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Research article

Bolted Joint Loosening Analysis Due to Structural Vibrations using Short-Time Fourier Transform and Wavelet Transform

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ABSTRACT

This research investigates the influence of bolt loosening on the dynamic behavior of a steel beam structure under continuous vibration excitation for 30 minutes. Bolted joints play a critical role in maintaining structural integrity; however, loosening caused by vibration remains one of the most common failure mechanisms in mechanical structures. To capture the effect of bolt loosening, acceleration responses were analyzed using time-domain inspection, Fast Fourier Transform (FFT), Short-Time Fourier Transform (STFT), and Continuous Wavelet Transform (CWT). The experimental setup involved controlled vibration excitation applied to a steel beam with bolted connections, and response signals were recorded at different stages of loosening progression. The time-domain analysis showed a gradual reduction in acceleration amplitude as bolt tightness decreased, indicating energy dissipation and stiffness loss. FFT provided an overview of frequency content but lacked sensitivity to localized variations. STFT and CWT enabled a more detailed examination of the time-frequency domain, revealing a loss of high-frequency components and significant redistribution of energy patterns during the loosening process. Both methods successfully identified shifts in natural frequencies and variations in response amplitude. Especially, CWT exhibited superior resolution in detecting early-stage loosening compared to STFT, making it more effective for practical monitoring applications. These results highlight the potential of time-frequency analysis as a diagnostic tool for vibration-based Structural Health Monitoring (SHM) systems. Early detection of bolt loosening through non-destructive vibration analysis can improve safety, reduce maintenance costs, and extend the service life of mechanical structures.

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1. INTRODUCTION

Bolted joints are essential mechanical components widely used in various engineering structures due to their simple design, adaptability, and ease of maintenance [1]. However, these joints are vulnerable to loosening under dynamic or vibrational loads, which can compromise structural integrity [2]. Bolt loosening may lead to reduced joint stiffness, increased damping, fatigue failures, and in severe cases, catastrophic structural collapse if not detected early [3]. Therefore, accurate and timely detection of bolt loosening is crucial for effective structural health monitoring (SHM) and preventive maintenance [4].

Early research by Junker [1] developed a specialized testing machine to quantitatively evaluate bolt locking performance. His findings revealed that transverse vibrations cause more significant loosening effects than axial vibrations. Sakai [2] furthered this research by conducting theoretical analyses and simple experiments to measure friction coefficients during transverse slip conditions, enabling comparison between empirical results and theoretical models.

One of the most reliable indicators of bolt loosening is the change in dynamic characteristics, particularly shifts in natural frequency and damping behavior [5]. As bolt preload decreases, joint stiffness reduces, causing measurable changes in the system's vibrational response [6]. This relationship can be modeled using a mass-spring-damper system, where the natural frequency $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$ decreases with reducing stiffness (k), while frictional dissipation at the loosened interface increases the damping ratio [7]. These dynamic changes provide the basis for non-destructive evaluation of bolt integrity [8].

Conventional Fourier analysis, while effective for stationary signals, cannot adequately capture transient vibration changes associated with initial loosening [9]. To address this limitation, time-frequency analysis techniques like Short-Time Fourier Transform (STFT) and Wavelet Transform (WT) have become prominent for their ability to analyze non-stationary signals in both time and frequency domains [10]. STFT provides fixed-resolution time-frequency representation, whereas WT offers multi-resolution analysis, making it more adaptable to transient features [11].

Recent studies have demonstrated the effectiveness of these methods in detecting bolt loosening, with WT often out performing STFT in resolving high-frequency discontinuities [12]. Despite these advances, a systematic comparison of STFT and WT for bolt loosening detection under various operational conditions remains insufficiently explored [13]. This study aims to experimentally evaluate the sensitivity and resolution of both techniques, identifying their strengths and limitations for real-time SHM applications. The findings will contribute to optimizing vibration-based diagnostics for bolted structures, addressing the growing need for predictive maintenance in mechanical engineering [12,13].

