporting structure. The amplitude of the first spectral peak demonstrates a gradual increase with increasing load, indicating that higher mechanical loading leads to greater vibration energy transmission to the foundation. In contrast, the amplitudes of the remaining spectral peaks remain relatively stable across all load conditions, with some exhibiting a slight downward trend. This attenuation of higher-order vibration components suggests that the motor base and mounting structure effectively dampen higher-frequency vibrations, thereby limiting their propagation into the surrounding environment.

4.2 Dominant Frequency Characteristics

The dominant frequency analysis provides additional insight into the stability and variability of vibration excitation mechanisms. At the drive end of the motor, as shown in Fig. 7, the frequencies corresponding to the first through third spectral peaks remain relatively constant across all load conditions. This stability indicates that these components are closely tied to the synchronous rotational speed and its lower-order harmonics, which are inherently load-independent. In contrast, the frequencies of the fourth and fifth peaks exhibit noticeable fluctuations with changing load, suggesting sensitivity to higher-order electromagnetic harmonics or structural resonances that are influenced by load-dependent stiffness and boundary conditions.

At the non-drive end, the frequency behavior displays greater variability, as illustrated in Fig. 8. Only the frequency of the first peak remains relatively constant across varying load levels, while the frequencies of peaks two through five exhibit significant fluctuations in response to load changes. This pronounced variability reflects the dynamic complexity of the non-drive end, where rotor overhang, bearing support conditions, and electromagnetic force distribution interact to produce load-sensitive vibration behavior. Additionally, a distinct clustering of peak frequencies is observed at the 80% load condition, suggesting the possible excitation of a localized resonance or modal interaction at this operating point.

The dominant frequency analysis at the motor base, shown in Fig. 9, indicates a comparatively stable frequency response. The frequencies of peaks one through four remain nearly constant across all load levels, implying that the vibration transmitted to the foundation is dominated by low-frequency components associated with synchronous rotation. However, the fifth peak exhibits irregular, load-dependent frequency variation, which may be attributed to structural resonance effects or nonlinear interactions between the motor and its mounting system.

4.3 Comparative Interpretation Across Sensor Locations

Overall, the experimental results presented in Figs. 4–6 demonstrate that the non-drive end consistently exhibits the highest vibration amplitudes under all loading conditions. This behavior is primarily attributed to the extended length of the rotor shaft beyond the stator at the non-drive end, which increases susceptibility to bending modes and oscillatory motion. The reduced mechanical constraint at this location further amplifies vibration response, particularly under low-load conditions.

In contrast, the motor base consistently records the lowest vibration levels across all load conditions. This outcome reflects the mechanical decoupling between the motor's internal vibration sources and the foundation, as well as the damping and stiffness characteristics of the mounting structure. The comparatively low vibration amplitudes at the motor base indicate that, under the tested conditions, vibration transmission to the surrounding environment is effectively attenuated.

Collectively, these findings highlight the importance of multi-location vibration measurement for accurately characterizing motor dynamic behavior and assessing environmental impact. The observed differences in amplitude and frequency characteristics among the drive end, non-drive end, and motor base underscore the need for location-specific diagnostic strategies in predictive maintenance applications. The implications of these results for fault detection, vibration mitigation, and sustainable motor operation are further discussed in the concluding section of this paper.

5. CONCLUSION

This study presented a comprehensive experimental investigation of vibration characteristics in an AC synchronous motor with particular emphasis on vibration distribution, load dependency, and transmission to the surrounding environment. By integrating multi-location vibration measurements with frequency-domain signal processing, the work addressed both machine health monitoring and environmental impact assessment within a unified analytical framework.

Vibration signals were systematically acquired at three critical locations—the drive end, non-drive end, and motor base—under six distinct load conditions ranging from no load to full rated load. The experimental results demonstrate that vibration behavior in synchronous motors is strongly dependent on both operating load and measurement location. Among the investigated positions, the non-drive end consistently exhibited the highest vibration amplitudes across all load conditions. This behavior is attributed to the extended rotor overhang and reduced mechanical constraint at the non-drive end, which increase susceptibility to bending modes and oscillatory motion. In contrast, the motor base recorded the lowest vibration levels, reflecting the attenuating effect of the mounting structure and its mechanical decoupling from direct vibration sources.

Frequency-domain analysis using the Fast Fourier Transform revealed that low-order dominant frequencies remain relatively stable with respect to load, particularly at the drive end and motor base, indicating their strong association with synchronous rotational speed. Higher-order spectral components, however, exhibited pronounced load-dependent variability, especially at the non-drive end. These fluctuations suggest complex interactions between electromagnetic excitation, rotor dynamics, and structural boundary conditions. Notably, anomalous vibration behavior was observed at partial load conditions, highlighting the importance of monitoring synchronous motors not only at rated operation but also under light-load scenarios, where dynamic instability and resonance effects may become more prominent.

From a diagnostic perspective, the spatial variation of vibration amplitude and frequency content underscores the necessity of multi-point sensor allocation for reliable condition monitoring. The results confirm that vibration signatures measured near the bearings provide high diagnostic sensitivity to mechanical and electromagnetic disturbances, while measurements at the motor base are essential for evaluating vibration transmission and environmental impact. The FFT-based feature extraction framework employed in this study proved effective in isolating dominant vibration components and identifying load-dependent trends, thereby supporting early detection of abnormal operating conditions.

The findings of this work have important implications for predictive maintenance strategies in industrial motor-driven systems. By enabling early identification of location-specific vibration patterns and load-sensitive anomalies, the proposed approach can reduce unplanned downtime, maintenance costs, and production losses. Furthermore, the assessment of vibration transmission to the motor base contributes to a better understanding of the environmental effects of motor operation, supporting the design of improved mounting systems and vibration mitigation measures in vibration-sensitive installations.

Despite its contributions, this study is subject to certain limitations. The experimental investigation was conducted on a single motor configuration under steady-state operating conditions. Future research may extend the proposed framework to different motor ratings, mounting configurations, and transient operating scenarios, as well as incorporate advanced signal processing techniques and machine learning algorithms for automated fault classification. Additionally, the integration of vibration analysis with acoustic and electrical signal monitoring may further enhance diagnostic robustness.

In conclusion, this study demonstrates that comprehensive vibration analysis of AC synchronous motors, when combined with strategic sensor allocation and robust spectral analysis, provides valuable insight into motor health and environmental impact. The proposed methodology offers a practical and effective foundation for advanced condition monitoring and predictive maintenance in modern industrial systems.

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