PROSIDING SNTTM XXIII 2025
Volume 23, No. 1, Tahun 2025, 9 Oktober 2025

e-ISSN 2623-0313
p-ISSN 3032-1972

# Analysis of bolted joint loosening due to structural vibrations using short-time fourier transform and wavelet transform

**Rahmatsyah Maksum Ramsi**[a,b,1], **Meifal Rusli**[c], **Feblil Huda**[b]
[a]Universitas Riau, Pekanbaru, 28293
[b]Program Studi Teknik Mesin, Universitas Riau, Pekanbaru, 28293
[c]Program Studi Teknik Mesin, Universitas Andalas, Padang, 25163
[1]Email korespondensi: rahmatsyah.maksum@lecturer.unri.ac.id

**Abstract.** This research investigates the effect of bolt loosening on the dynamic behavior of a steel beam structure under continuous 30-minute vibration excitation. Bolted joints play a critical role in maintaining structural integrity; however, vibration-induced loosening 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, the Fast Fourier Transform (FFT), the Short-Time Fourier Transform (STFT), and the 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. In particular, CWT exhibited superior resolution for 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.

**Keywords**: bolted joint loosening; structural vibration; time-frequency analysis; short-Time fourier transform (STFT); continuous wavelet transform (CWT); fast fourier transform (FFT);

**Received:** 30 September 2025; **Presented:** 9 October 2025; **Publication:** 9 March 2026
DOI: https://doi.org/10.71452/3wteep54

## PENDAHULUAN

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 greater loosening 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 decreases, leading to 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 changes in vibration associated with initial loosening [9]. To address this limitation, time-frequency analysis techniques such as the Short-Time Fourier Transform (STFT) and the Wavelet Transform (WT) have become prominent for their ability to analyze non-stationary signals in both the time and frequency domains [10]. STFT provides a 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 outperforming STFT in resolving high-frequency discontinuities [12]. Despite these advances, a systematic comparison of STFT and WT for bolt loosening detection across various operational conditions remains underexplored [13].

This study aims to experimentally evaluate the sensitivity and resolution of both techniques and identify their strengths and limitations for real-time SHM applications. The findings will help optimize vibration-based diagnostics for bolted structures, addressing the growing need for predictive maintenance in mechanical engineering [12,13].

Recent research on bolt loosening detection can be grouped into two main approaches: (i) vibration-based time–frequency analysis, and (ii) active/non-contact methods combined with machine learning. Huang et al. [14] provided a comprehensive review of methods for detecting threaded fastener loosening, emphasizing the sensitivity of time–frequency features to changes in joint stiffness. In passive vibration-based studies, many works have employed the Short-Time Fourier Transform (STFT) or the Continuous Wavelet Transform (CWT) to extract features indicative of loosening. For example, Lee et al. [15] applied STFT-based features with machine learning classifiers for multi-bolt loosening detection, achieving high classification accuracy. Similarly, Tang et al. [16] used wavelet-based time–frequency maps and convolutional neural networks (CNNs) to identify different levels of bolt loosening.

On the active sensing side, Chen et al. [17] combined piezoelectric sensing with attention-based CNNs to quantitatively assess bolt loosening. Vibro-acoustic modulation (VAM) techniques, coupled with machine learning, have also been explored to improve residual torque estimation [18]. In field-scale applications, Zhang et al. [19] investigated bolt loosening in transmission towers using time–frequency analysis and wavelet packet transform, demonstrating feasibility under real-world conditions. More recently, Li et al. [20] proposed the Summation Coefficient of Absolute Spectrum Ratio (SCASR), a spectral index derived from sweep excitation data, with the STFT serving as a comparative baseline.

## METHODOLOGY

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 excitation. 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.

### 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 with a fixed-free boundary condition. Each beam is fabricated from steel, with a width of 50 mm, a thickness of 6 mm, and a total connected length of 250 mm. The beams are joined with M10 bolts and nuts to simulate a bolted joint.

To characterize the structure's dynamic behavior, modal analysis was conducted to extract key modal parameters, specifically the natural frequencies and mode shapes. Various tightening torques were applied to the bolts to represent different degrees 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.

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).