2. PROBLEM DESCRIPTION

Bolted joints play a critical role in maintaining the structural integrity and mechanical reliability of engineering systems such as bridges, machines, and steel frameworks [1–3]. However, these connections are highly susceptible to loosening under cyclic or vibrational loading, which results in a progressive reduction in stiffness and an increase in damping [4–6]. This degradation alters the dynamic characteristics of the structure and, if undetected, may lead to fatigue damage or catastrophic failure [7].

Conventional analysis methods, such as time-domain observation and Fast Fourier Transform (FFT), have been widely used to evaluate vibration behavior and identify dominant frequency components [8]. However, these techniques assume that vibration signals are stationary, limiting their ability to capture transient or time-varying phenomena typically associated with the onset of bolt loosening [9]. As a result, early indications of stiffness reduction or energy redistribution often remain undetected.

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To address these limitations, time–frequency analysis techniques have been increasingly employed to investigate non-stationary vibration responses. Among these, the Short-Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT) are particularly effective due to their capability to represent signal energy simultaneously in both time and frequency domains [9–11]. STFT offers a fixed time–frequency resolution through windowed segmentation, but it suffers from a trade-off between temporal and spectral resolution [12]. In contrast, CWT provides multi-resolution adaptability, enabling enhanced sensitivity to transient features and high-frequency discontinuities [10,13].

Although recent studies have demonstrated the effectiveness of both STFT and CWT in detecting bolt loosening [9–13], comparative experimental evaluations of their performance in real-world structural health monitoring (SHM) scenarios remain limited [14–16]. Moreover, prior research has primarily focused on either simulated or stationary conditions, with limited attention given to the progressive loosening process under continuous excitation [17–19].

Therefore, this study aims to experimentally evaluate and compare the effectiveness of STFT and CWT in detecting progressive bolt loosening under controlled vibration excitation. The analysis focuses on determining each method's sensitivity, temporal resolution, and diagnostic accuracy, thereby providing a more robust foundation for non-destructive SHM applications and predictive maintenance strategies in mechanical systems [9–20].

3. METHOD

3.1. Experimental Design

The experimental investigation was conducted using the Experimental Modal Analysis (EMA) method at the Structural Dynamics Laboratory, Universitas Andalas. Theoretically, modal analysis provides a physical representation of a dynamic system characterized by mass, stiffness, and damping properties. The tests were performed on a bolted joint structure, in which the bolts were initially tightened to a specified torque level. The structure was then subjected to continuous mechanical excitation for 30 minutes using an electromagnetic shaker.

Piezoelectric accelerometers were installed at selected points on the structure to capture the dynamic response during the excitation process. The schematic presents the configuration of bolt joints and the dimensional specifications of two simple beams utilized in the design of an exciter system. It highlights the structural integration between the beams and fasteners to ensure mechanical stability during vibrational excitation.

3.2 Test Object and Bolted Joint Model

The system modeled in this study consists of two thin steel beams connected by bolts, washers, and nuts, as illustrated in Figure 1. This configuration represents a modified cantilever system, characterized by a fixed-free boundary condition. Each beam is fabricated from steel, with dimensions of 50 mm in width, 6 mm in thickness, and a total connected length of 250 mm. The beams are joined using M10 bolts and nuts to simulate a

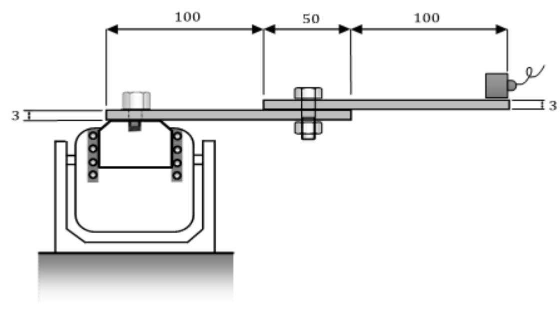

Figure 1. Schematic of Bolt Joints and Simple beam Dimensions in an Exciter

bolted joint structure. To characterize the dynamic behavior of the structure, modal analysis was conducted to extract the key modal parameters, specifically the natural frequencies and vibration mode shapes. Various levels of tightening torque were applied to the bolts to represent different states of bolt looseness. Exciter tests were performed under these varying conditions to systematically investigate the effects of bolt relaxation on the structural dynamic response. Through this approach, the progression of bolt loosening and its influence on modal parameters were monitored over time, enabling a comprehensive assessment of the relationship between joint integrity and dynamic behavior.

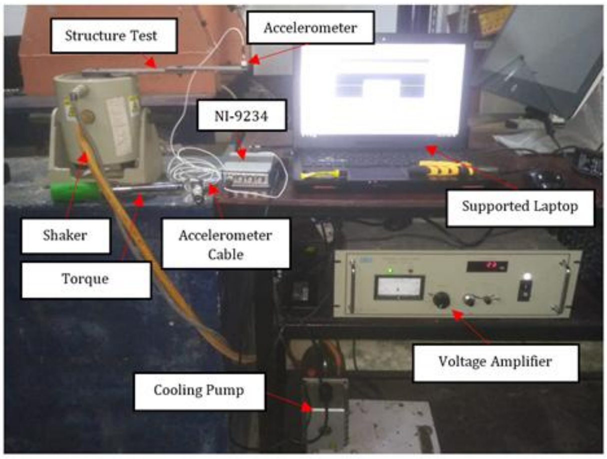

Figure 2. Experimental Set-up

This study employed an experimental method to detect bolt loosening through Experimental Modal Analysis (EMA), with the setup shown in Figure 2. An EMIC 512-A shaker with 372-A/G amplifier provided controlled excitation (5-5000 Hz), while a B&K 4508 accelerometer (10 mV/g sensitivity) measured structural responses. The NI-9234 DAQ system (24-bit, 51.2 kS/s) acquired vibration data, and a Tekiro TR-100 torque wrench (±0.5% accuracy) monitored bolt preload. The system detected loosening by tracking changes in natural frequencies and mode shapes, demonstrating EMA's effectiveness for structural health monitoring. Key components were carefully selected to ensure measurement accuracy across the 5-500 Hz frequency range of interest. (See Figure 2 for complete system configuration).

3.3 Data Acquisition for Bolt Loosening Investigation

The study examined the structure’s dynamic response under different bolt tightness conditions using exciter-based vibration testing. Five torque levels were applied: (1) 85% loosened, (2) 75% loosened, (3) 50% loosened, (4) 25% loosened, and (5) fully tightened. A mechanical torque wrench adjusted the bolts, and a shaker excited the structure at 20–21 Hz (its second natural frequency) for 30 minutes, with data sampled every 5 minutes. Piezoelectric accelerometers measured the response, while a data acquisition system recorded signals at 25.6 kHz. The resulting frequency response functions (FRFs) helped analyze modal parameter shifts due to loosening, ensuring consistent and high-resolution data for structural integrity assessment.

Post-processing of the collected data was performed using MATLAB software. Signal processing routines included the calculation of the Frequency Response Functions (FRFs) to quantify the relationship between input forces and output accelerations. These FRFs were further utilized to observe modal parameter shifts—such as changes in natural frequencies, damping ratios, and mode shapes—associated with different levels of bolt loosening. The use of MATLAB enabled efficient handling of large datasets, precise spectral analyses, and detailed visualization of the dynamic behavior, thereby ensuring a rigorous assessment of the structural integrity under varying connection conditions.

3.4 Signal Analysis for Monitoring Bolt Loosening

This study employs a comprehensive signal processing approach to analyze structural degradation caused by bolt loosening under harmonic excitation. Vibration analysis is a critical approach for early detection of structural damage, including bolt loosening in mechanical systems. The application of appropriate signal analysis methods enables accurate monitoring of changes in a structure's dynamic characteristics. Time-domain analysis focuses on observing variations in vibration amplitude over time. Statistical parameters such as Root Mean Square (RMS), skewness, kurtosis, and peak-to-peak values are commonly extracted to detect structural anomalies [14]. The RMS value is calculated as:

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

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Where (x_i) represents the amplitude at the i-th sample, and N is the total number of samples.