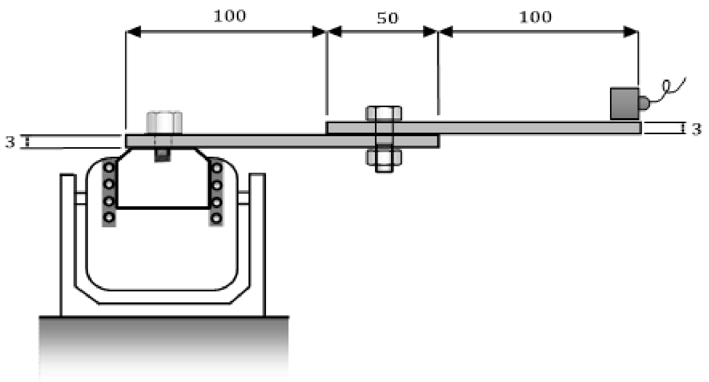

**Figure 1.** Schematic of Bolt Joints and Simple beam Dimensions in an Exciter System

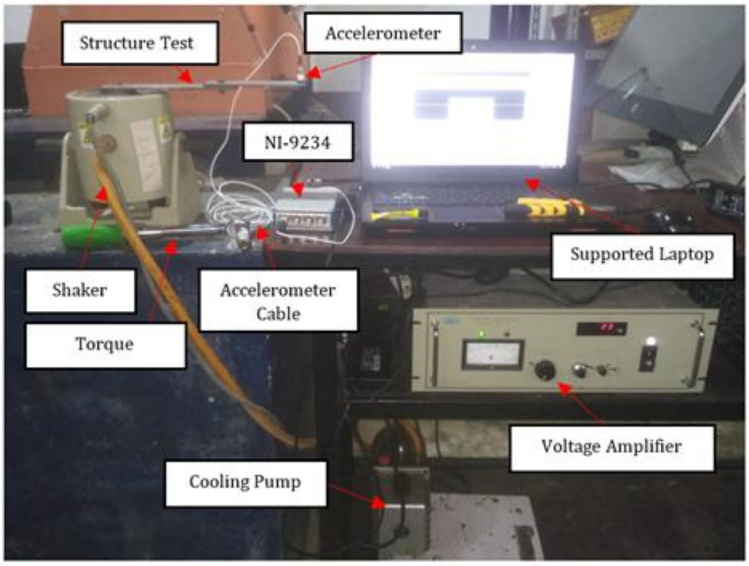

**Figure 2.** Experimental Set-up

## Data Acquisition for Bolt Loosening Investigation

The study examined the structure's dynamic response under varying 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.

## 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:

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

Where (xi) 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.

## RESULT AND DISCUSSION

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 illustrates the structure's acceleration responses recorded at different time intervals during the vibration test. In the early stage (0–5 minutes), the oscillations have relatively higher amplitudes, while the amplitude gradually decreases as time increases. The comparison across successive intervals (5–10, 10–15, 15–20, 20–25, and 25–30 minutes) highlights 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 for identifying dominant oscillatory components that may be difficult to distinguish 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 indicate structural degradation or evolving damage mechanisms. The frequency spectrum obtained using the Fast Fourier Transform (FFT), shown in Figure 4, provides insight into the signal's dominant frequency components.