Fast Fourier Transform (FFT) is employed to convert time-domain signals into the frequency domain, facilitating the identification of dominant frequency components [15]. This method is particularly effective in detecting shifts in natural frequencies due to structural changes. The discrete Fourier transform (DFT) is mathematically expressed as:

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

Where X (k) denotes the k-th frequency component.

For non-stationary signals, Continuous Wavelet Transform (CWT) provides a joint time-frequency representation, allowing the mapping of energy distribution across different scales and times [16]. The CWT is defined as:

$$CWT(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt$$

where α represents the scale parameter, b is the time translation, and ψ is the mother wavelet.

Short-Time Fourier Transform (STFT) segments the signal into short time windows and applies Fourier analysis to each segment, enabling dynamic tracking of the frequency spectrum over time [17]. The STFT is mathematically described as:

$$STFT\{x(t)\}(\tau,\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j\omega t} dt$$

Where ω (t) is the window function.

Practical applications of these techniques include monitoring the condition of bolted joints in rotating machinery, bridges, and gas turbines, where amplitude fluctuations, shifts in natural frequencies, and energy spectrum variations serve as key indicators of structural degradation or bolt loosening.

By integrating time-domain analysis, FFT, CWT, and STFT, a comprehensive and adaptive evaluation of structural health can be achieved, addressing the evolving dynamics of damage mechanisms. These findings collectively demonstrate progressive stiffness loss and the emergence of nonlinear damping mechanisms. The combined analytical methods provide a robust framework for early bolt loosening detection, with time-frequency techniques proving particularly effective for identifying incipient joint degradation, validating their utility for structural health monitoring applications.

4. DISCUSSIONS

In vibration-based structural health monitoring, the time-domain signal serves as the primary representation of system response, offering an initial perspective on dynamic behavior before transitioning to more advanced analytical domains. Time-domain observation is particularly useful for identifying general patterns such as oscillatory trends, amplitude variations, and possible transient events that may signify changes in structural integrity. However, since vibration signals often exhibit non-stationary characteristics, their interpretation in the time domain alone can be challenging and sometimes insufficient.

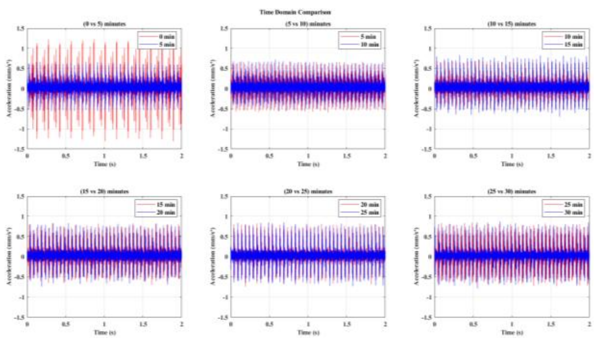

Figure 3. Loosening Test Results 1,5 Nm – Time Signal

Figure 3 illustrates the acceleration responses of the structure recorded at different time intervals throughout the vibration test. At the early stage (0–5 minutes), the oscillations appear with relatively higher amplitudes, while a gradual reduction in amplitude is observed as time increases. The comparison across successive intervals (5–10, 10–

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15, 15–20, 20–25, and 25–30 minutes) highlights the presence of amplitude modulation and evolving waveform complexity. These observations suggest that the system undergoes progressive changes, likely caused by bolt loosening under continuous excitation. Such findings confirm that the signal is non-stationary, with dynamic variations that necessitate complementary analyses in the frequency and time–frequency domains to reveal more detailed information about natural frequency shifts and energy redistribution.

In vibration signal processing, the frequency domain representation is a fundamental approach to identify dominant oscillatory components that may not be easily distinguishable in the time domain. By transforming the signal into its spectral content, specific frequencies associated with structural modes, resonance, or bolt looseness can be more clearly observed. This analysis is particularly important for detecting shifts in natural frequencies, which often serve as an indicator of structural degradation or evolving damage mechanisms over time. The frequency spectrum obtained through the Fast Fourier Transform (FFT), as shown in Figure 4, offers insight into the dominant frequency components present within the signal.

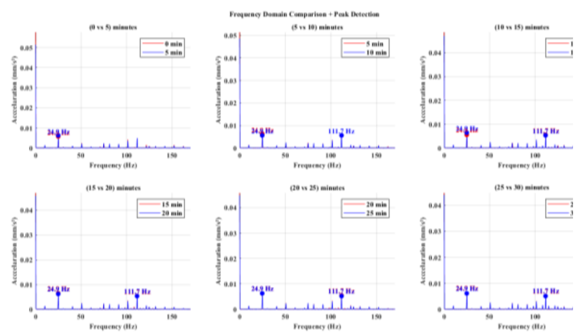

Figure 4. Loosening Test Results 2,5 Nm - FFT

The frequency spectrum obtained through the Fast Fourier Transform (FFT), as shown in Figure 4, reveals several distinct peaks, most notably around 24.9 Hz and 111.7 Hz, across different time intervals. These peaks represent the dominant frequency components of the system and remain consistent during the experimental duration, although their relative amplitudes vary slightly with time. The persistence of these peaks suggests stable modal frequencies, while variations in amplitude may indicate progressive changes in system stiffness due to bolt loosening. Despite its usefulness, the FFT only provides a global frequency overview without temporal localization, limiting the ability to detect when such frequency variations occur. This shortcoming highlights the necessity for advanced joint time–frequency analysis methods, such as the Short-Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT), for a more comprehensive interpretation of the dynamic response.

In vibration analysis, time–frequency methods provide deeper insights compared to purely time-domain or frequency-domain approaches, as they capture the temporal evolution of spectral components. Among these methods, the Short-Time Fourier Transform (STFT) is one of the most widely used techniques because it enables simultaneous observation of both frequency content and its variation over time. This is particularly important in monitoring bolt loosening phenomena, where dynamic changes in system stiffness may induce subtle shifts in the vibration spectrum that are not clearly detectable using FFT alone.

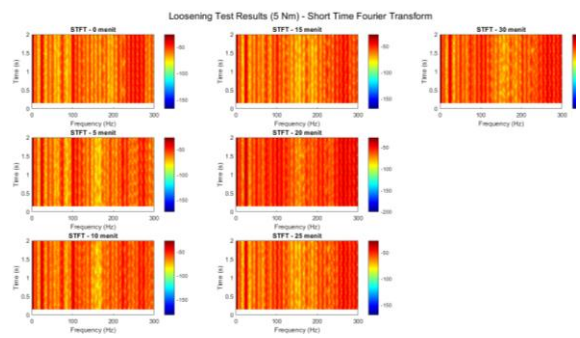

Figure 5. Loosening Test Results 5 Nm - STFT

Figure 5 presents the STFT spectrograms of the vibration signal recorded under a 5 Nm bolt loosening condition at different time intervals. The spectrograms demonstrate the distribution of signal energy across time and frequency, highlighting the persistence of dominant frequencies around 25 Hz and 111 Hz. These components appear consistently throughout the experimental duration, though their relative intensities exhibit temporal fluctuations as loosening progresses. Such observations confirm the sensitivity of STFT in detecting transient variations that may indicate progressive structural changes.

However, the use of a fixed analysis window introduces an inherent trade-off between time and frequency resolution. Low-frequency components are represented with better spectral resolution, whereas higher frequencies achieve better temporal resolution. Consequently, STFT may not fully capture rapid or non-stationary variations in frequency behavior, motivating the need for more flexible time–frequency methods such as the Continuous Wavelet Transform (CWT).

While STFT provides a valuable perspective on the time–frequency characteristics of vibration signals, its reliance on a fixed window size inherently limits resolution adaptability. To address this limitation, the Continuous Wavelet Transform (CWT) offers a more flexible framework by employing scalable windows that adapt to different frequency ranges. This allows for improved localization of transient features and more accurate representation of both low- and high-frequency phenomena within the signal.