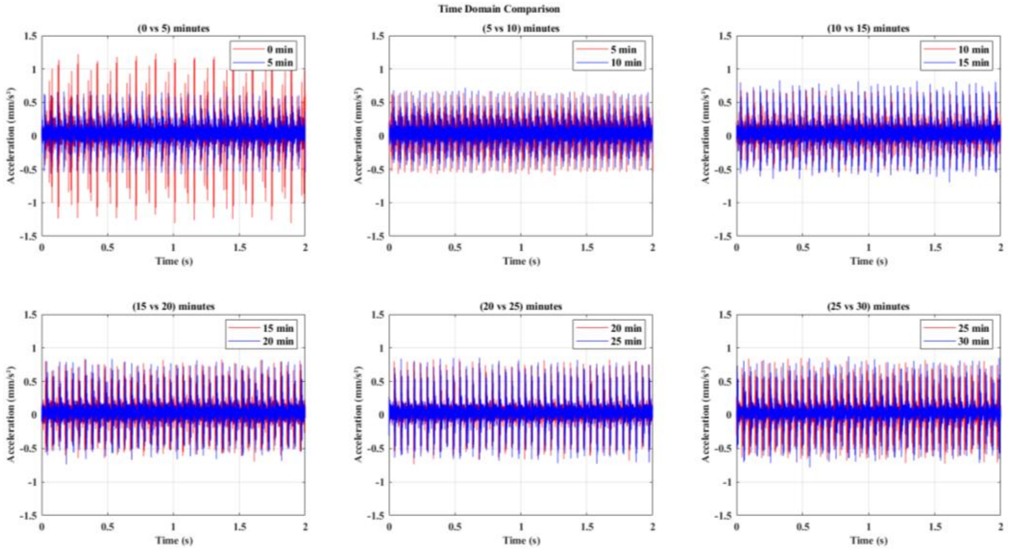

**Figure 3.** Loosening Test Results 1,5 Nm – Time Signal

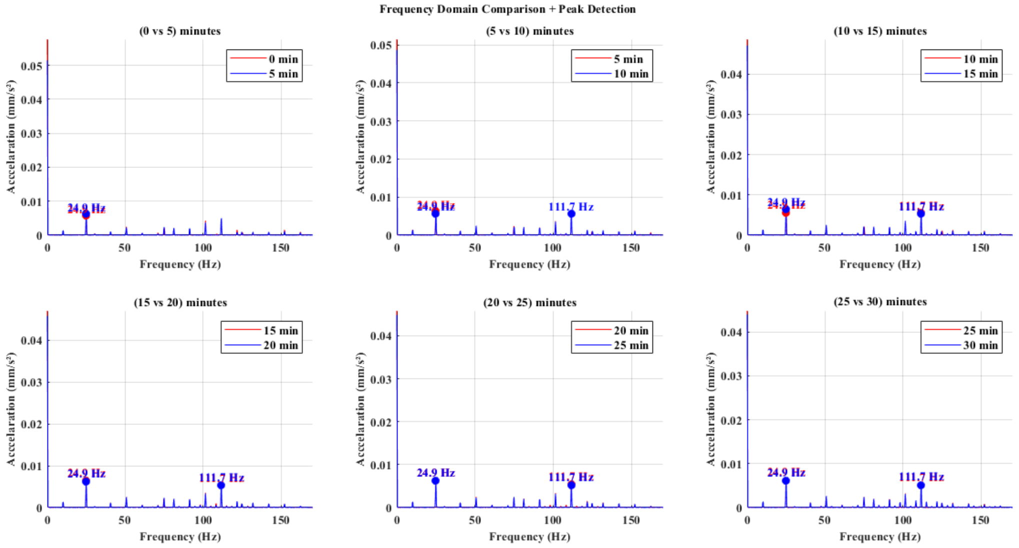

**Figure 4.** Loosening Test Results 2,5 Nm - FFT

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 system's dominant frequency components and remain consistent throughout the experiment, although their relative amplitudes vary slightly over 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 provides only a global frequency overview, lacking temporal localization, limiting the ability to detect when such frequency variations occur. This shortcoming underscores the need for advanced joint time–frequency analysis methods, such as the Short-Time Fourier Transform (STFT) and the Continuous

Wavelet Transform (CWT), to provide 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, where dynamic changes in system stiffness may induce subtle shifts in the vibration spectrum that are not readily detectable with FFT alone.

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 period, though their relative intensities fluctuate as loosening progresses. Such observations confirm the STFT's sensitivity to detecting transient variations that may indicate progressive structural changes.

However, using a fixed analysis window introduces an inherent trade-off between time and frequency resolution. Low-frequency components are represented with higher spectral resolution, whereas higher frequencies are represented with higher 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 its adaptability to resolution. 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 improves the localization of transient features and provides a more accurate representation of both low- and high-frequency phenomena in the signal.