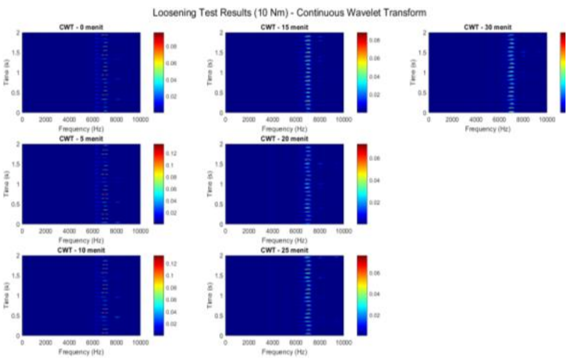

Figure 6. Loosening Test Results 10 Nm – All CWT signals (Range 10 kHz)

Figure 6 illustrates the CWT spectrogram of vibration signals under a 10 Nm bolt loosening condition, analyzed across different time intervals. The results reveal distinct frequency bands extending up to 10 kHz, with high-frequency bursts becoming more pronounced as loosening progresses. Compared to STFT, the CWT representation provides sharper localization of transient responses, allowing short-lived fluctuations to be captured with greater clarity. This advantage is particularly evident in the detection of high-frequency components that may be smeared or less discernible in STFT due to fixed window constraints.

The ability of CWT to reveal such fine temporal and spectral details demonstrates its effectiveness in monitoring non-stationary vibration behavior, especially under progressive loosening scenarios. By offering high resolution in both time and frequency domains, CWT enhances the diagnostic capability of vibration analysis and supports more accurate identification of structural changes. Nonetheless, interpretation of CWT results requires careful consideration of scale selection and computational demands, which may increase with higher frequency resolutions.

4.1 Comparative Analysis and Interpretation

The comprehensive investigation across multiple domains emphasizes the complementary strengths of each analytical method. In the time domain (Figure 3), the analysis provides preliminary insights into amplitude variations, offering a direct yet limited view of the signal's temporal behavior. Transitioning into the frequency domain (Figure 4), dominant spectral components are clearly identified, enabling the recognition of characteristic frequencies associated with bolt loosening. However, this frequency-only representation disregards the temporal evolution of these components. To overcome this limitation, time–frequency domain techniques were employed (Figures 5–6). The Short-Time Fourier Transform (STFT) successfully illustrates the temporal dynamics of spectral content, but its fixed window size inherently introduces a trade-off between time and frequency resolution. Consequently, while low frequencies are more clearly resolved in frequency, high-frequency components achieve better temporal localization, leaving rapid frequency transitions partially obscured.

In contrast, the Continuous Wavelet Transform (CWT) provides superior adaptability, as its scalable windows deliver high frequency

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resolution at low frequencies and high time resolution at high frequencies. This flexibility enables the precise capture of transient phenomena and short-lived bursts that remain less discernible in the STFT representation. Figure 7 demonstrates how CWT distinctly reveals frequency variations across the 0–10 kHz range, affirming its robustness for analyzing complex, non-stationary vibration signals. Overall, the multi-perspective approach demonstrates the necessity of hybrid analysis techniques when evaluating real-world signals with dynamic behaviors. The time domain offers initial amplitude trends, the frequency domain highlights dominant components, and the time–frequency domain—particularly through CWT—provides a comprehensive depiction of spectral evolution. This layered methodology enhances diagnostic reliability and ensures a deeper understanding of structural changes under progressive bolt loosening conditions.

5. CONCLUSION

This study highlights the critical role of advanced time-frequency analysis methods in diagnosing structural integrity issues, particularly bolted joint loosening. Through a systematic combination of time-domain observation, frequency-domain investigation, and time-frequency domain techniques, it was possible to comprehensively characterize the complex, non-stationary behavior of vibration signals induced by joint degradation. The results clearly demonstrate that while STFT offers an accessible overview of frequency evolution, its inherent resolution trade-off limits its effectiveness in highly dynamic scenarios. Conversely, CWT provides superior adaptability, capturing both gradual and abrupt vibrational changes essential for early detection and continuous monitoring. Integrating both STFT and CWT within a diagnostic framework enhances the reliability and sensitivity of structural health monitoring (SHM) systems. Future work may explore real-time implementation of these techniques, potentially incorporating machine learning algorithms to automate the detection and classification of loosening phenomena, further advancing predictive maintenance strategies in critical engineering structures.

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