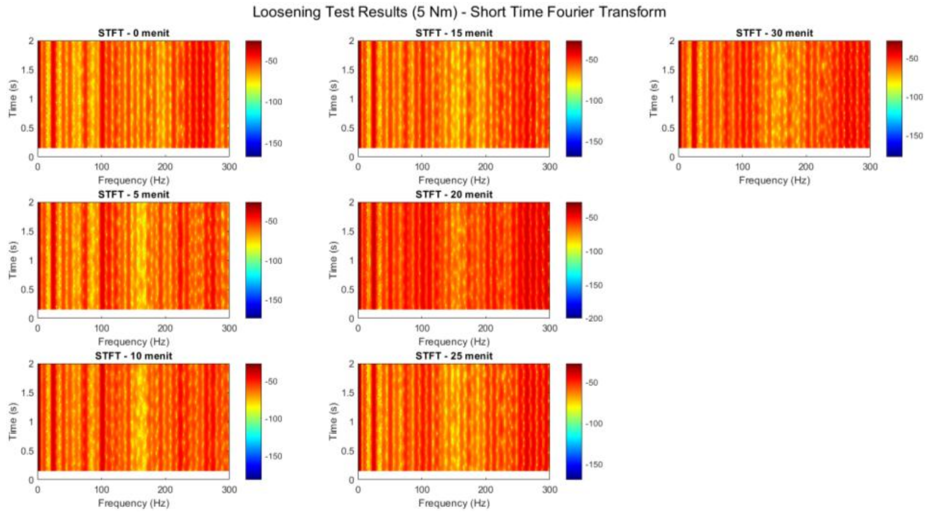

**Figure 5.** Loosening Test Results 5 Nm - STFT

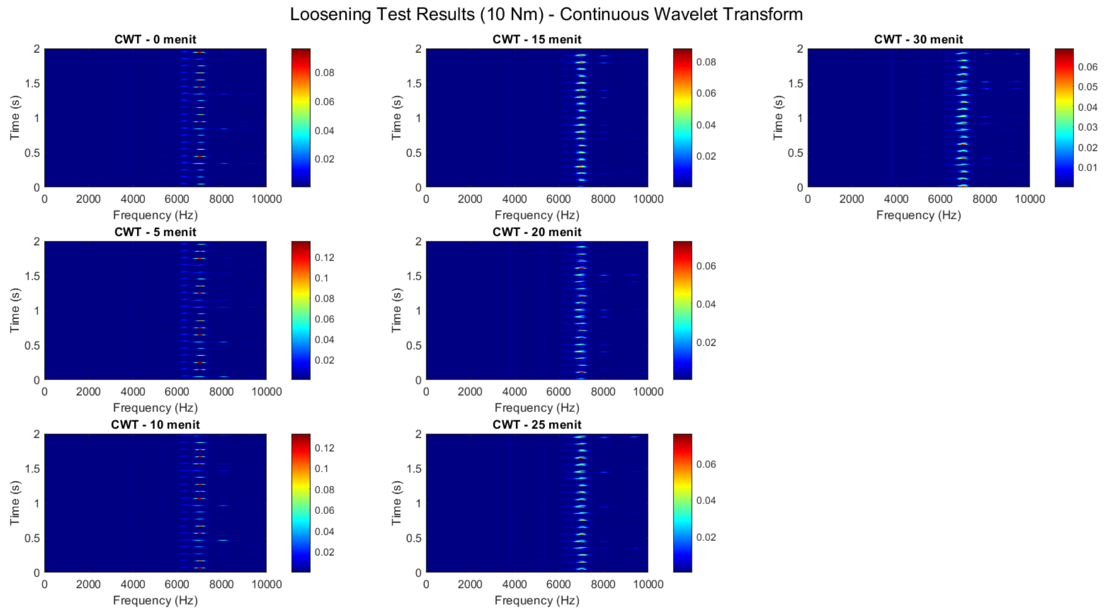

**Figure 6.** Loosening Test Results 10 Nm – All CWT signals (Range 10 kHz)

Figure 6 illustrates the CWT spectrogram of vibration signals under a 10 Nm bolt-loosening condition, analyzed over 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 the STFT due to fixed-window constraints.

The ability of CWT to reveal fine temporal and spectral details demonstrates its effectiveness in monitoring non-stationary vibration behavior, especially under progressive loosening. 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, interpreting CWT results requires careful consideration of scale selection and computational demands, which may increase with higher frequency resolution.

## 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) effectively captures the temporal dynamics of spectral content, but its fixed window size introduces a trade-off between time and frequency resolution. Consequently, while low frequencies are more clearly resolved in frequency, high-frequency components are better localized in time, leaving rapid frequency transitions partially obscured.

In contrast, the Continuous Wavelet Transform (CWT) offers superior adaptability, as its scalable windows deliver high-frequency 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 are less discernible in the STFT. Figure 7 shows that the CWT clearly reveals frequency variations across the 0–10 kHz range, demonstrating its robustness for analyzing complex, non-stationary vibration signals. Overall, the multi-perspective approach demonstrates the need for hybrid analysis techniques when evaluating dynamic real-world signals. The time domain reveals initial amplitude trends, the frequency domain highlights dominant components, and the time–frequency domain—particularly via the CWT—provides a comprehensive depiction of spectral evolution. This layered methodology enhances diagnostic reliability and provides a deeper understanding of structural changes under progressive bolt loosening.

## 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 the real-time implementation of these techniques, potentially incorporating machine learning algorithms to automate the detection and classification of loosening phenomena, thereby further advancing predictive maintenance strategies for critical engineering structures.

## DAFTAR PUSTAKA

[1] G. H. Junker, "Criteria for self-loosening of fasteners under vibration," NASA Technical Report, 1969.

[2] T. Sakai, "Theoretical and experimental study on bolt loosening mechanism under transverse loading," Journal of Mechanical Engineering Science, vol. 20, no. 1, pp. 53-60, 1978.

[3] B. Kenny and E. A. Patterson, "Load distribution in threaded connections due to bending," Journal of Strain Analysis, vol. 20, no. 3, pp. 139-146, 1985.

[4] Y. C. Tsai and C. C. Chou, "Identification of dynamic joint characteristics using substructure synthesis," Journal of Vibration and Acoustics, vol. 110, no. 2, pp. 146-153, 1988.

[5] M. Burdekin, "Finite element analysis of bolted joint relaxation," International Journal of Machine Tools and Manufacture, vol. 31, no. 1, pp. 1-14, 1991.

[6] G. E. Ramey and J. M. Jenkins, "Experimental evaluation of bolt loosening under vibration," Experimental Mechanics, vol. 39, no. 1, pp. 61-67, 1999.

[7] R. A. Ibrahim and C. L. Pettit, "Uncertainties and dynamic problems of bolted joints and other fasteners," Journal of Sound and Vibration, vol. 279, no. 3-5, pp. 857-936, 2005.

[8] H. Ouyang et al., "A simplified nonlinear dynamic model for the analysis of pipe structures with bolted flange joints," Journal of Sound and Vibration, vol. 297, no. 3-5, pp. 907-925, 2006.

[9] X. Chen et al., "Time-frequency analysis techniques for structural health monitoring: A comparative study," Mechanical Systems and Signal Processing, vol. 168, p. 108704, 2022.

[10] Y. Wang and Z. Li, "Wavelet-based damage detection in bolted connections under nonstationary excitation," Journal of Sound and Vibration, vol. 512, p. 116358, 2022.

[11] W. Jia and H. Li, "Dynamic characteristics and loosening mechanism of bolted joints under vibration," Engineering Structures, vol. 276, p. 115318, 2023.

[12] G. Liu et al., "Smart bolted joints for structural health monitoring: Recent advances and challenges," Mechanical Systems and Signal Processing, vol. 185, p. 109782, 2023.

[13] R. Zhang et al., "High-frequency vibration analysis for bolt loosening detection using wavelet transform," Journal of Vibration and Control, vol. 29, no. 1-2, pp. 123-135, 2023.

[14] J. Huang, J. Liu, H. Gong, and X. Deng, “A comprehensive review of loosening detection methods for threaded fasteners,” Mechanical Systems and Signal Processing, vol. 168, art. 108652, 2022, doi: 10.1016/j.ymssp.2021.108652.

[15] S. Lee, H. Kim, and J. Kim, “Vibration-Based Loosening Detection of a Multi-Bolt Structure Using Machine Learning Algorithms,” Sensors, vol. 22, no. 3, art. 1210, 2022, doi: 10.3390/s22031210.

[16] J. Tang, Z. Wang, and H. Li, “Bolt Loosening Monitoring of Multi-Bolt Connections Using Wavelet-Based Time–Frequency Diagrams and CNN,” Sensors, vol. 22, no. 21, art. 8323, 2022, doi: 10.3390/s22218323.

[17] Y. Chen, J. Jiang, X. Qin, and Q. Feng, “Quantitative Monitoring of Bolt Looseness Using Multichannel Piezoelectric Active Sensing and CBAM-Based CNN,” Frontiers in Materials, vol. 8, art. 677642, 2021, doi: 10.3389/fmats.2021.677642.

[18] H. Zhang, Y. Liu, and X. Wang, “Transmission tower bolt-loosening time–frequency analysis and wavelet packet transform,” Structural Health Monitoring, 2024, doi: 10.1177/14759217241242032.

[19] Y. Li, B. Cao, and X. Wang, “Detection Method for Bolt Loosening Based on Summation Coefficient of Absolute Spectrum Ratio (SCASR),” Sensors, vol. 25, no. 1, art. 246, 2025, doi: 10.3390/s25010246.

[20] J. Li, Y. He, Q. Li, and Z. Zhang, “AI-Based Evaluation of Bolt Loosening Using Vibro-Acoustic Modulation (VAM) Features from a Combination of Simulation and Experiments,” Applied Sciences, vol. 12, no. 24, art. 12920, 2022, doi: 10.3390/app122412920.